Power Electronics and Power Systems

For further volumes:
http://www.springer.com/series/6403

Rodrigo Garcia-Valle • João A. Peças Lopes
Editors

Electric Vehicle Integration into Modern Power Networks

Springer

Editors
Rodrigo Garcia-Valle
Electrical Engineering Department,
Technical University of Denmark
Electrovej Building 325
Kgs. Lyngby, Denmark

João A. Peças Lopes
Campus da FEUP
INESC TEC
Porto, Portugal

ISBN 978-1-4614-0133-9 ISBN 978-1-4614-0134-6 (eBook)
DOI 10.1007/978-1-4614-0134-6
Springer New York Heidelberg Dordrecht London

Library of Congress Control Number: 2012951617

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Preface

The need to largely reduce the amount of Carbon Dioxide (CO_2) emissions in the coming years all over the world requires a large effort in decarbonising the economy. One of the sectors most in need of this effort is the transportation sector. In fact, only a large reduction of CO_2 emissions in this sector will allow coping effectively with this problem. There are two ways to perform it (1) by increasing the amount of biofuels to be used by Internal Combustion Motors or (2) by making a shift towards electromobility. However, this shift towards the electrification of the transportation sector can only be well succeeded if one increases simultaneously the proportion of non-CO_2-emitting power generation technologies, namely renewable based power sources. European Union (EU) is developing a large effort on these matters. In fact, the energy-related targets set by EU policy require careful examination of potential solutions for the integration of renewable energy sources to meet the electricity demand. On the other side, the expected growing energy demand resulting from the introduction of electric-powered cars needs the development of innovative concepts to exploit the variable power supply. The application of dynamic techniques for prediction of electricity supply and demand, including electricity prices in the market, is expected to support the optimisation of the grid balance. The European wind markets predict an installed capacity that would provide 14 % of the electricity consumption in 2020. Today in Denmark and Portugal, the wind power accounts for more than 20 % of the power production. However, the variable character of this renewable power supply imposes special requirements on the whole system, including the future adoption of active load management and storage. Several recent research projects and studies indicate that the battery capacity of electric cars could contribute to obtain an efficient way of dealing with the variable power supply from wind plants. Also the relative static grid system will have to become intelligent in order to deal with the future electricity supply and demand. Utilities will have to integrate large-scale renewable power technologies as core parts of their long-term generation strategies. In parallel electric cars may ease the integration of renewable energies in the electricity networks and markets since they are very flexible loads and will be therefore most suited to provide balancing services to the grids. This book aims at establishing a state of the art and at identifying the needed solutions to support a massive integration of electricity consuming cars in our society. The book includes some material from the EU-funded project MERGE (Mobile Energy Resources in Grids of Electricity) and from the Danish EDISON project (Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks).

This book was inspired by the two courses held under the EES-UETP (Electric Energy Systems—University Enterprise Training Partnership) umbrella, in 2010 and 2011, in Denmark and Portugal, respectively.

This book encompasses nine chapters written by leading researchers and professionals from industry and academia who have a vast experience within this field.

Chapter 1 is the introductory part and gives an overview about the state of the art of this technology.

Chapter 2 describes the battery technology, including the modelling and performance of these devices for electric vehicle applications.

Chapter 3 demonstrates the influence of electric vehicle charging and its impact on the daily load consumption. The developed methodology may be used for new business models and management architectures for electric vehicle grid integration as further described in Chaps. 4 and 8, respectively.

Chapter 4 discusses different business models and control management architectures. The fuelling functions of an electric vehicle, how they influence the design of the electric vehicle and their grid connection infrastructure as enablers and limiters to the possible business models are mentioned. The comparison among three large electric vehicle integration projects is presented.

Chapter 5 shows up-to-date smart grid communication methods and related standardisation work for electric vehicle integration into modern power networks. A very extensive description of the information and communications technology solutions to incorporate electric vehicles is provided.

In Chaps. 6 and 7, steady state and dynamic behaviour advanced models, simulation tools and results for electric vehicle power system integration are presented. These chapters focus mainly on the development of different approaches and strategies to explain several important issues within this particular topic such as creation of load scenarios to evaluate electric vehicle grid impact, identification of charging management strategies for electric vehicle high controllability, identification of feasible electric vehicle penetration, feasibility of having electric vehicle participation in frequency control and electric vehicle contribution for the automatic generation control (AGC) to enable a higher renewable energy penetration into the electric system.

Chapter 8 gives a tutorial overview of the main regulatory issues of integrating electric vehicles into modern power networks, with more emphasis on the general role allocation and usual distribution of crucial functions. It describes and proposes a conceptual regulatory framework for various charging modes, such as home charging, public charging on streets and dedicated charging stations, giving justification for the development of two new entities as intermediary facilitators of the final service.

Chapter 9 illustrates the development of electric vehicle adoption from its very first steps to the numerous electric vehicle projects and activities around the world. The actual electric vehicle availability and the different electric vehicle manufactures are shown in this chapter with authentic photographs for the different electric vehicle technologies.

Acknowledgments

The editors would like to acknowledge all the different people involved in the creation of this manuscript, M. A. Pai for his encouragement to the realisation of this volume and Allison Michael from Springer US for her assistance and constant feedback during all this period. Special thanks must be given to the all contributors for their effort, great work and time spent to make this book a success.

Contents

Chapter 1
State of the Art on Different Types of Electric Vehicles

F.J. Soares, P.M. Rocha Almeida, João A. Peças Lopes, Rodrigo Garcia-Valle, and Francesco Marra

1.1 Introduction

In the first years of the automotive industry, there were three vehicle technologies competing for the market domination: Internal combustion engine (ICE) vehicles, steam cars, and electric vehicles (EV) [1]. All of them had their advantages and drawbacks and it was quite obvious that the technology that would become dominant was the one able to solve their problems faster.

The main drawbacks appointed to the ICE vehicles were the noise they produced, the difficulty in starting the engine, the short range, and the low maximum speed [2]. The steam cars, in their turn, had two main problems: they needed heating up around 20 min before travel and they consumed immense amounts of water [3, 4]. The main disadvantages of EV were related with the poor battery performance: they were unable to climb steep hills, and had a short driving range and a low maximum speed.

While the steam vehicles manufacturers were able to solve the need to heat up the vehicle before travel, they could not find any solution to reduce the water consumption, causing this technology to disappear from the markets around 1920 [1]. In the EV field, significant advances were attained in battery technology between 1910 and 1925, which increased their storage capacity by 35%, their lifetime by 300%, and their EV range by 230%, while their maintenance costs dropped 63% [5]. Nevertheless, ICE technology was even faster to evolve and outpaced by far EV technology. Between 1900 and 1912, some inventions helped ICE vehicles to increase the driving range and the maximum speed, to diminish the

F.J. Soares (✉) • P.M.R. Almeida • J.A. Peças Lopes
INESC TEC (formerly INESC Porto), Porto, Portugal
e-mail: filipe.j.soares@inescporto.pt; pedro.r.almeida@inescporto.pt; jpl@fe.up.pt

R. Garcia-Valle • F. Marra
Electrical Engineering Department, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark
e-mail: rgv@elektro.dtu.dk; fm@elektro.dtu.dk

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_1, © Springer Science+Business Media New York 2013

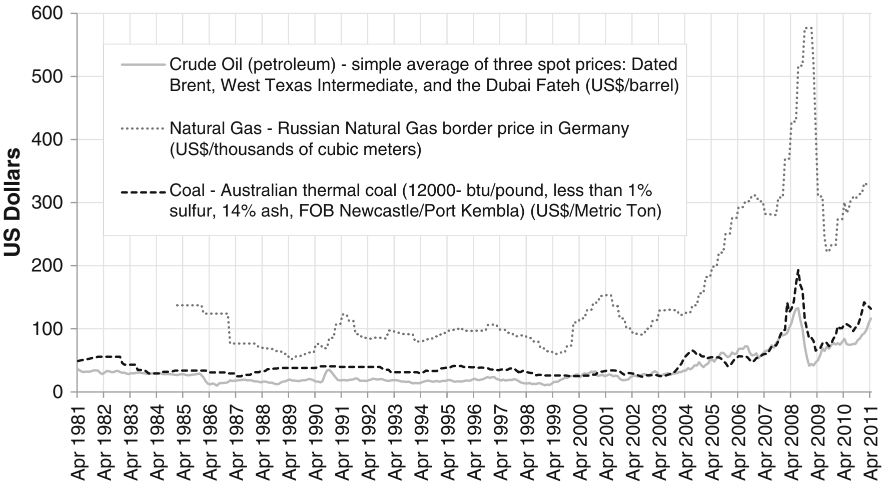


Fig. 1.1 Evolution of the fossil fuels prices [7]

water leakages, and to solve the start-up problem, giving them a significant market advantage that made them the leading technology till the present times [5, 6].

Nowadays, due to technical progresses, environmental demands, and the foreseeable shortage of fossil fuels in the medium-term, the EV industry seems to be starting to emerge. For several economic and environmental reasons, EV industry is very likely to have a noteworthy impact over the automobile world market.

The global warming problematic is one of the environmental reasons leveraging the large-scale adoption of EV. The growing concerns across the world with this issue, together with the increasing trend and high volatility of the fossil fuels prices (see Fig. 1.1), are leading policy makers to seek for measures to reduce these energy sources consumption and, consequently, to decrease the emissions of Greenhouse Gases (GHG) to the atmosphere. In addition, the absence of tailpipe emissions might be a very attractive characteristic of EV, principally for dense urban areas, given that it can provide a noteworthy contribution for the improvement of the air quality.

According to the OECD,[1] the transportation sector accounts for 53% of the world's oil consumption in 2009 and is expected to increase this value to 60% in 2035 [8]. This sector is responsible for 19.0% of the world's CO_2 emissions [9], being naturally one of the principal targets of countries' policies to mitigate the climate change problematic. The significance of the transportation sector is even higher in the developed countries, like in the USA and in European Union (EU),

[1] The Organization for Economic Co-operation and Development (OECD) is an international economic organization of 31 countries that defines itself as a forum of countries committed to democracy and the market economy, providing a setting to compare policy experiences, seeking answers to common problems, identifying good practices, and coordinating domestic and international policies of its members. For more information, see http://www.oecd.org/.

where it accounts for 31% and 24% of their total CO_2 production, respectively [9]. Even having a lower influence in the developing countries' CO_2 emissions, this sector is evolving very rapidly, accompanying these economies' fast growth. As an example, Angola's and China's CO_2 emissions increased 291% and 87%, respectively, between 2000 and 2007 [9].

Nevertheless, it should be stressed that the simple substitution of ICE vehicles by EV might not be enough to effectively reduce global GHG emissions inherent to the transportation sector. If the electricity used to supply EV is generated in power plants that use fossil fuels, the measure of replacing ICE vehicles, from a global perspective, will have a small impact. It will only shift fossil fuel consumption from the transportation sector to the electricity generation one, maintaining barely unchanged the global emissions of GHG. Nonetheless, it is certain that it would locally improve the air quality, mostly in the urban areas where vehicles density is higher, given that it would displace the tailpipe pollutants' emissions from these zones to the suburban or rural areas where, usually, the big power plants are sited.

Therefore, to significantly reduce the transportation sector GHG emission, policy makers need to ensure an increase in the Renewable Energy Sources (RES) exploitation, promoting, simultaneously, the conventional vehicles replacement by EV. These measures, if implemented together, will assure that the increase in the energy demand provoked by EV will not be followed by an increase in the amount of fossil fuels used to produce electricity and that part of the energy consumed in the transportation sector will be fulfilled with "clean" electricity.

However, while the integration of moderate quantities of EV into the distribution grids does not provoke any considerable impacts, their broad adoption would most likely create some problems in what regards grids' operation and management. Looking to EV as a simple uncontrollable load, it represents a large amount of consumed power, which easily can approach the power consumed in a typical domestic household at peak load. Thus it is easy to foresee major congestion problems in already heavily loaded grids, low voltage problems in predominantly radial networks, peak load and energy losses increase, and, probably, large voltage drops and load imbalances between phases in low voltage (LV) grids.

These problems may become a reality in the following years since, according to the IEA[2] projections, the sales of passenger light-duty EV/plug-in hybrid EV will boost from 2020 on and might reach more than 100 million of EV/plug-in hybrid EV sold per year worldwide by 2050 [10] (Fig. 1.2).

There are two ways of accommodating the presence of EV battery charging in the distribution grids, while avoiding the aforementioned problems. The first is to reinforce the existing infrastructures and plan new networks in such way that they can fully handle the EV integration, even for a large number of vehicles. Yet this rather expensive solution will require high investments in network infrastructures.

[2] The International Energy Agency (IEA) is an autonomous organization of 28 members which defines itself as an entity that works to ensure reliable, affordable, and clean energy for its member countries and beyond. For more information, see http://www.iea.org/.

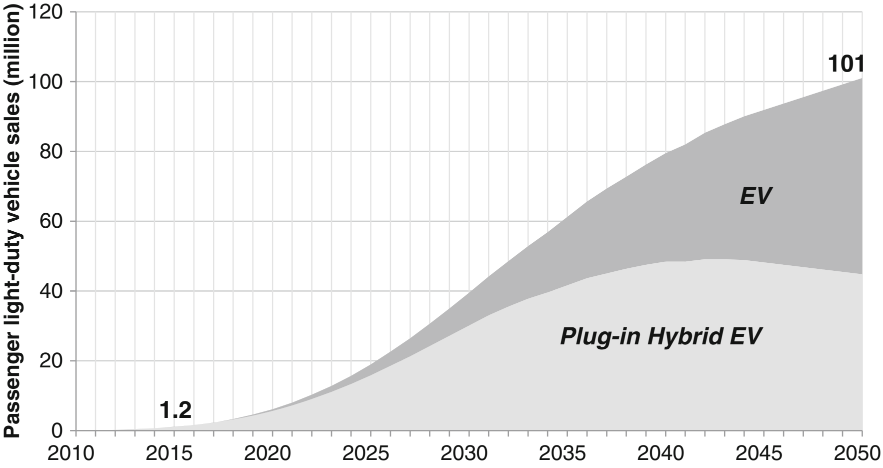


Fig. 1.2 Passenger light-duty vehicle sales [10]

The second is to develop and implement enhanced charging management strategies in the distribution networks, with demand side management (DSM) functionalities, capable of controlling EV charging according to the grid's needs and their owners' requirements. From the grid perspective, this approach yields more benefits once it provides elasticity to these new loads, allowing the management structure to reduce/increase its values when such action is needed to manage, for instance, branches' congestion levels or voltage problems. EV owners, by their turn, also benefit from these approaches, given that the services they provide to the grid will be remunerated accordingly.

In the long-term future, with the predictable improvement of batteries' performance, EV might not be regarded only as loads but also as dispersed energy storage. Under these conditions, the potential benefits from EV are even greater for the grid. This approach is based on the vehicle-to-grid (V2G) concept, which states that EV, when parked and plugged-in into the network, can either absorb energy and store it or inject electricity in the grid [11, 12]. Currently, the V2G concept is regarded by EV manufacturers with some suspicion, given that it imposes an aggressive operation regime to the batteries, constantly requesting shifts between absorption/injection modes, which leads to the premature aging of the battery.

The V2G concept is also very attractive from the environmental standpoint. The amount of RES that can be integrated into electrical power systems is restricted due to technical and economical limitations arising from their intermittent/variable nature. The high intermittency level associated with some of these resources, like wind, might cause high disturbances in the networks' dynamic behavior, namely, in isolated systems. Moreover, during the valley hours, the intermittent RES generation added to the must-run thermal units might exceed the energy demand, forcing RES generation curtailment, which is by all means undesirable. Besides the environmental drawbacks, the RES curtailment could make these technologies economically unattractive, given that they would not be allowed to produce whenever there were renewable resources available. The EV used in a V2G perspective can help to mitigate these problems.

The V2G capability, as described by Kempton and Tomic in [11], is the capability that EV have to "provide power to the grid while parked," meaning that V2G occurs only while the power flow occurs from the EV to the power grid.

Therefore, EV can be used as storage devices to compensate the intermittent nature of the RES production, performing primary frequency control and thus contributing to improve the systems' dynamic behavior [13]. The RES generation surplus problem can be solved by using the V2G concept embedded in an active charging management system implemented in the smart grid infrastructure. The result of such a combination might be a flexible management system, capable of mobilizing EV to charge during the periods where RES generation surplus exists, contributing to make the large-scale integration of RES economically feasible.

The progressive replacement of ICE vehicles by EV will also require the existence of different types of interfaces, i.e., charging infrastructures, between the grid and the EV to enable them to charge at different power rates. According to the findings of the MERGE Project,[3] the EV charging can be performed at three distinct levels: level 1 ($<$10 kW), level 2 ($>$10 kW and $<$40 kW), and level 3 ($>$40 kW) [14]. Level 1 charging is mainly related with individual slow chargers for domestic environment, while level 2 is related with chargers accessible in public areas, like malls or parking areas, and level 3 chargers are essentially associated to fast charging stations or battery swapping stations. These stations only make economic sense in urban areas, where the vehicles density is higher, or near highways and main roads, where a high number of EV make long journeys pass through. For rural areas, in economic terms, level 1 charging is very likely to be the most appropriate option since the geographic density of EV will probably be very low. Despite the charging level, all EV charging infrastructures will provoke undesired impacts in the distribution grid. Fast charging stations will, most likely, be connected to the Medium Voltage (MV) grid and they will require the availability of a very large amount of power in order to charge simultaneously several EV at level 3. One single slow charger, by its turn, has a very low probability of provoking any problem to the grid. However, the aggregated effect of a large number of these devices might lead the grid to be operated in very strained conditions or even to reach its technical limits.

The type of connection between the charging infrastructure and the grid is also a matter of great importance. Presently there are being developed in parallel several single-phase and three-phase solutions, as well as compatible plugs, like the SAE

[3] Mobile Energy Resources for Grids of Electricity (MERGE) is an EU-financed project to prepare the European electricity grid for the spread of electric vehicles. For more information, see http://www.ev-merge.eu/.

Yazaki plug,[4] the Mennekes plug,[5] the Walther plug,[6] the EDF plug,[7] or the Scame–Schneider–Legrand EV plug.[8] All these plugs are being developed to comply with some of the standards for EV connectors, like the EN 61851-1 [15], the EN 61851-21 [16], the EN 61851-22 [17], or the SAE J1772 [18]. However, to ease the large-scale adoption of EV, standards for hardware (connector/cable) and communication software should be the clearly defined and somehow unified, at least for large areas like Europe or North America.

Given this context, and especially considering the expected growth in EV integration levels, this book aims to provide a detailed and valuable study about EV impacts in electric power systems, which intends to alert all potentially interested parties for the various problems that will appear when EV start to be massively connected to the grid. Beyond the impacts assessment, it will also be presented appropriate management strategies for EV charging, to overcome all the technical issues identified. Envisioning future electrical power system's structure, these new strategies will be created taking into account the potential to control EV charging under the smart grid paradigm, being the EV regarded as active elements within the power system.

1.2 Electric Vehicles' Architectures

Battery Electric Vehicles (BEV) use solely a battery as energy source. An electric motor transfers the electric power to the wheels, by means of a power converter, connected between the battery and the motor.

Plug-in Hybrid Electric Vehicles (PHEV) are a hybrid technological solution, which uses both a battery and standard fuel as energy sources for driving. PHEV can utilize either only the battery for driving or only the Internal Combustion Engine (ICE), or their combination, depending on energy efficiency considerations. PHEV have the capability to be charged by the electricity grid, using either an on-board or an off-board charger. PHEV design includes a wide range of hardware options, the main ones are series hybrid, parallel hybrid, and series–parallel hybrid [19].

The main difference among the topologies is the drive system used and the interconnection of its components, before the power is transferred to the wheels.

[4] The YAZAKI plug was developed by a Japanese company with the same name. For more information, see http://www.yazaki.com/.

[5] The MENNEKES plug was developed by a North American company with the same name. For more information, see http://www.mennekes.com/.

[6] The Walther plug was developed by an international company with the same name. For more information, see http://www.waltherelectric.com/.

[7] The EDF plug was developed by the EDF group. For more information, see http://www.edf.com/.

[8] The Schneider–Legrand–Scame EV plug was developed in collaboration by three companies: Schneider Electric, Legrand, and Scame.

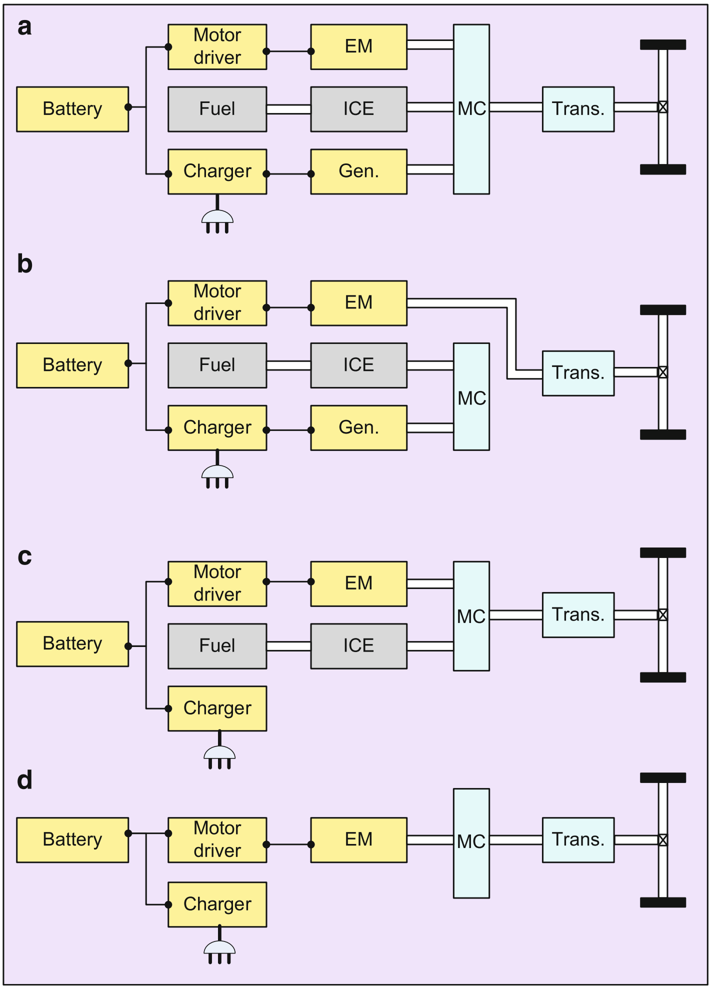


Fig. 1.3 PHEV system architectures, (**a**) Series–parallel PHEV, (**b**) Series PHEV, (**c**) Parallel PHEV, (**d**) BEV [19]

In the series–parallel hybrid vehicle, Fig. 1.3a, the system is designed to operate both in a series or a parallel configuration. The reconfigurable system is made possible by the use of a planetary gear, which is the mechanical coupling (MC) to the three machines. In the series hybrid vehicle (b), the electric traction system and ICE system operate in a series connection. In sequence, the ICE is coupled with a generator (Gen.) which generates the electric power for recharging the battery, the battery then supplies an electric motor driver to transfer power to wheels. In the parallel hybrid vehicle (c), the ICE and electric motor (EM) operate in parallel mode, where the ICE supports the electric traction at certain points of the driving pattern, e.g., when higher power is needed to the wheels. In the BEV, Fig. 1.3d, the drive system is realized using only an electric motor and a motor driver. The only energy source is the battery pack. For EV grid interaction, the main component of the vehicles is the battery pack due to its capability to store and provide electric energy. In the described architectures, the battery pack will have different capacity, due to the different vehicles' design. From a grid perspective, the plug-in vehicle is an energy storage unit, which can be plugged-in anywhere in the grid, independent of its architecture.

1.3 State of the Art of Energy Storage Solutions for Electric Vehicles

A state-of-the-art review about energy storage systems for automotive applications was performed by Lukic et al. in 2008 [20]. Several battery technologies were analyzed in detail and compared, with emphasis on the existent methods for battery monitoring, managing, protecting, and balancing. The authors also analyzed other storage systems, like ultracapacitors and fuel cells. In Fig. 1.4, it is presented a comparison between some of the main characteristics of batteries, fuel cell, and ultracapacitors. The specific power, specific energy, and life cycle values were not presented for the fuel cell technology as they were not available in [20].

In 2010, a new state-of-the-art review about energy storage technologies was performed by Khaligh et al. in [21]. Battery, ultracapacitor, and fuel cell technologies suitable for EV applications were again discussed and compared in great detail. In Fig. 1.5, it is presented a Ragone plot [23], for the referred energy storage technologies.

Despite the existence of several EV types with different powertrain architectures, there is an element that is common to all of them: the battery. In fact, batteries are so important to all the EV types that a significant part of the

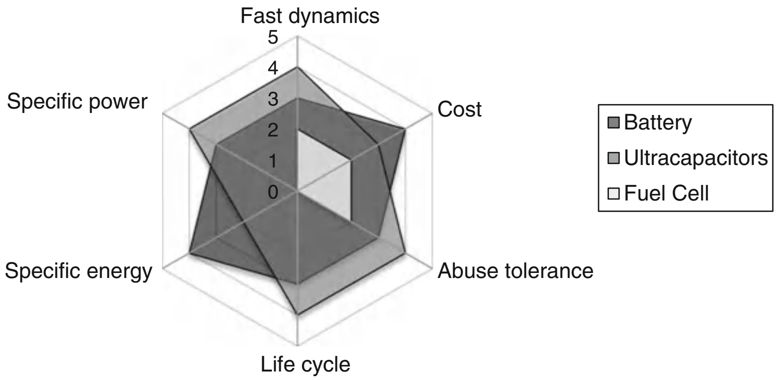


Fig. 1.4 Comparison of several available energy storage systems (adapted from [20])

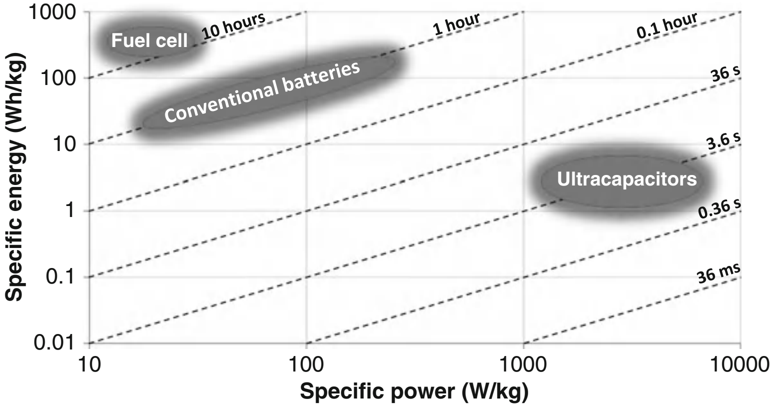


Fig. 1.5 Ragone plot for the various energy storage technologies suitable for EV (adapted from [22])

explanation for the EV flop in the past relies on the lack of progress in battery technologies. The lead-acid batteries, the same basic technology used 90 years ago, are still used in some EV, mainly due to their low cost and despite having low specific energies. According to Oman et al. in 1995 [24], lead-acid batteries had a nominal specific energy of 30 Wh/kg, while gasoline, by its turn, has an equivalent of 93 times more. While these two numbers are far from telling the entire technological story, they do point to the heart of the matter: high specific energy batteries at lower prices are required to make EV competitive regarding the performance features (in particular range and speed) thought necessary by today's consumers. Some opinions point out that in spite of this problem, the EV does represent a reasonable substitute for some urban uses, even though it is not yet a serious contender for extended highway use. Others mention that currently there are already batteries capable of making EV perform equally to ICE vehicles, despite their high costs.

In the beginning of this century, when the EV was one of the three prospective technologies, the intense research on battery technology led to significant improvements in their specific energy. According to Cowan et al. [1], in the 1890s, batteries' nominal specific energies were in the vicinity of 10 Wh/kg. By 1901 this value had been improved to 18 Wh/kg and by 1911 was close to 25 Wh/kg. Batteries' technological evolution was stopped at that point, however, and it has taken close to 80 years to double their capacity since then. A very important factor that contributed to halt the batteries' technological progress was the introduction of the starting lighting ignition into the gasoline car. This technology meant that every gasoline car would need a battery, and it was introduced at a point where sales of gasoline cars were beginning to grow very rapidly. This marked a dramatic change in the nature of demand for batteries, and battery manufacturers changed their R&D strategies accordingly, away from increasing the specific energy, since this was not nearly so important to the gasoline car, toward large-scale production [1].

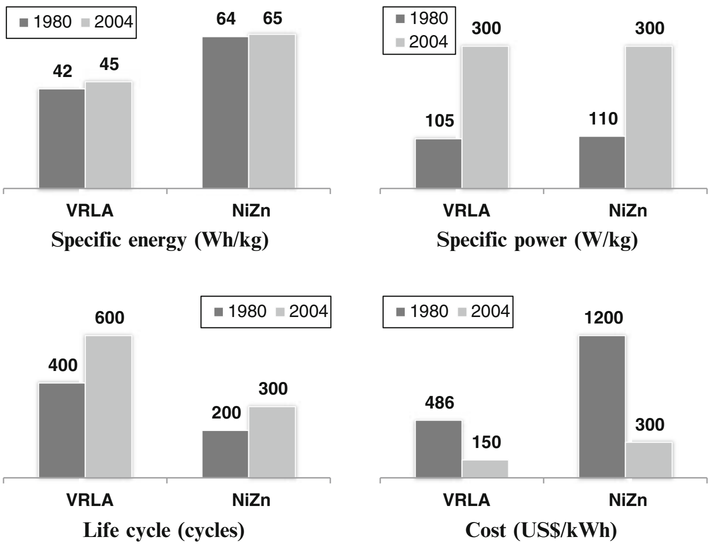


Fig. 1.6 Evolution of the VRLA and NiZn battery technologies between 1980 and 2004 (adapted from [25, 26])

There is some evidence now that the technological trajectory abandoned around 1915 was picked up again in the last years, as it can be seen in Fig. 1.6.

These figures show the evolution of the valve-regulated lead-acid (VRLA) and nickel–zinc (NiZn) battery technologies that occurred between 1980 and 2004, in terms of specific energy, specific power, life cycle, and cost, respectively. Moreover, despite their prohibitive cost, there are already some Lithium-ion (Li-ion) batteries that have specific energies between 90 and 190 Wh/kg and metal–air batteries with ca. 500 Wh/kg [27].

Some of the technological progress in this research field is no doubt due to the new market for batteries, namely, as a part of portable electronic goods.

The growth in this market and the accompanying demand for lighter, quickly rechargeable, and long-lasting batteries has created a strong enough demand for improvements that they are in fact taking place. These improvements, combined with advances in more exotic technologies, suggest that in the next few years batteries may cease to be the main bottleneck for the penetration of the EV into the automobile marketplace. Moreover, batteries development will also allow taking full advantage of the benefits arising from the dispersed storage that EV can provide, yielding profits both for the EV owner and for the distribution system operator.

A very large number of EV battery characterization and performance evaluation studies can be found in the literature, namely, from 1995 on, related with all the emerging battery technologies suitable for EV usage that are available in the market at the present time.

Table 1.1 Typical goals for HEV and BEV batteries (adapted from [28])

Parameter	Batteries for BEV	Batteries for HEV	Typical flooded lead-acid battery[a]
Specific energy (Wh/kg)	80–200	8–80	25–35
Energy density (Wh/l)	135–300	9–100	~70
Specific power (W/kg)	75–200	625–1,600	80–100
Life cycle (cycles; years)	600–1,000; 5–10	103–105; 5–10	200–400; 2–5
Cost (US$/kWh)	100–150	170–1,000	~100

[a]For comparison purposes

An overview about the battery requirements for EV technologies available in the markets and respective performances will be presented in Chap. 2.

Hunt, in 1998, presented an overview about battery technologies and their adequacy to the EV drivers' requirements [28]. The author refers that there are five key variables that influence the batteries performance in what regards their usage in EV: specific energy, energy density, specific power, life cycle, and cost. The typical goals for HEV and BEV batteries, in the author's viewpoint, are presented in Table 1.1.

In 2004, Chan et al. presented in [25] a detailed comparison between several EV battery technologies currently available in the markets and the goal figures defined by the USABC[9] for EV batteries.

The USABC goals are the following:

- Specific energy: 200 Wh/kg
- Energy density: 300 Wh/l
- Specific power: 400 kW/kg
- Life cycle: 1,000 cycles
- Projected cost: <100 US$/kWh

1.4 Conclusions

Currently, EV are a subject of great interest, either from the automotive industry or from R&D institutions, and are being faced by environmentalists and policy makers as one of most promising technologies to reduce the GHG concentration in the atmosphere and to strengthen the countries' energy security of supply.

---

[9] The U. S. Advanced Battery Consortium (USABC) seeks to promote long-term R&D within the domestic electrochemical energy storage industry and to maintain a consortium that engages automobile manufacturers, electrochemical energy storage manufacturers, the national laboratories, universities, and other key stakeholders. The main objective of USABC is to contribute to the development of electrochemical energy storage technologies which support commercialization of fuel cell, hybrid, and electric vehicles. For more information, see http://www.uscar.org/guest/view_team.php?teams_id=12.

Nevertheless, there are still some challenges that must be tackled in order to facilitate the large-scale deployment of EV. The safety and protection of the users during the EV charging process, the lack of standards for the charging infrastructures, and the technical problems related with the networks' operation, namely, when uncontrolled charging schemes are adopted, are some of the issues that must be timely and properly addressed in order to boost the adoption of this new type of vehicles.

Despite the problems they can provoke due to the unavoidable increase in the power demand, EV can also be very beneficial for the electricity networks. They can potentially contribute to make the load diagrams smoother along the day, to improve voltage profiles, and to decrease the congestion levels in the lines and transformers. Nevertheless, such benefits can only be achieved if proper EV charging management schemes are developed. In addition, if used under a V2G perspective, EV might also contribute to improve the system's dynamic behavior by performing primary frequency control and reducing the need for secondary reserves.

The high expectations concerning the potential of EV to reduce GHG emissions are essentially based on the reduction of fossil fuels consumption in the transportation sector that they will induce. However, to assure an effective reduction in fossil fuels consumption, the replacement of conventional vehicles by EV must be closely followed by a progressive increase in the RES integration. Nevertheless, especially in isolated systems, there is maximum threshold of RES integration (namely, in the case of variable sources) after which there is a high risk of renewable energy being wasted. In these cases, the EV storage capacity can potentially be used to increase the energy consumption in valley hours, where a renewable energy surplus may exist, contributing to avoid wasting "clean" energy and thus enabling higher RES integration levels.

References

1. Cowan R, Hultén S (1996) Escaping lock-in: the case of the electric vehicle. Technol Forecast Soc Change 53:61–79
2. D'Agostino S (1993) The electric car. Potentials IEEE 12:28–32
3. Garroway D (1961) Why don't we have a steam car? Steam Automobile 3:4
4. McLaughlin C (1965) The fall (and possible rise) of the steam car. Steam Automobile 7:2
5. Schallenberg RH (1980) Prospects for the electric vehicle: a historical perspective. IEEE Trans Educ 23:137–143
6. Sulzberger C (2004) An early road warrior: electric vehicles in the early years of the automobile. IEEE Power Energy Mag 2:66–71
7. Index Mundi. http://www.indexmundi.com/commodities/
8. OECD (2010) World Energy Outlook. OECD, Paris
9. World Resources Institute (2011) Climate Analysis Indicators Tool (CAIT) Version 8.0. World Resources Institute, Washington, DC. http://cait.wri.org/cait.php?page=sectors
10. IEA (2009) Technology roadmap: electric and plug-in hybrid electric vehicles. International Energy Agency (IEA), Paris

11. Kempton W, Tomic J (2005) Vehicle-to-grid power fundamentals: calculating capacity and net revenue. J Power Sources 144:268–279
12. Letendre SE, Kempton W (2002) The V2G concept: a new model for power? Public Util Fortnight Feb 15, pp 16–26
13. Lopes JAP et al (2009) Using vehicle-to-grid to maximize the integration of intermittent renewable energy resources in islanded electric grids. In: International conference on clean electrical power, pp 290–295
14. Bending S et al (2010) Specification for an enabling smart technology. Deliverable D1.1 of the European Project MERGE, Aug 2010
15. European Committee for Electrotechnical Standardization (2001) EN 61851–1:2001—Electric vehicle conductive charging system—Part 1: General requirements. CENELEC—European Committee for Electrotechnical Standardization, Paris
16. European Committee for Electrotechnical Standardization (2002) EN 61851–21:2002—Electric vehicle conductive charging system—Part 21: Electric vehicle requirements for conductive connection to an a.c/d.c. supply. CENELEC—European Committee for Electrotechnical Standardization, Paris
17. European Committee for Electrotechnical Standardization (2002) EN 61851–22:2002—Electric vehicle conductive charging system—Part 22: AC electric vehicle charging station. CENELEC—European Committee for Electrotechnical Standardization, Paris
18. SAE (2010) SAE J1772—Electric vehicle and plug in hybrid electric vehicle conductive charge coupler. SAE—Society of Automotive Engineers, Troy, MI
19. Marra F, Pedersen AB, Sacchetti D, Andersen PB, Traeholt C, Larsen E (2012) Implementation of an electric vehicle test bed controlled by a virtual power plant for contributing to regulating power reserves. In: IEEE Power and Energy Society (PES) General Meeting, San Diego, USA
20. Lukic SM et al (2008) Energy storage systems for automotive applications. IEEE Trans Ind Electron 55:2258–2267
21. Khaligh A, Zhihao L (2010) Battery, ultracapacitor, fuel cell, and hybrid energy storage systems for electric, hybrid electric, fuel cell, and plug-in hybrid electric vehicles: state of the art. IEEE Trans Vehicular Technol 59:2806–2814
22. Bertoldi O, Berger S (2009) Observatory NANO—Report on energy. European Commission, Brussels
23. Christen T, Carlen MW (2000) Theory of Ragone plots. J Power Sources 91:210–216
24. Oman H, Gross S (1995) Electric-vehicle batteries. IEEE Aerospace Electron Syst Mag 10:29–35
25. Chan CC, Wong YS (2004) Electric vehicles charge forward. IEEE Power Energy Mag 2:24–33
26. Webster WH Jr, Yao NP (1980) Progress and forecast in electric vehicle batteries. In: 30th IEEE vehicular technology conference, pp 221–227
27. Divya KC, Østergaard J (2009) Battery energy storage technology for power systems–an overview. Electric Power Syst Res 79:511–520
28. Hunt GI (1998) The great battery search [electric vehicles]. IEEE Spectrum 35:21–28

Chapter 2
Electric Vehicle Battery Technologies

Kwo Young, Caisheng Wang, Le Yi Wang, and Kai Strunz

2.1 Introduction

As discussed in the previous chapter, electrification is the most viable way to achieve clean and efficient transportation that is crucial to the sustainable development of the whole world. In the near future, electric vehicles (EVs) including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and pure battery electric vehicles (BEVs) will dominate the clean vehicle market [1, 2]. By 2020, it is expected that more than half of new vehicle sales will likely be EV models.[1] The key and the enabling technology to this revolutionary change is battery.

The importance of batteries to EVs has been verified in the history. The first EV was seen on the road shortly after the invention of rechargeable lead–acid batteries and electric motors in the late 1800s [4]. In the early years of 1900s, there was a golden period of EVs. At that time, the number of EVs was almost double that of gasoline power cars. However, EVs almost disappeared and gave the whole market to

[1] Though fuel cell vehicle (FCV) is one of the technologies under consideration of electric-drive vehicles, the durability, high cost, and production and distribution of hydrogen have hindered its development. The US Department of Energy (DOE) dropped its research support for FCV in its budget of fiscal year of 2010 [3].

K. Young
Ovonic Battery Company, Rochester Hills, MI, USA
e-mail: kyoung@ovonic.com

C. Wang (✉) • L.Y. Wang
Wayne State University, Detroit, MI, USA
e-mail: cwang@wayne.edu; lywang@wayne.edu

K. Strunz
Technische Universität Berlin, Berlin, Germany
e-mail: kai.strunz@tu-berlin.de

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_2,

Table 2.1 Batteries used in electric vehicles of selected car manufacturers.

Company	Country	Vehicle model	Battery technology
GM	USA	Chevy-Volt	Li-ion
		Saturn Vue Hybrid	NiMH
Ford	USA	Escape, Fusion, MKZ HEV	NiMH
		Escape PHEV	Li-ion
Toyota	Japan	Prius, Lexus	NiMH
Honda	Japan	Civic, Insight	NiMH
Hyundai	South Korea	Sonata	Lithium polymer
Chrysler	USA	Chrysler 200C EV	Li-ion
BMW	Germany	X6	NiMH
		Mini E (2012)	Li-ion
BYD	China	E6	Li-ion
Daimler Benz	Germany	ML450, S400	NiMH
		Smart EV (2010)	Li-ion
Mitsubishi	Japan	iMiEV (2010)	Li-ion
Nissan	Japan	Altima	NiMH
		Leaf EV (2010)	Li-ion
Tesla	USA	Roadster (2009)	Li-ion
Think	Norway	Think EV	Li-ion, Sodium/Metal Chloride

internal combustion engine (ICE) cars by 1920 due to the limitations of heavy weight, short trip range, long charging time, and poor durability of batteries at that time.

EV batteries are quite different from those used in consumer electronic devices such as laptops and cell phones. They are required to handle high power (up to a hundred kW) and high energy capacity (up to tens of kWh) within a limited space and weight and at an affordable price. Extensive research efforts and investments have been given to the advanced battery technologies that are suitable for EVs all over the world. The U.S. government has been strongly supporting its R&D activities in advanced batteries through the Department of Energy (DOE): about $2 billion grants to accelerate the manufacturing and development of the next generation of U.S. batteries and EVs [1]. European Commission and governmental organizations in Europe and Japanese Ministry of Economy, Trade and Industry (METI) have also been continuously supporting the R&D activities in advanced batteries. BYD, Lishen, and Chunlan have obtained strong subsidy supports from the Chinese government for its research and manufacturing of advanced batteries and electric vehicles.

As shown in Table 2.1 [4], the current two major battery technologies used in EVs are nickel metal hydride (NiMH) and lithium ion (Li-ion). Nearly all HEVs available in the market today use NiMH batteries because of its mature technology. Due to the potential of obtaining higher specific energy and energy density, the adoption of Li-ion batteries is expected to grow fast in EVs, particularly in PHEVs and BEVs. It should be noted that there are several types of Li-ion batteries based on similar but certainly different chemistry.

EVs can be integrated into the power grid in future. They can be aggregated together for grid supports such as renewable accommodation, frequency regulation, voltage profile regulation, and system optimization. They can also be operated in a distributed way and work with local loads to achieve demand side management. As to the EV grid integration issues discussed in the book, the battery inside the EVs is the key component. In this chapter, the fundamentals of EV battery technologies will be addressed. The focus will be given to the two most common EV battery technologies: NiMH and Li-ion. It is particularly important for power engineers to understand the basic chemistry of the different batteries, and specific EV battery requirements of energy density, specific energy, power density, cost, durability, etc. The EV battery modeling will be introduced in the way that it is suitable for power engineers to appreciate and use it for power electronic interfacing converter design, battery management, and system level studies. The performance of a battery changes as its operating conditions (temperature, charging or discharging current, state of charge (SOC), etc.) and its service time vary. This chapter will also cover the topic on battery characterization including battery model parameter estimation, SOC and state of health (SOH) estimation. The battery power management and the re-use of second-hand EV batteries for stationary power grid applications will be discussed at the end of this chapter.

2.2 Power and Energy of Electric Propulsion

Depending on the actual configuration of an EV, part or all of its propulsion power and energy is supplied by the battery inside the vehicle. Without loss of generality, the discussion in this subsection is for a pure battery EV. Similar to those in regular vehicles, the powertrain in an EV needs to provide power for the vehicle under all kinds of road conditions and driving modes. In addition, an EV also needs to handle regenerative braking so that the kinetic energy of the moving vehicle can be captured and stored in battery for future use.

The acceleration of a vehicle is determined by all the forces applied on it, which is given by Newton's second law as [5]

$$f_m M\alpha = F_t - \sum F_r, \tag{2.1}$$

where M is the overall mass of the vehicle, α is the vehicle acceleration, f_m is the mass factor that converts the rotational inertias of rotating components into equivalent translational mass, F_t is the total traction force to the vehicle, and $\sum F_r$ is the total resistive force. The resistive forces are normally the rolling resistance between tires and road surface, aerodynamic drag, and uphill grading resistance. The total resistance can be estimated as [5]

$$\sum F_r = MgC_{rr}\cos\theta + \frac{1}{2}\rho AC_d(V - V_w)^2 + Mg\sin\theta, \tag{2.2}$$

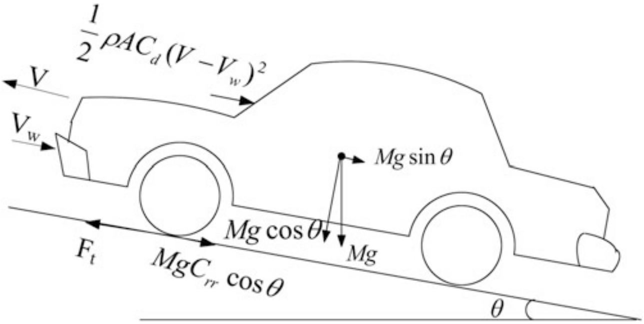


Fig. 2.1 Forces applied on a vehicle

where g is the acceleration of gravity, C_{rr} is coefficient of rolling resistance between tires and road surface, ρ is the density of the ambient air, A is the vehicle frontal area, C_d is the aerodynamic drag coefficient, V is the vehicle speed, V_w is the wind speed in the vehicle moving direction, and θ is the slope angle. For a downhill slope, θ will have a negative value (Fig. 2.1).

The total propulsion force can then be expressed as

$$F_t = f_m M\alpha + MgC_{rr}\cos\theta + \frac{1}{2}\rho AC_d(V - V_w)^2 + Mg\sin\theta. \qquad (2.3)$$

The power to drive the vehicle at speed V is then

$$P = F_t V = f_m M\alpha V + MgC_{rr}V\cos\theta + \frac{1}{2}\rho AC_d V(V - V_w)^2 + MgV\sin\theta. \qquad (2.4)$$

For a vehicle on a flat road ($\theta = 0$), at the early stage of acceleration, the propulsion power is mainly used to accelerate the vehicle and to overcome the rolling resistance. When the speed is reached, the power is used to keep the speed by overcoming the rolling resistance and aerodynamic drag force. For an electric vehicle, the battery power capability needs to be sufficient to meet acceleration requirements. For accelerating a vehicle with the parameters listed in Table 2.2, according to (2.4), it needs about 61 kW on average to accelerate the vehicle to 96.6 km/h (or 60 mph) in 10 s.

In the procedure of regenerative braking, the electric propulsion motor in an EV works as a generator to convert the kinetic energy of vehicle motion into electrical energy and charge battery. The braking power can be expressed as

$$P_b = F_b V = f_m M\mu V - MgC_{rr}V\cos\theta - \frac{1}{2}\rho AC_d V(V - V_w)^2 - MgV\sin\theta, \qquad (2.5)$$

where P_b is the braking power, F_b is the braking force, and μ is the deceleration of the vehicle.

Table 2.2 Propulsion power of a typical vehicle.

Mass	1,360 kg
Mass factor, f_m	1.05
Acceleration, 0 to 96.6 km/h in 10 s	2.68 m^2/s
Coefficient of rolling resistance	0.02
Air density	1.225 kg/m^3
Vehicle frontal area	2 m^2
Aerodynamic drag coefficient	0.5
Wind speed	0 m/s
Road slope angle	0°
Average power during the acceleration	60.8 kW

For the same vehicle listed in Table 2.2, the peak braking power for bringing the vehicle moving at 96.6 km/h to stop in 5 s can be as high as 186 kW. It can be seen that the power rating requirement is higher for braking since the de-acceleration may have to happen in a shorter period of time. The battery in the electric powertrain is required to meet the demands from both supplying and absorbing the high power.

A more challenging issue to EV is the energy capability of battery. According to the U.S. urban dynamometer driving schedule (UDDS) and the highway fuel economy driving schedule (HWFEDS) also called the highway fuel economy test (HWFET), typical energy consumption of a mid-size vehicle for urban driving is 165 Wh/km and 137 Wh/kg for highway. There are more aggressive driving schedules such as US 06 with an energy consumption close to 249 Wh/km [4]. Using the weighting factors of 45% urban, 45% highway, and 10% US 06, we can then get an average energy consumption rate of 160 Wh/kg (45% × 137 Wh/km + 45% × 165 Wh/km + 10% × 249 Wh/kg). Though the energy consumption during driving depends on many factors such as vehicle size, weight, body shape, and the driving habit of the driver, the key factor is the capacity of the energy storage device. The high value of specific energy of gasoline gives a conventional ICE powered vehicle a range of 300–400 miles with a full tank of gasoline. Gasoline has a theoretical specific energy of 13,000 Wh/kg, which is over 100 times higher than the specific energy of 120 Wh/kg of typical Li-ion batteries. It would be too big and heavy to have a battery pack with the same amount of energy as a full tank (e.g., 16 gallons) of gasoline. However, since the electric propulsion is much more efficient than an ICE, less energy is needed to propel an EV. Considering the efficiency of 80% for EV propulsion and 20% for ICE, the total amount of energy stored for EV can be a quarter of what a regular ICE powered vehicle needs for the same mileage. Based on the current battery technology, it is not practical to consider a pure BEV with a mile range of 300–400 miles since it would require a battery pack larger than 100 kWh that can weigh over 900 kg. Nevertheless, it is realistic to have a battery pack around 30 kWh to achieve 100 mile range even based on current battery technologies.

2.3 Basic Terms of Battery Performance and Characterization

Various terms have been defined for batteries to characterize their performance. Commonly used terms are summarized in the following as a quick reference.

Cell, Module, and Pack. A single cell is a complete battery with two current leads and separate compartment holding electrodes, separator, and electrolyte. A module is composed of a few cells either by physical attachment or by welding in between cells. A pack of batteries is composed of modules and placed in a single containing for thermal management. An EV may have more than one pack of battery situated in a different location in the car.

Ampere-hour Capacity. Ampere-hour (Ah) capacity is the total charge that can be discharged from a fully charged battery under specified conditions. The *Rated Ah capacity* is the nominal capacity of a fully charged new battery under the conditions predefined by the manufacturer. A nominal condition, for example, can be defined as 20°C and discharging at 1/20 C-rate. People also use Wh (or kWh) capacity to represent a battery capacity. The rated Wh capacity is defined as

$$Rated\ Wh\ Capacity\ = Rated\ Ah\ Capacity \times Rated\ Battery\ Voltage. \quad (2.6)$$

C-rate. C (*nominal C-rate*) is used to represent a charge or discharge rate equal to the capacity of a battery in one hour. For a 1.6 Ah battery, *C* is equal to charge or discharge the battery at 1.6 A. Correspondingly, *0.1C* is equivalent to 0.16 A, and *2C* for charging or discharging the battery at 3.2 A.

Specific Energy. Specific energy, also called gravimetric energy density, is used to define how much energy a battery can store per unit mass. It is expressed in Watt-hours per kilogram (Wh/kg) as

$$Specific\ Energy = Rated\ Wh\ Capacity/Battery\ Mass\ in\ kg. \quad (2.7)$$

Specific energy of a battery is the key parameter for determining the total battery weight for a given mile range of EV.

Specific Power. Specific power, also called gravimetric power density of a battery, is the peak power per unit mass. It is expressed in W/kg as

$$Specific\ Power = Rated\ Peak\ Power/Battery\ Mass\ in\ kg. \quad (2.8)$$

Energy Density. Energy density, also referred as the volumetric energy density, is the nominal battery energy per unit volume (Wh/l).

Power Density. Power density is the peak power per unit volume of a battery (W/l).

Internal Resistance. Internal resistance is the overall equivalent resistance within the battery. It is different for charging and discharging and may vary as the operating condition changes.

Peak Power. According to the U.S. Advanced Battery Consortium (USABC)'s definition, the peak power is defined as [6]

$$P = \frac{2V_{oc}^2}{9R}, \tag{2.9}$$

where V_{oc} is the open-circuit voltage and R is the internal resistance of battery. The peak power is actually defined at the condition when the terminal voltage is 2/3 of the open-circuit voltage.

Cut-off Voltage. Cut-off voltage is the minimum allowable voltage defined by the manufacturer. It can be interpreted as the "empty" state of the battery.

State of Charge (SOC). SOC is defined as the remaining capacity of a battery and it is affected by its operating conditions such as load current and temperature.

$$SOC = \frac{Remaining\,Capacity}{Rated\,Capacity}. \tag{2.10}$$

If the Ah capacity is used, the change of SOC can be expressed as

$$\Delta SOC = SOC(t) - SOC(t_0) = \frac{1}{Ah\,Capacity}\int_{t0}^{t} i(\tau)d\tau. \tag{2.11}$$

SOC is a critical condition parameter for battery management. Accurate gauging of SOC is very challenging, but the key to the healthy and safe operation of batteries.

Depth of Discharge (DOD). DOD is used to indicate the percentage of the total battery capacity that has been discharged. For deep-cycle batteries, they can be discharged to 80% or higher of DOD.

$$DOD = 1 - SOC. \tag{2.12}$$

State of Health (SOH). SOH can be defined as the ratio of the maximum charge capacity of an aged battery to the maximum charge capacity when the battery was new [7]. SOH is an important parameter for indicating the degree of performance degradation of a battery and for estimating the battery remaining lifetime.

$$SOH = \frac{Aged\,Energy\,Capacity}{Rated\,Energy\,Capacity}. \tag{2.13}$$

Cycle Life (number of cycles). Cycle life is the number of discharge–charge cycles the battery can handle at a specific DOD (normally 80%) before it fails to meet specific performance criteria. The actual operating life of the battery is affected by the charging and discharging rates, DOD, and other conditions such as temperature.

The higher the DOD, the shorter the cycle life. To achieve a higher cycle life, a larger battery can be used for a lower DOD during normal operations.

Calendar Life. Calendar life is the expected life span of the battery under storage or periodic cycling conditions. It can be strongly related to the temperature and SOC during storage.

Battery Reversal. Battery reversal happens when the battery is forced to operate under the negative voltage (voltage of positive electrode is lower than that in the negative electrode). It can happen on a relatively weak cell in a serially connected battery string. As the usable capacity of that particular weak cell runs out, the rest of batteries in the same string will still continue to supply the current and force the weak cell to reverse its voltage. The consequence of battery reversal is either a shortening cycle life or a complete failure.

Battery Management System (BMS). BMS is a combination of sensors, controller, communication, and computation hardware with software algorithms designed to decide the maximum charge/discharge current and duration from the estimation of SOC and SOH of the battery pack.

Thermal Management System (TMS). TMS is designed to protect the battery pack from overheating and to extend its calendar life. Simple forced-air cooling TMS is adopted for the NiMH battery, while more sophisticated and powerful liquid-cooling is required by most of the Li-ion batteries in EV applications.

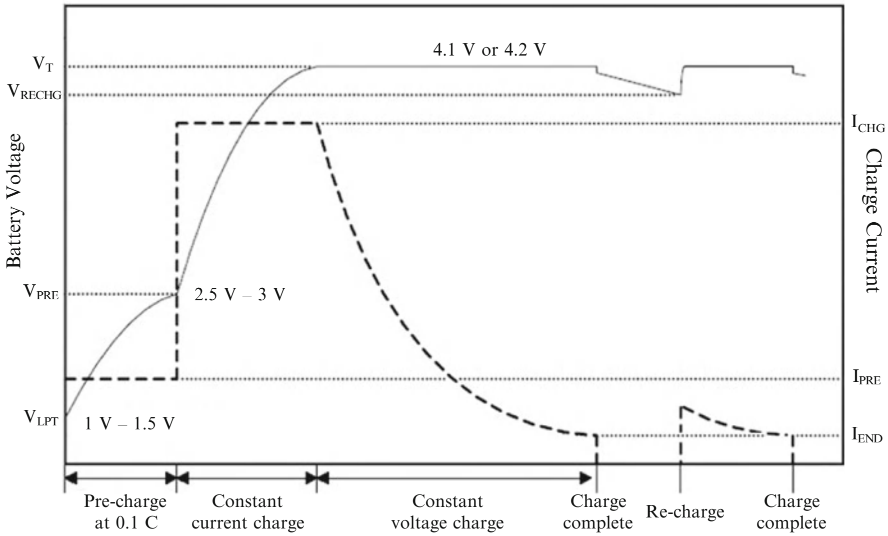
2.4 Battery Charging Methods and EV Charging Schemes

The safety, durability, and performance of batteries are highly dependent on how they are charged or discharged. Abuse of a battery can significantly reduce its life and can be dangerous. A current BMS includes both charging and discharging control on-board. In the future, it will be integrated into the grid energy distribution system. Hence, the focus here is given to the discussion on battery charging and charging infrastructure of EVs.

2.4.1 Charging Methods

For EV batteries, there are the following common charging methods [8]:

1. Constant Voltage. Constant voltage method charges battery at a constant voltage. This method is suitable for all kinds of batteries and probably the simplest charging scheme. The battery charging current varies along the charging process. The charging current can be large at the initial stage and gradually decreases to zero when the battery is fully charged. The drawback in this method



I_{CHG}:	Charge current. 0.5C-1C can be considered as fast charge.	V_T:	Battery terminal voltage.
I_{PRE}:	Pre-charge current, e.g. 0.1 C.	V_{RECHG}:	Threshold voltage to start recharge.
I_{END}:	Ending charge current, e.g. 0.02 C.	V_{PRE}:	Voltage when pre-charge finished.
		V_{LPT}:	Low protection threshold voltage.

Fig. 2.2 Typical Li-ion cell charge profile

is the requirement of very high power in the early stage of charging, which is not available for most residential and parking structures.

2. Constant Current. In this charging scheme, the charging voltage applied to the battery is controlled to maintain a constant current to the battery. The SOC will increase linearly versus time for a constant current method. The challenge of this method is how to determine the completeness of a charge with SOC = 100%. The cut-off can be determined by the combination of temperature raise, temperature gradient raise, voltage increase, minus voltage change, and charging time.
3. The combination of constant voltage and constant current methods. During the charging process of a battery, normally both the methods will be used. Figure 2.2 shows a charging profile of a Li-ion cell. At the initial stage, the battery can be pre-charged at a low, constant current if the cell is not pre-charged before. Then, it is switched to charge the battery with constant current at a higher value. When the battery voltage (or SOC) reaches a certain threshold point, the charging is changed to constant voltage charge. Constant voltage charge can be used to maintain the battery voltage afterward if the DC charging supply is still available.

For EVs, it is important for batteries to be able to handle random charging due to regenerative braking. As discussed in the previous section, the braking power of regenerative braking can be at the level of hundred kilowatts. Safety limitation has to be applied to guarantee the safe operation of batteries. Mechanical braking is usually used to aid regenerative braking in EVs as a supplementary and safe measure.

It is also critical to know when to stop charging a battery. It would be ideal if the battery SOC can be accurately gauged so that we can stop charging a battery when SOC reaches a preset value (e.g., 100%). As discussed later in the chapter, it has been a very challenging task to accurately estimate SOC. Even if the SOC of a battery can be exactly identified, it is also needed to have some other backup methods to stop charging. The following are some typical methods currently used to stop a charging process.

1. Timer. It is the most typical stopping method, which can be used for any types of battery. When a preset timer expires, the charging process is stopped.
2. Temperature Cut Off (TCO) . The charging will be stopped if the absolute temperature of battery rises to a threshold value.
3. Delta Temperature Cut Off (DTCO). When the delta change in battery temperature exceeds the safety value, the charging will be terminated.
4. Temperature change rate dT/dt. If the temperature change rate is over the safety threshold value, the charging process will be terminated.
5. Minimum Current (I_{min}). When the charging current reaches the lowest limit I_{min}, the charging process stops. This method is normally incorporated with a constant voltage charging scheme.
6. Voltage Limit. When the battery voltage reaches a threshold value, the charging process will be terminated. This method normally goes together with a constant current charging method.
7. Voltage Change Rate, dV/dt. The charging process stops if the battery voltage does not change versus time, or even if it starts to drop (a negative value of dV/dt).
8. Voltage Drop ($-\Delta V$). In NiMH battery, upon completion of the charge process (SOC = 100%), the temperature of the cell starts to increase due to the recombination of hydrogen and hydroxide ions and causes the cell voltage to drop. The charging will be terminated if a preset value of the voltage drop is reached.

2.4.2 EV Charging Schemes

The success of EVs will be highly dependent on whether charging stations can be built for easy access. This is also critical for the potential grid supports that EVs can provide. The first place considered for charging stations should be homes and workplaces. Other potential locations with high populations include gas stations, shopping centers, restaurants, entertaining places, highway rest areas, municipal facilities, and schools.

There have been various standards regarding the energy transfer, connection interface and communication for EV charging [8, 9]. Table 2.3 summarizes some of the standards, as also shown in Fig. 2.3. Since it is a very dynamic area, these standards may be either updated with new revisions or replaced by new standards in the near future.

Table 2.3 Standards related to electric vehicle charging

Standard	Title/description
National Electric Code Article 625	Electric Vehicle Charging System
SAE J2293	Energy Transfer System for Electric Vehicles
SAE J2836	Recommended Practice for Communication between Plug-in Vehicles and Utility Grid
SAE J1772	Electric Vehicle Conductive Charge Coupler
SAE J1773	Electric Vehicle Inductively Coupled Charging
IEC 62196	Plugs, socket outlets, vehicle couplers and vehicle inlets—Conductive charging of electric vehicles
IEEE 1547.3	Interconnecting Distributed Resources with Electric Power Systems

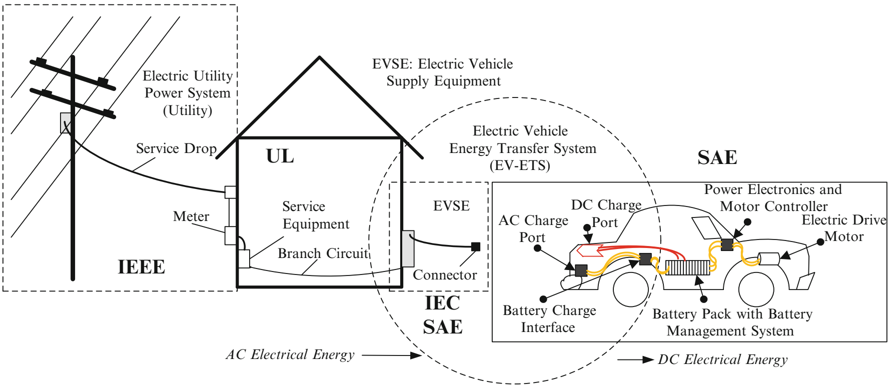


Fig. 2.3 Electric vehicle energy transfer system applicable standards. Modified from [9]

Table 2.4 EV charging power level

Charging level	Typical charging power
Level I	1.5–3 kW
Level II	10–20 kW
Level III	40 kW and up

In addition to the requirement of power quality (voltage, frequency, and harmonics) for EVs, the utility companies are most concerned about the charging power levels of EV. According to the Society of Automotive Engineers (SAE) Standard J1772, there are three charging levels, as shown in Table 2.4.

Level I and Level II are suitable for home. If, for example, one considers 2 kW as the average power demand of a typical home in North America, then the charging load of Level I is about 70–100% of the average home power consumption. The charging power of Level II can be over 5 times higher than that of Level II.

Table 2.5 EV charging schemes [10]

Features	V0G	V1G	V2G	V2B
Real-time communication		√	√	√
Communication with grid		√	√	
Timed charging		√	√	√
Backup source			√	√
Controllable load		√	√	√
Bidirectional grid ancillary service			√	
Load shifting for renewables			√	√

Therefore, it may be necessary to limit the charge rate to accommodate the rating of the on-board devices. For example, Chevy Volt and Nissan Leaf limit their charging rate to 3.3 kW [2].

Level III is for fast charging, which can give an EV 300 km range in one hour charging. The charger has to be off-board since the charging power can exceed 100 kW, which is significantly higher than Level I and Level II. It is obvious that Level III is not suitable for home use. However, it may be a better scheme for a company with a fleet of EVs. The total power and time that it takes to charge a group of EVs charged together at a low level can be the same as the fast charging of each vehicle in sequence. However, it is much more advantageous for an EV in the fleet can be charged quickly in less than 10 min.

Table 2.5 summarizes some of the various charging schemes of EV [10]. V0G is the most conventional one: plug in the vehicle and get it charged like any other regular load. V1G, also called smart charging, can charge the vehicle when grid allows or needs it to. There are communications between the grid and the vehicle. The smart grid concept with advanced metering infrastructure fits in this application well. Vehicles can communicate with advanced metering infrastructure (AMI) devices at home through home automation network (HAN); the AMI devices then communicate with the control center at the grid. V2G (vehicle to grid) is the most complicated scheme. In addition to the functions of V1G, it also allows the energy stored in the EV batteries to be delivered back to the grid for grid supports. V2B (vehicle to building) is similar to V2G. The difference is that in V2B, the vehicle does not communicate with the grid, but the building. The energy delivered back from the vehicle will be limited to the building.

2.5 Battery Chemistry

Various battery chemistries have been proposed as the energy source to power electrical vehicles since the 1990 California Zero Emission Vehicle was mandated, which required 2 and 10% of the automobiles sold to be zero emission in 1998 and 2003, respectively. These battery chemistries included improved lead–acid, nickel–cadmium, nickel–zinc, NiMH, zinc–bromine, zinc–chlorine, zinc–air, sodium–sulfur, sodium–metal chloride, and, later, Li-ion batteries, with each of these chemistries having its own advantages and disadvantages. Towards the end of the last century, the competition between battery chemistries was resolved with General Motor's choice of NiMH for its EV-1 pure electrical vehicles. In the following decade, the technology of the HEV developed by Toyota and Honda matured and gained popularity through its combination of fuel economy, acceptable pricing, and clean safety record. Up to this date of 2011, the leading battery chemistry in these HEVs remains NiMH. As the concerns over greenhouse gas emissions and fossil energy shortages grow in the recent years, the development target has shifted from HEV to PHEV, with the eventual target being a purely battery-powered EV. The requirement of a higher energy density in PHEVs and EVs reopens the discussion for automobile battery technologies, giving Li-ion battery chemistry another chance at entering the electric car battery market. In this section, the underlying principles, the current market status, and the future developmental trends of NiMH and Li-ion batteries are discussed.

2.5.1 Basic Operation of a Rechargeable Battery

A battery is composed of a positive electrode (holding a higher potential) and a negative electrode (holding a lower potential) with an ion-conductive but electrically insulating electrolyte in between. During charging, the positive electrode is the anode with the reduction reaction, and the negative electrode is the cathode with the oxidation reaction. During discharge, the reaction is reversed, and so the positive and negative electrodes become cathode and anode electrodes, respectively. As a side-note, the positive and negative electrode active materials are also conventionally referred to as cathode and anode material, respectively. In a sealed cell, the liquid electrolyte is held in a separator to prevent the direct short between the two electrodes. The separator also serves as a reservoir for extra electrolyte, a space saver allowing for electrode expansion, an ammonia trap (in NiMH battery), and a safety device for preventing shortage due to Li-dendrite formation (in Li-ion battery).

A schematic of the NiMH rechargeable battery is shown in Fig. 2.4. The active material in the negative electrode is metal hydride (MH), a special type of intermetallic alloy that is capable of chemically absorbing and desorbing hydrogen. The most widely used MH in NiMH today is the AB_5 alloy with a $CaCu_5$ crystal structure, where A is a mixture of La, Ce, Pr, and Nd, and B is composed of Ni, Co, Mn, and Al. The active material in the positive electrode is $Ni(OH)_2$, which is the same chemical used in the Ni–Fe and Ni–Cd rechargeable batteries patented by Thomas Edison more than a hundred years ago. The intrinsic $Ni(OH)_2$ has a poor conductivity; to make up for this shortcoming, coprecipitation of other atoms, formation of conductive network outside the particle, or multilayer coating structure is implemented in the commercial product. The separator is typically made from grafted polyethylene (PE)/polypropylene (PP) non-woven fabric. The commonly used electrolyte is a 30 wt.% KOH aqueous solution with a pH value of about

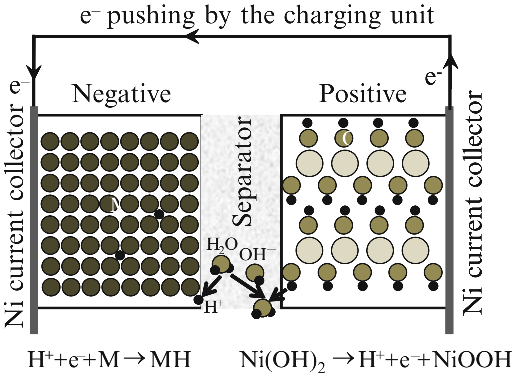


Fig. 2.4 Schematic of the charging operation of a NiMH battery

14.3. In some special designs for particular applications, certain amounts of NaOH and LiOH are also added into the electrolyte.

During charge, water is split into protons (H^+) and hydroxide ions (OH^-) by the voltage supplied from the charging unit. The proton enters the negative electrode, neutralizes with the electron supplied by the charging unit through the current collector, and hops between adjacent storage sites by the quantum mechanics tunneling. The voltage is equivalent to the applied hydrogen pressure in a gas phase reaction and will remain at a near-constant value before protons occupy all of the available sites. OH^- generated by charging will add to the OH^- already present in the KOH electrolyte. On the surface of the positive electrode, some OH^- will recombine with protons coming from the $Ni(OH)_2$ and form water molecules. The complete reaction for charging is as follows:

$$M + Ni(OH)_2 \rightarrow MH + NiOOH \tag{2.14}$$

Neither water nor OH^- is consumed; thus, no change to pH value occurs during charge/discharge. The oxidation state of Ni in $Ni(OH)_2$ is 2^+. As protons are consumed at the surface of the positive electrode, more protons are driven out of the bulk from both the voltage and the concentration gradients. Losing one proton increases the oxidation state of Ni to 3^+ in NiOOH. Electrons are collected by Ni-form or perforated Ni-plate and moved back to the charging unit to complete the circuit.

The whole process is reversed during discharge. In the negative electrode, protons are sent to the electrolyte and recombine with the OH^- as electrons are pushed to the outside load. The electrons reenter the positive electrode side of the battery through the outside load and neutralize the protons generated from the water split on the surface of the positive electrode.

A similar schematic with two half-cell reactions for the Li-ion battery in charging mode is shown in Fig. 2.5. The complete reaction is

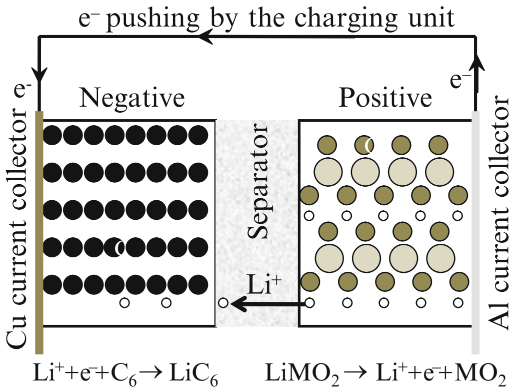


Fig. 2.5 Schematic of the charging operation of a Li-ion battery

$$C_6 + LiMO_2 \rightarrow LiC_6 + MO_2 \tag{2.15}$$

The most commonly used active material in the negative electrode is graphite. During charging, Li ions, driven by the potential difference supplied by the charging unit, intercalate into the interlayer region of graphite. The arrangement of Li^+ in graphite is coordinated by the surface–electrolyte–interface (SEI) layer, which is formed during the initial activation process. The active material in the positive electrode is a Li-containing metal oxide, which is similar to $Ni(OH)_2$ in the NiMH battery but replaces the hydrogen with lithium. During charging, the Li^+ (similar to the H^+ in NiMH) hops onto the surface, moves through the electrolyte, and finally arrives at the negative electrode. The oxidation state of the host metal will increase and return electrons to the outside circuitry. During discharge, the process is reversed. Li ions now move from the intercalation sites in the negative electrode to the electrolyte and then to the original site in the $LiMO_2$ crystal. The commonly used electrolyte is a mixture of organic carbonates such as ethylene carbonate, dimethyl carbonate, and diethyl carbonate containing hexafluoro-phosphate ($LiPF_6$). The separator is a multilayer structure from PP, which provides oxidation resistance, and PE, which provides a high-speed shutdown in the case of a short.

2.5.2 USABC Goals

USABC, composed of the Big Three (GM, Ford, and Chrysler) and a few National Laboratories belonging to the DOE, was established to develop the energy storage technologies for fuel cell, hybrid, and electrical vehicles. In the early 1990s, a set of performance targets was created and later modified. A few key qualitative goals set by the USABC for both the mid and long terms are listed in Table 2.6. One factor, specific energy, is important for the range a car can travel in one charge. The

Table 2.6 USABC battery performance goal

	USABC mid-term goal	USABC long-term goal	Impact on vehicle performance
Specific energy (Wh/kg)	150	200	Range and weight
Energy density (Wh/l)	230	300	Range and size
Specific discharge power (W/kg)	300	400	Acceleration and weight
Discharge power density (W/l)	460	600	Acceleration and size
Specific regenerative power (W/kg)	150	200	Energy saving and weight
Regenerative power (W/l)	230	300	Energy saving and size
Life (years)	10	10	Life-cycle cost
Life cycles	1,000	1,000	Life-cycle cost
Operation temperature (°C)	−40 to +50	−40 to 85	Life of battery
Selling price ($/kWh)	150	100	Acquisition and replacement costs

typical energy required for a car to drive a mile ranges from 0.25 kWh (GM's EV-1) to 0.30 (GM's Volt) and 0.33 kWh (Tesla's Roadstar). As an example calculation, a 200-l (50 gallons) battery pack with an energy density of 230 Wh/l can store 46 kWh of energy and travel 200 miles between charges. Another factor, power density, is important for acceleration and for the collection of regenerative energy from braking. The battery pack mentioned above, assuming a discharge power density of 460 W/l, can generate 92 kW (123 hp), which is acceptable for a typical passenger car.

With the exception of specific energy and selling price, all of the USABC mid-term goals were reached by the first-generation of Ovonic Battery Company's NiMH battery, which was installed on the EV-1. The specific energy of NiMH battery then was about 80 Wh/kg at the cell level, with the estimated cost at high volume production at $800/kWh. The near-term specific energy of 150 Wh/kg is still considered a formidable challenge for even today's top Li-ion battery used for propulsion purpose. The near-term cost target of $150/kWh remains unachievable but is becoming more attainable with improvements in today's technology.

The long-term goal of the USABC was set to replace conventional internal combustion engine cars with EVs; this attitude is reflected in the long-term goals set for battery specifications. For the same performance as the previously calculated example (46 kWh capacity battery and 123 hp electric motor), the weight of the battery can be reduced from 306 kg (when made with USABC's mid-term goal battery specifications) to 230 kg (when made with USABC's long-term goal battery specifications). Reductions in both the battery pack volume (200 to 152 l) and the selling price ($6,750 to $4,600) are also listed as long-term goals. These long-term goals are still challenging with today's technology.

Table 2.7 Comparison of HEV batteries from volume production

	NiMH	NiMH	Li-ion	Comment
Manufacturer	PEVE	PEVE	Hitachi	
Shape	Prismatic	Prismatic	Cylindrical	
Case material	Plastic	Metal	Metal	Metal case in NiMH improves 40% cooling performance
Cathode	$Ni(OH)_2$	$Ni(OH)_2$	$LiMn_2O_4$	
Anode	Rare earth AB_5	Rare earth AB_5	Amorphous carbon	
Cell capacity (Ah)	6.5	6.5	4.4	
Cell voltage (V)	1.2	1.2	3.3	Plastic-cased NiMH is a 6-cell module and the metal-cased NiMH is a 8-cell model
Specific energy (Wh/kg)	46	41	56	
Specific output power (W/kg)	1,300	1,200	3,000	
Operation temperature (°C)	−20 to +50	−20 to +50	−30 to +50	
Market	Toyota-HEV	Toyota-HEV	GM-HEV (2012)	

2.5.3 Performance Comparison Between NiMH and Li-Ion Batteries in PHEV

While many exciting results are being presented on the performance of emerging battery technologies, the majority of them come from laboratory reports based on small-scale test runs. In order to fairly compare the performances of NiMH and Li-on, the batteries currently in mass production by two reputable manufacturers were selected. Key performance statistics from the NiMH battery by Primearth EV Energy Co. [11] and the Li-ion battery by Hitachi Vehicle Energy Ltd. [12] are listed in Table 2.7. Two types of NiMH batteries, plastic and metal-cased, are shown here. The latter was introduced to trade 10% of the energy and power densities for a 40% improvement in cooling efficiency. A quick glance through the data reveals that the advantages of Li-ion are obvious: higher specific energy and output power.

However, with a closer look at the comparison of specific energies, the superiority of Li-ion is limited at the current development stage. At the cell level, the specific energy of Li-ion is about 20% higher than that of NiMH. However, after taking the two batteries' cooling mechanisms into consideration, the air-cooled NiMH may have a higher specific energy at the system level since, in order to optimize its service life, the Li-ion battery requires a powerful liquid-cooling structure that adds the weights of the coolant, compressor, evaporator, and controller to the system weight. Moreover, the battery management system for NiMH is on the system level, making it simpler and lighter than Li-ion's management system, which demands precise control at the cell level. An additional concern is that Li-ion needs to be overdesigned to overcome its short calendar life issue (as seen in the GM Volt where only 50–70% of its energy is "usable" to ensure it has an acceptable calendar life), while NiMH does not. From the more practical perspective of looking on the car level, the current Li-ion (battery pack) does not necessarily provide a higher specific energy. This observation explains the difference in driving range between the recently developed Li-ion battery powered Nissan Leaf EV (80–100 miles) and the fifteen-year-old NiMH battery powered EV-1 (180 miles).

Another point that needs to be addressed is the comparison in power performance. The data shown in the table compare the two batteries' output power, which assists the engine in PHEV during acceleration. As for input power, both NiMH and Li-ion batteries have the same impedance during charge and discharge, as opposed to the lead–acid battery, which has a charging impedance three times higher than its discharge impedance. Theoretically, a Li-ion battery should be able to take in 3,000 W/kg power during braking. However, in the modern Li-ion battery management systems, a safety factor of 3 is normally applied in order to reduce the risk of Li-dendrite formation and excessive heating of the battery. Therefore, in real cases, the maximum input power for Li-ion is limited to 1,000 W/kg at the cell level, with that number being further decreased after considering the added weight from the cooling system and controller.

From the published data, there seems to be little difference between NiMH and Li-ion batteries in power and energy performance. However, other factors such as calendar life, cycle life under realistic conditions, and, most importantly, abuse tolerance in aged battery packs (which may show the dangerousness of a degraded SEI layer in the Li-ion battery) are not available. Fair comparisons of these additional factors may be made only after the Li-ion battery technology has been used for many years, which may not be until the year 2022 when the GM PHEV celebrates its ten-year anniversary.

2.5.4 Current Status of Battery in Automobile Applications

NiMH batteries, mainly made by Sanyo and Primearth EV Energy Co. (PEVE), dominate the mass production lines of today's HEVs. While batteries from PEVE are prismatic (rectangular shaped), those made by Sanyo are cylindrical (standard D-size). Other NiMH manufacturers are entering the HEV market now, including Gold Peak, Corun, and TMK; however, both endurance and product consistency have yet to be proven for the batteries of these newcomers.

In PHEVs, a relatively new application for batteries, both Gold Peak (NiMH) and A123 ($LiFePO_4$) supply batteries for third parties to produce range extenders for the Prius. GM introduced the first commercial purpose-built PHEV built at the end of 2010 with batteries from LG Chemical ($LiMn_2O_4$). More prototype PHEVs made by various car manufacturers and OEMs use either Li-ion or NiMH to provide part of the power source.

Table 2.8 Li-ion battery cathode and anode material comparison

Material	Specific capacity, mAh/g	Voltage vs. L^+/Li, V	Characteristics
$LiCoO_2$	160	3.7	Most commonly used in consumer product, good capacity and cycle life, but expensive and unsafe upon fast-charge
$LiMn_2O_4$	130	4.0	Most commonly used in automobile, low cost, acceptable rate capability, poor cycle and calendar life
$LiFePO_4$	140	3.3	Low cost, improved abuse tolerance, good cycle life and power capability, but low capacity and calendar life
NMC	180	4.2	Lowest cost, high capacity, life is less than NCA
NCA	185	4.2	Highest capacity, low cost, but safety concerns
Graphite	372	0.0–0.1	Most commonly used in all applications, low cost
LTO	168	1.0–2.0	Highest cycle and calendar life, but costly and low in energy density
Silicon	3,700	0.5–1.0	Still in research stage, high energy, but large volume expansion during charging needed to be solved

Besides the obsolete EV-1, there are currently two pure EVs available on the market. One is the luxury Roadster (retailing for $109,000 in the USA) introduced by Tesla Motors; it is equipped with 6,831 small cylindrical Li-ion ($LiMn_2O_4$) batteries (size 18650) in 2008. The other is the Nissan Leaf (retailing for $32,780 in the USA), which has 192 prismatic Li-ion ($LiMn_2O_4$) cells from AESC.

While the chemistry of NiMH batteries was finalized fifteen years ago, this is not so for the Li-ion batteries for propulsion applications: the debate over which cathode or anode materials are better is still continuing. The issue is that none of the candidates are perfect; moreover, there are patent issues for a few key chemistries. Table 2.8 lists a few major candidates for cathode and anode materials.

Among the cathode materials, $LiCoO_2$ is the most popular one used in today's notebook computer, but it is notorious for catching on fire. $LiMn_2O_4$, widely used in cell phones, is low in specific energy and poor in both cycle life and calendar life. $LiFePO_4$, with improvements in both abuse tolerance and power capability, also suffers from low energy (both capacity and voltage) and short calendar life. Both Li (Ni, Mn, Co)O_2 (NMC) and Li(Ni, Co, Al)O_2 (NCA) are new additions to the list, but still have concerns in calendar life and abuse tolerance.

Among the anode materials, graphite is the most common. Although graphite has a relatively high specific energy and a low cost, it has an unstable SEI layer [13], especially at higher SOCs and elevated temperatures (>40°C), which causes severe performance degradation, especially in the output power. $Li_4Ti_5O_{12}$ (LTO) or the similar Li–Ti oxides provide solutions to both the cycle life and calendar life issues of graphite; however, the specific capacity of LTO is only half of that of graphite, and its half-cell potential is at least 1.0 V higher than graphite.

The specific energy is determined by both the specific capacity in Ah and the voltage of the cell. The voltage of a cell is the difference in potentials between

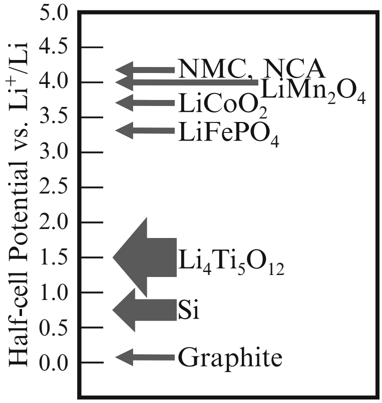


Fig. 2.6 Half-cell potentials of active material in Li-ion battery

cathode and anodes. The potentials of the materials listed in Table 2.8 are plotted in Fig. 2.6 to address the issue of cell voltage. The combination optimized for the greatest abuse tolerance ($LiFePO_4$ + LTO) gives a cell voltage of 1.9 V, which is less than half of 4.0 V, the voltage obtained from other combinations. Safer Li-ion batteries come at the cost of having significantly lower specific energy than unsafe ones do. Today, the balance between performance and safety remains a major challenge to the implementation of Li-ion technology in the propulsion application.

2.5.5 Development Trend of Battery Used in EV

The Regone plot (specific energy vs. specific power) shown in Fig. 2.7 summarizes the current status and the future outlook of batteries in propulsion application. While the advantages of Li-ion over NiMH and lead–acid in both specific energy and power are obvious, the potential of super-capacitors in very high power applications cannot be overlooked. One developmental effort will be to combine the superior specific energy offered by the battery with the superior specific power offered by the super-capacitor. The super-capacitor so offers a cache energy for fast access and shields the battery from very fast fluctuation [14].

The USABC requirements for HEV, PHEV, and BEV [15] are described in Fig. 2.7. While both the HEV and PHEV goals are either already reached or are close to being accomplished by both Li-ion and NiMH batteries, the goals for BEV are far beyond today's technology. The following paragraph is a review of the developmental trend of BEV battery in three different systems: NiMH, Li-ion, and metal–air batteries.

The current research on NiMH for EV application is focused on the following areas: MH alloy, γ-phase NiOOH, nonaqueous electrolyte, and bipolar structure. While the first two areas aim at reaching higher specific energies, the other two

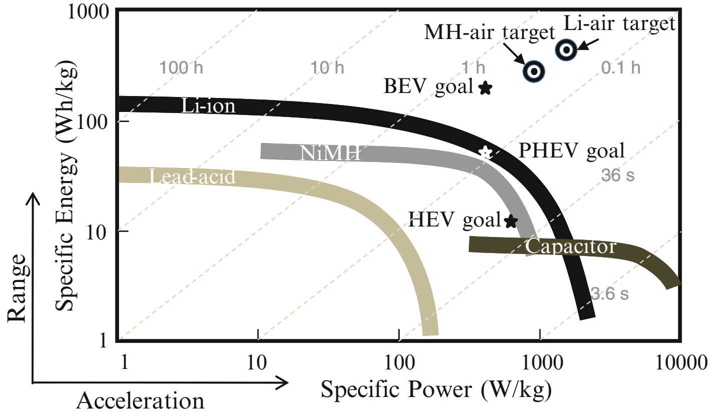


Fig. 2.7 Regone plot of a few electrochemical energy storage devices used in the propulsion application

target higher power densities. The currently used AB_5 MH alloy has a hydrogen storage capability of 1.2 wt.%, which is equivalent to an electrochemical storage of 322 mAh/g. The potential replacements for AB_5 are A_2B_7 (1.5 wt.%), AB_2 (2.0 wt.%), Ti–V–Cr solid solution (3.0 wt.%) and MgNi-based alloy (3.6 wt.%). A half-cell capacity of over 790 mAh/g was demonstrated from the combination of melt-spin and mechanical alloying for MgNi [15]. In the positive active material, the current β-$Ni(OH)_2$-NiOOH transition can supply one hydrogen per Ni, while γ-NiOOH can supply up to 1.7 hydrogen per Ni. The conventional γ-NiOOH is obtained by inserting water molecules together with some anions between the NiO_2 planes, which causes a large lattice expansion and deteriorates the cycle life. New γ-phase can be formed without expanding the lattice by doping the host $Ni(OH)_2$ matrix with other elements [16]. In the electrolyte, the operation voltage of current NiMH batteries is limited by the electrolysis of H_2O. Replacing water-based electrolyte with proton-conducting liquid gel or solid membrane enables the use of positive and negative active materials with much higher voltages. Recent reports on some oxide films capable of storing hydrogen are promising [17–19]. The last research area for NiMH is the bipolar structure. Although the theoretical charge/discharge rate of NiMH is very high, it is limited by the heat transfer in the cell. By adopting a bipolar structure with cooling water running through the connection plate, Kawasaki is able to increase the power capability of NiMH substantially [20]. G4 Synergetic is also working on a special design of bipolar NiMH battery [21].

Current research endeavors in Li-ion battery for EV application are similar to those of NiMH: new high capacity metal oxide cathode, high capacity anode, and new electrolyte with high oxidation potential. In the cathode material, only about 50% of the Li is currently pulled out during each charge operation. With high charging voltage, more Li can be transferred to the anode, and the capacity can be increased. In the anode area, Si has a very high theoretical capacity (about ten times that of graphite); however, the lattice expansion after a full charge can be as high as 270%. Alloying Si with an inert ingredient or depositing Si onto some types of supporting structures may be feasible solutions for realizing the ultrahigh capacity of Si. The third area of interest is the electrolyte: similar to the case of NiMH, the cell voltage of Li-ion battery is limited to 4.2 V at which the solvent starts to be oxidized. The adoption of a new electrolyte with a higher oxidation potential will enable the use of high-voltage cathodes, such as $LiCoPO_4$ [22] and $LiNi_{0.5}Mn_{1.5}O_4$ [23], which can increase the specific energy.

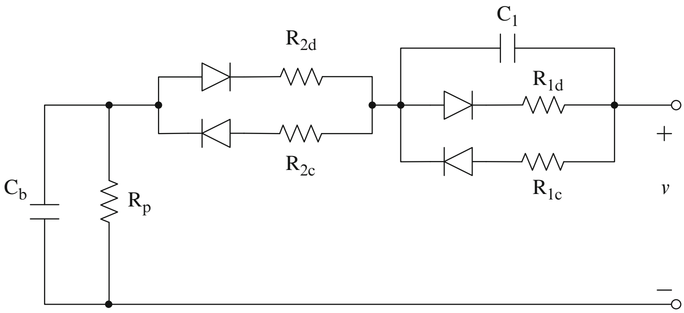
The last approach is about the metal–air batteries. Replacing the positive electrode with an air electrode from the fuel cell can substantially reduce the weight of the battery and increase both specific power and energy. This is a feasible approach to achieve the USABC EV goal. Both the potential goals of Li–air and MH–air batteries are indicated in Fig. 2.7. In this arena, Ovonic Battery Company has shown a prototype of MH–air battery capable of delivering 200 Wh/kg [24], and MIT has demonstrated a Li–air battery with a specific energy as high as 2,500 Wh/kg [25].

2.6 Battery Modeling

Battery modeling forms the basis of and stands as an effective tool for battery design, manufacturing, and control. It is particularly important for battery characterization (such as SOC and SOH estimation) and battery management since the model development is logically the first step in developing any system identification and state estimation algorithms.

Extensive research has been carried out on battery modeling and a variety of models have been developed from different aspects and for different purposes [26–47, 55]. The most common models can be generally classified into two groups: electrochemical models and equivalent circuit models. Detailed electrochemical models are normally targeted for the fundamental, physical aspects of batteries and most of them are static models. Some of these models are developed using finite element analysis to investigate the complexity of the electrochemical processes inside a battery. They are suitable for battery design, but not appropriate for dynamic simulation studies over a long time. On the other hand, electric circuit models are normally lumped-parameter models and developed for long-time simulation studies. Electrical engineers favor electric circuit models since the models are more intuitive and can be incorporated with other circuit devices for circuit design and simulation studies.

For the studies of EV system integration, control, optimization, and the interconnection of EVs to grid, lumped-parameter models are well-received. In those studies, the battery terminal and overall characteristics and dynamics including voltage, current, temperature, and SOC are more of interest than the detailed electrochemical reactions inside the battery. In this subsection, the focus is given to lumped-parameter circuit models of battery. Equivalent circuit models,



C_b = battery capacitance, R_p = self-discharge resistance, or insulation resistance,
R_{2c} = internal resistance for charge, R_{2d} = internal resistance for discharge,
R_{1c} = overvoltage resistance for charge, R_{1d} = overvoltage resistance for discharge,
C_1 = overvoltage capacitance.

Fig. 2.8 Equivalent circuit model of battery reported in [36]. C_b = battery capacitance, R_p = self-discharge resistance, or insulation resistance, R_{2c} = internal resistance for charge, R_{2d} = internal resistance for discharge, R_{1c} = overvoltage resistance for charge, R_{1d} = overvoltage resistance for discharge, C_1 = overvoltage capacitance

consisting of electrical circuit components such as capacitors, resistors, diodes, and voltage sources, can be readily developed using electric circuit simulation software such as PSpice. Other types of models, given in algebraic or differential equations, may be more suitable for a generic simulation environment such as Matlab/ Simulink. Matlab also released a generic battery model in its SimPowersystems toolbox [46, 68]. Nevertheless, an equivalent circuit model can be easily converted into other model formats. The choice of model representation will be determined by the matter of convenience and the simulation tools available.

2.6.1 Equivalent Circuit Models of Battery

Ideally, a battery can be represented as an ideal voltage source, which we have seen in various "electric circuit" textbooks. A more practical way but still ideal is to model battery using a resistive Thevenin equivalent circuit: a voltage in series with a resistor. These two are the simplest types of models and have been widely used in electric circuit analysis and design. However, they are oversimplified and cannot give any detailed and accurate information about the battery operation and performance such as the battery SOC, thermodynamics, etc. More advanced circuit models have been proposed for batteries.

A validated electrical circuit battery model, shown in Fig. 2.8, was reported in [36]. The diodes in the model are all ideal and just used to select different resistances for charging and discharging states. The values of model parameters (capacitances and resistances) defined in Fig. 2.8 are functions of actual electrochemical reactions

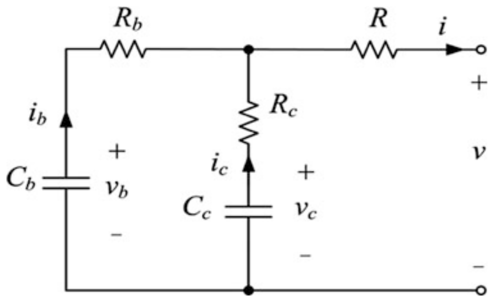


Fig. 2.9 NREL battery model [47]

and temperature dependent [36]. A least square algorithm and a temperature compensation formula were used to accommodate the variations [36].

$$BE = k_1 \exp\,[k_2(V_m - V_{oc})]^{k_3}, \tag{2.16}$$

where BE represents the battery elements modeled in Fig. 2.8; V_{m} is the mean voltage level; V_{oc} is the open circuit voltage; and k_1, k_2, and k_3 are the factors determined by the least square algorithm. For instance, the battery capacitance can be represented as $C_b = k_{1,cb}\exp[k_{2,cb}(V_m - 14.0)^{k_{3,cb}}]$ when the V_{oc} is 14 V. Quantities $k_{1,cb}$, $k_{2,cb}$, and $k_{3,cb}$ are the empirical factors determined by the actual data via the least square curve fitting [36].

