HIGH QUALITY 100W MOSFET POWER AMPLIFIER

By
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Getting started

The motivation for this project came about from the decision to upgrade my 20 odd year old hi-fi system. The sources consist of a Cambridge Audio CD4 CD player and a Thorens TD125/SME 3009/Goldring G900 record player which I'm perfectly happy with. The rest of the system consists of an own design and build preamplifier, a pair of Blomley 30W power amplifiers, and a pair of Bailey transmission line loudspeakers. The amplifier and loudspeakers still sound good, even by today's standards, but the relentless improvements in semiconductors and other devices over the years prompted me to believe that I could perhaps improve upon these components of my system. An additional goad was the fact that I didn't design the power ampifiers and loudspeakers myself; I get a lot of satisfaction from the everyday use of things that I design and build myself. As designing and building loudspeakers is a much more difficult and expensive task than doing the same for power amplifiers I decided to start with the power amplifiers.

My idea was to build a reasonably simple power amplifier which nevertheless gave excellent measured and sonic results. Using large numbers of semiconductors in pursuit of high performance is all very well, but the large number of components and the complex, invariably double-sided, printed circuit boards (pcbs) all conspire to push up costs.

Mosfets or bjts?

The next decision was whether to use bipolar junction transistors (bjts) or mosfets as the output devices. As far as I can see the arguments in favour of one or the other are finely balanced. Power mosfets have a much better high frequency response than power bjts; are easy to drive from simple voltage sources; and are not prone to thermal runaway like power bjts. On the other hand, power bjts suitable for high quality audio use are cheaper than audio power mosfets; and will deliver a higher power output in the emitter follower mode than will a mosfet in the source follower configuration; unless recourse is made to expensive multi-rail power supplies. This is because the power mosfet gate would need to rise to some 8 - 10V above the mosfet power supply voltage in order to turn the mosfet fully on; whereas power bjts saturate when V_{be} is around 2 - 3V, at high collector currents. This means that the output of emitter follower bjts can swing closer to the power supply rails than the output of source follower mosfets and thereby deliver more power into the load.

The measured performance of power amplifiers with mosfet and bjt output stages doesn't seem to be too different, and so the only remaining consideration is do they sound different? I made up a pair of the Maplin 150W/4Ω power amplifiers (very creditable performers considering the simplicity and low price) and compared them to the Blomleys, with their bjt output stages, in listening tests. To my not very golden, but still pretty effective ear, differences were small; with the Maplins sounding a little bright compared to the restrained smoothness of the Blomleys. I think this has more to do with the fact that the Maplins have a wide open bandwidth compared to the sensibly limited Blomleys, than any differences between bjt and mosfet sound.

Power mosfets seem able to produce power amplifier output stages that give good measured results, sound good, and have the other advantages listed in the previous paragraph. I therefore decided to go with the power mosfets despite the lower cost of "equivalent" bjts.

What's gone before

Having decided to use power mosfets the next step was to decide on a suitable circuit topology. It's always profitable to look at semiconductor manufacturers application notes and other published designs before embarking on one of your own; and doing this for mosfet power amplifier designs shows that an arrangement similar to that shown in Figure 1 crops up quite frequently. The input long-tailed pair, Tr1 & Tr2, is followed by a voltage amplifier stage, Tr3, with a bootstrapped collector load, R8 & R9 (bootstrapping increases the effective impedance of the collector load, which leads to better linearity). As the power mosfets are voltage operated devices with a high input impedance they require almost no input current and can be driven directly from the low current voltage amplifier stage (not quite true, as we shall see later). The variable resistor, VR1, between the gates of the mosfets is adjusted to give a current drain of around 100 mA through the mosfets, which biases them for class AB operation.