The temperature effect on resistors was compensated using

$$TC = \left(\frac{R}{R_{ref}}\right)^{\frac{T_{ref}-T}{T_{ref}}}, \tag{2.17}$$

where TC is the temperature compensation factor, R is the resistance at temperature T, and R_{ref} is the resistance value at the reference temperature T_{ref}.

The model given in Fig. 2.8 was developed for lead acid batteries, but it can be extended to model other types of battery. However, the model does not provide a way to estimate the SOC of battery. Though the parameters can be adjusted for different operating conditions, the correction given in (2.14) and (2.15) may not be accurate, which may limit the applications of the model.

National Renewable Energy Laboratory (NREL) also developed an electric circuit model for batteries, as a part of its ADVISOR tool package [47]. The model, shown in Fig. 2.9, is basically a RC network. The model contains two capacitors (C_b and C_c) and three resistors (R_b, R_c, and R). The capacitor C_b models the main storage capacity of the battery. The capacitor C_c captures the fast charge–discharge aspect of the battery and is much smaller than C_b.

The electric circuit model can be converted into other model formats for the convenience of simulation. For example, the circuit model in Fig. 2.9 can be expressed using a state space model. The electric circuit and thermodynamic variables in the circuit model are defined in Table 2.9.

Table 2.9 Variables used in the NREL circuit model of battery

Symbols	Description
v	Terminal voltage (V)
i	Terminal current (A)
v_{b}	Voltage of the capacitor C_{b} (V)
i_{b}	Current through the capacitor C_{b} (A)
v_{c}	Voltage of the capacitor C_{c} (V)
i_{c}	Current through the capacitor C_{c} (A)
T_{a}	Air temperature (°C)
T	Cell temperature (°C)
q_{c}	Conducting heat transfer rate (W)
q_{b}	Heat transfer rate generated by the battery cell (W)
q_{ac}	Air conditioning forced heat transfer rate (W)
R_{T}	Equivalent thermal resistance (°C/W)
C_{T}	Equivalent heat capacitance (J/°C)
S	SOC
S_b	SOC_{Cb}
S_c	SOC_{Cc}
η	=1, charge =0, discharge

The following basic circuit equations can be obtained for the circuit:

$$\begin{cases} C_b\dot{v}_b = -i_b \\ C_c\dot{v}_c = -i_c \\ v_b - i_bR_b = v_c - i_cR_c \\ i = i_b + i_c \\ v = v_c - i_cR_c - iR \end{cases}. \tag{2.18}$$

The battery thermal model is represented by a lumped first-order equation with linear dynamics:

$$\begin{cases} q_c = \dfrac{T - T_a}{R_T} \\ C_T\dot{T} = q_b - q_c - q_{ac} \end{cases}. \tag{2.19}$$

The parameters of the components are functions of the SOC and battery temperature (T). In addition, the resistance also depends on whether the battery is in "charge" or "discharge" mode. The overall SOC is a weighted combination of the states of charge on C_b and C_c:

$$S = \alpha_bS_b + \alpha_cS_c, \tag{2.20}$$

where $\alpha_b + \alpha_c = 1$. In the NREL model, $\alpha_b = 20/21$ and $\alpha_c = 1/21$ [47]. S_b and S_c are functions of v_b and v_c, i.e., $S_b = g_b(v_b)$ and $S_c = g_c(v_c)$, respectively. The circuit parameters can be expressed in general as

$$
\begin{aligned}
&R_b = f_{Rb}(v_b, v_c, T, \eta),\ R_c = f_{Rc}(v_b, v_c, T, \eta),\ R = f_R(v_b, v_c, T, \eta),\\
&C_b = f_{Cb}(v_b, v_c, T),\ C_c = f_{Cc}(v_b, v_c, T)
\end{aligned}. \tag{2.21}
$$

These condition-dependent parameters can be experimentally established or identified through system identification methods as discussed later in this chapter.

Choose v_b, v_c, and T as the state variables; inputs are i (battery current), T_a (air temperature), q_b (battery cell generated heat flow rate), and q_{ac} (convective heat flow rate due to cooling air); and outputs are v (terminal voltage), S (the overall SOC), and the battery temperature (T). The state space representation of the model can be obtained as

$$
\begin{cases}
\dot{v}_b = \dfrac{v_b - v_c}{(R_b + R_c)C_b} + \dfrac{R_c}{(R_b + R_c)C_b} i \\
\quad = f_1(v_b, v_c, T, \eta) + g_1(v_b, v_c, T, \eta) \\
\dot{v}_c = \dfrac{v_c - v_b}{(R_b + R_c)C_c} + \dfrac{R_b}{(R_b + R_c)C_c} i \\
\quad = f_2(v_b, v_c, T, \eta) + g_2(v_b, v_c, T, \eta) \\
\dot{T} = \dfrac{1}{C_T} q_b - \dfrac{1}{C_T R_T} T + \dfrac{1}{C_T R_T} T_a - \dfrac{1}{C_T} q_{ac} \\
v = \dfrac{R_b v_c + R_c v_b}{R_b + R_c} - \left(\dfrac{R_b R_c}{R_b + R_c} + R \right) i \\
\quad = h_1(v_b, v_c, T, \eta) + m_1(v_b, v_c, T, \eta) \\
S = \alpha_b S_b + \alpha_c S_c \\
T = [0\,0\,1][v_b\, v_c\, T]'
\end{cases}. \tag{2.22}
$$

Denote the state vector by $x = [v_b, v_c, T]'$, input vector $u = [i, T_a, q_b, q_{ac}]'$, and output vector $y = [v, S, T]'$. The state space model can be rewritten in general as

$$
\begin{cases}
\dot{x} = f(x, \eta) + g(x, \eta) u \\
y = h(x, \eta) + m(x, \eta) u
\end{cases}. \tag{2.23}
$$

The system given in (2.23) is a nonlinear system in an affine form. It is also a hybrid system since η is a discrete value for "charge" or "discharge" mode operation of a battery.

2.6.2 Future Development Needs of Circuit Model for Batteries

It would be desirable to have a comprehensive, unified electrical model that is developed based on physical properties of battery cells. The model should have the capability to estimate SOC and SOH accurately. A conceptual, unified model with

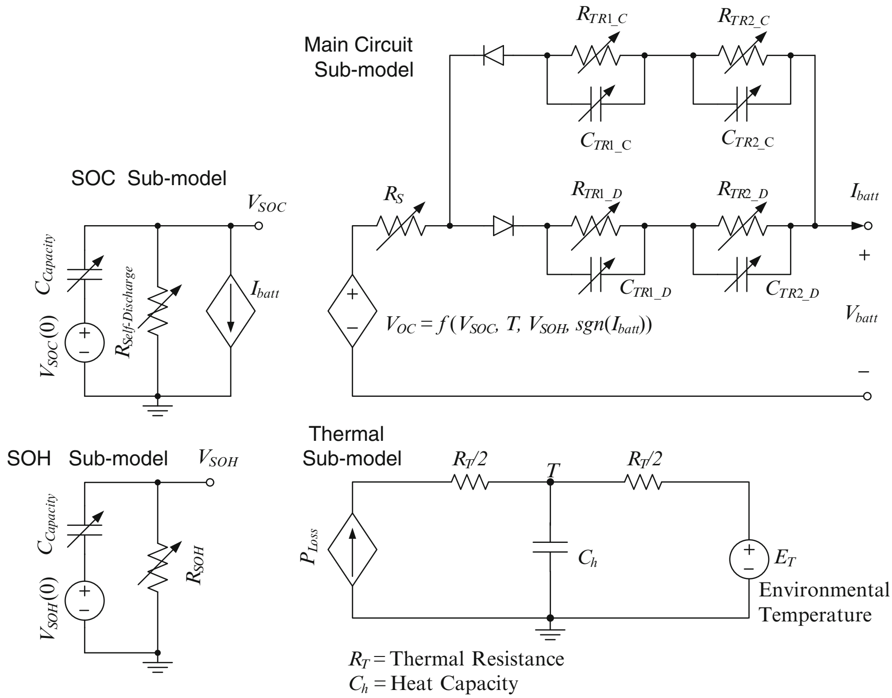


Fig. 2.10 A conceptual unified electrical circuit model of battery

the above desired features, shown in Fig. 2.10, consists of four parts: Main circuit, thermodynamic, SOC, and SOH sub-models.

In the main circuit sub-model, the charging and discharging processes will have different transient paths selected by the two diodes. The two RC circuits in either path are used to model the dynamic responses to load transients. For example, in the discharging path (denoted with subscript "*D*" in the figure), $R_{TR\_1\_D}$ and $C_{TR\_1\_D}$ are for a slow transient response, while $R_{TR\_2\_D}$ and $C_{TR\_2\_D}$ are for a faster one. The open circuit voltage V_{OC} is a function of SOC, SOH, and the battery temperature. V_{OC} will be obtained based on physical electrochemical properties of batteries. The circuit component values (*R* values and *C* values) are all functions of SOC, SOH, and temperature in general. The circuit values can be estimated through the state estimation method discussed later in the chapter.

The SOC and SOH sub-models will be used to indicate the SOC of a battery and to predict its SOH. $V_{SOC} = 1$ V corresponds to 100% of SOC and 0 V to 0%. The SOC will decrease as the battery is being discharged or self-discharges. The capacity capacitance ($C_{Capacity}$) is one of the most important parameters in the circuit model and its value is a function of SOC, SOH, and battery temperature. $C_{Capacity}$ and other important parameters including the initial values of V_{SOC} and V_{SOH}, self-discharging resistance ($R_{Self\text{-}Discharging}$), and lifetime deterioration equivalent resistance R_{SOH} will also be experimentally determined or estimated by the state estimation method and can be loaded externally before the simulation.

The analogies between the thermodynamic and electrical quantities [48] are employed to develop the thermodynamic sub-model. The input current source represents the battery loss, which can be simply estimated as $P_{Loss} = |V_{OC} - V_{batt}| \times I_{batt}$. The thermal resistance (R_T) due to air convection is split into half in the circuit and C_h is the lumped heat capacity of the battery. In Fig. 2.10, the constant voltage source E_T represents the environmental temperature, and the voltage across the capacitance (C_h) is the overall temperature of the battery.

It is a very challenging task to develop a model that is capable of predicting SOH and gauging SOC. At the same time, for investigating EVs as part of the grid, modularity of the model is also very important. A battery model needs either to be modular or upgradable so that a large battery system model can be readily developed based on the module model without fundamental changes. Future research efforts are required to address these needs in battery modeling.

2.7 Run-Time Battery Characterization and Management

Battery management systems (BMS) make decisions on charge/discharge rates on the basis of load demands, cell voltage, current, and temperature measurements, and estimated battery SOC, capacity, impedance, etc. Within these variables, the SOC is the most critical indicator. This is especially important for Li-ion batteries since their overcharge can accelerate battery degradation, catch fire, or, in a worst-case scenario, even cause explosion. On the other hand, over-discharge can result in loss of capacity and shortening of cell life. In EV applications, frequent charge/discharge cycles are common. To maintain the capability of absorbing returning energy from regenerative braking and large torque delivery in fast vehicle acceleration or cold-start, the SOC must be sustained in a middle range such as 40–75%.

2.7.1 SOC Estimation [69]

At present, most BMS rely on cell voltage regulation as a means of controlling SOC. This becomes more difficult for Li-ion batteries since their cell voltages vary only slightly in the middle range (before the "knee section" of the voltage-capacity curve). Consequently, many modified methods have been introduced and explored to improve SOC estimation. Typical methods include inverse mapping using the SOC-to-voltage characterization curves, computation of amp-hours by using load current integration, impedance measurements, and more advanced extended Kalman filtering (EKF) [49–53].

Here, an adaptive SOC observer that uses gain-scheduled pole placement design is described [69]. A special case of the general model representation given in (2.23) is a battery model that can be described by a state space model with a linear state equation and a nonlinear output equation, given below in (2.24).

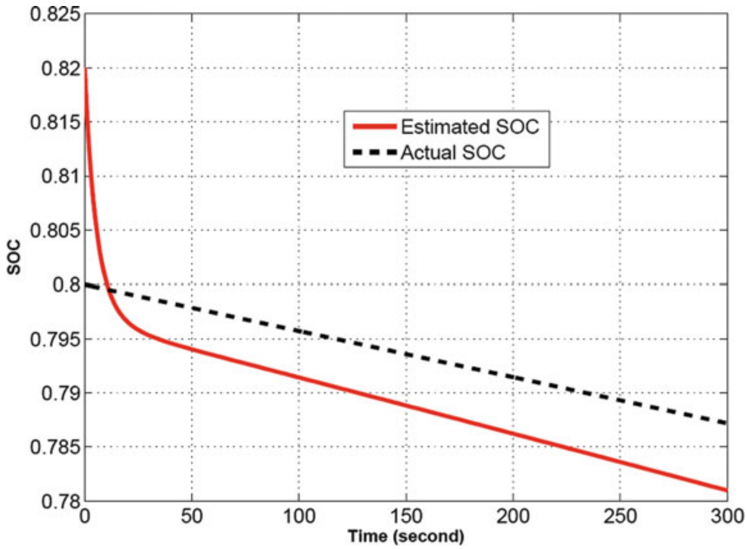


Fig. 2.11 Nonadaptive observer design under a constant discharge current [69]

An example model of (2.24) is the battery model in the SimPowerSystems Toolbox in Matlab/Simulink [47, 68].

$$\begin{aligned} \dot{x} &= Ax + Bi(t), \\ v &= f(x, i), \end{aligned} \tag{2.24}$$

where the input is the current load i, the output is the cell voltage v, and the state variable x contains SOC as one of its component. As a result, SOC estimation is now a state observation problem. The adaptive state observer has the structure

$$\begin{aligned} \dot{\tilde{x}} &= A\tilde{x} + Bi(t) - L(\tilde{x})(\tilde{v} - v), \\ \tilde{v} &= f(\tilde{x}, i). \end{aligned} \tag{2.25}$$

Here, the observer feedback gain matrix L is adjusted according to the estimated state. This is called a gain-scheduled feedback which is a special scheme of adaptation. Consequently, this observer is adaptive. The gain matrix L is designed, for each estimated state, such that the state estimation error $e = \tilde{x} - x$ has a stable dynamics, namely, it approaches zero asymptotically. One possible design is to place the poles of the closed-loop system for the error dynamics at selected stable locations (in the left half of the complex plane). This is called pole placement design [54]. Together, this becomes a gain-scheduled SOC estimator.

To illustrate its utility, the demonstration Li-ion model in the SimPowerSystems Toolbox in Matlab/Simulink for such battery models [47, 68] is used. Figure 2.11 provides the evidence why nonadaptive observers with a constant matrix L are not adequate for SOC estimation. Figure 2.12 demonstrates

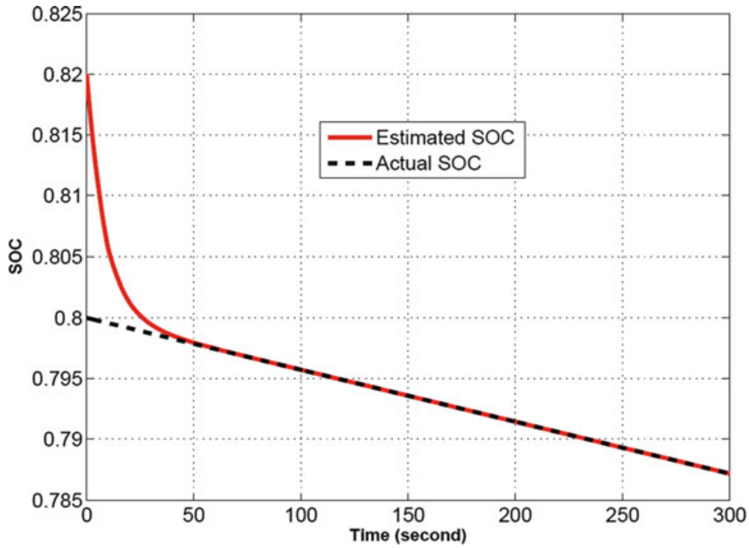


Fig. 2.12 Adaptive SOC observer design under a constant discharge current [69]

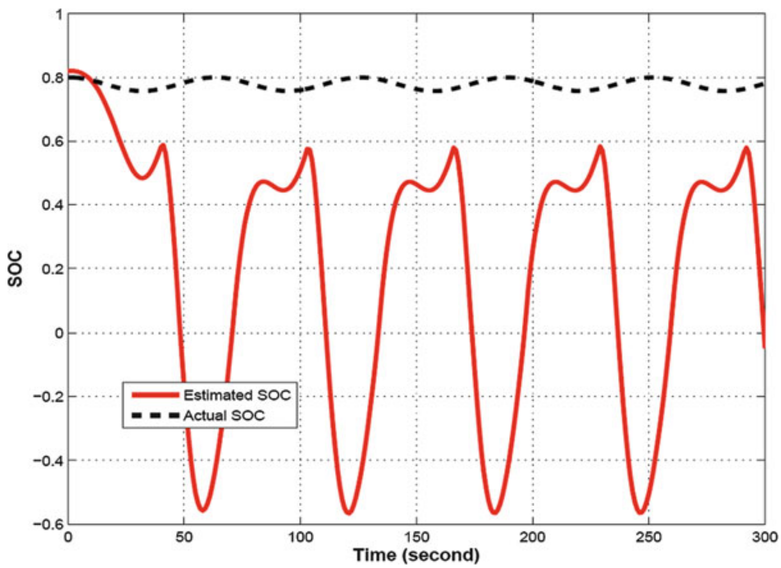


Fig. 2.13 Nonadaptive observer design under a cyclic charge/discharge current [69]

the accuracy of an adaptive SOC estimator. Similar comparison can be made between nonadaptive observer design in Fig. 2.13 and adaptive design in Fig. 2.14 for tracking the SOC in a cyclic charge–discharge operation. Further details of this methodology can be found in [54].

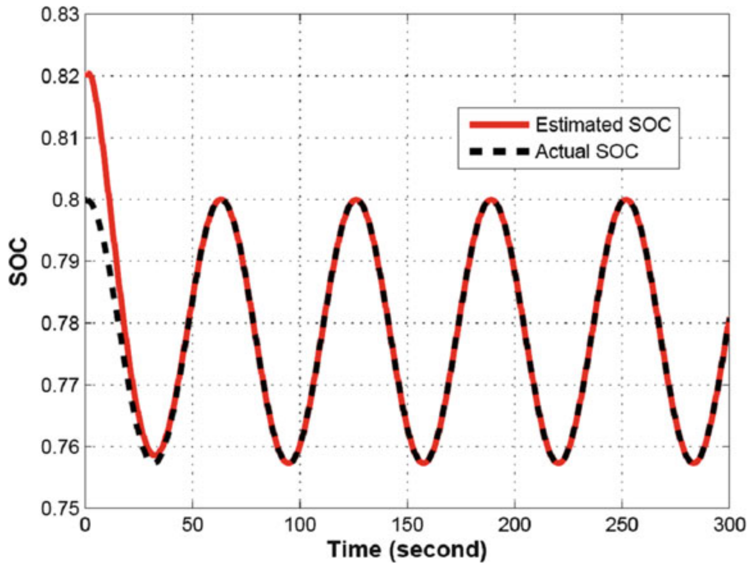


Fig. 2.14 Adaptive observer design under a cyclic charge/discharge current [69]

2.7.2 Run-Time and Cell-Level Individualized Battery Characterization

An EV battery system consists of many battery cells, which always have different characteristics. When manufacturers package battery cells into packs, efforts are often made to group cells of similar capacity and characteristics (often from the same batch) so that cell-to-cell variations are minimized for new battery packs. However, battery cells change with time and operating conditions due to a variety of factors such as aging, operational conditions, and chemical property variations. Consequently, during operating cycles over an extended time, SOC, battery health, remaining life, charge and discharge resistance, and capacitance demonstrate nonlinear and time-varying dynamics [49, 51, 55–57]. Consequently, for enhanced battery management, reliable system diagnosis, and improved power efficiency, it is desirable to capture individualized characteristics of each battery cell and produce updated models in real time. This is a problem of system identification [58, 59].

To facilitate model updating during run time, we first represent a linearized battery model in its input/output form, namely, a transfer function [60]. Since most battery models are either first-order or second-order and involve an integration of the input current, the typical form is

$$\frac{V(s)}{I(s)} = \frac{d_1 s^2 + d_2 s + 1}{c_1 s^2 + c_2 s}. \tag{2.26}$$

This can be conveniently modified to

$$H(s) = \frac{I(s)/s}{V(s)} = \frac{c_1 s + c_2}{d_1 s^2 + d_2 s + 1}. \tag{2.27}$$

This step relates the total charge or discharge to the voltage and makes the transfer function strictly proper, which is more suitable for system identification. $H(s)$ is then discretized for a given sampling interval, which is usually the actual sampling interval of the data acquisition system for the battery system, although other choices can be accommodated. This leads to a discrete-time system of transformed input–output variables u and y:

$$\frac{Y(z)}{U(z)} = \frac{b_1 z + b_2}{z^2 + a_1 z + a_2}, \tag{2.28}$$

which can be equivalently written in a regression form:

$$y_k = -a_1 y_{k-1} - a_2 y_{k-2} + b_1 u_{k-1} + b_2 u_{k-2} = \phi_k^T \theta. \tag{2.29}$$

Here, $\phi_k^T = [-y_{k-1}, -y_{k-2}, u_{k-1}, u_{k-2}]$ is called the regressor which is updated by the measurement data at each sampling time and $\theta^T = [a_1, a_2, b_1, b_2]$ is the model parameter vector that is to be updated. This regression form allows us to apply many standard identification algorithms and analyze their accuracy, convergence, and convergence speed, which are essential properties to ensure that updated models are authentic and accurate. For example, one may choose to use the Recursive Least Squares (RLS) estimation algorithm, as reported in [58].

To illustrate, the RLS estimation was applied to update the model parameters for the battery system in [47]. The model parameters are identified and the model output is compared to the true system. Convergence of parameter estimates are shown in Fig. 2.15.

2.7.3 Cell Balancing

Cell balancing is an essential function of BMS, especially for Li-ion batteries [61–64]. To supply required voltages, battery cells must be connected in series. During charge and discharge, each cell in the string will be subject to the same current, but will have different SOCs due to several factors. First, cells have different capacities. Even if the manufacturer makes the best effort to match capacities for new cells, nonuniform operating conditions impose different thermal and electrical stress on cells, causing changes in capacities. Although Li-ion cells have small self-discharge, small differences can accumulate over time, causing

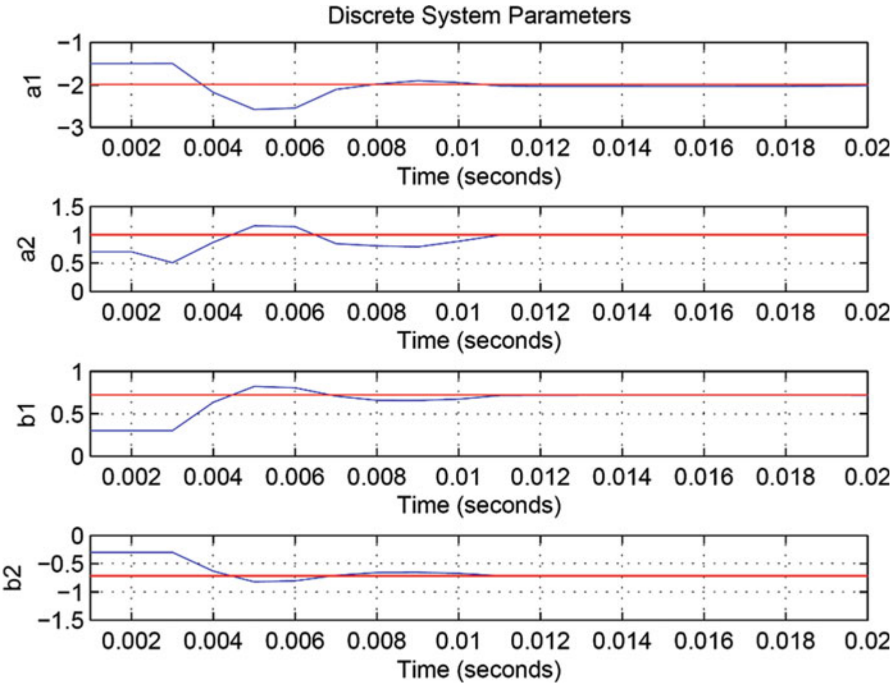


Fig. 2.15 Comparison of the model parameter estimates and the true model parameters (a simulated battery system with parameters established from lab experiments by NREL)

different SOCs even for cells with nearly identical capacities. Furthermore, variations in internal impedance and material aging inevitably lead to nonuniform cell characteristics. To protect the cells from overheat, overcharge, and overdischarge, the operation of the string is fundamentally limited by the weakest cell, the one reaches SOC upper and lower boundaries first. Such an imbalance prevents cells to supply their capacities fully, and consequently limits the battery run time, SOH, and life cycles.

Cell balancing aims to reduce SOC imbalances within a string by controlling the SOCs of the cells so that they become approximately equal. This can be achieved by dissipating energy from the cells of higher SOCs to shunt resistor (Fig. 2.16), or shuffling energy from the highest SOC cell to the lowest SOC cell (Fig. 2.17), or by incremental cell balancing through paired cells in stages [61–64].

The shunt resistor circuit in Fig. 2.16 is the simplest structure for cell balancing. When a cell's SOC is evaluated to be higher than others, its bypass circuit is turned on and the cell is discharged to reduce its SOC. The energy is lost as heat through the shunt resistor during the balancing. As a result, this cell balancing structure reduces battery efficiency. In contrast, the energy shuffling circuit in Fig. 2.17 will connect the cell with the highest SOC in the string to its balancing capacitor and charge the capacitor. The energy stored in the capacitor is then shuffled to the next

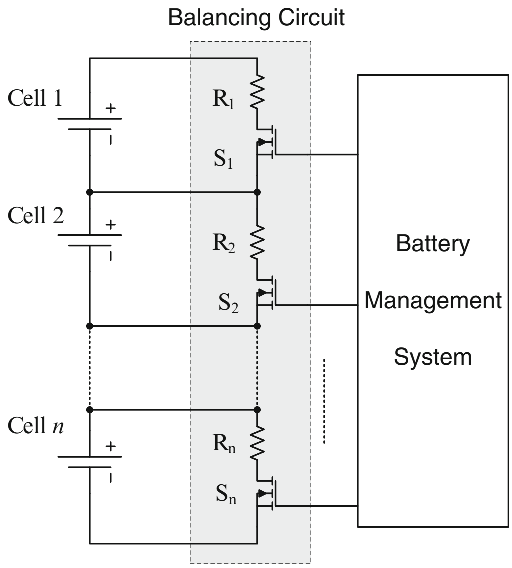


Fig. 2.16 Cell balancing through bypass resistors

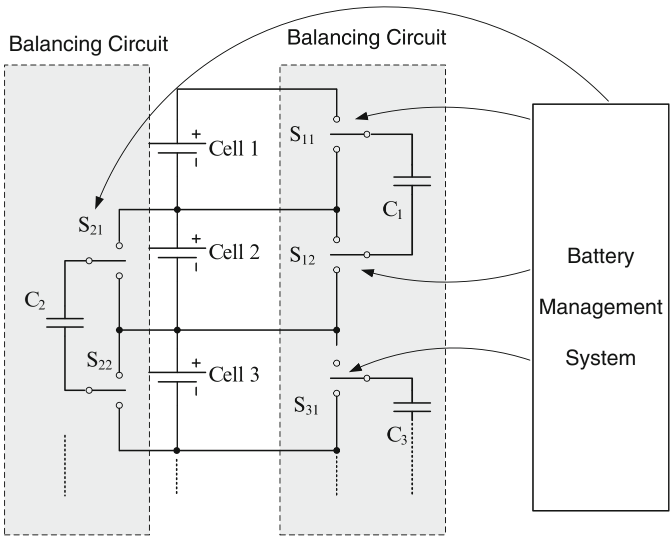


Fig. 2.17 Cell balancing through energy shuffling via capacitors

cell. This operation is repeated through the string to distribute gradually the energy from the cell with the highest SOC to other cells in the string. This balancing strategy increases battery efficiency, but incurs higher costs and longer time to finish the balancing process.

There are some principal design considerations and tradeoffs when cell balancing circuits are configured.

1. *Speed of Balancing*: It is always desirable to complete cell balancing as fast as possible. The downside of fast balancing is that the power rating of the balancing circuits will increase, causing higher loss and heat generation which in turn demands additional and costly thermal management. This also will make packaging more complicated.
2. *Energy Efficiency*: Dissipating energy to shunt resistors is a total energy loss, as shown in Fig. 2.16. As a result, it is only a viable choice for balancing of cells when the voltage deviations among cells are relatively small. However, such balancing circuits are very simple and sometimes the switching circuits and control can be integrated in ICs (integrated circuits). In contrast, energy shuffling can reduce significantly the energy loss, but requires additional energy storage components such as capacitors (or inductors) together with their power electronics and control functions, shown in Fig. 2.17. These increase costs and sizes with more sophisticated management systems.
3. *Voltage Balancing*: Although the intention of cell balancing is justifiably to equalize SOCs, for run-time implementation accurate SOC estimation and capacity determination are difficult. Consequently, many existing cell balancing systems are actually cell voltage balancing circuits. In other words, by comparing cell voltages, the balancing circuits try to equalize cell terminal voltages. This technology has fundamental drawbacks. Since terminal voltages are affected by cell impedances which are partially the reason for cell imbalance, equalizing terminal voltages will leave open-circuit voltages uneven when the cells are being charged or discharged at the same time. Since the open-circuit voltage is a better indicator of SOCs, terminal voltage balancing is always subject to imbalance on SOCs. In addition, the characteristic curves (terminal voltage vs. depth of charge/discharge) vary from cell to cell. When a cell ages, the cell voltage will be a poor indicator of its SOC. This is an acute problem for Li-ion batteries since their characteristic curves are quite flat in the normal operating ranges. This remains an active R&D area for manufacturers and research communities.

2.8 Battery Aggregation

The limited power capability of individual EVs prevents the direct participation of individual EVs in electricity markets. The integration of DER units using aggregation under the Virtual Power Plant (VPP) concept enables their visibility to the System Operator (SO) and so supports their market participation [65, 66]. In what follows, a classification of different VPP realizations is given and three VPP control architectures are introduced [67].

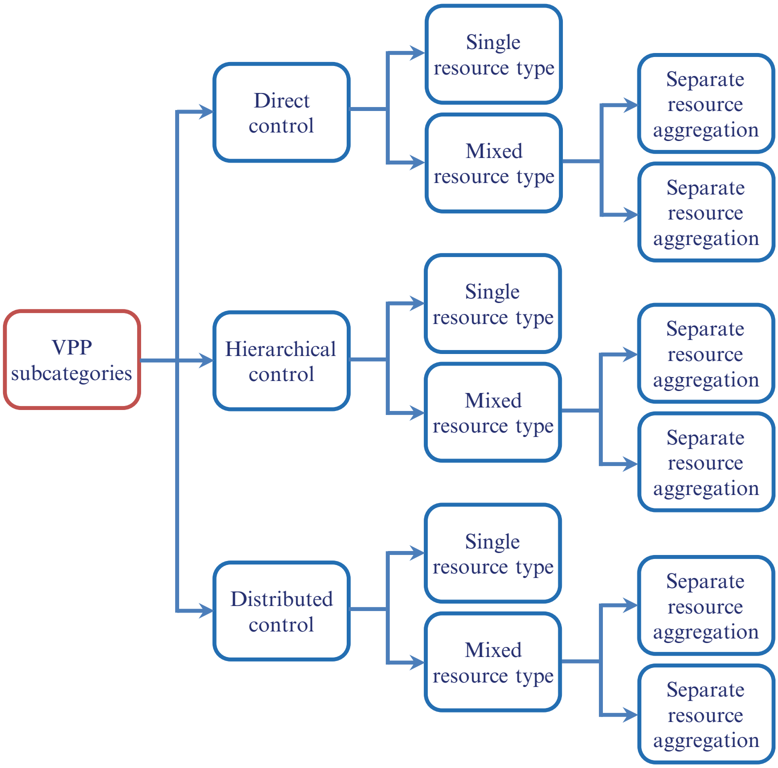


Fig. 2.18 Classification of different VPP realizations

2.8.1 Virtual Power Plant Realizations and Control

VPPs can be classified into several subcategories depending on the implemented control scheme and the aggregation type as presented in Fig. 2.18. The control approach used in VPPs may be direct, hierarchical, or distributed. The direct approach is based on a centralized control and decision-making concept. In the distributed control, on the other hand, the decisions for control of the VPP are made in a fully decentralized way. The hierarchical approach is the intermediate between direct and distributed control with some level of decision-making capability distributed in the VPP. In each VPP control approach, two subcategories of VPPs can be identified depending on the portfolio of the constituting resources. Contrary to single-resource-type VPPs, mixed-resource-type VPPs incorporate of a variety of resources. One approach to implementing these VPPs is to use a single module to handle all different resource categories. Alternatively, separate management modules for coordination of various types of resources may be considered. For example, an EV Management Module can be considered to specifically handle EV resources.

VPPs have so-called VPP Control Centers which are responsible for the optimal coordination of their resources and representing them as single entities to the market, DSOs, and TSOs. This unit needs updated information about the operation of VPP resources as well as the market status as inputs to its optimization functions. The use of information and communication technology (ICT) solutions allows the VPP Control Center to monitor and control the VPP resources in near real-time.

Within each VPP, it is possible that some entities are in charge of operating a number of individual resources. For example, so-called charging point managers (CPMs) may emerge as entities responsible for operating a number of EV charging points (CPs). In these cases, CPMs will represent their EVs to the VPP Control Center.

The CPs can be classified into three different categories based on their location. The CP location may be either in public areas with public access, private areas with private access, or private areas with public access. In each of these areas, the VPP Control Center may communicate with EVs in different ways. For example, the communication with EVs in private areas with private access may be realized through home energy management system (HEMS). An HEMS is an application that enables energy consumption management in a house taking into account the user preferences and allows interaction with the utility.

For the market participation, the VPP Control Center prepares bids and offers for the day-ahead and intraday markets based on the forecast about generation and demand of VPP resources. In real-time, using the measurement data from Smart Meters (SMs) and the updated input from market and the SO, the VPP Control Center decides and sends out adjustment requests to VPP resources.

2.8.1.1 Direct Control

In the direct control approach, the VPP Control Center is responsible for deciding and directly communicating the control requests with the individual VPP units or entities representing them. Within their limitations and based on preferences set by their owners, the resources will respond to the control requests received from the VPP Control Center.

Figure 2.19 summarizes the information flow paths in a direct VPP with a focus on EV integration. In this control approach, the VPP control center centrally takes care about the optimization of the operation of all individual VPP resources. The exceptions are cases where an entity such as a CPM is responsible for aggregating and representing a number of resources. Direct communication of the VPP Control Center with the VPP resources and the central decision-making process make this approach simple to implement.

2.8.1.2 Hierarchical Control

In a hierarchical control approach, intermediate aggregation functions are introduced for the VPP and aggregation takes place in different hierarchical layers.

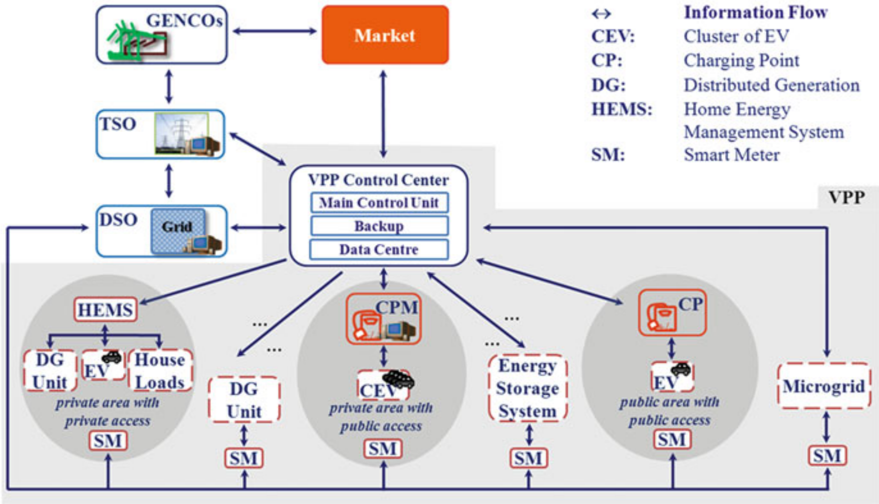


Fig. 2.19 Interaction between the VPP control center and the VPP resources, DSO, TSO, and market in the direct control approach

The EV Management Module (EVMM) is the module of the VPP which is responsible for the management of EVs under the VPP domain.

The EVMM prepares the EV market strategies as an input for the VPP Control Center, with the goal of minimizing EV battery charging cost and maximizing EV revenues. An EVMM comprises residential and commercial aggregation functions. This distinction enables the improvement of load predictions and identification of services to be offered from each group. Figure 2.20 shows the different levels of hierarchy.

2.8.1.3 Distributed Control

In a distributed control approach, a VPP Control Center does not have direct access to the DERs' operation but it can affect their behavior through price incentives. The VPP Control Center may follow different pricing strategies for consumption and generation. The core of the distributed concept is based on the ability of individual VPP entities to decide their optimal operational state. This requires that VPP entities have the adequate computational intelligence to obtain their private goals.

The information flow in the distributed VPP control is summarized is Fig. 2.21. In order to reduce the amount of information exchanged, an intermediate level of aggregation is implemented, referred to as VPP Local Aggregation (LA) functions, which is responsible for the coordinating of smaller geographical areas.

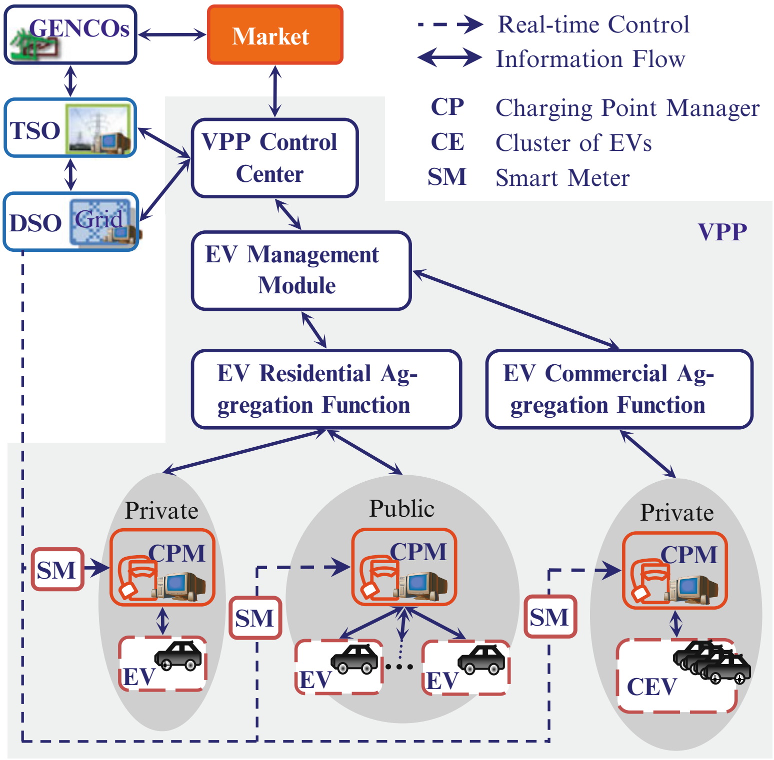


Fig. 2.20 Interaction between the VPP control center and the VPP resources, DSO, TSO, and the market in a hierarchical approach

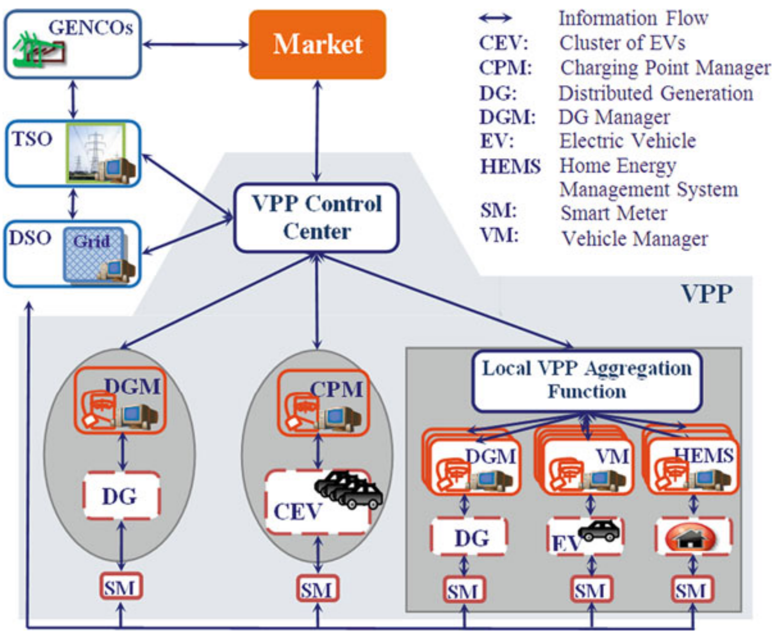


Fig. 2.21 Interaction between the VPP control center and the VPP resources, DSO, TSO, and the market in a distributed control approach

References

1. Howell D (2011) 2010 Annual progress report for energy storage R&D, Vehicle Technologies Program, Energy Efficiency and Renewable Energy. U.S. Department of Energy, Washington, DC
2. Boulanger AG, Chu AC, Maxx S, Waltz DL (2011) Vehicle electrification: status and issues. Proc IEEE 99(6):1116–1138
3. Xu X, Wang C, Liao G, Yeh CP, Stark W (2009) Development of a plug-in hybrid electric vehicle educational demonstration unit. In: Proceedings of 2009 North American power symposium, Starkville, MS, USA, 4–6 Oct 2009
4. Corrigan D, Masias A (2011) Batteries for electric and hybrid vehicles. In: Reddy TB (ed) Linden's handbook of batteries, 4th edn. McGraw Hill, New York
5. Ehsani M, Gao Y, Emadi A (2010) Modern electric, hybrid electric, and fuel cell vehicles: fundamentals, theory and design, 2nd edn. CRC, London
6. USABC (1996) Electric vehicle battery test procedures manual. http://avt.inl.gov/battery/pdf/usabc_manual_rev2.pdf
7. Coleman M, Hurley WG, Lee CK (2008) An improved battery characterization method using a two-pulse load test. IEEE Trans EC 23(2):708–713
8. Dhameja S (2002) Electric vehicle battery systems. Newnes, Boston
9. Pokrzywa J (2010) SAE Taipei: SAE ground vehicle standards SmartGrid. http://sae-taipei.org.tw/image/1283265726.pdf
10. Rocky Mountain Institute (2008) Smart garage Charrette pre-read v2.0. http://move.rmi.org/files/smartgarage/PreRead_v2_Core-1.pdf
11. http://www.peve.jp/e/hevkinzoku.html
12. Higashimoto K, Homma H, Uemura Y, Kawai H, Saibara S, Hirinaka K (2010) Automotive lithium-ion battery. Hitachi Hyoron 92(12):30–33
13. Moss PL, Au G, Plichta EJ, Zheng JP (2009) Investigation of solid electrolyte interface layer development during continuous cycling using ac impedance spectra and micro-structural analysis. J Power Sources 189:644–648
14. Strunz K, Louie H (2009) Cache energy control for storage: power system integration and education based on analogies derived from computer engineering. IEEE Trans Power Syst 24 (1):12–19
15. http://www.uscar.org/guest/article_view.php?articles_id=85
16. Ovshinsky SR, Fetcenko MA, Reichman B, Young K, Chao B, Im J (1997) US Patent 5,616,432
17. Ovshinsky SR, Corrigan D, Venkatesan S, Young R, Fierro C, Fetcenko MA (1994) US Patent 5,348,822
18. Esaka T, Sakagucji H, Kobayashi S (2004) Hydrogen storage in protpn-conductive perovskite-type oxide and their application to nickel-hydrogen batteries. Solid State Ionics 166 (3–4):351–357
19. Deng G, Chen Y, Tao M, Wu C, Shen X, Yang H, Liu M (2010) Electrochemical properties and hydrogen storage mechanism of perovskite-type oxide LaFeO3 as a negative electrode for Ni/MH batteries. Electrochim Acta 55 (3):1120–1124
20. http://www.khi.co.jp/english/gigacell/index.html
21. West JK, Higgins MP, Regalado J, George A (2009) US Patent Application 20090142655
22. http://www.arl.army.mil/www/pages/556/1109TFSHPCathodeLiIonBatteries.pdf
23. Sun Q, Li X, Wang Z, Ji Y (2009) Synthesis and electrochemical performance of 5V spinel LiNi0.5Mn1.5O4 prepared by solid-state reaction. Trans Nonferrous Met Soc Chin 19:176–181
24. Fetcenko MA (2011) In: Presentation in Batteries 2011, Cannes Mandelieu, France, 20–28 Sep 2011
25. Mitchell RR, Gallany BM, Thompson CV, Yang S (2011) All-carbon-nanofiber electrodes for high-energy, rechargeable Li-O_2 batteries. Energy Environ Sci 4:2952–2958

26. Dubarry M, Vuillaume N, Liaw BY (2009) From single cell model to battery pack simulation for Li-ion batteries. J Power Sources 186:500–507
27. Song L, Evans JW (2000) Electrochemical-thermal model of lithium polymer batteries. J Electrochem Soc 147:2086–2095
28. Min C, Gabriel AR (2006) Accurate electrical battery model capable of predicting runtime and I–V performance. IEEE Trans Energy Conversion 21(2):504–511
29. Gomadam PM, Weidner JW, Dougal RA, White RE (2002) Mathematical modeling of lithium-ion and nickel battery systems. J Power Sources 110(2):267–24
30. Dennis DW, Battaglia VS, Belanger A (2002) Electrochemical modeling of lithium polymer batteries. J Power Source 110(2):310–320
31. Newman J, Thomas KE, Hafezi H, Wheeler DR (2003) Modeling of lithium-ion batteries. J Power Sources 119–121:838–843
32. Rynkiewicz R (1999) Discharge and charge modeling of lead acid batteries. Proc Appl Power Electron Conf Expo 2:707–710
33. Rakhmatov D, Vrudhula S, Wallach DA (2003) A model for battery lifetime analysis for organizing applications on a pocket computer. IEEE Trans VLSI Syst 11(6):1019–1030
34. Rong P, Pedram M (2003) An analytical model for predicting the remaining battery capacity of lithium-ion batteries. In: Proceedings of design, automation, and test in Europe conference and exhibition, pp 1148–1149
35. Pascoe PE, Anbuky AH (2004) VRLA battery discharge reserve time estimation. IEEE Trans Power Electron 19(6):1515–1522
36. Salameh ZM, Casacca MA, Lynch WA (1992) A mathematical model for lead-acid batteries. IEEE Trans Energy Convers 7(1):93–98
37. Valvo M, Wicks FE, Robertson D, Rudin S (1996) Development and application of an improved equivalent circuit model of a lead acid battery. Proc Energy Convers Eng Conf 2:1159–1163
38. Ceraolo M (2000) New dynamical models of lead-acid batteries. IEEE Trans Power Syst 15(4):1184–1190
39. Barsali S, Ceraolo M (2002) Dynamical models of lead-acid batteries: implementation issues. IEEE Trans Energy Convers 17(1):16–23
40. Schweighofer B, Raab KM, Brasseur G (2003) Modeling of high power automotive batteries by the use of an automated test system. IEEE Trans Instrum Meas 52(4):1087–1091
41. Gao L, Liu S, Dougal RA (2002) Dynamic lithium-ion battery model for system simulation. IEEE Trans Compon Packag Technol 25(3):495–505
42. Baudry P, Neri M, Gueguen M, Lonchampt G (1995) Electro-thermal modeling of polymer lithium batteries for starting period and pulse power. J Power Sources 54(2):393–396
43. Abu-Sharkh S, Doerffel D (2004) Rapid test and non-linear model characterization of solid-state lithium-ion batteries. J Power Sources 130:266–274
44. Bard A, Faulkner L (2001) Electrochemical methods: fundamentals and applications, 2nd edn. Wiley, New York
45. Doyle M, Newman J, Gozdz AS, Schmutz CN, Tarascon JM (1996) Comparison of modelling predictions with experimental data from plastic lithium ion cells. J Electrochem Soc 143:1890
46. Tremblay O, Dessaint L-A (2009) Experimental validation of a battery dynamic model for EV applications. In: EVS24 international battery, hybrid and fuel cell electric vehicle symposium, Stavanger, Norway, 13–16 May 2009, World Electric Vehicle J 3
47. Johnson VH (2001) Battery performance models in ADVISOR. J Power Sources 110:321–329
48. Wang C, Nehrir MH, Shaw SR (2005) Dynamic models and model validation for PEM fuel cells using electrical circuits. IEEE Trans Energy Convers 20(2):442–451
49. Barbier C, Meyer H, Nogarede B, Bensaoud S (1994) A battery state of charge indicator for electric vehicle. In: Proceedings of the international conference of the institution of mechanical engineers, automotive electronics, London, UK, 17–19 May 1994, pp 29–34
50. Dai HF, Wei XZ, Sun ZC (2006) Online SOC estimation of high-power lithium-ion batteries used on HEVs. In: Proceedings of IEEE ICVES 2006, pp 342–347

51. Giglioli R, Pelacchi P, Raugi M, Zini G (1988) A state of charge observer for lead-acid batteries. Energia Elettrica 65(1):27–33
52. Plett G (2004) Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs. Part 1: Background. J Power Sources 134(2):252–261
53. Rodrigues S, Munichandraiah N, Shukla A (2000) A review of state-of-charge indication of batteries by means of ac impedance measurements. J Power Sources 87(1/2):12–20
54. Kuo BC (1995) Digital control systems, 2nd edn. Oxford University Press, Oxford
55. Barsoukov E, Kim J, Yoon C, Lee H (1999) Universal battery parameterization to yield a non-linear equivalent circuit valid for battery simulation at arbitrary load. J Power Sources 83(1/2):61–70
56. Plett G (2004) Extended Kalman filtering for battery management systems of LiPB-based HEV battery packs. Part 2. Modeling and identification. J Power Sources 134(2):262–276
57. Takano K, Nozaki K, Saito Y, Negishi A, Kato K, Yamaguchi Y (2000) Simulation study of electrical dynamic characteristics of lithium-ion battery. J Power Sources 90(2):214.223
58. Ljung L (1987) System identification: theory for the user. Prentice-Hall, Englewood Cliffs, NJ
59. Wang LY, Yin G, J-f Z, Zhao Y (2010) System identification with quantized observations. Birkhauser, Boston, MA. ISBN 978-0-8176-4955-5
60. Sitterly M, Wang LY, Yin G, Wang C (2011) Enhanced identification of battery models for real-time battery management. IEEE Trans Sustain Energy 2:300–308
61. Moore SW, Schneider P (2001) A review of cell equalization methods for lithium ion and lithium polymer battery systems. SAE Publication, Troy, MI
62. Linden D, Reddy T (2001) Handbook of batteries, 3rd edn. McGraw Hill, New York
63. Kutkut NH, Wiegman HLN, Divan DM, Novotny DW (1999) Design considerations for charge equalization of an electric vehicle battery system. IEEE Trans Ind Appl 35:28–35
64. Tang M, Stuart T (2000) Selective buck-boost equalizer for series battery packs. IEEE Trans Aerospace Electron Syst 36:201–211
65. Pudjianto D, Ramsay C, Strbac G (2008) Microgrids and virtual power plants: concepts to support the integration of distributed energy resources. Proc Inst Mech Eng A J Power Energy 222(7):731–741
66. Karfopoulos E, Tsikalakis A, Karagiorgis G, Dimeas A, Christodoulou C, Tomtsi T, Hatziargyriou N (2009) Description of the off-line simulations. Task and results presentation. EUDEEP Project WP4&5, Task Force 3, Jan 2009
67. Raab AF, Ferdowsi M, Karfopoulos E, Grau Unda I, Skarvelis-Kazakos S, Papado poulos P, Abbasi E, Cipcigan LM, Jenkins N, Hatziargyriou N, Strunz K (2011) Virtual power plant control concepts with electric vehicles. In: 16th International conference on intelligent system applications to power systems, Hersonissos, Greece, Sep 2011
68. http://www.mathworks.com/help/toolbox/physmod/powersys/ref/battery.html
69. Lezhang L, Wang LY, Chen Z, Wang C, Lin F, Wang H (2012) Integrated system identification and state-of-charge estimation of battery systems. IEEE Trans Energy Conversion (In press)

Chapter 3
The Impact of EV Charging on the System Demand

N. Hatziargyriou, E.L. Karfopoulos, and K. Tsatsakis

3.1 Introduction

The technical specifications of an EV fleet, i.e., EV technology (pure battery or plug-in hybrid) and their energy consumption, affect the energy requirements of EV charging. Moreover, the charging needs of EV are determined by random variables, such as their mobility, in terms of daily traveled distances and the EV owner driving profiles. This implies that deterministic methodologies for the energy analysis of EV operation are inefficient and the stochastic behavior of the EV needs to be taken into account. In this chapter, a stochastic simulation platform is presented providing the ability to define the additional EV charging demand. The allocation of EV demand within a day depends on the connectivity of EV (the time and duration of plug-in period) and the availability of charging infrastructures (home, workplace, public charging, etc.). These two factors determine the changes in the daily system demand and are case sensitive. In this chapter, five EU countries (UK, Germany, Spain, Portugal, and Greece) are analyzed, in order to obtain representative conclusions regarding the impact of EV on the system demand curve. The methodology and the results presented in this chapter can be used for the development of new business models, as well as control and management architectures for EV electrical grid integration, as analyzed in Chaps. 4 and 8.

N. Hatziargyriou (✉) • E.L. Karfopoulos • K. Tsatsakis
National Technical University of Athens, Zografou, Greece
e-mail: nh@power.ece.ntua.gr; ekarfop@mail.ntua.gr; tsatsakis_kostas@yahoo.gr

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_3, © Springer Science+Business Media New York 2013

3.2 Identification of EV Demand

This section aims to identify the additional demand of EV charging considering EV technical specifications and traffic pattern. Figure 3.1 shows the stochastic EV demand simulation methodology used to model the energy requirements of an EV fleet taking into account all the parameters defining an EV charging process.

The set of parameters can be separated into two subsets as follows:

Constant Parameters

1. EV penetration level
2. Charging station technologies (mode 1, 2, and 3)
3. Availability of charging (home, home/workplace)
4. Charging losses
5. Charging policy (Dumb, Dual-tariff, and Smart Charging, V2G)

Probabilistic Parameters

1. Classification of EV (PHEV, BEV, L7e,M1,N1,N2)
2. Daily travel distance
3. EV connectivity (return time)

These parameters are presented in detail in the following paragraphs.

3.2.1 EV Penetration Level

The number of simulated EV depends on the forecasted EV sales for each country. Assuming that vehicle sales are proportional to population changes, the future sales trend for all European countries' displays is increasing. Considering various key factors, such as technological development in batteries, fuel prices, investments on charging infrastructures, etc., three different EV sales scenarios can be identified [1]:

- Scenario 1: The most likely to occur
- Scenario 2: More optimistic than the one likely to occur
- Scenario 3: Very aggressive EV uptake

Figure 3.2 illustrates the expected EV deployment level for the three scenarios, as a percentage of the total vehicle sales. In the realistic scenario, it is expected that EV sales will amount for 15% of total vehicle sales in 2030, while in the optimistic scenario this EV share is almost double. In the very aggressive scenario, half of the vehicle sales in 2030 is assumed to be electric vehicles.

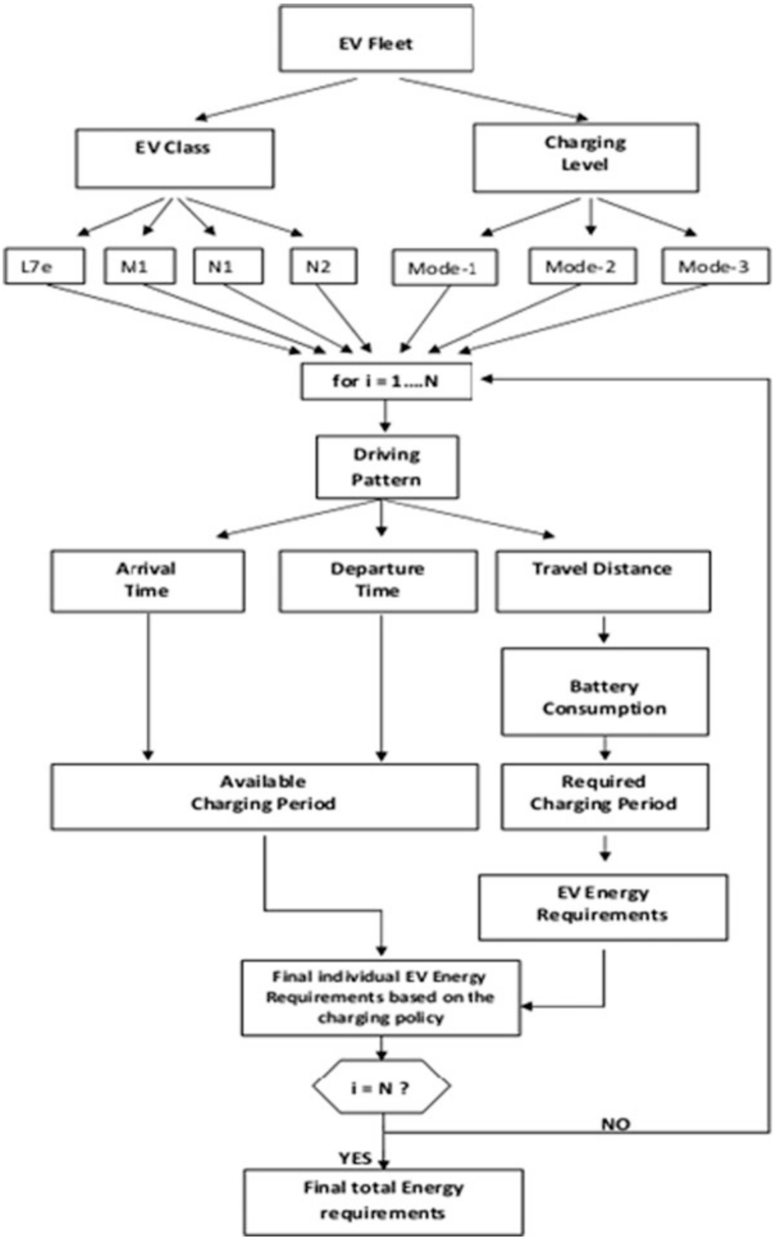


Fig. 3.1 Stochastic model for identifying the additional EV charging demand

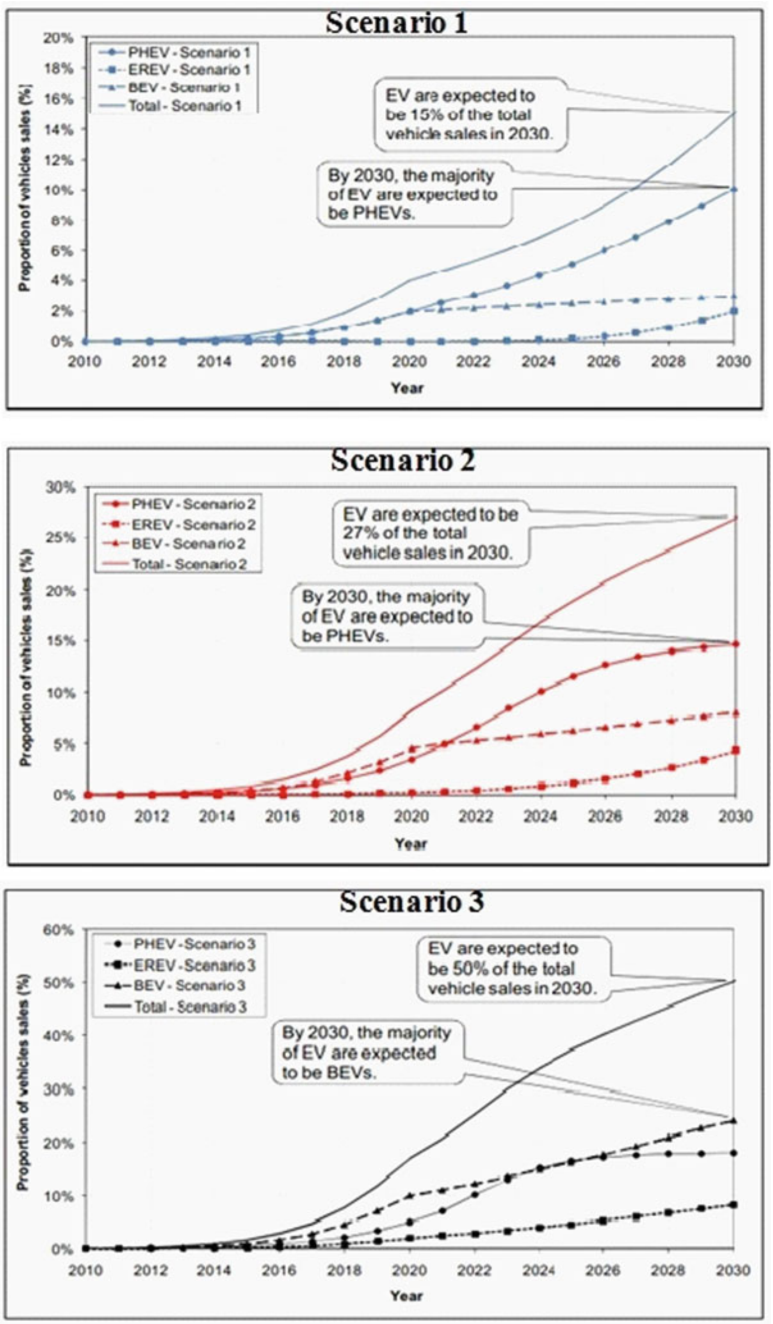


Fig. 3.2 EV deployment scenarios [1]

Table 3.1 Descriptions of EV classification and battery capacity

		Battery capacity (KWh)		
Type		Mean	Min	Max
L7e	BEV	8.7	3	15
M1	BEV	28.5	10	72
	PHEV	12.9	4	22.6
N1	BEV	23	9.6	40
	PHEV	12.9	4	22.6
N2	BEV	51.2	51.2	120

3.2.2 Classification of EV

EV can be classified into two categories depending on the type of engine:

- The plug-in hybrid EV (PHEV)
- The pure battery EV (BEV)

Pure battery EV can be further subdivided into several categories according to their technical characteristics as defined by the European Commission's official "Mobility and Transport: Vehicle Categories" document [2]. In this chapter, the categories examined are limited to the following ones, which are expected to dominate the vehicle market sales:

- L7e: small city purpose vehicles.
- M1: 4-seater passenger vehicles.
- N1: carriage of goods with a maximum laden mass of less than 3,500 kg.
- N2: maximum laden mass of 3,500–12,000 kg for commercial purposes.

Each type of EV has specific battery capacity ranging between a minimum and a maximum value. For simulation purposes, the battery capacity is expressed by a normal distribution with a mean value and a standard deviation as shown in Table 3.1. Exceptionally, a compound exponential distribution is considered for the EV type N2.

3.2.3 Daily Travel Distance

This parameter expresses the daily distance covered by an EV between two successive charging cycles. The daily travel distances depend highly on the purpose of EV usage. For example, during weekdays, vehicles are used mainly for working purposes, thus the distance profile exhibits approximately the same pattern. During weekends, vehicle mobility is reduced and users have the tendency to travel longer distances at different hours during the day. Moreover, since the daily travel distances depend on the habits in each country, a different profile is considered for each country studied.

Table 3.2 Models for home/multiple connections

	Charging procedure
Model 1	75 % Home–25 % home/work
Model 2	50 % Home–50 % home/work
Model 3	25 % Home–75 % home/work

3.2.4 Battery Consumption

By defining the total traveled distance, the corresponding amount of charging energy can be calculated. The ratio between energy consumption and traveled distance (kWh/km) depends on the driving speed, road and weather conditions, etc. These parameters are highly variable and thus an average value (kWh/km) can be implemented for EV analysis purposes.

3.2.5 Required Charging Period

This parameter specifies the minimum time period during which the EV must remain plugged-in, in order to be fully charged. This charging period is defined by the EV usage and the maximum charging power of the available charging infrastructures.

3.2.6 Availability of Charging

Different scenarios can be simulated for the availability of charging:

- Charging after last trip (home charging): Since the electrification of transportation remains at an initial stage, the number of charging points will be limited. Thus, most of the EV owners will not have the ability to charge their EV anywhere, but mainly at their home private charging posts.
- Charging when a (public or private) charging point is available: In the previous scenario, the EV owner will charge his EV only when returning home. In this scenario, an EV owner has also the ability to charge his EV away from home, for example, in a workplace. This requires installation of charging points at various private or public areas. Since it is not possible to define the exact number of EV that will be charged at home (workplace), different charging patterns should be adopted (Table 3.2).
- Charging when the battery state of charge is lower than a desired level: The average traveling distance of an EV exceeds 100 km based on current technologies. When the daily traveling distance is limited, for example, in urban areas it may be less than 30 km, then there is a possibility that the owner will not plug in his EV daily, but only when necessary. In this scenario, it is assumed that an EV owner will charge his EV only when the battery state of charge is lower than a threshold, typically 40%.

Table 3.3 Percentage of available charging infrastructures per EV type [1]

		Charging infrastructure (%)		
Type		Mode 1	Mode 2	Mode 3
L7e	BEV	90	10	0
M1	BEV	85	10	5
	PHEV	85	10	5
N1	BEV	85	10	5
	PHEV	85	10	5
N2	BEV	0	80	20

3.2.7 Charging Station Technologies

This parameter determines the maximum power flow between the EV and the power grid which depends on the line power capacity of the charging infrastructure. The power level of charging affects also the duration of the charging cycle. It is assumed that at the end of each charging cycle, the battery must be fully charged (SOC = 100%).

Three different charging modes have been adopted, namely, normal (Mode 1), fast (Mode 2), and dc (Mode 3), based on the IEC 62196 and IEC 61851 standards. The selection of the charging mode for each specific EV is probabilistic and depends on its type. For instance, the connection of type N2 with a battery capacity between 51.2 and 120 kWh at a normal charging point is not realistic. Table 3.3 shows the percentage of available charging infrastructures per each EV type which are considered in this analysis.

3.2.8 Charging Losses

This parameter expresses the losses of AC/DC power conversion from the grid to the DC charging of the EV batteries and vice versa, due to the power electronic interfaces. In the present simulations, these are considered equal to 10–15% of the total energy demand.

3.2.9 Charging Strategy

The assessment of the impacts of EV penetration in power systems should take into account the charging strategies, distinguished as follows:

- Dumb Charging: This is the unplanned “plug and play” connection of electric vehicles into the grid, typically after the last trip of the day or when a charging point is available.

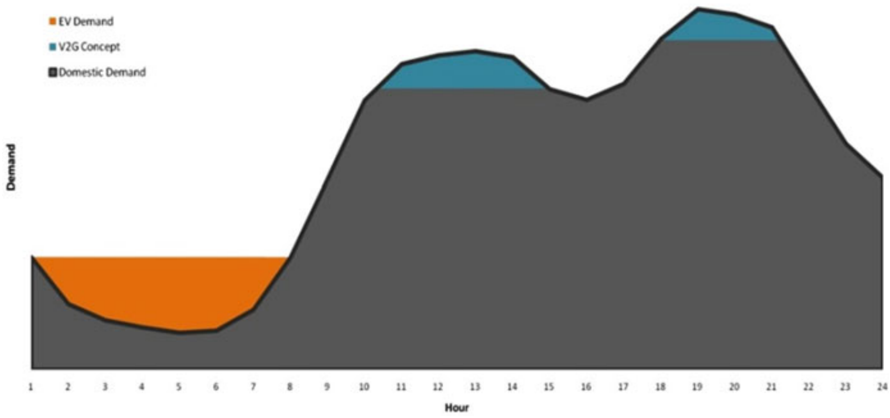


Fig. 3.3 Smart charging concepts

- Multiple Tariff Charging: This is the normal market way to manage energy demand. Cheaper energy tariffs are implemented at specific hours to shift demand to off-peak hours.
- Smart Charging: This scenario has a "valley-filling" effect, as shown in Fig. 3.3. EV charging load is shifted from peak to off-peak periods. Typically, EV mobility during off-peak hours is limited and this allows effective charging management.
- Smart charging: This can be considered as an extension of Smart Charging. In this strategy, bidirectional power flow exists between the EV and the power grid. It is based on the fact that average daily EV mobility lasts only 2–4 h and the respective energy requirements are only a fraction of their battery capacity. The excess battery power can be utilized during peak hours as a source of energy or for the provision of ancillary services to the grid, thus contributing to a more stable grid operation.

3.3 EV Impacts on System Demand

In this section, the impacts provoked by the additional EV charging load on the demand diagrams of selected countries are evaluated utilizing the methodology developed in Sect. 3.2. Five different European countries, namely, Germany, UK, Spain, Portugal, and Greece, are analyzed considering the individual charging specifications for each study case. The various charging strategies (i.e., dumb, multi-tariff, and smart charging) are simulated and the results are utilized to evaluate in a quantitative way the expected impacts of each strategy.

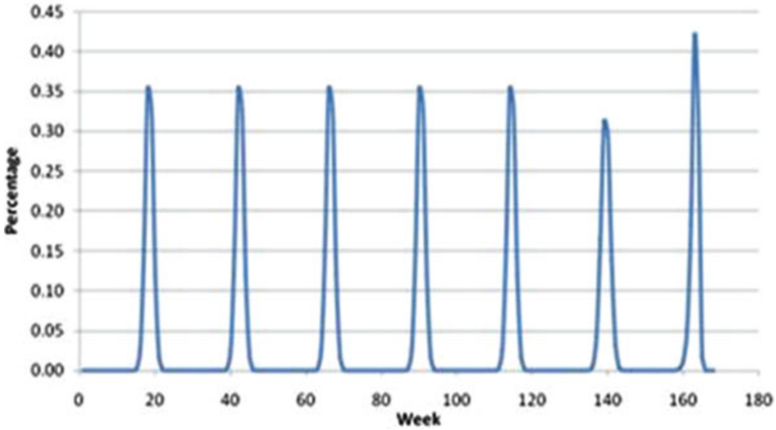


Fig. 3.4 Profile of time of return from last journey of the day (Germany)

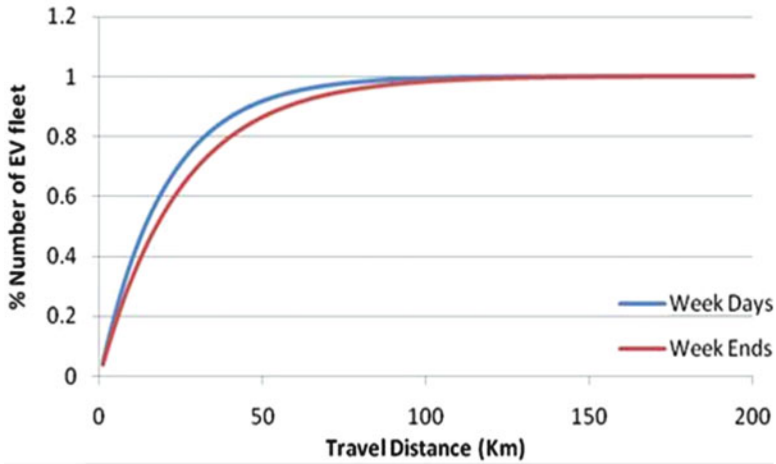


Fig. 3.5 Distances traveled per day on weekdays and weekends (Germany)

3.3.1 Germany

The traffic pattern for Germany is assumed to follow the normal distribution, as presented in Fig. 3.4 [3]. This analysis is performed on a weekly basis where the traffic profile is described by the same distribution function for the weekdays, and a different one for the weekends.

Figure 3.5 presents the cumulative probability function of traveling certain distances (km) daily. Due to the reduced mobility in weekends compared to weekdays, two separate functions are considered. It can be seen that the largest percentage of drivers (95%) travels less than 75 km daily. For simulation purposes, the mean value of the distribution density function for 95% of EV is taken equal to 18 km for weekdays and 24 km for weekends. The remaining 5% of EV is characterized by long travel distances and is simulated by a normal distribution. Since this part of EV fleet is small, its influence on the total results is limited.

In the following, the impact of electric vehicles for 2020 is examined. For the Base Load Demand, the forecast scenarios of the European Union [4] are used. For Germany, a total increase of 7.3% on base load is considered for this time horizon.

3.3.1.1 Dumb Charging

Dumb charging implies home connection to the grid after the last trip of the EV. The daily charging requirements for the three scenarios are displayed in Fig. 3.6. In the first EV penetration scenario, the daily EV peak demand is approximately 510 MW. This is doubled (1,020 MW) in the second one and quadrupled (2,115 MW) in the aggressive scenario 3. The additional energy demand for the three scenarios is 1,732 MWh, 3,520 MWh, and 7,224 MWh, respectively.

There is a small difference between the traffic patterns of weekdays and weekends. During weekends, there is a limited use of vehicles and the mobility of EV is reduced to 70%. On the other hand, weekend days are characterized by special traffic patterns and longer travel distances.

The impact of EV fleet on the total system demand is shown in Fig. 3.7. The profile of the EV charging demand is highly dependent on the time of return from the last journey of the day. During winter time, home arrival normally coincides with increased domestic consumption; thus, the EV demand coincides with the network peak load. As the number of EV increases, the impact of the additional charging is larger and thus the daily peak increases proportionally for the three penetration levels, i.e., 70,375 MW (+0.7%), 70,885 MW (+1.5%), and 71,980 MW (+3%). During summer period, the system demand curve is characterized by a peak demand during midday hours. The additional EV load increases the daily load during afternoon hours, but it does not affect the system peak demand.

Dumb Charging with Battery SOC Threshold

A large portion of the EV fleet exploits a small part of its battery capacity during a day. Thus, another scenario is examined, where EV owners charge their vehicles when the state of battery is lower than 40%. Figure 3.8 presents the additional EV demand for the three penetration scenarios. This is reduced by more than 50% compared to simple dumb charging. This can be explained by the small average daily travel distance, which results in limited daily energy consumption. The additional energy requirements are now 1,148 MWh, 2,434 MWh, and 4,943 MWh.

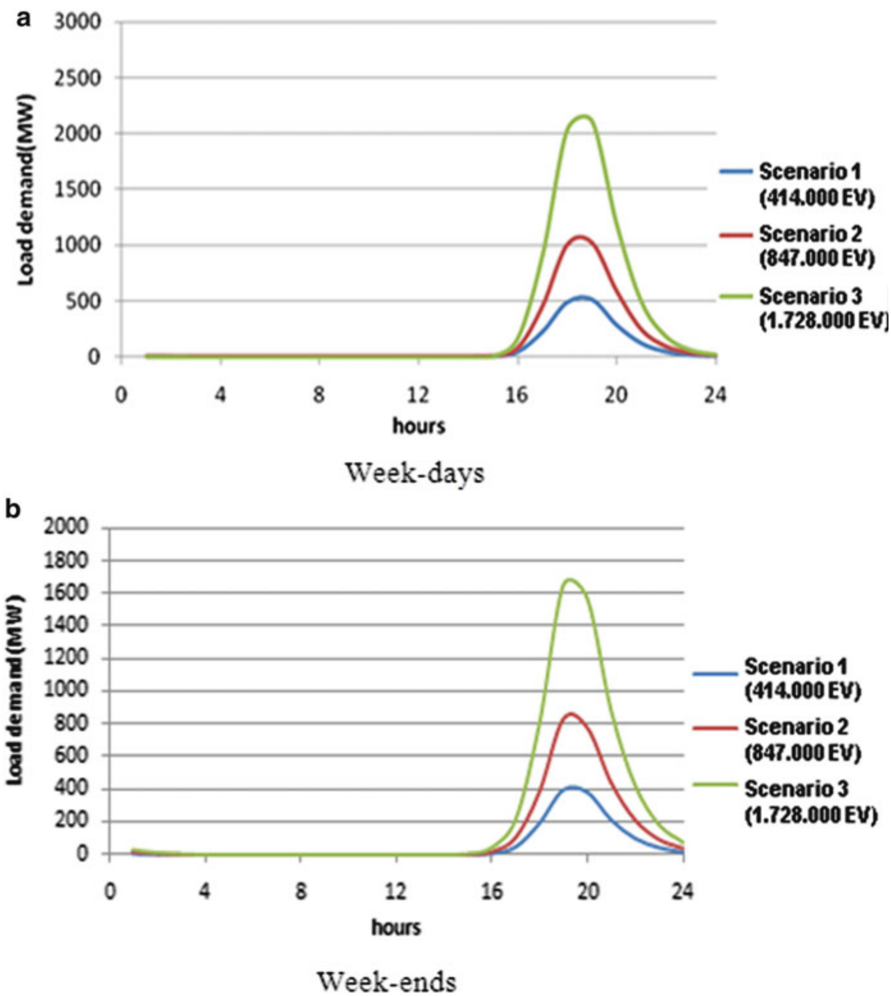


Fig. 3.6 Dumb charging—EV Load (Germany)

Dumb Charging—Workplace Chargers

In the previous scenarios, the EV owner was assumed to charge its EV only when returning home (single connection). In this scenario, the EV owner is offered the possibility to charge his EV elsewhere, for example, in a workplace (multiple connections). Figure 3.9 displays the EV charging demand for the three models of Table 3.2 for the optimistic EV penetration scenario (847,000 EV). Part of the daily EV charging needs can be fulfilled during morning hours at workplace, when the system demand is still relatively low. As the number of EV charging at workplaces increases, the additional system peak demand due to dumb charging reduces.

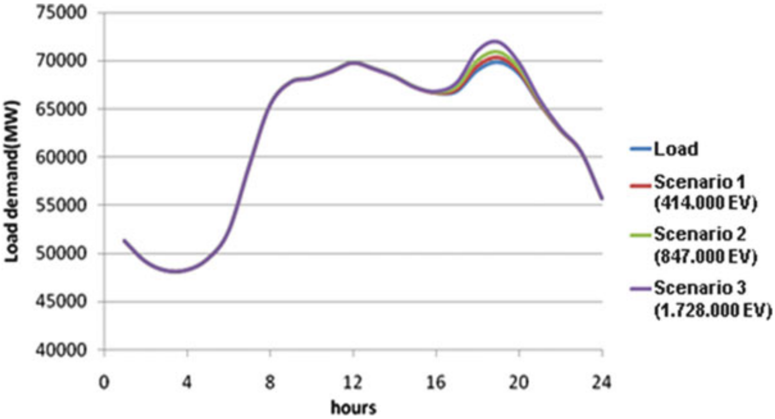


Fig. 3.7 Dumb charging—winter system demand diagram (Germany)

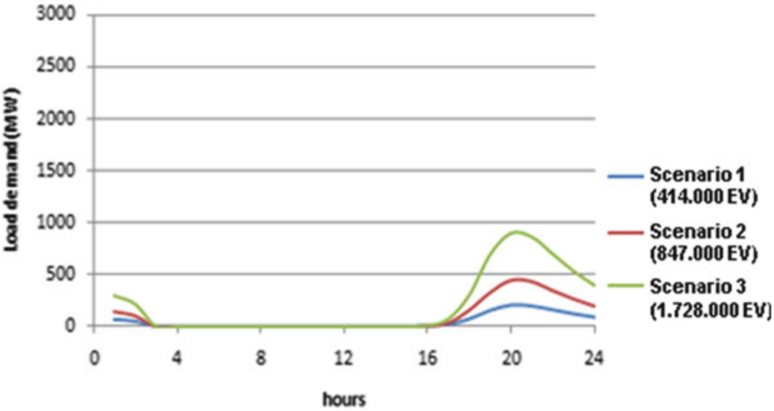


Fig. 3.8 Dumb charging—with battery SOC threshold (Germany)

The additional energy requirements of EV charging for the three models are 3,651.21 MWh, 3,782.14 MWh, and 3,913.06 MWh, respectively. The energy requirements of dumb charging with home/work connections are slightly increased compared with the ones of dumb charging (scenario 2). This can be justified by the fact that the morning charging enables PHEV to travel longer distances in battery mode during a day, since they are recharged after the first trip.

Figure 3.10 shows the annual system load diagram for Germany, including the EV charging requirements including weekdays and weekends.

3.3.1.2 Multi-tariff Scheme

Several energy providers offering different tariff schemes are active in the German energy market. Although it is not easy to represent all low tariff signals by a single

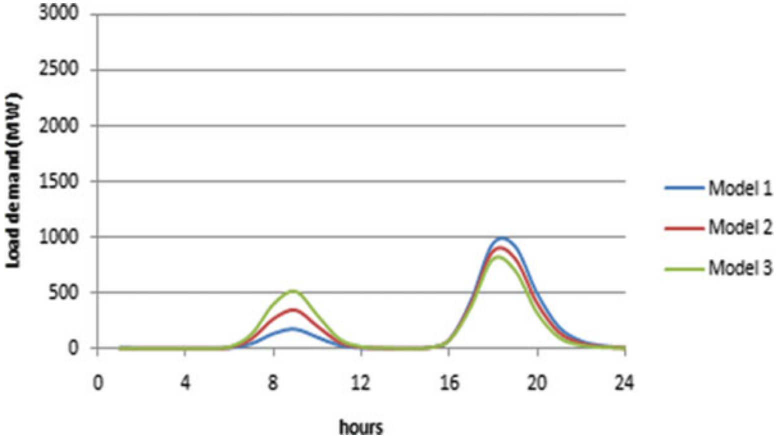


Fig. 3.9 Dumb charging with Home/Work charging-EV Load (Germany)

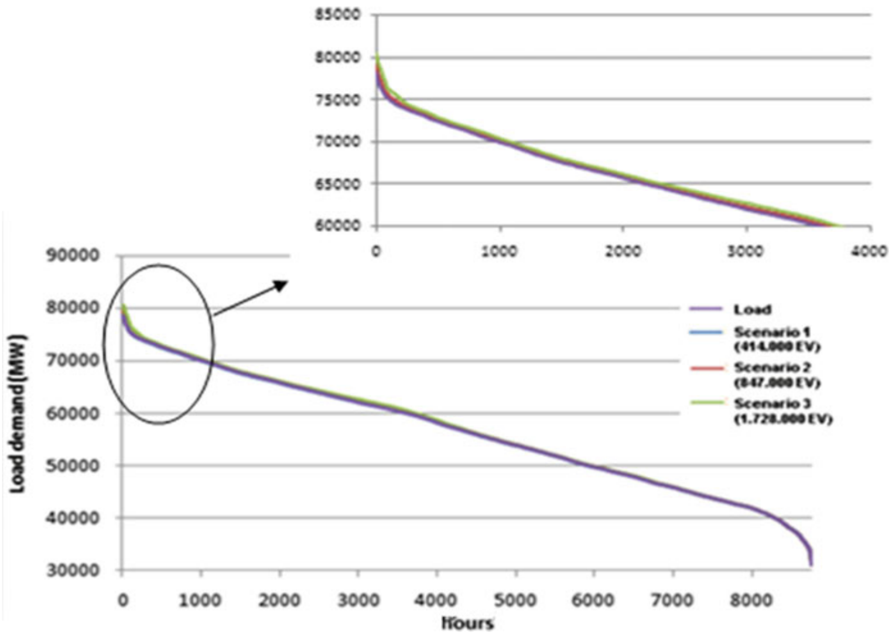


Fig. 3.10 Annual system load curve for dumb charging (Germany)

pattern, the majority of energy providers offer low tariffs during 22:00–06:00. The following analysis is based on a dual-tariff scheme, as follows:

- Winter Period (1/11–30/4): Low Charging: (22:00–06:00)
- Summer Period (1/5–30/10): Low Charging: (22:00–06:00)

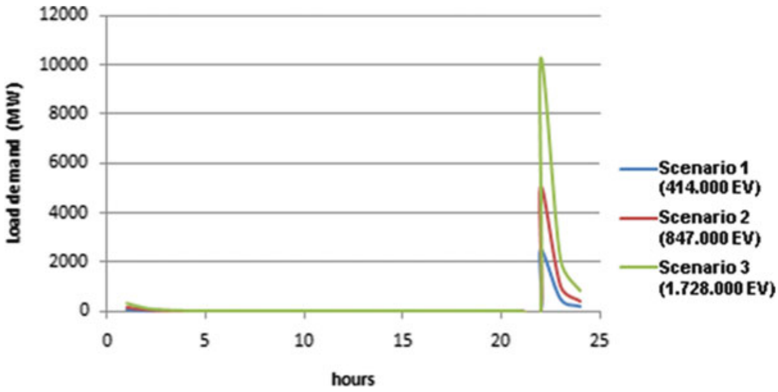


Fig. 3.11 Dual-tariff EV charging demand (Germany)

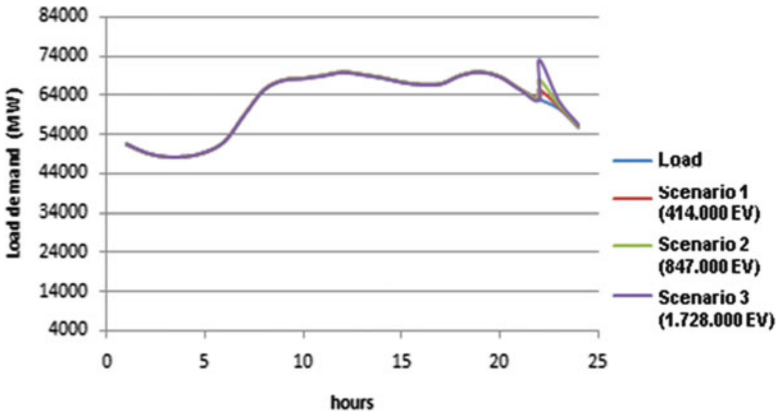


Fig. 3.12 Dual-tariff charging—winter system demand diagram (Germany)

Figure 3.11 presents the additional EV charging demand taking into account the tariff scheme and the restriction that EV can be charged only at home. According to the EV penetration scenarios, the additional energy requirements are 1,735 MWh, 3,532 MWh, and 7,190 MWh, respectively. The dual-tariff scheme results in an instantaneous increase in EV demand at the beginning of the period of low energy prices. The total amount of energy served is equal to the case of simple dumb charging; however, EV charging appears now completely synchronized.

Figure 3.12 presents the modified system load curve during a typical winter day. As the EV penetration level increases, the impact on the system demand becomes more serious. In the aggressive scenario, the synchronized EV charging results in a new peak demand, larger than the system's daily peak. This happens because the low pricing period starts while the system demand is relatively high.

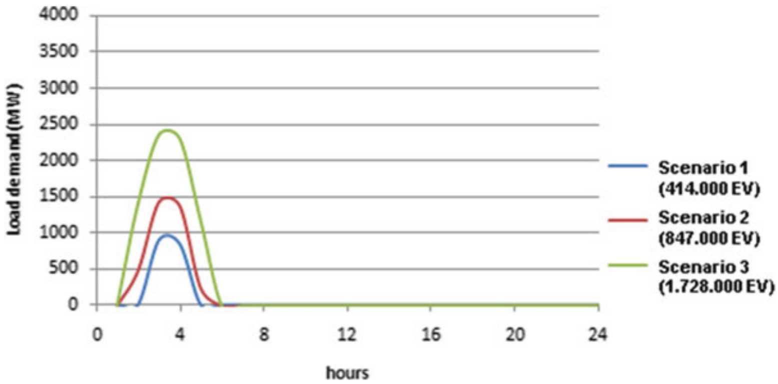


Fig. 3.13 Smart charging—EV demand (Germany)

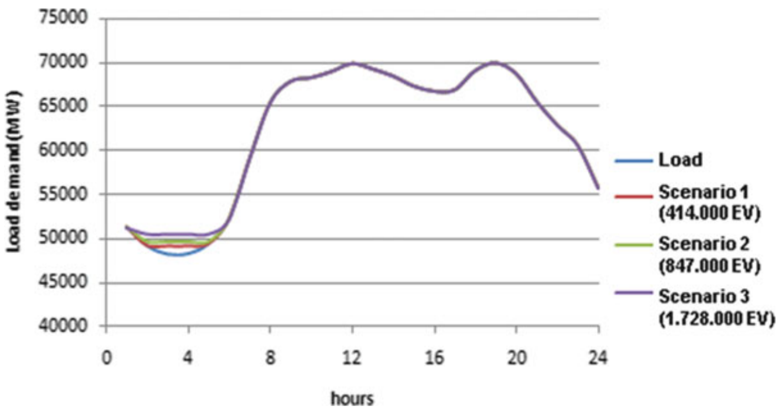


Fig. 3.14 Smart charging—winter system load diagram (Germany)

3.3.1.3 Smart Charging

The main idea of the adopted charging approach is to manage the EV load in a way that minimizes the total load variation.

Figure 3.13 shows the additional charging demand for the three penetration scenarios. Comparing the peak EV demand in case of smart charging with the previous charging concepts, it can be seen that the peak during smart charging is almost 1/4 of the peak of dual-tariff charging, but higher than the peak of dumb charging. However, the EV demand in smart charging is distributed effectively among the off-peak hours, improving the system load factor (Fig. 3.14).

Figure 3.15 presents the modified annual system load diagram considering the additional energy demand under the smart charging concept. Contrary to the system demand curve of dumb charging, smart charging EV demand increases the base load.

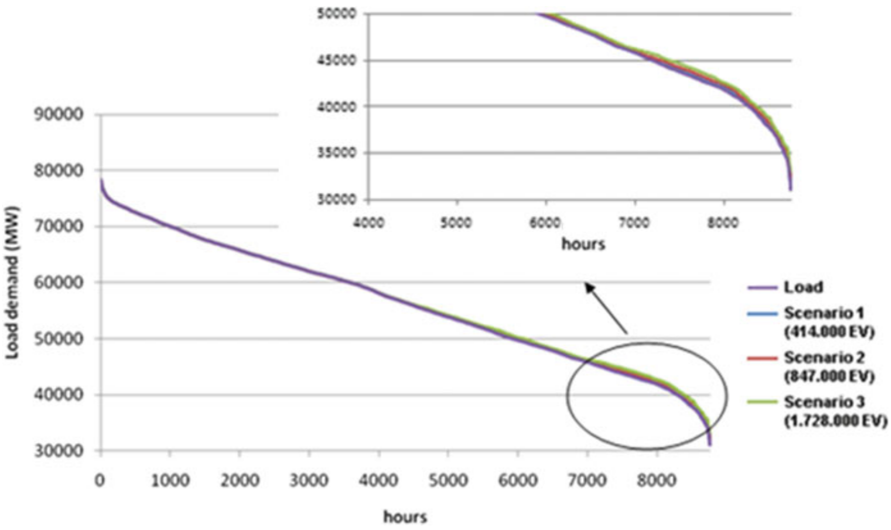


Fig. 3.15 Impact of EV smart charging in the system annual demand curve (Germany)

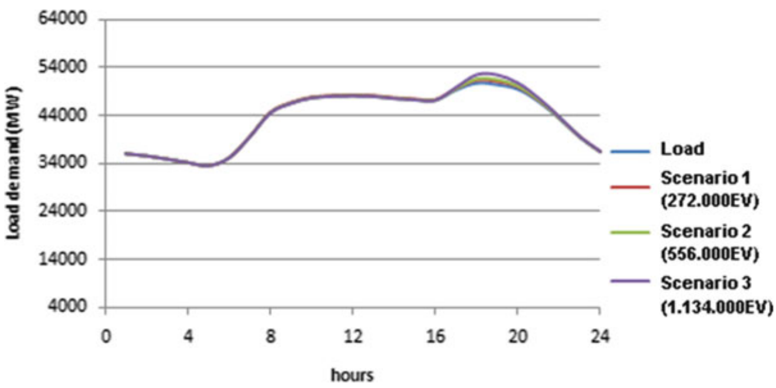


Fig. 3.16 Dumb charging—winter system demand diagram (UK)

3.3.2 UK

3.3.2.1 Dumb Charging

The impact of EV on the daily system demand, in case of dumb charging, is shown in Figs. 3.16 and 3.17. During winter time, the daily peak increases by 0.89%, 1.79%, and 3.69%, for the three penetration levels, respectively. Even though summer load demand is characterized by a peak demand during midday hours, the EV charging demand of the aggressive scenario is high enough to create a new daily system peak at afternoon hours when people return home.

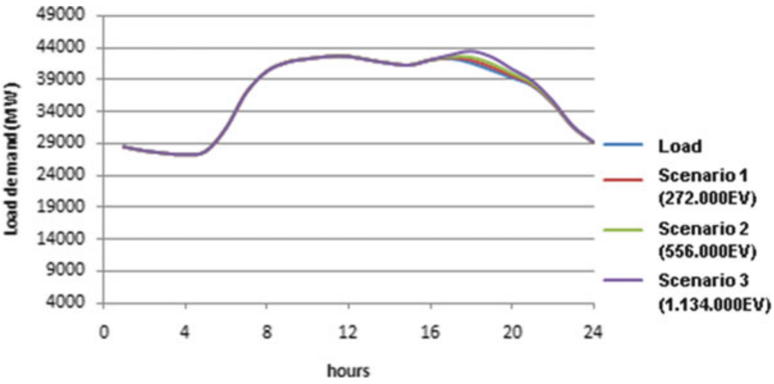


Fig. 3.17 Dumb charging—summer system demand diagram (UK)

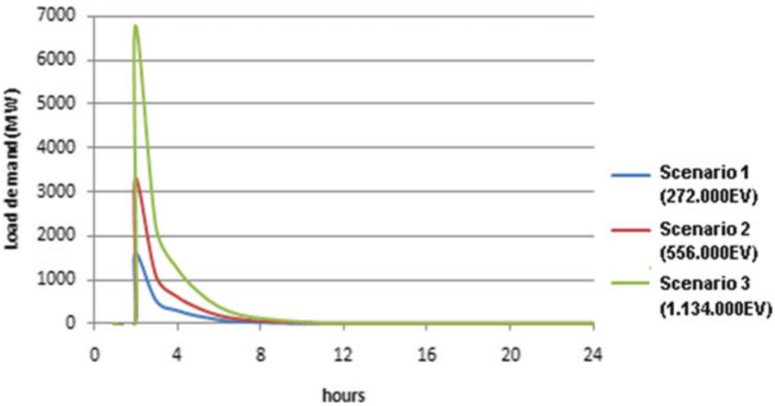


Fig. 3.18 Dual-tariff EV charging demand (UK)

3.3.2.2 Multi-tariff Scheme

The Electricity 7 scheme is used for the multi-tariff analysis. Economy 7 is the name of a differential tariff provided by U.K. electricity suppliers that provides cheap off-peak electricity offers based on the costs of base load generation. The times when Economy 7 applies vary among different regions and seasons. The dual-tariff adopted in this case is as follows:

- Winter Period (1/11–30/4): Low Charging: (24:30–07:30)
- Summer Period (1/5–30/10): Low Charging: (01:30–08:30)

Figure 3.18 presents the additional EV charging demand taking into account the tariff scheme and the restriction that EV can be charged only at home. According to the EV penetration scenarios, the additional energy requirements are 1,863 MWh, 3,848 MWh and 7,822 MWh, respectively.