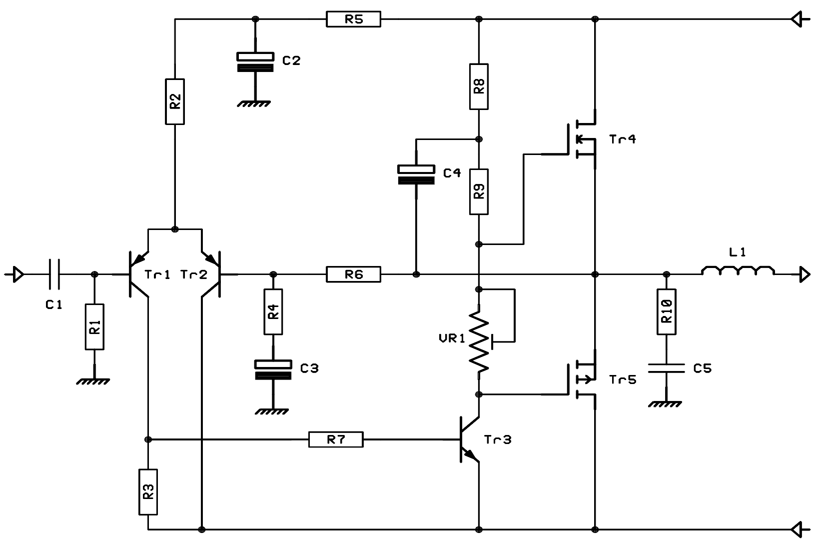


Figure 1: A simple discrete component power amp

Although the circuit shown in Figure 1 gives reasonable performance and probably sounds reasonably OK there are quite a number of ways in which it can be improved. The current through the input long-tailed is better set with a constant current source, Tr1 in Figure 2, rather than the simple resistor, R2, shown in Figure 1. The open loop gain can be increased, and the linearity improved, by using a pair of modern high voltage "super" transistors, Tr4 & Tr5, with an h_{FE} of 300-500 as a long-tailed pair voltage amplifier stage, as shown in Figure 2, rather than the single standard high voltage transistor, Tr3, with an h_{FE} in the 50-200 range of Figure 1. This increase in open loop gain leads to a reduction in the closed loop distortion of the power amplifier. Loading the voltage amplifier pair with a constant current source / current mirror, D1/Tr6, gives a higher collector load impedance than the bootstrapping of Figure 1 and leads to a further improvement in linearity.

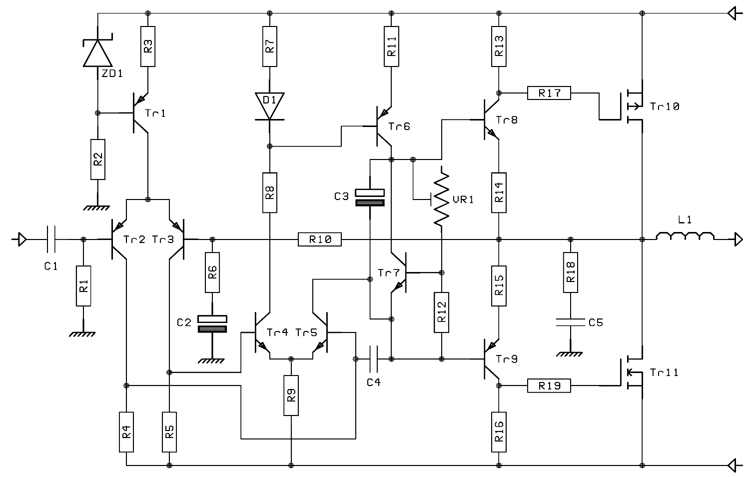


Figure 2: An improved discrete component power amp

The biasing of the power mosfets can be improved by replacing the variable resistor, VR1, of Figure 1 with the "amplified diode", Tr7, of Figure 2. Driving power mosfets directly from the voltage amplifier transistor is not a good idea because of the relatively high input capacitance of power mosfets (of the order of 400-1000pF). These capacitances will take a relatively long time to charge and discharge in the power amplifier of Figure 1 because of the limited current drive available from the voltage amplifier transistor. These long charge/discharge times lead to an increase in distortion at higher frequencies. Its much better to use individual driver transistors, Tr8 & Tr9, interposed between the collector of the voltage amplifier transistor and the gate of each power mosfet as shown in Figure 2. The driver transistors should have high gain, so as not to load the voltage amplifier transistor, good high frequency response, low input capacitance, and a reasonable current drive capability (around 100mA). This circuit arrangement also has the incidental advantage that the power mosfets are no longer operating as source followers, and so the power output will be greater than from the Figure 1 circuit with the same power supply voltage.