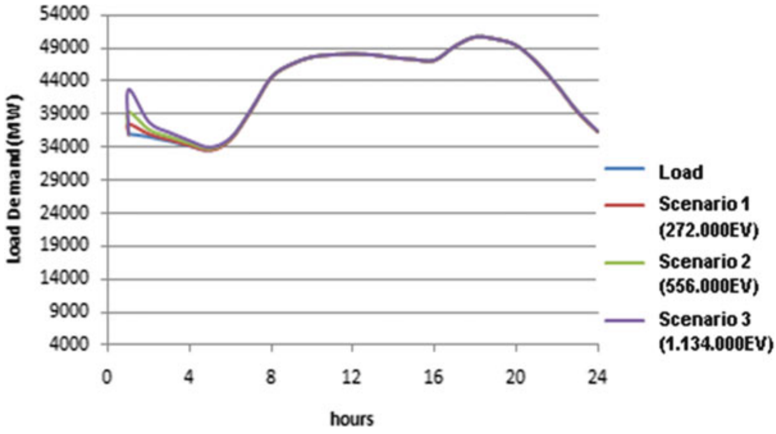


Fig. 3.19 Dual-tariff charging—winter system demand diagram (UK)

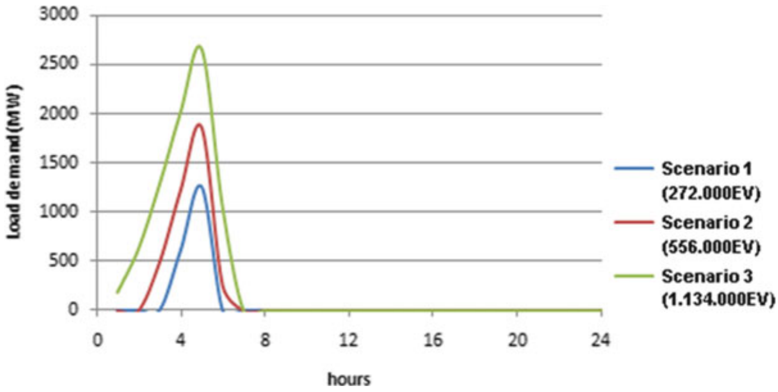


Fig. 3.20 Smart charging—EV demand (UK)

Figure 3.19 presents the modified system load curve in a typical winter day. As the EV penetration level increases, the impact on the system demand becomes more serious.

3.3.2.3 Smart Charging

Figures 3.20 and 3.21 show the additional charging demand for the three penetration scenarios under the smart charging concept.

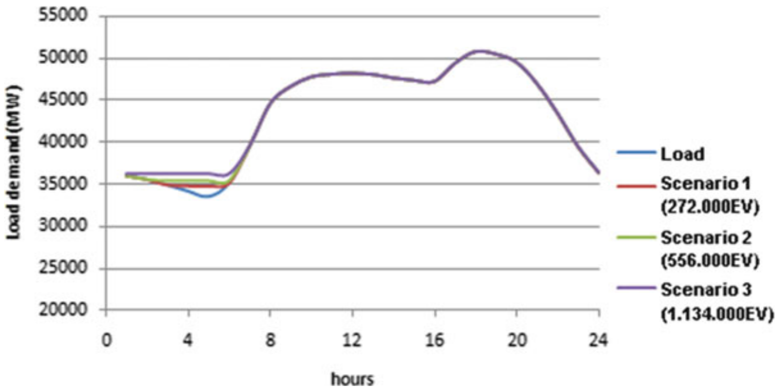


Fig. 3.21 Smart charging—winter system load diagram (UK)

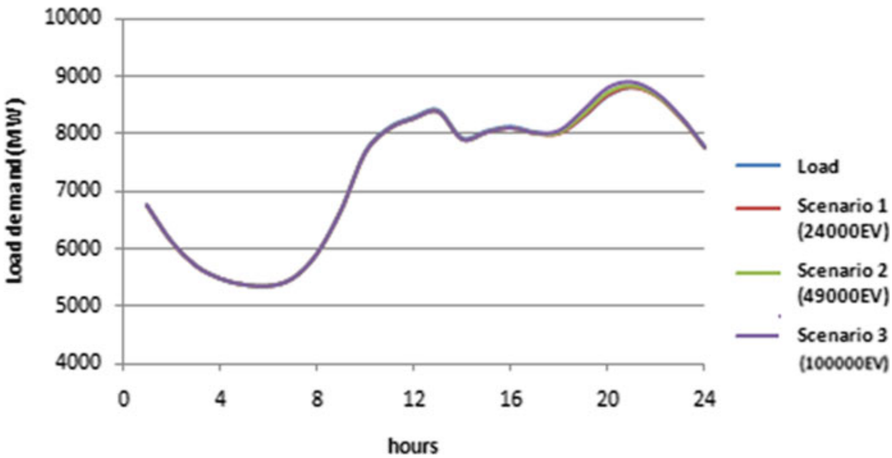


Fig. 3.22 Dumb charging—winter system demand diagram (Portugal)

3.3.3 Portugal

3.3.3.1 Dumb Charging

The impact of EV on the total daily system demand diagram is shown in Figs. 3.22 and 3.23. During winter time, the daily peak increases by 0.32%, 0.64%, and 1.32%, for the three penetration levels, respectively.

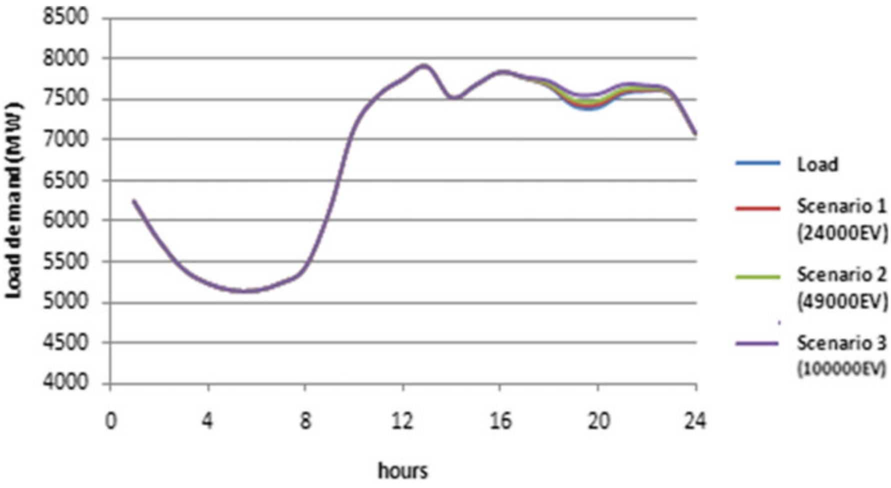


Fig. 3.23 Dumb charging—summer system demand diagram (Portugal)

3.3.3.2 Multi-tariff Scheme

In Portugal, the single operator (EDP) has established two dual-tariff policies:

1. Ciclo diario (Daily dual-tariff)
   a. Winter Period (1/11–30/4): Low Charging: (22:00–07:00)
   b. Summer Period (1/5–30/10): Low Charging: (22:00–07:00)
2. Ciclo semanal (Week dual-tariff)
   a. Winter Period (1/11–30/4)
      - Weekdays Low Charging: (24:00–07:00)
      - Saturday Low Charging: (22:00–09:00)
      - Sunday Low Charging: all day
   b. Summer Period (1/5–30/10)
      - Weekdays Low Charging: (24:00–07:00)
      - Saturday Low Charging: (22:00–09:00)
      - Sunday Low Charging: all day

Figure 3.24 shows the additional EV charging demand taking into account the "Ciclo diario" and the restriction that EV can be charged only at home. The respective diagrams for the "Ciclo semanal" are presented in Fig. 3.25.

3.3.3.3 Smart Charging

Figures 3.26 and 3.27 show the additional charging demand for the three penetration scenarios under the smart charging concept.

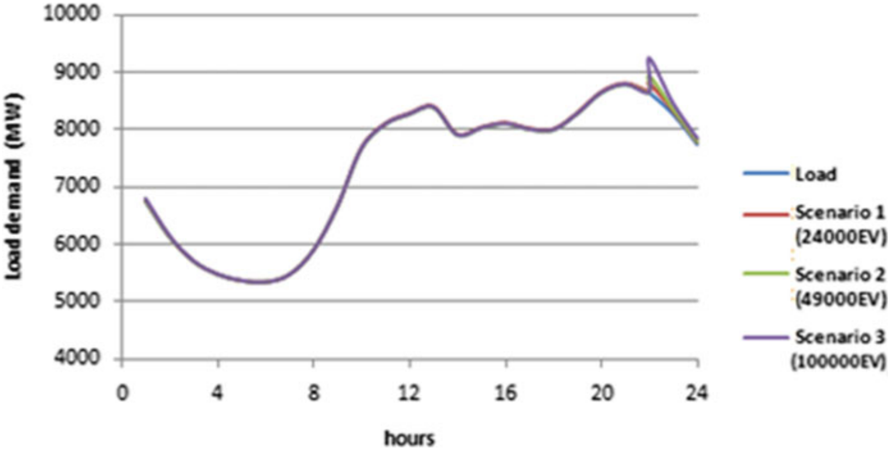


Fig. 3.24 "Ciclo diario"—winter system demand diagram (Portugal)

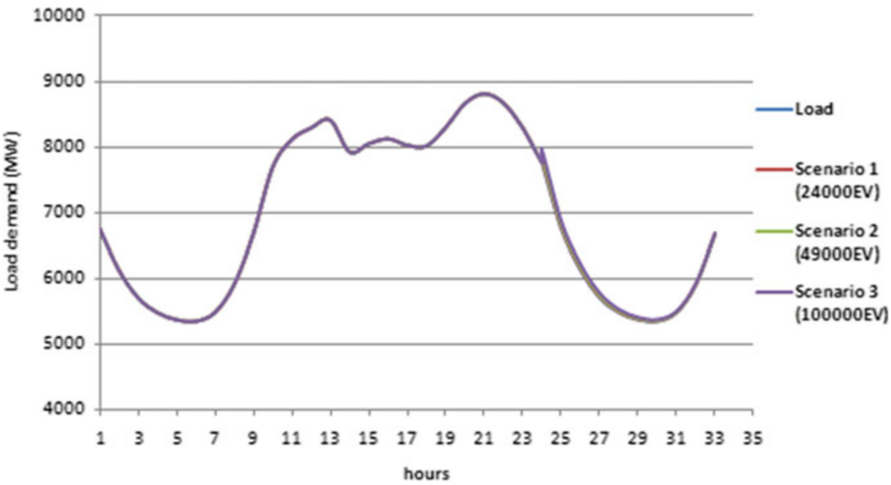


Fig. 3.25 "Ciclo semenal"—winter system demand diagram (Portugal)

3.3.4 Spain

3.3.4.1 Dumb Charging

The impact of EV fleet on the total daily system demand diagram is shown in Figs. 3.28 and 3.29. During winter time, the daily peak increases by 0.54%, 1.12%, and 2.32%, for the three penetration levels, respectively.

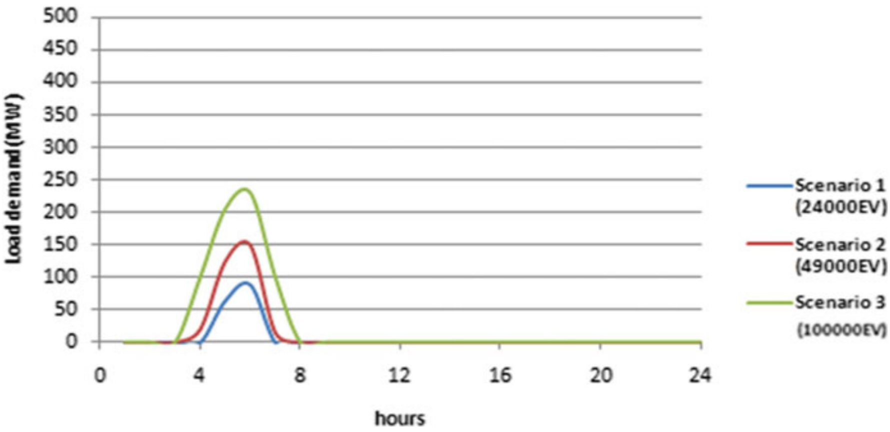


Fig. 3.26 Smart charging—EV demand (Portugal)

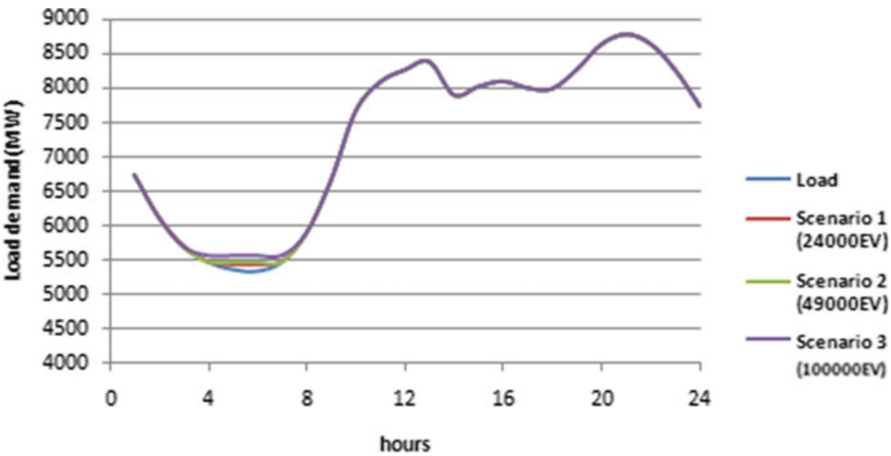


Fig. 3.27 Smart charging—winter system demand diagram (Portugal)

3.3.4.2 Multi-tariff Scheme

The dual-tariff scheme of Iberdrola is studied here:

- Winter Period (1/11–30/4): Low Charging: (22:00–12:00)
- Summer Period (1/5–30/10): Low Charging: (23:00–12:00)

Figure 3.30 presents the additional EV charging demand taking into account the tariff scheme and the restriction that EV can be charged only at home. According to the EV penetration scenarios, the additional energy requirements are 798 MWh, 1,629 MWh, and 3,315 MWh, respectively. Figure 3.31 presents the modified system load curve on a typical winter day.

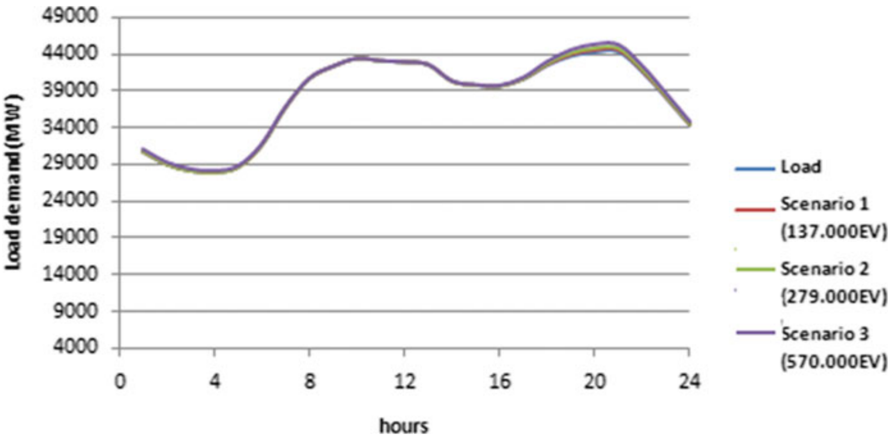


Fig. 3.28 Dumb charging—winter system demand diagram (Spain)

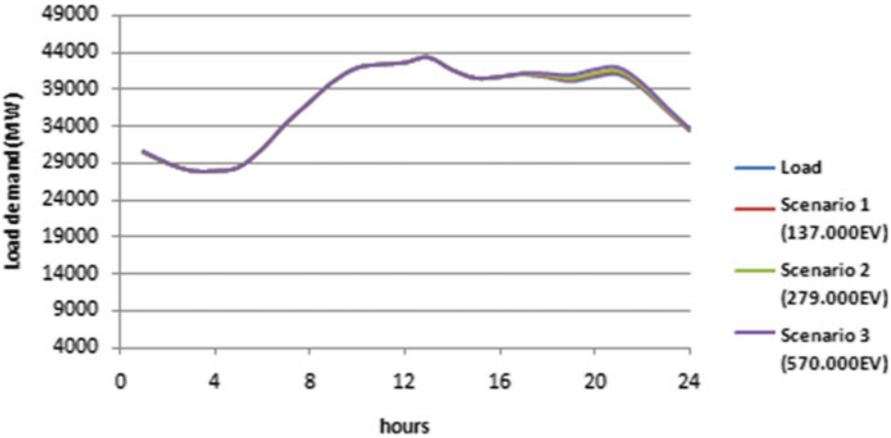


Fig. 3.29 Dumb charging—summer system demand diagram (Spain)

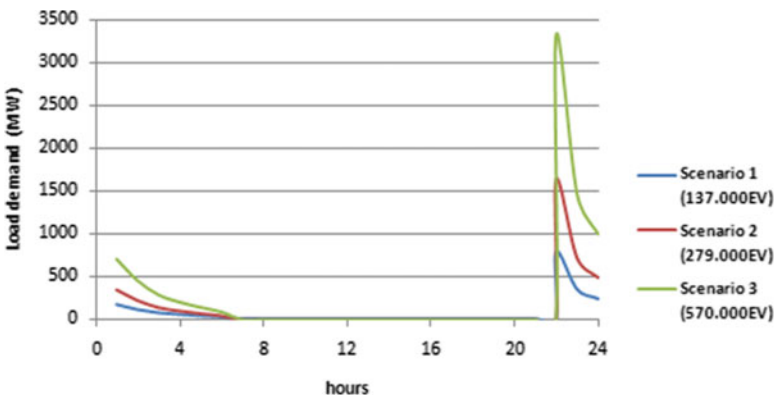


Fig. 3.30 Dual-tariff EV charging demand (Spain)

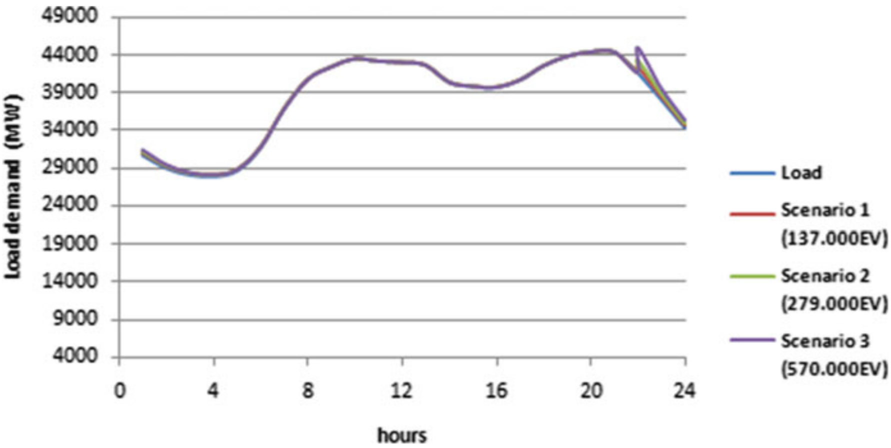


Fig. 3.31 Dual-tariff charging—winter system demand diagram (Spain)

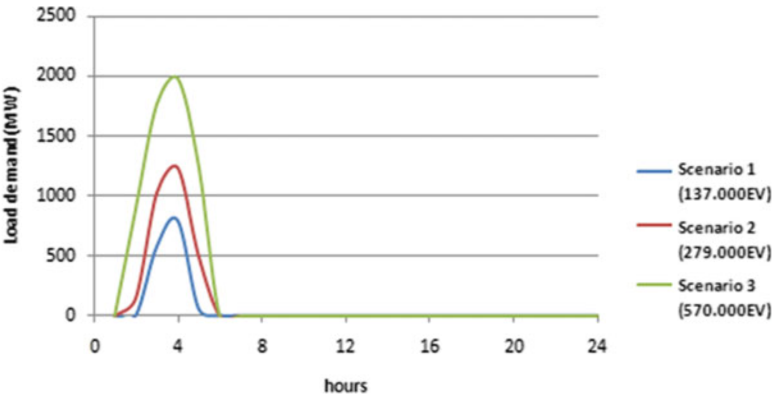


Fig. 3.32 Smart charging—EV demand (Spain)

3.3.4.3 Smart Charging

Figures 3.32 and 3.33 show the additional charging demand for the three penetration scenarios under the smart charging concept.

3.3.5 Greece

3.3.5.1 Dumb Charging

The impact of EV on the total daily system demand is shown in Figs. 3.34 and 3.35. During winter time, the daily peak increases by 0.51%, 1.02%, and 2.13%, for the

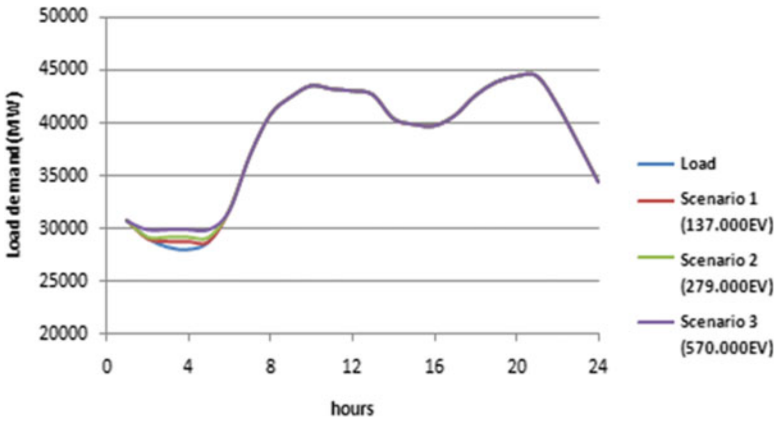


Fig. 3.33 Smart charging—winter system demand diagram (Spain)

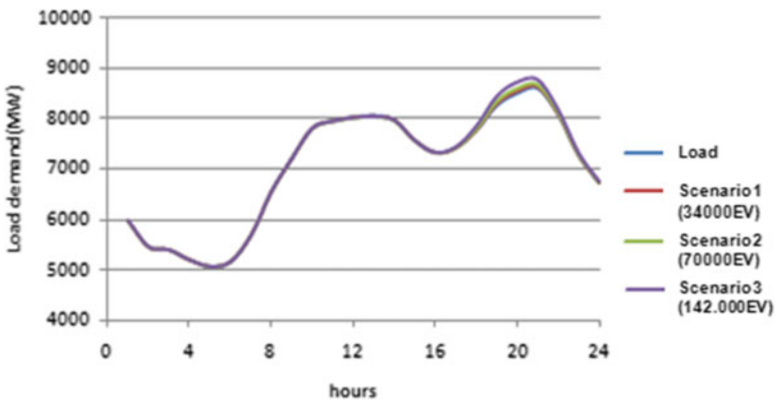


Fig. 3.34 Dumb charging—winter system demand diagram (Greece)

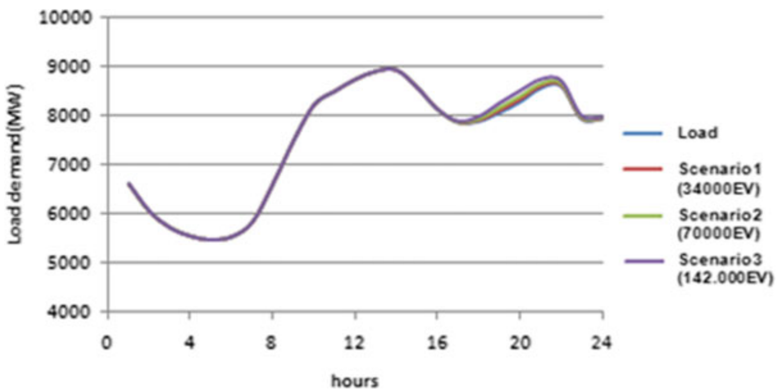


Fig. 3.35 Dumb charging—summer system demand diagram (Greece)

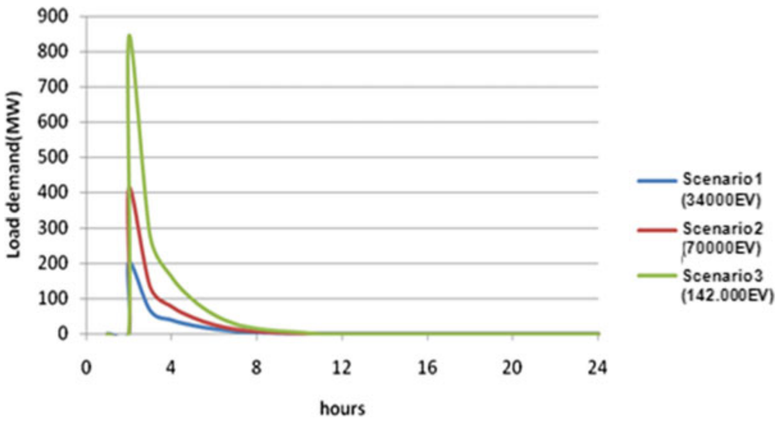


Fig. 3.36 Dual-tariff EV charging demand (Greece)

three penetration levels, respectively. Summer load demand is characterized by a peak demand during midday hours. Even in the aggressive deployment scenario, the EV charging demand is not high enough to create a new daily system peak at afternoon hours.

3.3.5.2 Multi-tariff Scheme

The dual-tariff scheme adopted in Greece by PPC is as follows:

- Winter Period (1/11–30/4): Low Charging: (2:00–08:00 and 15:30–17:30)
- Summer Period (1/5–30/10): Low Charging: (01:30–08:30)

Figure 3.36 presents the additional EV charging demand taking into account the tariff scheme and the restriction that EV can be charged only at home. According to the EV penetration scenarios, the additional energy requirements are 236 MWh, 485 MWh, and 995 MWh, respectively.

Figure 3.37 presents the modified system load curve on a typical winter day.

3.3.5.3 Smart Charging

Figures 3.38 and 3.39 show the additional charging demand for the three penetration scenarios under the smart charging concept.

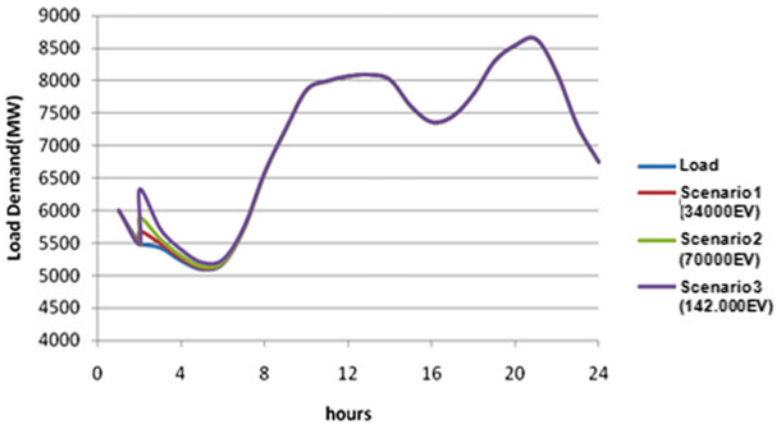


Fig. 3.37 Dual-tariff charging—winter system demand diagram (Greece)

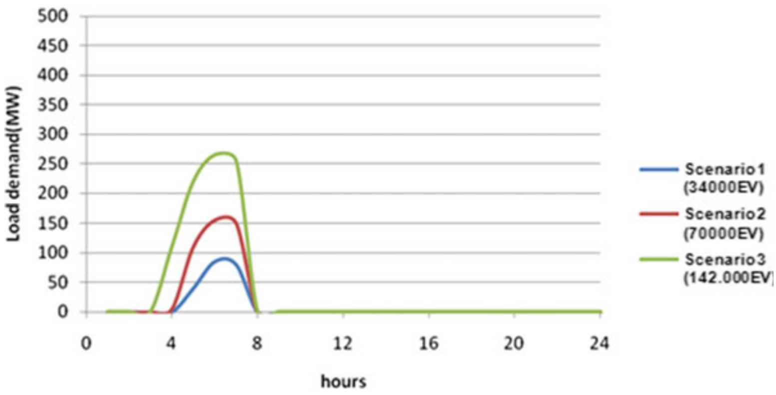


Fig. 3.38 Smart charging—EV demand (Greece)

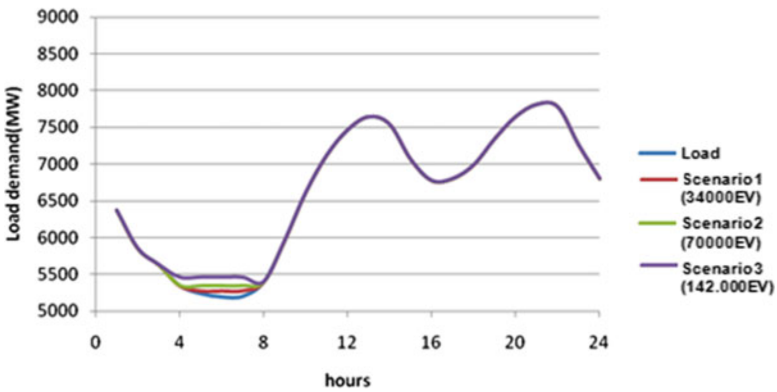


Fig. 3.39 Smart charging—winter system demand diagram (Greece)

3.4 Conclusions

In the previous sections, the additional energy requirements that fulfill EV charging needs have been identified, and their impact on the daily and annual system demand diagram of five European countries has been analyzed considering different charging modes and different traffic patterns of drivers, i.e., daily travel distance, time of plug-in, charging rate, and EV battery usage per kilometer.

Based on this analysis, the dumb charging mode can lead to “worst case” scenarios. When EV charging remains completely uncontrolled, the profile of the charging demand is highly dependent on the time of return from the last journey of the day. Since home arrival normally coincides with increased residential consumption, the EV demand can be synchronized with the system peak load. Thus, dumb charging might result in local distribution network congestions and a higher share of EV might require premature grid investments. Figure 3.40 shows the impact of the “dumb charging” in the system daily demand in different European countries and for various EV penetration scenarios. The worst-case scenario on a typical winter day is presented.

The grid impacts of home charging can be limited by developing charging infrastructures at workplaces. In this case, part of the daily EV charging needs compensating the battery consumption for driving from home to work can be fulfilled during morning hours at workplace, when the system demand is still relatively low. As the number of EV charging at workplaces increases, the additional system peak demand due to EV “dumb charging” reduces.

Dual-tariff charging is more effective than dumb charging, since it enables the shifting of the EV demand from high loading hours to off-peak hours. However, this

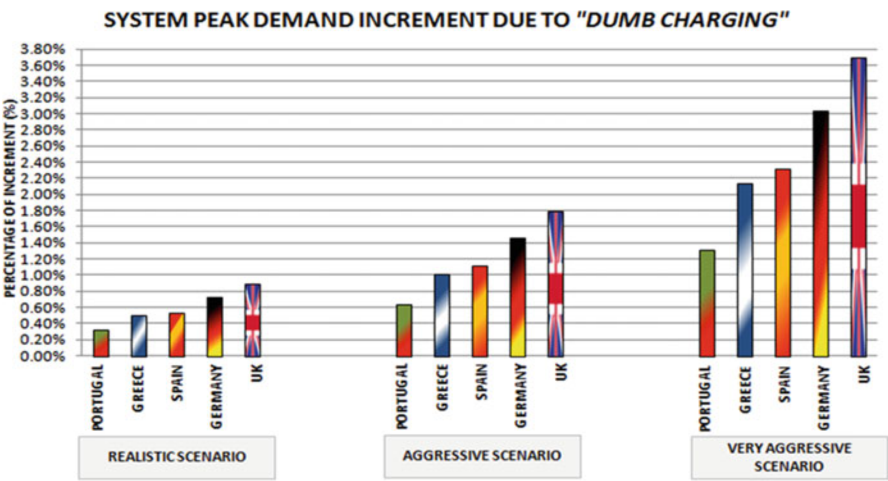


Fig. 3.40 The increase in system peak demand in different European countries due to “dumb charging” for the three penetration scenarios

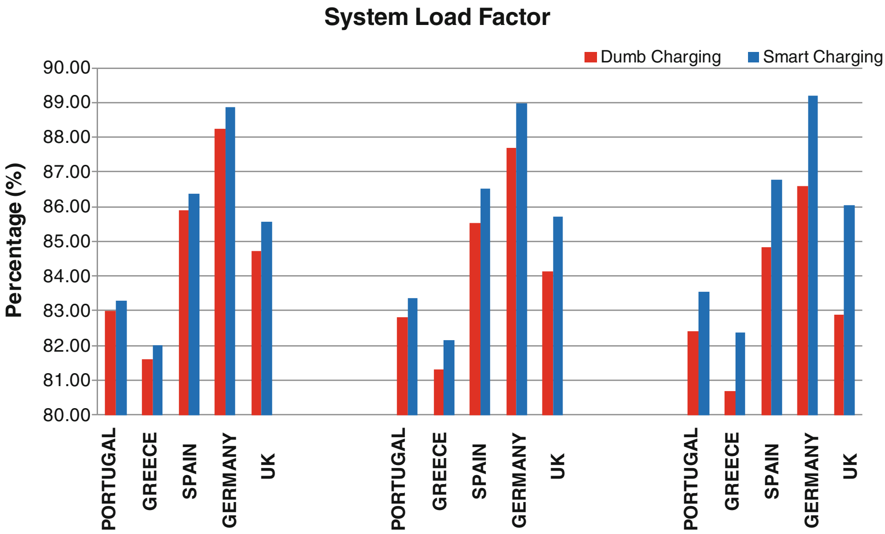


Fig. 3.41 The increase of system load factor comparing "dumb charging" with "smart charging"

is likely to result in a sharp increase in EV demand at the beginning of the low energy price period which might affect the network operation.

Smart charging avoids high peak loads by allocating the EV demand during off-peak hours. Figure 3.41 illustrates the effect of this load allocation to the system load factor. In smart charging, EV demand is managed in a way that reduces the system load variation between off-peak hours and high load hours. Smart charging is the most effective charging strategy; however, its implementation is not straightforward and for a large number of vehicles, it requires advanced control and management techniques.

References

1. MERGE Deliverable WP3_Task3.2(I), Part I of Deliverable 3.2, "Evaluation of the impact that a progressive deployment if EV will provoke on electricity demand, steady state operation, market issues, generation schedules and on the volume of carbon emissions-electric vehicle penetration scenarios in Germany, UK, Spain Portugal and Greece," 21 Feb 2011
2. European Commission (2009) Mobility and transport. Road safety: vehicle categories [online]. http://ec.europa.eu/transport/road_safety/vehicles/categories_en.htm
3. MERGE Deliverable D1.1: "Specifications for EV-grid interfacing, communication and smart metering technologies, including traffic patterns and human behaviour descriptions," 24 Aug 2010. http://www.ev-MERGE.eu/
4. European Network of Transmission System Operators for Electricity (2010) Hourly load values of a specific country for a specific month. Consumption Data [online]. http://www.entsoe.eu/index.php?id=92

Chapter 4
Business Models and Control and Management Architectures for EV Electrical Grid Integration

Willett Kempton, F. Marra, P.B. Andersen, and Rodrigo Garcia-Valle

4.1 Introduction

A liquid-fueled vehicle can be designed with little respect for the fueling infrastructure. An electric vehicle (EV) has a more intimate connection with its fueling infrastructure and this requires a rethinking of today's pervasive models. It will not be enough to just create an "electric gasoline pump." We believe that designers must re-conceptualize the process of fueling and the ways that fueling and driving patterns fit together. Further, we must consider the comparative advantages and disadvantages of liquid fuels versus electricity and how those may affect fueling. Otherwise, like the old generals who strategize from their prior experience and "Fight the last war," we may build an inconvenient, overly expensive fueling infrastructure that fails to take advantage of the radical differences in the characteristics of electricity as a fuel.

For example, the EV must respect fueling rate limits (in amperes or watts) that vary with location, but are inherently much slower than liquid fuels. On the other hand, EV fueling connections can provide valuable services, unlike liquid fuels that only consume energy. This example shows that the design of electrical fueling may be very different from that of liquid fuels. More broadly, the design must consider interactions between the vehicle and the user, the power capability (in watts), the total energy transferred (in watt-hours), the minimization of component costs, the lifetime, and the safety of refueling (see Fig. 4.1).

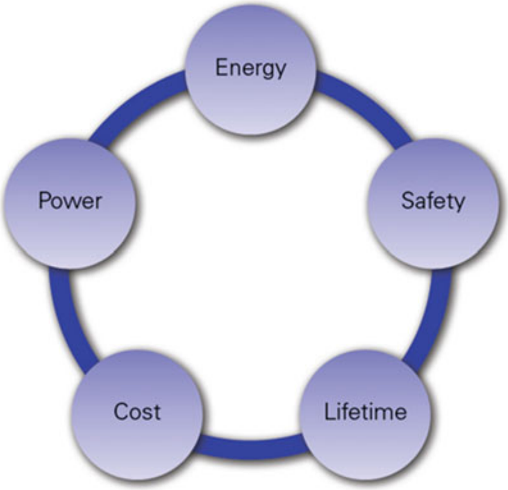
W. Kempton (✉)
University of Delaware, Newark, DE, USA

Electrical Engineering Department, Technical University of Denmark (DTU),
2800 Kgs. Lyngby, Denmark
e-mail: willett@udel.edu

F. Marra • P.B. Andersen • R. Garcia-Valle
Electrical Engineering Department, Technical University of Denmark (DTU),
2800 Kgs. Lyngby, Denmark
e-mail: fm@elektro.dtu.dk; pba@elektro.dtu.dk; rgv@elektro.dtu.dk

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_4, © Springer Science+Business Media New York 2013

Fig. 4.1 Factors characterizing a vehicle [1]



The vehicle characteristics, the grid-connection or electric vehicle supply equipment (EVSE), the building circuit, the local distribution system, and energy markets must operate well together.

Before considering business models and control, we analyze the fueling functions of an electric vehicle, and how they influence the design of the EV and its grid-connection infrastructure. Those, in turn, enable and limit the possible business models.

4.2 Vehicle Fueling Functions

A functional analysis must first consider the fueling functions of a vehicle. In this section, we consider fueling (or recharging) functions related to transportation; in the next section, we consider the fueling functions related to the electrical system.

Liquid-fuel vehicles lack an option for slow refuel, at a convenient location and at a lower cost (e.g., a plug adjacent to one's home or apartment parking location, charging overnight at a cost equivalent to 0.25–0.50 €/l, or $1/gallon in the USA). On the other hand, the fast and en route fueling functions are better suited to liquid fuels. The fueling capacity of a petrol vehicle is 21.4 MW, or an effective refuel rate of 5.3 MW after considering the much lower efficiency of petrol [2]. The proposed IEC61851 vehicle connector standard permits up to 43.6 kW power level from standard three-phase AC connection at the 400 V_{AC}, typical in Europe, whereas some off-board DC chargers allow 50 kW. In either of the electrical cases, the capacity rate is about 1/100 the rate of gasoline.

As a result of inherent differences in fueling rate, the function of "refueling en route" is inherently slower for electric vehicles. This is a natural limitation for some high-duty-cycle commercial vehicles. But most consumers rarely take trips longer than today's advanced EV batteries. A sample for European driving patterns has shown an average daily distance of about 40 km. In a larger US sample of individually owned (private) light vehicles, the average daily driving was 52 km (32.6 mi) or 19,000 km per year. Excluding days of no driving, average daily driving was 72 km (44.7 mi). Trips over 240 km (150 mi) occur only 9 times per year for the average person [2]. An average size EV battery would provide 150–200 km range. Since the driving data suggest few trips per year longer than this, en-route electric refueling may be more cost-effective than a much larger battery. This can be accomplished, for example, by combining a meal stop with refueling at 43 kW recharge. A 45-min lunch break would accumulate 30 kWh, so if we calculate driving at 6 km/kWh, that lunch break adds 180 km of range.

4.3 Functions in Relation to Electrical Infrastructure

We now consider the reverse perspective: what are the functions that the vehicle and its electrical or fuel storage can serve to the fueling infrastructure? For liquid fuels, there is only one function: the purchase of liquid fuels provides the primary revenue stream to the petroleum extraction, transport, and refining industries. The real-time operation of liquid fueling uses a simple pump drawing fuel from an underground tank to a tank in the vehicle. This fueling process is fast and low-cost. Although the fueling equipment is expensive, it is deployed only in a few selected locations with high traffic, the duty cycle is high, and the payback on fueling infrastructure investment reasonable.

With electricity as a fuel, the potential functions that the vehicle can serve to the electrical system lead to a more rich analysis. A key to this analysis derives from the opportunity implied by the first bullet in Table 4.1 because electricity is ubiquitous in modern human settlements, it offers the opportunity for slow, low-cost fueling at a convenient location (e.g., while parked at home or another destination, not requiring investment in a specialized refueling location). The consequence of convenience and ubiquity is that the vehicle can be connected to the fueling system most of the time; in OECD countries, private cars are typically driven 1 hour per day, idle 23 hours a day. Different types of vehicles can be refueled using a common refueling infrastructure that can be depicted as follows:

Figure 4.2 depicts two forms of electrical recharge equipment. Each has a pedestal and an electric cable connecting to the vehicle. In (a), the pedestal transmits AC electricity from the power grid and a charger is in the vehicle. The charger converts grid AC electricity to DC matched to the voltage needed by the

Table 4.1 Transportation-related fueling functions

Refueling slowly at a convenient location
Refueling quickly (possibly at specialized locations or at higher cost)
Refueling en route, to extend range beyond on-board energy storage
Meter and/or bill for fuel

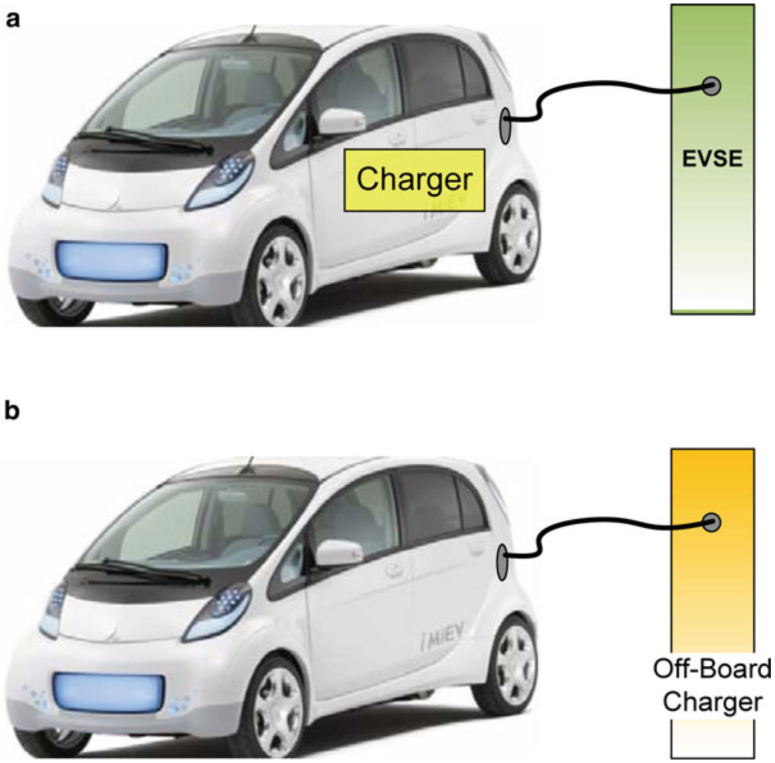


Fig. 4.2 Components of vehicle and charging system, (**a**) AC charging, and (**b**) DC charging

Table 4.2 Grid functions and markets

Load and revenue (consuming electricity as a fuel)
Scheduled charging (by time of day)
Responsive charging and discharging (in response to a real-time signal, cost or control signal)
Arbitrage (buy low, sell high)
Distribution system support
Reactive power compensation
Generation support (e.g., peak shaving and valley filling)
Ancillary services
Distribution upgrade deferral
Backup power (upon grid failure)

battery. In (b), the charger is in the pedestal, and the cable transmits DC electricity to the car for direct battery charging [3].

Thus, we come to the question of, what other functions can connected vehicles provide and what electrical infrastructures are required to make those functions possible. Table 4.2 gives a list of potential grid functions and markets. Some of these functions require features that not all EVs share. Some grid functions require data communication between the grid operator and the vehicle or EVSE, some require higher power flow (over 10 kW or minimally over 6 kW), and some require discharging of the vehicle battery to the grid. The latter functions are possible with more advanced hardware components that will be distinguished later.

The grid functions in Table 4.2 can be defined as follows:

- Load and revenue: due to driving, the vehicle inherently needs to refuel, so unless the electricity is given away, it provides a revenue stream to the fuel supplier.
- Scheduled charging: Times of higher system electrical load are roughly predictable; therefore, as simple a device as a timer, or a timer and air temperature sensor, can be used to set the charge minimal or low rate during times likely to be stressful to the grid. This is of value to the electric system. It is compensated to the customers only if there is a corresponding rate structure, such as off-peak electric rates.
- Responsive charging and discharging: requires some form of signal from a grid operator or grid monitor to the vehicle or to an EVSE controlling the vehicle. Some of these services can be dispatched by a local monitor (e.g., of frequency or of power factor). Others require communications from distribution equipment, from the local distribution electric system operator, or from the regional transmission operator (e.g., spinning reserves or local substation overload). When vehicles can both charge and discharge at moderately high power (6 kW up), they can be managed as dispatchable storage resources, which have very high value to various types of grid operators.
- Backup power: Energy stored in a car can be used to power the building to which the car is connected, if the local electrical system goes down. This of course requires the ability of the car to discharge the battery to the local grid, and also requires failsafe disconnection of the building from the grid, as well as other sensing and safety mechanisms. Providing backup (emergency) power, unlike responsive services, does not require communication to the grid operator, but generally will require more safety switches, and more communication to the building electrical system. This is sometimes referred to as "vehicle to home," in contrast to "vehicle to grid," suggesting that the power somehow stops flowing at the building boundary, or that it has a value at times other than power failures. We do not use the "vehicle to home" terminology because it obscures the very different technical problems and the serious safety problem of grid disconnection, thus we use the term "backup power"

Of the functions above, generally, "responsive" services can provide the greatest value. Backup power is of lower market value. Nevertheless, responsive services and backup power both can potentially produce revenue (or value to the customer in the case of backup power), whereas scheduled charging only reduces the already-low fuel cost of electric refueling. Electrical "load," of course, is by definition a cost to the vehicle operator, it does not provide revenue to the vehicle.

A quantitative analysis of the relative values of these services has been provided elsewhere [12] and is beyond the scope of this article, but sufficient to say that the most valuable services, in the higher priced of today's markets, can return a substantial fraction of the value of the vehicle. And even in more moderate markets, grid services can be more valuable than the fuel cost of electricity.

4.3.1 Business Models

If society is to transition to electric transportation, someone has to buy the cars, the EVSEs, and the electricity. Someone has to maintain the cars and EVSEs. Someone has to put EVSEs in public places, on city streets, at stops along throughways, in locations which the owners of those public properties may not directly benefit from the charging. A countervailing factor to these costs, and as we are noting, one of the biggest differences between liquid fuel and electricity, is that EVs have considerable value to the electric system. However, capturing that value is complex and requires infrastructure with some critical features added beyond purely fueling functions. For all these reasons, it is appropriate to discuss business models.

4.3.1.1 Business models for electric vehicle sales

Tax incentives for EVs, as they exist today in many countries, are a valuable policy to reduce the initial high cost of vehicles and overcome resistance to a new product. A recent comprehensive analysis of the cost versus the consumer willingness to pay for EVs suggests that such tax credits are important at the initial phases of the market, when batteries are especially expensive [13]. Apart from the value of this policy to start the industry, the business models for the liquid-fueled vehicle and electric vehicle are the same: the operator buys the vehicle, uses it for transportation and pays for fuel and repairs. By contrast, for electric fueling, there are several new business models, as follows.

4.3.1.2 EVSE as Appliance

The simple business model is the vehicle owner purchases and maintains the EVSE and buys electricity. The automaker makes money selling the vehicle, the EVSE manufacturer is selling a piece of electrical equipment, the electrician has a service job installing EVSEs, and the electric utility sells electricity.

4.3.1.3 EV Charging as a Service

This model packages all EVSE management and cost into a single package service with a monthly fee. We'll call this "charging services." The customer buys an EV and signs up for the charging service. The service installs an EVSE in their home or regular parking location(s), submeters the electricity and possibly pays for it at a €/kWh rate, provides some form of "in-plan" public charging, and charges the vehicle owner fees, for example, either monthly or per distance driven. One variant is to have the vehicle owner use an id such as a card swipe, to gain access to the public chargers. This provides an incentive for drivers to sign up for the plan and in turn, provides a funding stream to purchase and maintain public charging spots, and of course to pay for the electricity use.

4.3.1.4 EV Battery and Charging as a Package Service

This is like the prior example, except that the EV charging service additionally owns the battery in the car. This works like the example above, with the service additionally purchasing the battery within the car. To repay the expensive battery would, of course, require substantially higher monthly fees. One interesting byproduct is that the vehicle owner has a lower possessive stake in the battery. For example, batteries can be swapped for service, upgraded or downgraded, or swapped en route simply to provide a way of very fast "charging."

4.3.1.5 Paying the Owner for Providing Grid Services

Whereas the above are all taking payment from the vehicle owner, this fourth business model achieves revenue by aggregating cars to provide grid services, and can pay the vehicle owner for those services. For responsive services with two-way power flow, the value can be greater than the cost of purchasing fuel and maintaining the EVSE, so there could be a net positive payment to the vehicle owner. There are some additional requirements on the EV, and on the EVSE, in order to achieve this value.

4.4 Requirements of Electric Vehicles for Electric Grid Interaction

The opportunity to provide grid services using electric vehicles is possible if a set of hardware, software, and communication requirements are considered from the beginning in the value chain development for a vehicle.

The software aggregation of EVs can be achieved given that vehicles have an accessible hardware and software architecture which can externally be monitored and controlled during plug-in periods.

Monitoring and control functions should therefore include the following:

- Monitoring of internal vehicle data, relevant to the aggregator
- Control of refueling operations, charging and discharging

4.4.1 Monitoring of Internal Vehicle Data

EV coordination is fundamental for providing grid services using vehicles: this entails monitoring several internal vehicle data that can be acquired in real-time from the Vehicle Management System (VMS), and the Battery Management System (BMS). Accessing the vehicle info allows an aggregator defining the energy status of the vehicle, the charge stored in the battery, and potentially any other relevant parameters. The following internal vehicle data are required by an aggregator for the EV status identification.

- Nominal battery energy, E_n, stored once in the aggregator database
- Battery State-of-Charge, SOC, real-time monitored
- Instant power while providing grid services, real-time monitored (aggregated power)

The nominal energy of the battery is an invariant parameter which is expressed in kWh as follows:

$$E_n = V_{BATT} \cdot C_n, \tag{4.1}$$

where C_n (Ah) is the nominal capacity of the battery pack [4], while V_{BATT} (V) is the nominal voltage of the battery pack. The nominal energy is required by the VPP since it represents the absolute reference of energy of the vehicle.

The SOC of the vehicle battery, as defined in [4, 5], is the measure of the charge left in the battery with respect to its nominal capacity. This can be expressed as follows:

$$SOC = \frac{C}{C_n}, \tag{4.2}$$

where C (Ah) is the actual capacity contained in the battery at the time of measuring.

The third information needed to the aggregator is the power used by the EV during grid service operations. This could be achieved using either smart meters on a charging station or possibly BMS data.

In smart charging applications, the charging/discharging power should be measured in real-time and the information sent back to the aggregator which keeps track of the energy exchanged between the EV and the grid. The power levels used are constrained by the charging infrastructure available, i.e., electrical cables, transformer rating, circuit breakers, fuses, etc. In this context, EV coordination strategies are aiming to avoid, or at least postpone, any grid reinforcement [6].

The fast-charging scenario of EVs is not considered in the requirements definition for responsive power, as en route charging on demand is incompatible with EV coordination. Fast-charging entails the installation of ad hoc charging infrastructures as well as it requires a more complex refueling management which cannot be influenced by higher level coordination [3].

4.4.2 Capabilities of the EV, the EVSE, and the VPP

There is a natural break in functions and thus components between the EVSE and the EV. For business models involving providing grid services, there may also be another control and synchronization system, alternatively called the Virtual Power Plant (VPP), or the "aggregator," that would synchronize power flow to, and possibly from, the EVs. The capabilities of each are discussed below.

4.4.3 EVSE Capabilities

The EVSE is the stationary side, fixed in place and connected to a particular building's electrical system. The EV is the mobile side, it will be connected to many different points, and it has full knowledge of the vehicle characteristics and appropriate level of charge or discharge based on current conditions (e.g., battery temperature and wear characteristics). These characteristics alone dictate much of their division of functions and capabilities. These are the required EV capabilities:

- Power connection from the building or grid
- Standard connector to car
- No activation of power to connector until EV connection is confirmed
- Signal maximum current to EV using standard protocol
- Overcurrent protection (may be provided by building breakers)
- Ground-fault detection
- Trip upon ground fault or over current

Optional Capabilities

- Digital communications with car
- Stored information for:
  - Grid location, circuit ampacity, and grid capabilities
  - Authorizations (e.g., for backfeeding or emergency power)
- Metering of energy used in kWh
- Authorization of car/customer/driver to be allowed to charge

Table 4.3 Grid connections options

Current (A)	Voltage (VAC)	ϕ	Power (kW)	Standard
10	120	1	1.2	SAE J1772
10	230	1	2.3	IEC 62196-2
16	230	1	3.7	IEC
30	240	1	7.2	J1772
32	230	1	7.4	IEC
16	400	3	11	IEC
32	400	3	22	IEC
80	240	1	19.2	J1772
63	400 (EU)	3	43.6	IEC
63	480 (USA)	3	52	IEC

- Metering of kWhs
- Allocation of billed amounts to proper entity
- Transfer of billing or credit information to back office
- Real-time communications link between car and grid dispatch
- Fail-safe detection of building isolation (emergency power function)

Note that today's standards require only limited communications between the EVSE and the EV: the EVSE tells the EV how much current it can draw and the EV confirms that the EVSE's connector is in fact plugged into an EV. In the IEC standard, not the J1772 standard, the cable also signals how much current it can carry, by a simple passive resistor in the cable (under the US National Electrical Code, NEC 625, the J1772 cord must be permanently connected to the EVSE, so there is no need for a separate rating of the capacity of the cable).

The EVSE power capabilities are determined by standards. The primary two being IEC 62196-2, which applies worldwide, and SAE J1772, adopted by the USA and Japan. The SAE connector is the less capable, with a maximum of 19.2 kW and single-phase only. The IEC proposed standard provides for either single or three phase, and up to 44 kW. Each can be used at several power levels, as shown in Table 4.3.

4.4.4 EV Capabilities

On the EV, much more can be done due to two factors. First, the EV has intimate communications with the battery and power electronics systems. This allows monitoring of the many onboard systems. Second, due to the requirements of driving and charging, the EV controls current from the grid (and optionally to the grid) continuously. The power electronics components (and associated losses) are there already. By contrast, for each control function of the EVSE, it needs only to switch on or off. The EVSE is most economically and efficiently implemented as one or more switches, perhaps simple mechanical contractors (e.g., circuit breakers or latching relays). If power electronics were added on the EVSE side, they would introduce higher cost and complexity plus losses and heat.

4.4.5 Interaction Among EV, EVSE, and Aggregator

There are many possible ways that the EV, the EVSE, and an aggregator or VPP can interact. In this section, we review three approaches taken from actual projects. They are characterized by three parameters:

- Market integration and EV utilization concept
- Architecture
- Technology and standards

By "market integration" is meant the way that the EV, directly or indirectly, is connected to the power market to generate savings and possibly revenue for the EV owner. The number and composition of market stakeholders involved depend heavily on the business models and market environments in consideration. By "utilization concept" is meant which functionalities the EV will support, consisting of the following three concepts:

- EV as load
- Smart Charging, determined by time of day (and/or grid conditions)
- Two-way power flow and real-time control

(None of the integration projects reviewed here uses just dumb charging, that is, just load, although most commercial electric cars do, and no commercial electric cars have the capabilities needed for code-compliant emergency power).

4.5 Example of EV Integration Projects

The market integration and utilization concept chosen shape the architecture of a project. By "architecture" is meant the stakeholders and mechanisms used to influence the EV's behavior and interface it with power system and market. Architecture may be centrally controlled (totally controlled by the aggregator), distributed control (the EV is autonomous), or a mixture [7].

The technology descriptions of the projects cover two topics. First, the components in both soft- and hardware that has been developed to support the computation and logic necessary for managing smart or bidirectional charging are described. Second, the communication protocols used for transferring data between the entities are listed.

Related to technologies are the standards used by the projects. The standards can be subdivided into equipment and communication standards and are also mentioned in the project descriptions.

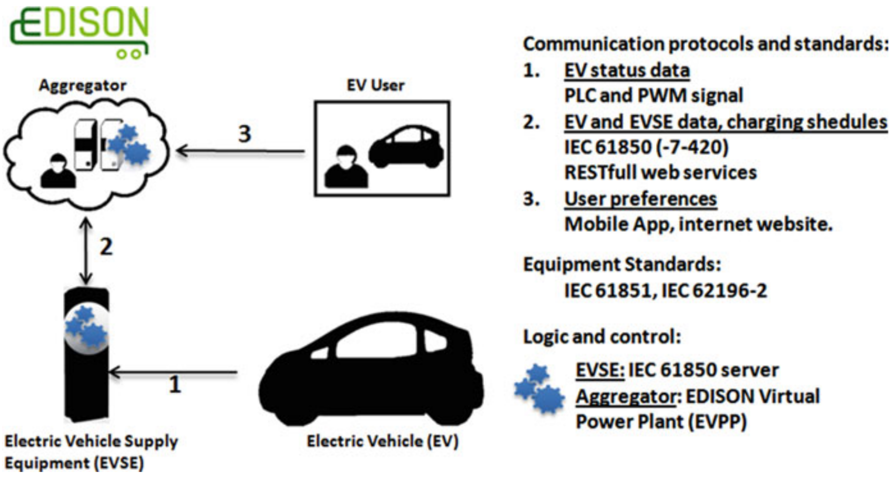


Fig. 4.3 The architecture of the EDISON project

This section will introduce two European and one American EV integration project. They have been chosen since they represent some of the biggest and most innovative research projects within the field.

Apart from the above, they all share certain traits when it comes to the integration approach followed. They are all "economic" integrations where money is earned through market participation. They also share a focus on existing markets and implement an either centralized or partly centralized architecture. Such similarities could be seen as a prerequisite for arriving at common solutions applicable for all such projects. There are, however, still many differences in the implementations, which illustrates the challenges to standardization.

The main elements in the architecture are the EV, the EV User, the Electric Vehicle Supply Equipment (EVSE), and the more generic Aggregator role, which would represent the "interface" between a group of EVs and the power system or energy market.

As will be shown by the following, the projects differ in by which means the above entities should communicate, what information should flow between them, and, in the end, which entity will control the behavior of the EV.

4.5.1 The Edison Project

EDISON [8, 9] is short for "Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks" and is a research project partly funded through the Danish Transmission System Operator (TSO)—Energinet.dk.

The goal is to develop optimal solutions for EV integration, including network issues, market solutions, and optimal interaction between different energy technologies (Fig. 4.3). The technical platforms developed by EDISON should be globally applicable and it has been tested on the Danish island of Bornholm.

The EDISON consortium consists of the Danish utilities DONG Energy and Østkraft, the Danish Technical University (DTU), as well as IBM, Siemens, Eurisco, and the Danish Energy Association. The 3-year project will conclude in 2012 but might be followed by an EDISON 2 project. The project Web page can be found at http://www.edison-net.dk.

4.5.1.1 Market Integration and EV Utilization Concept

While several market integration concepts are within the research scope of EDISON, the initial focus is on the current Nordic NordPool market. Within NordPool, the EVs can be connected to the day-ahead or intraday market. Alternatively, the EVs can participate in the TSO ancillary service markets an provide different types of reserves. The first project phase will put its emphasis on the first and indirectly connect the EVs with the day-ahead spot market by controlling the charging in correspondence with hourly energy prices. This follows the smart charging utilization concept.

4.5.1.2 Architecture

The setup shown in Fig. 4.3 represents the implementation done in EDISON. The setup uses a centralized architecture where an aggregator, called the "fleet operator" in EDISON, directly controls the charging patterns of the EV to facilitate smart charging. The conceptual role of a fleet operator could be maintained by any commercial party willing to adhere to the requirements of the Nordic power market. An EV in EDISON is seen as relatively simple with little local intelligence. The argument is that most OEM EVs initially will lack the capabilities for local optimization. The EV needs only to implement an interface that would allow the fleet operator to extract status information, such as state of charge, and possible constrains set by the OEM. In EDISON, the charging spot would play the role of a "proxy" in that it would extract EV information and enforce smart charging on behalf of the fleet operator. The user will in EDISON communicate her or his charging preferences directly to the aggregator.

4.5.1.3 Technologies and Standards

Between EV and EVSE, EDISON utilizes the IEC 61851 standard, which describes the charging of EVs using different AC or DC power voltages over a conductor using on- or off-board equipment. Apart from specifications for equipment interoperability and safety, the standard also defines simple EV–EVSE communication via a control pilot wire using a pulse width modulated (PWM) signal with a variable voltage level. This allows the EV to communicate its state to the EVSE. IEC 61851 is used in EDISON since it helps satisfy safety requirements and will improve interoperability.

The IEC 62196-2 Type 2 Mennekes plugs are used on the conductor connecting EV and EVSE.

Apart from the control pilot wire, EDISON will use Power Line Carrier (PLC) communication to support the exchange of information. Although not part of IEC 61851, this technology is a valid candidate for future standardization.

An EDISON I/O board is installed at the EV and the EVSE and includes a PLC adapter.

To connect the EVSE with the aggregator, the IEC 61850 standard is used. IEC 61850 was originally aimed at substation automation, but has been expanded to cover the monitoring and control of distributed energy resources. The standard includes a reusable data model that can be used to monitor and control both the EVSE and the EV.

The EVSE implements an IEC 61850 compliant server which uses HTTP/HTTPS-based RESTful Web services, instead of the MMS protocol usually associated with IEC 61850. The REST interface is combined with the SIP application level protocol to better facilitate scalability. The Transport Level Security (TLS) is used to provide data confidentiality.

After the aggregator has extracted information through the REST interface of the IEC server, it will use a software platform called the EDISON Virtual Power Plant (EVPP) that, through prediction and optimization, will compute a suitable charging strategy. The strategy is described using an IEC 61850-7-420 Energy and/or Ancillary Services Schedule (DSCH) which is sent to the EVSE IEC server. The schedule consists of a set of power set points and timestamps which will be followed by the EVSE during the charging of the EV.

An iPhone App and a Web page have been developed for the user to define charging requirements.

4.5.2 Vehicle-to-Grid Technology, University of Delaware

Vehicle-to-Grid (V2G) technology [10–12] is researched and developed at the University of Delaware (UD). The research focuses on the potential of V2G technology for improving the utilization of the EVs as active resources in the grid and market. The research conducted by UD V2G spans a broad set of disciplines such as soft- and hardware development, grid impact and driving pattern analysis, and aggregated fleet optimization. In addition to the technical aspects, UD V2G also covers policies, standards, and legislation and user adoption. For testing and demonstrating, UD V2G uses a fleet of V2G-enabled vehicles.

UD V2G is a research program rather than a project and will continuously work at research, development, and commercialization of V2G. Recently, the group has replaced the term "V2G" with "Grid Integrated Vehicle" to emphasize the importance of grid integration, regardless of which direction power is flowing.

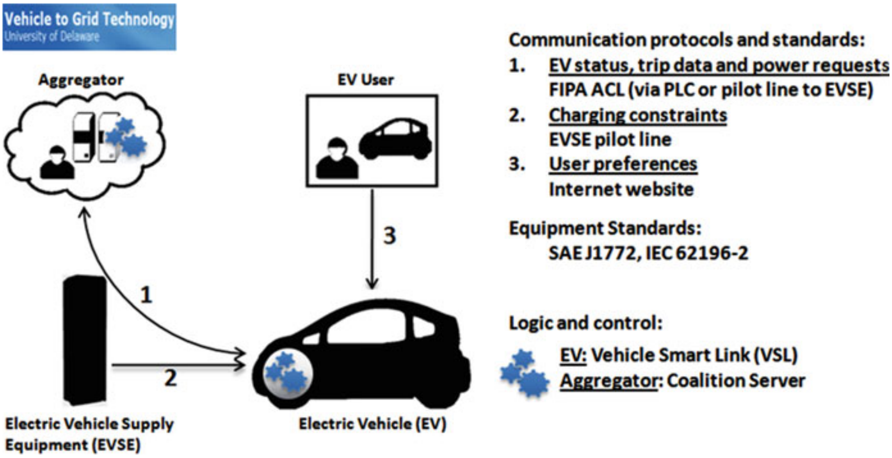


Fig. 4.4 The architecture of the University of Delaware project

AC Propulsion, a manufacturer of battery and propulsion systems, is an active partner in the project. The research is supported by the US Department of Energy (DOE) as well as several American utility companies. More information is available at http://www.udel.edu/V2G.

4.5.2.1 Market Integration and EV Utilization Concept

The UD V2G market integration concept has been tested by participating in the regulation services market where the vehicle responds to regulation power requests sent from PJM Interconnection, a Transmission System Operator (TSO). The bidirectional charging will allow the EVs to react to TSO requests for both up- and down regulation, and the EV user will be economically compensated for such services [13]. Regulating services has been implemented by UD V2G since it represents one of the most profitable markets to participate in. UD V2G publications have noted that their control mechanisms are also designed for other TSO markets such as spinning reserves and for distribution system services such as peak load reduction, valley filling, reactive power, and transformer upgrade deferral, but UD V2G cars are not actually participating in these markets yet.

4.5.2.2 Architecture

The UD V2G architecture depicted in Fig. 4.4 can be classified as partly distributed since the EV implements an intelligent agent that will use a negotiation-like communication toward the aggregator. The EV will control the charging process and be responsible for predicting and satisfying the energy requirements of the EV user.

Adding local intelligence and control in the EV can supply a better separation of concerns where a third party, like the aggregator, would not have full control over charging and free access to utilization data. This secures the EV against external mismanagement (e.g., driver's need for driving range has priority) and simplifies the optimization in the aggregator.

The purpose of the EVSE in the UD V2G architecture, aside from facilitating the power supply and Internet connection, is to supply information on possible grid-related charging constraints. The user can through a Web interface formulate her or his driving requirements. The collected trip information is then feed to the vehicle.

4.5.2.3 Technologies and Standards

In the UD V2G project setup, an electric vehicle contains a Vehicle Smart Link (VSL) implemented on an automotive-grade Linux computer. The VSL will communicate with the VMS and BMS of the EV to get battery information and to control charging. The Society of Automotive Engineers (SAE) J1772 standard is used for the equipment connecting EV and EVSE. J1772 defines the electrical and physical characteristics of conductive charging for EVs including requirements to inlets and connectors. An IEC 62196-2 version has also been developed. Either in-band communication over the pilot line or PLC communication is used for sending data via the charging cord.

Knowledge of grid and EVSE constraints are captured by a configuration file residing in the EVSE and will be sent to the VSL upon plug-in. This and direct wired communications ensure that the vehicle knows its electric power system node location, and the constraints, billing, and allowed services at that point. The EVSE is a repository of information (in the configuration file) rather than a computing agent with active control over V2G.

The VSL will communicate the battery status and trip predictions to the aggregator to signal the capacity of each EV. The aggregator uses the UD V2G "Coalition server" software to calculate the capacity of the EV (including grid constraints, battery state of charge, and scheduled or anticipated driver needs) and dispatch the TSO regulation requests accordingly. The result is a stream of power requests from the aggregator to the vehicle that states the number of watts with which the EV should charge or discharge.

Both the VSL and the aggregator use software agents based on the Java Agent Development Framework (JADE). The agents communicate via the Agent Communication Language (ACL) as defined by Foundation for Intelligent Physical Agents (FIPA). The concepts of coalition formation and multi-agent systems are applicable to the project in the sense that multiple entities (EVs) will group and cooperate to achieve some common goal, in this case revenue through TSO services. The UD V2G architecture, however, differs from the above concepts in

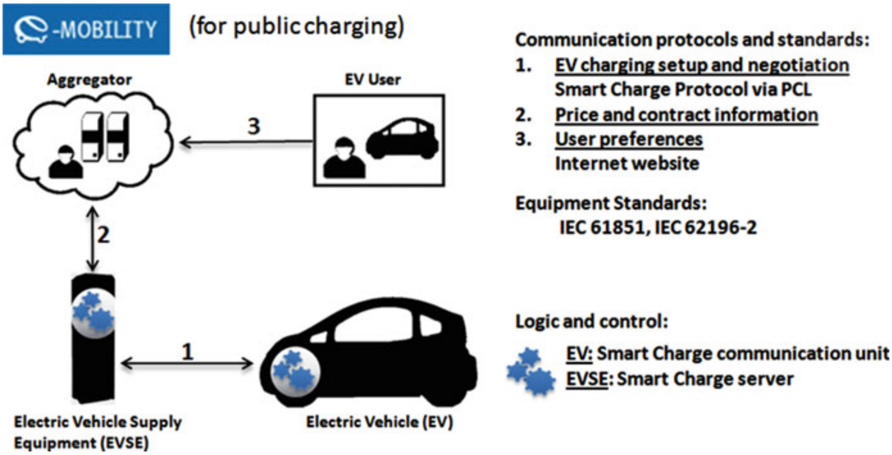


Fig. 4.5 The architecture of RWE

that a coordinating entity, namely, the aggregator, will be present. The use of agents also fits nicely with the fully distributed architecture.

4.5.3 E-Mobility Berlin Pilot Project

The German E-Mobility Berlin project was initiated by Daimler AG (Mercedes-Benz) and the utility RWE [14]. Among the participants are also battery, EVSE, and other automobile OEMs. The project introduces a fleet of 100 EVs supplied by Daimler and 500 EVSEs that are delivered and powered by RWE in the streets of Berlin for a large field test. The project is aimed at developing and testing standardized solutions for electric vehicles.

Daimler is heavily involved in EV standardization in Europe and supports the vision of roaming. The project was launched in 2008 and will continually expand the field tests with new vehicles and technologies. More information is available at http://www.rwemobility.com.

4.5.3.1 Market Integration and EV Utilization Concept

The aggregator in the e-mobility project is initially seen as the utility company, e.g., RWE, who could sell energy to EV users and reward them for flexibility. By letting the user specify an “end of charge” time, the utilization concept of smart charging is supported. E-mobility does not directly address bidirectional charging and the use of the EV for ancillary services. The protocols and use cases of the project, however, are designed to be open for additional unspecified utilization concepts.

4.5.3.2 Architecture

The e-mobility project puts a lot of emphasis on the EV–EVSE interaction in its architecture. As illustrated in Fig. 4.5, the EV acts as a client toward a server implemented at the EVSE. The tariffs and charging options of the utility company will be represented by the EVSE, which will serve as a proxy.

Despite the presence of an aggregating entity, the setup is only partly centralized since the EV will implement a lot of decision logic by knowing the needs and requirements of the end-user and use them in a negotiation-like communication with the EVSE.

4.5.3.3 Technologies and Standards

Each car is equipped with a Smart Charge communication unit that can communicate with the EVSE by using the e-mobility Smart Charge Protocol (SCP) over PLC. The SCP defines a series of application level messages that are sent back and forth in the following sequence. After a plug-in has been detected, "identification" messages will be used to configure the connection session and to establish identification, billing, and contract details (for roaming). The EV will then request a list of EVSE-provided services in a "service discovery" message. Services include the charging and payment options available at the specific EVSE. The EV will then send its energy demand and intended charging behavior in a "power discovery" message. The EVSE will compare the charging behavior with knowledge on local grid and equipment capabilities and send back price listings. When charging and billing have been settled, a series of messages initiates the power connection and monitors the charging process. SPC messages are encoded according to the Smart Message Language (SML), which is a mark-up language similar to XML that has been used for smart meter communication. Transport Layer Security (TLS) is used to supply data confidentiality through encryption. The DoIP protocol is used for EV diagnostics.

The e-mobility project has contributed significantly to the standardization of the IEC 62196-2 Type 2 compatible Mennekes plug. The EVSE equipment supports conductive charging in accordance to IEC 61851.

References

1. Marra F, Træholt C, Larsen E, Wu Q (2010) Average behavior of battery-electric vehicles for distributed energy studies. In: IEEE innovative smart grid technology conference, Manchester
2. Pearre NS, Kempton W, Guensler RL, Elango VV (2011) Electric vehicles: how much range is required for a day's driving? Transport Res C 19(6):1171–1184. doi:10.1016/j.trc.2010.12.010
3. Marra F, Sacchetti D, Træholt C, Larsen E (2011) Electric vehicle requirements for operation in smart grids. In: IEEE proceedings of innovative smart grid technology (ISGT 2011), Manchester

4. Marra F, Pedersen AB, Sacchetti D, Andersen PB, Traeholt C, Larsen E (2012) Implementation of an electric vehicle test bed controlled by a virtual power plant for contributing to regulating power reserves. In: Proceedings of IEEE Power and Energy Society (PES) General Meeting, San Diego, CA
5. Dogger JD, Roossien B, Nieuwenhout F (2011) Characterization of Li-ion batteries for intelligent management of distributed grid- connected storage. IEEE Trans Energy Conversion 26(1):256–263
6. Clement-Nyns K, Haesen E, Driesen J (2010) The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Trans Power Syst 25(1):371–380
7. You S, Træhold C, Poulsen B (2009) A market-based virtual power plant. In: Proceedings of the international conference on clean electrical power (ICCEP), IEEE, June 2009
8. Binding C, Gantenbein D, Jansen B, Sundstroem O, Andersen PB, Marra F, Poulsen B, Traeholt C (2010) Electric vehicle fleet integration in the Danish EDISON project—a virtual power plant on the Island of Bornholm. In: Proceedings of IEEE power & energy society general meeting 2010, Minneapolis, MN, USA, 25–29 July 2010. Also available as IBM RZ 3761
9. Østergaard J, Foosnæs A, Xu Z, Mondorf TA, Andersen CA, Holthusen S, Holm T, Bendtsen MF, Behnke K (2009) Electric vehicles in power systems with 50% wind power penetration: the Danish case and the EDISON programme. In: Paper presented at European conference on electricity & mobility, Würzburg, Germany
10. Kempton W, Tomic J (2005) Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. J Power Sources 144(1):280–294
11. Kamboj S, Pearre N, Kempton W, Decker K, Trnka K, Kern C (2010) Exploring the formation of electric vehicle coalitions for vehicle-to-grid power regulation. In: Proceedings of 2010 AAMAS workshop on agent technologies for energy systems
12. Kempton W, Tomic J (2005) Vehicle-to-grid power fundamentals: calculating capacity and net revenue. J Power Sources 144(1):268–279
13. Hidrue MK, Parsons GR, Kempton W, Gardner MP (2011) Willingness to pay for electric vehicles and their attributes. J Resour Energy Environ Econ 33:686–705. doi:10.1016/j.reseneeco.2011.02.002
14. Caleno F (2010) E-Mobility Project in Italy. In: Paper presented at EV charging infrastructures & grid integration 2010, London

Chapter 5
ICT Solutions to Support EV Deployment

Anders Bro Pedersen, Bach Andersen, Joachim Skov Johansen, David Rua, José Ruela, and João A. Peças Lopes

Abbreviations

ACSI	Abstract communication service interface
AMI	Advanced metering infrastructure
AMM	Automated meter management
AMR	Automatic meter reading
AP	Access point
BPSK	Binary phase shift keying
CA	Certificate authentication
CAMC	Central autonomous management controller
CP	Control pilot
CSMA/CA	Carrier sense multiple access/collision avoidance
DER	Distributed energy resource
DMS	Distribution management system
DR	Demand response
DSO	Distribution system operator
DSSS	Direct sequence spread spectrum
EAN	Extended area network
EB	Energy box

A.B. Pedersen (✉) • B. Andersen • J.S. Johansen
Technical University of Denmark, Kongens Lyngby, Denmark
e-mail: abp@elektro.dtu.dk

D. Rua • J. Ruela • J.A. Peças Lopes
INESC TEC (formerly INESC Porto), Porto, Portugal
e-mail: drua@inescporto.pt; jruela@inescporto.pt; jpl@fe.up.pt

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_5,

EMS	Energy management system
EPRI	Electric Power Research Institute
ES	Electric storage
EV	Electric vehicle
EVSE	Electric vehicle supply equipment
FAN	Field area network
FC	Functional constraint
FDD	Frequency division duplex
FEC	Forward error correction
Gbps	Gigabit per second
GW	Gateway
HAN	Home area network
IAP	Interoperability architectural perspective
IP	Internet protocol
IT	Information technology
kbps	Kilobit per second
LW	Low voltage
MAC	Media access control
MAP	Mesh access point
Mbps	Megabits per second
MG	Microgrid
MGAU	Microgrid aggregator unit
MGCC	Microgrid central controller
MMG	Multi-microgrid
MMS	Manufacturing message specification
MV	Medium voltage
NAN	Neighborhood area network
NB-PLC	Narrowband power line communication
ND	Neighbor discovery
NIST	National Institute for Standards and Technology
OEM	Original equipment manufacturer
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiplexing access
OSI	Open systems interconnection
PAM	Pulse amplitude modulation
PKI	Public key infrastructure
PLC	Power line communication
PWM	Pulse width modulation
QAM	Quadrature amplitude modulation
QoS	Quality of service
RAU	Regional aggregation unit
RBAC	Role based access control
REST	Representational state transfer
SCL	Structured configuration language

SCSM	Specific communication service mapping
SDO	Standard development organization
SDP	SECC Discovery Protocol
SG	Smart grid
SGIRM	Smart grid interoperability reference model
SM	Smart meter
SOC	State-of-charge
TCP	Transmission control protocol
TDD	Time division duplex
TLS	Transport layer security
ToW	Time-on-wire
UAN	Utility access network
UDP	User datagram protocol
V2G	Vehicle-to-grid
WAN	Wide area network
WMN	Wireless mesh network
XML	Extensible markup language

5.1 Introduction: Context and Scope

Numerous studies and projects have proven that the electric vehicle can offer value and services that go beyond its function as a means of transportation. The value and services can, for instance, be the reduction of charging costs, adherence to grid constraints, or adjustment of charging behavior to renewable energy production. If these possibilities are considered and supported by the ICT in due time, a large potential can be exploited.

Specifically, the protocols and technologies spanning the open system interconnection (OSI) stack need to support the various utilization concepts for EVs and be harmonized to obtain interoperability among numerous Electric Vehicle (EV) and electric vehicle supply equipment (EVSE) from original equipment manufacturers (OEMs).

This chapter describes contemporary EV communication methods in terms of requirements and specific solutions and relates them to relevant standardization work and projects within the area.

5.1.1 Relevant Projects and Studies

A considerable number of EV projects have been carried out throughout the world. These include the Berlin eMobility project [1], the Danish EDISON project [2], and the American V2G research program [3], just to name a few.

The experience from such projects is that the EV, as a resource, can be used for many different purposes such as smart charging, ancillary services and energy backup, as long as the communication software and hardware are made to support these.

Recognized Standard Development Organizations (SDO), such as IEEE and NIST, have made several contributions to Smart grid communication in general; much of this work is also applicable to EVs, being of particular relevance to the IEEE 2030 "Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System."

IEC, ISO, and SAE are driving the standardization process for DER and EV communication and the appropriate protocols are either refinements and/or extensions of existing standards or entirely new candidates (IEC 61850 and ISO/IEC 15118).

Additionally, both IEC [4] and NIST [5] have produced reference guidelines on how to implement security in smart grids, also relevant for EV integration.

The chapter starts by reviewing ICT architectures, models, and requirements in Sect. 5.2. Hereafter the focus will be on the specific protocols and technologies that can meet the communication requirements as well as relevant reference models and new emerging ICT solutions, which are discussed in Sect. 5.3. Finally, in Sect. 5.4, a few practical examples of EV communication implementations, as a set of use cases, will be described.

5.2 Architectures and Models for Smart Grids and EV

The continuous cost decrease of renewable technologies along with the increase in installed capacity has contributed to a more clean and cheap electricity use. It is expected that this will allow Electric Vehicle (EV) penetration to become economically viable. The increase in the number of entities/devices interacting with the electric grid, in particular EVs, will have a significant impact on the amount and type of exchanged information (for metering, monitoring, and control) placing new challenging requirements. Novel ICT architectures will be required to support the new generation of the electricity grid, the Smart Grid (SG).

The introduction of SG concepts has brought with it the redefinition of existing players in the electric industry along with the introduction of new ones. These players have created the need for new models and architectures, along with the definition of roles and domains of action. They are intended to interact among themselves in order to improve the overall electric grid operation.

This section will introduce an SG vision of the ICT players, having in mind the definitions and models developed by the National Institute for Standards and Technology (NIST), which were devised to facilitate the integration of EV, namely in distribution grids of electricity, considering technical, market, and customer perspectives.

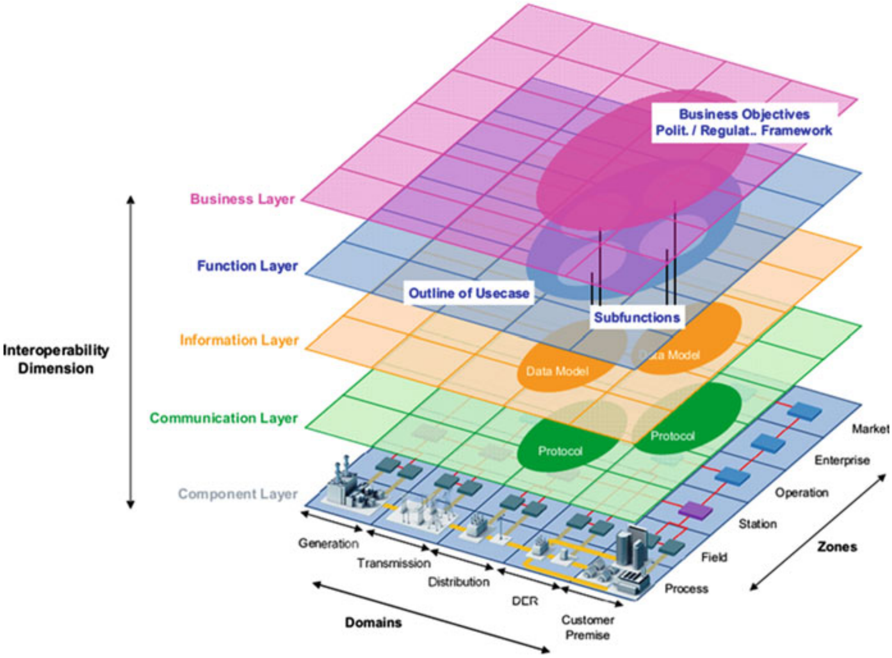


Fig. 5.1 CEN/CENELEC smart grid reference architecture (M/490 Reference Architecture WG—Framework for Smart Grid Architecture Models—2011)

5.2.1 Smart Grids: Introduction and Context

One of the base concepts used when referring to modern power systems is precisely the Smart Grid. The definition of SG can vary but at a baseline it consists of an electricity network which incorporates advanced sensing and automation mechanisms which are managed and controlled by central and distributed intelligent nodes supported by information and communication technology networks [6].

SG must integrate technology, market, regulatory issues, environmental impacts, standards, and ICT. There are still considerable challenges associated to smart grids namely in terms of communications, which will be the infrastructure that will allow the participation of different entities concerning technical and market operation. ICT will allow the implementation of different functions and business models accommodating the needs of the different participant, as depicted in Fig. 5.1.

One particular case is the integration of EV which will require the interaction between several entities concerning ICT players in SG. The importance of accommodating EV is mainly due to their mobile and highly disperse characteristic which along with the potential massive deployment in the next years will have a significant impact on SG.

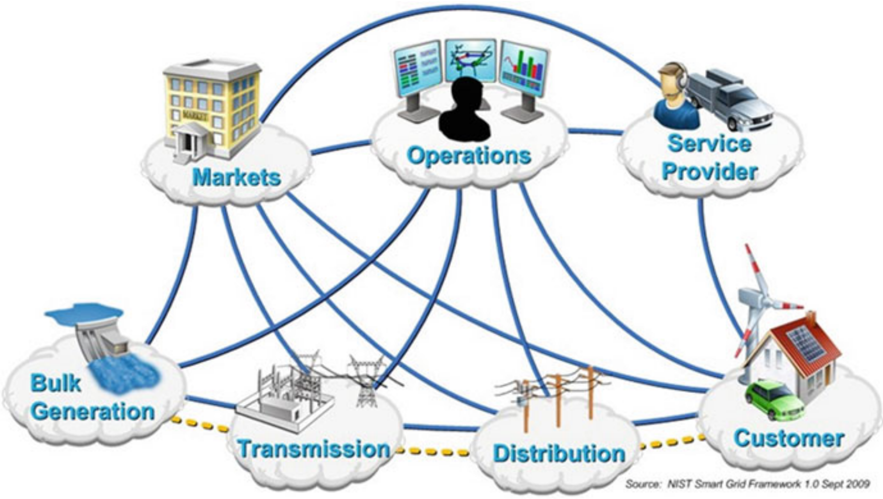


Fig. 5.2 NIST domains and interconnections

5.2.2 ICT Players in Smart Grids

One of the most active standardization bodies is NIST, the North American agency responsible for promoting innovation and competitiveness in the United States towards a better economic security and quality of life using standards and technology.

NIST has defined the main players envisaged to interact in SG using a domain perspective interconnection, as depicted in Fig. 5.2 from [7], where the lines in full define functional interconnections while the dashed lines represent electric interconnection. Internal elements inside each domain are also defined and interconnected in a functional subnetwork.

This domain-based functional architecture can be divided into:

- Markets—authorized market operators and participants
- Operations—entities directly associated with electricity flows
- Service providers—entities that provide services either to end customers or to the electric grid
- Transmission—entities responsible for the transmission of electric energy over wide distances
- Customer—end users of electricity (domestic, commercial, and industrial) that can consume, generate, store, and manage their energy

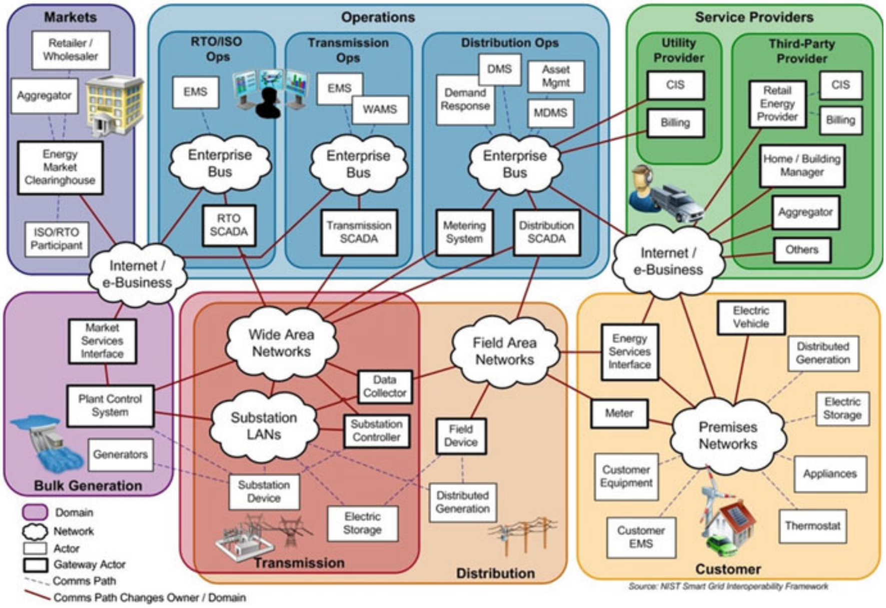


Fig. 5.3 NIST information network interconnecting domains and actors

The Electric Power Research Institute (EPRI) report to NIST [7] details the interconnection between the different domains and their respective actors, considering the most important use cases for Smart Grids requested by NIST:

- Wide area network (WAN) awareness—electric energy systems monitoring over wide areas
- Electric storage—the use of battery systems for energy storage managed individually or aggregated
- Electric transportation—EV integration as a potential flexible load and energy storage elements able to inject power into the grid
- Advanced metering systems—use of advanced metering systems allowing bidirectional information exchange between the end customer and the service provider
- Distribution grid management—electric distribution grid management and control considering the players of the previous use cases

Based on SG applications and use cases, NIST has defined a conceptual model, depicted in Fig. 5.3 [5], considering the expected information flow between actors inside each domain (intra-domain) and between domains (inter-domain). Domains are abstractions of organizations, buildings, entities, individuals, or other elements that share similar objectives and purposes. Actors can be devices, computation systems, software modules, individuals, or organizations participating in an SG. They are able to take decisions and exchange information with other actors.

Gateway actors interact with actors in other domains through information networks. In Fig. 5.3 the lines in full represent inter-domain logical connections or information paths, while dashed lines represent intra-domain connections. Information networks are composed of computers or other communication devices that form the infrastructure (technologies and resources) that allow information to be exchanged.

The EV integration will require flows within the customer domain. However, this domain interacts with the Distribution, Service Provider, Operations, and Market domains and will thus directly impact them all. The next section addresses the functional and logical models and the interaction between those domains at the distribution level. As it will be pointed out, it is considered that the Distribution Operations subdomain can be integrated with the Distribution domain into a single Technical Distribution Operation domain.

5.2.3 Reference Models

5.2.3.1 Smart Metering

Some early reference models can be pointed as the cradle that ultimately led to the Smart Grid concept and models; one of them embodies the Smart Metering concept.

The first smart metering version is associated with automatic meter reading (AMR), which is an automated mechanism to collect information initially from customers' electricity meters [8]. For that matter IEEE approved the IEEE 1377 standard, which defines a table structure for utility application data to be passed to and from end devices, although no device design criteria or specific protocol are defined to transport that information [9].

This model evolved with the introduction of the advanced metering infrastructure (AMI) concept, which is the designation for a more advanced system composed of metering, analysis, load management modules, and a bidirectional communications system. Along with AMI new concepts were defined, such as the AMI head-end, which is typically located at the control and operation system of the DSO, and the smart meter (SM), which is installed in the customer premises. An automated meter management (AMM) layer was incorporated at the SM in order to provide services to the customer.

The communications infrastructure associated with smart metering may consist of several networks, typically including a network of meters, a WAN, and backhaul networks for the connection of the metering network(s) with the utility central control/operation system.

The AMI concept was the starting point for the deployment of a communication and processing infrastructure capable of introducing services to the electric network within the smart grid vision. The definition of a smart grid is not consensual, either because of different functional model perspectives or due to specific implementation aspects. However, it is widely agreed that it is a complex system composed of interrelated systems that include the AMI or Smart Metering system.

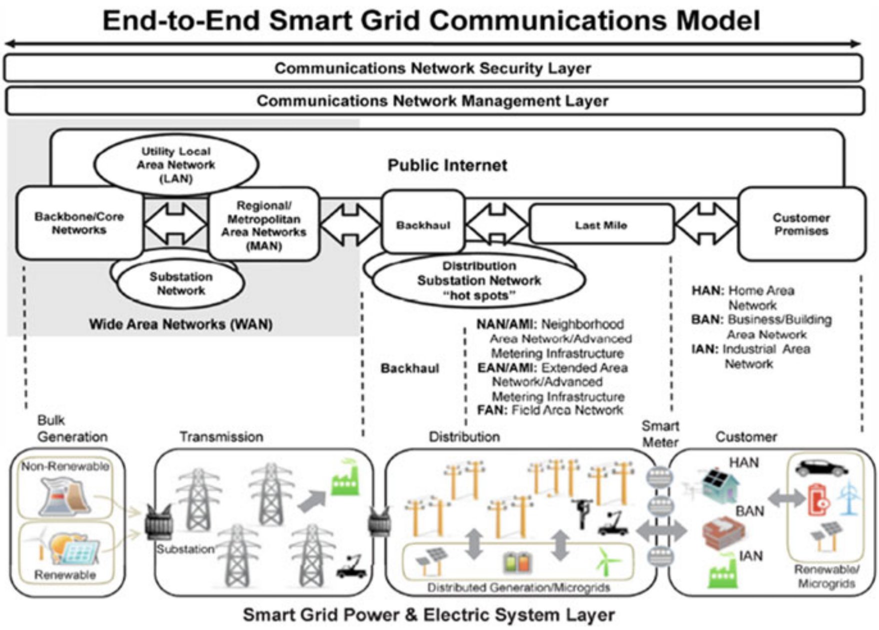


Fig. 5.4 IEEE 2030 smart grid communication model

Despite the fact that the first implementations of SG are majorly based on a sophisticated AMI, there is a concern that this approach may limit or introduce restrictions to the broader objective of progressively creating an integrated bidirectional communication system. The design of the communications system for a smart grid must take into account the expected long-term requirements, even if in the short term only a limited set of functions is necessary (e.g., monitoring or metering).