If all of these improvements are implemented we end up with the overall circuit shown in Figure 2. A number of designs similar to Figure 2 have been published and are capable of very good performance if properly constructed. The big question is can we improve on the circuit of Figure 2? Well yes we can, but things start to get quite complicated with such refinements as complementary pairs of long-tailed pairs on the input, complementary cascode voltage amplifier stages, etc., etc., until the circuit diagram begins to look like the circuit diagram for a commercial, high performance, op-amp. So why not use an op-amp for the input and voltage amplifier stages of the power amplifier?

Integrated or discrete?

Why not indeed! The op-amp analogue of the Figure 1 power amplifier is shown in Figure 3. So how good is the Figure 3 power amplifier? Well once again, with the right op-amp, it is capable of very good performance, at very low cost, but does have a number of shortcomings and limitations. One of the reasons that you don't see too many high quality audio power amplifiers with op-amp voltage amplifier stages is that until relatively recently commonly available op-amps have not been up to the job. Most of the currently available op-amps were not designed with audio in mind; and as a consequence are deficient in one or more of the following areas; gain bandwidth product, slew rate, harmonic distortion, noise, and output swing. However the op-amp manufacturers have perceived a market, risen to the challenge, and given us modestly priced (around £1.00 each) op-amps such as the TL071, NE5534, LF351 and LF411 which have gain bandwidth products (gbwp) of around 10MHz, slew rates of around 10V/µS, distortion of around 0.01%, are reasonably low noise, and have an output swing of around ±13V. Best of all of the low cost "audio" op-amps, however, is the OPA604 with 20MHz gbwp, 25V/µS slew rate, 0.0003% distortion, noise of 10 nV/%Hz, and an output swing of ±13V.

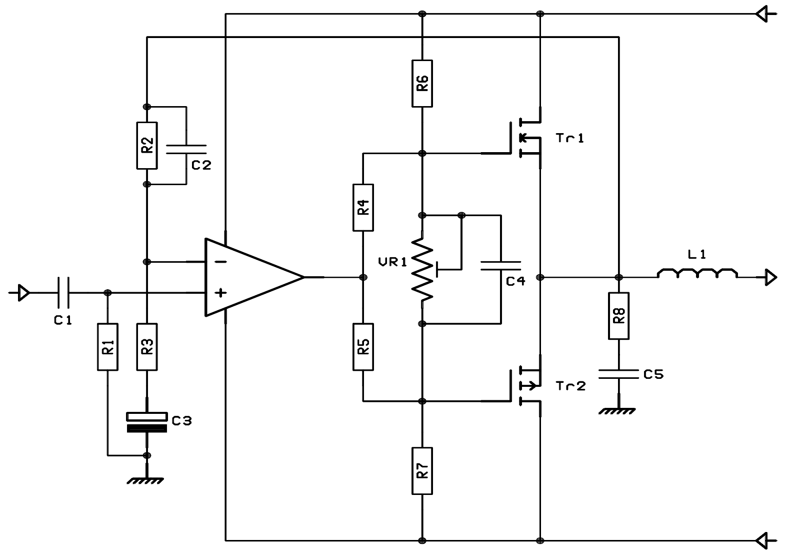


Figure 3: A simple op-amp power amplifier

Using one of these op-amps in the circuit of Figure 3 will give you a pretty good power amplifier, with some easily remedied drawbacks. In the same way that driving the power mosfets directly from the voltage amplifier transistor, as in Figure 1, is not a good idea in a high quality power amplifier; nor is driving the power mosfets directly from the op-amp, and for the same reason. The op-amps generally do not provide enough output current to charge and discharge the power mosfet input capacitances sufficiently quickly at high frequencies, leading to the previously mentioned increase in hf distortion. The remedy is the same too, use driver transistors. The resistors, R6 & R7, shown in Figure 3 which connect the output of the op-amp to the +ve and -ve power rails will load the output of the op-amp and give rise to slightly increased distortion. Replacing the resistors with high dynamic impedance constant current sources reduces the load on the op-amp, and consequently reduces the distortion.

The one remaining problem with the circuit of Figure 3 concerns power output. If the op-amp has an output swing of ±13V, corresponding to approximately 9V rms with a sinewave input, then the theoretical maximum output power into an 8Ω load is $9^2/8$ or about 10W! Obviously we would prefer a higher power output; which could be achieved by using an op-amp with a higher output swing, such as the ±35V obtainable from the OPA445. But this would still only give us about 75W/8Ω output at the price of increased distortion, because the OPA445 is not optimized for low distortion, and cost. The OPA445 costs around £8 and is not commonly available; Maplin have now stopped selling them and most other distributors favoured by hobbyists never did. The solution is to use one of the high performance, restricted output swing, op-amps mentioned earlier, together with an output stage which has a voltage gain of around five. This will give us a theoretical maximum output power of about 250 W/8Ω, much more satisfactory! However we won't actually get as much as this because we're only going to use a power supply of ±50V, rather than the ±65V necessary to get 250 W/8Ω; and in any case the power mosfets we're going to use wouldn't handle that much power without using pairs of devices.

The final circuit

The final circuit incorporates all of the refinements discussed previously and is shown in Figure 4.

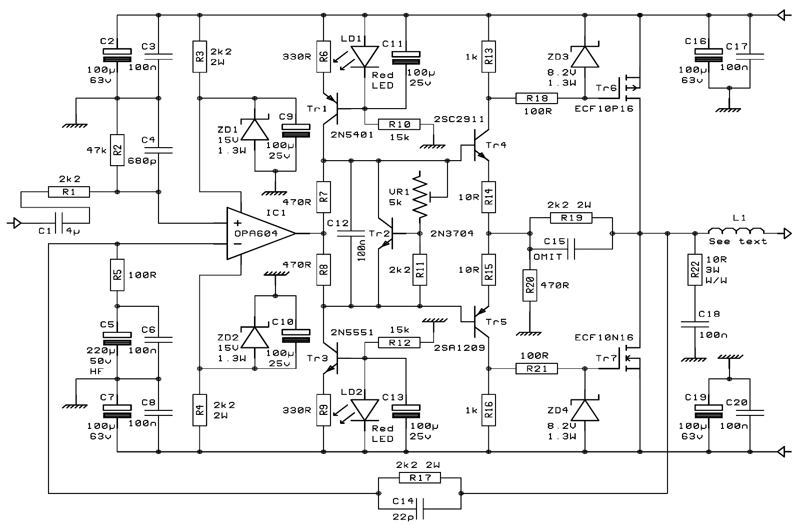


Figure 4: The final op-amp power amplifier circuit

The main features are as follows. The input capacitor C1 is composed of between one and four 1μF stacked film capacitors depending on desired bass response and depth of pocket (the caps are 50p each). I have deliberately chosen not to use an electrolytic in this position because they sound marginally different, and worse, to polymer film capacitors (they actually measure marginally worse, in terms of distortion, too). I tend to come down fairly heavily on the engineering side of the measurement/subjectivist debate but believe the subjectivists may be sometimes be correct, this is one of those instances. Thou shalt not put 'lytics in the signal path! R1 and C4 form an input low pass filter to restrict the bandwidth of the input signal and reduce intermodulation distortion. The ±15V power supply for the op-amp IC1 is provided from the main ±50V supplies by the resistor/zener diode combinations R3/ZD1 and R4/ZD2 and is smoothed/decoupled by C9/C10.

The resistors R7 and R8 together with C12 ensure that the bases of the upper and lower driver transistors Tr4 and Tr5 see the same signal. C12 also helps to iron out small changes in the bias voltage developed between the emitter and collector of the "amplified diode" bias transistor Tr2.