5.2.3.2 Information and Communication Models

NIST and IEEE have recently developed reference models that aim at providing an updated and detailed vision of the challenges and issues of communications in smart grid. Both models propose a segmentation of the global SG network into specific networks considering a logical separation due to functional aspects. These models incorporate requirements that were identified by several entities (governmental, standardization bodies, utilities, network operators, suppliers, etc.) and some of them are publicly documented [10, 11]. The model developed by NIST is presented in Fig. 5.3.

The IEEE standard (IEEE 2030) was based on the work developed by NIST. A smart grid interoperability reference model (SGIRM) is proposed; it is supported by an End-to-End Smart Grid Communication Model, as depicted in Fig. 5.4.

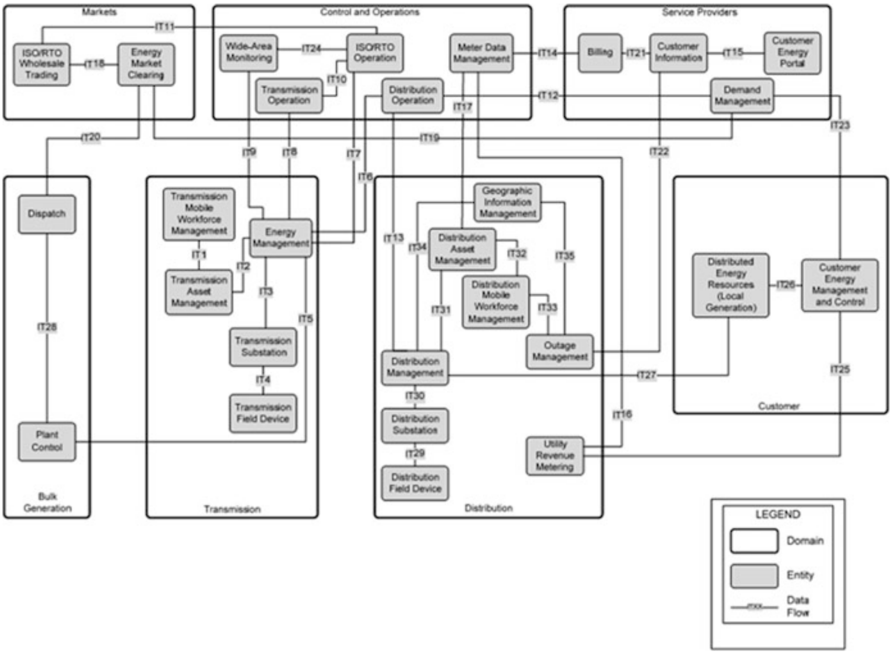


Fig. 5.5 IEEE 2030 information technology—interoperability architectural perspective (IT-IAP)

SGIRM defines three complementary views called interoperability architectural perspectives (IAP):

- Power systems (PS-IAP)—highlight the aspects of production, delivery, and consumption of electric energy. It identifies logical information to be conveyed.
- Communications technologies (CT-IAP)—highlight connectivity aspects among systems, devices, and applications. It identifies the general communication options for different interfaces.
- Information technology (IT-IAP)—highlights process control and identifies data flow management aspects.

The models used by NIST and IEEE are not incompatible, despite the different terminology and some functional differences, visible when comparing Figs. 5.3 and 5.5. There is, however, an effort to unify the terminology towards a consistent architectural framework for SG concepts.

Given the importance of the IT-IAP layer, it is depicted in Fig. 5.1. This layer gives an overview of the SG considering IT applications and associated interfaces and data flows with the goal of allowing interoperability between independently developed systems.

As previously emphasized, the interaction of EV with the SG will take place at the Customer domain, which in turn will interact directly with the Distribution and Service Provider domains and indirectly with Market and Control and Operations domains.

According to the IT-IAP model, the Customer domain has two entities:

- Customer energy management and control—it is an energy management system (EMS) (domestic, industrial, or business) that can receive management and control functions from the SM or from the service provider.
- Distributed energy resource—it is the set of generation and storage devices that may or may not be dispatchable.

Hence, the EV can be seen as an entity/device that can be managed and controlled by the SM according to the customer preferences or by the service provider. It is another DER that, according to the configuration in the SM, has the ability to participate in energy services.

On the Service Provider domain the following entities interact directly or indirectly with the customer:

- Billing—it uses the collected data from meters and is responsible for the billing of services according to tariff schemes.
- Customer energy portal—is a front-end for customers to send data pertaining to energy usage, billing, and authorization, through a universal telephone or data connection (Internet).
- Customer information—is a customer profile database with all the relevant data from the customer.
- Demand management—it is the indirect interface of the customer with the market domain. It uses customer data and negotiates service conditions in the market and with the customer, thus allowing enhanced load control strategies.

It is possible to incorporate EVs from customers in these IT entities. The billing schemes depend on the services and conditions negotiated with the customer and with the market. The EV as a load is also billable for the consumed energy. It represents extra information to add to the Customer Information entity for each customer owning an EV, like the charging rated power, since the EV is also a load. Due to the great flexibility of EVs it is very appealing to associate them with the Demand Management entity.

However, the ability to inject power into the grid also makes the EV very relevant in allowing the Service Provider entities to negotiate energy services in the Market domain. They become especially useful when managed and controlled through Aggregators as depicted in Fig. 5.3. Although the commercial aggregator of customers, in particular of EVs, is not explicitly defined in IEEE 2030, it does not conflict with the ICT architecture proposed by NIST.

The interaction of the customer with the Distribution domain may take place through two entities:

- Distribution management—it manages the distribution system operation, including load management, using information from customers, among others.
- Utility revenue metering—it is the AMI head-end for the distribution domain.

As far as the Distribution domain is concerned, the integration of EVs will be part of the load management scheme implemented in the Distribution Management entity. It will also be a target of the Outage Management entity, although indirectly through the Service Provider. As a potential element that can inject power into the distribution network, it needs to be considered as an active participant by the Control and Operations domain. For this purpose the Distribution Operation entity indirectly establishes an IT path towards the customer through the Distribution Management (Distribution domain) and Demand Management (Service Providers domain).

In the Market domain the following entities are defined:

- ISO/RTO wholesale trading—it is responsible for the trading between bulk generators, utilities, and transmission operators.
- Energy market clearing—it is responsible for conveying the market trading result to bulk generators and to Service Providers.

The integration of EV in the Market domain is also not explicitly defined in the IEEE model, but NIST suggests that it may be achieved through the Aggregator entity as a Service Provider. IEEE merely considers that aggregators, like any other service provider, are able to directly interact with the Market domain through the Energy Market Clearing to know the outcome of the energy market trading. If the Energy Market Clearing entity is able to account for bids from service providers, the inclusion of aggregators will have no impact on this ICT model proposed by IEEE.

Despite some different interpretation of the SG concept, NIST and IEEE models are very detailed and flexible and can thus ensure the proper interoperability when integrating the EV in SG ICT solutions. It is evident the importance of access networks, particularly in the Last Mile, both in terms of communication infrastructure and ICT, to enable the integration of EVs.

5.2.4 Functional and Logical Models

The functional and logical models involving the electric vehicle integration can be defined under two perspectives. One concerns the integration in models such as those proposed by NIST where the focus is placed on the interaction with the grid at a higher level with inter-domain interaction. The other concerns the models addressing the interaction of EV with the infrastructure within the customer domain.

5.2.4.1 Grid Interaction

The introduction of EV in electric grids will require changes to the SG paradigm. This will likely be a phased process that will include short- and long-term actions according to different levels of EV integration.

The Operations (in particular the Distribution Operations component) and the Distribution domains are here integrated and characterized by a hierarchical control

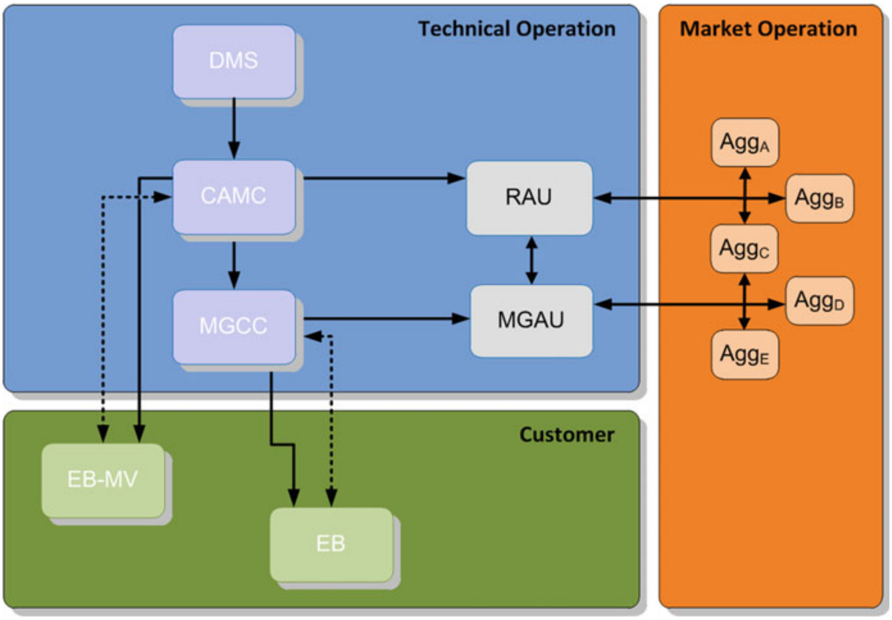


Fig. 5.6 Short-term model for EV integration

structure referred to as Distribution Technical Operation, while the Market and Service Provider domains are portrayed as a hierarchic market structure composed of aggregators. The Customer domain is defined by the Energy Box (EB) entity, which acts as an AMI and service gateway (GW), allowing the participation of customer devices, such as EVs, in energy markets.

In the short term the EV penetration is likely to be modest, but it can already have an impact on the operation of electric distribution networks, since it introduces new technical challenges. In this case the functional model of SG will mainly rely on control structures defined from the electric grid side with limited interaction with markets. Structures based on hierarchical control schemes such as microgrids [12] and multi-microgrids (MMGs) [13] will be used, allowing electric grid entities like the distribution system operator (DSO) to monitor and control different parts of the electric network, as represented in Fig. 5.6, where the market and technical operations are considered in a short-term perspective.

The Energy Box (EB) is the central actor in the Customer domain (MV or LV), since it is the interaction element with the grid. It is responsible for implementing a monitoring and metering platform (AMI) while providing a control scheme for customer devices. The microgrid central controller (MGCC) is the main actor at the secondary substation (MV/LV), which is the entity responsible for coordinating the control of associated EBs and exchanging information with a new technical management entity—the central autonomous management controller (CAMC). The CAMC is the main actor at the HV/LV substation and is responsible for the technical management of the MV grid interacting directly with MGCCs and with the distribution management system (DMS). Both MGCC and CAMC entities are associated with the DSO hierarchical structure.

On the market side, and according to the models proposed by NIST and other entities, the aggregator is one of the key actors that participate in this domain. The aggregator is as a generic commercial entity that can operate in the energy market, representing end customers, namely EV owners. Aggregators interact with the technical operation depending on the level of aggregation. At LV the interaction is ensured through the microgrid aggregator unit (MGAU) while at MV it is performed through the regional aggregation unit (RAU). Both RAU and MGAU are market interface entities that allow the DSO to ensure the participation of distributed entities such as Distributed Energy Resources (DER) and EVs in energy market services [14].

This model is based on a communications infrastructure provided by DSOs, which will allow technical entities to be aware of technical information associated with market operating conditions regarding the end customers connected to each MGCC and CAMC.

It should be pointed out that it is assumed that the distribution grid is capable of operating under two main states: normal and emergency. In the normal state the distribution network is operating without any kind of technical violation or near any operational limit. In the emergency state the electric network is operating near the technical limits or when any of the operation thresholds has been exceeded, leading or not to a violation of a technical restriction. Depending on distribution system and classification used, a given number of intermediate states may exist in between these two states.

In the normal state the electric grid operation is mainly driven by a market implementation, including the different variants, such as “day-ahead market,” “intra-day markets,” “corrective markets,” and others. The distribution network operation in normal state is mainly defined by the outcome of the market operation as depicted in Fig. 5.6 by the lines in full. However, the technical hierarchical structure is aware of the state of operation and in case it is impossible to maintain the market operation due, for instance to a technical violation, the distribution network changes to the emergency state. In this state the market operation is temporarily suspended, the RAU and MGAU stop receiving market inputs, and the technical operation takes over by activating the dashed links in the figure.

On the long-term perspective, it is expected that a more significant integration of EV will take place along with the implementation of a more dynamic energy market, which will require a different model to handle the much higher amount of information that will have to be exchanged in a Smart Grid.

With the introduction of a more complex information exchange in SG both in the technical plane and in the market, a natural segmentation of information is likely to occur. The information within an SG can be characterized primarily as having two different natures, one being technical and the other market related, as illustrated in Fig. 5.7. The customer domain now plays a central role in the model, as far as EV integration, since it has information concerning both sides.

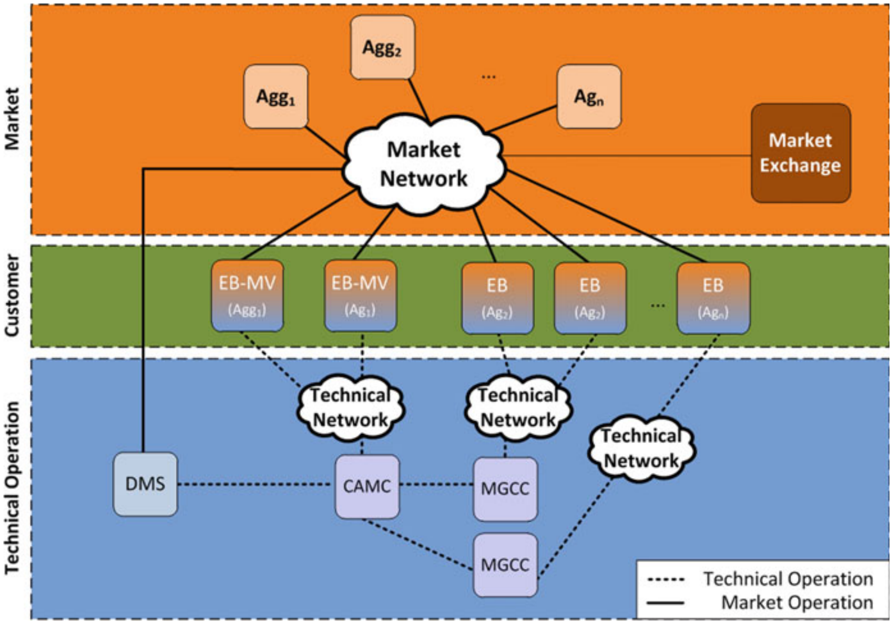


Fig. 5.7 Long-term model of EV integration

The separation of information can be supported by a physical separation using different communication networks of different technologies. It can also rely on a common communication infrastructure/technology with data and functional separation in different logical networks. One reason for information segregation is the different scopes of use. Moreover, the requirements (latency, bandwidth, and others) for the exchange of information under market operation can be quite different from those placed by the technical operation. This has obvious implications with regard to architectural and technological solutions to be adopted, especially in ensuring the proper levels of quality of service.

The separation of market and technical information is also suggested by NIST models namely through the use of Internet/e-Business networks for customer interaction with service provider and markets. The use of field area networks (FANs) is also suggested to ensure the interaction between the customer and the distribution network.

Similarly to the previous model, the lines in full in Fig. 5.7 represent the information flows when the system is operating in normal conditions and mainly controlled by the market. The dashed lines represent the technical operation information flows that are used in normal/market condition for monitoring purposes only. In case the system is not able to sustain market operation due to technical constraints the market operation is suspended and the system operator control infrastructure fully assumes monitoring and control of the distribution network.

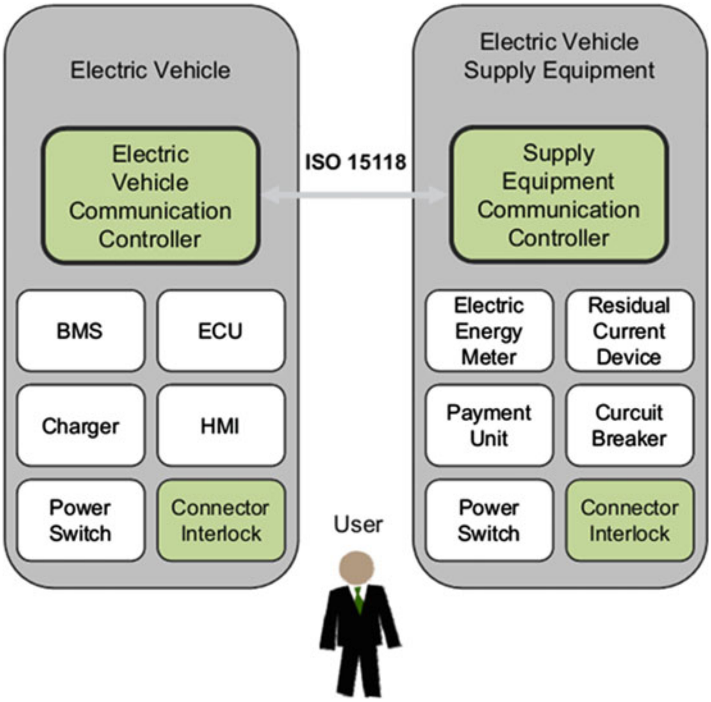


Fig. 5.8 Actors involved in EV and EVSE according to ISO/IEC

5.2.4.2 Infrastructure Interaction

In order to ensure the integration of EV in Smart Grids it is also necessary to define data models addressing the interaction between EVs and the access infrastructure. One of the most awaited standards regarding the communication model between EVs and the charging infrastructure, also known as electric vehicle supply equipment (EVSE), is the ISO/IEC 15118.

The ISO/IEC working group identified a set of actors concerning respectively the EV and the EVSE, with IEC 15118 specifying their interconnection, as illustrated in Fig. 5.8.

For a more detailed description, please refer to section "IEC 15118."

5.2.4.3 Information Flows

The flows regarding the EV integration in distribution networks can be functionally separated into technical and market information, as referred to in the previous section. However, the technical information that mainly concerns the electric operators may flow to more than one of the domains defined by NIST. The same rationale applies to market information flows.

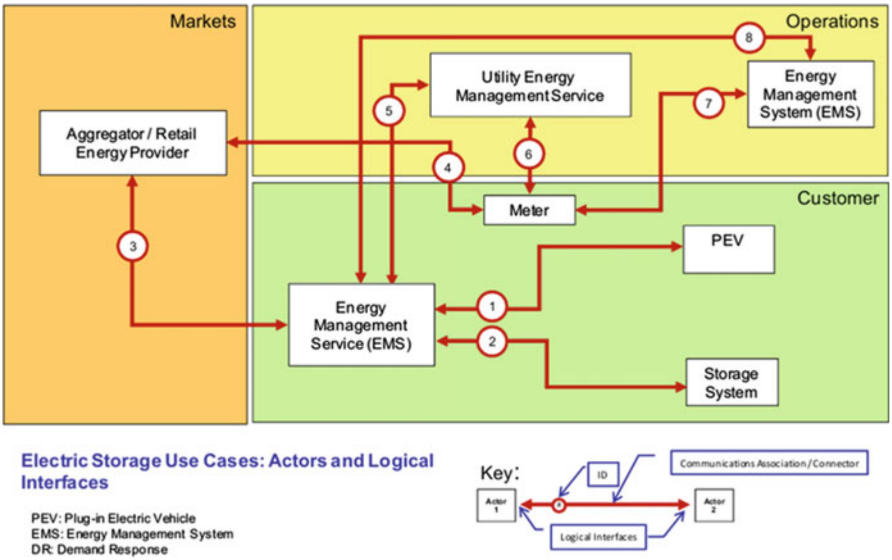


Fig. 5.9 Electric storage application

NIST has defined a set of SG applications, designating the involved entities and respective flows. As the name suggests, the Electric Storage (ES) application refers to storage devices that deal with resource adequacy and resource management. Storage devices can be deployed as bulk storage, like pump storage in hydroelectric power plants, or in a distributed fashion, like small flywheels and batteries. In the case of distributed storage, given the small scale of these systems, they can benefit from the use of market aggregators the same way as EVs can. In fact, EVs are mobile storage devices and as such can participate as actors in this application. Fig. 5.9 illustrates the domains, flows, and actors involved in the Electric Storage application according to NIST [6].

The following use cases were deemed in the Electric Storage smart grid application:

- Storage device draws energy from the grid
- Storage device supplies energy to the grid
- Storage device used in building energy optimization
- Storage device dispatched by the system operator to meet power demand
- Storage device dispatched by the utility to support intentional islanding
- Storage device used to provide fast voltage sag correction
- Impact on distribution operations of plug-in electric vehicles as electric storage

As storage devices, EVs can also participate in all of the use cases previously mentioned, especially if supported by aggregators in market negotiation, which can allow their feasible participation mostly in providing system services to the grid.

Another SG application where EVs can potentially participate is Demand Response (DR), which allows a temporary change in the consumption pattern to address market or technical constraints using Demand Resources. These are loads

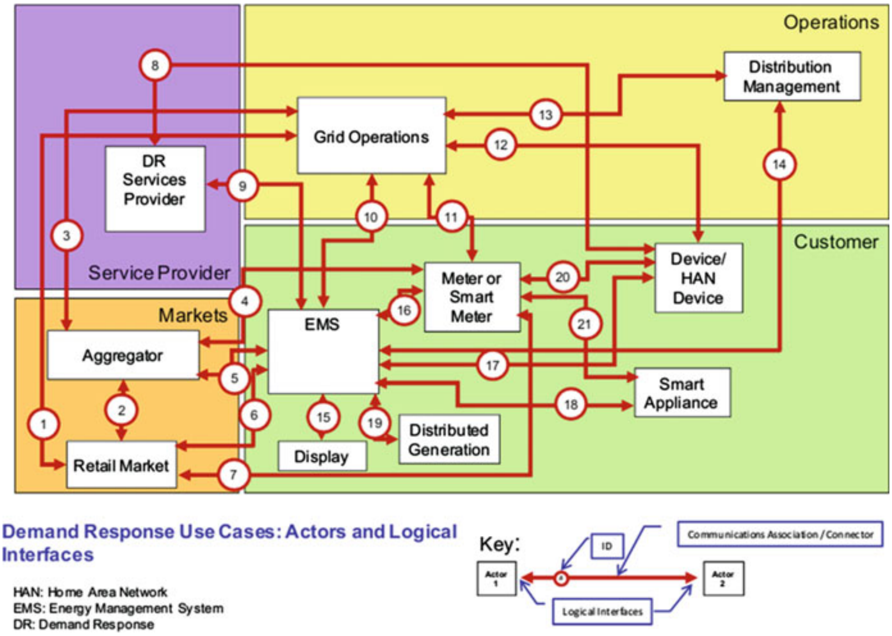


Fig. 5.10 Demand response application

or sets of loads with required flexibility to ensure feasible temporary changes in consumption levels. In SGs these Demand Resources are associated with DER, which are small scale electric energy sources that can provide temporary changes in supply, also known as Supply Management. A particular case is precisely the EV, since it can provide both services, especially when part of an aggregated set. Hence, it is common to address demand resources and DERs in an integrated fashion. Fig. 5.10 [6] depicts domains, flows, and actors involved in the Demand Response application defined by NIST.

Although the EV actor is not depicted in the figure, it is considered by NIST a participant entity in the defined use cases:

- Direct load control
- Management of DR to price signaling
- Customer reduces demand due to pricing or voluntarily
- Service provider interacts with SM/AMI to provide demand response services
- Customer implements DR strategy through the EMS
- Utilities negotiate DR with customer and settle energy market wholesale transactions
- Service providers use aggregated customer set to provide energy/ancillary services
- Voltage, VAr, and Watt control with DR, DER, EV, and ES

The characteristics of the electric vehicle make it a valuable entity that is able to participate both in demand response and supply management with no impact on ICT flows, being just another actor that can participate in both cases.

Table 5.1 SGIRM data classification[a]

Data characteristic	Classification or data range			
Use category	To be defined according to intended use and implementation			
Distance	Meters		Kilometers	
Information transfer time	<3 ms	3 ms < 10 s	10 s < mins	Hours
Data occurrence interval	Millisecond	Second	Minutes	Hours
Transmission scheme	Unicast	Multicast	Broadcast	All
Priority	Low	Medium		High
Latency	Very low (<3 ms)	Low (<16 ms)	Medium (<160 ms)	High (≥160 ms)
Synchronization	Yes		No	
Information reliability	Informative	Important		Critical
Availability	Low	Medium		High
Level of assurance	Low	Medium		High
Data volume	Bytes	Kilobytes	Megabytes	Gigabytes
Security	Low	Medium		High
Confidentiality	Low	Medium		High
Integrity	Low	Medium		High
Availability	Low	Medium		High

[a]Where the classification is stated in terms of “low,” “medium,” and “high” means that they can have limited, serious and catastrophic consequences

5.2.4.4 Characteristics of Information Flows

The IEEE 2030 standard proposes a classification of data flow characteristics that need to be considered when designing ICT solutions for smart grids. Table 5.1, adapted from [15], presents a set of characteristics that can be independently associated with different information flows. The range of each one of them depends on the real implementation of each SG application.

It should be noted though that the proposed classification for each data characteristic can be considered singly. This means, for instance, that information exchanged with an <Information Reliability> value of “informative” can have an <Information Transfer Time > of “hours.”

5.2.5 Last Mile

The concept of Last Mile within Smart Grids is very similar to the one usually found in communications networks. In fact NIST has defined it in [16] as being a bidirectional wired or wireless communications network overlaid on top of the power distribution network. A Last Mile network ensures connectivity between different elements within the electric distribution network and usually several different networks are distinguished, according to the type of interconnected devices and associated functions [15]:

- Feeder network—is a communication network overlaid on the electric power system for information exchange with field devices of the electric grid itself (e.g., reclosers, switches, capacitor banks, etc.).
- Neighborhood area network (NAN)—is a network connecting smart meters, field devices, distributed energy resources, microgrids, and the utility scale electric storage.
- Field area network (FAN)—is the network connecting distribution substations, feeder devices, and DER/microgrids.
- Extended area network (EAN)/advanced metering infrastructure (AMI)—is the network that interconnects smart meters with the distribution metering management systems.

These networks usually have a geographic span up to a few kilometers although this distance can vary substantially depending on whether a rural or an urban area is considered. Although all these networks are logically distinct and the information flows traversing them can originate and terminate at different systems, they can share the same communications infrastructure, in part or in full.

There are a considerable number of reasons that justify the definition of a last mile model, namely:

- A high number of devices (sensors, meters, controllers, actuators, etc.) deployed under the SG paradigm are (or will be) geographically located within the range of distribution substations.
- The expected increase in data traffic volume in SG will potentially be originated by smart devices deployed in distribution grids, which may require heavier communication mechanisms and data flow aggregation. This increase can also require complex security schemes and nontrivial traffic QoS for service discrimination.
- The availability of alternative technologies (both present and future) and the risk of adopting a unique technological solution (especially when considering the long-term evolution) may require the implementation of different coexisting communication networks over time.

5.3 Technologies and Solutions for Smart Grids

5.3.1 Interoperability

The presence of a potentially high number of different devices in SG will require an interoperable approach allowing technologies and solutions from different implementers to cooperate towards a unified smart grid.

Interoperability challenges are posed at different layers of the OSI model. At the network layer the agreement on IP-based solutions is already widely accepted as universal solution. Using IP as a common interworking layer allows using different technologies with different PHY and MACs. Higher layers concerning information models are addressed by different working groups typically using a decoupled approach regarding other layers. However it is at lower layers, which are inherently technology driven, that interoperability finds the biggest challenges.

Normative and standardization bodies as well as manufacturer alliances have a key role in defining solutions for SG and interoperability is a transversal concern that is becoming a recurring topic in their work.

5.3.1.1 Network Interoperability

The Internet Protocol (IP) is currently the de facto standard, and thus the most popular choice, of a network service that provides connectivity among end-systems attached to the same or different networks. In the particular case of smart grids, IP has an increased importance due to its interworking characteristics.

Its use is considered in current and future developments of SGs, where utilities are able to use multiple communication networks of different technologies and end devices from different manufacturers. The flexibility associated with IP networks when considering aspects such as network reconfiguration and expansion, with dynamic routing schemes and scalable design, represents an advantage for its use in SG.

In SGs, an IP end device/node is any IP-enabled device; this includes smart meters, sensors, relays, actuators, intelligent electronic devices, or any device with embedded data collection and reporting functionalities that can communicate at the IP layer [16].

IP is pointed out by NIST [5] as a central element for Smart Grids information networks and it is expected to be widely adopted. Nonetheless it is also assumed that not all devices in the SG are required to use IP, since they might not be suited to be part of an IP infrastructure.

The importance of IP as an interworking layer is more evident in the Last Mile segment of the SG, where the majority of systems, subsystems, and elements will be located. Given the high number of IP devices that potentially can operate in SGs, advantages can be found in using IPv6, despite the existing mechanisms currently used to overcome the depletion of available IPv4 addresses. The use of IPv6 over Low-Power Wireless Personal Area Networks along with Compression Format for IPv6 Datagrams in 6LoWPAN network, which addresses header compression and subnet architecture, may be also used in SGs. The IP suite with enhanced routing and QoS features, among other mechanisms, provides an appropriate interoperable layer to support the implementation of data networks in smart grids [17].

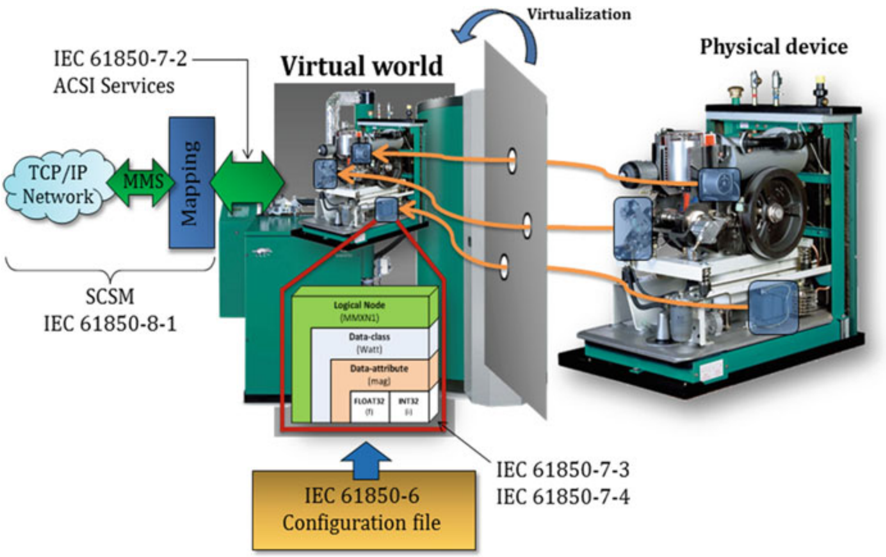


Fig. 5.11 IEC 61850 modeling approach

5.3.1.2 Information Interoperability

IEC 61850

Originally designed to allow for interoperability between different devices within a substation environment, as well as for the adaptation of future networking technologies, IEC61850 is quickly becoming a key standard within smart grid communications. Besides its versatility, one of the main reasons for this adaptation is the continuous addition to its device portfolio. One such extension is in the form of IEC61850-7-420, which specifically outlines DERs encompassing, among others, EVs. The outline is as follows:

- Logical nodes for DER management systems
- Logical nodes for DER generation systems
- Logical nodes for specific types of DERs
- Logical nodes for auxiliary systems

Fig. 5.11 shows some of the more common parts of the IEC 61850 standard and the areas they cover. Of special interest are the sections IEC 61850-7-1 and IEC 61850-7; the former gives an overview of the use of the substandard and the latter describes the common data-classes that should be used to model the vehicle. The *Virtual World* box in Fig. 5.11 shows how individual components of a substation are modeled using the IEC 61850 standard and the yellow plane marked *virtualization* represents the mapping from the physical substation environment to the logical model. The *TCP/IP* cloud and *MMS*-mapping on the left, covered by

IEC 61850-8-1, is in this case the *Specific Communication Service Mapping* (SCSM) for the *MMS* protocol—ISO 9506.

There are several key features to IEC 61850; the following are some of the more commonly used:

- Object-oriented data model (devices, nodes, data, services, etc.)
- An object naming scheme to ensure easier familiarization
- Predefined names for all data-classes (see above)
- A common XML-based substation configuration language (SCL)
- Self-describing devices (directory listing)

Other benefits include:

- Using SCL not just for configuration but also for specifying requirements
- Lower costs due to easier hardware implementation
- Expandability in using for example TCP/IP (over RS232, etc.)

Data Model

One of the primary features of the IEC 61850 standard is the data model. This has been designed to provide an object-oriented virtual representation of the physical devices within the substation.

As illustrated in Fig. 5.12, the data model is really a tree structure. At the root of the tree is the physical device, containing a server that represents the publically visible behavior of the device.

Any object within the data model can be referred to directly via its object path. Due to the fact that the data-structure is a tree, this path will resemble a file-system path or a URL. The path lists all the objects from the root of the tree to the object in question, which is illustrated in Fig. 5.13.

Where file-systems usually use a fixed delimiter between object names, the IEC 61850 references use a slash ('/') to separate the logical device from the rest of the path, which is then separated by periods ('.'). This scheme does however vary depending on its usage; the typical MMS notation, for instance, uses the dollar sign ('$') exclusively. An example of an object reference as specified by the standard could be:

EV/MMXN1.Watt.mag.f

Included in the object reference is a filtering mechanism referred to as *functional constraints* (FC). The standard defines 17 different functional constraints.

The functional constraints are used in the data-classes to divide their data-attributes into categories. Adding the functional constraint *MX* to an object reference will, for example, result in only the data-attributes containing measurements being returned. As with the delimiter example above, the functional constraints are usually at the end of an object reference, incased in square brackets ('[]'). For the *MX* example, this would look like this:

EV/MMXN1.Watt.mag.f[MX]

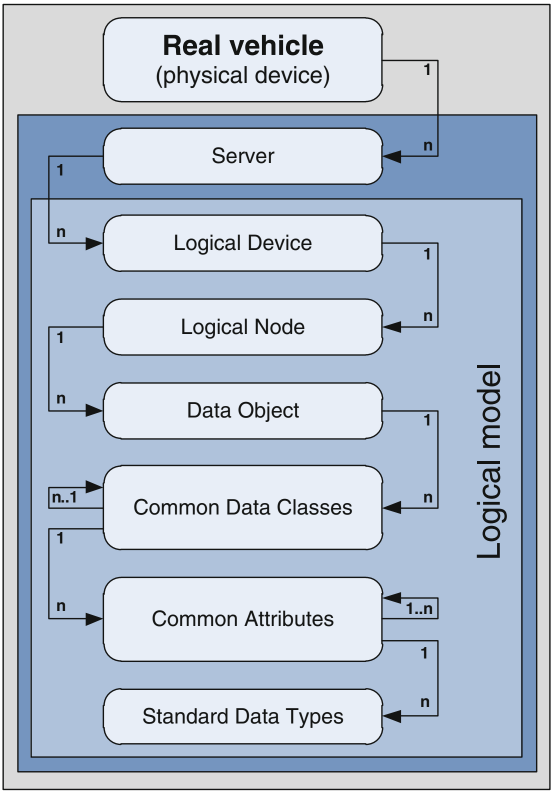


Fig. 5.12 Data model hierarchy

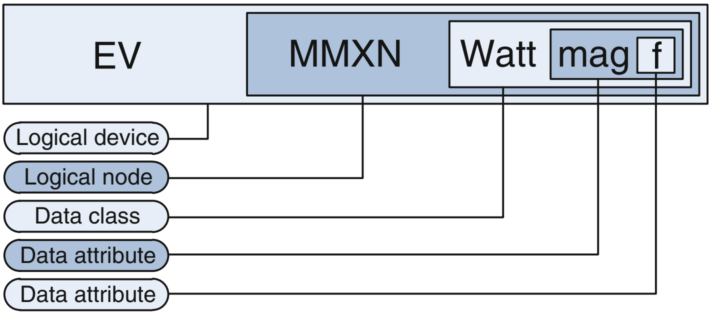


Fig. 5.13 Example of object path

Communication

IEC 61850-7-2 describes an interface called the *abstract communication service interface* (ACSI), which can be seen in the middle of Fig. 5.14, for accessing the IEC 61850 data model. *ACSI* defines a service interface for clients to inspect the

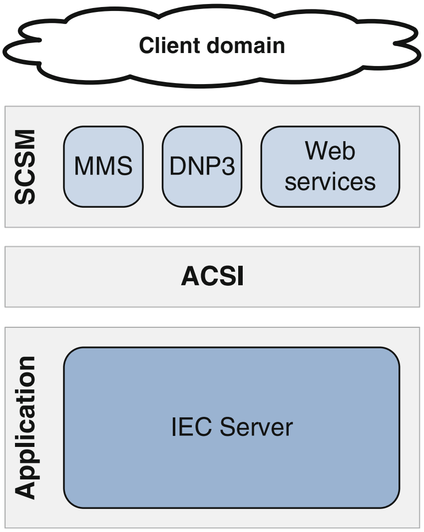


Fig. 5.14 Illustration of the *specific communication service mapping*

data model, to read and set data, to access datasets, logs, and more. As the name implies, this interface abstracts away the details of the communication protocol useful for providing a consistent interface across protocols.

For every communication protocol that is used with the standard, there is a so-called *specific communication service mapping* (SCSM). At present only a few communication mappings exist for IEC 61850, the most common of which is the MMS standard, also known as ISO 9506, which is described in IEC61850-8-1.

Where ACSI describes things on a higher, more abstract level, it is the job of SCSM to define the specifics of protocols such as MMS, DNP3 or as is the case in the Danish EDISON project, restful web services [44].

IEC 62351

In order to secure the communication, the IEC61850 standard can be paired with the IEC62351 standard that provides mechanisms such as encryption, network- and system security as well as role based access control (RBAC). Through the use of transport layer security (TLS), IEC62351 prevents eavesdropping on any communication based on the TCP/IP stack. Further measures against man-in-the-middle penetrations are ensured via either an X.509 public key infrastructure (PKI) or a token server like, for example, Kerberos.[1]

The RBAC mechanism provided by IEC62351 (depicted in Fig. 5.15) is similar to what is found in most modern computer operating systems, and provides custom roles and rights to be defined on an individual subject basis. This model is very

[1] http://web.mit.edu/kerberos/.

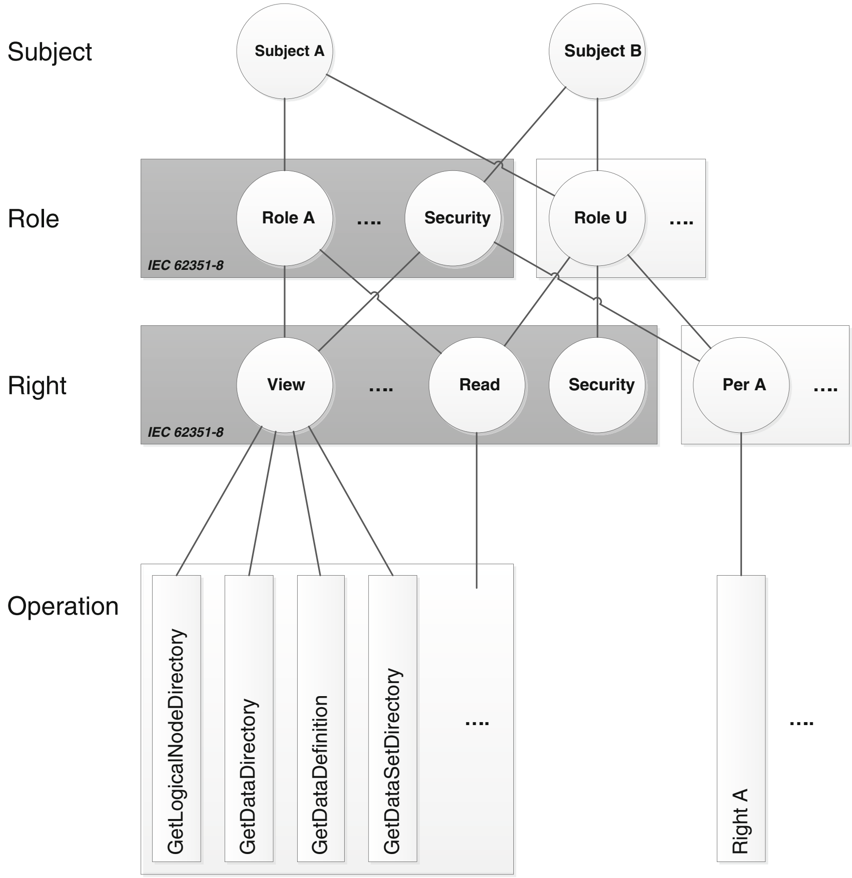


Fig. 5.15 Role based access control (RBAC)

flexible, and in a highly volatile environment allows multiple users to operate simultaneously; some with write and others only with read permissions. Due to this logical separation or responsibility, one client can safely monitor a process controlled by another without risking an accidental race condition on the control side.

Besides facilitating security within the IEC61820 standard, IEC62351 also addresses IEC60870 (dealing with SCADA systems), IEC61968 (inter-substation communication), and 61970 (EMS).

IEC 61851-1: Control Pilot Signaling

The IEC61851-1 standard is part of the IEC 61851 series, which is titled "Electric vehicle conductive charging system." The second edition of the IEC61851-1

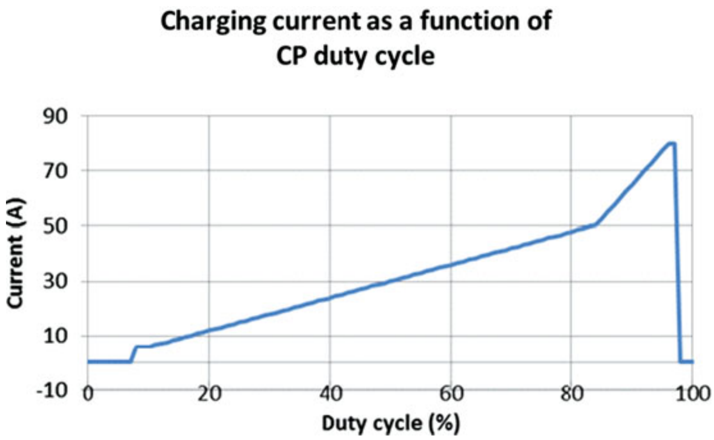


Fig. 5.16 Charging current CP duty cycle

Table 5.2 IEC61851-1 charging modes

EV charging modes	Description
Mode 1	Max 16A per phase. Directly connected to mains
Mode 2	Max 32A per phase. Connected to mains through RCD. Utilizing the control pilot function
Mode 3	Connected through an AC charging station, which contains protection equipment. Utilizing the control pilot function
Mode 4	Connected through an off-board charger, that is, DC-charging. Utilizing the control pilot function

standard was published in Q4 2010, and the scope is to describe "general requirements" for charging systems. Among other aspects, the IEC61851-1 standard provides mechanical and electrical supply equipment requirements as well as a naming scheme for identifying common charging setups, as shown in Table 5.2. The standard outlines requirements for the physical connector, for instance, that a charging station must be able to verify that a cable is plugged in.

Furthermore, the IEC61861-1 standard describes a "basic" interface for AC charging connectors. This AC connector has six wires and a proximity detection pin (used for the detection of a plugged in connector). Five of the wires are used for mains wiring, i.e., three phases, a neutral, and a protective earth. The sixth wire is the *control pilot* (CP) signal, which is used for indicating available charging current to the EV. The usage of the control pilot function is described in the normative annex A in the standard. The Mennekes AC charging cable complies with IEC 61851-1.

The signaling in the CP wire is a 1 kHz $\pm$ 12 V pulse width modulated (PWM) signal. A function of the duty cycle indicates the available charging current, as illustrated in Fig. 5.17. Furthermore, a resistive voltage division allows the EV to

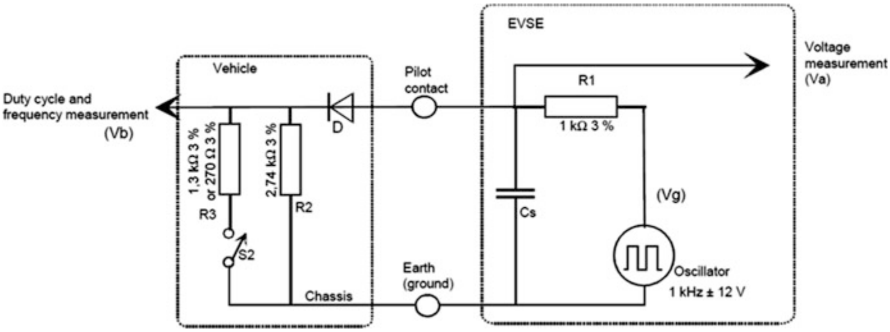


Fig. 5.17 61851-1 control pilot interface reference schematic

indicate a charging *state* to the supply equipment. The PWM signal and the resistor combinations used in the CP circuit are shown in the reference schematic in Fig. 5.17.

It can be noticed from Fig. 5.17 that the charging state is indicated by using different resistors on the EV side. The charging states indicate to the supply equipment if the EV is ready to be charged and if it needs ventilation during charging. The amplitude of the PWM signal is measured at the supply side (at *Va*), and the supply equipment can thus detect the resistor value used in the EV due to the voltage division formed by the R1 resistor and the parallel connection of R2 and R3. The wire between the EV and the EVSE will be capacitively loaded by the Cs capacitor in order to reduce EMI. This also implies that an RC filter is formed by R1 and Cs, which puts a natural limit to the slew rate of the PWM signal. However, this is not a major concern, since the PWM generator emits a relatively low-frequency (1 kHz) signal.

It is evident from the previous description that the IEC61851-1 CP PWM signaling technique cannot be used for general purpose communication, but simply provides low-level functionality in order to establish an electrically safe charging session. In the AC interface specified by IEC61851-1, no dedicated communication wires are specified, and any higher level communication must therefore be provided by other means. A strongly positioned technology in this context is power line communication (PLC), which does not require any additional wiring in IEC61851-1 compliant connectors.

IEC 15118

The ISO/IEC 15118 standard is produced by a joint working group formed by IEC and ISO.[2] It is divided into three parts. The main title of the standard is "Vehicle to grid communication interface" (V2G CI). The parts are:

[2] For brevity, the "ISO" part will often be omitted when referring to the standard.

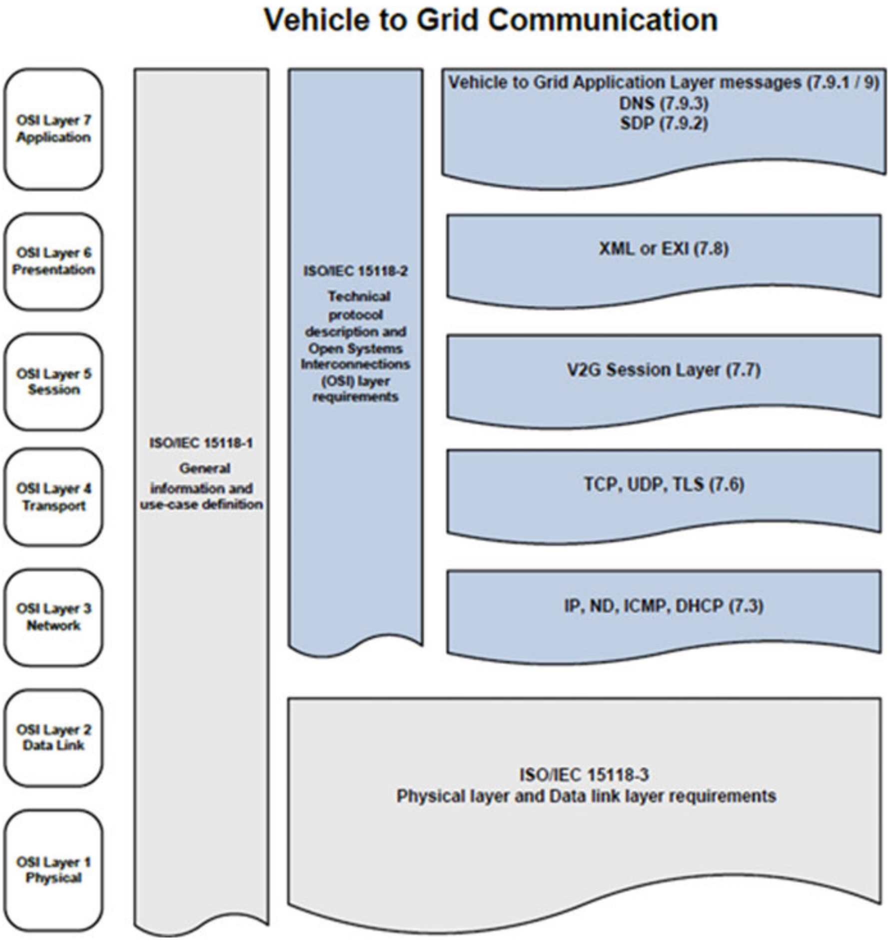


Fig. 5.18 IEC 15118 overview [44]

- ISO/IEC 15118-1: General information and use-case definition
- ISO/IEC 15118-2: Technical protocol description and Open Systems Interconnections (OSI) layer requirements
- ISO/IEC 15118-3: Physical layer and Data Link layer requirements

As can be seen from the titles of the individual parts, part 2 covers upper communication layers while part 3 covers lower layers. This is illustrated in Fig. 5.18.

The 15118-3 standard should comply with the SAE J2931. This SAE standard is divided in seven parts, and all are marked as “work in progress.” Specifically, part 3 (J2931/3) covers narrowband PLC while part 4 (J2931/4) covers wideband PLC, so it seems that SAE will support both narrowband and wideband PLC [18].

The general content of part 2 of 15118 can also be seen in Fig. 5.18. TCP/IP communication is used on the network and transport layers and a binary XML format known as EXI (efficient XML interchange) is used on the presentation layer. The usage of these layers will be described further in the next section.

ISO/IEC 15118 Part 2 Overview

Because the information in this section is based on a preliminary version of ISO/IEC 15118-2, some information may have changed since the writing of this book. Also, references to specific sections in the standard are avoided. However, some of the central concepts will very likely also apply to the final version.

ISO/IEC 15118-2 specifies the use of IPv6 in the network layer along with the Neighbor Discovery (ND) protocol to avoid IPv6 address conflicts when stateless address autoconfiguration (SLAAC) is used. Also, ICMP and DHCPv6 must be supported.

On the transport layer, TCP is used for the V2G CI, which ensures end-to-end reliable data transmission. UDP is used as the underlying protocol for the SECC[3] Discovery Protocol (SDP) which is used for the EV to find an EVSE on the network when it is initially plugged in. The EV transmits a multicast UDP packet on port 15118, and the EVSE will listen for an SDP packet on this port and respond with the TCP port that the EV is allowed to connect to. In ISO/IEC 15118, the EV is always the client and the EVSE is always the server that the EV connects to. Furthermore, communication is always solicited, that is, the EV requests data from the server, which responds to the request (as opposed to unsolicited or event-based communication, where the server is allowed to initiate communication, which is valid as seen from a transport layer perspective).

TLS is used as authentication and encryption protocol to ensure secure data communication. TLS session information and certificates are negotiated after the TCP connection has been established.

The ISO/IEC15118 session layer defines three timeouts that ensure that connections are reset and TCP ports are de-allocated if faults occur (known as "Generic Inactivity," "Initial Inactivity," and "Alive Check" timeouts). The session layer also describes the low-level message header structure as shown in Fig. 5.19.

It can be seen from the figure that the payload following the session header can be encoded as either XML or EXI. The EXI format is a W3C-supported binary XML format and is located on the presentation layer. It provides a fast and compact way to transmit XML, while keeping the XML format functionalities intact. For example, data types can still be described using XSD (XML schema definition) and XML Security can be used to ensure authentication and encryption inside XML streams.

ISO/IEC 15118 ensures authentication and encryption of metering and billing data using, as mentioned, TLS-secured communication between the EV and EVSE.

[3] Supply equipment communication controller.

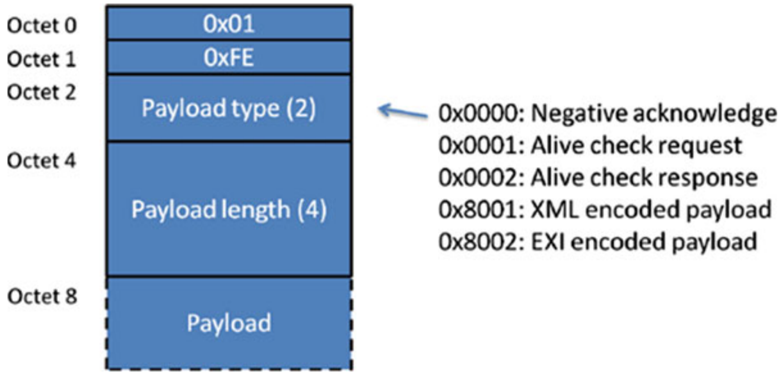


Fig. 5.19 IEC 15118 session header

Furthermore, sensitive data is encrypted and signed (that is, authenticated) inside the XML stream using XML Security. An EV must use two distinct private keys and certificates to ensure encryption and authenticity at the same time. The EVSE uses a single private key and certificate for the TLS communication establishment. All certificates must be registered with a Certificate Authority (CA). Certificates are exchanged with the EV using specific application layer certificate message types as described below.

Application layer messages (the payload) are defined in the XSD format and constructed using a header and a body in the XML stream. The header is encoded as an XML element that contains information on the current session ID. The body is another XML element, which can be one of 19 predefined message types as listed in Table 5.3. The message types are grouped in the table according to functionality. A description of each message type is also given, which should make it easier to get an overview of the functionality that ISO/IEC 15118-2 provides on application and user layers.

Furthermore, basic data types are defined in ISO/IEC 15118-2, which are used to encode and transmit data inside the application messages. Examples are definitions for price tables, certificates, response/error codes, different enumerated values, and time tags. All types are defined in a hierarchical XSD format. However, the complete list of data types is not shown here.

The OpenV2G Project

OpenV2G is a software project initiated by Siemens to support the development of the ISO/IEC 15118-2 standard. It can be retrieved from SourceForge on http://openv2g.sourceforge.net/. It is written as a console application in C and can be compiled using Eclipse CDT or using makefiles.

OpenV2G provides implementations of all application layer messages and data types as defined in ISO/IEC 15118-2 as well as message encoding and decoding

Table 5.3 ISO/IEC 15118-2 application layer message types

Message type	Description
Communication link setup	
Handshake	EV and EVSE agree on a mutually supported protocol
Session setup	Session ID is created
Service discovery and selection	
Service discovery	Find all services provided by EVSE with regard to charging the EV. Can be extended for future use
Service detail	EVSE sends specific information about a particular service
Service and payment selection	EV selects specific services and payment options. Depending on selection, EVSE provides security information for following messages
Payment details	EV sends specific payment details (e.g., contract identifier). EVSE accepts the payment method
Contract authentication	The EVSE authenticates the contract by verifying an EV signature
Charging service and metering	
Charge parameter discovery	EV sends details about needed energy and anticipated end of charge. EVSE responds with status, prices, maximum allowed power output, etc.
Power delivery	EV sends information on currently chosen price and charging profile
	EVSE responds with status
Metering status	Provides sanity checks on meter readings so that the EV and EVSE can agree on the energy drawn. Cyclically transmitted
Metering receipt	EV acknowledges the metering information from the EVSE sent previously. Cyclically transmitted
Certificate handling	
Certificate update	Updates certificates in the EV that are about to expire
Certificate installation	Installs new certificates by using an OEM certificate in the EV to ensure temporary security
AC specific	
Line lock	EV sends charging cable lock status and EVSE responds with lock status in the EVSE charging cable
DC specific	
Cable check	EVSE reports current status
Pre-charging	Adjusts EVSE output voltage to the EV battery voltage
Current demand	Cyclic exchange of requested current from EV during charging
Welding detection	Requests a detection of a welded breaker in the EVSE
Terminate charging	Separate termination of charging for DC

using EXI (located in the codec folder[4]). Function calls are provided which simulate the transmission of IEC 15118 messages from the EV and the responses from the EVSE.

[4] A large part of the OpenV2G source code seems to be auto generated by various EXI tools that are not provided along with the code. The use of auto generated code makes sense, however, because it could become quite cumbersome to define all types manually in C when they are already defined using XSD in IEC 15118.

However, the OpenV2G code is still at an early stage (current version is 0.5) and lacks a lot of features when compared to the complete ISO/IEC 15118 standard. OpenV2G "only" defines the application layer messages and no lower layer functionality is provided such as socket-based TCP communication, session layer timeouts, SDP, TLS, certificate management, XML Security, and related functionality.

5.3.2 Communication Technologies

5.3.2.1 Network Segmentation

Both the NIST and the IEEE communication models consider different network segments within the scope of smart grids. One possible criterion for segmentation can be based on the functional areas of the electric power system: generation, transmission, distribution, and end customer.

A WAN is typically defined integrating all entities participating in the transmission segment, which may include bulk generators, HV/MV substations, and transmission operations entities. Similarly, a FAN is defined aggregating entities participating in the distribution segment, including HV/MV substations, MV/LV secondary substations, and End Customers. A local area network (LAN), typically in-building, can be associated to customer premises (Premises Networks), interconnects devices, which may include loads, microgeneration, and EVs. These LANs can have specific designations such as home area network (HAN) or even industrial area networks (IAN) due to their usage in domestic or industrial buildings.

It is also usual to aggregate part of the FAN, specifically the segment below the MV/LV secondary substation, and the HAN/IAN, defining what is also known as Last Mile or utility access network (UAN), as illustrated in Fig. 5.20. This aggregation is mainly due to the number of nodes that potentially can participate in exchanging information. This segment covers a geographic distance generally below 2 km.

Besides functional reasons, network segmentation may also take into account geographical, administrative, physical, or logical criteria, which have an impact on technological choices and solutions. It is usual to consider the need for back-haul networks that bridge the gap between access/last mile networks and a WAN backbone. The boundaries between such networks is not always clear, since in some cases they may share a common infrastructure and interworking systems may operate at different protocol layers, acting as repeaters, data concentrators, routers, or even application gateways. In the access or last mile segment the distinction between different networks (according to the type of devices they interconnect or the applications they support) may be enforced at the physical level, by using separate infrastructures (possibly of different technologies), or by a logical separation over a shared infrastructure.

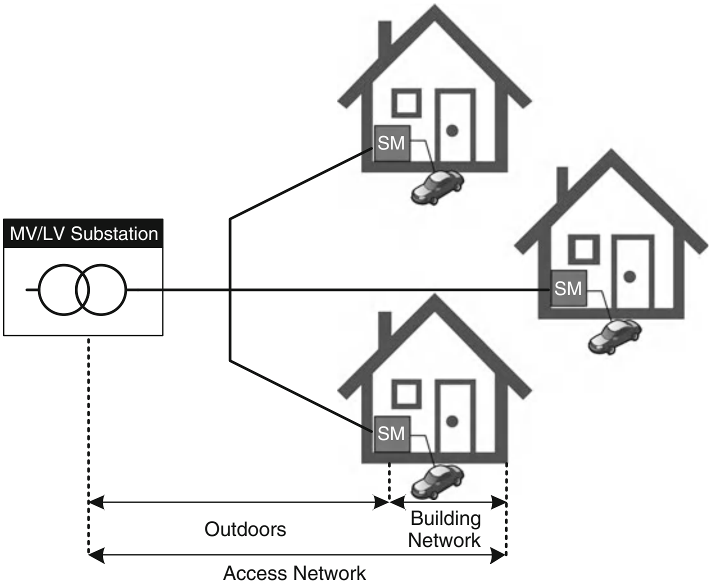


Fig. 5.20 Access network

5.3.2.2 Communications Technologies and Services: Main Options

Since the deployment (and evolution) of such networks may occur at different evolutionary steps of the electric grids, coexistence of different communications and networking technologies is not only natural but maybe even necessary, provided that seamless interworking is planned from the outset.

For the scope of this analysis, the choice of communications technologies and services may be classified along two axels: on one hand, the use of public or private networks and services and, on the other hand, the use of wired or wireless technologies.

The use of services provided by telecom operators (over their copper, fiber, or cellular networks) is usually a matter of concern for the electric utilities, since they do not have any control over the service provided, which may not guarantee security, availability, reliability, and performance levels required by critical applications. However, since these are commercial services, they may be subscribed to fulfill specific objectives (for example, for some noncritical applications or as a back-up solution).

On the other hand, the deployment by the electric utilities of private networks in the backbone and back-haul segments has been common practice over the past years—using either optical fibers, copper or, more recently, wireless technologies (such as WiMAX) in point-to-point or multipoint configurations.

For the above reasons this debate is focused on the use of private networks in the last mile segment, for which the solutions are still quite open, in terms of research challenges as well as opportunities for the different players involved.

The option for wired technologies reduces, in practical terms, to using the existing power lines as the communications medium, since deploying a new private infrastructure (fiber or copper) seems unfeasible, at least in the short to medium term, and there is no evidence that such an option is being considered by the utilities.

PLC is already being used in the narrowband variant, which offers modest rates (up to a few dozens of kbps). Although this may be acceptable for smart metering, the adverse characteristics of the PLC channel may introduce severe limitations even for this application (particularly in dense urban areas with hundreds of meters attached to the same broadcast channel), let alone for future smart grid applications. The recently approved IEEE 1901 standard (BPL—Broadband over power line) promises throughputs in the order of hundreds of Mbps, and thus is a new candidate to be considered and evaluated for medium-to long-term adoption, as the technology matures.

In the meanwhile, wireless technologies have started to emerge as a feasible alternative to PLC, as reflected in a number of initiatives led by standards bodies, research projects, utilities and manufacturers, as well as in pilot trials that have shown promising results. However, when short range wireless technologies are used, extending the coverage area requires relaying data over multiple hops and thus deploying multiple access points (nodes), organized as a wireless mesh network (WMN).

Both PLC and its variants and the currently available wireless technologies and solutions like WMNs will be addressed in the following sections.

5.3.2.3 Power Line Technologies

PLC has been used for decades in the utility industry for remote metering and load control applications [19]. In recent years, smart grid activities as well as advances in building and home automation have brought a lot of attention to PLC technologies as an alternative to unwanted or impractical wiring. Also, PLC technologies are becoming more advanced and promise to achieve data rates up to 1 Gbps [20].

However, the objective might not always be a matter of applying advanced modulation technologies to achieve higher data rates. Power lines are inherently exposed to time-frequency-varying noise, unmatched loads, and interference from similar equipment. At the same time, national legislation puts an upper limit to the allowed transmission power and accepted frequency bands. For these reasons, a large number of PLC technologies have evolved; each addresses different applications and specifies different target throughputs, frequency bands, and channel access mechanisms.

This section will address PLC from a technological point of view approaching the different implementations (narrow, wide, and broadband) and the targeted segments of application within Smart Grids. The supporting standards will be mentioned along with the major characteristics of each PLC application.

Narrowband Power Line Communication

The narrow band PLC (NB-PLC) is typically distinguished between low-speed and high-speed versions. The narrow-band high-speed version is also referred to as medium-speed implementation.

The narrowband frequency range is typically between 3 and 500 kHz while the wideband region ranges from 2 to 30 MHz. The narrowband region can be further divided into legally allowed frequency bands depending on continent or country:

- In Europe, CENELEC has standardized the allowed use and width of the frequency bands from 3 to 148.5 kHz. This is described in EN50065-1. The bands are further subdivided, which are generally known as "CENELEC bands"[5]:
  - Band A: 3–95 kHz. Only utilities are allowed to use this band.
  - Band B: 95–125 kHz. All may use this band.
  - Band C: 125–140 kHz. All may use this band when using CSMA.
  - Band D: 140–148.5 kHz. All may use this band.
- In USA, the FCC has established the use of band ranges from 10 to 490 kHz.
- In Japan, the ARIB defined band ranges from 10 to 450 kHz [21].

Besides the allowed frequency ranges, there is also a maximum allowed transmission power in each range that must be respected.

The first generation of PLC implementations made use of single or double carrier transmission schemes with simple modulation schemes like PSK and FSK to achieve only a few kbps towards usually remote metering applications.

G3 and PRIME are two non-SDO second generation NB-PLC technologies that focus on smart meter communication. They both use an OFDM-based modulation technique, but subtle physical layer details make the two technologies differ a bit [22]. As a general rule, PRIME achieves higher data rates while G3 has a more powerful error correction algorithm that increases reliability [22]. As seen from a higher layer perspective, the two technologies are similar. Data rates for the CENELEC A band are maximum 33 kbps for G3 and 128 kbps for PRIME.

G3 is maintained by the G3-PLC Alliance,[6] whereas PRIME is maintained by the PRIME Alliance. Both G3 and PRIME are available as open industry standards.

Even though G3 and PRIME are targeted at smart meter communication,[7] EV communication is also a valid application. As stated earlier, one of the main advantages of using narrowband communication is the usage of a dedicated "utility frequency band" and physical and MAC layers implemented in DSP software. For

[5] A total frequency range from 3 to 148.5 kHz is available for utilities whereas for end-user application the 95 to 148.5 kHz band is available.

[6] http://www.g3-plc.com.

[7] Recall that EVSEs typically contain an energy meter, which might be relevant to communicate with using G3 or PRIME. This communication might be completely separated from the EV to EVSE communication link.

this reason, companies have implemented point-to-point variants of G3 and PRIME, which are designed to communicate between two nodes, for example between an EV and an EVSE. The frequency range used in G3 can also be extended beyond the CENELEC A band to achieve higher data rates.

However, neither G3 nor PRIME was originally designed for EV/EVSE communication and they are not SDO-based. These two facts render it uncertain that they can be used without modification to the standardization work in ISO/IEC 15118-3. The IEC Smart Grid Standardization Roadmap report [23] published in June 2010 states that several communication media are being evaluated for ISO/IEC 15118-3, including G3, PRIME, HomePlug GP, and others. Therefore, it is still uncertain which PLC variant will be chosen for EV/EVSE communication.

The International Telecommunication Union (ITU) defined G.HNEM project to address home networking for energy management using high-speed OFDM NB-PLC. One of the objectives of ITU Telecommunications Sector (ITU-T) in this project was to develop a unified next generation NB-PLC. It integrates some features from PRIME and G3 which are complemented with coherent reception, enhanced protection against power line impulsive noise, multiple bands for worldwide compatibility, adaptive medium access rules, and support for multiple network protocols [24]. In this project the ITU-T targets applications such as AMI (residential or business), in-home automation and energy management (DR and Smart Appliances), and EV charging. Recommendations G.9955 and G.9956 are part of G.HNEM and define respectively the physical layer and data link layer. At the physical level CENELEC and FCC bands are supported, with up to 16QAM subcarrier modulation that enable rates up to 1 Mpbs. Forward error correction (FEC) codes are used to improve robustness against noise. The medium access method used is a prioritized CSMA/CA. Automotive support is provided allowing operation over main and pilot wires [25].

An emergent standard for narrow band PLC is P1901.2 being developed by IEEE since 2009. Defined as a low-frequency OFDM-based narrowband power line standard for smart grid applications, it is set to use frequencies below 500 kHz and data rates up to 500 kbps, supporting indoor and outdoor communications. In the outdoors scope this standard targets the use of MV and LV distribution networks for both urban and long-distance rural feeders, defining a communication medium for the WAN and FAN segments, ensuring connectivity between the electric grid and the end customer (through the smart meter). In the indoors scope the standard is an alternative technology for HAN applications. One particular application targeted for P1901.2 is the electric vehicle charging, for potentially charging stations and charging infrastructure.[8] One particular key aspect seems to be the coexistence philosophy, defined by NIST in Priority Action Plan 15, being adopted by IEEE. It aims at providing the required mechanisms to allow this technology to coexist with PRIME and G3, similarly to ITU-T within G.HNEM (G.9955 and G.9956).

---

[8] http://standards.ieee.org/develop/project/1901.2.html.

Broadband Power Line Communication

The cradle of broadband PLC implementations was the domestic environment as a technological alternative to enable Internet services to end user customers through existing power lines. The use of Broadband over Power Lines has been employed using different technologies and approaches and recently has been considered to be used outside the building environment, in what was previously referred to as Access Network.

The wideband frequency range is generally available worldwide for all purposes except in Japan, where it is illegal to use PLC in this frequency range. Technically the upper limit to wideband communication is usually dictated by the minimum communication distance and the use of TV broadcast signals above 80 MHz. Some wideband solutions use a frequency range up to 60 MHz. Naturally, a larger frequency band permits a higher number of OFDM subcarriers and thus yields higher theoretic data throughputs, although this also depends on the modulation format in the individual subcarriers. For wideband PLC a high number of subcarriers in a frequency bandwidth of 28 MHz (2–30 MHz) can be used, depending on the standard [22], compared to a narrowband where the typical number of subcarriers in the CENELEC bands is around 36 [22].

A particular implementation of BPL is HomePlug which is targeted at the domestic environment. Developed by a non-SDO industrial grouping, the HomePlug Power Alliance is responsible for the development of different versions. HomePlug defines MAC and PHY layers.

In 2001 HomePlug 1.0 was made available using DBPSK and DQPSK modulations with different FEC mechanism to achieve data rates near 14 Mbps [26]. The variant HomePlug AV [27], released in 2005 and targeted at high quality multi-stream data over power lines, uses flexible modulation schemes ranging from binary phase shift keying (BPSK) to 1024-QAM. Using FEC mechanisms along with ROBO or Adaptive Bit Loading, it enables up to 10 and 200 Mbps data rates at physical level. The HomePlug Green PHY (GP) [28] released in 2010 is a recent version that targets PLCs for in-home smart grid applications. HomePlug GP is basically a scaled-down version of the HomePlug AV, since for domestic smart grid communication context a high data throughput is not paramount. The objective is not to achieve high-performance audio/video streaming or similar applications but rather to ensure reliable and good coverage communications. HomePlug GP does not support adaptive bit loading using only QPSK as ROBO modulation scheme, to ensure high reliability, achieving up to 10 Mbps [22]. The simplifications introduced in GP make it lightweight in terms of processing power, memory, and power consumption requirements when compared to HomePlug AV.

Since GP and AV use the same frequency band, they will naturally have to share the available time-on-wire (ToW). Both technologies use CSMA and can thus access the wire if no other devices transmit. This can lead to conflicts since consumer HomePlug AV equipment will then adversely affect HomePlug GP throughput and vice versa. The HomePlug GP specification tries to solve this issue by only allowing GP devices 7 % ToW, which equals an effective data throughput of 700 kbps (at 10 Mbps base rate). This is a compromise that must be accepted when using the GP technology.

On the other hand, the sharing of bandwidth and compatibility between HomePlug AV and GP enables smart grid communication to be a part of the HAN. Some auto manufacturers see this is an opportunity to easily connect EVs to the Internet and thus provide convenient features such as GPS map updates, car software updates, intelligent call for service, etc.

Another implementation of BPL, from an SDO, can be found on IEEE 1901 standard, which defines the MAC and PHY layer for high-speed communications over power lines (>100 Mbps). The standard defines two MAC layers, targeting respectively in-home and access networks (over MV and LV distribution lines), with different requirements and potential applications. It defines two PHY layers based on different modulation schemes: one based on FFT OFDM (FFT-PHY) and another on Wavelet OFDM (Wavelet-PHY). These two implementations are not compatible and manufacturers can implement only one of them or both. The FFT-PHY can use up to 1974 carriers from 1.80 to 50 MHz with different subcarrier modulation from BPSK up to an optional 4096-QAM. The Wavelet-PHY uses 512 subcarriers within the 1.8–28 MHz band using M-PAM modulations (up to 32-PAM). Robust signaling schemes and FEC mechanisms are used to ensure resilience over the transmission medium [29].

ITU-T has also defined in 2010 a broadband PLC for home networking (G.hn) with the purpose of supporting smart grid applications such as AMI and energy management for electric vehicles. This technology can be used for robust in-home or in the last mile of the access network. It comprises the definition of the physical layer, in G.9960, and data link layer, in G.9961. It defines an OFDM transmission technique and two frequency bands: one ranging from 2 to 100 MHz with up to 1 Gbps data rate at the physical layer; and another band between 2 and 25 MHz within a Low Complexity Profile definition with data rates between 5 and 50 Mbps. Robust transmission schemes, FEC mechanisms, and repetition encoding are used to address the power line medium [30].

PLC for Smart Grids

In a smart grid context, both narrowband (high-speed) and broadband PLC technologies can be used. Both versions use multicarrier-based[9] encoding formats, the predominant being OFDM that use different modulation schemes for the subcarriers.

[9] Many (older) technologies are single-carrier based, but these are not applicable in an SG or EV context [19].

Despite implementations of wideband PLC, there are still some reasons to use a narrowband implementation[10]:

- Narrowband communication has a much larger geographical coverage than wideband, and some narrowband technologies are capable of passing through local distribution transformers. This is a huge advantage in, for example USA, where only a few households are connected to each (pole-top) transformer. This essentially deprecates wideband communication for smart meter communication. Currently, around 100 million narrowband PLC smart meters have been deployed [19] and the future potential is huge.
- Regulations limit the use of wideband PLC in some countries, e.g., Japan. The only worldwide available frequency band is the CENELEC narrowband.
- Narrowband has dedicated frequency bands not used by consumer PLC electronics in the HAN. This comfortably ensures that consumer PLC products do not adversely and unpredictably affect noise and data throughput for smart grid-related communication purposes.
- Narrowband solutions are still cost-effective when compared to the broadband counterpart since in general they require less demanding HW implementations.
- Not all applications require high data throughput.

On the other hand, wideband solutions can be preferred for the following reasons:

- Achieves higher data throughputs when the data is only transmitted over a short distance, e.g., in a HAN. In general, wideband PLC is the only practically acceptable solution for a HAN (other than wireless and dedicated wiring).
- More than 45 million devices use HomePlug-based devices [22], so it is almost as widespread as narrowband PLC solutions and the future potential is huge. A large number of wideband PLC devices are available off-the-shelf.
- There is generally less noise in the 2–30 MHz frequency range. One reason is the low-pass filters in, for instance, switch mode power supplies that attenuate high-frequency noise. This makes it easier to achieve high data rates.
- Using recent wideband PLC advances in, e.g., HomePlug GreenPHY, robust modulation formats (known as ROBO) have shown to increase transmission reliability at the expense of lower data rate. However, the data rate can still be up to 10 Mbps [22].

This shows that the choice between narrowband and wideband PLC is not straightforward and must be assessed on a case-by-case basis.

For the particular case of EV/EVSE PLC communication, it is obvious that the communication distance to the HAN is small and thus a wideband solution might be viable, which will also yield high data rates. On the other hand, EVs and EVSEs should clearly be a part of the future smart grid communication infrastructure and

[10] Adapted from [19].

thus a narrowband solution that is separated from consumer (wideband) PLC solutions and that is able to communicate directly to utilities or aggregators might be preferable.

5.3.2.4 Wireless Technologies

We start by briefly analyzing the main advantages and limitations of using wireless technologies in the last mile segment, which includes devices located in critical points of the electric grid, such as sensors and controllers, and in end-users premises, such as smart meters, as well as traffic aggregators and concentrators located in transmission and distribution substations.

Among the main advantages we can mention the low cost and ease of installation, maintenance and future expansion, support for mobility and interoperability, as well as flexibility, since the location of access points (nodes) that provide wireless access to end devices is not constrained by an existing physical infrastructure, as in PLC. However, the location and number of such wireless nodes may require a careful planning to overcome potential problems that typically arise in WMNs, as will be discussed.

The main disadvantages of adopting wireless technologies are related with the adverse characteristics of wireless channels (bit error ratios are much higher than in guided media), which are aggravated by the time varying conditions of the channels and interference.

On the other hand, different technologies are quite different as far as cost, coverage (which, among other factors depends on the maximum allowed emission power), spectrum (free or licensed bands), available bandwidth, and how it is shared (which impacts the useful throughput, both aggregate and per user). Some of these problems are aggravated in WMNs, as said; nevertheless, WMNs also have some interesting properties that make them suitable for smart grid environments. Moreover, there are also some challenges as far as performance, interoperability, and security that have to be addressed.

IEEE 802.11/Wi-Fi

The IEEE 802.11 group has specified over the past years a set of standards [31] for low cost wireless LANs with the aim of providing a service similar to wired Ethernets. Two modes of communication are possible: in the infrastructure mode the stations communicate through an Access Point (AP) typically connected to a wired network, while in the ad hoc mode the stations communicate directly without the intervention of an AP.

Multiple alternatives are available at the Physical Layer, either employing direct sequence spread spectrum (DSSS) or orthogonal frequency division multiplexing (OFDM) in the 2.4 and 5 GHz non-licensed ISM (industrial, scientific, and medical)

Table 5.4 IEEE 802.11 variants

	802.11	802.11a	802.11b	802.11g	802.11n
Bandwidth (MHz)	20	20	20	20	20/40
Frequency band (GHz)	2.4	5	2.4	2.4	2.4/5
Number of channels	3	12	3	3	Up to 13
Modulation	BPSK, QPSK DSSS, FHSS	BPSK, QPSK MQAM, OFDM	BPSK, QPSK DSSS	BPSK, QPSK MQAM, OFDM	BPSK, QPSK, MQAM
Maximum rate (Mbps)	1.2	54	11	54	600
Maximum range (m)	–	30	75–100	75–100	150–180
MAC Protocol			CSMA/CA		

bands. At the MAC layer a carrier sense multiple access with collision avoidance (CSMA/CA) protocol is adopted. The IEEE 802.11n amendment [32] introduced improvements at the Physical layer that allow a higher throughput and coverage than its predecessors. Other IEEE 802.11 documents address specific aspects, such as security improvements (802.11i), support for Quality of Service (802.11e), WMNs (802.11s), and vehicular communications (802.11p).

The IEEE 802.11standard is promoted by the Wi-Fi Alliance [33], which has favored the widespread availability and deployment of this technology, at low cost; it is thus becoming ubiquitous in traditional LAN environments, hot spots, and making progress into wider areas that may include traditional last mile scenarios.

The principal characteristics and differences of the IEEE 802.11 variants are summarized in Table 5.4.

IEEE 802.15.4/ZigBee

The IEEE 802.15.4 standard [34] was specified for low-data-rate, low-power, and low-complexity short-range radio frequency transmissions between devices in wireless personal area networks (WPAN). These networks include full-function devices (FFD) that may operate as coordinators (which are devices capable of relaying messages) and talk to any other device, and reduced-function devices (RFD), which are intended to run simple applications, may have power constraints, and can only talk to an FFD.

The standard specifies the physical and MAC layer functions and protocols. The physical layer is based on the DSSS technique combined with different modulation schemes, on different bands. In particular, in the ISM 2.4 GHz band, offset quadrature phase shift keying (O-QPSK) is employed, achieving a rate of 250 kbps. At the MAC layer, CSMA/CA is adopted.

The standard defines two topologies. The star topology is established between RFDs and the PAN coordinator, which is an FFD. In the distributed peer-to-peer topology devices can communicate directly, provided they use the same radio channel; this allows more complex configurations, such as mesh structures, which are useful for example in sensor networks or in monitoring and control applications (interconnection of smart meters falls in this category).

The ZigBee Alliance [35] is promoting the use of networks based on this standard, having defined a complete stack on top of the IEEE 802.15.4 Physical and MAC layer services.

IEEE 802.16/WiMAX

The IEEE 802.16 standard [36] specifies the Physical and MAC layers of the radio interface of combined fixed and mobile point-to-multipoint broadband wireless access (BWA) systems.

The MAC layer is structured to support different Physical layers suited for particular operational environment, in two frequency bands.

In the 10–66 GHz band, line-of-sight (LOS) is required; single carrier modulation is adopted, typical channel bandwidths are in the order of 25 MHz, and raw data rates in excess of 120 Mbps are possible. Both frequency division duplex (FDD) and time division duplex (TDD) modes are supported.

In the frequency bands below 11 GHz LOS is not required and different alternatives are specified, both in licensed and license-exempt bands. In the latter case the 5–6 GHz range is primarily used and additional interference and compatibility issues and radiated power constraints are taken into account. Both OFDM for fixed wireless access and OFDMA (orthogonal frequency division multiple access) for fixed and mobile systems are specified, with both duplexing alternatives (FDD and TDD), and typical channel bandwidths of 10 and 20 MHz. The maximum channel rates depend on various factors (radio technology, duplexing mode, channel bandwidth, distance) but values in the order of 140 Mbps are achievable. Channel rates more than double with improvements at the Physical layer and antenna design, according to IEEE 802.16m amendment that is intended for an advanced air interface.

The WiMAX Forum [37] certifies and promotes the compatibility and interoperability of broadband wireless products based upon the IEEE 802.16 standard.

Wireless Mesh Networks

Among other possible applications, WMN are used as a means of extending the wireless coverage of single hop networks and provide access to infrastructure networks (either wired or wireless). The requirements of last mile smart grid networks may fall in this category and thus WMNs are currently being considered as a feasible and promising alternative to PLC.

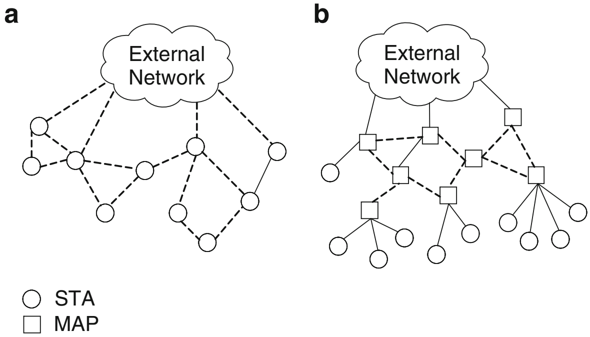


Fig. 5.21 Wireless mesh networks topologies

In the simplest case, a WMN may be formed by end-stations (STA) only. However, a more structured, robust, and scalable solution is possible if the wireless network is organized in two tiers: at the higher level a set of mesh access points (MAP) are interconnected in a mesh fashion, forming a wireless mesh backbone, while the end-stations reside at the lower level and communicate with a neighbor MAP to gain access to the network. The higher level is in fact a cooperative mesh network that enables information to be relayed between source and destination nodes; one or more MAPs act as gateways to external networks. As a third alternative, MAPs and end-stations may form a hybrid mesh network. These three arrangements are depicted in Fig. 5.21.

When WMNs are used as an infrastructure extension, the internal traffic between MAPs is limited since the main services are usually provided by external networks, with a considerable amount of information exchanged through a gateway MAP. In smart grids the expected traffic patterns seem to be compatible with such type of WMN—traffic aggregation is performed along the path towards a gateway MAP, which is the concentrator point for the traffic exchanged with external networks.

Since these networks are meshed by nature they offer a degree of redundancy and thus robustness in the data path in case of a node loss or link quality degradation, either temporary or permanent. As such, routing algorithms must take into account the proper metrics to deal with these issues, by dynamically adapting to topology changes or varying channel conditions in order to determine the best routes. The use of complex routing schemes at the network layer can have a beneficial impact, especially in the case of non-homogenous data traffic patterns, but at the cost of introducing additional overheads, when compared to its implementation at the data link layer. In the latter case, the use of bridging techniques implies that packets are simply forwarded by mesh nodes along a logical tree; this simplification comes at the price that the routes followed by some packet flows may not be the best ones. However, this drawback does not arise when most of the traffic is exchanged between end devices and external networks. This is the typical situation in smart grids and thus the use of bridging techniques may be an advantage in case WMNs are adopted in this environment.

However, WMNs also have some drawbacks that must be solved or mitigated through additional mechanisms on top of the native MAC service provided by the specific wireless technology adopted.

In shared medium wireless networks such as IEEE 802.11 and 802.15.4 competition among end devices is handled by the CSMA/CA contention-based mechanism. However, collisions may still occur and trigger retransmissions that cause additional delays; under heavy traffic this may lead to serious throughput degradation, uncontrolled delays, and even losses.

The multi-hop nature of WMNs introduces new challenging problems. In the first place, the existence of multiple hops in the data path means that delay increases with the number of hops; moreover, when most of the traffic is exchanged through a gateway, competition for wireless resources and the risk of congestion are higher in nodes closer to the gateway, because they have to forward all aggregated traffic generated by upstream nodes. This not only causes additional throughput degradation but also unfairness among nodes, since nodes farther away from the gateway have to contend for the channel a higher number of times—besides a higher delay, they may suffer severe throughput degradation and even starvation, since successive collisions on each hop contribute to a higher probability of packet loss. These problems may be diminished if it is possible to reduce the number of hops by means of carefully planning the location of mesh nodes.

But WMNs introduce an additional problem, not found in wired store-and-forward networks. Besides inter-flow interference, collisions also occur due to intra-flow interference; spatial contention extends beyond one hop distance and thus only one packet of a given flow can be successfully transmitted within a neighborhood region of the sending node. This contributes to further reducing the capacity of a WMN and thus requires exploitation of spatial reuse techniques to optimize the use of wireless resources, which is not trivial.

The practical exploitation of WMNs thus requires solving a number of problems deeply analyzed in the literature, such as fairness [38], scheduling schemes (with, for example, fair sharing [39, 40] or resource optimization [41] as the main goal), cross-layer mechanisms (that combine scheduling with congestion control [42]), etc.

The use of WMN in a smart grid context has a few characteristics that can simplify the implementation. First of all, there is no mobility inside this kind of networks; once an end device or mesh node is deployed for the first time it is very likely to stay at the same position for a long time. Second, since most of the end devices are part of an electric network there are almost no constraints regarding power supply, although a blackout might require a battery backup even if for short periods of time. Third, the adoption of a two-tiered approach may require a limited number of mesh nodes and a moderate number of hops in the data path and thus the need for less complex overlay mechanisms than those required in large WMNs. Fourth, it requires the roll-out of simpler and less costly infrastructures (for instance, based on IEEE 802.11, possibly combined with IEEE 802.15.4), when compared with other solutions, such as WiMAX, for example, which is best suited for point-to-multipoint communications in back-haul networks.

5.4 Conclusions

This chapter addressed ICT solutions and supporting communications for Smart Grids that will enable the integration of different players and entities such as the EV.

It is clear that the ICT foundation already exist to start supporting diverse SG concepts and applications tailored for EVs. ICT implementations need to account for the requirements for different applications and consider different models and scenarios as described in this chapter. Despite the lack of a general solution for SG, the combination of existing technologies for different segments, paired with specific solutions, is already able to address SG communication requirements.

The deployment of smart grids is an evolutionary process and the planning, design, deployment, and operation of ICT solutions for smart grids must take into account the full scenarios even if only a subset of functions are initially supported.

The importance of interoperability between devices from different manufactures is also clear, in order to ensure expansion capabilities in the future, with seamless integration of new systems and applications.

Except for very specific cases, the rule should not be designing and optimizing solutions for specific applications, but rather a globally integrated approach should be taken into account—sharing information and communication resources is not only more efficient but also eases interoperability in integration, thus saving costs.

Interoperability at the IP level is the current trend—in particular IP is agnostic to the underlying communication technologies and supports a wide diversity of applications.

It is likely that in a smart grid environment, in particular in the last mile segment, a diversity of communications technologies will be adopted since:

- Diversity minimizes risks.
- Different technologies may coexist and complement each other, benefiting from their abilities to handle specific problems (e.g., different technologies and solution may be adopted in rural areas as opposed to dense urban zones).
- Emerging and future technologies will be introduced as they mature, either coexisting with legacy ones or replacing them.

Currently there is a need for pilot trials to evaluate and compare solutions based, among others, on performance, cost, scalability, flexibility, and robustness, to better understand open issues and to help defining a roll-out strategy.

References

1. RWE Mobility. www.rwemobility.com
2. Electric vehicles in a distributed and integrated market using sustainable energy and open networks – EDISON. www.edison-net.dk
3. The grid-integrated vehicle with vehicle to grid technology. http://www.udel.edu/V2G/

4. International Electrotechnical Commission (IEC) TC57 WG 15 (e.g. IEC 62351). http://tc57.iec.ch
5. NIST (2010) NIST framework and roadmap for smart grid interoperability standards, release 1.0. Office of the National Coordinator for Smart Grid Interoperability
6. European Technology Platform, Smart Grids (2010) Strategic deployment document for Europe's electricity networks of the future
7. EPRI (2009) Report to NIST on smart grid interoperability standards roadmap
8. Khalifa T, Naik K, Nayak A (2011) A survey of communication protocols for automatic meter reading applications. IEEE Commun Surv Tutor 13(2):168–182
9. IEEE (1998) IEEE standard for utility industry end device data tables. IEEE Std 1377(1997):i
10. Department of Energy (2010) Communications requirements of smart grid technologies
11. Open Smart Grid (Open SG) (2010) SG network system requirements specification, interim release 3, 17 May 2010
12. Peças Lopes JA, Moreira CL, Madureira AG (2006) Defining control strategies for microgrids islanded operation. IEEE Trans Power Syst 21(2):916–924
13. Gil NJ, Peças Lopes JA (2007) Hierarchical frequency control scheme for islanded multi-microgrids operation. In: Proceeding of IEEE power tech, Lausanne, 1–5 July 2007, pp 473–478
14. Peças Lopes JA, Soares FJ, Rocha Almeida PM (2011) Integration of electric vehicles in the electric power system. Proc IEEE 99(1):168–183
15. IEEE (2011) IEEE guide for smart grid interoperability of energy technology and information technology operation with the electric power system (EPS), end-use applications, and loads. IEEE Std 2030–2011, pp 1–126, 10 Sep 2011
16. NIST (2009) The role of the internet protocol (IP) in AMI networks for smart grid. NIST Priority Action Plan, Jun 2009
17. Baker F, Meyer D (2011) Internet protocols for the smart grid. Request for comments RFC 6272, IETF, Jun 2011
18. Scholer R. Standards status ISO/IEC & SAE. http://www.pointview.com/data/2011/05/51/pdf/Rich-Scholer-KEPKKETS-11326.pdf
19. Galli S, Scaglione A, Wang Z. Power line communications and the smart grid
20. Tonello A, Katayama M (2011) Power line communications for the smart grid, Brussels
21. Low frequency, narrowband PLC standards for smart grid. http://cms.comsoc.org/SiteGen/Uploads/Public/Docs_Globecom_2009/6_-_12-03-09_shaver_smart_grid_panel_final.pdf
22. Hoch M (2011) Comparison of PLC G3 and PRIME. In: IEEE international symposium on power line communications and its applications, 2011
23. IEC (2010) IEC smart grid standardization roadmap
24. Oksman V, Zhang J (2011) G.HNEM: the new ITU-T standard on narrowband PLC technology. IEEE Commun Mag 49(12):36–44
25. Oksman V (2011) New ITU-T recommendations for smart grid in-home access communications. Presentation, April 2011
26. HomePlug Powerline Alliance (2001) HomePlug 1.0 white paper
27. HomePlug Powerline Alliance (2005) Home Plug AV white paper
28. HomePlug Powerline Alliance (2010) HomePlug green PHY white paper- Home Plug green PHY, The standard for in-home smart grid powerline communications
29. IEEE standard for broadband over power line networks: medium access control and physical layer specifications. IEEE Std 1901–2010, pp 1–1586, 30 Dec 2010
30. ITU-T (2010) Series G: transmission systems and media, digital systems and networks, applications of ITU-T G.9960, ITU-T G.9961 transceivers for Smart Grid applications: advanced metering infrastructure, energy management in home and electric vehicles, June 2010
31. IEEE 802.11-2007. IEEE standard for information technology – telecommunications and information exchange between systems – local and metropolitan area networks – specific requirements – part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications

32. IEEE 802.11n-2009. IEEE standard for information technology – telecommunications and information exchange between systems – local and metropolitan area networks – specific requirements – part 11: wireless LAN medium access control (MAC) and physical layer (PHY) specifications – amendment 5: enhancements for higher throughput
33. The Wi-Fi Alliance. http://www.wi-fi.org/
34. IEEE 802.15.4-2006. IEEE standard for information technology – telecommunications and information exchange between systems – local and metropolitan area networks – specific requirements – part 15.4: wireless medium access control (MAC) and physical layer (PHY) specifications for low rate wireless personal area networks (LR-WPANs)
35. The ZigBee Alliance. http://www.zigbee.org/
36. IEEE 802.16-2009. IEEE standard for local and metropolitan area networks – part 16: air interface for broadband wireless access systems, May 2009
37. The WiMAX Forum. http://www.wimaxforum.org/
38. Gambiroza V, Sadeghi B, Knightly E (2004) End-to-end performance and fairness in multihop wireless backhaul networks. In: MobiCom'04 - tenth annual international conference on mobile computing and networking, Philadelphia, USA, 26 Sept–1 Oct 2004, pp 287–301
39. Ernst J, Denko M (2011) The design and evaluation of fair scheduling in wireless mesh networks. J Comput Syst Sci 77(4):652–664
40. Lee J, Kuo W (2010) Fairness provisioning in multi-hop wireless backhaul networks: challenges and solutions. Comput Commun 33(15):1767–1772
41. Gupta G, Shroff N (2010) Practical scheduling schemes with throughput guarantees for multi-hop wireless networks. Comput Netw 54(5):766–780
42. Akyol U, Andrews M, Gupta P, Hobby J, Saniee I, Stolyar A (2008) Joint scheduling and congestion control in mobile ad-hoc networks. In: INFOCOM 2008 - 27th annual IEEE conference on computer communications, Phoenix, USA, 13–18 April 2008, pp 619–627
43. ISO/IEC (2011) Road vehicles—vehicle-to-grid communication interface - part 2: technical protocol description and open systems interconnections
44. Pedersen AB, Hauksson EB, Anders PB, Poulsen B, Træholt C, Gantenbein D (2010) Facilitating a generic communication interface to distributed energy resources mapping IEC 61850 to RESTful services. IEEE SmartGridComm 2010

Chapter 6
Advanced Models and Simulation Tools to Address Electric Vehicle Power System Integration (Steady-State and Dynamic Behavior)

F.J. Soares, P.M. Rocha Almeida, and João A. Peças Lopes

6.1 Introduction

This chapter is intended to identify grid operational management and control strategies that should be available to deal with a large-scale deployment of electric plug-in vehicles (EVs). EVs are high flexible loads that can be used as mobile storage devices, thus being capable of providing several power system services [1]. In fact, EV batteries when in charging mode can behave as controllable loads, providing spinning reserves as a result of a load decrease or even providing power back to the grid under the so-called vehicle-to-grid (V2G) mode, helping peak load demand management. In this way, the growing prospects of an EV market expansion may strengthen the concepts that aim at the active grid management.