The high impedance load for the op-amp is provided by the complementary constant current sources R6/R10/C11/LD1/Tr1 and R9/R12/C13/LD2/Tr3. Notice the use of light emitting diodes as voltage references; they give better temperature compensation than a pair of silicon diodes, and generate less noise than zener diodes. The configuration of the driver transistors Tr4 and Tr5 is fairly standard and the voltage developed across their collector load resistors R13 and R16 provides the gate drive for the output mosfets Tr6 and Tr7. The gain of the output stage is set to approximately five ((R19+R20)/R20) by negative feedback via the resistors R19 and R20. The capacitor C15 serves to roll off the high frequency response of the output stage before the MHz region (after all its not a radio transmitter we're building here!).

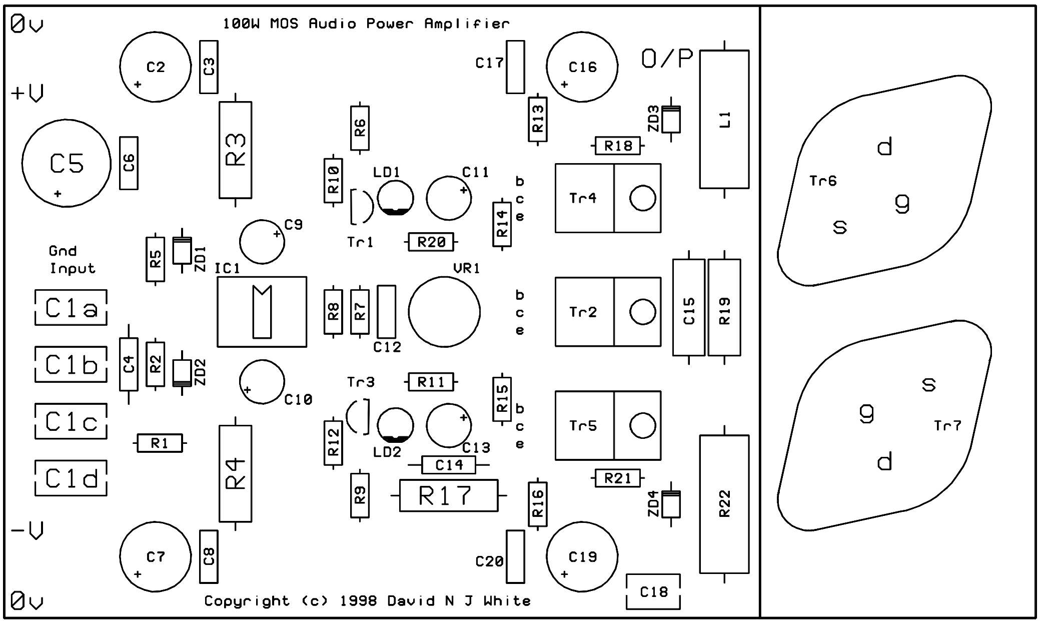
R18 and R21 are "stopper" resistors which help to prevent high frequency oscillation in the output mosfets. All mosfets are somewhat prone to high frequency oscillation because of their extended frequency response. The zener diodes ZD3 and ZD4 provide a measure of short circuit protection for the power mosfets by limiting the gate/source potential difference to 8.2 V, and therefore the maximum drain current to a little under 8 amps. This is usually enough to prevent destruction of the output devices (prolonged shorts are handled by a fuse).

The Zobel network R22/C18 and the small inductor L1 enable the power amplifier to deal with awkward (e.g. heavily capacititive) loads whilst maintaining stability and low distortion. The power supply lines are heavily decoupled by C2/C7/C16/C19 and C3/C8/C17/C20. The polyester film decouplers are necessary because the impedance of large electrolytic capacitors, whilst close to zero at low frequencies, is not sufficiently low at high frequencies.