Future deployment of EV should also consider the fact that the power system of the future is facing considerable challenges due to the large-scale integration of distributed generation (DG) [2], which brought new technical, commercial, and regulatory challenges to the power systems. In the beginning, DG integration to the distribution system was made on the basis of a "fit-and-forget" policy. Consequently, while the penetration of DG was moderate, these generation units were regarded as passive elements within the power system.

In order to accommodate these changes, active management solutions were sought to deal with more DG, breaking with the conventional paradigm, being created new concepts such as those of microgrid (MG) and multi-microgrid (MMG) [3, 4]. Within this new paradigm, MG can be defined as low-voltage (LV) feeders with several microsources (such as microturbines, micro wind generators, photovoltaic panels, etc.) together with storage devices and controllable loads connected on that same feeder and managed by a hierarchical control system. EV will then become as an additional actor within these new grid concepts.

F.J. Soares (✉) • P.M.R. Almeida • J.A. Peças Lopes
INESC TEC (Formerly INESC Porto), Porto, Portugal
e-mail: filipe.j.soares@inescporto.pt; pedro.r.almeida@inescporto.pt; jpl@fe.up.pt

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_6,

Under this vision, the management and control architecture for the distribution networks would then follow a hierarchical control structure, with a central controller unit for each control level, one at the high voltage (HV), other at the MV, and the other at the LV. So, if properly managed, EV may integrate these concepts and create the opportunity of further DG integration expansion.

This chapter focuses on the effects and benefits of EV and EV active management on the power systems, both in steady-state and dynamic operation modes. Major synergies between utilities and EV owners are envisioned through means of cost reduction for both parties. By adopting adequate strategies, several benefits for the environment, quality of life, and social welfare may be achieved.

This chapter addresses the following issues:

- *Definition of a specific EV integration framework*: Moving from a "fit-and-forget" policy to the active EV management and control implies the creation of a conceptual framework. This framework should be able to deal with the technical aspects of electricity grid operation, with market operation. This will require an advanced communication infrastructure to link all the involved players. The technical operation layer considered under this framework is supposed to be managed by the distribution system operator (DSO) and expands the concepts of MG and MMG to establish a hierarchical control structure, from the central distribution management system (DMS) down to specific EV controllers to be housed in EV charging points. For the market layer, a new player will have to be considered for aggregating EV and represent them in the electricity and reserve markets. This layer should have a similar hierarchical structure to the technical layer, in order to be able to share the communication path and control entities.
- *Development of an approach to create different load scenarios to evaluate EV grid impacts*: This approach will include a stochastic model to simulate the EV movement in a geographic region, as well as their owners' behaviors, and a Monte Carlo simulation method to create the different scenarios of EV load in a given network. The analysis of a large number of scenarios generated with the Monte Carlo simulation method is of utmost importance for an accurate evaluation of the grid impacts provoked by EV presence, namely in what concerns branches' overload, voltage profiles, and networks' energy losses.
- *Development of charging management strategies, involving the exploitation of the EV high controllability*: These new strategies can be used in real-time applications to solve the technical problems identified and to maximize the number of EV that can be safely integrated in the system, without performing any network reinforcements. These management strategies should, however, take into account the drivers' requests concerning the foreseen use of the vehicles, assuming for that purpose the existence of some smart grid functionalities, like smart-metering and a reliable and efficient communication platform.
- *Development of an approach to identify the maximum number of EV that can be integrated in a given network without provoking violations of its components'*

technical limits: This approach will be developed taking into consideration both uncontrolled and controlled EV charging modes.

- *Participation of EV in primary frequency control*: In isolated systems, load/generation imbalances may lead to large frequency deviations. If EVs, when connected to grid, are capable of adjusting their charging rates or even to inject power into the grid as a response to frequency changes, increased robustness of operation will be achieved. Such a control approach should be able to allow further integration of intermittent RES in these systems.
- *Participation of EV in the Automatic Generation Control (AGC)*: EV may be integrated in the AGC operation, providing secondary frequency control and reducing the dependency on the conventional secondary reserves, which may also lead to an increase in variable renewable power sources into the electrical system.

6.2 Models for Studies of Electric Vehicle Integration in the Electrical Power System

6.2.1 Charging Methods

EV batteries are loads with unique characteristics, medium-to-high power consumption over a given period of time and with some degree of predictability. Such features can either be disregarded, and EVs are faced as regular loads, or they can be exploited and then specific EV charging strategies might be defined to take advantage of these unique characteristics.

There are several types of charging solutions being currently adopted [5], which involve distinct power levels:

- *Level 1*: Around 3 kW charging power that can be obtained through common domestic outlets.
- *Level 2*: 10–20 kW charging power that can be obtained only through dedicated charging outlet and wiring.
- *Level 3*: More than 40 kW charging power that can be obtained only through dedicated charging outlet and wiring and using a dedicated off-board charger for DC fast charging.

The charging type commonly classified as slow charging refers to level 1, whereas the fast charging refers to level 3. Level 2 is an intermediary level that can be considered either as a slow or a fast charging type. Slow charging is assumed to correspond to level 1, while fast charging includes both level 2 and 3.

Depending on the type of application, EV controllability may vary, and, therefore, several control schemes may be adopted. There are different solutions, which may arise according to EV owners' needs, namely the following:

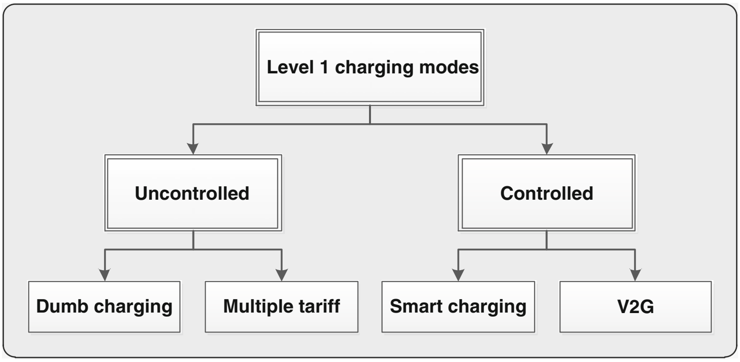


Fig. 6.1 Level 1 charging modes

- *Domestic or public individual charging points for slow charging*: This solution is the most suited for controlled charging, as EV parked in these places will remain there for longer periods (overnight stays if it is a residential area or during working period while in industrial/commercial areas). These charging points are expected to use level 1 charging rates.
- *Charging stations dedicated to fleets of EV*: This solution presents high controllability potential if EV can be charged in level 1 charging mode, as fleets of vehicles (such as buses or trucks) typically have well-known mobility patterns. When level 2 or 3 charging is required, charging management cannot be performed.
- *Public individual charging points for medium charging rates*: This solution is not suited for controlled charging, as EV parked in these places will remain there for relatively short periods (in public parking lots or in commercial areas like malls). These charging points are expected to use level-2 charging rates.
- *Battery swapping stations*: For this solution, controlled charging procedures may be defined depending on the existing battery stock on the station. Both slow (level 1) and fast (level 2 or 3) charging methods can be used depending on the specific demand patterns and on the available stock per station.
- *Fast charging stations*: As dedicated fast charging stations, this solution is not suitable for control actions due to the need of having a full charge in the minimum time span possible. The fast charging stations are expected to use level-3 charging rates.

In the solutions involving fast charging (level 2 or 3), a full charge might take <1 h [5]. Due to the urgent needs from the user of these types of services, especially level-3 clients, no controllability is envisaged. On the other hand, depending on the EV battery state of charge (SOC) and capacity, full charge solutions involving level 1 might take up to 12 h [5]. Within this charging alternative, it is assumed that EV owners can choose between a set of four charging options, two passive or uncontrolled (dumb charging and multiple tariff) and two active or controlled (smart charging and V2G), as shown in Fig. 6.1.

6.2.1.1 Dumb Charging

This is an uncontrolled charging mode where EV can be freely operated having no restrictions or incentives to modulate their charging. Therefore, EVs are regarded as normal loads, like any other appliance. In dumb charging mode, it is then assumed that EV owners are completely free to connect and charge their vehicles whenever they want.

The charging starts automatically when EVs plug in and lasts until its battery is fully charged or charge is interrupted by the EV owner.

In addition, electricity price for these EV users is assumed to be constant along the day, what means that no economic incentives are provided in order to encourage them to put their vehicles charging during the valley hour when the grid operating conditions are more favorable to an increment in the energy consumption.

For scenarios of large EV deployment with a considerable number of dumb charging adherents, it is very likely that EV load provokes several technical problems on the grid (potential large voltage drops and branches overloading).

The only way to tackle the foreseen problems is then to reinforce the existing generation system and grid infrastructures and plan new networks in such way that they can fully handle EV grid integration. Yet this is a somewhat expensive solution that will require high investments in network infrastructures and generation facilities.

6.2.1.2 Multiple Tariff

As in the previous approach, the dual tariff policy assumes that EV owners are completely free to charge their vehicles whenever they want.

However, electricity price is assumed not to be constant along the day for EV users, existing some periods where its cost is lower.

This method is based on the already existing approach where, during valley hours (normally during the night), electricity price is lower. However, as this is not an active management strategy, the success of this method depends on the EV owner willingness to take advantage of this policy. In this case only part of the EV load eventually would shift toward valley hours.

This solution could have been included in the controlled EV charging/discharging approaches, but as this type of control is not directly imposed to EV, it is considered an uncontrolled charging approach.

It should be taken into account that the economic signals provided to EV owners with the multiple tariff policy might have a perverse effect in scenarios characterized by a high integration level of EV.

It might happen that a big number of EV connect simultaneously in the beginning of the periods when the electricity cost is lower, making the grid reach its technical limits.

6.2.1.3 Smart Charging

The smart charging strategy envisions an active management system where there exists a hierarchical control structure headed by an EV aggregating entity that is used to control the EV charging rates.

However, as it will be explained later on this chapter, EV will only be exclusively managed and controlled by the EV aggregators when the grid is operating in normal conditions.

The EV aggregators' main functionality will be grouping EV to exploit business opportunities in the electricity markets, always taking into account the EV owners' charging requests. They will monitor all the EV under their domain, providing power or requesting from them the services that they need to cope with what was previously defined in the markets' negotiations.

As electricity markets are not usually present in small isolated systems, like the ones from small islands, the existence of EV aggregators is not required. In these situations, the smart charging should be controlled by the DSO.

This type of EV charging management is likely to provide the most efficient usage of the resources available at each moment, since EV aggregators will naturally try to buy electricity during valley hours in order to provide energy at a lower cost to their clients. Therefore, the EV aggregators' market actions are likely to naturally enable overload prevention and excessive voltage drops, avoiding the need to invest largely in network reinforcements.

This charging approach also enables EV to provide several ancillary services, like reserves, since they can increase/decrease their charging rates in order to deliver upward/downward reserves. EV aggregators are thus capable of also negotiating reserve provision in the respective electricity markets.

6.2.1.4 Vehicle-to-Grid

This approach is an extension of the previous one where, besides the charging, the EV aggregators control also the power that EV might inject into the grid.

In the V2G mode of operation, both EV load controllability and storage capability are exploited. From the grid perspective, this is the most interesting way of using EV capabilities given that besides helping managing branches' overloading and voltage-related problems in some problematic spots of the grid, EV have also the capability of providing peak power in order to make the energy demand more uniform along the day.

Nevertheless, there are also some drawbacks related to the batteries' degradation that need to be accounted for. Batteries have a finite number of charge/discharge cycles, and its usage in a V2G mode might represent an aggressive operation regime due to frequent shifts from injecting to absorbing modes. Thus, the economic incentives to be provided to EV owners must be even higher than that in the smart charging approach, so that they cover the battery damages owed to its extensive use.

As in the smart charging, EVs that adhere to the V2G mode are also capable of providing several ancillary services to the system. As besides adjusting their charging rates, EVs are also capable of injecting power into the grid. This operating mode provides then more flexibility to the EV aggregators regarding reserve provision negotiations in the market, namely in what concerns downward reserves.

6.2.2 Structure of Control

6.2.2.1 Electric Vehicle Integration in Interconnected Systems

The technical management of an electric power system having a large-scale deployment of EV will require, for their battery charging, a combination of a centralized hierarchical management/control structure with a local control located at the EV grid interface.

The simple use of a smart device interfacing the EV with the grid does not solve all the problems arising from EV integration in distribution networks. These interfaces can be rather effective when dealing with the likely occurrence of voltage drops that may be caused by EV charging, by locally decreasing charging rates through a voltage droop control approach. However, this local solution fails to address issues that require a higher control level, such as managing branches' congestion levels or enabling EV to participate in the electricity markets. For these cases, coordinated control is required, and so a hierarchical management and control structure responsible for the entire grid operation, including EV management, must be available. Therefore, the efficient operation of such a system depends on the combination/coordination of local and centralized control modes. The latter control approach relies on the creation of an adequate communication infrastructure capable of handling all the information that needs to be exchanged between EV and the central control entities organized in a hierarchical structure.

When operating the grid in normal conditions, EVs will be managed and controlled by a new (central) entity—the aggregator—whose main functionality will be grouping EV, according to their owners' willingness, to exploit business opportunities in electricity markets [6, 7]. If EV would enter this market individually, their visibility would be small and, due to their stochastic behavior, rather unreliable. Nonetheless, if an aggregating entity exists, with the purpose of grouping EV to enter in the market negotiations, then the services provided would be more significant and the confidence on its availability much more accurate.

Nevertheless, even considering the EV aggregators' activities, a still high degree of uncertainty will exist related to when and where EV will charge, namely in LV grids. Due to these uncertainties and assuming that networks will evolve toward a decentralized generation paradigm, the existence of a grid monitoring structure, such as the one developed for MG and MMG, will be expected. This structure will be controlled by the DSO and should be capable of acting over EV charging in

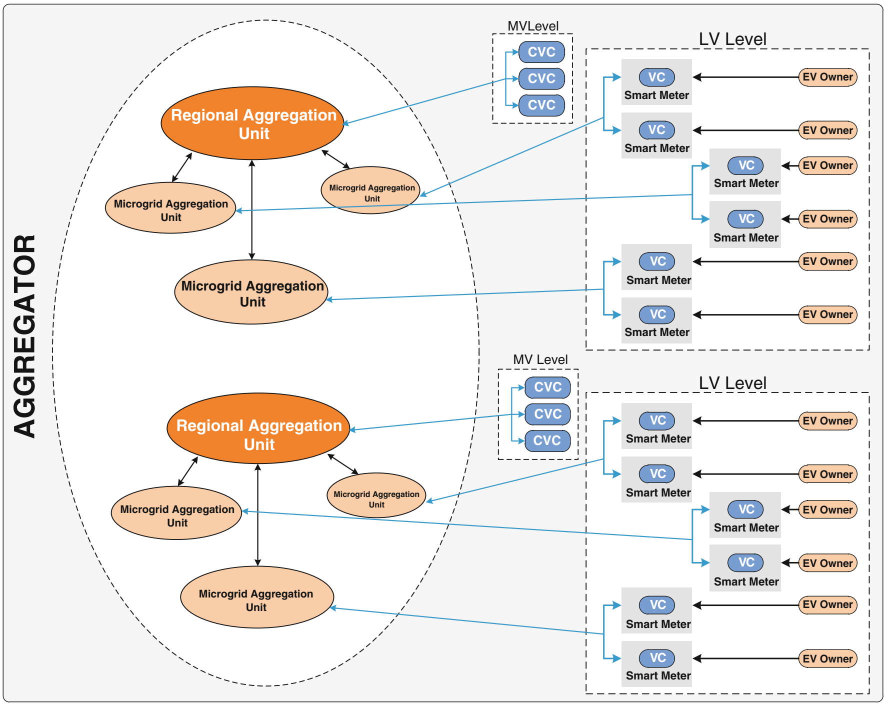


Fig. 6.2 Aggregators' hierarchical management structure

abnormal operating conditions, i.e., when the grid is being operated near its technical limits, or in emergency operating modes, e.g., islanded operation [8].

Normal System Operation

In order to manage a large amount of EV parked in a large geographical area, where MV and LV grids exist, the existence of aggregators will be necessary, in order to serve as an interface between EV and electricity markets. These aggregators will have the capability of grouping EV so that together they represent a load/storage device with the adequate size to participate in electricity markets, in a similar way as described in [6]. It is important to stress that the aggregator will always take into account the drivers requests, which will provide information about power demand and connection period via the smart meter. In the same regional area, several aggregators might coexist and compete to gather as much clients as possible. This competition will be beneficial for the EV owner who will be able to choose for his aggregator the company that better fits his needs.

Given the complexity of the information that an aggregator needs to collect and process, a hierarchical management structure, independent of the DSO, is suggested (Fig. 6.2).

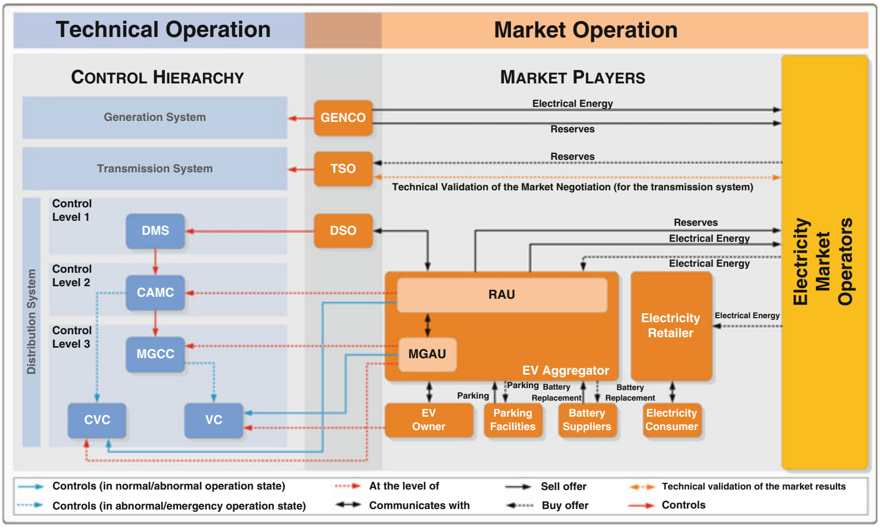


Fig. 6.3 Technical management and market operation framework for EV integration in interconnected systems

Since each aggregator develops its activities along a large geographical area, e.g., a country, it will be composed of two different entities: the regional aggregation unit (RAU) and the micro-grid aggregation unit (MGAU). The RAU is considered to be located at the HV/MV substation level, communicating with several downstream MGAU, which, by their turn, will be located at the MV/LV substation level. The RAU and the MGAU were created in order to decrease communication and computational burden that a real implementation of the concept would require. This will provide the aggregator preprocessed information regarding groups of EV located in the LV and MV grids. Each EV must have a specific interface unit—the vehicle controller (VC)—to enable bidirectional communication between the EV and the upstream aggregator. The VC may be located in the smart meter to which EV will be connected and the smart metering communication infrastructure should be used to support this architecture. In addition to the VC, there is a new type of element, the cluster of vehicles controller (CVC), designed to control the charging of large parking lots (e.g., shopping centers), and fed directly from the MV network. Individual controllers of EV under a CVC management do not need to have an active VC communicating with higher hierarchical controllers. During normal operation, the VC will interact with the MGAU and the CVC directly with the RAU [7].

The market operation column in the right-hand side of Fig. 6.3 presents an overview of the aggregators' market activities.

Based in historical data, the aggregators will forecast the market behavior for the next day and will prepare their buy/sell bids. Having this defined, a prior negotiation with the DSO might exist to prevent the occurrence of severe congestion and voltage problems in the distribution networks. The aggregators will thus present their day-ahead proposal to the DSO, which will analyze it to evaluate its technical feasibility. If valid, the aggregator can proceed to the market negotiation. If not, the DSO will ask the aggregator to make the changes needed to guarantee a safe operation of the distribution grid in the next day. It is foreseeable that in this case, the DSO will have to compensate the aggregator for this service.

If market prices of electricity are cost reflective (i.e., include the cost of electricity generation, transmission, and distribution), a direct consequence of the hourly energy prices variation will be the flattening of the daily load diagram. As response to the energy prices, aggregators will naturally perform load shifting in order to provide energy at a lower cost to their clients. They will buy electricity from the market mainly during the night, at lower prices, to charge their clients' EV, and they may sell it during the day, at peak hours, taking advantage of their clients' EV storage capability. Aggregators will then compete directly with electricity retailers for energy acquisition and with Generation Companies (GENCO) for selling energy.

Taking advantage of EV capability to provide reserves, EV might also offer in the electricity markets these systems' services to the transmission system operators (TSO), competing once again with the GENCO. Also with this approach, it will be possible to have EV participating in secondary frequency control, through the link TSO → aggregator. After market closure, the TSO proceeds to the evaluation of the load/generation schedules, and if problems on the transmission system are foreseen, it requests modifications to these schedules until feasible operating conditions are attained. Everyday the aggregator will manage the EV under its domain, according to what was previously defined in the market negotiations and validated by the TSO, by sending set points to VC or CVC related to rates of charge or requests for provision of ancillary services. To accomplish such a complex task successfully, it is required that every fixed period (likely to be defined around 15 min), the SOC of each EV battery is communicated to the aggregator, to assure that, at the end of the charging period, batteries will be charged according to EV owners' requests [7].

Additionally, the aggregators can also negotiate with other entities parking and battery supplying services for EV, as mentioned in [6] and included in Fig. 6.3. Yet these parallel negotiations will not be addressed in this chapter.

For secondary control, the AGC operation is the centerpiece in the control hierarchy. The TSO, who is responsible for the AGC, will acquire in the electricity markets the secondary reserves that it needs from GENCO and aggregators. Then, in accordance with the secondary reserve services negotiated in the market with the TSO, the aggregator will receive requests from the AGC to participate in secondary control. Each aggregator will receive a given set point value of regulation up/down, split this participation value by EV willing to provide this service, and send set points to these EV. The set points EV will receive from the aggregator will lead to a load charging adaptation or to the injection of stored power into the network for the period of time the AGC requires this service.

Abnormal System Operation or Emergency Mode

When grid-normal technical operation is compromised, market management can be overridden by the DSO, through the technical operation control hierarchy, described in the left-hand side column of Fig. 6.3. For these abnormal or emergency conditions, it makes sense to adapt the MG and MMG concepts [3, 4]. In fact, as referred in Sect. 6.1 of this chapter, the MG and MMG already contemplate the existence of a hierarchical monitoring and management solution that includes a suitable communication infrastructure, capable of managing the presence of EV, either individually connected at the LV level or as a cluster of EV (fleet charging station or fast charging station cases) connected at the MV level. Within an LV MG, a micro-grid central controller (MGCC) may control EV batteries through the VC. As depicted in the "Technical Operation" column of Fig. 6.3, within an MMG environment, the elements of the MV grid, including MG and CVC, can be technically managed by a control entity, named Central Autonomous Management Controller (CAMC), to be installed in the HV/MV substation. All the CAMC will be under the supervision of a single DMS, which is directly controlled by the DSO. It is important to stress that, in abnormal system operation conditions or in emergency modes, all the technical management and control tasks are a responsibility of the DSO, being performed by a main control entity, the DMS, and by the other distributed entities, CAMC and MGCC [3].

6.2.2.2 Grid Control Architecture for Isolated Systems

In small isolated systems, the framework presented in the previous section may not be applicable, as no real market participation is possible. For these cases, the electricity supply chain remains vertically integrated. Yet these systems have evolved by integrating whenever possible intermittent RES in their generation mix. RES potential is, however, not usually fully explored in order to assure enough security of operation.

The integration of EV in such systems is a natural occurrence as fossil fuel scarcity, and environmental concerns are present in both interconnected and isolated systems. Being low resilience electricity grids, the greatest beneficial and adverse effects are expected from the integration of these new loads. When EVs are regarded as common loads, then these systems may get even more fragile. Conversely, if properly controlled, these systems could even benefit from further integration of RES.

The next two sections present the necessary adaptations of the previously exposed concepts, in order to manage EV in isolated grids. On the one hand, the MG and MMG concepts will still be required for these systems. On the other hand, some of the functionalities that were shared among aggregators must now be assured by the sole energy provider in the island, which typically is also the DSO.

Normal System Operation

As previously mentioned, small isolated systems are vertically integrated. Therefore, system operators are responsible for its management at the generation, transmission, and distribution levels.

Therefore, only the existence of the hierarchical control structure presented in the Technical Operation column (left hand side) of Fig. 6.3 is necessary. As it is observable, the complexity of the control structure is smaller than that in interconnected grids due to the inexistence of market players.

In normal system operation, VC and CVC are controlled by the system operator's sub-entities, MGCC and CAMC. Depending on the type of contract established with EV owners, the system operator may be allowed to control EV charging rate through those sub-entities. Day ahead, the system operator will run a smart charging algorithm using forecasted data on load (both typical consumption and EV) and generation profiles. During the day, it will update this solution, eventually by providing real-time pricing, so that consumers shift EV charging for cheaper electricity periods harmonizing the load/generation diagram.

In some cases, regulation may make EV response to the system operator's request mandatory, in order to not jeopardize the system operation and, eventually, allow increased intermittent RES penetration. In these cases, the local government or the system operator may have to be the co-owner of the EV batteries or provide a large incentive on EV purchase.

All the ancillary services presented for interconnected systems may also be provided by EV in isolated grids, provided that EV owners are granted sufficient incentives. The system operator control structure will be responsible for managing the provision of these ancillary services.

Abnormal System Operation or Emergency Mode

When grid-normal technical operation is compromised, the system will be controlled in the same way as described for interconnected systems. The main difference is that the system operator does not need to override market operation, as it does not exist.

6.2.3 Modeling EV for Steady-State Studies

The process of modeling EV for steady-state studies can be divided into three main categories: EV modeling for LV, for MV, and for HV/VHV network studies.

In what regards LV networks, as EV will charge in the majority of the situations at level 1 power rates (~3 kW), they are very likely to be connected to the LV grids using single-phase connections. For this reason, aiming at representing EV as realistic as possible, they should be modeled as single-phase loads. The addition of these new single-phase loads to the conventional loads that already exist in LV grids, which are typically three-phase unbalanced systems, will probably aggravate the load and voltage imbalances in these networks.

Conversely, for MV network studies, the loads resulting from EV batteries charging at level 2 and 3, directly connected to the MV grids, should be modeled as three-phase balanced loads, as the power levels involved in these charging modes (*c.a.* 12 and 40 kW, respectively) will probably require three-phase connections in the majority of the situations. Concerning the load of EV charging at level 1, in the LV grids downstream the MV network under analysis, they should be aggregated and represented as a single load value, per LV grid, at the MV bus of the respective MV/LV substation. This approximation is needed for MV network studies, as in this type of analysis, the detailed modeling of the LV grids downstream the MV/LV substations is not usually considered.

Regarding HV networks, the approach described for MV grids can be used to compute the EV load in the system downstream a given HV network and generate EV load profiles that can then be allocated to the respective node of the HV network. This process is similar to the one described for MV grids in what concerns the modeling of the load of EV charging at level 1 in LV grids. The full analysis of the HV network under study can then be performed by adding, bus by bus, the respective EV load profile to the conventional load profile. This procedure can also be used to compute the EV load and perform impact studies in VHV networks.

In what concerns the modeling of the EV batteries, it was assumed that their charging is performed always at a constant power rate for a given set point, as the detailed modeling of the battery charging cycle and of the battery ageing due to the charging/discharging cycles are not relevant for network impact studies.

6.2.4 Modeling EV for Dynamic Behavior Studies

In Europe, frequency regulation involves three layers of control: primary, secondary, and tertiary reserve provision. Primary frequency control is based on a decentralized proportional control performed on turbine governors, while secondary frequency control, performed through an AGC (AGC), requires the calculation of the integral of the area control error (ACE). Tertiary control is usually activated manually by the TSO and can only provide upward reserve in case of observed or expected sustained activation of secondary control [9]. This coordination depends on an appropriate communication infrastructure through which frequency and power measurements are obtained and set points are sent to the generation units that participate in these services. The ultimate goal of the load-frequency coordinated control is to stabilize frequency in the nominal value and keep inter-area power flows as defined in the daily market negotiations.

When EVs are considered active participants in reserve provision, the currently existing system should be adapted to include aggregators and EV, as depicted in Fig. 6.4. Similar to the governors of the conventional generation units, the power

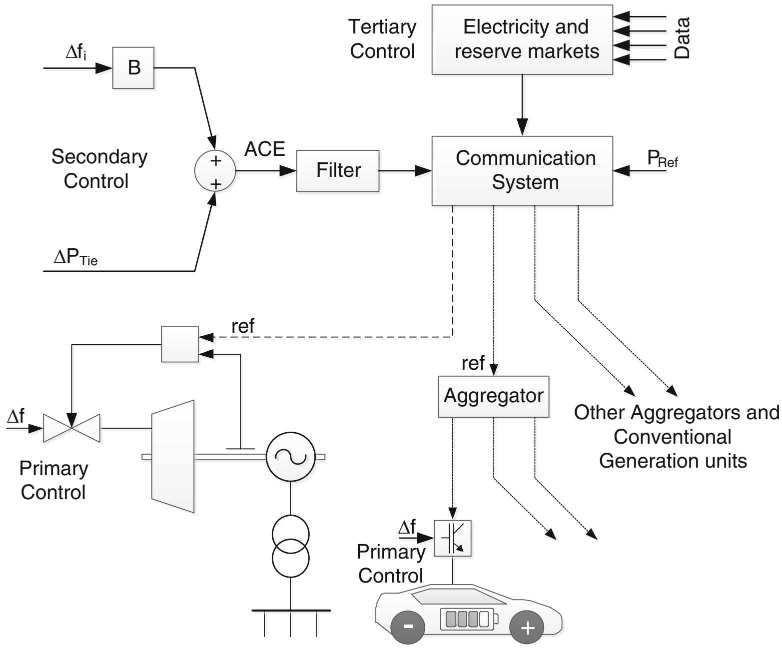


Fig. 6.4 Load-frequency control levels with EV

electronic interfaces of individual EV may react to frequency deviations to participate in primary control. Regarding secondary control, the AGC communicates the participation value to the conventional generators and aggregators. The latter must then divide and redistribute the participation value by the EV under its domain.

6.2.4.1 Electric Vehicles Participation in Primary Frequency Control

The control scheme for EV participation on primary frequency control may have two loops:

- The droop control that mimics the governors of conventional generators.
- The inertial control that also emulates the behavior of conventional generator so that EV can provide inertia to the system.

For both control loops, frequency must be read locally and the reaction to frequency deviations is performed autonomously. This reaction should consist of providing new set points for the electronic power converter that interfaces EV batteries and the grid. The control scheme should be installed on every VC, which is located next to the vehicle charger and has access to the smart grid communication infrastructure. The latter enables the upstream controllers to be logged about the activity of the VC concerning primary control provision and if needed redefine the droop control parameters or the settings for the inertial emulation.

So apart from the set point imposed by the aggregator or the charging control, the load value of the EV may be influenced by one of or both the control loops. Equation (6.1) presents the active power change requirement for the EV due to the influence of the droop. The load will change by an amount that is obtained by multiplying a proportional gain by the actual frequency change. The proportional droop is characterized for being a measure of the sensitivity of the controller to frequency deviations, expressed in units of power per unit of frequency. While a frequency error is sustained, the proportional controller will always impose a change in the load of the EV.

$$\Delta P_{\mathrm{Droop}} = k_P \bullet \Delta f, \tag{6.1}$$

where $\Delta P_{\mathrm{Droop}}$ is the load change provoked by the droop control; k_P is the proportional gain; Δf is the frequency deviation.

Equation (6.2) provides the amount of active power change, in case of a load/generation imbalance, that results from the inertial emulation implementation in the controllers of EV. In this case, the load will change by an amount equal to the product of a gain by the derivative of frequency change in respect to time. The derivative gain is a measure of the sensitivity of the controller to the rate of change of frequency, expressed in units of power per units of frequency per unit of time. The influence of this type of control is bigger for periods when frequency is changing fast and will be null when frequency stabilizes, independently of how big the absolute frequency error may be. Thus, the action of this control loop is predominantly noticeable in the initial moments succeeding a disturbance.

$$\Delta P_{\mathrm{Inertial\,Emulation}} = k_{in} \bullet \frac{\mathrm{d}}{\mathrm{d}t}\Delta f, \tag{6.2}$$

where k_{in} is the derivative gain of the controller.

Considering that k_P and k_{in} are real positive values and that the frequency error is calculated by $\Delta f = f_0 - f$ (where f_0 is the nominal system frequency), being a real positive value for underfrequency events and real negative value for overfrequency events, the load value of an EV if both control loops are active is given by (6.3):

$$P_{\mathrm{Load}}^{\mathrm{EV}} = P_{\mathrm{Set-point}}^{\mathrm{EV}} - \Delta P_{\mathrm{Droop}} - \Delta P_{\mathrm{Inertial\,Emulation}}, \tag{6.3}$$

where$P_{\mathrm{Load}}^{\mathrm{EV}}$ is the load of the EV; $P_{\mathrm{Set-point}}^{\mathrm{EV}}$ is the required EV load value defined by the aggregator as a set point.

Yet EV should not react to every small mismatch in power, and so some extra controls must be added to limit the participation of EV to the cases that really matter. Figure 6.5 shows schematically a droop configuration that could be implemented for enabling the EV grid interface control strategy. The plugged-in

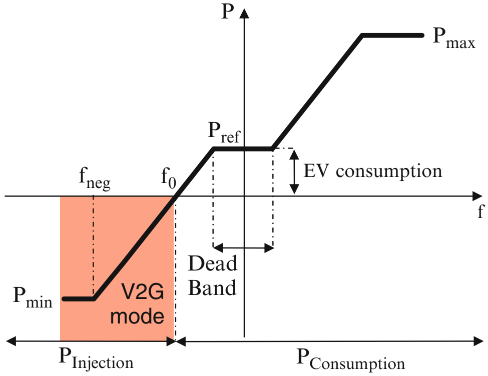


Fig. 6.5 Generic droop control for VC

EV providing primary control in steady-state conditions is charging at a given power rating, with a maximum value equal to its nominal charging power. It may occur that the EV is not charging in steady state, but is still plugged-in ready to provide primary control, if power delivery from the EV batteries to the grid is allowed. The charging reference power, P_{ref}, may be defined in two different ways:

- Set point from the aggregator or the DSO for EVs that adhere to smart charging schemes
- Local decision of EV owners who do not adhere to smart charging

The charging reference power may change as a function of the set points sent by the aggregator or the DSO, depending on the strategies for minimizing charging costs and the occurrence of possible grids technical violations.

A margin between the actual power rating and the maximum power rating may be imposed to EV participating in primary frequency control, in order to allow the participation in regulation down.

The maximum power rating, P_{max}, is the nominal charging power of the EV, whereas the minimum power rating, P_{min}, is the nominal discharging power, zero or a value between the minimum and maximum power ratings.

For frequency deviations larger than a defined dead band, the EV battery will respond according to one of the given slopes. If frequency suffers a negative deviation, then the battery charging will, first, reduce its power consumption, and, if frequency decreases further, it may inject power into the grid. Oppositely, if there is a positive deviation, the battery will increase the power absorbed from the grid.

A dead band, where EVs do not respond to frequency deviations, should be considered to guarantee longevity of the batteries and thus a beneficial synergy between parties, the grid operator/aggregator, and the EV owners. This dead band, as well as the slopes of the droops, should be defined according to not only the composition of the system, but also the EV owners' willingness to help with system frequency regulation and the characteristics of the EV battery.

As to the inertial emulation loop, the implementation may be performed in different ways in order to restrain the possible actions of EV. A dead band similar to the one implemented is also a possibility, but less interesting as the inertial behavior should be mobilized very fast. So the dead band should be reduced, at least for negative frequency values, as the most severe events are linked to the loss of generation capacity, due to either variability of primary resource or tripping of generation units. In this sense, it may be wise to introduce a saturation following the derivative of the frequency deviation to block positive rates of change and consequently prevent the action of the inertial emulation loop for periods where generation exceeds load.

In addition to the control techniques discussed so far, it is still possible to introduce further control laws, such as voltage control loops. Dealing with frequency and voltage at the same time might end with conflicting signals that may result in worsening of the operating conditions. Therefore, in case of adoption of the voltage and frequency controls simultaneously, a merit order should be established. The frequency control should override the voltage control in case of conflict.

For EV to participate in primary frequency control, a proper electronic interface control should be adopted, different from a simple diode bridge usually adopted for charging purposes. Being the system frequency an instantaneous indication of the power balance in a grid, the active power charging/discharging levels of the EV batteries must be adaptable by being capable of receiving set points. In this way, a smart EV grid interface, capable of responding locally to frequency changes, should be adopted, instead of a passive battery charging solution.

Active and reactive power set points may be sent to the power electronic converter interfacing EV and the electricity grid. To allow this, a current-controlled voltage source, a PQ inverter, is suggested [10], as depicted in Fig. 6.6.

This method computes the instantaneous active and reactive components of the inverter current: the active component is in phase with the voltage and the reactive component with a 90° (lagging) phase shift, being both limited in the interval $[-1, 1]$, as described in [4].

The active component is used to control the DC link voltage and, consequently, the inverter active power output, in order to balance the EV battery and inverter active power output. The reactive component controls the inverter's reactive power output. Power variations in EV battery lead to a variation of the DC link voltage, which is corrected via both proportional–integral regulators (PI-1 and PI-2), by adjusting the active power output. The frequency control droop present on the VC will adjust the active power set point of the PQ EV inverter interfaces (P_{ref}).

To perform dynamic simulations, the model for EV participation on primary frequency control might be easily implemented in any software that allows using block diagrams.

Figure 6.7 presents the complete model implemented to provide local primary frequency control and inertial emulation. In the droop control block diagram, the frequency deviation signal, Δf, goes through a dead band block to prevent EV charging from being disturbed by minor frequency changes and gets multiplied by the proportional gain, k_P, to determine the contribution of the EV droop for primary frequency control, $\Delta P_{\mathrm{Droop}}$. In the block diagram of the inertial emulation loop, the derivative of the input signal, the frequency deviation, Δf, is calculated, then the

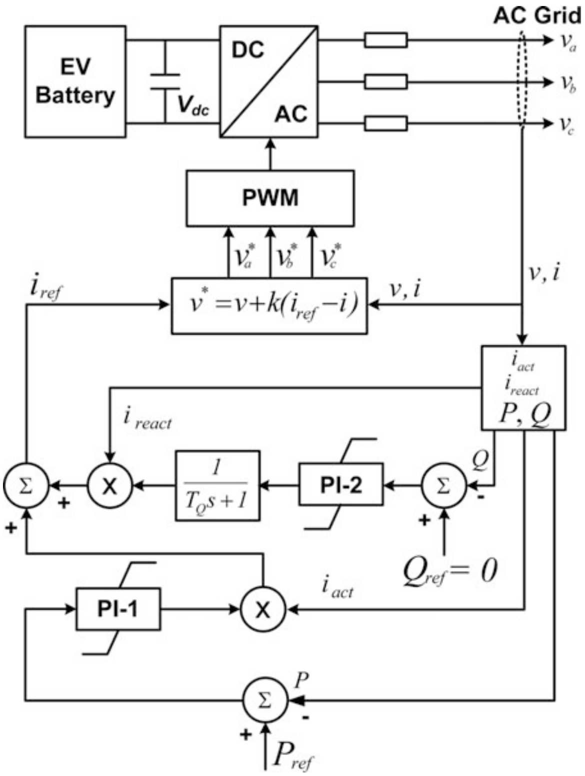


Fig. 6.6 PQ inverter control type

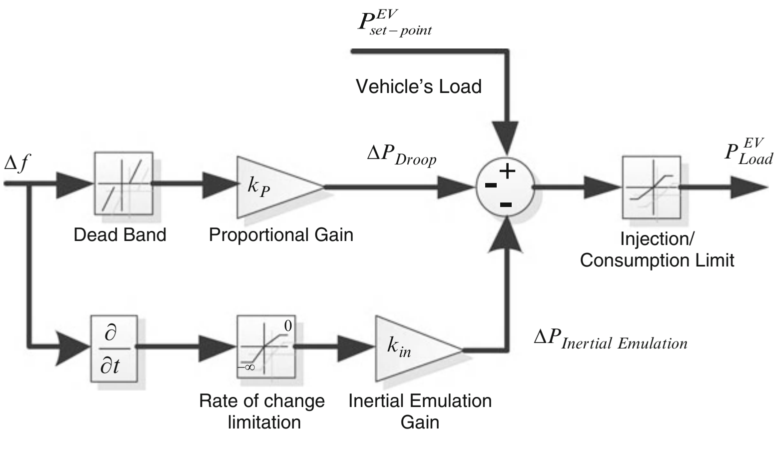


Fig. 6.7 Active power set point control for the power injector

result goes through a saturation block to limit the rates of change and the derivative gain is applied, k_{in}, to determine the contribution of the EV for primary control due to the action of the inertial emulation, $\Delta P_{\text{Inertial Emulation}}$. Finally, the contribution of both droop control and inertial emulation is added to the EV load set point, $P^{\text{EV}}_{\text{Set-point}}$, and a new saturation block assures that the request power for the EV is within its operation limits. These limits in a real implementation would depend on the contract established between EV owners and aggregators, being possible to block V2G capability. The resulting signal will be the new active power set point value for the power injector that represents the EV—$P^{\text{EV}}_{\text{Load}}$.

There are some simplifications made to implement this model:

- The SOC of the EV battery is assumed to be neither fully discharged nor fully charged, thus allowing neglecting SOC considerations for the implementation of the model.
- The EV batteries are expected to react to new set points without delays.
- The state of health of the batteries was not accounted for in this model. It is assumed that the batteries do not suffer significant damage from providing primary frequency control.
- As the time periods being studied are of the order of a few seconds, these storage elements can be modeled as constant DC voltage sources using power electronic interfaces, DC/AC inverters, to couple them to the grid. These devices act as controllable AC voltage sources (with very fast output characteristics) to face sudden system frequency changes.

6.2.4.2 Automatic Generation Control with Electric Vehicles

In secondary frequency control, the AGC operation is the centerpiece in the control hierarchy. In a scenario characterized by large-scale EV deployment, the TSO, who is responsible for the AGC, will acquire in the electricity markets the secondary reserves that it needs from GENCO and/or aggregators.

If a sudden loss of generation or load increase takes place in a control area, the AGC exploits the available secondary reserves, guaranteed by the reserve market negotiations, by sending set points to the participants in the secondary frequency regulation service. If EV aggregators are participating in this service, the AGC will send set points to aggregators that afterward will distribute their participation among the EV providing this service by sending individual set points to these EV. The set points EV will receive from the aggregators will lead to a load charging adaptation for the period of time the AGC requires this service.

To perform AGC operation with EV, some modifications as presented in Fig. 6.8, need to be introduced in conventional AGC systems in order to make the regulation of EV power consumption/output possible in response to deviations of system frequency, f_i, in relation to its reference, f_{ref}, and of the tie-lines active power flow, Pif_i, in relation to the interchanges scheduling, Pif_{ref}. As in the conventional AGC, B is the frequency bias that measures the importance of

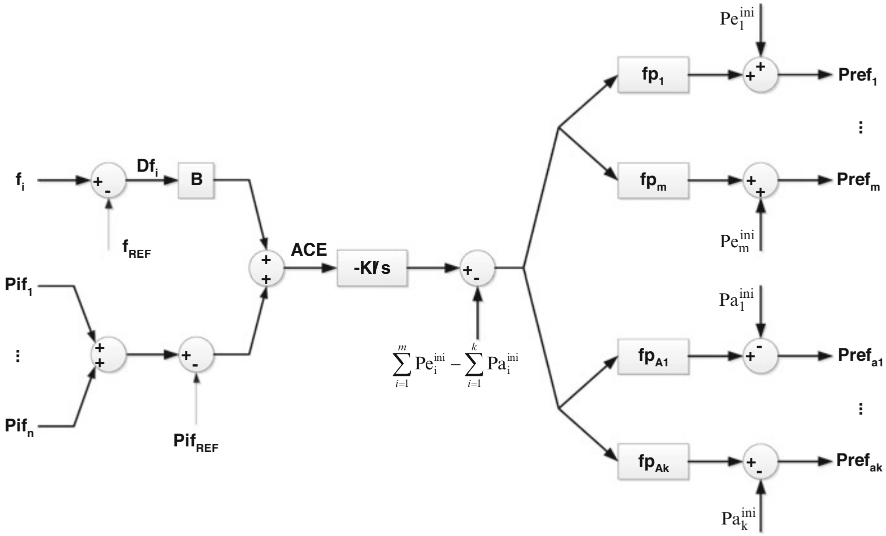


Fig. 6.8 AGC operation in the presence of EV aggregators

correcting the frequency error, when compared with the correction of the interchange power error; k_I is the gain of the integral controller; Pe_m^{ini} is the current dispatch for machine m, fp_m its participation factor; and $P_{\mathrm{ref}\,m}$ is its new active power set point value. Pa_k^{ini} is the current load of EV aggregator k (entity whose importance will be further developed in this section) and fp_{Ak} and $P_{\mathrm{ref}\,ak}$ are the aggregator k participation factor and new active power set point, respectively.

It should also be considered that the AGC with EV operation has a delay similar to the conventional AGC, within the 5 s period available for the controller cycle [9]. Yet it may happen that once the aggregators receive the set points from the AGC unit, there will be another delay to send the final set points to EV, and each EV will then take some more time before outputting the required value. The former should assume a value that should not exceed the controller cycle time of the AGC. Both actions are nearly identical, and the computational burden that the aggregator endures, distributing its set point among the participating EV possibly already predetermined once the signal is received, is likely to be lower than that of the AGC controller, integrating the error signals and distributing the set points according to the participation factors of the controlled units. The delay on the action of the individual EV is of the order of magnitude of utmost a 100 ms, being caused by the electronic interface. This delay should be negligible in the context of the AGC operation, whose deployment period starts 30 s after the disturbance and lasts for 15 min. As a matter of fact, the delay caused to the machine response by their inertia overthrows the full extra delay caused by the binomial aggregator and EV.

For the purpose of dynamic simulation, EV charging can be modeled, as any load, as constant power load, constant current load, constant admittance load, or a combination of those. The following equations present the mathematical formulation of such a modeling [11]:

$$P = P_0[p_1\bar{V}^2 + p_2\bar{V} + p_3], \quad (6.4)$$

$$Q = Q_0[q_1\bar{V}^2 + q_2\bar{V} + q_3], \quad (6.5)$$

where P is the active power; Q is the reactive power; p_1 to p_3 and q_1 to q_3 are coefficients that define the proportion of each component.

In addition to this dependency on voltage, loads may suffer the influence of frequency and so (6.4) and (6.5) may be written as follows:

$$P = P_0[p_1\bar{V}^2 + p_2\bar{V} + p_3](1 + k_{pf}\Delta f), \quad (6.6)$$

$$Q = Q_0[q_1\bar{V}^2 + q_2\bar{V} + q_3](1 + k_{qf}\Delta f), \quad (6.7)$$

where Δf is the frequency deviation; k_{pf} and k_{qf} are coefficients that reflect the dependency of the load value to Δf.

Typically, in dynamic simulation, a simplification is done and all loads are considered to be of constant admittance type. This occurs due to the fact that is virtually impossible to achieve perfect knowledge on the loads distributed through the network that is being studied. Some particular cases, such as networks representative of industrial areas, may consider certain portions of the load to have specific behaviors, and consequently specific models are adopted to study their influence. This happens in the case where large induction motors or air-conditioning devices have a large presence, which requires additional load modeling.

In this particular case, EVs are assumed to be a known proportion of the total load and so EV load was distinguished from the conventional load. Being interfaced with the electricity grid by power electronics, EV charging is controlled following well-known patterns. The constant current, constant voltage charging process of a lithium-ion battery cell [12], is depicted in Fig. 6.9.

It is observable that current is constant during most of the time, while voltage slowly varies over time, except for very low values of SOC. When SOC reaches a high value, then voltage is kept constant and current decreases tending to zero.

AGC operation regards time periods of 15 min. For these small periods of time, one can assume a constant power load for the EV battery charging process, also because variations of voltage at EV terminals are quite small during the large majority of this period of time and can therefore be neglected.

When advanced management strategies are considered, to the adopted model, extra control loops have to be added to EV loads, enabling them to respond to the following:

- Frequency, when participating in primary frequency control
- Upstream active power set points, when participating in AGC operation

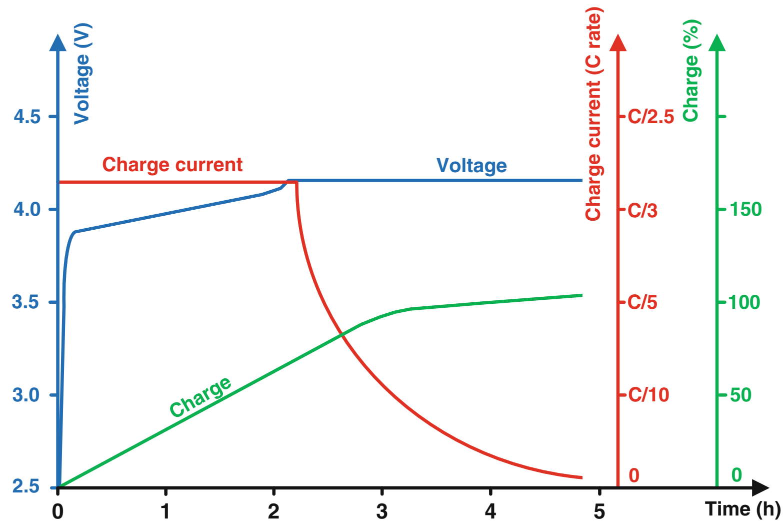


Fig. 6.9 Constant current, constant voltage charging, based on [13]

6.3 Steady-State Studies of Electric Vehicles Integration in Distribution Networks

The foreseen deployment of EV will considerably affect the way distribution grids will be managed and operated. The extra amount of power they will demand from the grid will oblige DSO to understand the impacts resulting from EV connection into distribution networks. Several approaches to this problem have been pursued. As an example, the works published in [14] and [15] present two strategies for assessing EV grid integration impacts. The work presented in [14] follows a deterministic strategy to locate EV along the network buses and, consequently, determine EV loads during an entire day. Conversely, the work presented in [15] introduced a probabilistic method for determining EV load. Both options proved to be interesting approaches, though they were able to reveal only the effects of a possible scenario for a given period. To overcome this limitation, it is important to develop tools that allow exploring different scenarios in a coordinated way, enabling the analysis of both average scenarios and extreme case scenarios that may appear when EVs start being integrated in the networks. Such tools can be used to enhance the current planning techniques of DSO, allowing them to obtain additional knowledge on the impacts of a new type of load, so far unknown or negligible to the electrical power systems, the EV battery charging. Given the fact that EVs are mobile loads that may appear in almost any bus of a given electricity network, voltage profiles, lines loading, peak power, and the variations of the energy losses in the network need to be properly evaluated for the planning exercise.

In this sense, two approaches are presented in this section, henceforth referred to as Methodology 1 and Methodology 2, aiming at performing a steady-state evaluation of the EV impacts in distribution networks, both LV and MV networks. In both methodologies, the EVs are modeled as described in Sect. 6.2.3. As it will be discussed in the following sections, charging at levels 2 and 3 was only considered in Methodology 2.

The first approach, Methodology 1, follows a deterministic method to distribute EV along the network buses and determine EV loads during an entire day. Three charging strategies are used to evaluate the EV impacts in the networks, one for each charging strategy addressed: dumb charging, multiple tariff, and smart charging.[1] An algorithm based in this methodology is also presented, for which main characteristics are described further ahead in this chapter.

The second approach, Methodology 2, uses a Markov chain to simulate the expected movement of EV during 1 week and a Monte Carlo simulation method that allows exploring different scenarios in what regards the EV locations in the grid and their power requirements [16]. This approach includes a set of management and control strategies that may be used by DSO and aggregators to manage the EV charging in real time, which allow attaining the following objectives:

- Minimizing the deviations between the energy bought in the markets by the aggregators and the energy sold to EV owners
- Minimizing the renewable energy wasted in systems with a large integration of intermittent RES
- Flattening, as far as possible, the load diagram of a given network
- Solving technical problems related to voltages outside the allowable limits and branches' overloading that might appear in the networks due to EV charging

An algorithm based in Methodology 2 is also presented further ahead in this chapter.

6.3.1 Identification of EV Integration Limits: Methodology 1

This approach assumes that the load inherent to EV charging will appear in the grid nodes proportionally to the residential power installed in each node. It allows evaluating the maximum number of EV that can be safely integrated in a given distribution network when the different charging strategies are implemented.

[1] As the V2G mode of operation (described in Sect. 6.2.1) is the most aggressive mode for charging EV, due to possible implications with EV batteries' life cycle, this option is not likely to be a reality neither in the short run nor in the medium term. Only in the very long term, when battery technology has reached a high maturation stage, this strategy may be adopted. For this reason, the V2G mode of operation was neither considered in the development of Methodologies 1 and 2 nor in the implementation of these approaches in the steady-state algorithms presented.

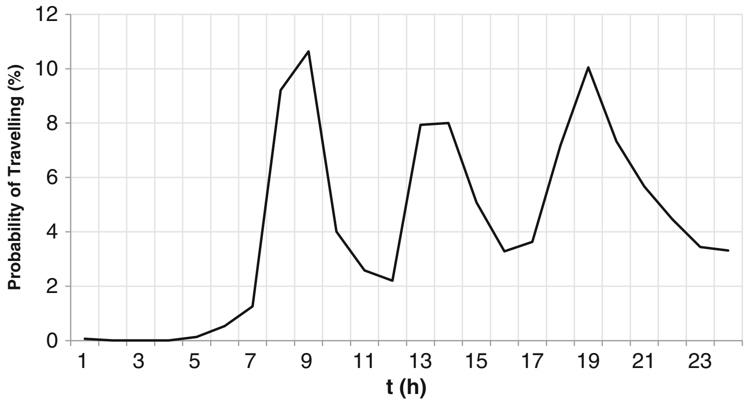


Fig. 6.10 Probability distribution used to define the EV daily journeys

The methods proposed for the dumb charging and multiple tariff are based on a simple set of rules, whereas the smart charging methodology involves an optimization problem with the objective of managing the EV load in order to minimize the networks' peak load.

It should be noted that in this methodology, the EV batteries charging was assumed to be performed always at a constant power rate of 3 kW in all the charging strategies addressed (at level 1 charging rate, as described in Sect. 6.2.1).

As in this approach it was not taken into account the real amount of energy spent by EV during their daily journeys, being impossible to know their battery SOC in the moment they plug in to the grid to recharge, an average charging time of 4 h was assumed for all the EV. This means that all EV absorb 12 kWh from the grid during the day under analysis. Assuming an energy consumption of 0.2 kWh/km [17], the daily energy absorbed would be enough for traveling 60 km without needing to recharge.

6.3.1.1 Formulation of the Approach

The formulation of this approach is essentially focused on the determination of the locations and time periods during which EV will be plugged in to the grid for charging purposes, when the three different charging strategies are adopted.

Thus, its first step is defining the period during which each EV will be connected to the grid. For that, it is assumed that EVs make only two journeys per day and that they are plugged in only in the periods between the last journey of 1 day and the first journey of the next day. The two moments when EVs make their daily journeys are drawn using the probability distribution presented in Fig. 6.10.

This procedure is constrained by the fact of the charging time being assumed to be 4 h for all EV. Thus, it is always assured that the time period between the last and the first journey of the day is at least 4 h.

The probability distribution in Fig. 6.10 was obtained from a statistical study of which the main goal was the characterization of the common traffic patterns in a region in the north of Portugal, covering the city of Porto and other smaller surrounding cities [18].

The following step of the approach is defining the periods during which EV will effectively absorb power from the grid. These periods will vary in accordance with the charging strategy under consideration.

When dumb charging is considered, it is assumed that EV owners are completely free to connect and charge their vehicles whenever they want. Thus, the charging starts automatically when EVs are plugged in, right after home arrival, and, as previously referred, lasts for the following 4 h.

When considering the multiple tariff, it is supposed that the economic incentives provided with this policy are enough to make the EV owners changing their charging to the cheaper electricity period.[2] Therefore, EV will preferably charge in the period between 22 and 8 h. They will charge only outside it if they are not plugged in the required 4 h in the period between 22 and 8 h.

Regarding smart charging, it is assumed the existence of an EV charging management system that controls the EV charging in order to avoid, as far as possible, increasing the networks' peak load. This system provides high flexibility to the EV charging, and thus it is possible to shift the EV load from the peak to the valley periods. Following this assumption, the smart charging was formulated as an optimization problem, as shown below, for which the main objective is the minimization of the networks' peak load.

$$\min \left\lfloor \max_{t=1:24\,\mathrm{h}} \left(\sum_{j=1}^{m} CL_t^j + \sum_{i=1}^{n} \left(EVC_t^i \right) \times 3 \right) \right\rfloor, \tag{6.8}$$

subject to

$$\sum_{t=1}^{24} EVC_t^i = 4, \quad \begin{cases} i \in [1, n] \\ t \in [1, 24] \end{cases}, \tag{6.9}$$

$$EVP_t^i \geq EVC_t^i, \quad \begin{cases} i \in [1, n] \\ t \in [1, 24] \end{cases}, \tag{6.10}$$

where $\left\lfloor \max\left(CL_t^j + \sum_{i=1}^{n} \left(EVC_t^i \right) \times 3 \right) \right\rfloor$ represents the network's peak power, in kW, given by the maximum value registered along the 24 h of the sum of the network conventional load and the EV load; CL_t^j is the conventional load in bus j,

[2] The lower electricity price period assumed was that of the dual tariff policy currently implemented in Portugal: 22–8 h. More information can be found in http://www.edpsu.pt/pt/particulares/tarifasehorarios/ (in Portuguese).

in kW, in time step t; EVC_t^i is used to define the periods t when EV i will charge; if $EVC_t^i = 1$, the EV i will charge in moment t, else if $EVC_t^i = 0$, the EV will not charge; the $n \times 24$ binary variables EVC_t^i are the decision variables of the optimization problem; t is the time step index; i is the EV index; n is the number of EV assumed to be within the network's geographical area; j is the bus index; m is the number of buses in the network; EVP_t^i is used to define the periods t when EV i is parked and plugged in to the grid; if $EVP_t^i = 1$, the EV i is plugged in in moment t, else if $EVP_t^i = 0$, the EV is neither plugged in nor available for charging; the $n \times 24$ binary values EVP_t^i are parameters of the optimization problem.

The equality constraint presented in (6.9) assures that all EV will charge exactly 4 h along the day, whereas the condition implemented in (6.10) assures that EV will only charge when they are plugged in to the grid. The number 3 presented in (6.8) is referred to the charging rate, in kW, assumed for all the EV.

The problem formulated for the smart charging strategy is a pure integer problem, as all the decision variables are restricted to be integers.

After determining the periods when EV will charge, in accordance with the charging strategy addressed, the network buses where EVs plug in for charging are calculated taking into account the proportion of residential power installed in each node, as presented in (6.11).

$$Nr.EV_j = \frac{\text{Load}_j^R}{\sum_{j=1}^{m} \text{Load}_j^R} \times n, \quad j \in [1, m], \tag{6.11}$$

where $Nr.EV_j$ is the number of EV allocated to bus j; Load_j^R is the residential load, in kW, installed in bus j; $\sum_{j=1}^{m} \text{Load}_j^R$ is the total residential load, in kW, in the network.

A consequence of (6.11) is that buses with a higher residential load will have allocated a higher number of EV. Following the results obtained with this equation, all the EVs are tagged with a bus number, indicating the bus where they plug in for charging. This procedure allows computing the EV load in the system, node by node and for each time step.

Finally, the total load in the network with the three charging strategies is calculated by adding the conventional load to the respective EV load, as follows:

$$TL_j^t = CL_t^j + \sum_{k=1}^{Nr.EV_j} EVC_t^k \times 3, \quad \begin{cases} j \in [1, m] \\ k \in [1, Nr.EV_j], \\ t \in [1, 24] \end{cases} \tag{6.12}$$

where TL_j^t is the total load in bus j, in kW, in time instant t; EVC_t^k is the EV charging vector composed of 24 binary variables used to define the periods t when EV k will charge; if $EVC_t^k = 1$, the EV k will charge in moment t, else if $EVC_t^k = 0$, the EV will not charge; k is the index used for the EV allocated to bus j.

6.3.1.2 Development of the Approach

An algorithm based in the approach proposed can be developed, with the objective of characterizing the impacts provoked by a given EV integration level in a distribution network or quantifying the maximum number of EV that can be integrated in a given network, without violating its components' technical limits.

The algorithm should include the following steps:

1. Definition of the type of study to be performed (evaluate the impacts of a given level of EV integration or quantify the maximum number of EVs that can be safely integrated in a given network).
2. Evaluation of the initial operating conditions of the network (power flow analysis[3]), without considering the presence of EV (for comparison purposes).
3. Definition of the number of EVs assumed to be enclosed in the geographical area covered by the network.
4. Definition of the periods during which each EV will be plugged in.
5. Definition, in accordance with the specificities of the charging strategy being addressed, of the periods during which EV will effectively absorb power from the grid (the analysis of the smart charging strategy demands the resolution of the pure integer optimization problem formulated in (6.8)–(6.10)[4]).
6. Distribution of the EVs through the network nodes.
7. Calculation of the total load in the network, node by node and for each time step, by adding the conventional load to the EV load.
8. Evaluation of the new grid operating conditions (power flow analysis).
9. If no technical violations are registered, increase the number of EVs and repeat steps 4–9 (this step is only performed if the type of study selected in step 1 is "quantify the maximum number of EVs that can be safely integrated in a given network").
10. Store all the relevant data.

The flowchart of the algorithm is presented in Fig. 6.11.

6.3.2 Spatial–Temporal EV Simulation Tool: Methodology 2

Methodology 2 is an improved version of Methodology 1. It fully copes with the conceptual framework described in Sect. 6.2.2, namely in what regards the smart charging, which was addressed assuming the possibility of adjusting the EV

---

[3] All the required power flows were run using the *PSS/E* software.

[4] The optimization problem was solved using LINGO 13.0, which is an optimization modeling software that includes a set of built-in solvers for linear, nonlinear, quadratic, quadratically constrained, second-order cone, stochastic, and integer optimization. More information can be found in http://www.lindo.com/index.php?option=com_content&view=article&id=2&Itemid=10

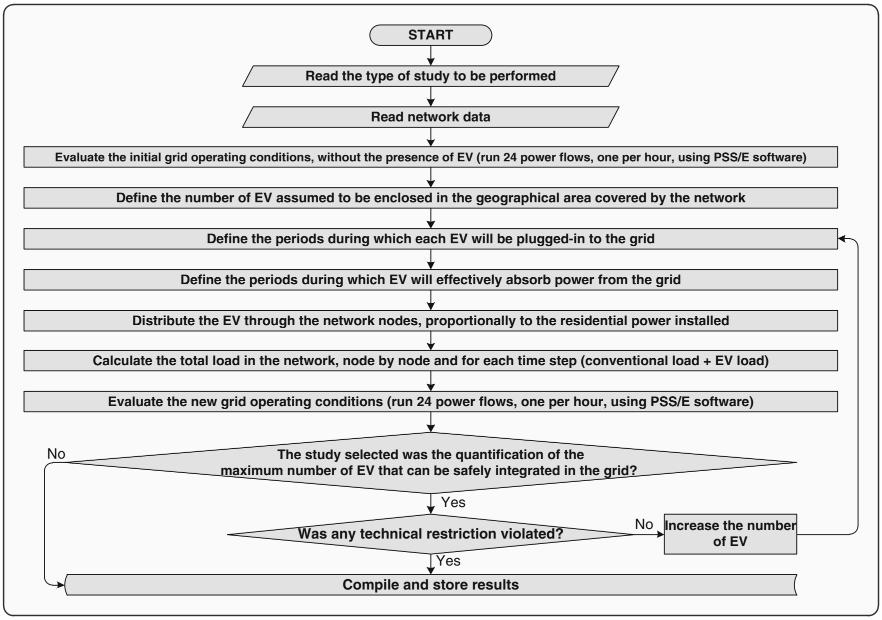


Fig. 6.11 Flowchart of the algorithm based in Methodology 1

charging rates between zero and the maximum power rate of the charging point where a given EV is plugged in (3 kW for level 1, 12 kW for level 2, and 40 kW for level 3 charging infrastructures, as described in Sect. 6.2.1). This methodology uses a Markov chain to simulate the expected movement of EV during 1 week and a Monte Carlo simulation method that allows exploring, in a coordinated way, different scenarios in what regards the EV locations in the grid and their power requirements.

Different from Methodology 1, where the period of only 1 day was considered, with time steps of 1 h, the time horizon of 1 week was considered in Methodology 2, with time steps of ½ h. This improvement allows not only evaluating the EV impacts taking into account the load variations that usually occur between week and weekend days, but also quantifying the EV impacts in time steps shorter than 1 h, as 1 h is a very long period of time during which the network operating conditions can change considerably. It should be mentioned that the formulation of this methodology can be easily adapted to analyze the EV impacts during different periods of time, like 1 year, if the objective is evaluating other seasonal load variations, like load changes between seasons.

As it will be described later on, this approach also includes a set of management and control strategies that may be used by DSO and aggregators to manage the EV charging in real time.

6.3.2.1 Mathematical Formulations

This section covers the mathematical formulation of the Markov chain used to simulate the expected movement of the EV during 1 week in the geographical area covered by a given network, as well as of the set of procedures created to manage the EV charging in real time.

Electric Vehicle Motion Simulation

The EV movement during 1 week is simulated using a discrete-state and discrete-time Markov chain [19–21], to define the states of all the EVs at each time step of 30 min. In this Markov chain, it was assumed that, at every unit of time, one and only one event from a set of a finite number of events can occur to a given EV: E_M, E_R, E_C, and E_I. When the event $E_k(k = M, R, C, I)$ occurs, it is said that the EV passes into the state E_k:

- E_M—The EV passes into the state "in movement"
- E_R—The EV passes into the state "parked in a residential area"
- E_C—The EV passes into the state "parked in a commercial area"
- E_I—The EV passes into the state "parked in an industrial area"

As the time terminology will be used, i.e., it is considered that one trial is performed at every unit of time, when the event E_k occurs at the moment t, it is represented by E_k^t. Besides this, it is assumed that at the initial moment $t = 0$. Therefore, E_k^0 denotes that the initial state of the EV was E_k.

This method is classified as a discrete-time process, given that t is finite and can be enumerated [19]. As the objective is to simulate EV movement along 1 week (7 days), 337 time steps of ½ h will be considered. Thus, $t \in [0, 336]$.

One trial is performed initially to define every EV state when $t = 0$. In this trial, an EV may be in the state E_k with probability $P(E_k)$.

The conditional probability that at the moment t, for $t \in [1, 336]$, a given EV passes into the state E_k is denoted by $p_{j\to k}^t$ provided that at $t-1$ it was in the state $E_j(j = M, R, C, I)$:

$$p_{j\to k}^t = P(E_k^t | E_j^{t-1}). \tag{6.13}$$

As mentioned above, this sequence of trials forms a Markov chain, given that for any j and k and for any $t \in [1, 336]$, the equalities

$$p_{j\to k}^t = P(E_k^t | E_j^{t-1}) = P(E_k^t | E_j^{t-1} \bullet E_j^{t-2} \bullet \ldots \bullet E_j^1 \bullet E_j^0), \tag{6.14}$$

are satisfied for arbitrary $E_j^{t-2}, \ldots, E_j^1, E_j^0$.

This Markov Chain is periodically stationary, or cyclostationary [22], as the transition probabilities are periodically repeated. The period of this cycle is 1 week and will be represented by τ. As time steps of ½ h are being considered, $\tau = 7 \times 48 = 336$. If the purpose of the study was evaluating the EV impacts during one complete year (365 days), τ would have to be repeated ≈ 52.14 times.

$$p^{t}_{j\to k} = p^{t+\tau}_{j\to k}. \tag{6.15}$$

One transition matrix can be created with the transition probabilities $p^{t}_{j\to k}$ for each moment t, where $t \in [1, 336]$. This matrix is denoted by M_t, and given the cyclostationary properties of this Markov chain, it will be periodically repeated every τ time steps, in accordance with (6.16):

$$M_t = M_{t+\tau}. \tag{6.16}$$

For a given moment t, the transition matrix assumes the following form:

$$M_t = \begin{bmatrix} p^{t}_{M\to M} & p^{t}_{M\to R} & p^{t}_{M\to C} & p^{t}_{M\to I} \\ p^{t}_{R\to M} & p^{t}_{R\to R} & p^{t}_{R\to C} & p^{t}_{R\to I} \\ p^{t}_{C\to M} & p^{t}_{C\to R} & p^{t}_{C\to C} & p^{t}_{C\to I} \\ p^{t}_{I\to M} & p^{t}_{I\to R} & p^{t}_{I\to C} & p^{t}_{I\to I} \end{bmatrix}, \tag{6.17}$$

where the indexes M, R, C, and I stand for "in movement," "parked in a residential area," "parked in a commercial area," and "parked in an industrial area," respectively.

Logically, all the elements $p_{j\to k}$ of the matrix, being probabilities, are nonnegative.

Supposing that an EV is in the state E_j, the event where, as a result of one trial, the EV remains in the state E_j or passes to any of the states E_k, where $j \neq k$ is the sure event. Since the events E_k are mutually exclusive, for $k = M, R, C, I$, the following equation can be obtained:

$$P[\sum_k E^{t}_{k} | E^{t-1}_{j}] = \sum_k p^{t}_{j\to k} = 1. \tag{6.18}$$

Thus, the sum of the terms in each row of the matrix M_t equals one. However, the sum of the terms in a column might be different from one.

Figure 6.12 presents an overview of the Markov chain developed.

As denoted in Fig. 6.12, there are some restrictions when defining the EV states for each time instant. While EV in movement can keep their state or change for one of the others, parked EV can only remain in the same state or change to in movement.

As mentioned previously, the Markov chain developed is cyclostationary and the period of one complete cycle, τ, is 1 week. This cycle is, in fact, a composition of two sub-cycles with the duration of 1 day: one for the weekdays (repeated five times in a row) and the other for the weekend days (repeated twice consecutively).

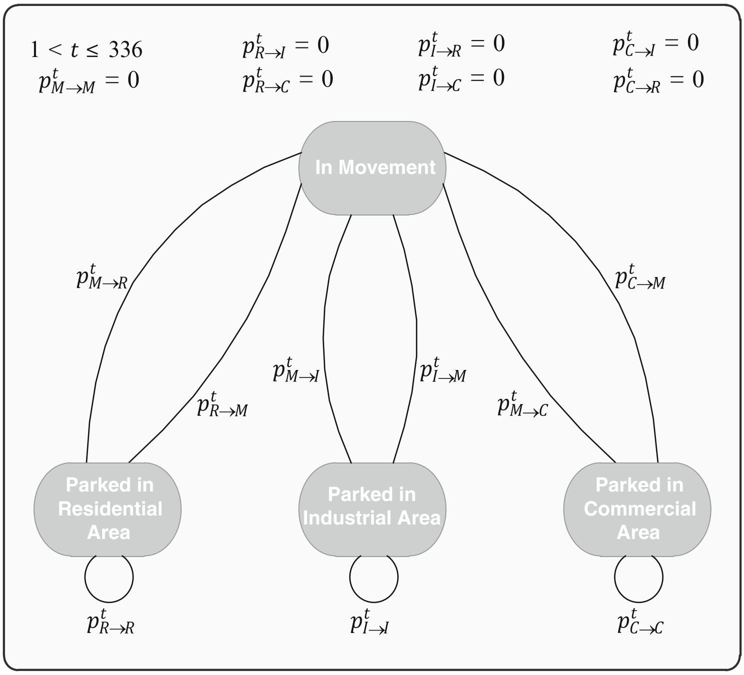


Fig. 6.12 Discrete-state and discrete-time Markov chain

Therefore, to have the Markov chain completely characterized, it is only needed to define the initial probabilities, for $t = 0$, and the state transition probabilities, for $t \in [1, 48]$, of these to sub-cycles, as shown in (6.19) and (6.20), and then repeat them to compose the full weekly cycle.

Initial probabilities:

$$P(E_k^t) \quad \text{for} \begin{cases} t = 0 \\ k = M, R, C, I \end{cases}. \tag{6.19}$$

Transition probabilities:

$$p_{j \to k}^t = P\left(E_k^t \mid E_j^{t-1}\right) \quad \text{for} \begin{cases} t \in [1, 48] \\ k = M, R, C, I \\ j = M, R, C, I \end{cases}. \tag{6.20}$$

The required probabilities were determined by analyzing the results of the same statistical study referred previously, of which the main goal was the characterization of the common traffic patterns in a region in the north of Portugal [18].

The values obtained from the study presented in [18], for the EV initial-state probabilities ($t = 0$), were 0.89 for “parked in a residential area,” 0.04 for “parked

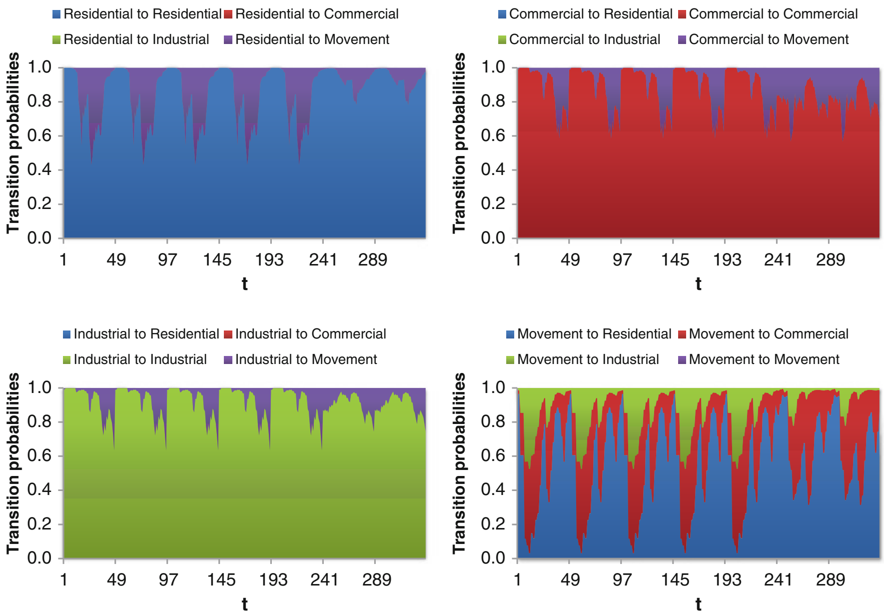


Fig. 6.13 EV state transition probabilities: full weekly cycle (Monday to Sunday)

in a commercial area," 0.02 for "parked in an industrial area," and 0.05 for "in movement."

Regarding the state transition probabilities, the values obtained for the full weekly cycle, which already includes the results of the weekday and weekend day sub-cycles, are presented in Fig. 6.13.

Procedures to Define Which "Flexible EV[5]" Should Charge at Each Time Step

Taking into consideration the characteristics of the problem to be analyzed, two procedures to define which of the "flexible EVs" should charge at each time step are presented along the current section. These procedures were specifically developed to accomplish the EV charging management performed by the aggregator for interconnected systems or by the system operator for isolated systems.

Procedure 1

The main objective of Procedure 1 is to define which "flexible EV" should charge at each time step, in order to minimize the deviations between the energy bought in the market by the aggregators and the energy consumed by EV. It should be stressed that it was assumed that the charging rate for level 1, in what regards smart charging adherents, could vary between 0 and 3 kW.

[5] "Flexible EVs" are the EVs whose owners adhered to the smart charging scheme.

To achieve the intended objective, it is required to find a set of n load values, being n the number of "flexible EV," which can be defined as optimal in the sense that they allow minimizing the deviations between the energy bought by the aggregators and the energy consumed by EV.

This problem can be formulated as an optimization problem, as shown below:

$$\min\left|EBA_t - TIEVL_t - \sum_{i=1}^{n} FEVL_t^i\right|, \tag{6.21}$$

subject to

$$0 \le SOCR_{td}^i - SOC_t^i \le \frac{(FEVL_t^i + (td - (t+1)) \times 3) \times 1/2 \times EV_{ce}}{EV_i^{bc}} \times 100, \tag{6.22}$$

$$0 \le FEVL_t^i \le 3, \tag{6.23}$$

$$0 \le SOCR_{td}^i \le 100, \tag{6.24}$$

$$0 \le SOC_t^i \le 100, \tag{6.25}$$

$$t + 1 \le td, \tag{6.26}$$

where i represents the "flexible EV" index; t represents the time index; n is the No. of "flexible EV" under the aggregator control; EBA_t represents the average power along ½ h, in kW, related to the energy bought in the day-ahead market by the aggregator for time period between t and $t + 1$; $EBA_t(\text{kW}) = (\text{energy bought}_{t \to t+1}(\text{kWh}))/(1/2\,\text{h})$, which is a parameter of the optimization problem; $TIEVL_t$ represents the total "inflexible EV[6]" load, in kW, in time step t, which is a parameter of the optimization problem; $FEVL_t^i$ represents the power absorbed by "flexible EV" i, in kW, in time step t; the $n\,FEVL_t^i$ are the decision variables of the optimization problem, which can assume continuous values in the interval $[0, 3]$; td represents the time step at which a given "flexible EV" disconnects from the grid; SOC_t^i represents the battery SOC of EV i, in percentage, in time step t; the SOC_t^i values are parameters of the problem; $SOCR_{td}^i$ represents the battery SOC required by the owner of EV i, in percentage, in time step td; the $SOCR_{td}^i$ values are parameters of the optimization problem; EV_i^{bc} represents the battery capacity, in kWh, of EV i; the $n\,EV_i^{bc}$ values are parameters of the optimization problem; EV_{ce} is the efficiency of the EV charging process, which is a parameter of the optimization problem.

[6] "Inflexible EVs" are the EVs whose owners adhered to the dumb charging or multiple tariff schemes.

Equation (6.22) is used to assure that the EV battery SOC required by the EV owners at the moment of disconnection is possible to attain when considering a maximum charging rate of 3 kW. The condition implemented in (6.23) assures that only charging rates between $[0, 3]$ kW will be attributed to "flexible EV," as it was assumed that a "flexible EV" is a smart charging adherent that is charging either in a residential or in an industrial area at level 1. Equations (6.24) and (6.25) are used to guarantee that the required EV battery SOC and EV battery SOC in the time step t are always within the interval $[0, 100]$ %. Equation (6.26) assures that the time of disconnection is always posterior to time step $t + 1$.

The objective of this optimization problem is to minimize the sum of the absolute value of the deviations, as there can be positive deviations (energy bought by the aggregators higher than energy consumed by "flexible EVs" and "inflexible EVs") and negative deviations (energy consumed higher than energy bought).

The problem formulated is a linear optimization problem, which is suitable for real-time applications since it does not require any type of forecasted data. It is only necessary to know, for the current time step (t), the energy bought by the aggregators, the power consumed by the "inflexible EV," the moment of disconnection of the "flexible EV" that are currently plugged in, and the amount of energy required by their owners during the period they will stay connected to the grid.

It should be noted that the approach presented in this section can be easily adapted for other cases, like the minimization of the renewable energy wasted in systems characterized by a large integration of intermittent RES (e.g., wind). Under these circumstances, the renewable power generated by intermittent RES that is in risk of being wasted would be treated as parameters of the problem.

Procedure 2

The main objective of Procedure 2 is defining which "flexible EV" should charge at each time step and with which charging rate, in order to flatten the network load diagram as much as possible. As described next, this objective can be accomplished in two distinct stages.

During the first stage, an optimization technique is used to find a set of 336 "flexible EV" load values, which can be defined as optimal in the sense that they allow obtaining a load diagram as flat as possible for a given network. The value 336 is referred to the number of time steps of ½ h that compose 1 week.

The formulation of the optimization problem is shown below.

$$\min \sum_{t=1}^{336} (FL_t + IL_t)^2, \tag{6.27}$$

subject to

$$FL_t \geq 0, \tag{6.28}$$

$$\sum_{t=1}^{336} FL_t = TFL, \tag{6.29}$$

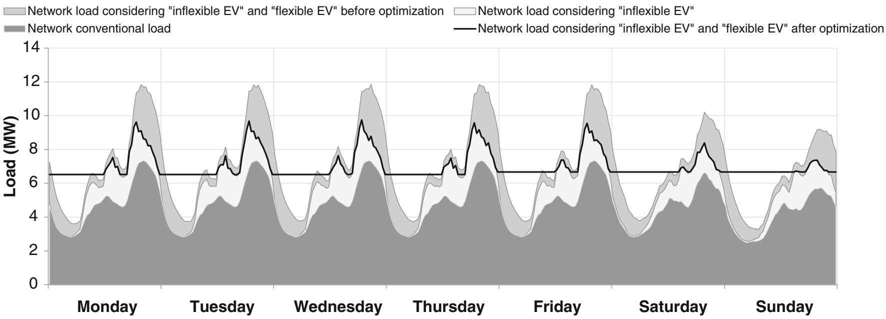


Fig. 6.14 Results obtained with the optimization problem presented in (6.27)

where t is the time step index; FL_t represents the "flexible EV" load, in kW, in time step t; the 336 FL_t values are the decision variables of the optimization problem; IL_t represents the "mandatory load[7]" in the network, in kW, in time step t; the 336 IL_t values are parameters of the optimization problem; TFL is the load consumed by the "flexible EV," in kW, during the 336 time steps considered and it is a parameter of the problem.

In order to solve the formulated problem, there are some data that need to be available, like IL_t and TFL. In practical applications, and since the optimization problem should be solved by the DSO, these data should be obtained using forecasting techniques to predict the "mandatory load" and the "flexible EV" load for the next week (the problem can also be formulated in a daily basis).

Figure 6.14 illustrates the type of results that can be obtained with the optimization problem (considering the formulation for 1 week).

The second stage of Procedure 2 is dedicated to put the results obtained with the optimization problem into practice. For this purpose, during this stage, a problem analogous to that presented in (6.21) is formulated, as shown next:

$$\min \left| FL_t - \sum_{i=1}^{n} FEVL_t^i \right|, \tag{6.30}$$

where i represents the "flexible EV" index; n is the No. of "flexible EV" assumed to be under the DSO control; FL_t represents the optimal "flexible EV" load, in kW, in time step t; the 336 FL_t values are parameters of the optimization problem; $FEVL_t^i$ represents the power absorbed by "flexible EV" i, in kW, in time step t; the $n \times 3$ $36\,FEVL_t^i$ are decision variables of the optimization problem, which can assume continuous values in the interval $[0, 3]$.

[7] "Mandatory load" is the conventional load of the network plus the load from the EV whose owners adhered to the dumb charging or multiple tariff schemes.

This problem is subject to the same restriction of the problem presented in (6.21). Its objective is minimizing the absolute value of the deviation between the optimal amount of “flexible EV” load, determined with the optimization problem presented in (6.27), and the real amount of load consumed by the “flexible EV.” The absolute value of the deviations is considered as there can be positive deviations (optimal load higher than load consumed) and negative deviations (load consumed higher than optimal load).

It should be noted that unlike in the problem presented in (6.27), where FL_t were the decision variables, in this problem, FL_t are treated as fixed parameters. The decision variables of the current problem are the power absorbed by the flexible EV for each time step—$FEVL_t^i$.

Procedures to Solve Network Operating Problems by Adjusting the EV Charging Rates

After defining which “flexible EV” should charge and with which charging rate at each time step, the network operating conditions should be analyzed to detect eventual technical problems that may appear due to the EV load. The increase in the power consumption might provoke LV or line overloading problems that demand corrective measures in order to being solved. Under these circumstances, it is necessary to define the amount of load that is required to decrease to bring voltages and lines’ ratings again to the allowable limits and to define which of the “flexible EVs” should decrease their charging rates in order to attain the desired load reduction. A procedure to tackle these problems, Procedure 3, is presented in this section. This procedure is capable of tackling simultaneously multiple LV and line overloading problems, whether these problems occur in separate feeders or in the same feeder of a given network, as both these problems require the same measure: a load reduction.

It should be referred that the two problems referred above, LV and line overloading, could be solved simultaneously using an (Optimal Power Flow) OPF-like method. However, as the resolution of this type of problems is usually very time-consuming, due to its high dimension, the expeditious approach provided by Procedure 3 was chosen over the OPF-like option since the latter is rather impractical for real-time applications.

Procedure 3

To achieve the intended objective, it is required to find a set of n load values, being n the number of “flexible EV,” which can be defined as optimal in the sense that they allow minimizing low bus voltages and line overloading problems detected in the network in a given time instant t.

This problem can be formulated as an optimization problem, as shown below.

$$\min NLVP_t + NLOP_t, \tag{6.31}$$

subject to

$$0 \leq SOCR_{td}^{i} - SOC_{t}^{i} \leq \frac{(FEVL_{t}^{i} + (td - (t+1)) \times 3) \times (1/2) \times EV_{ce}}{EV_{i}^{bc}} \times 100, \quad (6.32)$$

$$0 \leq FEVL_{t}^{i} \leq 3, \quad (6.33)$$

$$0 \leq SOCR_{td}^{i} \leq 100, \quad (6.34)$$

$$t + 1 \leq td, \quad (6.35)$$

where $NLVP_t$ represents the number of LV problems in time instant t; the number of LV problems is determined by counting all the situations where $V_t^j < V^{\min}$, where V_t^j is the voltage in bus j, in time step t, and $V^{\min}$ is the minimum allowable voltage; $NLOP_t$ represents the number of line overloading problems in time instant t; the number of line overloading problems is determined by counting all the situations where $S_t^b > S^{\max}$, where S_t^b is apparent power flow in branch b, in percentage, in time step t, and $S^{\max}$ is the maximum allowable apparent power flow, in percentage; i represents the "flexible EV" index; t represents the time index; n is the No. of "flexible EV" assumed to be under the DSO control; td represents the time step at which a given "flexible EV" disconnects from the grid; $FEVL_t^i$ represents the power absorbed by "flexible EV" i, in kW, at time step t; the n $FEVL_t^i$ are decision variables of the optimization problem; they can assume continuous values in the interval $[0, 3]$; SOC_t^i represents the battery SOC of EV i, in percentage, in time step t; the n SOC_t^i values are parameters of the optimization problem; $SOCR_{td}^i$ is the battery SOC required by the owner of EV i, in percentage, in time step td, which is the instant when the EV disconnects from the grid; the n $SOCR_{td}^i$ values are parameters of the problem; EV_i^{bc} represents the battery capacity, in kWh, of EV i; the n EV_i^{bc} values are parameters of the optimization problem; EV_{ce} is the efficiency of the EV charging process, which is a parameter of the optimization problem.

The solution of this problem demands the resolution of the power flow equations in order to check if the bus voltages and the apparent power flow in the branches are off-limits. This becomes a complex optimization problem due to the nonlinearity introduced by the power flow equations that might take a considerable amount of time to solve, namely when the number of buses and branches of the network and the number of "flexible EV" under consideration are very high.

These reasons make the optimization problem presented above rather impractical for real-time applications, as the amount of time required to solve it might not be compatible with the time available to mitigate the problems detected.

In order to overcome these limitations, an expeditious approach can be used to deal with this problem in an efficient way, which, despite not providing optimal results, allows tackling the LV and line overloading problems quickly and with very satisfactory results.

This approach is based in a heuristic that comprises two stages.

In the first stage, all the relevant network data are gathered, its topology is processed, and a power flow is run to evaluate its operating conditions. Then, a list of problematic buses is created and the buses are sequentially analyzed. A given bus is flagged as problematic if it has a voltage value below V^{min} or if it is located in the upstream end of a branch with a rating above S^{max}.

For each problematic bus, the feeder that contains the bus under analysis is selected, and the amount of load that is required to decrease in each of the feeder's buses, which allows solving the problem identified, is calculated. This calculation is performed iteratively, by decreasing in steps of a fixed value, in this case assumed to be 10 %, the existing EV load in each of the feeder's buses.

In the second stage, the "flexible EVs" that should reduce their charging rates are selected, in order to decrease the amount of power calculated in the first stage that allows solving all the problems identified. The "flexible EVs" whose charging rates are decreased are selected taking into consideration their location in the grid, being only chosen "flexible EVs" that are capable of effectively contribute to solve the LV or line overloading problems identified.

It should be noted that in a first phase, this heuristic process reduces only the charging rates of "flexible EV," always taking into consideration their owners' requests in what regards the battery SOC required in the moment they will disconnect from the grid. Nevertheless, when LV and line overloading problems are so severe that the emergency operating state is triggered, this heuristic reduces the charging rates of all the EV located in the problematic areas of the grid, disregarding if they are "flexible EV" or "inflexible EV," in order to avoid jeopardizing global system security.

The implementation of this heuristic is briefly illustrated in Fig. 6.15.

After processing the network topology and running a power flow, the buses 31 and 45 are flagged as "problematic buses." Bus 31 is flagged since it is the bus in the upstream end of a branch with congestion problems, whereas bus 45 is flagged due to its voltage value, which is assumed to be below the threshold that triggers the abnormal operating state. Then, feeders 4 and 5 are flagged as "problematic feeders," as these are the feeders that contain the buses 31 and 45, respectively.

The total load that is required to decrease is then calculated (first stage), by simulating that the EV load in the buses that belong to feeders 4 and 5 is decreased by 10 %. Afterward, a power flow is run to verify if the LV and line overloading problems were solved.

If so, the total amount of load that is required to decrease in the buses that belong to feeders 4 and 5 is computed. It should be noted that two load values are computed separately, one for feeder 4 and the other for feeder 5.

If not, the EV load in the buses that belong to feeders 4 and 5 continues to be iteratively decreased in steps of 10 %, until feasible operating conditions are attained. Then, the total amount of load that is required to decrease in the buses that belong to feeders 4 and 5 is computed.

After having knowledge of the amount of power that is required to decrease in the buses of the problematic feeders, it is defined which "flexible EV" should decrease their charging rates to achieve the desired load reduction (second stage).

In order to avoid interfering repeatedly with the same EV charging in buses 31 and 45, as branches' overloading and voltages under the allowed limits are

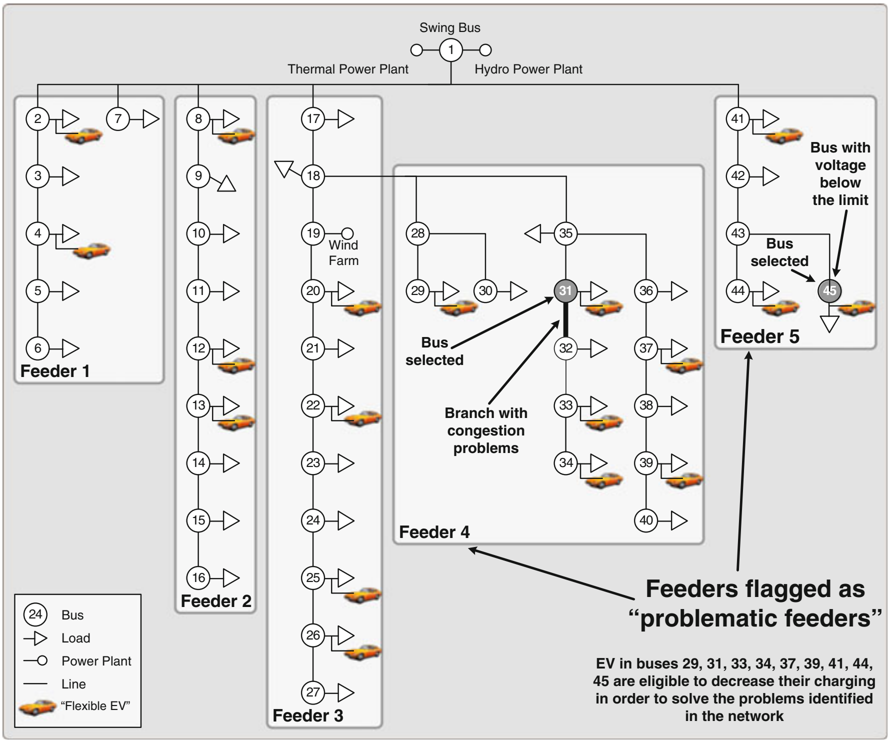


Fig. 6.15 Method used to select the EV whose charging will be decreased

problems that usually appear recurrently in the same locations of the grid, all the "flexible EVs" charging in the "problematic feeders" are considered to be eligible to decrease their charging rates in order to solve the network problems.

In the example presented in Fig. 6.16, all the "flexible EVs" charging in buses 29, 31, 33, 34, 37, 39, 41, 44, and 45 are considered to be eligible to decrease their charging rates. Thus, their charging rates are iteratively decreased in steps of 10 %, being run a power flow to evaluate the network operating conditions after each reduction, until feasible operating conditions are attained.

6.3.2.2 Development of the Approach

An algorithm based in the approach proposed can be developed, aiming to evaluate its efficiency when addressing EV impact studies. A Monte Carlo simulation method can be included in the algorithm, to iteratively generate samples of EV load in the network, terminating only when a predefined convergence criterion is met. Each sample generated provides the total amount of load in the network (conventional load plus EV load) in each time step of the week simulated,

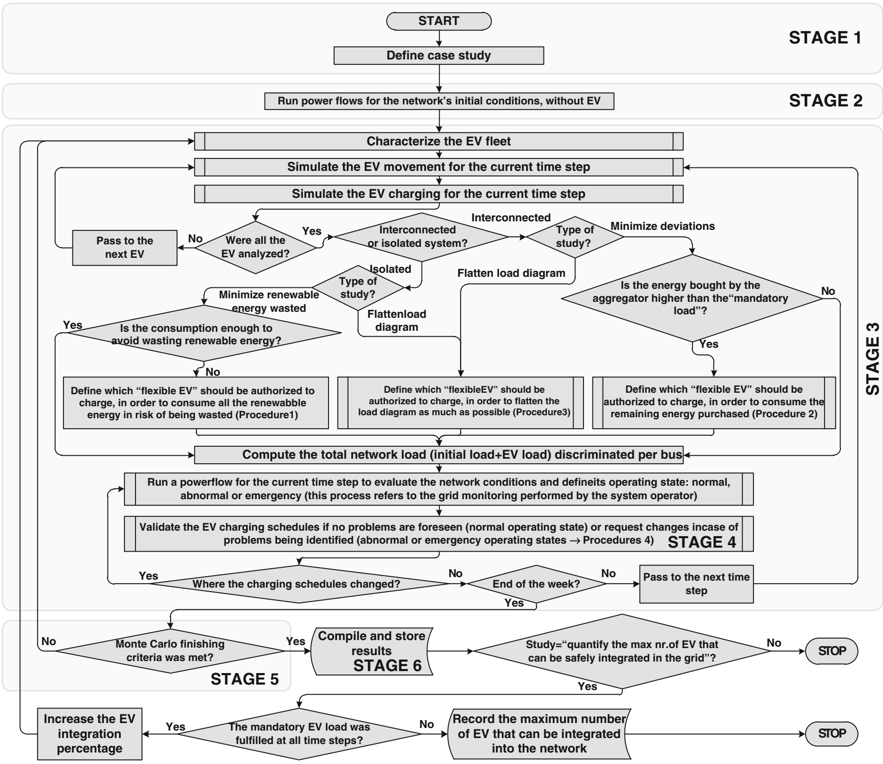


Fig. 6.16 Flowchart of the algorithm

discriminated per bus. The sample evaluation, which corresponds to the evaluation of the network operating conditions, is performed by running a power flow for each time step of the week and by analyzing the respective results. This section presents the algorithm's functionalities, as well as the most important details related to the implementation of the procedures described above.

The algorithm can be divided in six major stages, as depicted in Fig. 6.16:

1. *Study definition*: During this phase, the details related to the case study are defined, namely the type of analysis to be performed.
2. *Assessment of the initial network conditions*: After gathering all the relevant network data, the network's operating conditions, without the presence of EV, are evaluated by running consecutive power flows,[8] one per time step, until the end of the simulation period is reached. The results obtained (voltages, lines ratings, energy losses in the network, and loads) are stored and used later for comparison purposes.

[8] All the required power flows were run using the *PSS/E* software.

3. *Samples generation*: In this stage of the algorithm, the following steps are performed: (a) initial characterization of each EV in terms of battery capacity, charging power, energy consumption, and battery SOC in the beginning of the simulation [23]; (b) simulation of the EV movement and calculation of their energy requirements (using the Markov chain previously described); (c) definition of which EVs are available for charging and which will effectively charge at each time step (using Procedures 1 or 2); (d) evaluation of the grid operating conditions (by running power flows); and (e) if technical problems are detected by the DSO, the required changes in the EV charging schedules to solve them are calculated (using Procedure 3). Each sample generated provides the total load in the network (conventional load plus EV load) in each time step of the week simulated, discriminated per bus. It should be noted that the optimization problems of Procedures 1 and 2 were solved using LINGO 13.0 software.
4. *Sample evaluation*: The evaluation of the samples is made by running a power flow for each time step, being gathered information regarding loads, voltages, power flows in branches, and energy losses in the grid.
5. *Termination criteria*: To terminate the Monte Carlo simulation method, two criteria are used: (a) number of iterations; and (b) variances obtained, along the iterations of the Monte Carlo simulation method, of the aggregated grid load of each one of the 336 time instants. The second termination criterion presented means that one variance value is computed, during the iterations of the Monte Carlo simulation method, for the total network load per time instant $t, t \in [1, 336]$. The Monte Carlo simulation method is set to perform 4,000 iterations (4,000 weeks) and check, in the end, if the variation of all the 336 variances in the last five iterations is lower than $1\mathrm{e}^{-6}$. The variance variation is calculated using the following equation:

$$\Delta\text{Variance} = \left|\text{Variance}_h^t - \text{Variance}_{h-5}^t\right| < 1 \times 10^{-6}, \tag{6.36}$$

where t is the time instant index; h is the index used for the iterations of the Monte Carlo simulation algorithm; ΔVariance represents the variance variation of the aggregated network load, in time instant t, in the last five iterations of the Monte Carlo simulation algorithm; Variance_h^t represents the variance of the aggregated network load, in time instant t, in the hth iteration of the Monte Carlo simulation algorithm; Variance_{h-5}^t represents the variance of the aggregated network load, in time instant t, in the $(h-5)$th iteration of the Monte Carlo simulation algorithm.

If at least one of the 336 variances does not meet the referred convergence criterion, the process keeps running more iterations until all the variance variations are lower than the predefined value.

6. *Algorithm outputs*: The algorithm allows obtaining the EV fleet characteristics, the EV state at each time step (parked or in movement), the periods during which EVs are plugged in and available to charge, the network bus where EVs are plugged in (only for parked EV), the power absorbed by each EV at each 30 min interval (discriminated per network bus), the amount of energy provided at each

time step by the aggregators or by the DSO (depending on whether the network under analysis belongs to an interconnected or an isolated system), the total network load at each time step, the energy losses in the network at each time step, the network's voltage profiles at each time step, the network's branches ratings at each time step, among other results.

6.4 Dynamic Studies of Electric Vehicles Integration in the Power System

The implementation of the dynamic simulation models for EV may be performed differently, according to the type of application that will be analyzed. Mainly, two implementation methods can be followed, one for primary frequency control and the other for AGC operation [24].

Regarding primary frequency control, most of the commercially available software provides a module where the block diagram associated with the model that represents EV can be implemented using a graphical user interface (GUI). *Eurostag* or *Matlab* and even the very recent Graphical Module Builder add-on for *PSS/E*, among others, allow GUI implementation of dynamic simulation models, by drawing the block diagrams of the functionalities that may be required. Alternatively, these functionalities can be coded, using, for instance, *Fortran* to perform the classical implementation of the dynamic models in *PSS/E*. Being the most user-friendly option, the GUI implementation tends to be the preferred method for primary frequency control.

Concerning the modeling of AGC operation, a different strategy for implementation is followed, mainly due to the reason that AGC is a centralized control and primary control is a distributed control. This fact implies that several measurements from different points of the grid are provided to the AGC, like tie-line interconnection power flow, which computes new set points and distributes them across the generation units that participate in secondary reserve provision.

PSS/E was the adopted simulation environment for the AGC operation modeling, as it is widely used by TSO to model their networks, and so the implementation of AGC control in this software provides reassurance regarding the obtained results. In *PSS/E*, there are two approaches to the implementation of the desired control actions:

- *Conventional implementation, PSS/E focused*: Internal to the simulation procedures used by the software
- *Python script focused, interacting with PSS/E*: External to the simulation procedures used by the software

To implement the first option, it is necessary to develop a model using *Fortran*,[9] including specific *Fortran–PSS/E* routines and global variables, compile it, and declare its usage in the dynamic simulation data input file for *PSS/E*.

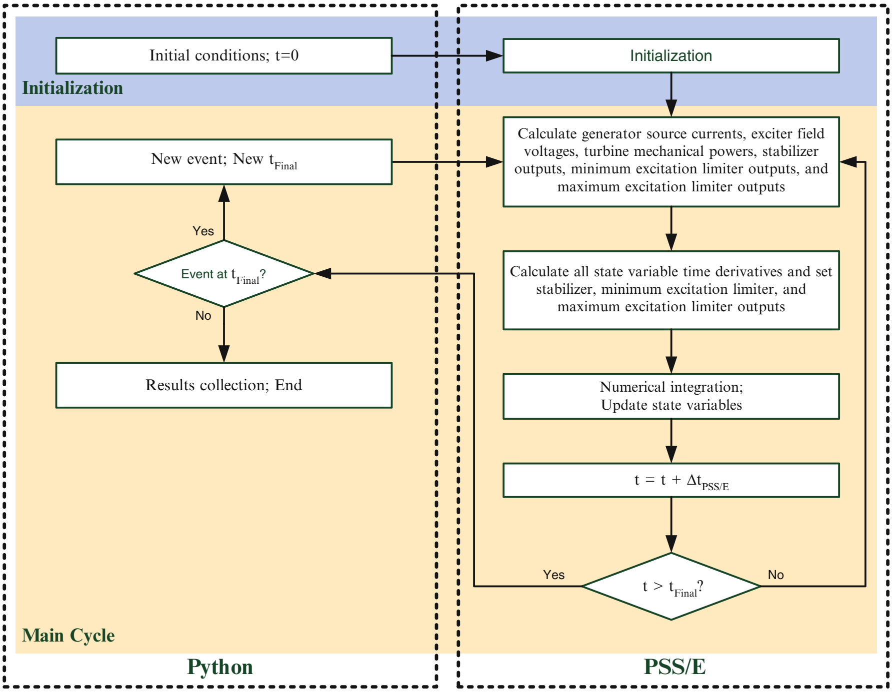


Fig. 6.17 Simulation scheme with conventional modeling, *PSS/E* focused

Following the typical implementation scheme, the developed model gets embedded in the simulation.

This alternative is robust and does not delay the simulation time. The simulation is stopped only when an event, such as load variation or bus fault, occurs. Event file is coded using *Python*.

Figure 6.17 is a flowchart of the simulation process using the conventional model implementation. On the left, the activities external to *PSS/E* operation are presented, whereas *PSS/E* simulation is depicted on the right (this part was adapted from *PSS/E* Operation Manual [25]).

To implement the second option, the dynamic data input file remains unchanged, keeping all the data related to generation.

Advanced modeling is now executed using a *Python* script. Instead of being used only to generate events, the *Python* file is also used to collect the system state evolution and manage control variables.

In opposition to what happened with the *Fortran* modeling, the data collection period, in this case, is user defined and can be as short as the integration period defined internally by *PSS/E*.

To create fast controllers using this implementation, the script must stop the simulation with time steps close to that used by *PSS/E* (using a larger time step means that a larger delay is being introduced to the response time of the controllers).

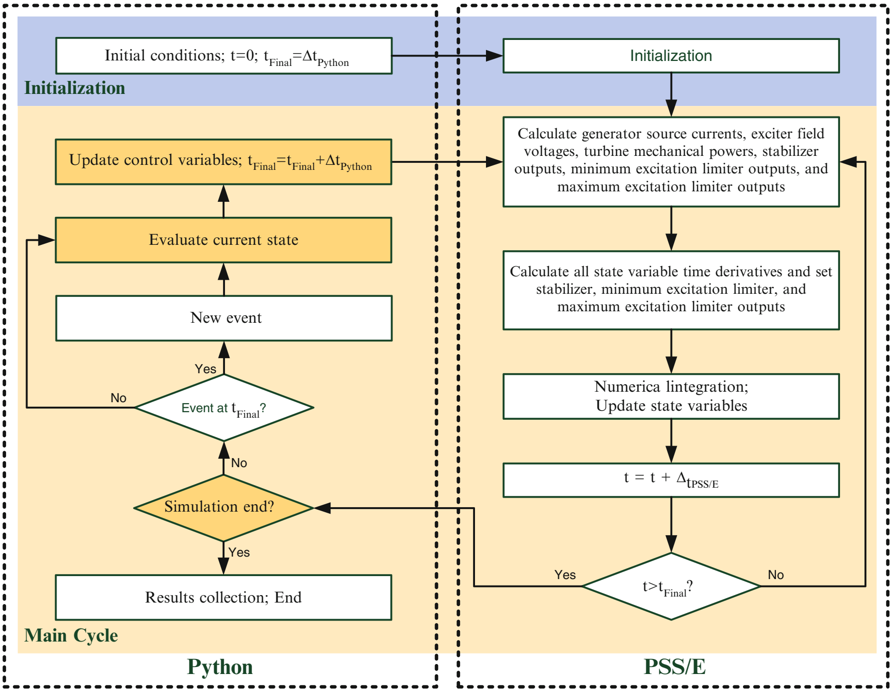


Fig. 6.18 Simulation scheme with Python script modeling, interacting with *PSS*/*E*

Then, the state evolution is evaluated and used to update the control variables that are passed into *PSS*/*E*.

Similar to Fig. 6.17, Fig. 6.18 depicts a flowchart of the simulation scheme with *Python* script modeling, interacting with *PSS*/*E*. The highlighted text boxes are the new functionalities necessary within this approach.

This method is as robust as the previous but more flexible regarding the control options that may be taken. However, external state evaluations and control actions may lead to an increase in simulation time that with nowadays processing capability is not a real drawback.

If EV frequency control droop would be the aim for implementation, the conventional modeling technique would likely be the easiest implementation method, due to the fact that the power electronic interface that is being emulated works in a decentralized way. It reads a local state variable and controls, locally, EV power consumption.

Nevertheless, as AGC operation is sought, a centralized control unit is needed. This unit requires the knowledge of state variables spread over the grid—interconnection power flows and the frequency of the center of inertia of the system. The implementation of such a control unit under the conventional approach is possible, by programming a subroutine of the simulation process of *PSS*/*E* called CONET. As previously explained, it would have to be compiled along with the rest of the models, but the outputs would have to be treated in a different way when compared with typical local models. In this case, the script included in the CONET subroutine would not deal only with global state variables that allow direct observation in the *PSS*/*E* post-simulation environment. Consequently, a post-processing work would be necessary within the *Python* script to collect all the data to replicate the state variables necessary to illustrate the reaction of the controller. If this activity is used to implement the controller in the *Python* environment, then there is no need to repeat it, as results get created along with the evolution of the script. Thus, *Python* script modeling, interacting with *PSS*/*E*, was chosen to model the AGC, and as it involved part of the variables needed to implement the EV droop control, this functionality was also implemented using the same strategy.

6.5 Conclusions

6.5.1 Steady-State Studies

The integration of EV in distribution networks is expected to impact the management and operation of distribution grids. For this reason, the DSO will have to understand the impacts that the extra amount of power consumed by EV will provoke in these systems.

In this sense, two approaches were presented in this chapter to evaluate the EV impacts in distribution networks: Methodology 1 and Methodology 2.

The deterministic approach followed in Methodology 1 to distribute EV along the network buses and determine the EV load during one entire day is appropriate to perform studies in small distribution networks. Yet it is only able to reveal the effects of a possible scenario in what regards the EV locations in the network. Even with these limitations, it allows satisfactorily evaluating the network impacts of a given integration percentage of EV and quantifying the maximum number of EVs that can be safely integrated in a given network with the three charging strategies addressed (dumb charging, multiple tariff, and smart charging).

These limitations were overcome in Methodology 2, which uses a more sophisticated and consistent approach for the same purpose. This improved approach, besides using a Markov chain tailored to simulate the EV movement, also uses a Monte Carlo simulation method that allows exploring different scenarios in what regards the EV locations in the grid and their power requirements. Moreover, this approach allows quantifying the EV impacts in time steps shorter than 1 h, as 1 h is a very long period of time during which the network operating conditions can change considerably. Furthermore, instead of only 1 day, it also allows analyzing the EV impacts in a longer time frame, like 1 week or 1 year.

The algorithm presented based in Methodology 2, besides being fitted for impact assessment studies at a regional level and for the networks' planning exercise, it also includes EV charging management modules suitable to be used in real applications. The referred modules can be used to manage the EV charging in real time by both aggregators and system operators.

From the DSO perspective, the algorithm can be used as a tool for the following purposes:

- Evaluate the impacts of a given number of EVs in a specific regional distribution network, taking into account the charging modes EVs have adhered to.
- Compute the maximum number of EVs that can be safely integrated in a particular network, also taking into consideration their charging modes.
- Detect the network components that are subject to the more demanding operating conditions and that might need to be upgraded.
- Validate the provisional bids of the aggregators.
- Perform grid monitoring and evaluate its operating conditions.
- Define the requests of load increase/decrease to mitigate voltage or line overloading problems that might appear in the network.
- Manage the EV charging in real time (when the system is in the emergency operating state).
- The algorithm might also be very helpful for the aggregators, since it allows.
- Defining the optimal bids for the day-ahead and intraday markets.
- Managing the EV charging in real time (when the system is in the normal operating state).

6.5.2 Dynamic Studies

EVs may be valuable resources in the provision of primary and secondary frequency control, either through the adjustment of their batteries' load charging rates or through the injection of active power into the grid. The activation time of such participation is shorter than that of conventional generators, due to ramping limitations. For that, EVs may be exploited as controllable loads or as storage devices.

While providing ancillary services, the EV behavior on the event of short-circuit disturbances is an important issue. Being the EV approximately constant power loads from a grid-side perspective, this leads to a worst case scenario in terms of voltage drops. As power requirements are constant to compensate for a voltage drop caused by a short circuit, EV will request more current from the grid, contributing for additional voltage drops. So in a future massive integration scenario, this issue may have to be dealt with, by creating new control rules that prevent these hazardous conditions. While EV integration is moderate, in the short to medium term, such considerations are not necessary as the systems may cope with EV load behavior. Additionally, when EVs are ancillary service providers, it is necessary to guarantee their availability to react after disturbances. It was verified that while EVs are regarded as controllable loads, the system behavior is controlled, but if the energy stored in the EV batteries is to be explored, then additional measures must be taken with the inclusion of the fault ride through capabilities.

In primary frequency control, EV in pre-disturbance environment can be charging or in idle operation mode, and when the disturbance occurs, the consumed value varies linearly with the frequency change. To perform primary frequency control, EV should mimic the reaction of the governing systems of the generators, implementing a power–frequency droop on the EV power electronic converter control. The usage of EV in primary frequency control can be particularly important in isolated systems with large amounts of RES that present great output variability or small controllability.

The operation of the AGC is the centerpiece of secondary frequency control. The AGC uses the resources that got committed with secondary reserve provision in the reserve market, and in case of a disturbance, it distributes set points among the participants. As individual EV would not be able to enter the reserve market alone, the aggregator is needed for market negotiations. Aggregator providing secondary reserves receives a set point from the AGC and splits it by the EV that established contracts with the aggregator for secondary reserve provision. To create the set points, the AGC must be constantly updated on frequency value and interconnection power deviations, integrating the error to define the set points that will fade possible steady-state deviations in relation to nominal frequency and scheduled tie-line power. The provision of secondary reserves by EV is potentially beneficial for interconnected systems with limited reserve margins due to large-scale deployment of uncontrollable RES or composed by generators with small ramping slopes.

Finally, simulation capability was described in this chapter with the development of models for EV and an algorithm for recreating AGC operation. These adaptations to existing dynamic simulation software allow testing the expected effectiveness of these control schemes exploiting EV and comparing the global system performance to the conventional approaches to the problem. In both cases, EV controllability will add to existing system controllers, contributing for the robustness and resilience of both isolated and interconnected systems.

References

1. Kempton W, Tomic J (2005) Vehicle-to-grid power fundamentals: calculating capacity and net revenue. J Power Sources 144:268–279
2. Lopes JAP et al (2007) Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities. Electric Power Syst Res 77:1189–1203
3. Gil NJ, Lopes JAP (2007) Hierarchical frequency control scheme for islanded multi-microgrids operation. In: Power Tech, 2007 IEEE, Lausanne, p 473–478
4. Lopes JAP et al (2006) Defining control strategies for MicroGrids islanded operation. IEEE Trans Power Syst 21:916–924
5. Bending S et al (2010) Specification for an enabling smart technology. Deliverable D1.1 of the European Project MERGE, August 2010
6. Guille C, Gross G (2009) A conceptual framework for the vehicle-to-grid (V2G) implementation. Energy Policy 37:4379–4390

7. Lopes JAP et al (2011) Integration of electric vehicles in the electric power system. Proc IEEE 99:168–183
8. Lopes JAP et al (2005) Microgrids black start and islanded operation. Presented at the 15th PSCC, Liège, Belgium
9. European Network of Transmission System Operators for Electricity (ENTSO-E, formerly UCTE) (2004) Operation Handbook. Available: https://www.entsoe.eu/resources/publications/system-operations/operation-handbook/
10. Barsali S et al (2002) Control techniques of dispersed generators to improve the continuity of electricity supply. In: Power Engineering Society Winter Meeting, 27-31 January, 2002, New York, NY, USA, IEEE, vol 2, p 789–794
11. Kundur P (1994) Power system stability and control. McGraw-Hill, New York, NY
12. Madureira AG (2010) Coordinated and optimized voltage management of distribution networks with multi-microgrids. Ph.D., Faculty of Engineering, Universidade do Porto
13. AGM Battery Technology: Lithium-ion Cell ICR34490HC—Product Datasheet. Available: http://www.agmbatteries.com/documents/ICR34490HC.pdf
14. Lopes JAP et al (2009) Identifying management procedures to deal with connection of electric vehicles in the grid. In: PowerTech, 2009 IEEE, Bucharest, p 1–8
15. Clement-Nyns K et al (2010) The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. IEEE Trans Power Syst 25:371–380
16. Soares FJ (2011) Impact of the deployment of electric vehicles in grid operation and expansion. Ph.D. thesis, Department of Electrical and Computer Engineering, Faculty of Engineering, University of Porto, Porto
17. Ball R et al (2010) Modelling electric storage devices for EV. Deliverable D2.1 of the European Project MERGE, January 2010
18. Inquérito à mobilidade da população residente. INE - Instituto Nacional de Estatística, 2000 (in Portuguese)
19. Fisz M (1980) Probability theory and mathematical statistics. Krieger Pub. Co., Huntington, NY
20. Karlin S, Rostand F (1969) Initiation aux processus aléatoires. Dunod, Paris
21. Rozanov YA (1973) Procesos Aleatorios: Editorial Mir Moscu
22. Bittanti S, De Nicolao G (1991) Markovian representations of cyclostationary processes. In: Gerencséer L, Caines P (eds) Topics in stochastic systems: modelling, estimation and adaptive control, vol 161. Springer, Berlin, pp 31–46
23. Soares FJ et al (2011) A stochastic model to simulate electric vehicles motion and quantify the energy required from the grid. Presented at the PSCC, Stockholm, Sweden
24. Almeida PMR (2011) Impact of vehicle-to-grid in the power system dynamic behaviour. Ph.D. thesis, Department of Electrical and Computer Engineering, Faculty of Engineering, University of Porto, Porto
25. Siemens PTI - Software Solutions (2009) PSS®E 32.0 Program Application Guide: Volume II. Siemens Energy, Inc., Power Technologies International

Chapter 7
Impacts of Large-Scale Deployment of Electric Vehicles in the Electric Power System

P.M. Rocha Almeida, F.J. Soares, and João A. Peças Lopes

7.1 Introduction

In this chapter, the most relevant results that were obtained from testing the approaches and algorithms developed in Chap. 6 are presented.

The chapter is divided into two major sections, one dedicated to steady-state analysis and the other to dynamic studies.

The steady-state section encloses the results obtained from the implementation of Methodology 1 and Methodology 2.

As referred in Chap. 6, Methodology 1 follows a deterministic method to distribute electric vehicle (EV) along the network buses and determine EV loads during an entire day. Differently, Methodology 2 uses a stochastic method to simulate the expected movement of EV during 1 week, allowing exploring different scenarios in what regards the EV locations in the grid and their power requirements. Methodology 2 also includes a set of management and control strategies that may be used by Distribution System Operator (DSO) and aggregators to manage the EV charging in real time.

For both methodologies, it is made, firstly, a description of the type of studies performed. Then, the distribution test networks used to create the cases used for the simulations are characterized. Afterward, results from the simulations are presented for evaluating the performance of the algorithms, as well as for validating and consolidating the approaches developed.

The section dedicated to the dynamic studies includes a description of the test systems and the results obtained for the primary frequency control with EV and for the automatic generation control (AGC) with EVs in this case.

P.M.R. Almeida (✉) • F.J. Soares • J.A. Peças Lopes
INESC TEC (Formerly INESC Porto), Porto, Portugal
e-mail: pedro.r.almeida@inescporto.pt; filipe.j.soares@inescporto.pt; jpl@fe.up.pt

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_7,

7.2 Steady-State Studies

7.2.1 Identification of EV Integration Limits: Methodology 1

In this section, the impacts provoked by the EV battery charging on an MV grid from a semi-urban area, used as test case, are evaluated using the algorithm developed based in Methodology 1. This methodology assumes that the load inherent to EV charging will appear in the grid nodes proportionally to the residential power installed in each node.

Voltage profiles, lines loading, energy losses variations, as well as changes in load diagrams and the additional requirements to fulfill EV needs have been the object of analysis in the simulations performed.

7.2.1.1 Description of the Studies Performed

Firstly, the maximum number of EVs that be safely integrated in the MV network are evaluated for three distinct scenarios: all EV as dumb charging adherents, all EV as multiple tariff adherents, and all EV as smart charging adherents.

The maximum allowable EV integration is computed by increasing the integration of EV in the network in a stepwise manner, until a violation of the voltage limits or a branch overloading occur.

Then, three more simulations are performed in order to evaluate the effectiveness of the smart charging strategy, when compared with the dumb charging and the multiple tariff, in what regards the impacts provoked in the grid operating conditions. These simulations allow evaluating the network operating conditions when the number of EVs that can be integrated with the smart charging behave as, dumb charging adherents, multiple tariff[1] adherents, and smart charging adherents.

7.2.1.2 Case Study

Figure 7.1 describes the MV network used in this study as test case. It corresponds to a typical semi-urban, 15 kV grid, which despite being meshed is explored using a radial configuration (the dashed branches are open). It has two feeding points, represented by the round shapes in the figure, energizing two separated areas. The areas are separated by normally open branches, as marked in the figure. The specified voltage in the feeding points is 1.05 p.u., whereas the power factor assumed for the conventional load is 0.96.

[1] The lower electricity price period assumed was that of the dual tariff policy currently implemented in Portugal: 22–8 h. More information can be found in: http://www.edpsu.pt/pt/particulares/tarifasehorarios/ (in Portuguese).

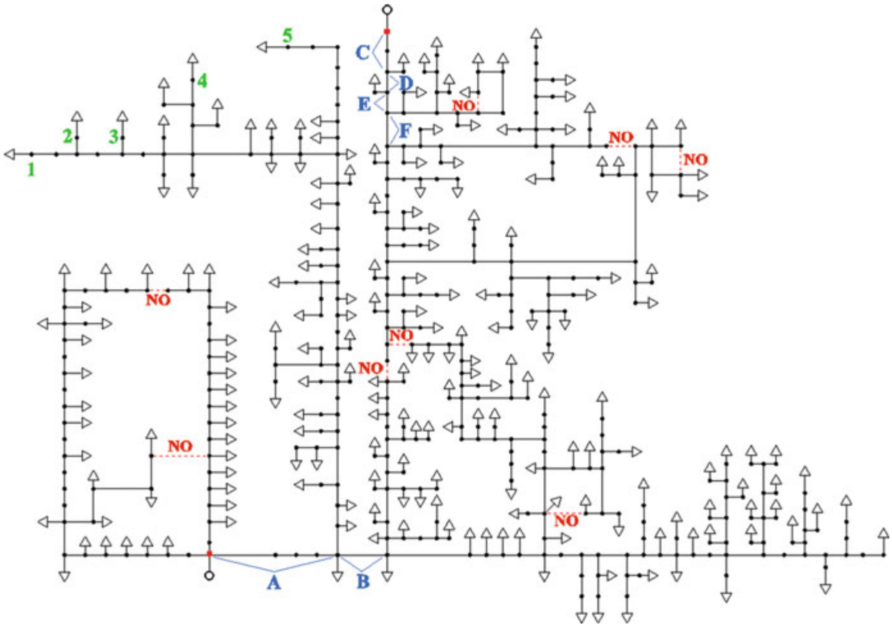


Fig. 7.1 MV distribution grid. The numbers 1–5 identify the buses that are more prone to having voltage problems. The letters A–F identify the most congested branches (normally open branches are marked as NO)

In order to perform a 24 h simulation, a typical daily load diagram for a semi-urban MV grid was used [1]. This diagram, depicted in Fig. 7.2, was obtained by aggregating load diagrams of different types of Portuguese consumers.

The residential, commercial, and industrial consumers' diagrams were combined considering the proportion of installed power related with each type of these consumers. Thus, as shown in the pie chart of Fig. 7.2, the final diagram has a contribution of 66 % of the residential sector, 28 % of the commercial, and 6 % of the industrial, as these are the proportions of installed power related with each type of load. The peak power, during the typical day chosen, is 16.6 MW, while the energy consumed is *ca.* 277 MWh. The total number of vehicles considered to be enclosed in the geographical area of this grid is approximately 12,700, which was determined assuming an average value of 1.5 vehicles per household.

7.2.1.3 Results

1. Maximum allowable EV integration

   The maximum allowable EV integration percentages in the MV grid were 17 % with the dumb charging, 20 % with the multiple tariff, and 63 % with the smart charging. The percentages are relative to the total number of conventional

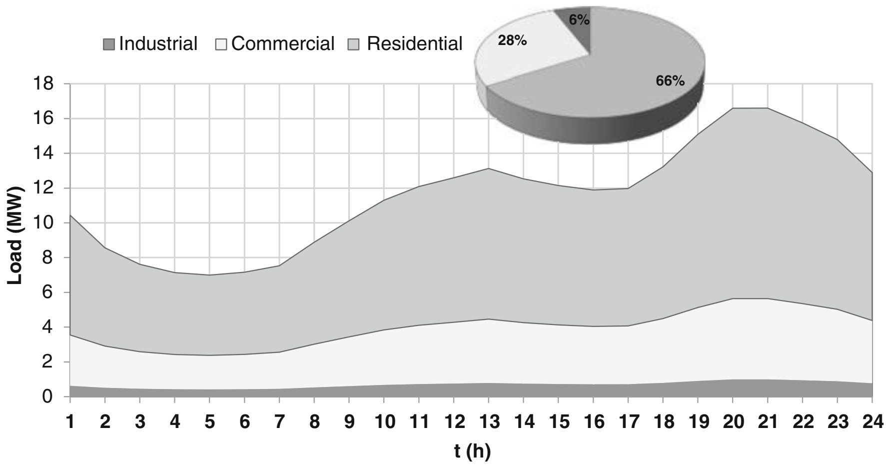


Fig. 7.2 Load diagram of a typical day (the pie chart shows the energy consumption per sector)

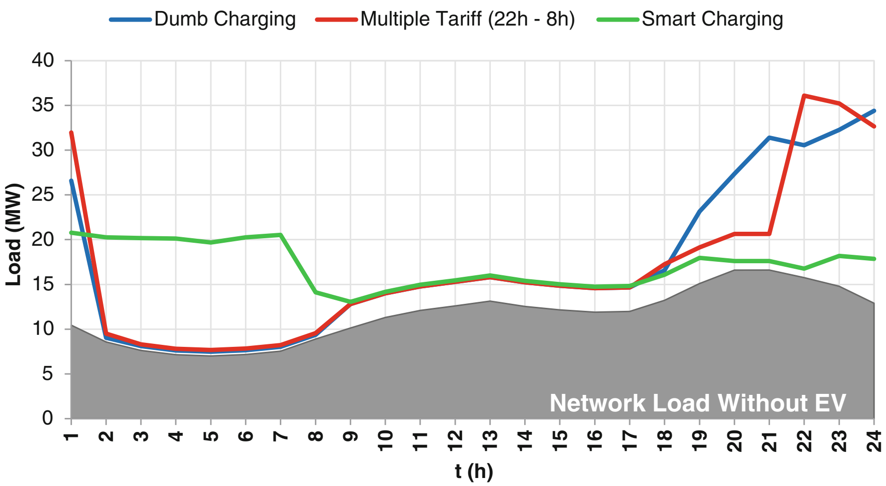


Fig. 7.3 Changes in the load diagram with an EV integration of 63 %

vehicles enclosed in the geographical area covered by this network, which is, as referred previously, *ca.* 12,700 vehicles. For the dumb charging, multiple tariff, and smart charging, the number of EVs that can be safely integrated in this network is therefore 2,159, 2,540, and 8,001, respectively. As it will be further discussed in the section dedicated to the voltage profile analysis, under-voltage problems was the factor that limited the EV integration in all the charging modes studied.

2. Changes in load diagrams
   Figure 7.3 shows the load diagram changes for the charging strategies addressed, assuming an EV integration of 63 %, which is the maximum EV integration possible with the smart charging strategy, without network reinforcements.

Table 7.1 Voltage of the buses 1–5 (see Fig. 7.1)

Bus	Voltage (p.u.)				
	1	2	3	4	5
Without EV	0.961	0.962	0.962	0.962	0.964
Dumb charging	0.843	0.844	0.847	0.851	0.858
Multiple tariff (22–8 h)	0.833	0.835	0.835	0.837	0.838
Smart charging	0.902	0.902	0.904	0.905	0.905

In the scenario without EV, this network has a peak load of 16.6 MW, which is incremented to 34.4 MW using the dumb charging, to 36.3 MW using the multiple tariff, and to 20.8 MW using the smart charging. The latter is a noteworthy achievement, since the peak load increased only 4.2 MW with an EV integration of 63 %, representing *ca.* 8,000 EV.

It is interesting to notice that the EV charging, for the dumb charging and the multiple tariff, provokes changes in the hour at which the grids' peak load occurs. In the particular case of this network, the peak load occurrence changes from 21 to 24 h with the dumb charging, to 22 h with the multiple tariff, and to 1 h with the smart charging.

3. Voltage profiles

Looking at Table 7.1, it is possible to evaluate the impact of the EV integration in the voltage profiles of some buses electrically distant from the feeder.

Regarding dumb charging, the average voltage drop in the five most critical buses is 11.8 %. Bus 1, which is the farthest from the feeder, experiences the largest voltage change. All the other grid nodes not included in Table 7.1 suffer similar changes in their voltages, but the five presented are those with bigger drops. When the multiple tariff is implemented, the average voltage drop in the same five buses is 13.2 %. The smart charging is the strategy that allows obtaining better voltage profiles, as with this charging strategy, the voltages in these buses, despite decreasing 6.1 % in average, do not drop below the lower limit of 0.90 p.u. [2].

Figure 7.4 shows the voltage of bus 1 for the scenarios studied and a dashed line indicating the voltage lower limit, which is almost reached in the smart charging scenario. For this reason, an EV integration of 63 % represents the maximum feasible limit for this charging strategy, as for higher integration levels, the voltage of bus 1 would drop below 0.90 p.u. The same happened for the dumb charging and multiple tariff strategies, where the voltage lower limit was reached with EV integrations of 17 and 20 %, respectively.

When analyzing the worst bus voltage (bus 1) in the different charging methods, results show that voltage is the limiting factor to higher levels of EV integration. For the same integration level, voltage lower limit is reached first than branches' maximum rating. The smart charging always attains the best results. The dual tariff policy provides better results than the dumb charging for low integration levels, but for higher integration levels, it is not a good strategy since it concentrates a very high number of EVs charging simultaneously at 22 h.

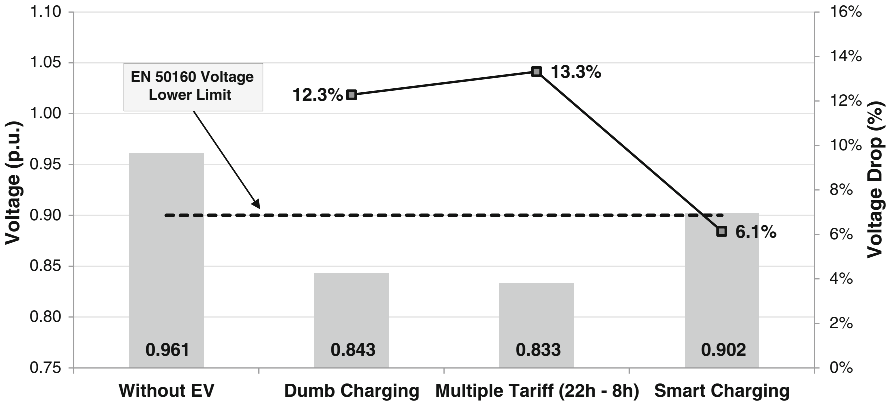


Fig. 7.4 Worst bus voltage (bus 1)

4. Branches' loading
   Table 7.2 shows the evolution of congestion levels, in six of the most loaded branches in the grid. As expected, the most problematic spots are located near the feeding points once all the power demanded flows through the lines adjacent to it.
   With the dumb charging, the average increase in the congestion levels of the six line sections, when comparing with the scenario without EV, is 122.8 %. The biggest changes were observed in line sections C, D, and E. Their ratings increased by *ca*. 130 %. The maximum allowable rating was surpassed in all the branches, except branch F. The power flows through all the other branches along the grid raises as well but never reaching ratings above 85 %.
   For the multiple tariff, the average increase in the congestion levels of the six line sections is 138.2 %. The biggest changes were observed again in line sections C, D, and E. Their ratings increased by *ca*. 150 %. The maximum allowable rating was surpassed in all the lines, showing that the multiple tariff strategy, for high EV integration levels, provokes even worst impacts than the dumb charging. Nevertheless, it should be stressed that for low EV integration levels, the dual tariff, compared with the dumb charging, has a positive impact in the grid performance, as it was proven by the higher number of EVs that can be safely integrated in the grid with it (20 % with the multiple tariff vs. 17 % with the smart charging).
   In what regards the smart charging, the average increase in the congestion levels of the six line sections is only of 33.9 %. The maximum allowable rating was never surpassed in any line, proving the effectiveness of this charging strategy. Even though this is not the most critical aspect of this network, branches' congestion is also an issue that deserves special attention, given that it can be the limiting factor to higher EV integration levels in networks with different characteristics from the one analyzed in this section.

Table 7.2 Congestion levels of the branches A–F (see Fig. 7.1)

Branch	Branch rating (%)					
	A	B	C	D	E	F
Without EV	71.7	63.5	43.2	43.1	42.9	35.1
Dumb charging	145.3	132.8	101.2	100.7	100.5	75.5
Multiple tariff (22–8 h)	156.4	143.3	107.6	107.1	107.1	80.2
Smart charging	87.8	81.3	60.2	60.1	60.1	46.3

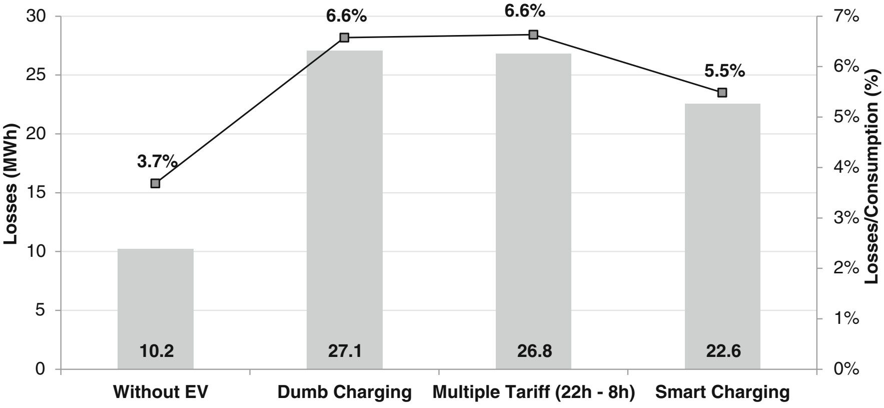


Fig. 7.5 Energy losses in all the scenarios studied (during the entire day)

5. Energy losses
   The values of the daily losses, for the three charging strategies studied, are presented in Fig. 7.5.
   The bars show their absolute values (referred to the left vertical axis), while the squares represent their value relative to the overall energy consumption (referred to the right vertical axis).
   As expected, the smart charging method is the one that provides better results since it optimizes the load distribution during the day, minimizing the occurrence of high peak loads where the consumption reaches very high values. The peak load periods are the most critical for the losses as they are proportional to the square of the current, which is very high in such conditions.

7.2.2 Spatial–Temporal EV Simulation Tool: Methodology 2

In this section, the impacts provoked by the EV battery charging on an MV test network are evaluated using the tool developed based in Methodology 2. This methodology uses a Markov chain to simulate the expected movement of EV during 1 week and a Monte Carlo simulation method that allows exploring different scenarios in what regards the EV locations in the grid and their power requirements. This approach also includes a set of management and control strategies that may be used by DSO and aggregators to manage the EV charging in real time.

As Methodology 2 allows performing a wider variety of studies than Methodology 1, the results presented in this section are more extensive than those presented in the previous section. In addition, results are presented for a week period, instead of only 1 day, and considering time steps of 30 min, instead of 1 h. It should also be stressed that, for each of the simulations performed in this section, 4,000 iterations were run with the Monte Carlo simulation method described in Chap. 6. Thus, all the results presented are referred to the average values obtained from all the iterations performed.

Besides the analysis to the maximum allowable EV integration levels, voltage profiles, lines loading, energy losses variations, and changes in load diagrams, several other variables are also analyzed in this section, like the following:

- The amount of EV load that would have to be reduced in each scenario in order to avoid violating the networks' technical restrictions
- The average number of interruptions per EV and the non-delivered energy (in the cases where it is necessary to reduce some EV load)
- The EV mobility patterns (number of journeys and traveled distances)
- The evolution of the EV batteries' State-of-Charge (SOC) during the simulation period
- Deviations between the energy bought in the electricity markets by the aggregators and the energy effectively consumed by EV

7.2.2.1 Description of the Studies Performed

Similar to the procedure followed for Methodology 1, in the first place, the maximum number of EVs that can be safely integrated instead of that be safely integrated in each of the network was evaluated for three scenarios: all EVs as dumb charging adherents, all EV as multiple tariff adherents, and all EVs as smart charging adherents.

The maximum allowable EV integration is computed by increasing, in a stepwise manner, the integration of EV in the network, until a violation of the voltage limits or a branch overloading occur.

Then, four more simulations are performed in order to evaluate the effectiveness of the smart charging strategy, when compared with the dumb charging and with two distinct multiple tariff policies, in what regards the impacts provoked in the grid operating conditions. These simulations allow evaluating the network operating conditions when the number of EVs that can be integrated with the smart charging behave as dumb charging adherents, multiple tariff (22–8 h) adherents, multiple tariff (1–7 h) adherents, and smart charging adherents.

In each simulation performed, two distinct situations are evaluated: the presence and the absence of the grid monitoring performed by the DSO. While in the former the DSO might reduce the EV load to avoid the violation of the network

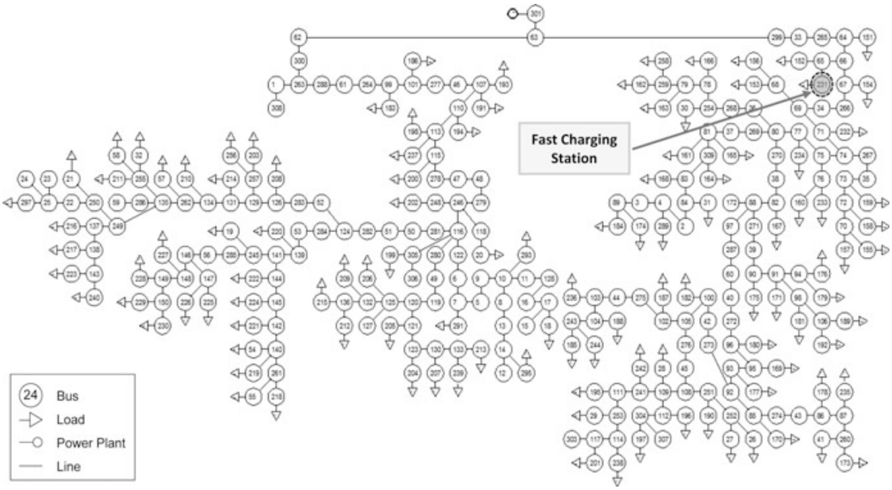


Fig. 7.6 Single line diagram of the network

components' technical limits, in the latter it is assumed that the DSO never interferes with the EV charging. These two distinct situations were evaluated for comparison purposes, with the objective of analyzing the influence that the DSO might have over the EV charging.

Two multiple tariff policies were also tested in order to prove that better results could be attained with this charging strategy if a dedicated multiple tariff for EV is created, instead of using the current one into force in Portugal.

7.2.2.2 Case Study

Figure 7.6 depicts the single line diagram of the MV network from a rural area (15 kV) used as test case. It is composed by residential, industrial, and commercial areas, as it covers a larger geographical region and thus allows tracking each EV while commuting to and from work and to and from leisure activities.

The power factor assumed for the conventional load is 0.96, whereas the specified voltage in the feeding point is 1.05 p.u.

There is a total of 7,035 EV enclosed in the geographical area covered by this network, and it was assumed that only one fast charging station exists, located in a very robust area of the network (bus 231), not prone to technical limit violations.

In order to perform the simulations, a typical weekly load diagram for this network was used. This diagram, depicted in Fig. 7.7, was obtained by aggregating the load diagrams of the different types of consumers within the network.

The residential, commercial, and industrial consumers' diagrams were combined, taking into account the proportion of installed power related with each type of these consumers. As shown in the pie chart of Fig. 7.7, the final diagram has a contribution of 65 % of the residential sector, 20 % of the commercial,

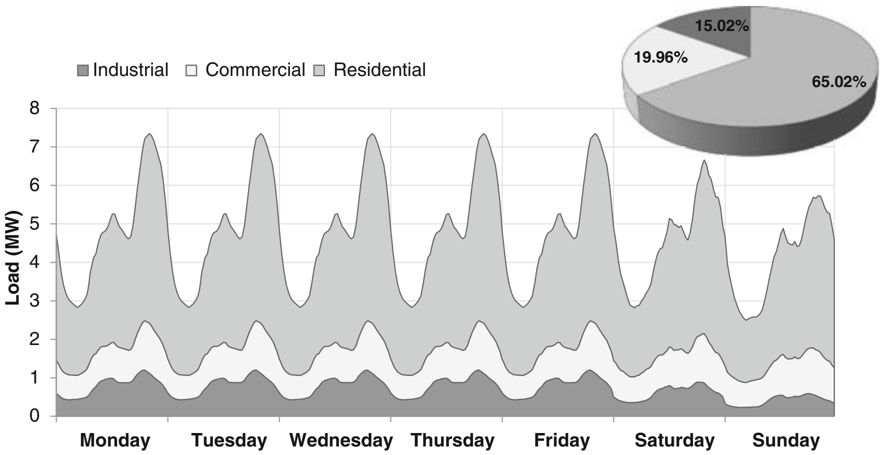


Fig. 7.7 Load diagram of a typical week (the pie chart shows the energy consumption per sector)

and 15 % of the industrial, as these are the proportions of installed power related with each type of load within this grid. The night consumption in the commercial sector is essentially due to the activities developed by restaurants and hotels in the geographical area covered by the network. The peak of conventional load is 7.3 MW, distributed over 115 of the 309 network buses, and the energy consumption during a typical week assumes the value of 789 MWh.

7.2.2.3 Results

1. Maximum allowable EV integration
   The maximum allowable EV integration percentages in this MV network are depicted in Fig. 7.8.
   The percentages are relative to the total number of conventional vehicles enclosed in the geographical area covered by this network, which is, as referred previously, *ca.* 7,035 vehicles. For the dumb charging, multiple tariff (22–8 h), and smart charging, the number of EVs that can be safely integrated in this network is therefore 422, 563, and 1,759, respectively. As it will be further discussed in the subsection dedicated to the voltage profile analysis, undervoltage problems were the factor that limited the EV integration in all the charging modes studied.
2. Changes in load diagrams
   Figure 7.9 shows the load diagram changes for the charging strategies addressed, assuming an EV integration of 25 %, which is the maximum EV integration possible with the smart charging strategy, without network reinforcements.

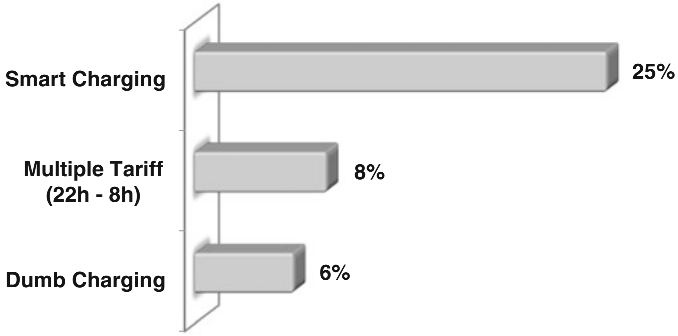


Fig. 7.8 Maximum allowable EV integration in the MV network from a rural area

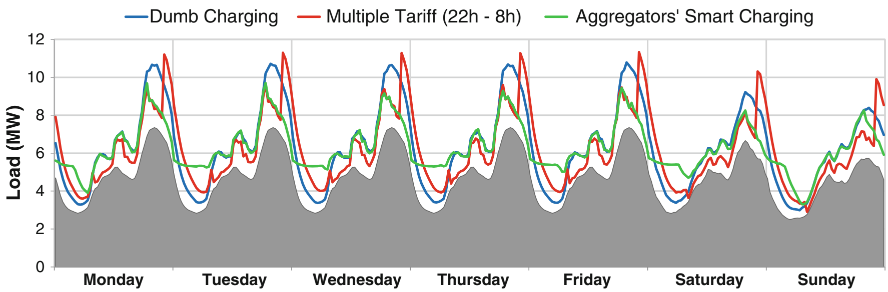


Fig. 7.9 Changes in the load diagram with an EV integration of 25 %

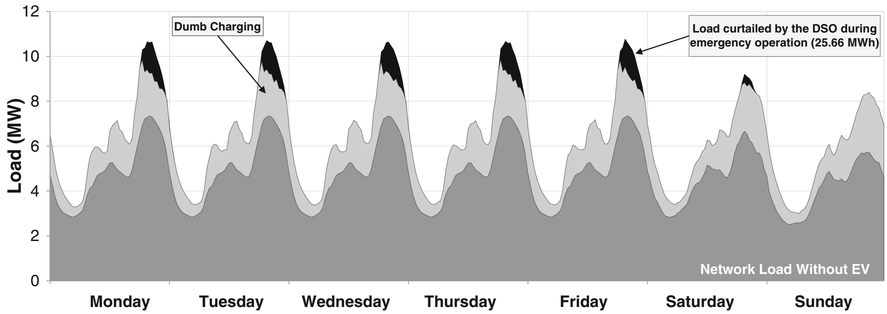


Fig. 7.10 Load diagram in the dumb charging scenario

The changes in the load diagram with the dumb charging are depicted in detail in Fig. 7.10. With this charging strategy, the EVs tend to charge mostly at the end of the day, which is the time period when people arrive home from work. In the weekdays, there are two other periods in the day where the EV load is considerably high. The first occurs in the morning, after the first journey of the day of the majority of the drivers, which is from home to work. This load

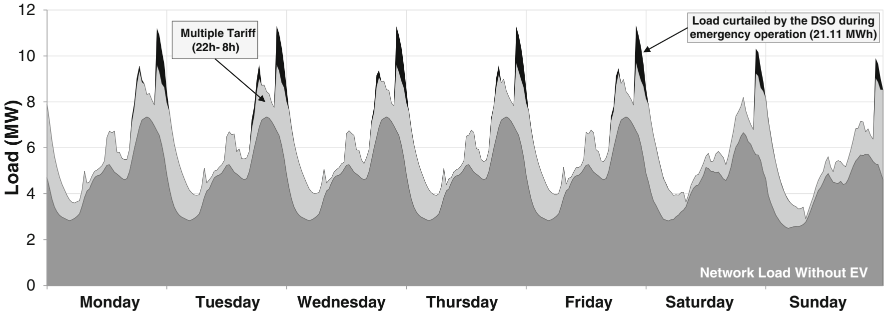


Fig. 7.11 Load diagram in the multiple tariff (22–8 h) scenario

appears mostly in commercial and industrial areas, as it was assumed that EV owners have the possibility of charging their EV at their working places. The second occurs after the lunch period, when there are a considerable number of vehicles in movement that might need to be recharged afterward.

As shown in Fig. 7.10, the amount of power requested by the EV in the dumb charging mode provokes a very large increase in the peak load, leading to the violation of the technical limits of several network components. In order to avoid these violations, the DSO would have to reduce 25.66 MWh of the energy demanded by EV during the week (black areas in Fig. 7.10). The amount of EV load that needs to be reduced in order to bring the system again to its normal operating state is calculated in accordance with Procedure 3 defined in Chap. 6.

Figure 7.11 shows the changes in the load diagram in the multiple tariff (22–8 h). With this charging strategy, the EV only charge in level-1[2] charging facilities between 22 and 8 h, which is the period of time when the energy prices are assumed to be lower. For this reason, there are a high number of EVs connecting to the grid for charging at 22 h and the amount of power requested provokes the violation of the technical limits of several network components. In order to avoid these violations, the DSO would have to reduce 21.11 MWh of the energy demanded by EV during the week (black areas in Fig. 7.11). Once again, the amount of EV load that needs to be reduced in order to bring the system again to its normal operating state is calculated in accordance with Procedure 3 defined in Chap. 6.

The remaining EV consumption, outside the period 22–8 h, is due to EV charging at level 2[3] (commercial areas) and at level 3[4] (fast charging stations). As it is shown in Fig. 7.11, the multiple tariff policy currently into force in Portugal is not the most adequate to be adopted for the EV, as it does not allow to shift a substantial part of the EV load to the valley periods.

[2] Level 1—3 kW charging power for EV charging in residential or industrial areas.

[3] Level 2—12 kW charging power for EV charging in commercial areas.

[4] Level 3—40 kW charging power for EV charging in fast charging stations.

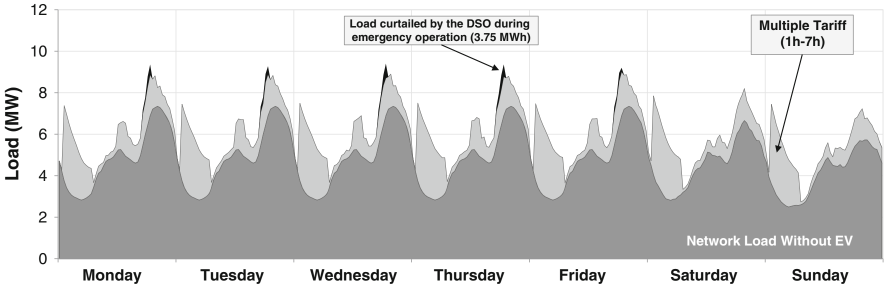


Fig. 7.12 Load diagram in the multiple tariff (1–7 h) scenario

For this reason, a different multiple tariff policy was tested, where the energy prices were assumed to be lower between 1 and 7 h. The results obtained are presented in Fig. 7.12.

As it is shown, this multiple tariff allows shifting a very significant part of the EV load to the valley hours. As a result, the occurrence of technical limit violations is greatly reduced. The DSO would only have to reduce 3.75 MWh of the energy demanded by EV, against the 18.16 MWh with the previously discussed multiple tariff strategy (22–8 h).

As this network belongs to an interconnected system, it is assumed that aggregators exist, which are responsible for the EV charging management in normal operating conditions. As referred in Chap. 6, the aggregators will try to buy energy in the markets in the periods when its price is lower and manage the "flexible EV"[5] charging accordingly. Nevertheless, as the "flexible EV" availability and electricity price forecasting performed by the aggregators are outside the scope of this work, it was assumed that the electricity price has a quadratic dependency of the total consumption and thus the aggregators' optimal bids would basically be those that allow flattening the load diagram as much as possible.

The procedure followed to calculate the aggregators' optimal bids, presented in Procedure 2 subsection in Chap. 6, is based in an optimization problem, which take into account the forecasts of "mandatory load"[6] and the "flexible EV" load.[7] These data are obtained by running a preliminary iteration of the Monte Carlo algorithm for the current scenario. The results obtained are treated as forecasted data and used directly in the optimization problem.

[5] "Flexible EVs" are the EVs whose owners adhered to the smart charging scheme and that are charging at level 1 (residential and industrial areas—3 kW).

[6] "Mandatory load" is the network base load plus the load of dumb charging and multiple tariff adherents plus the load of smart charging adherents charging at levels 2 (commercial areas—12 kW) and 3 (fast charging stations—40 kW).

[7] "Flexible EV" load is the load from smart charging adherents charging at level 1 (residential and industrial areas—3 kW).

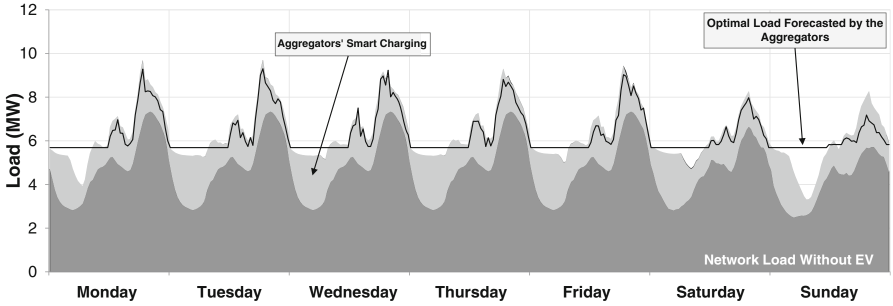


Fig. 7.13 Load diagram in the smart charging scenario

The result of the optimization problem is represented by the black line in Fig. 7.13. Assuming that the aggregators' optimal bids are fully accepted in the electricity markets, the aggregators will try to manage the "flexible EV" charging in order to minimize the deviations between the energy they bought and the energy effectively consumed by EV (light gray area in Fig. 7.13, referred to as aggregators' smart charging). The "flexible EV" charging management is performed in accordance with the second stage of Procedure 2, as defined in Chap. 6.

It should be noted that the deviations between the energy bought by the aggregators and the energy consumed by EV would probably be greatly reduced if the availability restrictions of the "flexible EV" were included in the problem used to calculate the aggregators' optimal bids (first stage of Procedure 2).

In the scenario without EV, this network has a peak load of 7.3 MW, which is incremented to 10.8 MW with the dumb charging, to 11.3 MW with the multiple tariff (22–8 h), and to 9.7 MW with the aggregators' smart charging.

3. Load reduced by the DSO during emergency operation

As described in Section 6.2.2 of Chap. 6, the emergency operating mode is triggered when, for some reason, the grid normal technical operation is compromised. Under such conditions, the aggregators' control signals can be overridden by the DSO, who will reduce the EV load in order to overcome the technical problems responsible for triggering the emergency operation state (low voltage problems or branches' overloading). The amount of EV load reduced by the DSO, in the scenarios where such actions were needed, is presented in Fig. 7.14.

The scenario that leads to the worst operating conditions is the dumb charging, where, during the entire week, 25.7 MWh of EV load hat to be reduced by the DSO. When comparing both multiple tariff scenarios, it is obvious that a lower price for the energy consumed by EV between 1 and 7 h leads to a lower number of technical limit violations, as the DSO would only have to reduce 3.8 MWh of the EV load, against the 20.1 MWh reduced if the lower energy price period was established between 22 and 8 h.

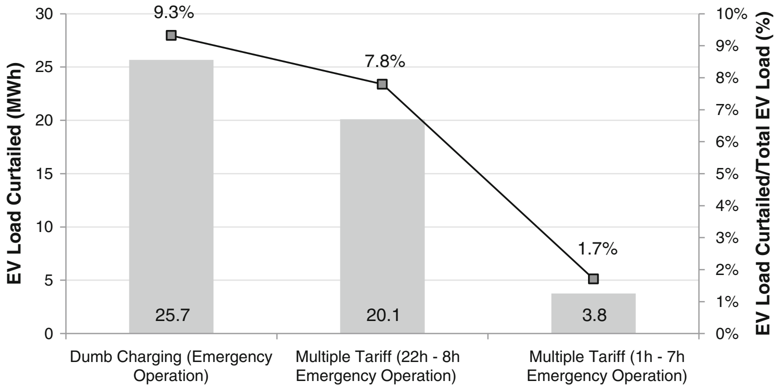


Fig. 7.14 EV load reduced in all the scenarios where the emergency operating mode was triggered (during the entire week)

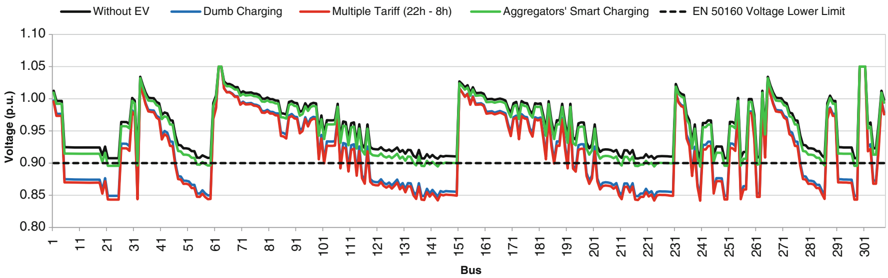


Fig. 7.15 Voltage profiles during the peak hour in the dumb charging, multiple tariff (22–8 h), and smart charging scenarios

4. Voltage profiles
   In order to assess the worst voltages that an EV integration level of 25 % might lead to, the highest peak load registered in the iterations performed for each scenario was analyzed, and the corresponding values were plotted in Fig. 7.15. The extra power demanded by EV provokes a significant voltage drop along the grid, namely during the periods when the demand is higher, that, as Fig. 7.15 shows, violates by far the lower limit of 0.90 p.u. in the dumb charging and multiple tariff (22–8 h) scenarios. These are the violations that trigger the emergency operating state and that obliges the DSO to reduce some of the EV load.
   The network voltage profile for the peak load in the scenario without EV is also presented in Fig. 7.15, for comparison purposes, as well as the reference voltage level stipulated by EN 50160 [2].

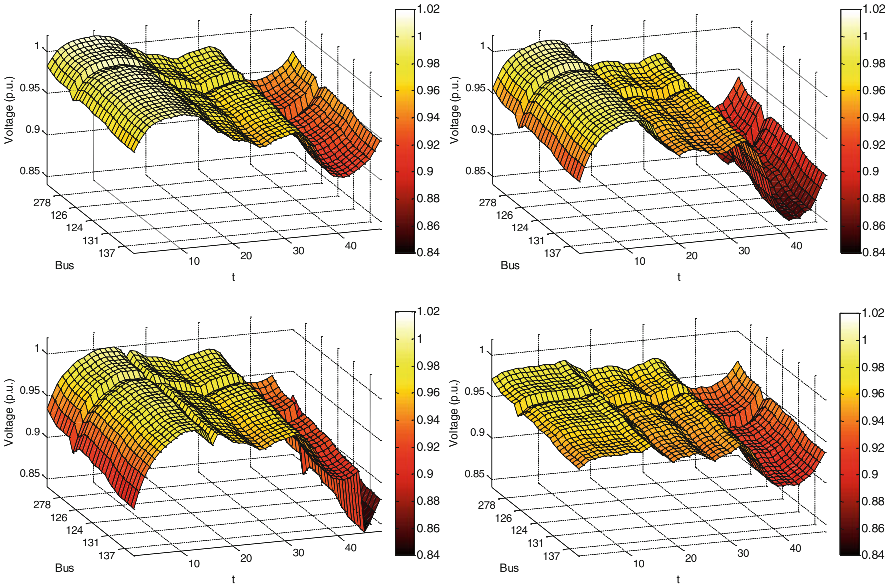


Fig. 7.16 Voltages downstream bus 107 in the scenario without EV (*upper left*), dumb charging (*upper right*), multiple tariff (22–8 h) (*lower left*), and smart charging (*lower right*)

To provide a clear picture of the EV impact in the voltage profile of one feeder, during 1 day (the day selected was Wednesday), the average voltages obtained for the buses downstream bus 107 were compiled and presented in Fig. 7.16. As these charts show, in the dumb charging and multiple tariff (22–8 h) scenarios, the extra power demanded by EV provokes a considerable voltage drop along this feeder, namely at the beginning and at the end of the day, leading to the violation of the voltage lower limit. The voltage drop is greatly reduced in the aggregators' smart charging scenario, where no violations were detected.

5. Branches' loading

   Even though this is not the most critical aspect of this network, since the highest branch loading registered in all the scenarios addressed was 104 %, branches' loading is also an issue that deserves special attention. In fact, in other networks with different characteristics, the branch loading can be the limiting factor to higher EV integration levels.

   Figure 7.17 provides an overview of the impact provoked by EV in the network line loading, for the peak load demand in the scenario without EV (upper left), dumb charging (upper right), multiple tariff (22–8 h) (lower left), and smart charging (lower right). The color grading between blue and red stands for increasing line loading values, ranging from 0 to 100 %.

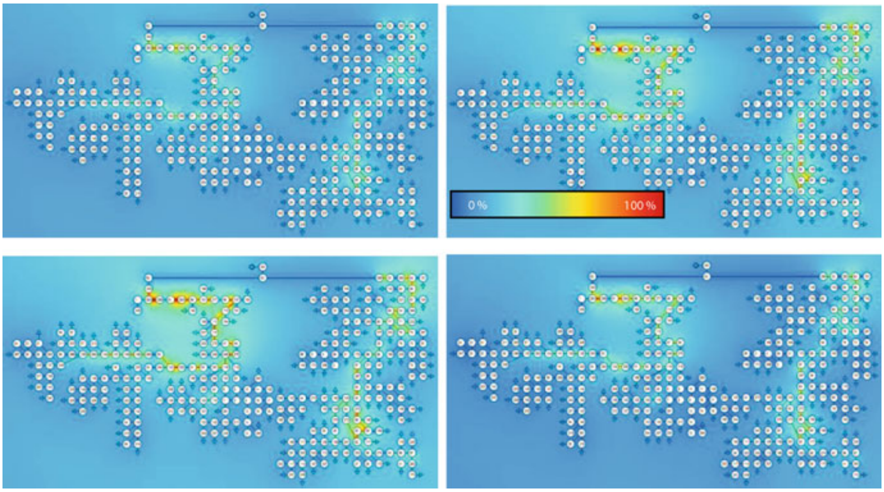


Fig. 7.17 Branches' loading in the scenario without EV (*upper left*), dumb charging (*upper right*), multiple tariff (22–8 h) (*lower left*), and smart charging (*lower right*)

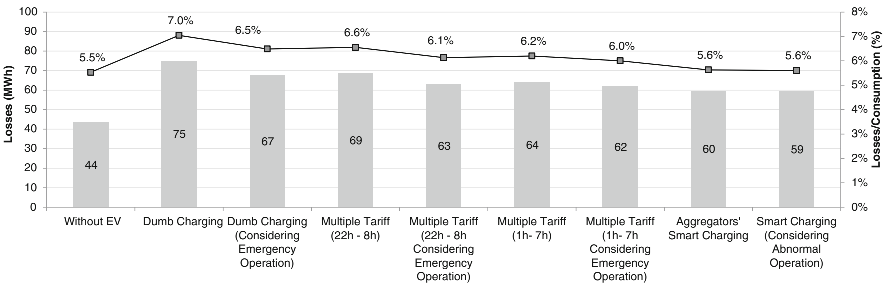


Fig. 7.18 Energy losses in all the scenarios studied (during the entire week)

6. Energy losses
   In Fig. 7.18, it is depicted the average value of the weekly energy losses, obtained along the 4,000 iterations performed for each scenario, as well as the percentage of the consumption they represent.
   The weekly energy losses grow 70 % from the scenario without EV to the dumb charging, 57 % to the multiple tariff (22–8 h), 45 % to the multiple tariff (1–7 h), and 36 % to the aggregators' smart charging scenario.
7. Mobility patterns and EV availability
   The journey distribution during a week- and a weekend day (Friday and Saturday) for the dumb charging, multiple tariff (22–8 h), and aggregators' smart charging scenarios is presented in Fig. 7.19. As it can be observed, the curves for the three charging strategies follow the same trend. This is, in fact, an expected result, as the same assumptions were used to simulate the EV

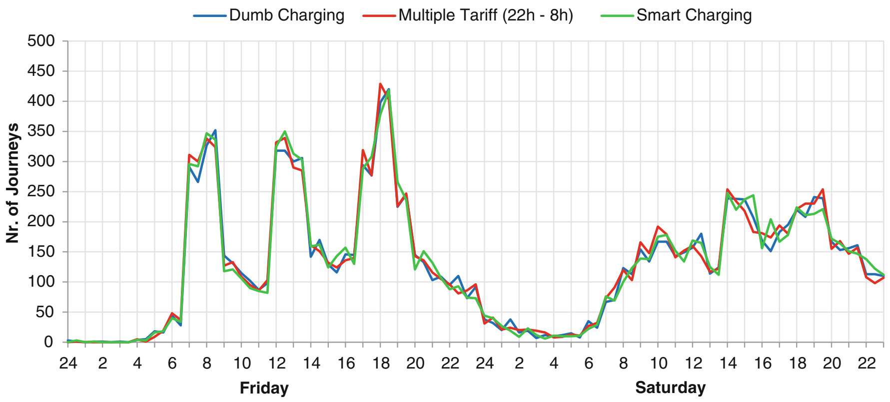


Fig. 7.19 Journey distribution during a week- and a weekend day for the dumb charging, multiple tariff (22–8 h), and smart charging scenarios

movement in all the scenarios addressed (the discrete-time, discrete-state Markov chain described in Chap. 6).

Only a week- and a weekend day results were presented in Fig. 7.19, since, as described in Chap. 6, only two different sets of probabilities were used to simulate the EV movement, one applied to the five weekdays and the other applied to the two weekend days.

During the weekdays, three peaks are clearly noticeable in the figure, two most likely related with household–work commuting (around 8 and 18 h), and the third, slightly after noon, probably related with people leaving their working places to have lunch somewhere else.

In the weekend days, probably due to the absence of the household–work commuting, the journeys are more distributed during the day.

It should be noted that one set of results for the EV journeys are obtained in each of the 4,000 iterations run with the Monte Carlo simulation method. The values presented in Fig. 7.19, as well as those presented in the remaining charts of this section, are referred to the last iteration performed in the simulation of the scenarios referred in each figure. Although these values are likely to suffer slight changes from iteration to iteration, their global behavior is kept almost unchanged along all the simulations performed, as it can be observed by the common trend shown by the three curves in Fig. 7.19.

In order to provide some insights about the places where the EV stay parked during the day, the number of EVs parked in residential, commercial, and industrial areas is presented in Fig. 7.20, obtained in the last iteration of the simulation performed for the aggregators' smart charging scenario.

In what regards residential areas, as expected, there is a large number of EVs parked during the night period, both on the week- and on the weekend days. During the day, the number of EVs parked in these areas is considerably lower during the week than during the weekend, probably due to the fact of most of the people not working during the weekend.

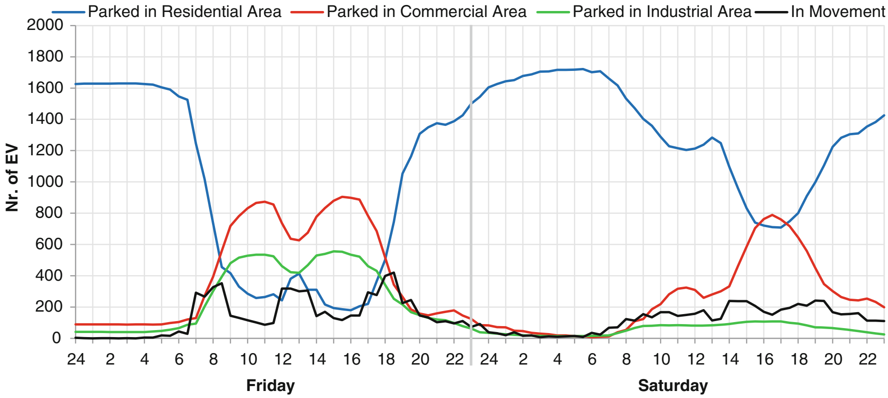


Fig. 7.20 No. of EVs in movement and parked (in residential, commercial, and industrial areas) during a week- and a weekend day in the aggregators' smart charging scenario

The results are quite different for commercial and industrial areas, where the number of EVs parked reaches the highest values during the day, both on week- and weekend days. Nevertheless, while the number of EVs parked in commercial areas reaches almost the same maximum value during all the days of the week, the number of EVs parked in industrial areas is considerably lower during the weekend than during the week.

8. EV power consumption

   In this subsection, three charts are presented, showing the power absorbed by EV in levels 1, 2, and 3 charging facilities in the dumb charging, multiple tariff (22–8 h), and aggregators' smart charging scenarios.

   The dashed lines presented in the figures represent the maximum power consumption possible, assuming that all EV plugged-in at level 1 are capable of absorbing 3 kW (blue line) and all EV plugged-in at level 2 are capable of absorbing 12 kW (red line). They were included in the charts only to provide an idea of the worst case scenario theoretically possible, which would be having all the plugged-in EV charging simultaneously. Nevertheless, this scenario is very unlikely to occur, since it disregards that some of the EV will have their batteries fully charged over time and will not absorb more power from the grid. As it was assumed that when an EV plugs in in a fast charging station it will always be charging, the maximum power consumption possible is equal to the power effectively consumed. For this reason, no dashed line was included in the charts for the maximum power consumption possible at level 3 (green line).

   In the dumb charging (Fig. 7.21), the EVs tend to charge at level 1 mostly at the end of the day, which is the time period when people arrive home from work. The amount of power requested by the EV during these periods would provoke some violations of the technical limits of several network components, and in order to avoid them, the DSO would have to reduce part of the EV load (dotted blue line). As referred in Chap. 6, when the system enters in the emergency

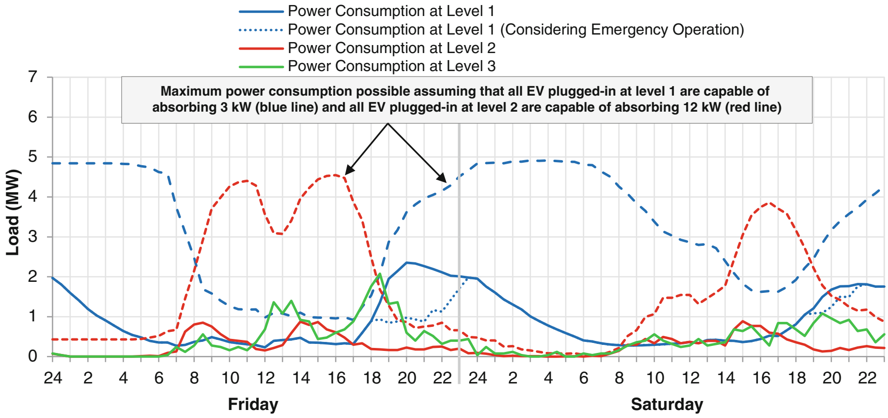


Fig. 7.21 Power consumption by EV plugged in in levels 1, 2, and 3 charging facilities during a week- and a weekend day in the dumb charging scenario

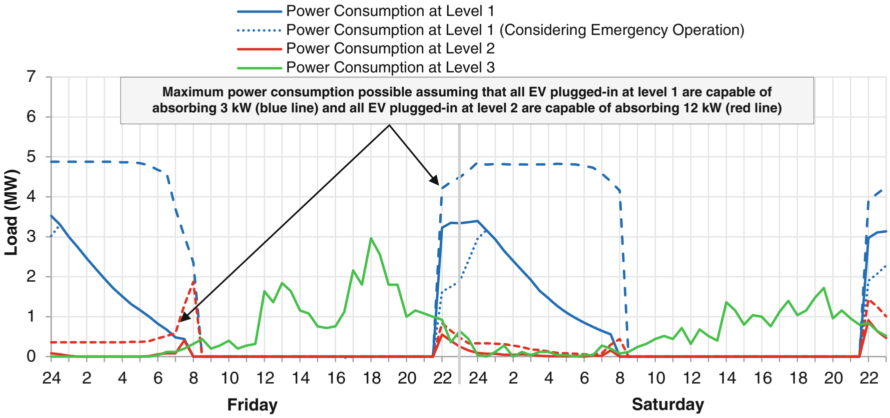


Fig. 7.22 Power consumption by EV plugged in in levels 1, 2, and 3 charging facilities during a week- and a weekend day in the multiple tariff (22–8 h) scenario

operating state, the DSO tries to solve the problems detected only by reducing load from EV charging at level 1. Then, if this measure is not enough, the DSO might also reduce load from EV charging at level 2 (in commercial areas) and at level 3 (in fast charging stations). However, it should be stressed that in all the scenarios addressed in this chapter, only load from EV charging at level 1 was reduced.

Regarding charging at level 2, the power absorbed by EV follows the trend of the number of EVs parked in commercial areas, as Fig. 7.20 shows. Concerning level 3 charging, the power absorbed by EV follows the trend of the number of EVs plugged in in fast charging stations, as depicted in Fig. 7.20.

In the multiple tariff (22–8 h) scenario (Fig. 7.22), the EVs only charge in level 1 and 2 charging facilities between 22 and 8 h, which is the period when the

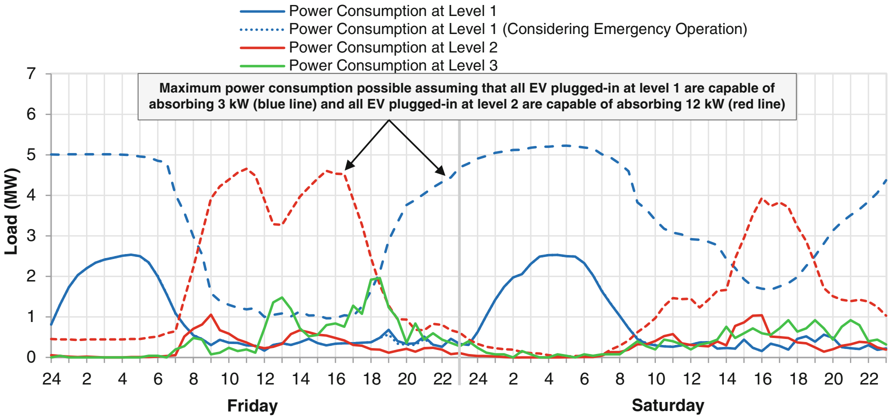


Fig. 7.23 Power consumption by EV plugged-in levels 1, 2, and 3 charging facilities during a week- and a weekend day in the smart charging scenario

energy prices are assumed to be lower. For this reason, there are a high number of EVs connecting to the grid for charging at 22 h and the amount of power requested provokes the violation of the technical limits of several network components. In order to avoid them, as it happened in the dumb charging scenario, the DSO would have to reduce part of the EV load (dotted blue line). Similar to the dumb charging scenario, in what regards level 3 charging, the power absorbed by EV follows the trend of the number of EVs plugged in in fast charging stations, as depicted in Fig. 7.20.

The results obtained in the aggregators' smart charging scenario (Fig. 7.23), are very similar to those obtained with the dumb charging, namely in what concerns level 2 and 3 power consumption. The only relevant differences are related with the power consumption at level 1, where it is clear a shift of the EV consumption from the 19–24 h period to the 2–7 h period.

9. Battery SOC evolution

   In order to exemplify the battery SOC evolution of a smart charging adherent, it is represented in Fig. 7.24 how the battery SOC is influenced by the charging management performed by the aggregator and by the DSO. Figure 7.24 shows three distinct situations: when the EV charging is not controlled, i.e., when the EV behaves as a dumb charging adherent (black line), when the EV charging is exclusively controlled by the aggregator, in normal operating conditions, in accordance with the market negotiations (black dashed line), and when the EV charging is controlled by the DSO under emergency operating conditions.

   As it can be observed, in the first situation, the EV charging starts immediately after the EV being plugged-in, while in the other situations the charging is postponed according to the needs of the aggregator or of the DSO.

10. Frequency of EV charging interruptions and non-delivered energy

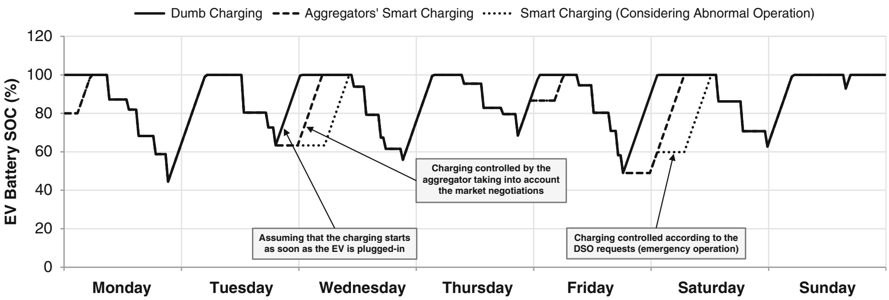


Fig. 7.24 EV battery SOC evolution of a smart charging adherent

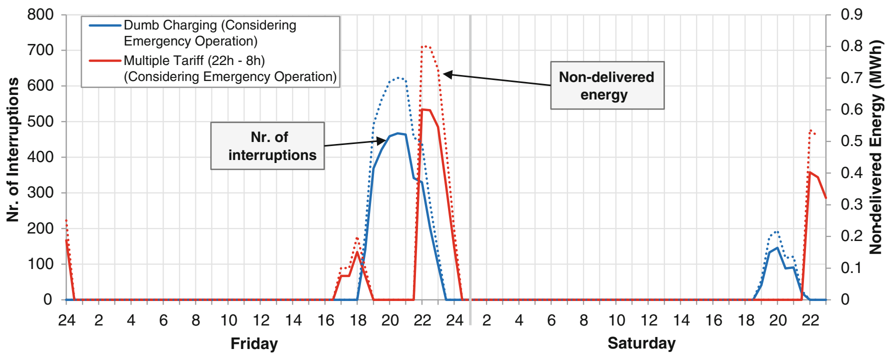


Fig. 7.25 Frequency of interruptions and non-delivered energy during a week- and a weekend day in the dumb charging and multiple tariff (22–8 h) scenarios

In order to quantify the number of times that EV charging is halted by the DSO, when the system enters in emergency operation state, all the interruptions were stored along the simulations, as well as the related non-delivered energy.

The results obtained for the dumb charging and multiple tariff (22–8 h) for a week- and a weekend day are presented in Fig. 7.25. As expected, both curves follow the same trend, as the amount of non-delivered energy is proportional to the number of EVs whose charging is interrupted by the DSO.

As it was already presented in Fig. 7.10, in the dumb charging scenario, the system enters in the emergency operating modes only in the period between 20 and 24 h. During these hours, there are a high number of EVs whose charging is halted by the DSO in order to avoid the violation of the network components' technical limits. As in this scenario the load reaches higher values during the weekdays, the number of interruptions is considerably higher during the weekday presented in Fig. 7.25 than during the weekend day (*ca.* 475 against 140 interruptions, respectively).

In the multiple tariff (22–8 h) scenario, there are two periods on the weekday when the DSO interrupts the EV charging: 17–19 h and, in a

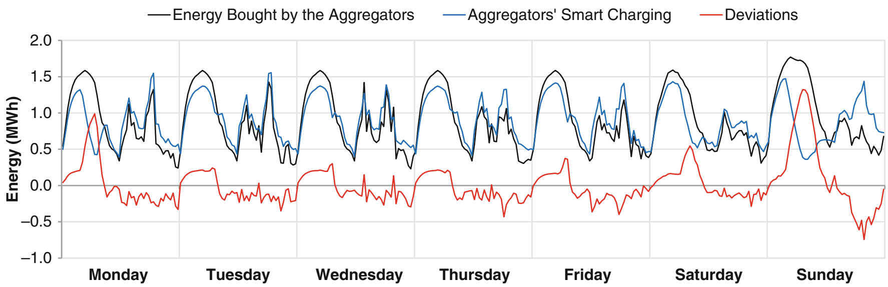


Fig. 7.26 Deviations between the energy bought in the markets by the aggregators and the energy consumed by the EV

higher extent, 22–24 h. During the weekend day, besides the number of EVs whose charging is interrupted being lower, there is only one period of the day when the system enters in the emergency operating mode, which occurs after 23 h.

11. Deviations from the energy bought in the market by the aggregators
    The deviations from the energy bought in the markets by the aggregators (black line) and the energy effectively consumed by the EV (blue line), in the smart charging scenario, are depicted in detail in Fig. 7.26.
    When the energy bought by the aggregators is higher than the EV consumption, it means that no further "flexible EVs" are available for charging and thus the aggregator will have an energy surplus that should be sold in adjustment markets.
    Conversely, when the EV consumption is higher than the energy bought by the aggregators, it means that the availability restrictions imposed by some of the "flexible EV" exhausted the possibility of the aggregator postpone further their charging and thus they will start charging immediately. In these situations, the aggregator will have an energy deficit that can be compensated by buying extra energy in the intraday markets.
    As referred previously, in the comments to Fig. 7.13, these deviations would probably be greatly reduced if the availability restrictions of the "flexible EV" were included in the optimization problem used to calculate the aggregators' optimal bids.
12. Monte Carlo convergence and sample variance
    As mentioned in Chap. 6, the Monte Carlo simulation ends when two criteria are met: when 4,000 iterations are performed or when the variations of the 336 variances in the last five iterations are lower than 1×10^{-6}. The variance variation is calculated using the (6.36) presented in Chap. 6.
    For all the scenarios simulated for this network, the variance variation criterion was met before the algorithm reach iteration 4,000. As an example, Fig. 7.27 shows the evolution of one ΔVariance per scenario studied. As it is shown, the variation rate after iteration 750 is very low, indicating that the algorithm reached the convergence criteria.

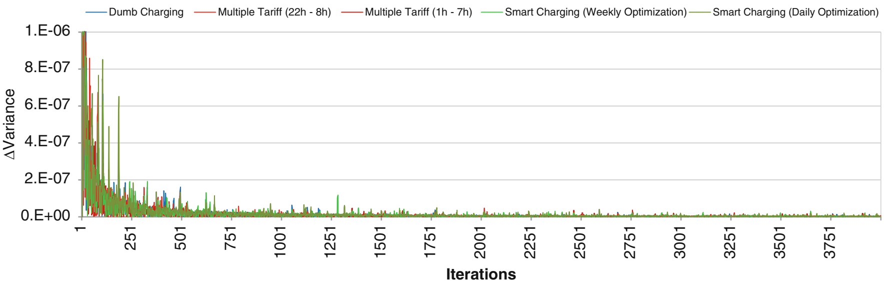


Fig. 7.27 Evolution of the variance variations

7.3 Dynamic Studies

7.3.1 Electric Vehicles Participation in Primary Frequency Control

7.3.1.1 Case Study and Description of the Studies Performed

The case study chosen for testing EV capability of performing primary frequency control is based on the power system of a small Portuguese island. This island has a 15 kV distribution network with two substations, each located in one of the two existing generation plants, as described in Fig. 7.28. In 2009, the annual peak load was 2,200 kW and the minimum valley load was 750 kW. The generation system is composed of four diesel generators with the nominal power of 625 kV A, two wind turbines of 330 kV A, and four hydro units, three of 370 kV A, and one with 740 kV A.

In this grid, the most critical period is the load valley. The rather small number of generation units dispatched is associated with small system inertia. Therefore, frequency stability issues may be expectable, especially when there are good wind resource conditions. In fact, the island could explore more of its endogenous resources, wind and hydro power, but operational restraints prevent this occurrence.

Current operational practices always include at least one diesel unit to perform load following and frequency control, but the existing hydro units could in theory replace the diesel units in this task. However, the high head height and long conduit impose a long water starting time [3]. Long water starting times may lead to larger frequency fluctuations, and the mechanical wear and tear on the turbines is bigger due to the fast governing actions.

To test the primary frequency control techniques described in Chap. 6, a valley hour with a total conventional load of 731 kW, where the load from EV was added to the conventional load, was considered. It was assumed that 25 % of the island's vehicle fleet (2,000 vehicles) was replaced with EV, and all of them adhered to smart charging schemes that follow the methodology presented in [1].

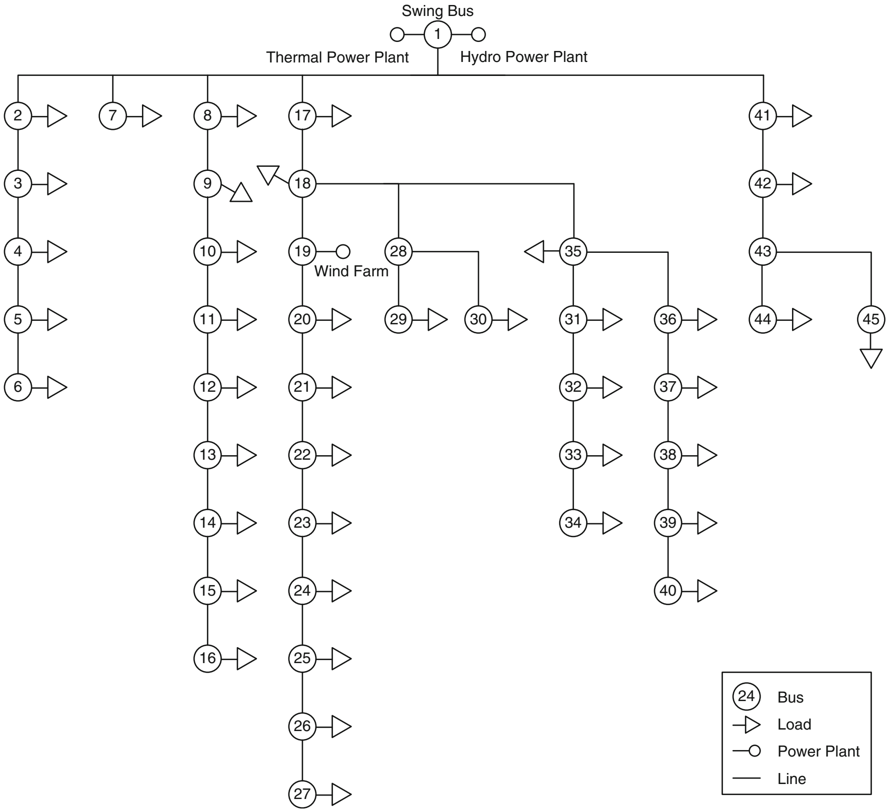


Fig. 7.28 Single line diagram of the isolated system case study

The EV fleet considered was composed by three vehicle types, 20 % of which with 1.5 kW of rated power for battery charging, 40 % with 3 kW, and 40 % with 6 kW. A full charge cycle of 4 h was assumed. EV SOC, charging power per consumption node, and flexibility of the EV were determined as follows:

- Location: EVs were sorted randomly across the nodes with conventional loads.
- SOC: Determined by a normal distribution with an average value of 70 %, standard deviation of 30 %, and limited to the range of values (10 %, 100 %).
- Normal charging rate: 0.8 C.
- Controllability range: Charging rate change possible between 0.2 and 1.0 C, if SOC is below 100 %.

Table 7.3 shows the load of the considered scenario, the range of values for EV in response to frequency deviations, and the EV controller parameters.

- In order to match the load of the island during the defined period, the following generation dispatches were created.
- Basic scenario: A full renewable dispatch was performed exploiting the existing hydro and wind resources.

Table 7.3 Conventional and EV load and EV controller parameters

Conventional load (kW)	731
Required EV load at 0.8 C (kW)	964
Total load (kW)	1,695
EV maximum power consumption at 1.0 C (kW)	1,200
EV minimum power consumption at 0.2 C (kW)	250
EV proportional gain (kW/Hz)	P_{Rated}
EV inertial emulation gain (kW Hz^{-1} s)	$5{*}P_{\text{Rated}}$
EV dead band (Hz)	±0.1

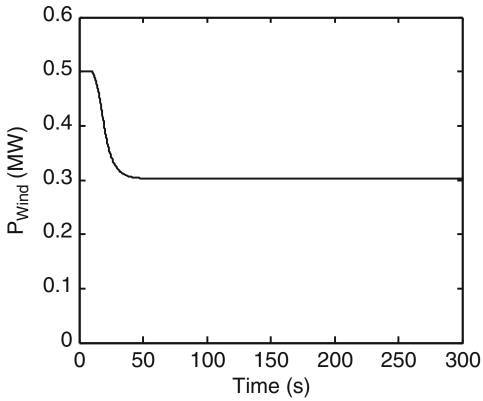


Fig. 7.29 Shortfall on wind resource availability

- Wind generation expansion scenario: More wind power installed capacity was included. Identical to the basic scenario, it included more generation from wind and less generation from hydro units.

Two disturbances on the wind resource availability were considered. The European norm EN50160 [2] defines that the admissible operation conditions for isolated system and introduces a limit of ±1 Hz for frequency deviations. First, a shortfall on wind resource availability was considered leading to the loss of 40 % of the total wind power, 200 kW in 10 s, as depicted in Fig. 7.29.

Second, a chain of events based on the variability of the wind resource was created for both generation dispatches over a period of 15 min. The wind resource variability is the same for both generation dispatches, but has different repercussions on the wind farm output power (Fig. 7.30).

The two control techniques described before should be tested separately first, compared with each other and, if beneficial for the system, tested for combined effect. Additionally, there may be some influences of possible delays in the reaction of the EV electronic grid interfaces, and so this situation must also be addressed for the different generation dispatches. The existence of delays may lead to the asynchronous reaction of the EV, leading to EV reactions in different moments, which can cause instability in the system. Thus, there are several scenarios that were addressed and are presented in Table 7.4. Yet, in the results section, only a

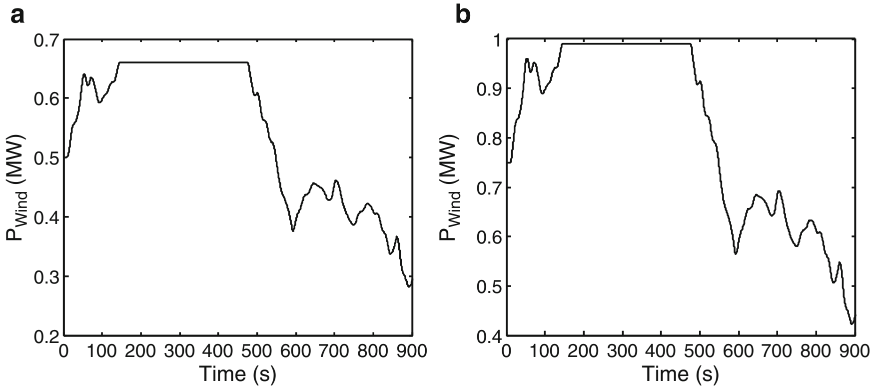


Fig. 7.30 Chain of events due to the variability of wind resource in (**a**) basic dispatch scenario and (**b**) wind generation expansion scenario

Table 7.4 Summary of studied cases

EV electronic interface		Without delay	With delay
Shortfall on wind and chain of events in the basic dispatch scenario			
Without EV droop control	Without inertial emulation	**Case 1**	Case 3
	With inertial emulation	**Case 5**	Case 7
With EV droop control	Without inertial emulation	**Case 2**	Case 4
	With inertial emulation	**Case 6**	**Case 8**
Chain of events in the wind generation expansion scenario			
With EV droop control	With inertial emulation	–	Case 9

selected number of scenarios (highlighted in bold in the table) is presented, illustrating the most representative cases to evaluate the performance of the EV control techniques.

7.3.1.2 Results

This section presents the results of the dynamic simulation of the behavior of the electric power systems of the island, when the flexibility of EV load is explored to provide primary frequency control, being divided in five subsections based on comparison of scenarios. First, the EV droop control (case 2) is compared to the case of inexistence of EV control (case 1). Second, the differences between the usage of EV with droop control (case 2) and the usage of inertial emulation (case 5). Third, the two control techniques proposed for EV are combined (case 6) and the simulation results compared to the base case where EVs are uncontrollable loads (case 1). The benefits of having both controls (case 6) in relation to having just EV droop control (case 2) are also compared. Then, the effects of possible delays in EV reaction were addressed. So the case with droop control and inertial emulation were

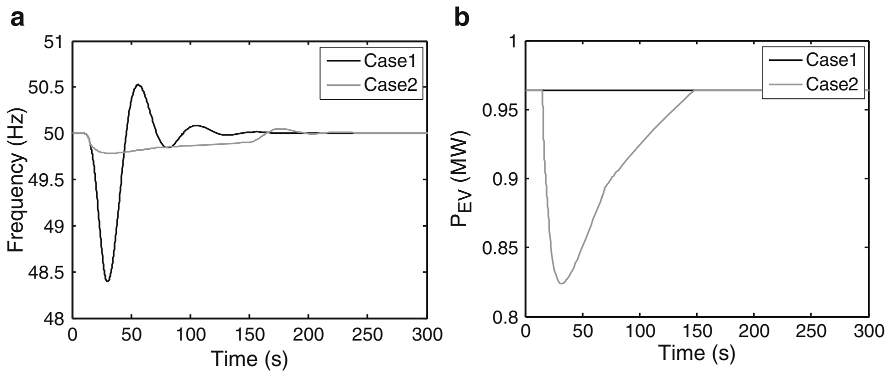


Fig. 7.31 Without control vs. EV droop control: (**a**) frequency and (**b**) EV active power

compared with (case 8) and without (case 6) delay. Finally, a wind generation expansion scenario where EVs provide both controls (case 9) was compared to the base scenario with both EV controls (case 8) and with no EV control (case 1) for a chain of disturbances.

1. Droop control with electric vehicles
   Figure 7.31 depicts the system frequency and the evolution of the total EV load for the event of a shortfall on wind power. If the system is operated without EV participation on frequency control and using a full renewable-based generation dispatch, frequency drops to a minimum value of 48.39 Hz. In opposition, when the EV droop control is considered, frequency does not fall below 49.78 Hz. There are two factors influencing this discrepancy: the slow dynamic reaction of the hydro generation units and the fast reaction of EV to frequency deviations. In terms of EV participation on frequency control, the total charging power temporarily changes from the original 964 to 824 kW, resulting in a reduction of 3.6 % in the energy absorbed by the batteries of EV during the 300 s of simulation. The participation of EV not only sustains the frequency drop but also avoids the oscillations verified in the frequency response without EV participation.
2. Comparison between droop control and inertial emulation
   From Fig. 7.32, it is possible to observe that the droop control is more effective than the inertial control. In fact, this would be an expected result. However, a careful analysis shows that inertial emulation manages to hold frequency drop more efficiently in the first seconds following the disturbance. Only about 20 s after the disturbance does the droop control perform better than the inertial control. Both strategies are quite effective with some overall advantage for the droop control, while the inertial emulation addresses more properly the initial moments that follow a disturbance. In terms of load variation, the initial decrease in EV load is evidently faster with inertial emulation, following a period where both techniques evolve side by side. When the rate of change of frequency decreases, the contribution of EV with inertial emulation also decreases,

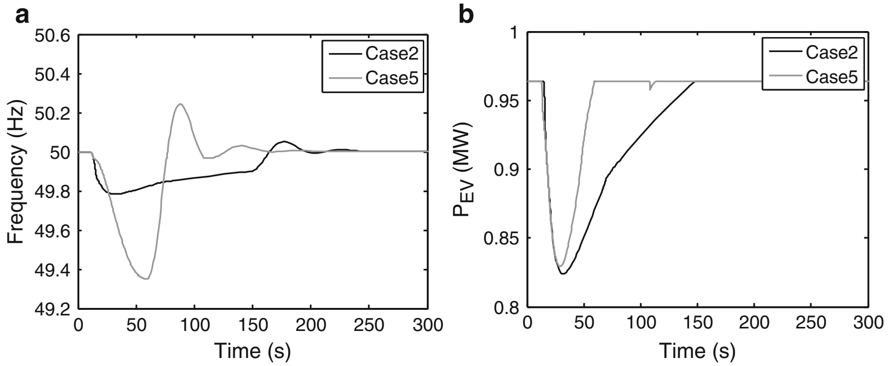


Fig. 7.32 EV droop vs. inertial emulation with EV: (**a**) frequency and (**b**) EV active power

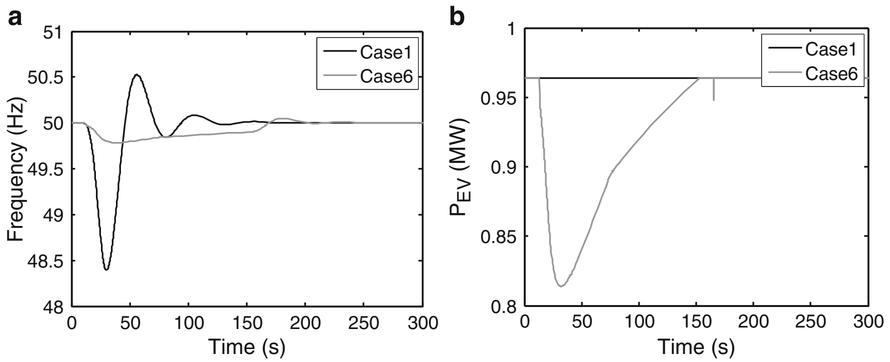


Fig. 7.33 Without EV control vs. EV droop control and inertial emulation with EV: (**a**) frequency and (**b**) EV active power

whereas the droop control accompanies the absolute error on frequency. EV contribution is sustained until frequency enters the dead band of the controller. For the tested event, the inertial control lets EV charge 2.9 % more energy than the droop control.

3. Combined effect of droop control and inertial emulation
   Figure 7.33 shows the evolution of frequency and EV load. Frequency falls to a minimum value of 49.78 Hz, a similar value to the case with droop control only. Yet it performs better in the initial seconds of the disturbance. The droop control case would follow, during these instants, the base case frequency, whereas in this case the benefits of inertial control are present and the system gains additional robustness. Regarding EV participation, their load gets reduced by 10 kW more than the case with droop control. Regarding energy consumption, the case presented in this section manages to charge EV batteries by 0.05 % more than the droop case.

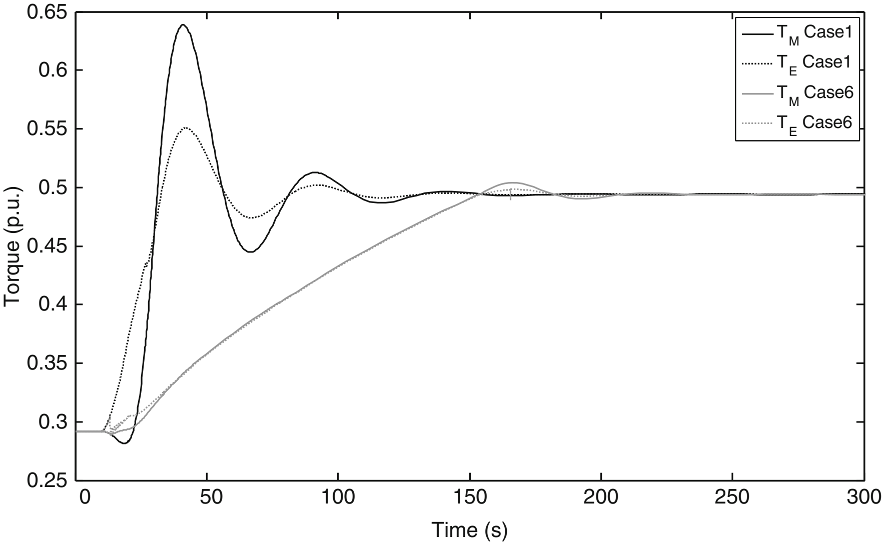


Fig. 7.34 Without EV control vs. EV droop control and inertial emulation with EV: mechanical and electrical torque of hydro unit 4

Regarding the conventional generation units, the presence of the droop control and the inertial emulation provides the smoother ramps and the most damped responses of all the presented cases.

This is particularly noticeable by observing the plots of the electrical and mechanical torques (Fig. 7.34). The two periods of EV action are quite visible. First, the fast response of the derivative gain that makes inertial control loop is able to attenuate the effects of the water starting time of the hydro units. Second, the droop control loop with its proportional gain sustains frequency control during the time that the conventional generation units need to compensate for the generation loss caused by the shortfall on wind availability. During this second stage, the derivative control-driven contribution is almost null. As it was mentioned while presenting the case study of the island, nowadays a full renewable energy generation dispatch is likely to be more rarely adopted. The system may get unstable, problem that can be solved with the adoption of EV droop control, and the hydraulic phenomena may be very abrupt and lead to premature exhaustion of the turbine and the mechanical equipment that performs the gate opening control. The inertial control may help prevent this premature exhaustion from happening and become the missing piece to make renewable-based dispatches a current practice in the operation of systems with high renewable energy availability, when sufficient penetration of EV is present.

Another analysis that can be performed confronts the case where the EVs only have droop control to the case where both controls are active. Figure 7.35 shows the frequency response and the contribution of EVs in both scenarios. It is visible that with little additional effort, the inertial control manages to hold frequency

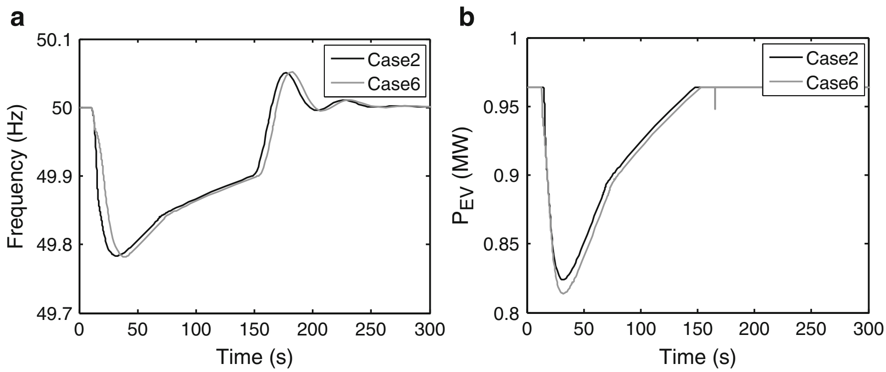


Fig. 7.35 EV droop control vs. both EV controls: (**a**) frequency and (**b**) EV active power

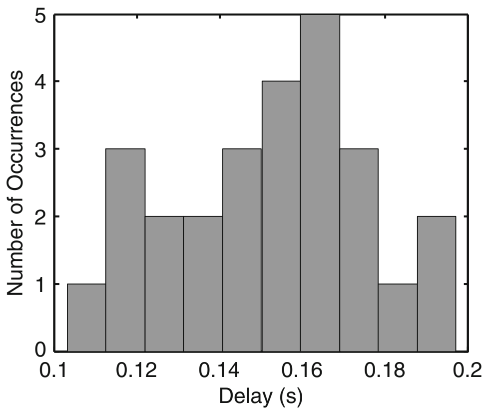


Fig. 7.36 Histogram of EV grid interface delays

drop a while longer. Yet it is in the event of a series of disturbances that the combined effect of the droop control and the inertial emulation is most relevant. Frequency presents fewer oscillations with the both controls, managing, in most of the events, to reduce frequency drops. Nonetheless, the minimum frequency is nearly identical. The benefits of the combined effects of both control measures are obtained at the cost of a negligible increase on consumed power of 0.4 %.

4. The effect of delays in frequency measurement and electronic interface
   The value for delays in EV battery response may depend, among other factors, on the type of measurement scheme and the equipment manufacturer or model. Consequently, it is not expected to be uniformly distributed by all the EV, and so a normal distribution was used to attribute different delays to each aggregation node on the MV distribution grid. An average value of 150 ms was considered with lower and upper limits of respectively, 100 and 200 ms. The considered range of values is intended to address a worst case scenario as the overall delay of an EV is not expected to be so large. Figure 7.36 presents a histogram with the

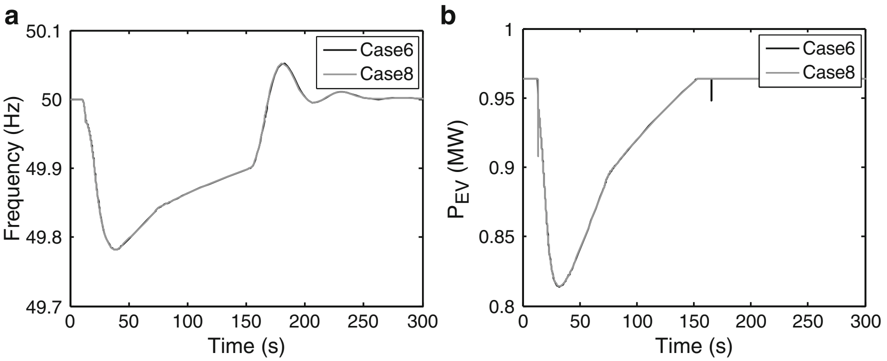


Fig. 7.37 With vs. without EV response delay: (**a**) frequency and (**b**) active power of EV

distribution of considered delays and their frequency. As the number of load nodes and inherently EV aggregations is rather reduced, the histogram does not tend to the perfect bell-shaped form of the normal distribution.

The simulation results are presented next, placing side by side the cases of droop control and inertial emulation with/without delay. Figure 7.37 shows that the frequency response is practically equal in both cases and also that the reaction of the EV is the same. There is a minor difference after the first overshoot, where the EVs without delay suddenly reduce their load and reestablish it immediately after, and in the case with delay, the EVs do not react. This is probably related to the duration of event that is smaller than the delay period of the EV grid interface.

Zooming into the participation of selected EV aggregations (Fig. 7.38), the effect of the delay is visible, being perceivable that their reaction is not synchronized. Such delay disparity would likely be acceptable in a real-world implementation of these concepts and would have no harmful effects in the system response.

5. Wind generation expansion

Having demonstrated the efficacy of the proposed control techniques and their robustness even when considerable delays are introduced in EV operation, the possibility of expanding the share of wind generation and keeping a full renewable-based dispatch is also tested. In this sense, an extra wind turbine is considered, with the same characteristics of and located near to the existing wind generation units. This new unit shares the connection point of the other units. For the simulation, the same wind availability and variability conditions are assumed and so the generation dispatch has to be modified. Being unfeasible to operate the network with the four hydro units, only three of the units are dispatched. It is also considered that EVs participate in primary frequency control with droop control and inertial emulation, while suffering the effects of the previously introduced delays.

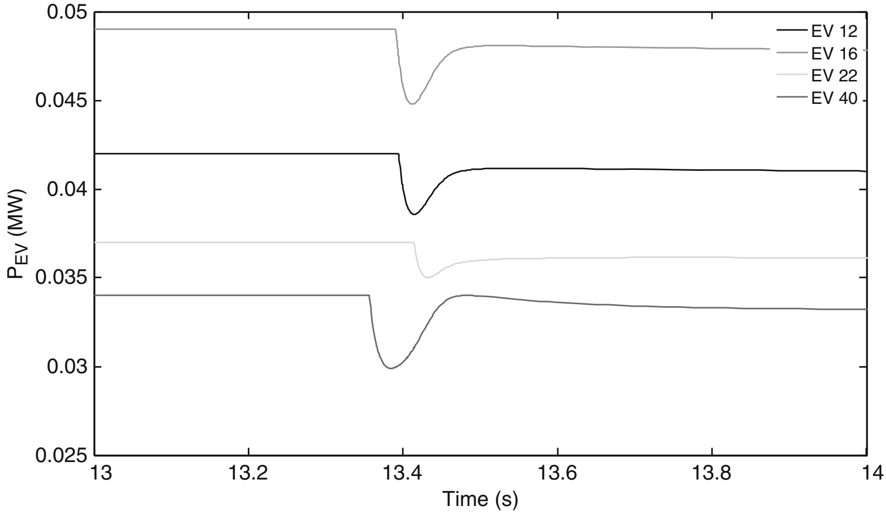


Fig. 7.38 With vs. without EV response delay: individual power of EV

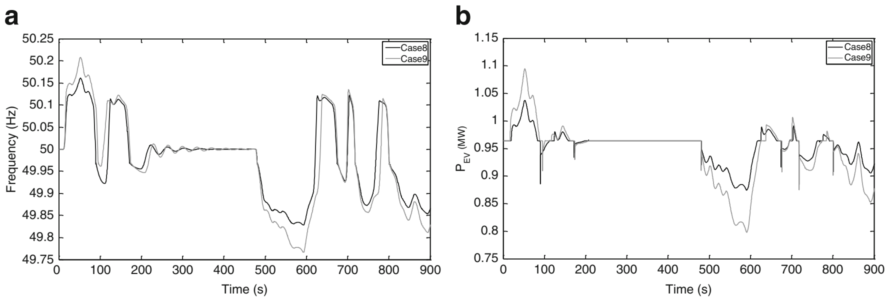


Fig. 7.39 Two wind turbines vs. three (continuous disturbance): (**a**) frequency and (**b**) active power of EV

Figure 7.39 presents the attained results in response to a chain of disturbances in wind availability when the system with additional wind generation is set against the original dispatch. Without surprise, the frequency deviation amplitude increases, still within admissible values and with a large margin for the ±1 Hz allowable band of the norm EN50160 [2]. Frequency oscillates between 49.77 and 50.21 Hz, increasing the oscillation from 0.33 to 0.44 Hz. In what regards the participation of EV, the wind generation expansion poses more demanding conditions for EV to deal with and so the participation is stronger. Load variation ranges from 798 to 1,095 kW, being 82 % bigger than the load range of 874–1,037 kW in the original dispatch. Yet this strong growth in the contribution of EV represents just a maximum deviation of 17 % in relation to the required load of 964 kW. Concerning the energy not consumed by EV, during the 15 min

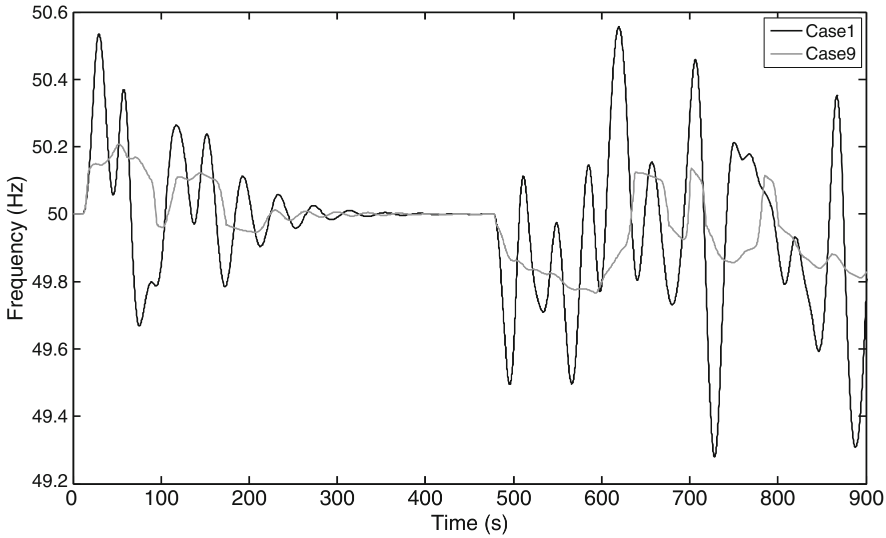


Fig. 7.40 System frequency comparison between the case with two turbines and no EV control and the case with three turbines, EV droop control, and inertial emulation

of simulation, a difference of 1.8 % was registered in relation to the case where EVs are uncontrollable loads.

When the performance of the system with an extra wind turbine is compared to the base case, it is noticeable that even with more demanding conditions, having EV contributing for frequency control enables the integration of further wind generation in the system (Fig. 7.40). It would possibly be feasible to go even further, and the system would still be able to cope with the variability of the wind resource, in what respects frequency control.

7.3.2 Automatic Generation Control with Electric Vehicles

7.3.2.1 Case Study and Description of the Studies Performed

In interconnected systems with two or more areas, controlling active power apart from frequency also influences the interconnection power flow value in inter-area links. Therefore, the control of interconnection power flows is added to the control of frequency in these systems.

The adopted test system (Fig. 7.41) is an adaptation of the three area transmission network example case of *PSS/E*, to which new conventional generators, wind generators, loads, and lines were added. The technical data of the base test system can be found in [4]. There are two voltage levels in the transmission system, 230 and 500 kV, and frequency was set to 50 Hz.

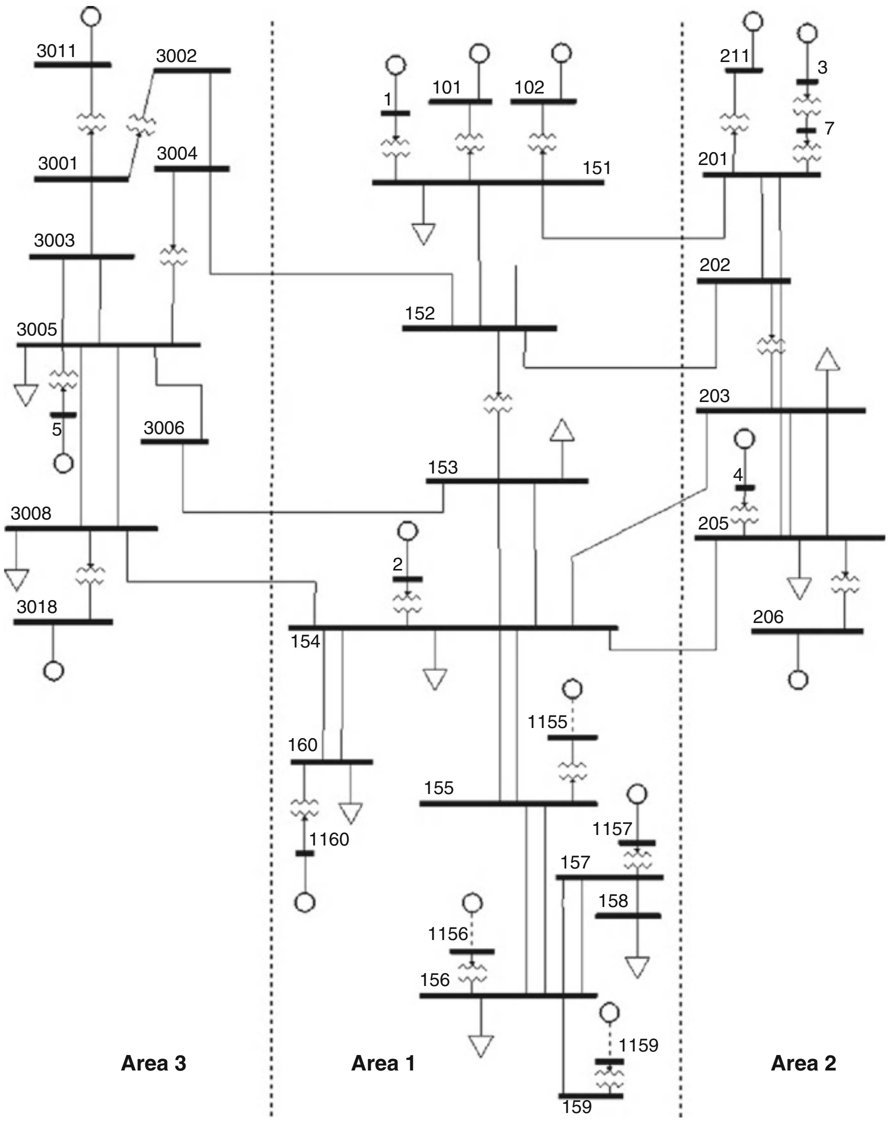


Fig. 7.41 Single line diagram of the grid used for presenting AGC operation with EV

To test AGC operation, a scenario with a total load of 4,850 MW was considered. Table 7.5 presents the division of the load per area of control. Regarding the presence of EV, it was considered that 20 % of the load at each bus comes from EV. As this is a representation of a transmission network, it is not possible to consider individual vehicles per node.

In terms of the generation system, Table 7.6 details the conventional generators by primary resource, type, rated power, active power dispatch, and governor. Only

Table 7.5 Load per area of control

Area	Load (MW)
1	2,850
2	1,500
3	500

Table 7.6 Conventional generation dispatch

Bus	Area	Primary resource	Rated power (MVA)	P_{dispatch} (MW)	Generator	Governor	Bus
101	1	Diesel/fuel	900	739	GENROU	TGOV1	101
102	1	Diesel/fuel	900	750	GENROU	TGOV1	102
1157	1	Hydro	725	378	GENSAL	HYGOV	1157
1160	1	Diesel/fuel	1,000	600	GENROU	TGOV1	1160
206	2	Diesel/fuel	1,000	378	GENROU	TGOV1	206
211	2	Hydro	725	600	GENSAL	HYGOV	211
3011	5	Diesel/fuel	1,000	112	GENROU	None	3011
3018	5	Diesel/fuel	130	100	GENROU	None	3018

Table 7.7 Wind generation dispatch

Bus	Area	N_{Gen}	P_{dispatch} (MW)
1	1	79	180
2	1	79	180
1155	1	79	180
1156	1	79	180
1159	1	98	225
3	2	98	225
4	2	98	225
5	5	66	150

two generator types are considered: GENROU (round rotor generator) and GENSAL (salient pole generator). Two governor types, one per primary resource, are adopted: TGOV1 (steam turbine-governor) and HYGOV (hydro turbine-governor). The units of area 3 are not equipped with a governor so that they will not react to frequency deviations. There are only two AGC units, one in area 1 and the other in area 2. All the models are explained in detail in the *PSS/E* model library manual [5].

Table 7.7 presents the number of wind turbines, wind generation dispatch, and location of wind farms per area. All winds generators have a rated power of 2.3 MW. Area 1 has the largest share of wind generation, 61 %, followed by area 2 with 29 %, and finally area 3 with 10 %. It was assumed that the wind farms cannot survive to severe voltage sags. The under-voltage relay setting of the wind farms is set to 0.8 p.u.

Table 7.8 Participation factors for every studied scenario

Scenario		Area 1 Machines N	Area 1 Machines PF	Area 1 EV	Area 2 Machines N	Area 2 Machines PF	Area 2 EV
Regular scenario	With EV	4	0.1	0.6	2	0.2	0.6
	Without EV	4	0.25	0	2	0.2	0
Extreme scenario	With EV	3	0.13	0.6	2	0.2	0.6
	Without EV	3	0.33	0	2	0.2	0

Concerning the disturbances for AGC testing, two events were defined:

1. The first was the loss of a large conventional generator. Hundred seconds after the beginning of the simulation, generator 102 trips and goes out of service. Part of the spinning reserves is lost as generator 102 was performing primary control and providing secondary reserves. The role of EV as secondary reserve providers is then assessed and confronted with the action of a conventional AGC.
2. The second event is the loss of some wind farms motivated by a short circuit at bus 1155. This event lasts for 150 ms and leads to the tripping of wind farms 1155, 1156, and 1159 due to under-voltage relay action. It is assumed also that the wind generators that trip do not reconnect within the 15 min AGC period defined by the ENTSO-E [6].

An additional scenario was created, considering that generator 101 is removed from AGC operation. The loss of generator 102 is then retested to evaluate the action of EV in an extreme situation, where insufficient conventional secondary reserve capacity is available for handling the disturbance. A global participation factor (PF) is attributed by type of reserve provider (EV/machine) and evenly distributed between reserve providers of each type. A different distribution could have been made if the secondary reserve market would be simulated. Table 7.8 presents the PF of the AGC participants per type and the number of participating conventional generation units (*N*). For all the scenarios, an AGC delay of 5 s was considered, to account for frequency measurement, processing, and communications delays. All other AGC parameters were assumed to be constant for every scenario. The integral gain, K_I, was set to 0.05 and the bias factor, *B*, to 40 p.u. MW/p.u. Hz for both areas of control.

7.3.2.2 Results

1. Loss of a large conventional generation unit
   Figure 7.42 presents the frequency oscillation verified for area 1 center of inertia. Frequency drops to the value of 49.2 Hz immediately after the disturbance. Unlike the work presented in [7], EVs do not participate in primary frequency control in any of the studied scenarios. Therefore, the initial response is similar, and frequency recovery differences may only be found when secondary reserves

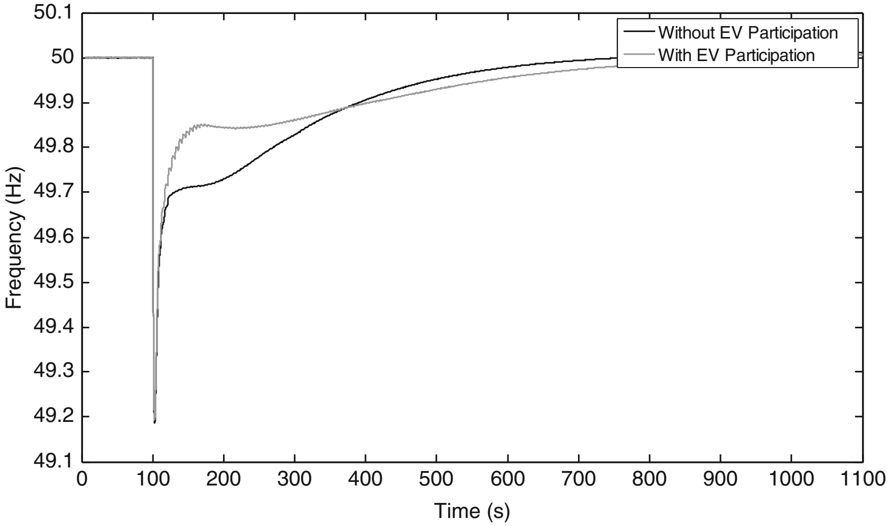


Fig. 7.42 Frequency of the center of inertia of area 1

are mobilized. Observing the action of the AGC, it is perceivable that EV contribution is much faster than that of the participating machines. After the first 100 s that follow the disturbance, most of the frequency deviation is eliminated by the action of EV, whereas in the case where only conventional generation units provide reserves around 150 s, more are required to achieve the same level. From that moment on, the case with EV appears to be slightly slower than the one with only conventional generators, even though the difference is minimal and frequency is already very close to the reference value. This phenomenon may be explainable by two influencing factors. First, the amount of reserves provided by EV is insufficient to face the loss of generation. The second is the moment at which reserves are requested to the conventional units. Without EV participation, the conventional generations are requested to participate in AGC from the beginning by a large value, leading to fast generator ramping.

Regarding frequency in control area 2, there are no substantial differences worth mentioning. Evidently, this result would be expectable as frequency changes get propagated throughout the network very quickly and the interconnections between the areas are sufficiently strong for assuring synchronized control.

Concerning the aggregate value of the interconnection power flow from area 1 to 2, it is again verified that the initial system reaction is very similar in both analyzed cases (Fig. 7.43). The scenario without EV participation seems to recover the interconnection value faster, having an overshoot approximately 80 s after the loss of the generator, surpassing the power flow scheduled value, and making a steep inversion on the control action leading to a second overshoot below the reference value more or less 100 s after the first overshoot. Oppositely,

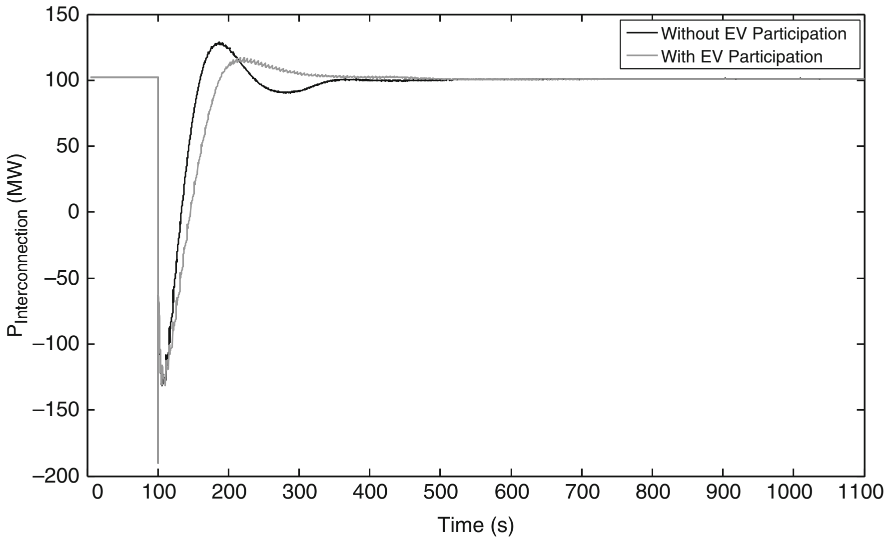


Fig. 7.43 Tie line interconnection power for area 1

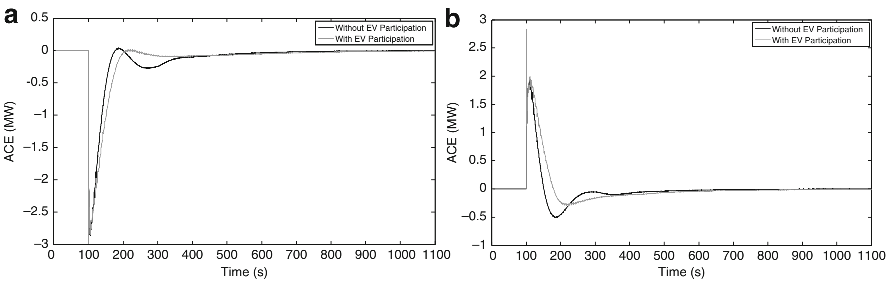


Fig. 7.44 Area control error: (**a**) for area 1 and (**b**) for area 2

the reaction of the system with the participation of EV is much more damped, and avoiding big overshoot situations, the reference value is achieved sooner. Obviously, the interconnection power flow from area 2 to area 1 is equivalent to the power flow from area 1 to area 2 minus the existing losses in the tie-lines. The area control error (ACE) signals of the AGC units of area 1 and 2 are presented in Fig. 7.44a, b. Once again it is clear that the reaction of the system for AGC units with the same parameters of frequency bias and integral gain, only with a redefinition of the PFs, is more accurate with EV. The error gets within a smaller deviation band much faster with EV participation. Observing the plots, it is possible to conclude that after the disturbance the fact that a machine is lost in area 1, which was exporting, leads to a negative ACE in area 1 for mobilization of upward reserve and a positive ACE in area 2 to counteract the effects of the primary response in that area with downward reserve. Yet the

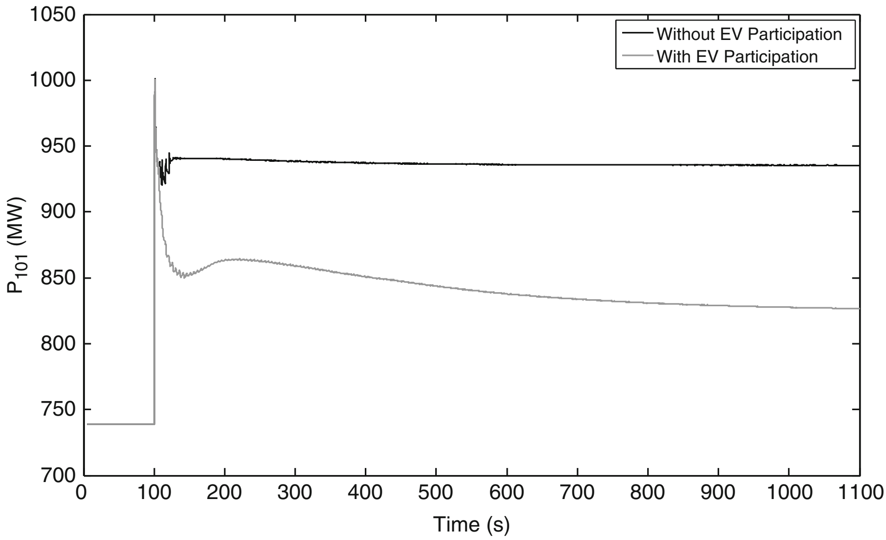


Fig. 7.45 Electric power of conventional generator 101

magnitude of the ACE in area 2 is smaller than in area 1 as the second term that composes the ACE is for frequency restoration, and so as frequency is not fully reestablished, it is still a negative parcel.

Figure 7.45 depicts the electric power of one of the conventional generation units of area 1. Immediately after the disturbance, this as well as all other machines, with the exception of generator 102 that was lost, use the energy stored in their rotors to provide inertia to the system, and the electrical power increases while losing some mechanical power. It is followed by the action of the governors that perform primary control. Only after will the secondary control take effect. Generator 101 reaches the maximum power output just a few tens of seconds after the disturbance when EVs do no participate in AGC, whereas with EV participation it reaches steady state with a reasonable reserve margin.

Similar to generator 101, the other generators also achieve or almost achieve their maximum output power in the base case. With EV participation, the reserve margin in the end of the simulation is much bigger.

Concerning the generators in control area 2, it is verified that without EV participation, both generators participating in AGC control have an initial reaction due to the effect of the primary frequency control by the governors. Then, the AGC of area 2 gradually leads the machines to their original operating point to compensate the governing action. Yet the inexistence of EV primary control loop, in AGC operation with EV, leads to overcompensation by EV and consequently a steady-state operation level for conventional units below their initial operating state.

In relation to the EV aggregate load evolution, given the magnitude of the disturbance, there was a decrease from 830 to *ca.* 180 MW, when participating in AGC. Of course, without EV participation, load remains unchanged.

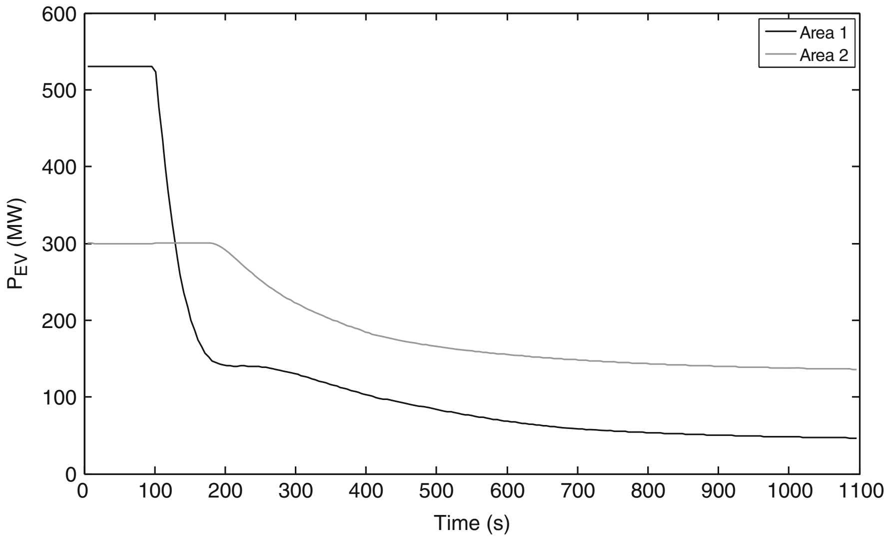


Fig. 7.46 EV power consumption per area when EVs participate in AGC control

Regarding the distribution of EV participation per area, for AGC operation with EV, there was a load decrease by 91 % in the affected area and only by 55 % in area 2 (Fig. 7.46). Again, this occurs due to the exclusive participation of EV in secondary control. Otherwise, EV load in area 2 would not suffer a big change. In relation to EV contributions per aggregation node in area 1, it is verified that all EV aggregations follow the same pattern. This is due to an even division of the total EV PF by the number of nodes of aggregation. Other rules could be established, but in practical terms, this would not make a real difference in this case as AGC overall efficacy would be similar. In real implementation, the aggregators would have to define PFs for individual EV under their domain. This would result in different participation factors per aggregation node, which would then be mainly dependent on EV availability, location, and amount of power. As expected, in area 2, an equivalent situation occurs.

Figure 7.47a presents a contour plot of the branches' loading in the studied network in pre-disturbance conditions. The loading ratings are expressed in percentage of the maximum power flow that can occur for each branch. The red arrows indicate the flow on the tie-lines and the blues arrows the flows in internal lines of each area. The network is being operated without overloading problems. As the load is concentrated on the lower part of the plot and the biggest generation units are located on the upper part, there is an intense flow from the top to the bottom of the chart. Regarding the power flowing from area 1 to area 2, there are two strong links in the upper part of the network, 151–201 and 152–202, and two links with smaller capacity, 154–208 and 154–205. Even though the exchanges of power between areas result in the scheduled interconnection power flow of 100 MW, the total amount of power flowing between

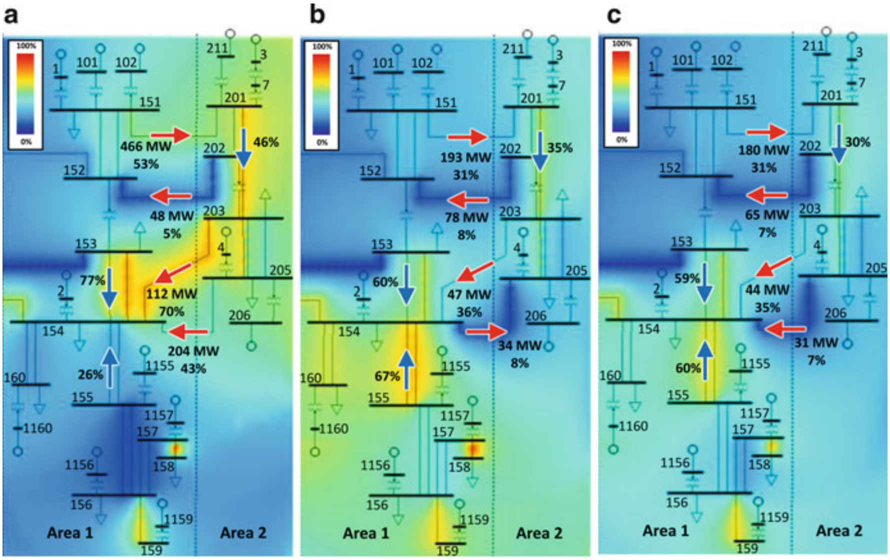


Fig. 7.47 Branches loading: (**a**) in the beginning of the simulation; (**b**) at the end of the simulation without EV participation; (**c**) at the end of the simulation with EV participation

areas is much bigger. In fact, the line 151–201 is exporting 466 MW to area 2, while the other lines are importing 364 MW from area 2. So, in order to feed the load that is mainly concentrated in buses 154–160, electricity follows the path of smaller impedance, which increases the loading rate of the tie-lines and the lines at area 2.

When the generator 102 trips out of the system, there is a large mismatch between generation and load and, consequently, a drastic change on the power flowing in the network.

When the AGC control action is concluded, the provision of secondary reserves by EV resulted in an overall reduction of loading in the network as shown in Fig. 7.47. The EV load reduction decreased the need for increasing the generation in the same extent as in AGC operation without EV. In any of the cases, the power flowing in the line 154–155 increased due to the action of the AGC unit of area 1.

2. Loss of wind generation

   The second scenario considered that a fault occurred and consequently 585 MW of the existing wind generation tripped due to inexistence of fault ride through capability. Being a smaller loss than in the first case, it is expectable that the AGC handles this disturbance properly.

   When the wind farms trip, frequency drops to 49.6 Hz, and the tie-line mismatch in this case is a shift from around 100 MW export to area 2 to 50 MW import. As the power loss was smaller and the lost units were not participating in primary or secondary control, this event appears to be less severe.

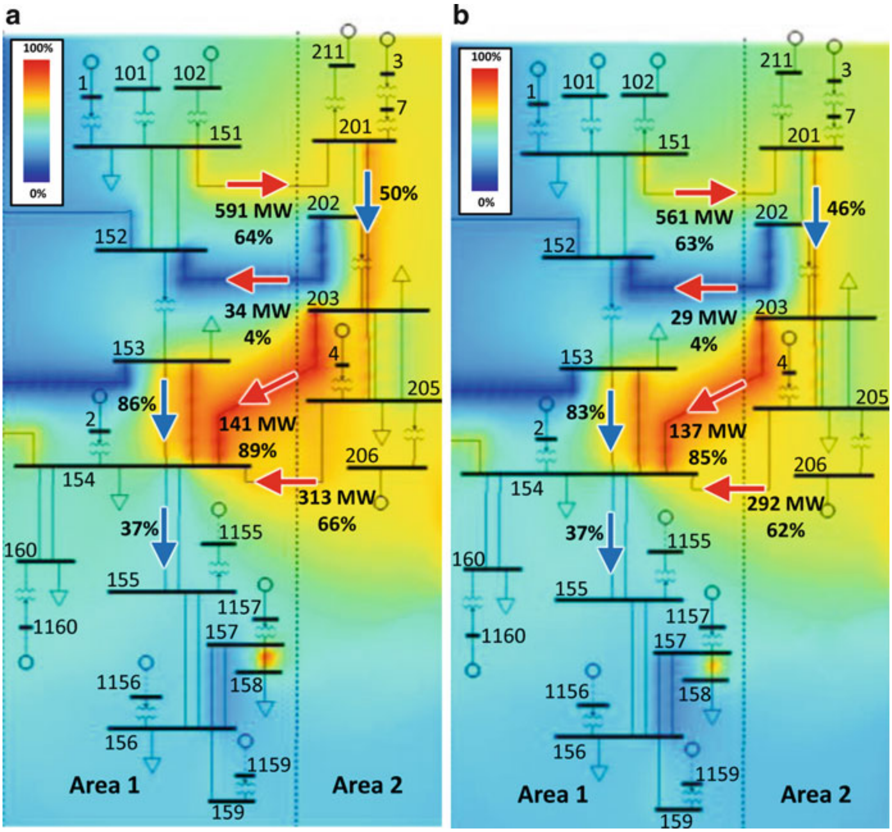


Fig. 7.48 Branches' loading rating at the end of the simulation: (**a**) without EV participation and (**b**) with EV participation

Yet regarding the branches' loading, there are some differences when compared to the loss of generator 101. Initially, the conditions presented in Fig. 7.47a were verified. Yet the loss of generation occurs closer to the consumption nodes, and even though it is less demanding for the AGC operation perspective, the network faces more stressful conditions in terms of loading of its branches.

Branches loading at the end of the simulation are presented in Fig. 7.48. Comparing the steady-state conditions of the case of AGC with EV to the case without EV participation, it is verified that EV grant almost 6 % loading reduction of the flow in the tie-lines and an overall loading reduction of the branches internal to each control area.

3. Extreme scenario

   The last presented case is built upon the first, where generator 101 goes out of service. In this scenario, a redistribution of PFs was made, considering that one of the generators, 1157, would no longer provide secondary reserves. Subsequently, area 1 does not have sufficient reserves to face the loss of generator 102 if EVs are not reserve providers.

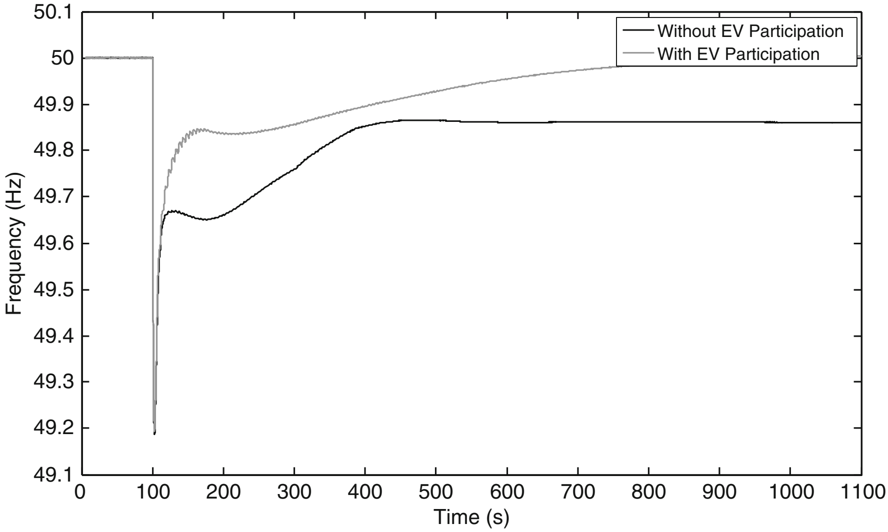


Fig. 7.49 Frequency of the center of inertia of area 1

Observing Fig. 7.49, it is possible to verify that frequency when EVs are not reserve providers does not return to its original value as there are no sufficient reserves. When EVs participate in AGC operation, the system manages to correct frequency within the mobilization period of the secondary reserves. Likewise, the lack of sufficient amount of reserves impeded the restoration of the original power flow value in the case of AGC without EV, while with the participation of EV, the power flow is reestablished in <300 s (Fig. 7.50). Naturally, the error in area 1, when EVs do not participate in AGC operation, never disappears due to the lack of reserves in this area.

7.4 Conclusions

7.4.1 Steady-State Studies

In the section dedicated to the steady-state studies, the performance of the tools developed based in the deterministic and stochastic methods (presented in Chap. 6) has been evaluated.

Concerning the performance of the tool based in the deterministic method (Methodology 1), it was shown that it is appropriate to make expeditious studies in small networks. Yet as it follows a deterministic approach to distribute EV along the network buses, it is only possible to evaluate the effects of a possible scenario for a fixed period of 1 day.

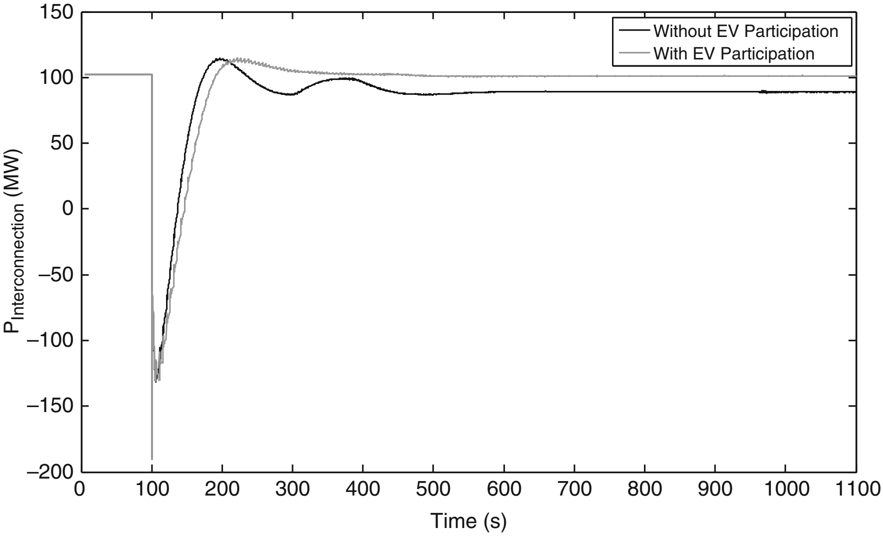


Fig. 7.50 Tie line interconnection power for area 1

The tool based in the stochastic method (Methodology 2) uses a Markov chain to simulate the EV movement, allowing exploring different scenarios in a coordinated way. It proved to be useful to

- Obtain detailed knowledge on the grid impacts provoked by the EV battery charging
- Identify the most critical operation scenarios and detect the network components that are subjected to more demanding conditions, which might need to be upgraded
- Compute detailed information related with the EV availability to charge and with their mobility patterns
- Compute information about the aggregators' activities in the electricity markets

In conclusion, the combination of the stochastic procedure to simulate the EV movement with the heuristic/optimization algorithms referred above allows modeling adequately the EV power consumption in distribution system under different charging modes. This methodology can thus be used to perform impact assessment studies, for the EV charging management in real-time applications, to perform the grid monitoring and evaluate its operating conditions, to define the optimal bids to submit in the markets by the aggregators, among other possibilities.

7.4.2 Dynamic Studies

It was possible to verify that EV may gain a crucial role in the operation of isolated systems by participating in primary frequency control. The EV presence in islanded systems may benefit the system operation in different ways. The fact that a new load is integrated in the electricity grids is naturally beneficial for the resilience of this kind of system that tends to have low load values, especially during valley hours. In fact, EVs add up to the preexisting load and allow the dispatch of an increased number of generators. Yet reserves still have to cover for any losses of generation or for the variability of the primary sources of Renewable Energy Sources (RES)-based generation. This requirement may lead to limitations to the maximum installed RES-based generation capacity as dispatches deeply rely on thermal units, fossil fuel based, to perform regulation and load following. As EVs are considered active participants in primary frequency control, then the reserve requirements can be met resourcing to loads instead of just generation. The dependence on the conventional reserve providers is reduced, and the possibility of increasing the share of RES is enabled.

The effectiveness of having EV participating on primary frequency control in an isolated system was tested in a small test system, where an uncommon fully renewable dispatch was considered. It was verified that EV participation reduced the frequency oscillation band of the system, with a small effort for EV in terms of consumed energy. Evidently, by responding to frequency deviations with the reduction or increase in load EV consumed energy changes and as the most demanding conditions are related to the loss of primary resource availability, the consumed energy will tend to be lower when EVs participate in primary control. However, given that the charging period of an EV may take several hours, the substantiated 1 % decrease in the consumed energy may represent just a few extra minutes to charge the vehicle.

The second part of the dynamic studies section was dedicated to evaluate the ability and performance of EV in the provision of secondary reserves. The results prove that EVs are quite effective performing this task, being possible to extend the general conclusions to systems with similar characteristics, pending for individual tests for every new system to enable the quantification of the benefits. It was demonstrated that the performance of the AGC operation increased with EV presence. Once EVs receive new set points, they almost instantaneously respond, changing their load to the required value. In this situation, the AGC achieved, for the tested disturbances, a bigger reduction of the error in frequency and interconnection power flow than the conventional AGC, during the first couple of minutes. As the conventional AGC has a slower reaction, it demands a swifter reaction from the participating generators that culminates with some relatively large overshoots. The AGC with EV also managed to damp this reaction, performing a better control of the error.

So far, it was shown how the performance of the AGC can be enhanced with the presence of EV, yet the most important conclusion is that EV provide an additional source of secondary reserves that can be operated side by side with conventional reserves or even replace them. By using EV, it will be possible to integrate further RES in interconnected systems as the secondary reserve requirements do not need to be met entirely by conventional generators. This decrease in conventional reserves not only allows the integration of new RES generation but also avoids the operation of some conventional generators in the spinning reserve and consequently the greenhouse gases emissions these units would be responsible for.

References

1. Lopes JAP et al (2009) Identifying management procedures to deal with connection of electric vehicles in the grid. In: PowerTech, 2009 IEEE, Bucharest, p 1–8
2. EN 50160—voltage characteristics of electricity supplied by public distribution systems. European Committee for Electrotechnical Standardization—CENELEC (2007)
3. Kundur P (1994) Power system stability and control. McGraw-Hill, New York, NY
4. Almeida PMR (2011) Impact of vehicle-to-grid in the power system dynamic behaviour. Ph.D. thesis, Department of Electrical and Computer Engineering, Faculty of Engineering, University of Porto, Porto
5. PSS®E 32.0.5, PSS®E Model Library (2010) Siemens PTI
6. ENTSO-E (2010) Operation handbook. https://www.entsoe.eu/resources/publications/system-operations/operation-handbook/
7. Almeida PMR et al (2011) Electric vehicles participating in frequency control: operating islanded systems with large penetration of renewable power sources. In: PowerTech 2011, Trondheim, Norway

Chapter 8
Regulatory Framework and Business Models Integrating EVs in Power Systems

Ilan Momber, Tomás Gómez, and Michel Rivier

8.1 Introduction

At the supra- and national level of the European Union among others, different initiatives and policy measures have been launched, including strong commitments to the allocation of funds concerning energy related environmental impacts and energy efficiency. These large government stimulus programs and the increasing awareness surrounding sustainability issues in relation to energy consumption have paved the way for an electrification of transportation.

Furthermore, they have lead to the expansion of research in energy efficiency and clean technology specific to introduce electric vehicles for road transportation. However, to achieve the goal of electrifying personal transportation, there are a number of prerequisites to a mass market of electric vehicles (EVs).[1] Hence, both the electric power industries and the automotive industries will have to rise to a number of challenges. The implications of these, focusing on the electricity sector, are elaborated in the subsequent paragraphs and sections.

Even though EVs may possess environmental advantages compared to conventionally propelled transportation, i.e., fossil fuel dependent internal combustion engines, decision makers have to bear in mind that these benefits are a

[1] A more precise denomination of the class of vehicles that is discussed in this chapter would be plug-in electric vehicles (PEV), as there exist many other vehicles with electric propulsion that have no interface with—and hence no impact on—the electric power system. EV and PEV are synonyms in this text.

I. Momber (✉) • M. Rivier
Institute for Research in Technology (IIT), Comillas Pontifical University,
Calle Alberto Aguilera 23, 28010 Madrid, Spain
e-mail: ilan.momber@iit.upcomillas.es; michel.rivier@iit.upcomillas.es

T. Gómez
National Energy Commission of Spain, Alcalá 47, 28014 Madrid, Spain
e-mail: tgs@cne.es

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_8,

function of electricity generation at the source, and therefore demand advanced control strategies for the charging processes. Nevertheless, certain studies conclude that, even in rather unlikely but most carbon dioxide (CO_2) intensive scenarios, both annual and cumulative greenhouse gas (GHG) emissions could be reduced significantly, due to a certain electrification level of the car fleet under analysis [1].

Storage technology is still very expensive. Even though capacity degradation may effectively turn out to be less severe, with the currently projectable lifetime performance, the use of relevant commercial lithium-ion based batteries for grid application as peak power generators remains economically unattractive [2]. Alternative revenue sources for battery storage valuation in power markets for ancillary services, such as secondary frequency regulation may have to be sought for [3].

At the consumer level, the proposition of EVs compared to conventional vehicles is similarly uncertain. The currently perceived purchase premiums compared to internal combustion engines are widely being discussed and the multitude of different policy schemes to foster EV adoption are evaluated. A comparative study shows that from a user perspective one time support at the initial investment is highly appreciated. However, recurring instruments like an annual tax benefit are more effective yet usually smaller in volume [4].

Coordination issues for utilities (mostly distribution system operators (DSOs)) and car manufacturers but also fleet operators and potentially other charging station operators constitute finding functional standards for charging interfaces including physical equipment, metering, and communication protocols for billing at home or en route.[2] The relevant standardization organizations at the level of the European Union are the European Committee for Standardization (CEN) with its sub-branch the European Committee for Electrotechnical Standardization (CENELEC) and the European Telecommunication Standardization Institute (ETSI). All of the above mentioned organizations are in collaboration with the biggest international standardization bodies: International Electrotechnical Commission (IEC) and the International Standardization Organization (ISO). Standards need to be addressed to a variety of topics to achieve interoperability, allow for competition in manufacturing, and agree on communication protocols as well as the information to be exchanged. Furthermore they can improve safety of certain products [5]. Currently, especially for fast charging connectors there is a big controversy involving different proposals from the USA, Germany and Japan (CHAdeMO), such that the standardization process might continue until the end of 2012.

The further integration of EVs may require new models of ownership and lease for personal transport vehicles and a change in thinking about the business as

[2] An introduction to standardization issues and definitions concerning the electrical as well as information communication interfaces between energy management systems and vehicles is given in [21]. Therein, interface requirements are given as a function of the technical capabilities of the connection called: passive, dynamic, and vehicle-to-grid.

usual practices. Mobility as a product or a service may have to be consumed under new types of arrangements and contracts. Moreover, a great challenge is the installation of a publicly available charging infrastructure for EVs. This would demand active collaboration of national and regional policy makers, vehicle fleet managers, electricity distribution companies, payment service providers, and many other areas that may not directly be associated to the sectors of transport or energy [6]. For the latter however, finding a suitable and well established operation state description from the power system point of view for all affected entities to manage different activities such as load shifting, ancillary services provision and their interdependencies, may be crucial [7].

However, the central responsibility for supporting the commercial introduction of EVs lies with the electric utility company. A number of potential roles includes outreach and education to create customer acceptance, safe and secure infrastructure development, as well as understanding and potential of mitigating adverse system impacts [8].

To provide the reader with an understanding of the intentions of this book chapter the contribution of it can be summarized as:

1. Providing a tutorial introduction to the main characteristics, role allocation and distribution of crucial functions among the agents of modern, vertically disintegrated, i.e., unbundled electric power industries, with different penetration levels of EVs connected to the grid.
2. Introducing a classification of charging modes, i.e., different scenarios in which EVs can be charged, such as home charging, public charging on streets and dedicated charging stations.
3. Proposing a conceptual regulatory framework for these charging modes, governing the interaction of the involved agents and giving justification for the development of two new entities as intermediary facilitators of the final service.

The chapter is organized as follows. Section 8.2 recapitulates each role of the existing agents in the electricity sector that will be involved during EV charging processes. It explains market mechanisms for efficient functioning of electric power systems. The objective of Sect. 8.3 is to derive a classification of possible scenarios in which EVs are likely to be charged. Therefore, different characteristics that help describing these scenarios, including the location and control modes, are introduced. Justification for the emergence of new agents that facilitate EV charging as intermediary entities for energy resale is given: the charging point manager (CPM) and the electric vehicle supplier aggregator (EVSA). Section 8.4 presents a regulatory road map for charging EVs in three consecutive steps from short term to very advanced implications in the long term. For home charging, charging on public property as well as vehicle-to-grid (V2G) arrangements, the contractual interactions of the different existing and new agents of the electric power system are analyzed in detail. Finally, conclusions and some policy recommendations are given in Sect. 8.5.

8.2 Electricity Markets and Regulatory Framework

The electric power industry has a long history, ever since its birth, strongly contributing to the technical industrialization of manufacturing goods as well as to the economic development of modern society. Until its present maturity, tremendous endeavors have gone into the improvement of current processes of planning, operating, monitoring and controlling. These have to endure in a world that is on the one hand technologically quickly advancing but, on the other hand, growing technically and economically ever more complex.

Traditional regulation of this strategically important sector was designed with electricity utility companies vertically integrating all processes of the value generation chain for the final product of electricity: procurement of primary energy sources, generation, transmission, distribution, and retail. The enhancement of computing and communication technology has propelled the intention to drive for efficiency with appropriate economic signals sent to the final customer. The innovations in production technology and the advancement of renewable energy generation equipment that can be deployed in a less centralized manner than conventionally large electricity generation plants have further weakened the stance of monopolistic ownership of vertically integrated companies such that today, the electric power industry has changed drastically.

Modern power systems since the 80s and 90s have undergone the processes of unbundling and liberalization. They have developed electricity markets with decision making hierarchies for long, medium, short term and real time horizons. The physical characteristics of electricity as such and the not yet economically attractive storage technologies demand for generation and consumption to always equal each other, which make the design of these markets for such systems a highly complex and non trivial task. To fulfill it, technically both the frequency of the alternating current and the voltage magnitudes at the different physical nodes of the network have to be kept within a certain range. The terminology and the technical specification of the services may vary, however such services have to be provided. Usually, in liberalized systems the system operator procures them from other agents [9]. The services are usually called ancillary, as, in addition to being needed, they they help optimize the utilization of the system, such that for instance reactive power reduces the technical losses in the network. Setting up and designing these markets properly is not a trivial task [10].

The following subsections give rise to the functions that are taken on by the various agents in the electric power system. First, those known and well defined existing agents are introduced, that current regulation has yet defined on the one hand. On the other hand, the expected, yet sketched and upcoming agents in a changing picture of EVs penetrating the power system, are explained thereafter. Finally a small example on how these agents may interact in a coordinated way is provided.

8.2.1 Known and Well Defined Existing Agents

Electric power system agents can be distinguished by the nature of their basic activity: There are some agents that are sometimes referred to as *non-regulated*[3] agents with competitive activity. These include *generation* companies acting on wholesale energy markets and *suppliers*[4] acting on retail markets. The other group of agents is mostly referred to as *network operators* or *regulated agents*. Due to the economies of scale in network infrastructures, these agents, including the operators of *transmission* and *distribution networks*, act in natural monopolies but with what is called incentive based regulation. As opposed to what is commonly referred to as traditional cost of service regulation, these sets of rules[5] set the remuneration of the service by revenue caps and therefore are emulating the competition of markets to artificially induce efficiency gains in the operation and planning of the networks.

For the charging modes and their classification in Sect. 8.3, mostly distributions system operators, transmission system operators and suppliers are of particular interest and hence are further introduced and abbreviated at this point:

- Transmission system operator (TSO): is responsible for keeping a secure system operation at the regional or national transmission level. For meeting this obligation he procures system services, such as operational reserves and frequency regulation, from market participants.
- Distribution system operator (DSO): is the owner and operator of the distribution grid. It is assumed that distribution is legally unbundled from generation, transmission and particularly from supply and retail. Therefore, DSOs cannot trade energy. They only provide network services and are fully regulated monopolies.
- Supplier or retailer (SA): is the agent who sells energy to final customers, the electricity end consumers. Under the assumption that distribution and supply have been unbundled,[6] final customers remunerate their supplier for the service, who in return procures the energy from the market and pays the DSOs regulated charges for grid services and other system costs.
- Final customer: is the agent that requires electricity for end uses and purchases it from a supplier. In general, by legislation, a final customer is not allowed to resell electricity to another final customer or to another agent. Final customers

[3] The term non-regulated is actually misleading as all agents are governed by some piece of regulation or document legislation. There are merely some agents, to which a stricter set of rules applies.

[4] Sometimes these agents are also referred to as *retailers*.

[5] Incentive regulation schemes are, effectively, also cost based approaches to remunerating network activities.

[6] This is not true for the regulatory frameworks in most of the electric power systems in the United States of America, where distribution and supply activities are carried out by the same agent, the traditional vertically integrated utility.

are residential, commercial or industrial customers. In some countries, small residential customers used to purchase electricity at regulated rates, while large customers negotiated a supply contract with any supplier.[7]

8.2.2 Expected, Sketched and Upcoming Agents

In addition to the known, well defined electric power system agents above, the penetration of EVs in the system expectantly requires, along with the EV driver, two new agents, depending on the later to be introduced charging modes. These expectation of these agents is sketched as:

- Electric vehicle owner: is the agent that owns an EV and requires electricity to charge its EV battery. In the future, he would be able to provide other services to the networks as well. When charging, EVs would be physically connected to a charging point and in some scenarios a specific EVSA will procure system services from the EVs under his control (see definition below). In the following, we consider two main alternatives regarding the development of charging infrastructure: (a) privately owned charging areas with private or public access for EV owners, and (b) public charging areas with public access for EV owners.
- EV supplier-aggregator (EVSA): the EV supplier is the agent selling electricity to the EV owner. EV suppliers are retailers and therefore similar to other wholesale market agents. Their business should be declared as competitive activity unbundled from other vertical functions in the electric power system. EV suppliers in general are expected to aggregate multiple EVs to conduct an integrated management may hence also be referred to as EV aggregator.[8]
- Charging point manager (CPM): it is assumed that the installation of charging infrastructure on private property will be made by the property owner. Acting as a final customer CPMs will buy the required electricity to charge its own EV or to resell it to other EV owners connected to the charging station under a commercial agreement. Different situations could be possible:
- An office building owner who installs several EV charging points in the office parking area for private use of its employees.
  - A commercial building owner who installs several EV charging points in its parking area for use of its clients.
  - An EV charging station owner who installs several charging points with different charging options, specifically fast charging modes, for delivering this service to the public.

---

[7] Later on, it will be clarified that EV owners might not always be considered as final customers.

[8] It should be noted that, in the near term home charging scenarios, the function of the supplier/retailer can be assumed by the retailer which already contracts the final customer for domestic residential electricity sale. Please compare Sect. 8.4 on Home Charging.

- By legislation so far, CPMs who resell electricity to a third party (EV owner) in a competitive activity would be defined as suppliers or retailers. In this case, the access to the charging services would be made available on the terms and conditions set by the CPM. For obtaining a license to exercise this type of activity, they should demonstrate technical capability and financial liability according to legislation

In public parking areas, streets and areas with public access, the installation of EV charging points will be more expensive. To have a large roll out will involve substantial expenditure and risk. When involving the use of a public good such as the public location, there is a strong argument, that the business should be regulated and charging stations developed by either the corresponding DSO or the municipality in the area. In this case, the infrastructure would be considered as other grid expenditures and the access to the charging points should be made universal to EV owners contracted with different EV suppliers. In this way, private companies monopolizing limited resources would be avoided. In the case of CPMs acting on privately owned property, however, infrastructure could be installed and investment risk assumed by private agents. The activity would be open to competition depending on the development rights of the location.

8.2.3 Interaction and Coordination of Electric Power System Agents

In Guille and Gross [11] a proposal of a framework for effective network integration of battery EV into the grid as distributed energy resources (DERs) is included. In addition to the aggregator interfaces with other agents mentioned the description of the contractual arrangements in Table 8.1 complements this picture in a more general way.

The table lists all agents with physical assets for the electricity flow in the header row: Generation, Transmission, Distribution and the final customer.[9] In the first, i.e., the leftmost, column, the electric power agents are listed. At the intersection of a row with a line, the downstream flow of electricity is indicated with an arrow (→). All other cells contain, if existent, existent the specified types of contracts between the agents. If a cell is gray there is no direct contractual relationship between the

Table 8.1 Generic contractual relationships and electric power flow for charging EVs

	Generation	Transmission	Distribution	Final customer
Generator	→	→	→	→
TSO	–	→	→	→
DSO	–	→	→	→
Final customer	–	–	–	→
EVSA	Wholesale contract	Network access	Network access	EV retail contract

[9] The final customer could be either EV User or the CPM as reseller to the EV User.

two agents. For example electricity flows from the TSO via transmission and distribution assets to the final customer equipment and there exists a network access contract between the EVSA and the DSO as well as between the EVSA and the TSO. However there is no direct contractual relationship TSO/DSO and final customer. This table visualizes very well, how the EVSA is simply a market player facilitating the commercial relationships between agents with physical assets, however not owning any itself.

8.3 Electric Vehicle Charging Modes

As mentioned in previous sections, for the purpose of this book chapter a charging mode is defined as a situation in which an EV can be charged [12]. This definition is so important, because these situations can vary a lot and it makes sense to determine characteristics that distinguish and categorize them. For that, certain characteristics of a charging mode have been made out: It is determined by factors such as charging point location, interacting agents and their relations for delivering the final product or providing the final service, as well as the level of control over the charge and degree of sophistication for the charge.

As opposed to charging modes, business models describe how a product or service is provided, including perceived value creation of a certain product for a final customer. It is internal to one single agent and usually easy to assess by spending strategic thoughts on opportunities and threats. However, charging modes provide the access to the changing interrelations as they put each single agent into perspective in relation with others. In that sense charging modes are the first and necessary more general step to formulate the business models of the agents.

An overview of the different imaginable charging scenarios as well as a logical nomenclature can be seen in Table 8.2, but first the discussion explains all the elements in detail.

8.3.1 *Location and Access*

The location and access of the charge is defined by the property ownership on which the charging process itself is taking place. The different cases are: charging points located on public areas, private areas with public access and private areas with private access.

Table 8.2 A nomenclature for classifying different EV charging modes

Location		Agent		Control	
Home	HO	Supplier-aggregator	SA	Uncontrolled charge	UCO
				Controlled charge	CCO
Private property	PR	Charging point manager	CPM	Vehicle-to-home	V2H
				Vehicle-to-building	V2B
Public property	PU	EV supplier-aggregator	EVSA	Vehicle-to-grid	V2G

8.3.1.1 Public Areas (PU)

For public areas being municipal, regional or national property, merely public access is possible; therefore a charging station or a charging point should enable free access to all citizens, which does not mean that the electricity should be sold for free. However, dealing with a public good, the assumption that the distribution system company, or the local municipality would be developing the infrastructure, is not very farfetched.

At this point it seems important to note that it has been implicitly assumed that DSOs are likely or favorable to develop public charging infrastructure. However the outcome of this market development is uncertain at this point. It remains to be seen what will happen in the future as different approaches for developing public charging infrastructure from different stake holders with diverging interests are currently out there on the table.

The Union of the Electricity Industry at pan-European level initiated the discussion about the "structure of the e-mobility market" in September 2010 [13], this excerpt picks up the dialogue and aims at introducing the given regulatory options for fostering the deployment of public charging infrastructure. The paragraphs below illustrate the proposed regulatory options for rolling out the public infrastructure for charging EVs. These are potential alternative for the ownership and operation of the infrastructure placed in public areas with public access.

1. Option: The integrated infrastructure: This option is characterized through full integration of the charging infrastructure in the asset base of the DSO. This would mean that retail and distribution of the electricity for electric mobility are unbundled from each other.
2. Option: The separated infrastructure: The charging infrastructure would be a completely new and separate step in the value chain of EV electricity delivery, at least legally unbundled from the rest of the distribution network as well as from retailing.
3. Option: Independent E-mobility: Here the ownership of assets and the retailing of the electricity for EV are combined under one roof. Like in the second option, the charging infrastructure would be outside the asset base of the distribution system company, yet the retailing would be part of the functions for the new entity. There would be a proprietary network with the licensed and conceded territory. This territory could be maximally as big as the electric power system of the country or as little as a few spots.
4. Option: Spot operators: Finally the fourth option proposed is a derivative of number three with the main difference that the license is single spot based and not for a regional territory.

The DSO developing the charging infrastructure in public spaces as the network operator provides the advantage of having the best knowledge about the grid behavior and can take direct measures in the planning and operation processes to keep the costs as small as possible.

The importance of this discussion lies in finding appropriate solutions as to how these investments are going to be acknowledged as costs to DSOs and how electricity customers are going to pay for them. All this has to be compliant with incentive based regulation for networks in place.

8.3.1.2 Private Areas with Public Access (PR)

For private areas with public access, the case is completely different. These areas include company owned parking lots or dedicated charging stations. Here, the property owner can decide to commercialize the service of charging EVs himself, subcontract other companies or sell a license to do so. The arrangement would be made between the operator of the charging point and possibly multiple EV users. Other contractual relationships, such as office or commercial building owners giving the service away for free are possible.

Especially offices with a high share of the staff commuting with personal vehicles might be an interesting field of application for EVs. There, the managed fleet size could be significant, cars are usually parked during a multiple hour periods of time, and sophisticated energy management systems will be in place, sometimes integrating on-site generation with small-scale photovoltaic arrays and combined heat and power systems.

8.3.1.3 Private Areas with Private Access (HO)

Private areas with private access are the third and last group of charging modes, concerned with all the charging processes with restricted access to a limited group of EV owners. Examples are home charging in domestic garages or multi-dwelling units. In this case the electric vehicle service equipment (EVSE) or the charger is most probably going to be owned by the EV user himself and the cost can be added to the purchase price for the vehicle itself.

8.3.2 Control Modes

Concerning the technical grid aspects of EV integration, different control modes are imaginable. The following gives a short introduction to the differentiation of control in the charging modes presented underneath. There are five different denominations for control modes: uncontrolled charging (UCO), controlled charging (CCO), vehicle-to-home (V2H), vehicle-to-building (V2B) and finally vehicle-to-grid (V2G). Even though in the final nomenclature and roadmap they are presented equally, a certain degree of hierarchy exists. This is shown in Fig. 8.1 and individually explained in the subsequent subsections.

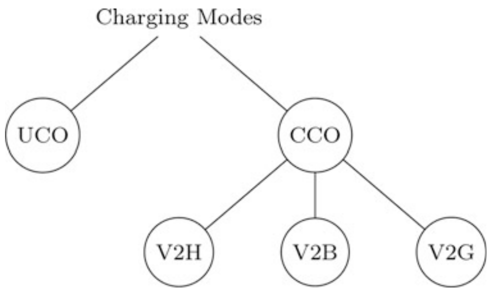


Fig. 8.1 Hierarchy of charging modes

8.3.2.1 Uncontrolled Charging

UCO stands for the simplest, least sophisticated way of operating the charging of an EV. UCO is the intuitive, traditional way of supplying any given electrical device with power: plugging it in and instantaneously taking the required power. Since there is no intelligence to improve the scheduling of the charge to any criterion whatsoever, it is often times referred to as *dumb charging*.

With sufficient EV penetration in the system, UCO may lead to adverse impacts on the network operation and finally high costs in operation and investment in generation and network assets. However, with appropriate electricity prices as economic signals, beneficial behavior of the final customer may be induced and thereby reduce the negative impact of such charging. A good example are peak and off-peak prices to promote charging at off-peak hours, or with higher time resolution, a contract with hourly prices.

UCO in combination with time or load variable end-user tariffs, supported through smart metering,[10] is expected to be the most prominent way of charging EVs in the near term until high penetration scenarios require more sophisticated control modes.

8.3.2.2 Controlled Charging

CCO complements UCO. CCO is more sophisticated, hence sometimes merely called *smart charging*, than UCO as it disposes of a certain degree of control over the charge. In its most trivial form, CCO may be a simple switch that cuts off the load if it negatively impacts on the system—for instance in the case of overloads or voltage problems in the network—or if it becomes too expensive for the system to reinforce itself against these impacts. More advanced solutions may permit bidirectional energy flow between the battery storage system of the vehicles and the local network at the grid connection.

[10] Smart metering in this context refers to the ability of the measurement device to discriminate between different time periods (resolution may vary from two periods per day, up to 15-min intervals) and potentially even communicate this data close to real-time to the user and to the DSO.

The control may be exercised by different energy management systems operated by different entities such as EV aggregators, DSOs, or local CPMs. When EV sales have sufficient uptake such that high penetration levels and concentration of EV charging in certain feeders becomes significant, CCO may have to be imposed by legislation.

8.3.2.3 Vehicle-to-Home

V2H is the first element in the subset of CCO control modes for charging electric vehicles. It specifies the criterion for the optimization of the charge control to be according to local domestic devices. Assuming that a household has a local energy management system[11] installed, V2H charging could be controlled to level out the net load of the home avoiding peak demand charges or shift electricity consumption to off-peak hours.

8.3.2.4 Vehicle-to-Building

V2B charging control is very similar to the precedent and not clearly distinguishable from the above. However it is recently more frequently used and therefore listed here. In this classification it refers to situations in which the EVs are connected to an integrated management of a greater size building. In addition to the energy management system in V2H this may compose of an integrated control with local loads and even other distributed energy resources (DER), low voltage distributed generation (DG) or distributed storage (DS) devices.

8.3.2.5 Vehicle-to-Grid

The control mode V2G has received a lot of attention in scientific literature. This section is not ample enough to give an exhaustive explanation but intends to deliver an introductory overview of what is, often times referred to. In any case V2G presents the most sophisticated and hence futuristic application of connecting EVs to power networks.

Security of the physical operation of the electric power system requires the frequency of the alternating currents, as well as the node voltage magnitudes of the network to stay within a certain range [9]. During the process of unbundling vertically integrated utility companies and liberalizing energy markets most systems adopted fundamentally similar designs for procuring ancillary services in market arrangements [10]. Although in research there has been an abundant intuitive use of the term V2G, two completely different understandings of the term can be distinguished:

[11] Sometimes referred to as *energy box*.

1. On the one hand, to some it means that there is a bidirectional power flow, for which the vehicles sometimes act as a generator, injecting electric energy into the grid.
2. On the other hand it is understood in a more general way, as providing an ancillary service to the grid, which could be delivered by unidirectional power flow as well. From a technical view point lowering the aggregated power draw of a given fleet of cars has the same effect on the system as an injection of the same amount of power. What counts is the rate of change in power draw indifferent of the current level of own demand. Hence, just the stopping of a charge, when regulation energy to lower demand is required,[12] would be provided by an interruptible power connection of an EV. Sortomme and El-Sharkawi [14] argues that even though further limited in capacity unidirectional V2G should be logically addressed first, as it requires less sophisticated EVSE.[13] Among a similar train of thought the aggregator of EVs for V2G is believed to be the potential link between automatic generation control (AGC) entities and the fleet of vehicles for providing secondary frequency regulation [15].

In best-case scenario simulations of German and Swedish power markets, Andersson et al. [3] found that secondary frequency regulation markets could be significantly profitable but may saturate quickly if high capacity connections are available to a broad mass of vehicles.

To understand the above given descriptions of the control modes, an additional, short discussion of the state of the art literature of related topics is provided. From a regulatory point of view, the entire system should be designed such that in the long run aggregated EV fleets are serving the unbundled electric power industry in various ways. The competition among aggregators can lead to price reductions of the services to the final user, while the EV suppliers as commercializing entities are adapting the tariff options and tariff schemes to the specific preferences of the final customer by promoting new products and services.

There exist very strict formulations of the justification for control, if certain services such as V2G should be provided by EV. It is clear that the efficient integration of EV in certain scenarios at public charging points and with sophisticated control hierarchies is simply not possible without proper communication. According to these concepts the aggregating entity acts as an intermediate agent for performing market behavior forecasts, preparing bids for buying and selling energy in wholesale markets. However, this activity and the resulting market bids might have to be validated with the operator of the network to assure an efficient functionality of the system [16].

Along the same line of thought is locational pricing for distribution grid capacity as described by Pehnt et al. [17]. There the final tariff of the EV customer includes local grid fees, which account for acutely overloaded lines and voltage problems via larger grid fee components.

[12] Also referred to as regulation up.

[13] This claim is backed up by the EV interface studies of [21] and it avoids negative effects of depleting EV batteries in cases where the charge is highly valued by the customer.

In any case, the EV aggregator's behavior with respect to scheduling the charge, depending on different levels of PEV penetration, can have a significant impact on distribution network investments and incremental energy losses, which in turn, cause costs for the regulated DSO [18]. Therefore, facilitating the charging schedule according to the costs and needs of the DSO and the inherent flexibility of EV load itself can generate value. To impose the rescheduling, control over the charge is needed.

The following sections come back to rather market related, economic aspects of EV integration. They explain the regulatory setting and once again give justification why two new figures, CPMs and EVSAs may, in a future with high penetration levels of EV in the power system complement the incumbent supplier aggregators (SAs).

8.3.3 Incumbent Supplier Aggregators

This section focuses on the interactions of market agents such as SAs and the regulation they have to follow in order to perform their tasks when supplying EV users. Day-ahead and intra-day markets refer to the wholesale energy market, where generators meet SAs which procure electricity to resell it to final customers on the so called retail market.

The activities of SAs comprise technical and economic tasks. They include the billing of the energy consumed by the final customer according to energy and capacity prices set in the agreed contract. Also, a retailer has to store and use the information on the consumption of each final customer for load forecasting. Furthermore, the tasks embrace the acquisition of energy, e.g., in a power exchange, and managing the commercial relationships with the existing and potential new customers.

The SAs are market players that bridge the trading gap between generation and demand, fulfilling various functions from the wholesale to the retail market.[14] The profits result from the difference in prices, quantities, terms and risks at wholesale compared to final customer level. In order to assure a viable business model, the aggregated demand for the final customers has to be as accurately forecasted as possible, and then accordingly procured. If positions do not close as expected, that is, if the forecasting errors are causing a need for balancing of supply and the aggregated SA's demand, more costly ancillary service products have to be procured on the balancing markets. SAs have to pay the regulated access tariff according to the contracted capacity and consumption measured on the interface to the network at the final customer's metering point. In countries where electricity

[14] In capital market theory these functions mainly include *transforming lot sizes*, i.e., trading volumes and quantities of goods, *risk transformation*, i.e., hedging against undesirable events, and *term transformation*, i.e., monthly payments for domestic customers.

distribution and supply have been unbundled to favor competition among agents, all final customers should have access to competing generators through their choice of SAs. Fully regulated tariffs, if they exist, are intended to only present a back-up option. In these cases, final customers remunerate the electricity supplier for the service, who in return procures the energy and pays the distributors regulated charges for grid services and other system costs.

Due to the uncertainty, stand-alone retailing is regarded a high-risk and low-return business. In theory it is of high interest to the SA to obtain a very flexible demand which is able to respond to varying market prices in order to reflect the actual opportunity cost of the customers more appropriately and pass on part of the risk exposure to the final customers. In this sense, including a percentage of flexible demand procured by smart charging of EVs in their portfolio can be of interest for SAs in the future.

8.3.4 Charging Point Managers

CPMs are yet new to the power system. Slowly, regulation has started sketching these figures as vague understanding has hit the regulatory authorities, that an agent for reselling electricity in local contexts is demanded by a world of massive propagation of EVs.

CPMs are expected to be acting as final customers on private property with public access. They are understood to be buying the required electricity to resell it to other EV owners connected to the local charging station under a commercial agreement with specific terms and conditions. It is very important to understand that to the distribution system, however, a CPM is regarded as a single final customer. The final customer, depending on the size of the parking lot managed, could have an electricity demand as big as a small industrial customer in terms of energy consumption, or constitute just a few cars and therefore be similar to a household. In any case, the CPM in general would have a supply contract with a supplier. The supplier would have to pay the regulated access tariff according to the contracted capacity and consumption measured on the interface to the network.

CPMs should be free to define their objective function that is most beneficial to them. This could include an installation of EVSE that meters the connection points of each and every car and design according rates for the usage of this infrastructure. On the other hand, it could be favorable for the CPM to simply charge for parking time and space without measuring user specific consumption by internalizing energy procurement and infrastructure investment costs on an aggregated level in the parking time rates. Hence, the CPM could be offering the charging of the EV as an additional service to customers with whom there already is some other type of commercial agreement, like in a shopping mall or for the commuting staff of an office building. The second arrangement alludes to the main challenge of a regulatory framework forming the basis of legislation that fixes the rules for such operation of the charging service. Any set of requirements concerning metering layouts, financial liability and technical capability should be designed according to the principle of non-over-complication, applying restrictions only where absolutely necessary.

8.3.5 Electric Vehicle Supplier Aggregators

EVSAs are expected to fill the gap for an agent who sells energy to final customers, the electricity end consumers using EVs. The supplier therefore aggregates contracts with final customers and procures the energy in the wholesale markets, and possibly agrees on demand side reduction measures of the final customers to offer other services to the market. Hence, these agents already exist and are denominated supplier aggregators (SAs), with the only distinction of being specialized in serving a theoretically highly flexible load of a fleet of EVs.

In the near term uncontrolled and home charging modes are very likely to dominate the scene, in which most of the functions and objectives of the SA stay the same. In the HO scenarios where EVs are charged at home, the EVs will merely present and additional net load to the SAs of domestic electricity customers. In short, this load is more volatile because it is a flexibly schedulable charge and hence presents the opportunity for more business, but also the threat of adding uncertainty to the forecasting. As there is no control over the charging process from the SA, the main means of influencing the charge of the EVs will be the offer of EV user customized electricity prices with at least ToU differentiation. The main objective remains, to get the demand side involved in the market game by passing on the volatility of prices and thereby reducing its own risk.

The proposition by EVs could be theoretically a valuable one, as they present schedulable loads, which, if reacting to the price signals, or being controlled, may contribute to reduce uncertainty and risk exposure of the SAs, while increasing turnover significantly. However, if the penetration of EV gets very large and the bids sent by the aggregators to the market become very relevant, new specialized EV aggregators should arise and additionally in close interactions with DSOs the operation of distribution networks will also have to be considered. In such a case, the DSO might be called to validate the flows resulting from normal demand from a technical point of view and at least be informed about the amounts to be bought by the aggregators.

In general the use of EV aggregators may be viewed under a strictly quantitative aspect of consolidating many small entities to represent a more powerful agent to the system in terms of energy demand and capacity for market participation as well as buying power with low transaction cost [11].

However, in literature, the most common aspect that is mentioned is the concept of V2G [19] in which the vehicles provide ancillary services to the system, which is why in the following classification EVSAs are mentioned as the intermediary for facilitating these services.

8.3.6 Classification of the Charging Modes

Having introduced the different elements that define a charging mode, the following classification and denomination becomes more evident. It is consistent with what has been published in Momber et al. [20].

Each charging mode is named according to its classification, including the characteristics: charging point location (*LOCATION*), intermediate agent for organizing energy procurement or system services (*AGENT*), and the degree of optimization and control over the charging process (*CONTROL*). Each three characteristics can assume the above introduced occurrence *HO*, *PR* and *PU* for the location, *SA*, *EVSA* and *CPM* for the intermediate agent as well as *UCO*, *CCO*, *V2H*, *V2B* and *V2G* for the control.

A typical future charging mode for street parking with charging infrastructure would then be for instance *PU-EVSA-CCO*, in which the EV user has a contract with an EV aggregator providing a controlled charge according to electricity market prices.

8.4 Development Stages of Electric Vehicles and Associated Charging Modes

Different levels of EV penetration have different requirements on design of electricity markets and network regulation. Therefore three different phases have been identified in order to distinguish the policy recommendations given in this chapter. They are grouped in those that are immediate, rather mid-term and merely important in the long run. Immediately, the biggest challenge might be to foster the uptake and create trust in the new technology. Further on, the proposed figures, i.e. the electric power system agents introduced above, facilitating the integration of EV via aggregation and market participation should be created and addressed by regulation. Then, in the long run, more complex and technically challenging power system service provision by EV should be made possible.

The phases are denominated accordingly. Hence, Phase I for immediate recommendations is called *Catalyst*, Phase II is named *Consolidation*, and Phase III is titled *Advanced*. All of them are grouped in the chevron diagram depicted in Fig. 8.2.

8.4.1 Catalyst Phase and Home Charging

In the first phase, for immediate attention, absolute priority should be devoted to breaking important psychological barriers. As it has been mentioned above, in the near term uncontrolled and home charging modes are very likely to dominate

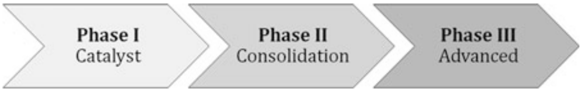


Fig. 8.2 Development stages of electric vehicle road map

the scene. In this phase of initial uptake, EVs can still be regarded as mere additional loads like any other domestic device. Besides the already undertaken setting of EV penetration goals, regarding public relations and press communication a broad mass of people, all stake holders should be very cautious in transmitting messages that are counterproductive for creating consumer trust in new technologies. This hint can be generalized; communication to the public should always focus on the positive messages, such as recommending time-of-use pricing instead of requiring control or giving up priority to other devices, to give one example.

Another principle should be noted: non-over-complication. Where possible, regulation should ease the life of early adopters striving towards new and challenging technology. Legislation should facilitate chance instead of creating complicated restrictions. The most ad hoc and hands on solutions should be favored with the least requirements for potential participants. Obviously, the *Catalyst* phase, as compared to the others, is burdened with the least amount of uncertainty, being the closest to the near term. It actually starts as of right now and will only end when EV penetration ratios become more significant.

8.4.2 Consolidation Phase, Public Charging and EV Aggregators

Depending on EV uptake, which is hard to foresee, the Consolidation Phase is considered to arise in the mid-term and hence is not of immediate concern. For this phase the electric power sector regulation should allow for the emergence of new business models of EV aggregators which are capable of managing the contracts of thousands of EVs connecting simultaneously at different locations. Their participation in energy markets should be facilitated. Participation in balancing and ancillary service markets may be more adequate for the last phase of EV integration. Risk hedging mechanisms will need to be develop for ensuring a stable functioning of systems. The potential relationship between charging points in public with the aggregator as well as with the final customer, i.e., the EV, will need to be defined.

The development of expensive charging infrastructures in public sites, mainly driven by distributors and municipalities might become indispensable for the universal access of customers to this new technology, unless there is a leap forward regarding energy density for mobile storage. The catalyst phase actually is the phase where smart charging and potentially control of fleets of EV for load management will become significant. DSOs might have to validate control strategies and network flows in case of voltage of congestion problems.

Table 8.3 Road map overview of different charging modes classified

	Charging mode overview and road map		
	Immediate (2011–2015)	Short to medium term (2015–2020)	Long term (2020–2030)
HO-SA-UCO	■	■	
HO-SA-V2H		■	■
HO-EVSA-CCO		■	■
HO-EVSA-V2G			■
PR-CPM-CCO		■	
PR-CPM-V2B		■	
PR-CPM-EVSA-V2G			■
PU-EVSA-CCO		■	
PU-EVSA-V2G			■

8.4.3 Advanced Phase, TSO and DSO Markets

The advanced phase gathers the recommendations for the rather long term and somewhat futuristic EV scenarios in power systems. EV aggregators playing a substantial role in providing V2G services and facilitating the aggregated participation of EVs in balancing and ancillary service markets. Furthermore, they could be interacting with DSOs in setting up local markets for system services. For such a scenario, more sophisticated control, measuring and billing infrastructures need to be put in place. There is a high need for cost/benefit studies to assess the profitability of these businesses before actual investment will take place. Other issues such as warranty releases for battery performance of car manufacturers need to be addressed as well. It is to be noted, that the concepts grouped in the advanced phase are not regarded as less important, especially as for instance frequency and voltage support might be highly important in integrating renewable energy resources in electric power systems and propagating the smart grid paradigm. However, they are yet premature and not marketable and therefore need other attention than policies for the immediate deployment.

Table 8.3 summarizes the developed stages of the roadmap and sorts the charging modes into a timely scope. Home charging modes are already starting to be reality as EV sales are slowly developing with only few changes in regulation. The short to medium term time horizons will be witness to the uptake of CCO modes over all locations, as the EV penetration shares will become more significant. Finally, in the long term, rather futuristic deployment of V2G service provision by aggregated fleets of vehicles will come into place.

8.5 Conclusions

This chapter has given a tutorial overview of the main regulatory issues of integrating electric vehicles into modern electric power networks. It has given an introduction to the important characteristics, the general role allocation and usual distribution of crucial functions among the agents of modern, vertically disintegrated, i.e., unbundled electric power industries, with different penetration levels of EVs connected to the grid.

It has described an adjuvant classification of various charging modes, such as home charging, public charging on streets and dedicated charging stations. Development costs and interface requirements concerning communications and control vary significantly depending on the aforementioned options. Finally it has proposed a conceptual regulatory framework for these charging modes, governing the interaction of the involved agents and giving justification for the development of two new entities as intermediary facilitators of the final service.

In this context, the chapter has highlighted the importance of new agents in the electric power systems called charging point manager and EV aggregator. CPMs are regarded as crucial for developing and commercializing publicly available charging infrastructure on private property such as privately owned parking lots. These agents would be acting as regular final customers in the electricity retail market. In public spaces it has been argued that the local DSO should play a key role for developing publicly available charging stations, while the commercial activity for selling electricity to final EV customers should be left to EV aggregators. However, in both cases, private of public spaces, CPMs and EV aggregators should be qualified and authorized agents to provide charging services on a competitive basis.

As the infrastructure costs currently vary widely depending on the sophistication of control over the charge, a three phased roadmap for policy recommendations regarding the development and massive application of EVs has been proposed.

Acknowledgments The work described in this book chapter has been partially developed during the MERGE project supported by the European Commission's Seventh Framework Programme for Research and Technological Development under contract No: 241399.[15] Ilan Momber is a candidate of the Erasmus Mundus Joint Doctorate on Sustainable Energy Technologies and Strategies (SETS) funded by the European Commission's Directorate-General for Education & Culture.

[15] This document or any other document produced within the MERGE project does not represent the opinion of the European Commission. Neither the European Commission, nor any person acting on behalf of the Commission, is responsible for the use that might be made of the information arising from the MERGE project.

References

1. Electric Power Research Institute (2007) Environmental assessment of plug-in hybrid electric vehicles: executive summary environmental. http://mydocs.epri.com/docs/CorporateDocuments/SectorPages/Portfolio/PDM/PHEV-ExecSum-vol1.pdf
2. Peterson SB, Whitacre JF, Apt J (2010) The economics of using plug-in hybrid electric vehicle battery packs for grid storage. J Power Sources 195:2377–2384. doi:10.1016/j.jpowsour.2009.09.070
3. Andersson S-L, Elofsson AK, Galus MD, Göransson L, Karlsson S, Johnsson F, Andersson G (2010) Plug-in hybrid electric vehicles as regulating power providers: case studies of Sweden and Germany. Energy Policy 38:2751–2762. doi:10.1016/j.enpol.2010.01.006
4. Kley F, Wietschel M, Dallinger D (2010) Evaluation of European electric vehicle support schemes. Fraunhofer ISI working papers, pp 1–28
5. Bending S, Ferdowsi M, Channon S, Strunz K (2010) Merge D1.1 - specifications For EV-grid interfacing, communication and smart metering technologies, including traffic patterns and human behaviour descriptions, EU 1–247. http://www.ev-merge.eu/images/stories/uploads/MERGE_WP1_D1.1.pdf
6. The Royal Academy of Engineering UK (2010) Electric vehicles: charged with potential
7. Galus MD, Zima M, Andersson G (2010) On integration of plug-in hybrid electric vehicles into existing power system structures. Energy Policy 38:6736–6745. doi:10.1016/j.enpol.2010.06.043
8. Electric Power Research Institute (2011) Transportation electrification - a technology overview. EPRI, Palo Alto
9. Rebours YG, Kirschen DS, Trotignon M, Rossignol S (2007) A survey of frequency and voltage control ancillary services—part I: technical features. IEEE Trans Power Syst 22:350–357. doi:10.1109/TPWRS.2006.888963
10. Rebours Y, Kirschen DS, Trotignon M (2007) Fundamental design issues in markets for ancillary services. Electricity J 20:26–34. doi:10.1016/j.tej.2007.06.003
11. Guille C, Gross G (2009) A conceptual framework for the vehicle-to-grid (V2G) implementation. Energy Policy 37:4379–4390. doi:10.1016/j.enpol.2009.05.053
12. Gómez San Román T, Momber I, Rivier Abbad M, Sánchez-Miralles Á (2011) Regulatory framework and business models for charging plug-in electric vehicles: infrastructure, agents, and commercial relationships. Energy Policy 39:6360–6375. doi:10.1016/j.enpol.2011.07.037
13. EURELECTRIC (2010) Market models for the roll-out of public charging infrastructure for electric vehicles. EURELECTRIC concept paper, pp 1–19
14. Sortomme E, El-Sharkawi MA (2011) Optimal charging strategies for unidirectional vehicle-to-grid. IEEE Trans Smart Grids 2:131–138. doi:10.1109/TSG.2010.2090910
15. Pecas Lopes JA, Rocha Almeida PM, Soares FJ (2009) Using vehicle-to-grid to maximize the integration of intermittent renewable energy resources in islanded electric grids. In: 2009 international conference on clean electrical power, pp 290–295. doi:10.1109/ICCEP.2009.5212041
16. Peças Lopes JA, Soares FJ, Rocha Almeida PM (2011) Integration of electric vehicles in the electric power system. Proc IEEE 99:168–183. doi:10.1109/JPROC.2010.2066250
17. Pehnt M, Helms H, Lambrecht U, Dallinger D, Wietschel M, Heinrichs H, Kohrs R, Link J, Trommer S, Pollok T, Behrens P (2011) Elektroautos in einer von erneuerbaren Energien geprägten Energiewirtschaft. Z Energiewirtschaft. doi:10.1007/s12398-011-0056-y
18. Pieltain Fernandez L, Gómez San Román T, Cossent R, Mateo Domingo C, Frias P (2011) Assessment of the impact of plug-in electric vehicles on distribution networks. IEEE Trans Power Syst 26:206–213. doi:10.1109/TPWRS.2010.2049133
19. Lund H, Kempton W (2008) Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy 36:3578–3587. doi:10.1016/j.enpol.2008.06.007
20. Momber I, Gómez San Román T, Rivier Abbad M, Cossent R (2011) Merge D5.1 - new actors and business models for the integration of electric vehicles. Technical report, pp 1–67
21. Rautiainen A, Evens C, Repo S, Järventausta P (2011) Requirements for an interface between a plug-in vehicle and an energy system. IEEE Trondheim PowerTech, pp 1–8

Chapter 9
Electrical Vehicles Activities Around the World

Gerd Schauer and Rodrigo Garcia-Valle

9.1 Introduction

Mobility has always been a basic need, using more and more sophisticated means as the present car industry shows. Highly developed cars provide comfort, safety, and powerful and efficient drives—standards far away from the first motorized vehicles. Research and development is more and more driven to create an ecofriendly car. Under the boundary conditions of increasing dependency on fossil fuels, rising oil prices, the necessity for emission reduction, and increasing efficiency, electrically powered vehicles are experiencing a renaissance. The European Commission endorses these goals through legislation for eco-friendly transport systems. But the electric vehicle (EV) is not a present-day invention and it is worthwhile to give an overview of the development of the EV and the lessons learned.

The development of electrically driven cars can be divided into four phases:

- The early beginnings of development in the 1880s to around 1930;
- Development up to the 1990s;
- Renaissance of the EV, preparing and beginning with EV roll-out (around 2010) by offering the customer adequate cars;
- Significant market penetration to 2020.

G. Schauer (✉)
VERBUND AG, Vienna, Austria
e-mail: Gerd.Schauer@verbund.com

R. Garcia-Valle
Electrical Engineering Department, Technical University of Denmark (DTU), 2800 Kgs. Lyngby, Denmark
e-mail: rgv@elektro.dtu.dk

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6_9,

Fig. 9.1 Three-wheeler electric drive. *Source*: http://de.wikipedia.org/w/index.php?title=Datei:Trouve_trike_1881a.jpg&filetimestamp=20110815090503

9.1.1 The Early Beginnings of EV Development

The development of the electric car in Europe and in the U.S. goes back to the early 1900s. The basis was the development of the electric motor and the lead-acid battery for storing energy. First constructions go back to pioneers such as Thomas Davenport who operated an electric vehicle using a primary cell battery (not rechargeable) in 1834, Gustave Trouvé, who presented a three wheeler with an electric drive in 1881 (see Fig. 9.1), and Werner von Siemens who presented the electrically driven carriage in 1882. The Belgian engineer and racing driver Camille Jenatzy constructed the "La Jamais Contente," which already in April 1899 achieved a top speed of nearly 106 km/h (Fig. 9.2).

The first highlight of the dissemination of the EV was its easy handling in comparison to the loud and difficult-to-start combustion engine. The Austrian engineer Ferdinand Porsche (1875–1951) developed the electric hub motor in 1897, and together with Ludwig Lohner (1858–1925), the owner of the largest horse-drawn carriage factory in Austria-Hungary, jointly constructed the "Lohner-Porsche" and presented that sensation at the World Exhibition in Paris in 1900 (Fig. 9.3). They soon realized its limits in terms of range as the weight of the battery had already reached half of the weight of the car. This barrier could be broken by combining the range advantage of the gasoline motor and the advantages of the easily controlled electric drive in a serial hybrid system.

In 1912 around 20 manufacturers produced 34,000 electric vehicles. For example, Detroit Electric produced electric vehicles from 1907 to 1939.

Fig. 9.2 Camille Jenatzy with his “La Jamais Contente.” *Source*: http://de.wikipedia.org/w/index.php?title=Datei:Jamais_contente.jpg&filetimestamp=20061018082520

Fig. 9.3 Lohner-Porsche Electric car. *Source*: http://de.wikipedia.org/w/index.php?title=Datei:TMW_1428_Lohner-Porsche-Elektromobil.jpg&filetimestamp=20110318212547

Fig. 9.4 Sigfried Markus Car

Conversely, Siegfried Marcus (1831–1898) for example identified benzene as a useful energy source, constructed a carburetor, an electromagnetic ignition, and constructed a modern car with a four-stroke cycle engine in 1875 (Fig. 9.4). It is well known that the development of the electric starter around 1910 blazed the trail of success for gasoline motors. Electrically driven systems remained in niche markets such as, for example, for the postal service.

Manufacturers recognized in the 1910–1920 period that electric vehicles with their limits in terms of range and power will not represent the future of vehicular transport. As an example, Studebaker Electric, which had produced electric vehicles since 1902, switched in 1912 to production of gasoline motor cars. The dominant role of the upcoming gasoline vehicle can be seen in their sales figures; 15 Mio Ford Model T, also called the Tin Lizzy, were sold between 1908 and 1927 in the USA. The construction was simple, durable, and designed for mass production. Thus, electric vehicles remained in niche markets.

9.1.2 Development up to the 1990s

Oil shortage, *rethinking after the years 1973 and 1979*: The first drastic change in mobility behaviors was caused by the Jom Kippur war (6–26 October 1973). The organization of oil exporting countries, OPEC, reduced their production to assert pressure on western countries, thus leading to an increase in the oil price from 3$/barrel (159 L) by 70 % to 5$/barrel. Several governments in Europe limited demand for example via car-free days. A second peak in oil price was reached in 1979 during the Iran-Iraq war leading to a price of 38$/barrel. In the later 1980s the price decreased again to 20$/barrel, but later on a more continuous increase in oil price can be seen driven more by increased demand than by conflicts.

It's not astonishing that in 1973 ambitions began to move away from oil. E-mobility moved back into focus as one of several possibilities to reduce emissions with the initiation of an array of research and development projects; especially utilities increased their investments in this field.

Electric vehicles, technological progress: Cars were usually converted to use of electrical power, and only a few manufacturers presented light-weight vehicle prototypes. There was research progress in the improvement and development of battery systems and different types of motor drives.

Batteries: Formerly, most cars were equipped with lead-acid batteries in different designs (pasted plate, gel-type, absorbed glass mat [AGM]). Few cars used nickel-cadmium batteries with much better performance in power, energy density, and cycle stability. Although the sodium-sulfur battery seemed to be promising, later production of the Na-S battery was stopped because of serious manufacturing problems. The zinc-bromine battery could show suitable performance, but could not perform in terms of lifetime. Later, tests were performed with the zinc-air battery system.

Battery management: To reach adequate performance and lifetime, battery management helps to avoid deep discharge and overcharge, and thermal management maintains the variously located batteries at the same temperature. Charge equalizers help to avoid divergence of the batteries or cells.

Motor drive systems: The cars were equipped with DC-motors (series and shunt excitation) or AC asynchronous motors, and a few with the permanent magnet type and rare earth magnets for excitation.

Vehicles: In this phase development was more concentrated on the development of key electric components such as the battery, charger, and drive system, so most engineers converted existing cars, vans, buses, and transporters to electrically driven ones and few built specific light-weight vehicles.

9.2 Examples of Electric Vehicles

In several countries around the world different electric vehicles were manufactured and tested. Some examples are given below; however, it is not possible to present a detailed and complete list.

The Volkswagen Golf was converted to the "CitySTROMER" with a top speed of 100 km/h and a range of 60 km. Limited quantities were built by Volkswagen for testing at utilities.

FIAT produced in small production numbers the "Panda E" as depicted in Fig. 9.5. One of them was modified by VERBUND AG to test the Zinc-Flow-Battery® (Zinc-Bromine) with a 20 kWh capacity.

Nevertheless, few inventors tried to optimize performance with light-weight vehicles. In 1981–1982 one example of a newly constructed car, a pure electric vehicle with gullwing doors was the Pöhlmann EL. The project was financed by RWE. The car was equipped with two series of excited DC motors driving the rear

Fig. 9.5 FIAT Panda

Fig. 9.6 Pöhlmann EL. *Source*: http://www.traumautoarchiv.de/html/2671.html

wheels separately. The motors were normally operated in series achieving good acceleration and climbing ability. For higher speeds they could be switched in parallel achieving a top speed of 120 km/h. The car had a weight of 1,300 kg and passed a crash test, a novelty at that time. The range was about 60–90 km. The production price was relatively high, with low demand, and in total only 18 units was built.

One car was even exported to Tohoku Electric Power Company, Sendai, a utility in the northern part of Japan. At the first "Grand Prix Formel E" in 1986 the car won the race and was a real eye catcher (Fig. 9.6). In 1988 Erich Pöhlmann looked into a

Fig. 9.7 Horlacher GL-88 "EGG," 1988. *Source*: http://www.horlacher.com/products_services/ev_development/gl_88_egg.htm

conversion of the Audi 100 Avant. He modified the back axle of the Quattro with an additional electric motor, replaced the spare wheels with batteries, and created the first Audi Duo, a hybrid car which was presented at the Internationale Automobil-Ausstellung (IAA) in 1989.

Another pioneer should be mentioned: Max Horlacher developed and built the GL-88 EGG in 1988 (Fig. 9.7), a car with a carbon-reinforced plastic body with dimensions of 2.55 m length, 1.31 m width, and 1.42 m height. The car had a weight of only 300 kg, was equipped with an 8-kW asynchronous motor, and reached a top speed of 80 km/h. The energy consumption was only between 3 and 4 kWh (DC).

One should mention that many other prototypes were designed at this time, for example the Twike (a light-weight three wheeler), the BMW series 3 and BMW E1, the Hotzenblitz with limited production, and Norway developed the city car Think.

In 1991 the Peugeot S.A. (PSA) group started with electric vehicles. The Peugeot 106 electrique had a weight of 980 kg, a top speed of 90 km/h, and a range of 80 km. The Peugeot 106E and Citroen Saxo, equipped with the Ni-Cd battery, had a quite acceptable performance for the customer. Over 1995–2005 PSA produced 10,000 EV. A big change was brought in by an EU environmental law concerning the restricted use of cadmium.

A very good example of how strict regulations and law can influence the development of technologies is the EV1 from General Motors (GM) presented in 1996. EV1 was primarily brought to market in order to accomplish the zero-emission vehicle mandate introduced in 1990 in California. As California is one of the biggest markets for cars the new mandate was quite a shock for the car industry and they had to rethink propulsion concepts. GM did a lot of development in electric vehicles and after the concept car "Impact" produced the EV1 in series. EV1, a two-seater, set new levels. For charging a paddle was used which worked via induction and the remarkable car shape enabled the lowest air resistance ever seen on a series vehicle. First, two separate motors where placed at each front wheel, but these were later replaced by a single AC induction motor. A top speed of 130 km/h, an acceleration of 9 s from 0 to 100 km/h, and a driving range of 220 km could be reached. Initially 26 lead-acid batteries were used and later these were replaced by nickel-metal-hydride batteries. They had a capacity of 16.3 kWh and a nominal voltage of 312 V. EV1 was first introduced in Los Angeles and San Diego for a price of $33,995, although the production price was much higher. Similar to today's business models the EV1 was only offered as a leasing car with monthly rates of $349–$640. The last piece of news relating to the EV1 was in 2006 when the film "Who killed the electric car" was released. The filmmakers criticized the takeover of GM's patents by Texaco.

9.3 Demonstrations at Electric Vehicle Races

Car racing events provided a good possibility to present technical developments to a broader audience, including the participation of technicians at technically orientated conferences. Safety aspects have great importance; races organized under FIA (Federation Internationale de L'Automobile) rules had to receive expert technical approval before races and the FIA promotes moves towards e-mobility. Some of these races are mentioned below.

Tour the Sol: It was the intention of solar pioneer Josef Jenni to demonstrate that solar energy works also in the middle of Europe and not only in sunnier areas. An essential impulse to the public came from the first "Tour the Sol" in 1985 in Switzerland. Aimed at demonstrating sustainable vehicles, light-weight concept vehicles demonstrated their performance and charged their batteries directly using onboard photovoltaic (PV)-modules. In another class, additional human power via pedals was allowed. Later, EV charging was allowed from stationary batteries energized by PV modules and later again charging using 230-V AC mains was allowed under the condition that the amount of energy used was provided by a grid-connected PV-system.

As the cars drove on public roads, they achieved good visibility and positive reaction in the media. Several reports, books, articles in newspapers were written and reports transmitted by television. Thousands of people observed the event and visited the cars in the daily camps over the 5 days of the first race from June 25 to June 30, 1985. This race was held until 1993 and it is worth mentioning that similar activities were organized (Fig. 9.8). It was fascinating that these prototypes could drive the routes required with minimal energy.

World Solar Challenge: This Australian solar-powered car race covers a distance of 3,021 km. The route starts north of Darwin, goes through the Australian outback travelling south to Adelaide. The first race was held in 1987, and until 2011 a total of 11 car races took place. As the name suggests, the solar-powered cars have to be powered by PV modules on the car. It is a challenge for participating teams from

Fig. 9.8 Tour the Sol 1987, solar cars at the goal in Arosa, Switzerland. *Source*: http://de.wikipedia.org/w/index.php?title=Datei:1987_TdS_Arosa.jpg&filetimestamp=20110523014223

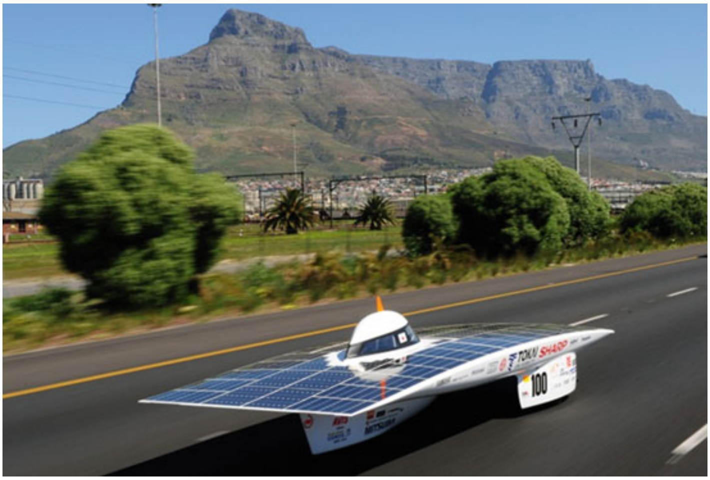


Fig. 9.9 Tokai Challenger, winner of the World Solar Challenge. *Source*: http://en.wikipedia.org/wiki/File:Sasc2010_tokai_challenger_table_mountain.jpg

universities and companies to optimize the car in terms of an efficient drive, high solar cell efficiency, and finding an effective energy management system to calculate the right driving strategy. The first race in 1987 was won by the GM sun racer with an average speed of 66.9 km/h, and after a few races the average speed was up to around 100 km/h. Figure 9.9 shows the winner of the race in 2001, the Tokai Challenger of Tokyo university.

Similar car races were organized, for example the North American Solar Challenge, The Solar Car Challenge, and the South African Solar Challenge.

Grand Prix of Formula E: The first “Grand Prix Formel E” was held in 1986. From 1987 this race was held at the airport area of Interlaken. Cars divided into different weight categories had to demonstrate performance, perform acceleration tests, a long time-period test, and had to drive the course three times quickly.

Austro Solar: The first Austro Solar took place in 1988 and aimed to demonstrate that EVs are suitable for daily use. Under conditions of a car race different tests for measuring range, acceleration, skills, and slalom had to be undertaken. Over the years different routes through Austria were chosen to include important cities in the regions of Austria. In 1989 a special challenge was the route over the Glockner pass, because of the many hills and huge altitude difference, meaning climbing up to 2,500 m above sea level. The Austro Solar was organized ten times—annually until 1999 except for 1998.

12 Electric Hours: Test demonstrations organized by Citelec. As there were constraints imposed by energy density and power at that time, a successful approach was the implementation of electric vehicles for cities which usually needed a low daily range. In this regard, regenerative braking, high efficiency of the electrical drive system, and minimal standby losses during waiting time at signal lights are great advantages. They can bring solutions to urban areas in relation to a cleaner environment. Citelec is the Association of European Cities interested in Electrical vehicles and was founded in 1990 as an international non-profit organization under Belgian law. It promotes hybrid and electrical vehicles by participating in research and demonstration projects, executing testing with involvement in standardization.

At the fifth “12 electric hours” in Namur, September 27–28, 1991, 20 vehicles of different type such as passenger cars and vans with different drives and battery systems demonstrated their suitability for daily use. At this time lead-acid batteries were the most commonly used followed by four cars by with nickel-cadmium. Two cars were prototypes with high-density batteries, one using the high-temperature sodium-sulfur (NaS) battery and one was a converted FIAT Panda E using the zinc-bromine battery developed by Powercell at Mürzzuschlag, Austria.

In total, many of the cars demonstrated successfully the ability for 6 h continuous daily operation. The average speed of most of the cars was around 20–22 km/h (limited by traffic), half of the cars needed less than 1 h for recharging within the 12 h.

9.4 Renaissance of the Electric Vehicle

As already mentioned, the battery is the key element for the performance of an electric vehicle. As slight improvements were made to conventional lead-acid batteries, a new battery type has in recent years captured the market, lithium-based batteries. Lithium systems offer high specific energy and power. Conversely, lithium is highly reactive and poses a fire danger. Significant help came from the information and communication technology side. Mobile phones and notebooks achieved high market shares; powering these devices brought Li-battery development into the mass market, replacing the former Ni-Cd and Ni-MH battery systems. Also other key factors such as improved drive systems, the ability of new batteries to charge quickly, and the development of new electric vehicles brought a breakthrough.

9.4.1 Li-Battery for the Mass Market

The power density of the Li-Ion battery is 40–70 % higher compared with Ni-MH batteries and at the same weight energy is about 20–80 % higher and provides a better efficiency. The goal for EV-batteries is to reach some thousand cycles though they could reach the life time of car. After this, there is the opportunity use them as stationary storage system (2nd life of battery). Depending on the composition of the positive and negative electrodes, different characteristics could be achieved. For application in vehicles there are five key factors that are most important: energy density, power density, safety, life time, costs. By choosing different components, characteristics can be tuned in terms of higher power or energy, better safety features, life time or costs. For EV in principle four typical technologies were developed.

Lithium nickel cobalt aluminum (NCA) cathodes demonstrated an extremely long life time and have the highest energy and power density. Conversely, they have disadvantages in terms of costs and safety as there is a danger of thermal run away at high charge level. Lithium manganese spinel (LMO) and Lithium manganese polymer cathodes are safer, though their energy density is lower. Capacity fading during cycling at temperatures greater than 40 °C was measured. Lithium titanate (LMO/LTO) cathode/anode materials feature more stability, high life time, and allow a wide use of the capacity. Conversely, they store comparably less energy (they operate at 2.5-V cell voltage in comparison to the 3.7–4.0 V of other chemistry systems). Lithium iron phosphate (LFP) batteries are relatively safe, more resistant against overcharge and have low production costs; however, their low temperature performance is weaker.

9.4.2 New Image of Electric Vehicles

Using the latest technologies, Tesla Motors created a sophisticated sports car. They used light-weight components from the Lotus Elise for the car, about 6,831 high-power Li-batteries from the mass market, and a powerful drive. The laptop batteries of the 18650 type are connected to a nominal voltage of 375 V, store 56 kWh, and have a weight of about 400 kg. A battery management system monitors each cell.

Fig. 9.10 Tesla Roadster

The Tesla Roadster was presented for the first time in July 2006 at Santa Monica Airport, California, and it took 2 years for production of the Tesla roadster to start in 2008. With a peak power of 225 kW (302 PS) and a torque of 370 Nm from the asynchronous motor, developed by AC Propulsion, the car offered a new dimension, an acceleration from 0 to 100 km/h in 3.9 s and a top speed of 200 km/h. This sporty, pioneering Tesla roadster, depicted in Fig. 9.10, changed the image of electric vehicles entirely concerning range, acceleration, and top speed.

9.4.3 Fast-Charging Possibility Changes Minds and Created Acceptance

Of interest is the experience made in Japan after provision of the "possibility" for fast charging. The result, shown in Fig. 9.11, was impressive. The psychological barrier of limited range on people using an EV can be seen clearly. Before the fast charger was installed (Fig. 9.11a) only 20–50 % of the available battery capacity was used, after installation of the fast-charging station, drivers made extensive use of the EV and used up to 70 % of the available capacity (Fig. 9.11b). The barrier and fear of running out of electricity no longer counted because of the possibility of fast charging. On the whole, acceptance increased dramatically; the monthly range was seven times higher than before installation of the fast charger.

9.4.4 EV Availability

In discussions the "chicken" or "egg" problem is often mentioned, cars need charging posts, but they will only be erected, if there are enough cars on the market.

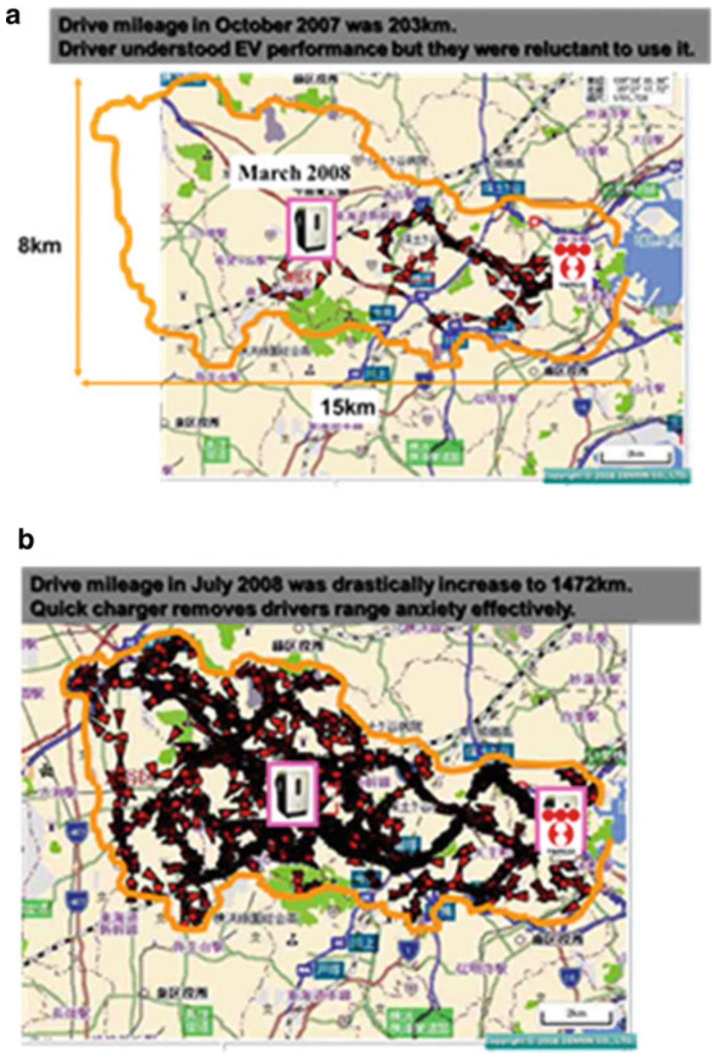


Fig. 9.11 Use of EV before (**a**) and after (**b**) installation of quick chargers (*Source*: H. Aoki, Tepco; CHAdeMO)

It was therefore of great interest to investigate the availability of electric vehicles. An investigation, initiated by Verbund showed interesting results. After several months of research a data base could be created, documenting 151 EV [1]. It could be seen that 81 different vehicle manufacturers were recorded in the vehicle database. Figure 9.12 illustrates the distribution in terms of continents.

Europe has with an identified 42 EV companies the most vehicle manufacturers compared to other continents. Asia is the next with 21 EV manufacturers, followed by North America with 17 EV manufacturers. In Africa activities in developing

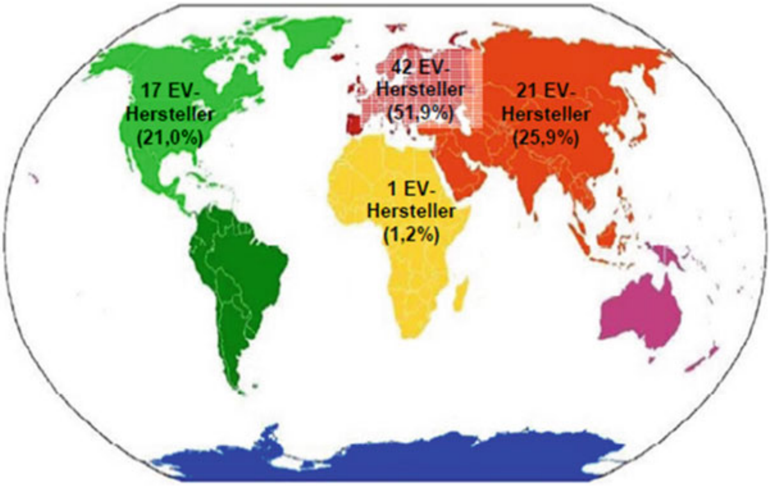
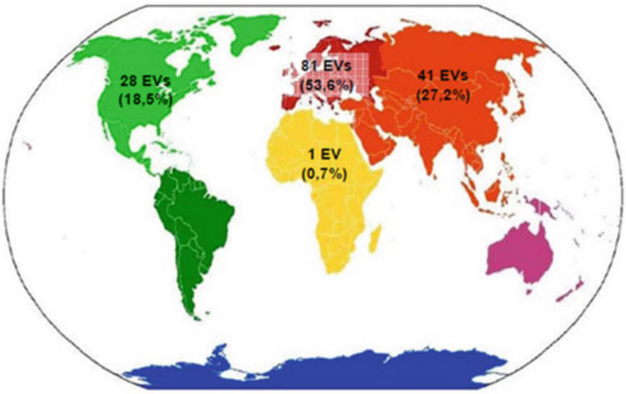


Fig. 9.12 Distribution of EV manufacturers

Table 9.1 Worldwide EV manufacturers

Region	EV Manufacturer
Africa	Optimal energy
Asia	BAIC, Brilliance, BYD, Chery, Dongfeng, EuAuto Technology Limited/Hong Kong Polytechnic University, Geely, Great Wall Motor, Haima, Honda, Hyundai, Japan Automobile Research Institute, Luis, Mitsubishi, Nissan, Reva Electric Car Company, Subaru, Tata, Tianjin Qingyuan, Toyota, Zotye
Europe	Audi, Bellier, Bluebird Automotive, BMW, Brabus, Citroen, Citycom AG (now Smiles AG), Comarth Engineering, Courb, Duracar, Effedi, elbilNorge, E-Wolf, Fiat, Heuliez, HSR, Kamoo AG, Karmann, Koenigsegg, Lightning, Loremo, Lotus, Magna, Mercedes, MES-DEA, Microcar, Modec, Nice, Peugeot, Piaggo, Pininfarina, Protoscar, Renault, Rinspeed, Ruf, Tazzari, Think, Trabant, Twike, Venturi, Volvo, VW
North America	AC Propulsion, Aptera, Chrysler, Commuter Cars, Corbin Motors, Dodge, Energetique, Ford, Myers Motors, Phoenix Motorcars, Shelby, Smith Electric Vehicle, Steenstra, Tesla, Universal Electric Vehicle, Zab, Zenn

electric vehicles could be seen. In Australia and South America research in this area was not found; this could be caused by the relatively small automobile industry in those continents or other key aspects of activity such as for example the use of ethanol as a fuel in Brazil, South America. Table 9.1 provides an overview of the manufacturers involved with EV. Besides the well-known large automotive manufacturers from around the world, there are some, which are not well known in Europe. Even small manufacturers pursue the field of electric mobility and develop their own concepts. But it is questionable in which dimension the smaller companies will prevail against the bigger ones in the future.



Korea	1
Niederlande	1
S-Afrika	1
Österreich	1
Schweden	2
Kanada	3
Norwegen	4
Schweiz	7
Spanien	2
Indien	6
Großbritannien/UK	9
Italien	12
Japan	16
China	18
Deutschland	18
Frankreich	25
US	25
Gesamt	151

Fig. 9.13 EV vehicles per origin countries [1]

Figure 9.13 provides an overview of the different types of electric vehicles and shows the identified number of car types in the different countries. Reflecting the manufacturer's distribution, 53.6 % of the electric vehicles are developed in Europe. Asia comes in second (27.2 %), followed by North America with a share of 18.5 %. Most EV concepts in Europe are being developed in Germany and France. Especially Renault, Citroen and Venturi in France, and BMW, Mercedes and VW in Germany show high activities. The activity in the Asian region is growing very fast with large contributions from China, Japan, and India. In the future manufacturers from those countries want to compete with the European ones.

9.4.5 EV Moving into Public Awareness, Preparing Roll-out

Companies develop strategies to bring electric vehicles to market. Depending of the brands, they highlight specific characteristics as Fig. 9.14 shows.

Worldwide activities have begun and the car industry has been presenting its concepts. They have developed prototypes and delivered test fleets for field tests. Around 2010 in all important exhibitions car manufacturers presented their studies, prototypes or electric vehicles, already prepared for market entrance.

Below in Figs. 9.15, 9.16, 9.17, 9.18, 9.19, 9.20, 9.21, 9.22, and 9.23, some impressions from the Frankfurt Motor Show 2009 are presented. As a series hybrid car, the Opel Ampera with a range extender has potential for wide acceptance and to substitute conventional cars.

Beside the purely electric vehicles, it should be mentioned, that the Toyota Prius is available now in the third generation of its hybrid drive system. It has an innovative power steering system branching electric drives with combustion engine. Especially in cities with stop and go operation, it could benefit from the electric drive and save fossil fuels (Fig. 9.24).

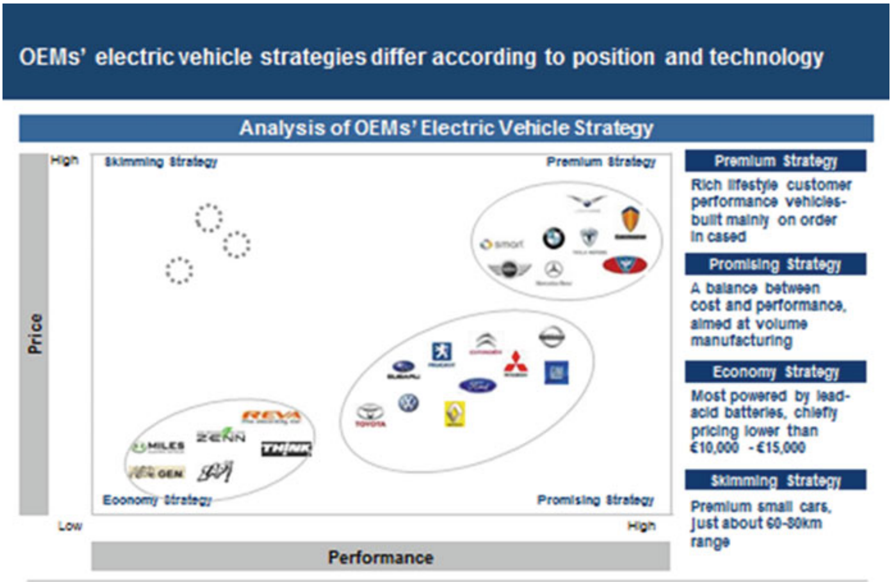


Fig. 9.14 OEM electronic vehicles strategies (*Source*: Results of a study made by Frost and Sullivan 2010)

Fig. 9.15 Audi e-tron

As already mentioned, the battery is the key element for the performance of an electric vehicle. As slight improvements were made to conventional lead-acid batteries, a new battery type has in recent years captured the market, lithium-based batteries. Lithium systems offer high specific energy and power. Conversely, lithium is highly reactive and poses a fire danger. Significant help came from the

Fig. 9.16 BMW concept car

Fig. 9.17 Ford Focus BEV

information and communication technology side. Mobile phones and notebooks achieved high market shares; powering these devices brought Li-battery development into the mass market, replacing the former Ni-Cd and Ni-MH battery systems. Also other key factors such as improved drive systems, the ability of new batteries to charge quickly, and the development of new electric vehicles brought a breakthrough.

Fig. 9.18 Open Ampera

Fig. 9.19 Renault Fluence Z.E.

9.5 Overview of Electric Vehicle Activities

The car industry is improving existing technologies step-by-step, optimizing the combustion engine to lower specific consumption and emissions. It starts from a wide variety beginning with mild hybrid systems, full hybrid and plug-in hybrid cars, electrical vehicles with range extenders and fuel cell vehicles; all that technical solutions are important steps to lower emissions. In the following an overview of certain projects, which are currently underway, is given with a focus on the

Fig. 9.20 Renault Zoe Z.E. concept

Fig. 9.21 Renault Twizy Z.E. concept

development and demonstration programs for purely electric vehicles. The market introduction of EV needs international cooperation, with the topic of standardization showing the difficulty and efforts of several stakeholder associations. R&D activities and demonstration projects are discussed. For some countries, in an exemplary way, an overview of research activities for electric vehicles, national associations for EV, and a description of research projects are given and country-specific characteristics defined.

Fig. 9.22 Electric smart

Fig. 9.23 VW up

9.5.1 International Energy Agency

At the International Energy Agency (IEA) the topic is addressed in two different working groups, the renewable energy working group and the hybrid & electric vehicle group. The working groups investigated the two topics renewables and EV in a combined way within the IEA RETD, RETRANS studies. Low- and zero-emission vehicles are a topic of worldwide interest; cooperation between key players can accelerate the common effort to reduce emissions, increase energy efficiency, and optimize integration of renewable energies. It can be seen, that both,

Fig. 9.24 HEV: Toyota Prius

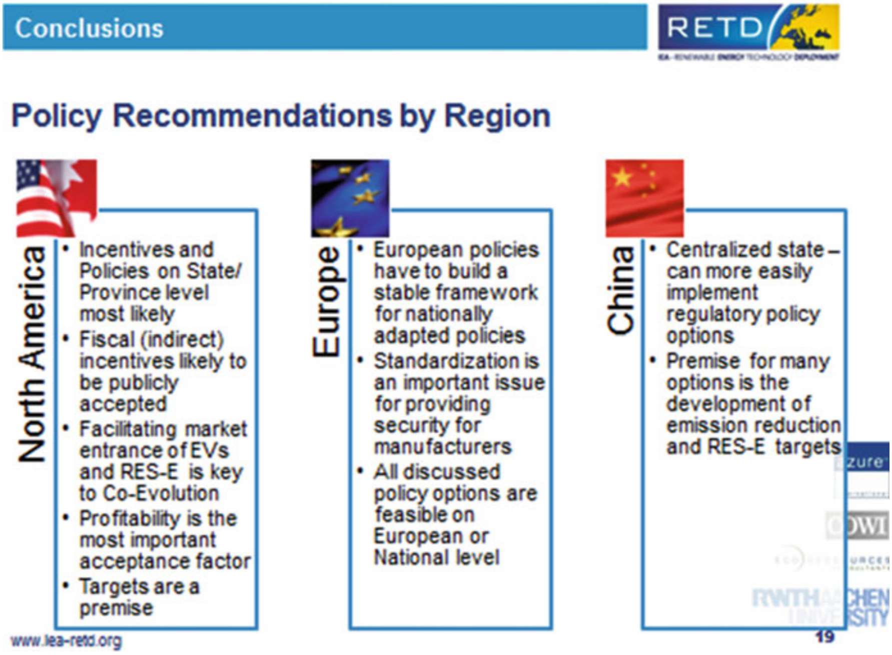


Fig. 9.25 Policy recommendations (*Source*: IEA)

renewables and EV contribute to emission reduction, and their co-evolution will cross-fertilize both technologies [2]. EV can be seen as a chance for economy. This is a global topic; Fig. 9.25 reflects the motivations and parallelism of different regions and summarizes policy recommendations.

9.5.1.1 IEA Implementing Agreement Hybrid Electric Vehicles (IA-HEV)

The IEA promotes execution of research by cooperating States on related topics through implementing agreements (IAs). Countries contribute information and benefit by sharing information and resources. In the HEV several topics are delineated into several tasks; in general, the first task is usually for information exchange concerning topics such as research and technology development, commercialization, marketing and sales, regulation, standards and policies. Specific tasks focus on batteries, market deployment of EV, plug-in hybrids, system integration, sustainability aspects and quick charging (see [3]).

9.5.2 Deriving Results from EV Tests

Evaluation criteria: In the last few years many pilot schemes in various regions tested electrical vehicles of the latest generation evaluating them in routine daily use. The scientific evaluation of pilot projects has no standardized methodology. To identify the most promising pilot projects, certain criteria should be defined which will lead to an evaluation model that is able to compare these different projects [1].

To be able to evaluate these projects some criteria should be considered. To help in benchmarking these criteria additional sub-criteria were defined and weighted differently, which is given by the following percentages:

- Innovation, pioneer position (5 %): Depends on project start, the earlier, the greater the pioneer position given.
- Business model (20 %): Assesses the availability of a master plan (in comparison to an isolated approach) and values cross-border concepts.
- Payment concept (20 %): This criterion evaluates the existence of an accounting system, the possibility of price determination by market prices, simplicity for the customer, package and product definition for the customer, and a guarantee of 100 % renewable energy for EV charging.
- Charging infrastructure (15 %): evaluates the density of charging posts, and availability of cooperation partners, for example in shopping centers or car parks.
- Car adoption (15 %): This criteria judges if the cars were used by many different users, private consumers/companies/public authorities and accounts for the density of EV and the number of different types of vehicles.
- Economic feasibility (25 %): For the pilot regions funding is considered in terms of economic operation in future times.

With such a systematic approach it is easier to compare different pilot regions as shown in Fig. 9.26.

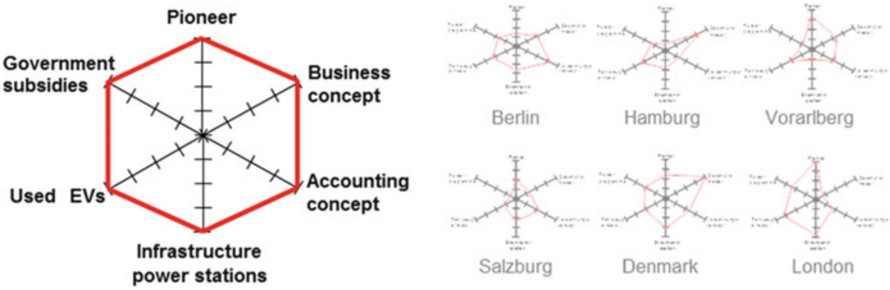


Fig. 9.26 Evaluation criteria and comparison of different pilot projects in Europe [1]

9.5.3 World Electric Vehicle Association

The World Electric Vehicle Association (WEVA), launched in 1990, is an international organization to promote research, development, and dissemination of electric vehicles. WEVA consists of three regional associations representing Europe, America, and the Asia-Pacific area and organizes the Electric Vehicle Symposium (EVS).

9.5.3.1 European Activities

Within the European research program, there is an effort to improve mobility and transport regarding efficiency, emissions, and use of renewable energies. With the *Green Cars Initiative* financial support is provided for research activities into green technologies. It comprises R&D support for cars, trucks, and buses in a variety of areas such as greener combustion engines for trucks, biofuels, electric and hybrid cars. Hydrogen technology and fuel cell research is bundled in *The Fuels Cells and Hydrogen Joint Technology Initiative*. Some actual EU-funded research projects will be mentioned in the following. Standardization is a key topic because without agreement between countries investing in the wrong plug design would lead to stranded investments or lead others to postpone investment until binding decisions are made. Eurelectric has made an effort to accelerate that process, but harmonization between different stakeholders is time consuming.

CARS21: In January 2005 the Competitive Automotive Regulatory System for the twenty-first century (CARS21) initiative was launched. It is a high-level expert group chaired by the vice president of the European Commission. Members of ministries, the European Commission and Parliament, representatives of the car industry and car manufacturers have joined this group. The task is the preparation of suggestions for the European Commission to increase the competitiveness of the EU car industry, which is a key technology in Europe for 2.1 Mio involved employees.

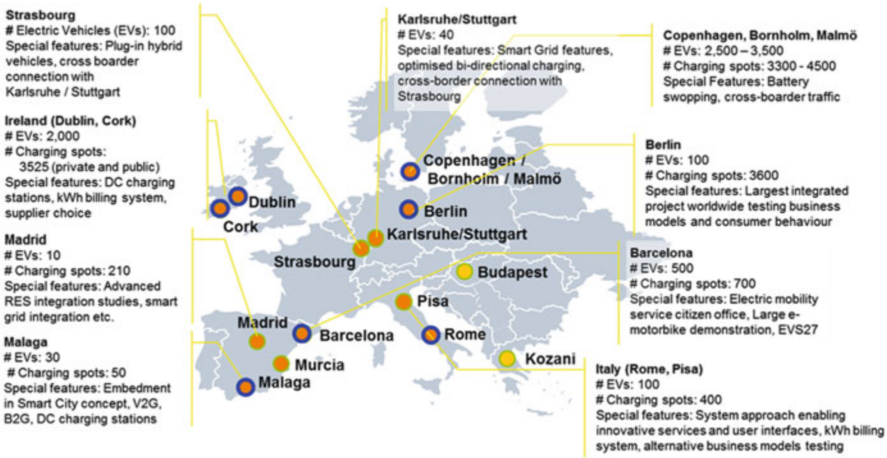


Fig. 9.27 Overview of demonstration regions in the Green eMotion project. *Source*: http://www.greenemotion-project.eu

9.5.3.2 EU Research Activities

Green e-Motion

Research and development for electric vehicles and erection of the charging infrastructure cannot be carried out by single countries or companies. Of course, there is high specific Know-how in different states available, but the implementation of e-mobility needs R&D cooperation on a European, or better worldwide, scale. One of the intentions of this large Green eMotion project with 43 partners involved is to bring all necessary stakeholders together, to investigate best practice, and collect the distributed knowledge in European countries to create a common system. The project budget is 42 Mio € with 24 Mio € funded by the European Commission.

The project consortium consists of partners from major industry (Alstom, Better Place, Bosch, IBM, and Siemens), utilities (Danish Energy Association, EDF, Endesa, Enel, Electricity Supply Board [ESB], Eurelectric, Iberdrola, RWE, and PPC), electric vehicle manufacturers (BMW, Daimler, Micro-Vett, Nissan, and Renault), municipalities (Barcelona, Berlin, Bornholm, Copenhagen, Cork, Dublin (represented by the energy agency Codema), Malaga, Malmo, and Rome), universities and research institutions (Cartif, Cidaut, CTL, DTU, ECN, Imperial, IREC, RSE, TCD, and Tecnalia), and EV technology institutions (DTI, fka, and TÜV NORD) and covers a great variety of issues, such as building electric vehicles, preparing charging infrastructure, deals with charging strategies and grid issues and is aiming to overcome international billing problems. User aspects are well addressed and experience can be collected by the involved demonstration regions (Fig. 9.27).

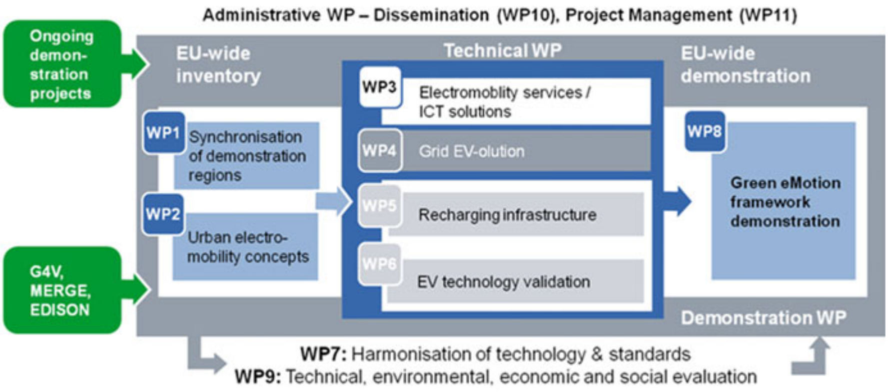


Fig. 9.28 Structure of work packages in the Green eMotion project. *Source*: http://www.greenemotion-project.eu/workpackages/index.php

The comprehensive research and development tasks have been assigned to 11 work packages (WP), as shown in Fig. 9.28. In the following, the key work is described. Within the 12 demonstration regions there is a great variety of different cars, fleets, concepts and implementing mechanisms, incentives, and charging infrastructures. In WP1 they evaluate all the experience of the different demonstration regions and aim to synchronize those activities. It is the task of WP2 to assess the different concepts of municipality planning, policy measures and regulations. It should be clarified, which key features are necessary for a successful mass roll-out of EV in Europe. In WP3 the electromobility services and ICT solutions are addressed. As ICT is penetrating daily life to a greater and greater extent, it could advance EV technology by providing roaming solutions for easy charging and fleet management services. WP4 investigates solutions for the future requirements of the grid, as high penetration of EV charging has a strong impact on the stability of the grid. The influence of EV is investigated from the grid operator's viewpoint to plan charging infrastructure in the best way. Users need a simple and reliable system to accept e-mobility; within WP5 the interoperability and DC fast charging, battery swapping and inductive charging is demonstrated and smart network management systems developed. WP6 evaluates the EV technology in daily life, different climatic zones for user performance, durability and costs. In WP7 the harmonization of technology and standards is addressed on the vehicle, infrastructure and communication side for mass roll-out of plug-in hybrid and electric vehicles. WP8 will demonstrate the enhanced interoperable and upgradable e-mobility solutions of the Green-eMotion framework. In WP9 technical, economic, environmental, and social aspects of the mass roll-out are investigated. WP10 aims at dissemination of information gained and offers an external stakeholder board to exchange information in a bi-directional way to companies and stakeholders outside of the partners of the consortium. Execution of the project is carried out through effective project management (WP10).

Grid for Vehicles (G4V)

It should be mentioned, that the results of the "Grid for Vehicles" project, finished at the end of June 2011, have been published. Within the 1½ years of the project, an analytical framework to plan the required technological developments in the grid infrastructure was developed and defined the related ICT and policy requirements to cope with mass roll-out of EVs [4].

Mobile Energy Resources in Grids of Electricity (MERGE)

This project aims to prepare Europe's grid for electric vehicles. Grid planning and operation is already changing by increasing the number of decentralized generators such as PV or wind power. Mass penetration of EV has a serious impact on the grid, EV can be seen as a simple load, a controllable dynamic load, or as storage in the future. Studies were carried out by 16 partners based on certain power systems in various countries and showed interesting results.

An adequate EV integration into the system could mean an increase in the use of renewable resources. EV charging in hours where there is a surplus of renewable power in the system decreases demand of wind power spillage. A high penetration of EV increases slightly system-specific costs and CO_2 emissions. Simulations for the transmission grids have shown that major complications will arise for the transmission grid. However, it is recommended smart charging strategies be implemented. A steady state analysis has been performed in order to assess the impact to the medium-voltage (MV) distribution grid and showed that only with smart charging are more EVs allowed to be connected as it takes into account the power produced from renewable energies. Transformers/lines tend to be more quickly overloaded in cities, while in rural networks low voltage problems are expected. For low-voltage (LV) networks, large-scale EV integration may affect quality of service and cause technical problems (increased losses, power quality and imbalances) [5].

9.5.4 Standardization

For E-mobility, there is a strong requirement for harmonized plugs for the charging infrastructure. Working documents have been prepared within CEN/CENELEC, but until 2012 there is no union European agreement for a specific type of plug.

The Union of the Electricity Industry, Eurelectric, is supporting the harmonization process and published already on 27 October 2009 a declaration on "Standardisation of Electric Vehicle Charging Infrastructure" [6], signed by 49 CEOs of European electricity companies.

In September 2010 Eurelectric completed a concept paper "Market Models for the Roll-Out of Electric Vehicle Public Charging," (Fig. 9.29) with a description of

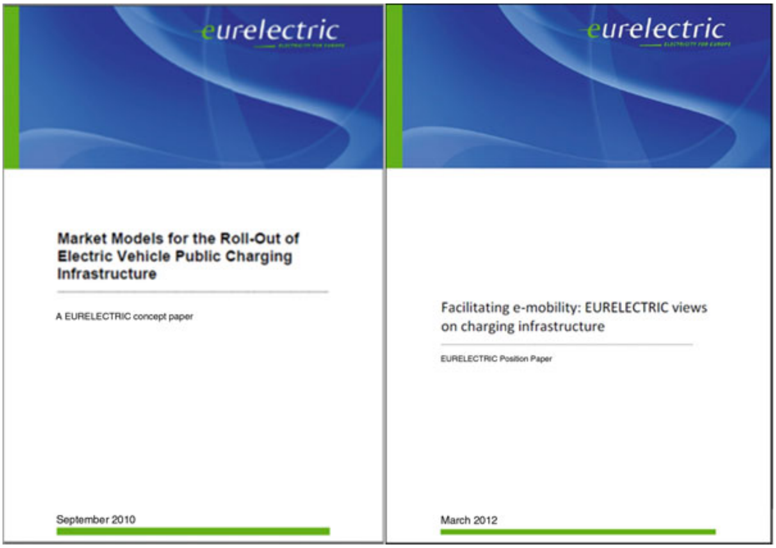


Fig. 9.29 Eurelectric concept paper to market models and position paper related to charging infrastructure. *Source*: www2.eurelectric.org

four market models. These models represent the value chain from "electricity distribution," "charging station ownership and/or operation" to "retail of electricity." Within this value chain the four market models are described:

1. The integrated infrastructure market model.
2. The separated infrastructure model.
3. The independent e-mobility model.
4. The spot operator owned charging station model.

These identified market models give an overview and allow the development of different business models, which depend on different national market conditions given by specific national laws, government decisions, incentives and economy of scale or different technical solutions. This paper shows the different options with various regulatory degrees; for example nonregulation, self-regulation, framework regulation, full regulation, and regulation through public provision. The possible locations and their specific characteristics are explained, for example Charging on public area on public property (typical public parking lots), public area on private property (shopping mall, multioffice-building garages), and private area on private property.

At least Eurelectric addressed in March 2012 with its position paper "Facilitating e-mobility: EURELECTRIC views on charging infrastructure" the need for a harmonized European charging solution. It is now necessary to undertake appropriate actions and decisions to enable an EU-wide e-mobility market. Different stakeholders and countries have different suggestions and safety requirements; in general there are different types of plugs under consideration. Controlled charging of EV is seen as part of the smart grid of the future. Actual uncertainties have led to a situation where some countries are waiting for a common solution while others are installing the Type 2 connector (with/without shutters) or the Type 3.

9.5.5 Activities in European Countries

In the following examples of some countries are given (in alphabetic order) to obtain an impression of ongoing EV activities.

9.5.5.1 Austria

In the following Austrian activities are described, including the best practice example of establishing an interdisciplinary platform Austrian Mobile Power (AMP) with all relevant stakeholders to push the topic, the lighthouse project EMPORA to stimulate development, a cross-border project and other demonstration projects to enable easy charging.

AMP Platform: The introduction of electric vehicles needs an interdisciplinary approach. Stakeholders of different areas have to make an effort to design and integrate the new system, although to prepare a possible market penetration by suggestion of specific measures (incentives, regulatory framework) at the starting phase.

The "Austrian Mobile Power" (AMP)-platform as association at the good example of best practice. Big steps need key players which guarantee continuity and a stable financial background for the development of such an intention. In 2009 Verbund (utility) began together with five key players including three from the car industry (AVL, KTM, and MAGNA), an electricity company (SIEMENS) and a research institute (AIT Austrian Institute of Technology) to write a position paper for R&D demand and established the "Austrian Mobile Power" (AMP)-platform as association at the end of 2009. They committed to bringing Austria into a leadership position in e-mobility, to implement an overall system in pilot regions with more than 10,000 EV, to establish energy, infrastructure and a uniform accounting system and to trigger around five billion € investments by 50 million € investments in R&D. The AMP open platform creates solutions that fit Austria and develops an open system for e-mobility for all market players, based on EU-standards.

Two years later, in 2012 AMP has reached more than 30 members that are involved in lighthouse projects related to e-mobility, strategy development, and participates and represents specific topics in working groups to provide input to Austrian ministries. AMP communicates its activities by initiating high-level events and organized for example an EV-day during the world exhibition 2010 in Shanghai, China. AMP's members strive to make e-mobility a reality.

E-Mobile Power Austria (*EMPORA*): EMPORA, initiated and coordinated by Verbund is the largest Austrian R&D lighthouse project for e-mobility with a total

Fig. 9.30 EVs of the cross-border VIBRATe test fleet

project volume of 26 Mio €; it involves 21 core companies from car and system development, infrastructure and research. It is organized into two supplementary research projects Empora1 and Empora2 (Jan 2010 to March 2014), which are funded with 12 Mio € by the "Klima- und Energiefonds" (energy and climate fund) of the federal government. The main focus is the benefit for the customer; barriers for implementation are identified and solutions elaborated.

Specific tasks are formulated in 28 work packages; project coordination and management is led by VERBUND, system architecture and data analysis is coordinated by SIEMENS with support from AIT. Car technology development addresses Li-Ion battery packs, cooling, steering, the E-drivetrain, regenerative braking, high-voltage systems including DC/DC converters and charger vehicle control units and low voltage systems, and is coordinated by MAGNA with AVL and Infineon. The infrastructure topic comprises renewable energy generation, day ahead forecast and planning of e-car charging, data aggregation and intelligent charging control for the charging points and is organized by SIEMENS with VERBUND, WIEN Energie and A1. User aspects are handled by AIT with the support of A1, VERBUND, AVL DiTest, and finally the demonstration of EV, which starts in 2012 is organized by Raiffeisen Leasing in cooperation with AIT and VERBUND.

Within the project the whole value chain is covered. Connection with other European projects is managed for active information exchange.

VIenna BRATislava e-mobility (*VIBRATe*): Complementary to this, some other interesting activities should be mentioned. VIBRATe (*VI*enna *BRAT*islava *e*-mobility) is a cross-border e-mobility pilot project between Austrian and Slovakian companies. Within the project on public and semi-public areas normal power and five high-power charging stations will be erected to enable barrier-free cross-border e-mobility. Electric vehicles are supported to provide sustainable mobility [7] (Fig. 9.30).

The first EV demonstration test "VLOTTE" started in 2008 in Vorarlberg. After a countrywide call for proposals they could offer an integrated mobility card including electric vehicle, charging infrastructure, maintenance, Austrian Automobile Association and mobility card for public transport. The intention was to bring cars to the streets and test them. Different types of EV, such as Th!nk, City, Fiat500, Mitsubishi i-MIEV, Citroen C-Zero, Peugeot Ioin and a few cars of other types, in total a planned 357 until the end of 2012, were to be applied. Energy for the EVs is generated by small hydro power plants and PV.

An interesting approach started in March 2012 in Salzburg in the form of a car-sharing project using EVs. The local utility Salzburg AG and the department store chain Rewe jointly funded a company called *EMIL* and gave the city an impulse to test and supplement the public transport system with EVs. They started with five renting stations; the customers can book the EV car over the internet. One study suggests that one shared car could replace up to eight conventional cars.

Two of the leading technology companies, SIEMENS and VERBUND announced in April 2012 that they were going to erect infrastructure for electric vehicles in the next years and offer a mobility package for private persons and companies. The official start of the company is in summer 2012. By 2020 this e-mobility provider plans to erect 4,500 (semi-) public charging stations for normal power and high power for fast charging (especially needed on highways), thus will trigger an investment of around 300 Mio €. To achieve break-even point in the next 8 years 80,000–240,000 EV should be on the road.

9.5.5.2 Denmark

To explain the high interest in electric vehicles one needs some information on the electricity system. Energy companies will change from generation based on fossil fuels to a system that is dominated by renewable energies. There is significant experience in wind power and decentralized biomass generation available. Wind power has already reached 3 GW in total, which leads to a situation where power from wind can be higher than energy demand for certain hours, reflected in a negative electricity price for that time. Denmark plans to double wind energy capacity to 6 GW. The situation would be critical for dispatcher (oversupply by wind energy) without additional measures (smart charging of EV), the and an intelligent charging strategy is seen as a solution to integrate more wind power.

EDISON project: The Danish transmission system operator funded the "Electric vehicles in a Distributed and Integrated market using Sustainable energy and Open Networks" (Edison) project to develop optimal system solutions for the integration of electric vehicles. The Danish government sees the EV as a potential storage device for fluctuations in wind energy. Emissions of CO_2 can be reduced and vehicles are energized by wind power. The project budget is 49 Mio DKK, within seven work packages the seven project partners analyze EV technology, design system architecture for EV including vehicle to grid (V2G), develop solutions for distributed integration technology development, develop fast charging and battery swapping station design, and work out solutions for power and information/communication management [8] (Fig. 9.31).

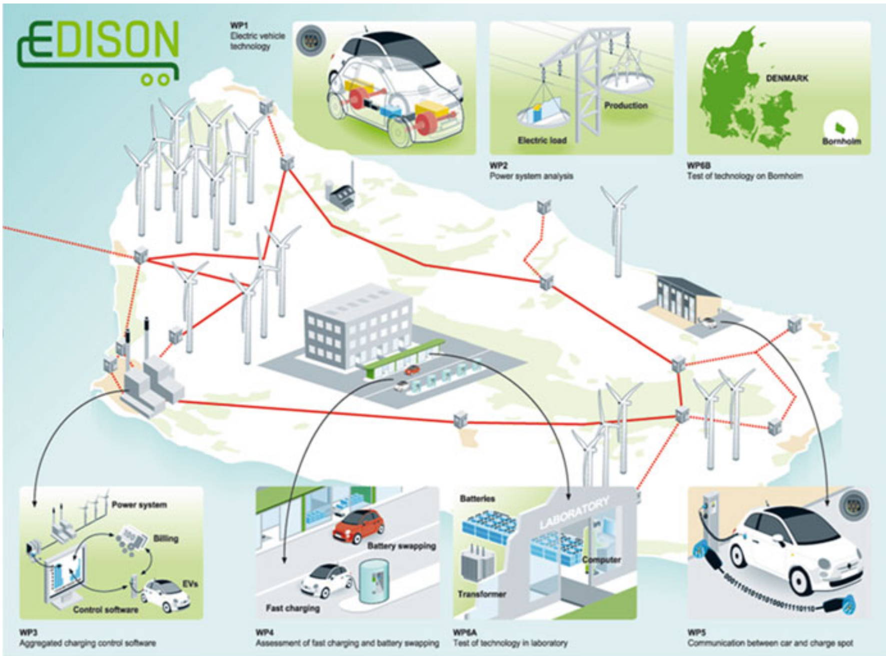


Fig. 9.31 EDISON project overview [8]

In July 2011 Better Place unveiled the first battery swap station in Europe. The process of battery exchange is automated. The driver drives into the station, after identification the battery changing procedure starts, it needs less than 1 min and is faster than conventional refueling of a car, and the disadvantage is the high investment cost for such a station (Fig. 9.32).

9.5.5.3 Finland

In December 2011 a private-public partnership of public authorities, private corporations, entrepreneurs, and researchers developed a business model for electric vehicles. The "Electrictraffic.fi project" is part of the 100-Mio € Electric Vehicle Systems Program EVE, administered by the Finnish Funding Agency for Technology and Innovation. The program addresses three relevant topics, i.e., electric vehicles, smart grids, and intelligent traffic.

Several companies committed to the project and it is still possible to join later. The test fleet of 500 EVs is the source for gathering basic information within the research part of the project, carried out within 15 work packages; the planned project time is 4 years.

Fig. 9.32 Demonstration model of battery swapping

9.5.5.4 France

EV test center: France is addressing customers to obtain information on personal experiences with electric vehicles. The EV manufacturer Renault opened a test center for zero-emission (Z.E.) electric vehicles in Boulogne-Billancourt (at Paris) in December 2011. This center is the first of its kind in Europe; the zero-emission test center also includes a reception and exhibition area. It is open to the public and potential users and customers are informed about EV technology, receiving information about different cars, batteries, and charging infrastructure. Test drives are offered at the 1.8-km-long test route to experience silent e-drives in the Kangoo Z. E., Fluence Z.E., and the four-wheeler Twizy.

brilleCarsharing: Autolib has offered car charging for the 46 communes of greater Paris. Infrastructure will be erected to achieve around 1,100 charging stations by the end of 2012 for the planned fleet of 1,740 electric vehicles. Driving license holders may choose between two subscription models consisting of a fixed fee and time-dependent rate.

9.5.5.5 Germany

Germany has put much effort into promoting electric vehicles, and a 10-year national strategy plan foresees the implementation of 1 Mio EV by 2020. This needs close cooperation between all relevant ministries such as those for economy and technology, traffic, construction and city planning, research and environmental protection, and reactor safety. First, the market and technology will be prepared, followed by commercialization and market growth and as a fourth step large-scale production is planned.

Electric vehicles will change requirements for the automotive supply industry dramatically; there is a need for investment to establish a commercially competitive product and market, requiring subsidies only during the starting phase. Effort is focused on the development of the battery system, drive motor, power electronics and control. Over a long transition phase of about 20 years, fossil and biogenic fuels will dominate the mix of automobile energy source.

Pilot regions: Within a support program eight pilot regions (Oldenburg-Bremen, Hamburg, Berlin-Potsdam, Leipzig-Dresden, Rhein-Main, Rhein-Rhur, Stuttgart, and Munich) were funded (source: BMVBS Modellregionen Elektromobilität, 2009).

Car2go mobility concept: In autumn 2008 Daimler started the new mobility concept car2go in Ulm, Germany, which meets customer needs for mobility in a simple and flexible way. After application to car2go, the customer has access to the cars via a car2go member card. Then he is able to take the closest available car, searching for the nearest one on car2go.com by clicking the car finder, using a mobile phone (iPhone or Android), or by calling a service number. After placing the member card near a card reader behind the windshield, the car opens and can be put into operation with a 4-digit customer PIN code and the input of a form of payment. He can drive his individual route and use the navigation system if necessary. After reaching his destination, he is able to park the car at any allowed free parking area and end the car rental. He is able to make an intermediate stop whilst continuing the rental or end the rental. There is no need to return the EV to a particular location in the car2go city area. However, it is suggested the car be parked at one of the charging stations within the network. Further cities using the car2go fleets in Germany are Düsseldorf and Hamburg. Several car2go fleets have been introduced in European and North American cities with a total of 70,000 users (March 2012).

9.5.5.6 Ireland

In Ireland *ESB* is an international energy company and is one of the forerunners in the implementation of electric vehicles. They designed a concept for the introduction of e-mobility, working together with partners and involved government and car industry players to develop a sustainable transport system. They have foreseen home chargers for the vehicle owner and a public charging infrastructure of 1,500 charging posts and additionally about 60 DC-fast charging stations to enable inter-urban travel. The official launch of this project was in May 2011. To introduce electric vehicles, ESB is involved in several organizations; for example they support the development of products such as home charging boxes and mobile charging units and work with relevant car manufacturers. An electric taxi is included in this field test; when customers order a taxi, they check whether this is within the range of the EV to guarantee transport. To demonstrate the performance of the modern EV a promotional tour over 900 km within 3 days was organized; it could be shown that driving with an electric vehicle within Ireland is possible.

An internet-based platform for ESB ecars shows on a map the location of all the installed and planned AC charging and DC fast-charging stations. The map is available for download to a smart phone. Information regarding address, type of plug, and access time is delivered. After registration the EV car users can use charging points via a charge point access card. Until the IT infrastructure and payment system has been developed (in 2012), public charging is free. The driver will have the opportunity to select the energy supplier, will see the status of charging points for reservations, but various features are still under development.

9.5.5.7 Portugal

Portugal wants to enlarge the share of renewable energies by usage and intelligent charging of electrical vehicles. There was an early decision by the government to erect EV infrastructure and they supported that intention. To build a market-orientated approach, they launched the *Mobi.E* project with an open-access approach to enable investors to erect public charging posts. Simple access to the charging infrastructure operated by different providers is guaranteed by a universal smart card, which the customer can buy. A countrywide charging infrastructure of 1,300 charging stations and around 50 fast-charging stations had already been erected by the middle of June 2011. The Portuguese model can be seen in Fig. 9.33.

9.5.5.8 The Netherlands

In the Netherlands the Distribution System Operators (DSO) agreed to erect the infrastructure for EV charging and suggested their government a challenging proposal for EV-infrastructure erection.

e-laad: Within the e-laad project they erected from 2009 to 2012 around 10,000 charging stations and created a uniform technology and communication platform. They will benefit in the future because of the developed control appliances for optimum control of the charging algorithm. This is not only to shave peaks, other ancillary services include congestion management, power balancing, better integration of fluctuating production from renewable power, and disturbance management.

Treaty of Vaals—international roaming: National initiatives for enabling cross-country mobility announced in April 2012 a transnational roaming system via the use of RFID cards with partners in seven European countries (Ireland, the Netherlands, Belgium, Luxembourg, Germany, Austria, and Portugal). The three partners ladenetz.de, e-laad, and Blue Corner developed and founded the agreement on e-roaming, which bases on an Open Clearing House Protocol (OCHP). It is an

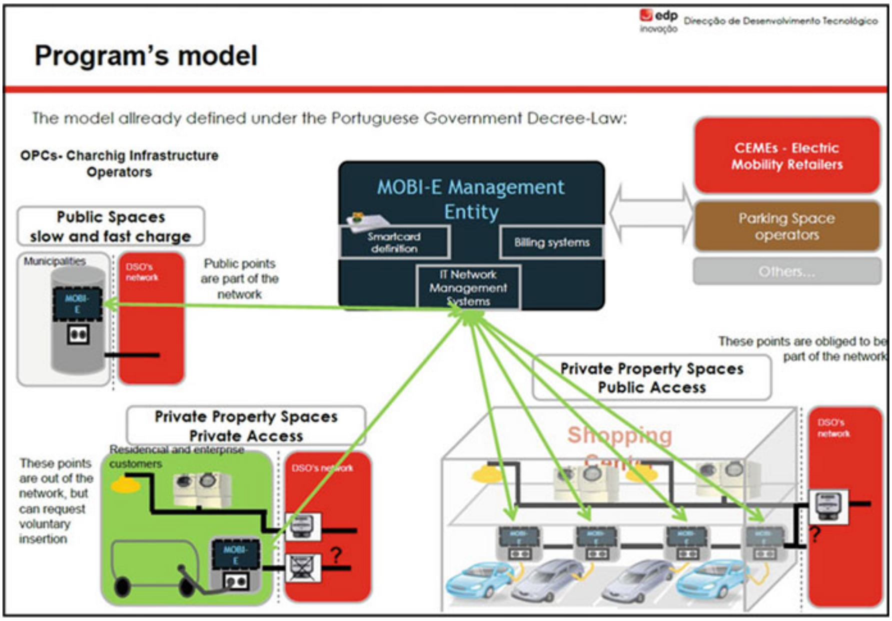


Fig. 9.33 Structure of the Mobi-e model in Portugal. *Source*: www.edp.pt

important step towards enabling international charging; automatic data exchange enables easy payment comparable to the use of a credit card.

We cannot provide a description of all activities across Europe for reasons of space and a few were picked out to give an impression. It is worthwhile to mention a few further activities. In the *Czech Republic*, the CEZ Group realized concepts for e-mobility within the FutureMotion strategies. They will begin testing electric vehicles and will implement a pilot fleet test in Prague and Ostrava for real long-term operation and erect a charging infrastructure. The long-term plan is to be with partners a provider for e-mobility. In *Italy* various cities are performing demonstration projects and ENEL, a utility, is introducing e-mobility and smart grid technologies. They have in 2012 around 460 low/high-power chargers in private and public areas (Rome, Pisa, Milan, and Bologna) but they are planning to erect 8,000 low/high-power charging stations. An easy way to find a free charging post is provided by the plug serving service, showing possible charging points on a map-based program.

9.5.6 Activities in the USA

There is a great deal of experience in the development of electric vehicles in the USA. Already in the 1960s and later in the 1980s the key driver was to reduce air pollution; the Clean Air Act was announced to reduce emissions. California was a forerunner, founding the California Air Resources Board (CARB) in 1967 as a regulatory agency.

Recovery Act: Under the Obama administration's comprehensive plan 1,800 electric vehicle charging stations were installed to save money and improve the nation's energy security. Since 2009 the Department of Energy (DOE) has invested more than $5 billion in grants and loans to spur the growth of the EV and battery industry to force competitiveness in their industry in the fast growing market. Within the Transport Electrification Initiative they will deploy 13,000 grid-connected EV and over 22,000 charging points in residential, commercial and public locations by December 2013 [9]. Under the *Coulomb* project the deployment of 2,000 GM Volt, 200 Ford Transit Connect, 100 Ford Focus EV, and 100 Smart EV vehicles, as well as establishing 4,600 EV charging locations nationwide is planned.

Recent activities include a partnership between the DOE and car industry players (USCAR, US Council for Automotive Research) and the project "FreedomCAR" was established to develop fuel cell technologies for the mass market. The DOE identified within the Energy Efficiency & Renewable Energy (EERE) offices research topics for hybrid and electric vehicles giving an overarching vehicle system perspective. All basic topics were addressed such as the hybrid and plug-in hybrid EV, modeling and simulation, integration and validation, benchmarking, propulsion system and power electronics, energy storage, fuels, advanced combustion engines, and material technologies. Partners from industry support the working team within the U.S. DRIVE partnership. Research work is carried out at several universities and in national laboratories. The Plug-in Hybrid Electric Vehicle Center (PHEV Research Center) is at the University of California, Davis, and helps to solve questions related to the topic of commercializing the PHEV and electric cars. The DOE hosts multidisciplinary transportation research centers in their laboratories and include relevant topics concerning fuel cell, hybrid and EV research.

9.5.6.1 National Research Centers

Idaho National Laboratory: Light-duty vehicle testing activities of the Advanced Vehicle Testing Activity (AVTA) are conducted by the Idaho National Laboratory. Within the vehicle testing activities, they provide benchmark data for technology modeling and validating of different technologies, for example PHEV, REX-EV, HEV, EV and hydraulic technologies, advanced electric drive technologies and engine technologies, advanced energy storage (i.e., batteries) technologies and chemistries, advanced climate control, power electronic, and other ancillary systems technologies and internal combustion engines burning advanced fuels (i.e., 100 % hydrogen and hydrogen/CNG-blended fuels) [10].

National Renewable Energy Laboratory (NREL): In the focus of NREL's Center for Transportation Technologies and Systems (CITS) is the reduction of dependency on fossil fuels and air pollution by means of innovative vehicles and fuel technologies. Within their advanced vehicle activities they conduct research projects in advanced power electronics, energy storage and thermal management of the vehicle and supports with modeling, analysis, development and demonstration activities. They have long experience in renewable energy generation and investigate fuels and lubricants. Fleet vehicles were assessed in real-world tests as well as in controlled laboratory experiments. NREL is joining with Google and other industries to provide consistent, up-to-date information about EV charging stations in communities nationwide. On the basis of Google Maps the coordinates of all U.S. charging stations (not only electric, also alternative fuels) are available online and easy to use in customer navigation systems.

Sandia National Laboratories: Within the Sandia national labs they have a wide spectrum of experience, especially in hydrogen and related topics such as influence of hydrogen on materials as a basis for hydrogen storage, safety, codes, and standards. Within their research programs they contribute to the development of batteries, supercapacitors, and thermoelectric heating and cooling as well as increasing overall performance of energy efficiency.

Argonne National Laboratory: They perform research into alternative fuels, batteries, hybrid electric vehicles, hydrogen and fuel cells, modeling, plug-in hybrid technologies, and also cover intelligent EV charging by the use of smart grids, for example by connection of a EV to the grid using a J1772 connector featuring power and communication pins [11].

Oak Ridge National Laboratory (ORNL): This laboratory covers research areas in fuel cell technologies to develop materials, components, and processes within the Hydrogen, Fuel Cells & Infrastructure Technologies Program (HFCIT). They carry out research on storage technologies, hydrogen generation, and the transition to a hydrogen economy. In the Power Electronics and Electrical Power Systems Research Center (PEEPSRC) they focus on drive systems consisting of advanced power electronics, machines and system control. An integrated approach covering advanced engine technologies, power electronics, vehicle testing and evaluation, modeling and simulation is enabled by the Advanced Vehicle Systems (AVS) Research Program.

Electric Vehicle Infrastructure Training Program (EVITP): The Electric Vehicle Infrastructure Training Program provides training and certification for people installing electric vehicle supply equipment (EVSE). As a voluntary collaboration of electrical industry organizations, EVITP supports the development of electric vehicle (EV) charging infrastructure for residential and commercial markets. In their courses they cover topics concerning different types of batteries, charging characteristics, utility interconnection requirements, fundamentals of charging stations and integration of EV to the grid, national standards, and support the roll-out phase of EV.

Fig. 9.34 Tesla S

9.5.6.2 Industry Activities and Field Tests

In the following we select and describe some examples of activities and experiences gained during a commercial trip to California to car manufacturers, utilities, battery manufacturers, component developers, partnership organizations, regulators, and others [12].

9.5.6.3 Car Manufacturer

The car manufacturer *Tesla motors* was founded in 2003 and demonstrated the Tesla Roadster, an electric vehicle with unique performance shedding a new light of power and efficiency on e-mobility. They produce cars in relatively small production runs (in comparison to the car industry). The basis is the Lotus Elise from Great Britain, and it will be completed at Pomona with the addition of an electric drive train and battery system. The next generation, Tesla S is a four-seat limousine and they predict a cost reduction as they can build on lessons learned with the roadster (Fig. 9.34).

Fisker Automotive with its headquarters in Anaheim, CA, was founded in 2007. They designed the electric hybrid sports car Karma. It combines a sustainable and efficient electric drive with a range extender and offers a luxury interior.

Phönix Motorcars has developed several EVs as zero-emission vehicles since 2002. They use the Altair-Nano Battery, a lithium titanate oxide battery based on nano-technology; the graphite electrode is substituted by one made from lithium titanate oxide. This enables fast battery charging and provides high battery lifetime.

Fig. 9.35 Race car at NASA Test Center

9.5.6.4 Battery Producer

Altair nano produces the lithium titanate oxide battery with a high energy and power density. This battery type can be charged with high power, operates over a wide temperature range from −50 to 150° F, has a good performance at low temperatures, and provides high cycle lifetime under deep discharge conditions.

Quallion is specialized in cell and battery development and optimize batteries depending on a combination of lithium, cobalt, Manganin, and nickel for different applications such as long life batteries for satellites, high density, high cycle lifetime, or safety. *A123* offers different cells (cylindrical, prismatic type), modules and systems for several applications. Nanophosphate technology of the LFP delivers high energy and power density, extended cycle life time and safety.

Imara Corporation is producing a high-power 18,650 lithium nickel manganese cobalt oxide cell (NMC) for the outdoor equipment and transportation market. The cycle life is very stable, and low cathode impedance enables high currents.

9.5.6.5 Component Development

NASA Ames Research Facility realized high-power drive trains that enable fast acceleration (to 130 km/h in 4 s) for race cars. A high efficiency (97 %) synchronous disc type motor is excited with a minimal required current to provide torque with minimum possible losses (Fig. 9.35).

AC Propulsion developed an integrated box which contains the motor controller and charger. Parts of the motor windings are used as inductivity for the charger. They deliver power electronics components for several car manufacturer such as

Fig. 9.36 AC propulsion vehicle

Tesla, BMW mini, Toyota, and Volvo. Power range is from 150 to 300 kW. They also offer vehicle-to-grid (V2G) features, for example the car was part of the European EDISON project and can be operated as an uninterrupted power supply unit (Fig. 9.36).

System design: Electric vehicles have to be integrated into the electrical grid and *OSIsoft* develops software for smart grid, smart home and smart city applications. *Better Place*, Palo Alto, CA, started with the goal of realizing sustainable transport without fossil fuels; e-mobility was the result of various scenarios. They deliver services, plan, erect and operate infrastructure and systems to enable confident adoption and use of EVs.

9.5.6.6 Hydrogen Technology

California Fuel Cell Partnership: In 1999 CARB and CEC (California Energy Commission) joined with partners from industry to form the California Fuel Cell Partnership to demonstrate and promote fuel cell vehicles and opened 1 year later the headquarters in West Sacramento. The building is equipped with models of the FC vehicle; they have a show room for fuel cells and their function and deliver all relevant information. As this technology has a chance for success on the market, further members from the car industry, fuel cell manufacturers, energy companies, and governmental agencies joined. Particularly impressive is the test fleet of cars to obtain real experience by driving cars which have the fuel cell as their core element; a compact model of the UTC power S300 is shown in Fig. 9.37. For refilling

Fig. 9.37 UTC power's S300 automotive fuel cell stack

hydrogen a station is available at the site, providing hydrogen at two pressure levels 3,600 and 5,000 psi and cryogenic liquid H_2.

9.5.6.7 Utilities

Southern California Edison is a utility and interested in new technologies. They operate a large test center for batteries and can simulate different situations for stationary and mobile use. As the electricity grid is already highly utilized, decentralized generation and electricity storage is of high interest; the EV is a part of this concept of the smart grid. Vehicle-to-grid (V2G) has the potential to contribute balancing power to the grid. Demonstration tests are running with real-time demand response (DR) meters, measuring 30 times per second data which are compressed before data transmission, thus helping to maintain stable grid operation. An interesting approach is the use of ice, which can be produced during electricity oversupply as a storage medium for air conditioning.

9.5.6.8 EV Demonstration Projects

The EV Project

"The EV project," managed by ECOtality and its subsidiary ECOtality North America, was launched in autumn 2009 and received a grant of 99.8 Mio $ from the DOE for deployment of EV and charge infrastructure. With the contribution of partners and an additional grant from the DOE a total volume of 230 Mio $ could be reached. Within the project data from the vehicles are collected and analyzed for lessons learned. The partners (ECOtality, ECOtality North America, Nissan, Chevrolet, Idaho Nat. Lab., Zero Emission) cooperate with more than 60 strategic partners (car manufacturers, states, cities, national laboratories, utilities, companies, and associations). In addition to data collection and analysis The EV Project is writing position and policy papers to support the transition.

Car2go

The *car2go* concept was launched on 18 Nov 2011 in San Diego; within 3 months about 6,000 new EV users registered with the car-sharing program and they used the cars for more than 25,000 trips. The 300 Smart two electric drive vehicles have the estimated potential to substitute about 2,000 individual cars. This makes San Diego one of the top cities in terms of EV users. It was announced that car2go would be introduced in Washington, DC and Portland in March 2012.

An analysis has shown that usually the average trip distance is between 5 and 10 miles and the rental time for the car2go is from 15 to 30 min. As can be seen in the rapidly increasing registrations, customers accepted and assimilated this additional mobility service well as a new life style option. They can simply take a car, drive, park at their individual destination, give it back within the car2go area by closing the car and checking out by placing the car2go member card close to the windshield reader. Thus, the next customer can take the car for another individual route.

The calculated price for using the car2go service bases on three rental modes: The car can be rented for a short period by the minute depending on the time the car was used. In San Diego the rate is $0.35 per minute and includes all services such as re-charging, parking, mileage, insurance, maintenance, cleaning, support service and hotline. For longer renting periods, costs decrease to an hourly rate of $12.99 and for daily use to $65.99 plus taxes.

9.5.7 Asian Activities

In comparison to other regions, there is high economic growth in the Asian region; large investments go into economy and infrastructure projects. Vehicles with alternative drive systems offer a chance to enable efficient and environmentally friendly transport systems.

9.5.7.1 China

Traffic in China is growing rapidly, causing environmental pollution and traffic jams. So they limit growth by reducing new licenses for cars; for example, permissions for new drivers are selected in Beijing by random generator, while Shanghai is auctioning them. China has a rapidly growing car industry and focuses on the EV to decrease dependency on oil with resulting increasing costs for fossil fuel imports.

Fig. 9.38 CRH high-speed train

Policy by central government is able to realize infrastructure projects such as new highways, but that is not seen as the only solution; significant investments go into the public transport system too. For example, Shanghai opened the first metro in 1999, and after rapid construction activity they have 11 lines with a metro grid of about 430 km today. The CRH high-speed trains (Fig. 9.38) enable a countrywide fast and high capacity transport system enabling travel between the large megacities within a few hours; this is more efficient and faster than connection by airplane. E-mobility is already a reality with two wheelers like scooters and motor bikes. The government introduced these electric drive systems and more than 120 Mio of them are now in operation.

National Strategy Plan

863 Program: The main activities concerning electric vehicles go back to the year 1986, when the state council initiated in March the so-called 863 program with policies for "New Energy Vehicles" (NEV). The ministry coordinates the technology and research projects, provinces subsidize NEV car purchases. The tenth Five-Year plan (2001–2006) funded research projects for fuel cell, hybrid and pure electric vehicles. Increased funding was given in the 11th Five-Year plan (2006–2011). On 23 March 2009 MII (Ministry of Information Industry) presented an additional "Plan on Adjusting and Revitalizing the Auto Industry" and set ambitious goals for 2011, 5 % should be NEV ones.

From 2012 to 2022 the Chinese government will invest more than 15 billion US$ in subsiding the country's industry for energy-saving technologies and announced as an official goal 500,000 plug-in hybrid and electric vehicles. That will be accompanied by a nationwide program to install charging stations. A key element of the 12th Five-Year plan (2012–2017) is development of automotive electronics, information, communication and software solutions according to the Ministry of Industry and Information Technology (MIIT) of the People's Republic of China [13].

Well-known Chinese research centers and universities are involved in the development of electric vehicles, for example in the development of power electronics, chargers, battery and battery management systems, drive systems, car components, and charging infrastructure.

25 Pilot Cities: In 2011 China reported about 25 new energy vehicle demonstration pilot cities, including for example Beijing, Shanghai, Dalian, Chongjing, Guangzhou, Shenzhen, and Hefei. China State grid will erect infrastructure; more than 6,000 charging posts and additional fast-charging stations are planned in the pilot regions over the short term. These cars are supported by parking fees and road access to force individual customers, companies, institutions and the government to buy this NEV.

In *Shenzhen* a *taxi fleet* trial was initiated; they tested the BYD e6, a relatively large and comfortable car, in daily use. BYD developed a reliable Li-FeP battery with a battery management system enabling a range up to 300 km. Operation for one shift of work was possible, but the theoretical range was reduced by consumption for the air conditioner. Large incentives were given for this pilot test such as investment funding and a taxi license exemption; in combination with saved fuel costs this resulted in cheaper total costs for the taxi operator. A hybrid car is offered by BYD too, enabling emission-free operation and large range by use of a range extender.

EXPO 2010: At the world exhibition, in Shanghai, May to Oct 2010, China demonstrated its competence in this sector. Several car manufacturers are located in the northwestern area of Shanghai. Transport within the exhibition area was enabled with electric vehicles, and many projects were presented, for example a joint venture project between AVL List and Tongji University in developing a fuel cell car was demonstrated as well as future concept cars.

9.5.7.2 India

In India, as the second highest populated country, the economy is growing second fastest and is fourth ranked in terms of oil consumption. India has a young population; 60 % of the people are aged below 30 years. Sixty-eight cities have more than 1 Mio inhabitants and will generate 70 % of the country's GDP. That fact causes rapid growth in the transport sector; private transport is predicted to double in the next 20 years.

Current traffic bases on bicycles, public transport, scooters, motorcycles, and cars. E-scooters seem to be a cheap means for individual transport; around 50 Mio

Fig. 9.39 Mahindra REVA NXG

two wheelers are on Indian roads. They are already in mass market production, increasing by around 9 Mio every year.

A small electric car designed for city commuters is the Mahindra REVA, produced from an Indian company based in Bangalore, India. The car was shown at the Frankfurt Motor Show and it can be equipped with lead-acid batteries or Li-Ion phosphate batteries. The NXR shown in Fig. 9.39, an M1 class model, is a four seat EV with a range of 200 km and a top speed of 130 km/h. The car offers dual charging ports for regular low-power (80 % SOC in 6.5 h) and if needed high-power (15 min increases range by 40 km, 1.5 h for 100 %) charging.

Remarkable is the monitoring system of the Lithium-Ion battery. If the battery discharges below a certain charge level, normally the car stops to prevent damage to the battery. The REVA offers telematics remote control of the battery; the support center is able to analyze and check the battery's state of health remotely and can individually allow a deeper discharge of the battery, thus enabling the customer to reach the next charging station. They called this system REVive (remote emergency charge over SMS).

9.5.7.3 Japan

Comparing the car industries of several regions, it could be said, that Japan has a pioneering position in developing hybrid and electric vehicles. In terms of the development of hybrid cars, the Toyota Prius has been for 10 years the most well-known one and is now available in the third generation of development; the company has been able to collect experience over many years for actual development.

Fig. 9.40 CHAdeMO charger at TEPCO, Yokohama

They brought the Mitsubishi i-MIEV (Mitsubishi Innovative Electric Vehicle) to the mass market. The car offers four seats, air conditioning, power-assisted steering, traction control, and safety features. The Lithium-Ion battery is produced in a joint venture company together with GS Yuasa. A 16-kWh energy package enables a nominal range of 150 km and the 49-kW permanently excited synchronous machines accelerate the car to a top speed of 130 km/h. As verified at the test bench and in daily use, these figures could be reduced considerably by use of the heating system in winter and air conditioning during hot summers. Charging is possible within 6–8 h at a conventional socket; DC high-power charging enables one to reach 80 % state of charge within 30 min.

In comparison to other vehicles, the Nissan LEAF was designed from the beginning as an electric vehicle. The batteries are integrated under the bottom of the car, thus offering enough space for five persons and luggage. An 80 kW drive enables a top speed of 145 km/h, the nominal range is 160 km. In addition to the production in Japan, manufacturing capacity is being built up in the US (2012) and France (2013) to reach a capacity of 250,000 cars per year.

CHAdeMO: For nearly unlimited mobility high-power charging (fast charging) is necessary, although most of the time low-power charging is the regular case. The utility TEPCO (The Tokyo Electric Power Company), together with the car companies Nissan, Mitsubishi, Fuji Heavy Industries and Toyota developed the “CHAdeMO” (Charge de Move) standard for DC high-power charging (Table 9.2). The power electronics is part of the fast-charging station and therefore causes no additional weight in the car. Charging current is controlled by the battery management system of the car; all necessary data for control are sent to the charging station. In the meantime around 300 companies have joined the CHAdeMO association (Fig. 9.40).

Table 9.2 Specifications of CHAdeMO quick charger

Type	Switching type, constant current power supply
Input power	3-Phase 200 V (200–430 V)
Output power	50 kW (10–100 kW)
Maximum DC output voltage	500 V
Output current	125 A (20–200 A)
Target charging time	5 min for 40-km driving range 10 min for 60-km driving range

As they were the first with a "de facto standard" for DC charging, many countries overseas have erected these DC high-power charging stations for their pilot and demonstration regions. From the point of view of the car, the CHAdeMO standard is compatible with the following EV: Subaru Plug-in Stella, Mitsubishi Motors i-MiEV, Nissan LEAF, Protoscar LAMPO2, Peugeot iON, Citroen C-ZERO, Toyota iQ based EV, THINK City, and Micro-Vett Fiorino.

References

1. Simone Frey. Entscheidungsbasis für die Konzeption der Elektromobilität in Österreich. MSc thesis, Technikum Wien, 2010
2. Available online: http://iea-retd.org/archives/events/retrans-2
3. Available online: http://www.ieahev.org/
4. Available online: http://www.g4v.eu/
5. Available online: http://www.ev-merge.eu/
6. Available online: http://www.eurelectric.org/PublicDoc.asp?ID=60468
7. Available online: www.emobility-vibrate.eu
8. Available online: www.edison-net.dk
9. Available online: http://www.evpowersystems.com/Blog/9%2008%2005%20Awards%20List.pdf
10. Available online: http://avt.inel.gov/
11. Available online: http://www.transportation.anl.gov/
12. Schauer G. Electric vehicles. Lessons learned from California and China, Verbund, 2012
13. Available online: http://www.miit.gov.cn/

Index

R. Garcia-Valle and J.A. Peças Lopes (eds.), *Electric Vehicle Integration into Modern Power Networks*, Power Electronics and Power Systems,
DOI 10.1007/978-1-4614-0134-6, © Springer Science+Business Media New York 2013