The overall gain of the power amplifier is set to approximately 20 by negative feedback via R5 and R17 (gain = (R5+R17)/R5) whilst the overall bandwidth (excluding the input filter) is determined by C14. The values of the various feedback resistors R5, R17, R19, R20 may be lower in value than those you are used to seeing (a gain of approximately 20 is often set by a 22k/1k resistor combination) but this is deliberately done to reduce high frequency distortion. The only penalty for using for low value feedback resistors is the requirement to use high power devices for the larger resistor in each feedback pair, because of the magnitude of the ac current that flows around the feedback loops at high power outputs. In actual fact the amplifier would not fry R17 and R19 at full output even if they were the standard 0.6W, rather than the specified 2W, devices; although they would get rather hot at full power. However, the constantly changing temperature of the smaller resistors with real programme material played at high volume would continually alter the value of the resistor and thereby modulate the gain of the power amplifier. Not a good thing! Using a higher power resistor than is strictly necessary is equivalent to fitting a heatsink on a lower power device, which reduces the gain modulation to insignificant proportions.

Construction

The power amplifier can be constructed quite satisfactorily on stripboard, indeed the prototype for this design was made that way, but I would strongly recommend the use of glass fibre pcbs rather than stripboard. If you do use stripboard it is essential to either solder thick copper wire, or run solid solder, along the tracks which carry heavy currents (e.g. power rails, between the drains of the power mosfets, to the Zobel network, to the output inductor, etc). If you make your own pcbs you'll need to use the component overlay shown in Figure 5 to place your parts, if you use the boards that I've had commercially manufactured there is a component overlay silk screened onto the pcb. Take care to orient the transistors, zeners, leds, and particularly the electrolytic capacitors, the correct way round. Electrolytics will plop open and spread their somewhat messy contents all over the place if inserted with the wrong polarity (tantulum capacitors explode like small firecrackers if you mistreat them in this way!).



Construction is pretty straightforward and follows the usual guidelines; solder in the small discrete components first, then small actives, followed by larger discretes, and finally large actives. Be careful not to let polystyrene capacitors and active components get too hot when soldering them into position. I find that the best kind of soldering iron to use for delicate (i.e. small surface mount parts), and general electronic assembly, work is a high wattage (50W) type with a fine tip. That way you can get plenty of heat to the soldering site very quickly and complete a joint in under a second. With a low wattage iron it takes much longer to get enough heat into the pcb and component for the solder to melt, and all the time the heat is damaging your components.

If you intend to experiment with various types of op-amp then it is best to solder an 8-pin IC socket in the IC1 position, otherwise solder the op-amp directly in position. I have tried a number of moderately priced op-amps (and some expensive ones too) for IC1 and recommend the TL071 as the best cost/performance compromise, or the slightly more expensive OPA604 for the highest performance. IC1 is probably the most important single component as far as good measured and audible performance is concerned.

The constant current loads for the op-amp will track changes in temperature much better if Tr1 is in close thermal contact with LD1 and Tr3 in close thermal contact with LD2. Tr1/LD1 and Tr3/LD2 are adjacent to each other on the pcb and each transistor/diode pair should be clipped together either with a cable tie or a short length of copper strip (cut a 5-10mm wide hoop from a length of 15mm copper water pipe, cut the hoop to make a narrow strip, cut the strip to the correct length , wrap the strip around the devices). Alternatively stick them together with a blob of quick setting epoxy adhesive. Only fix the devices together with adhesive when you know the power amplifier works and you know that you're not going to tinker/experiment with the constant current loads, getting the devices apart once the epoxy has set is almost impossible! Best performance is obtained if Tr1, Tr3 and LD1, LD2 are matched for V_{be}/h_{FE} and V_F respectively, but this is a more expensive option than using randomly chosen (i.e. as they come across the counter) parts because of the need to buy 5 or 10 of each component to be reasonably sure of getting a match (and even then its not guaranteed). The performance degradation as a consequence of using randomly chosen parts is very small and matching is really only for perfectionists (like me!).

The quiescent current is most stable with temperature if Tr2, Tr4, and Tr5 are in thermal contact. This is easily arranged by putting a suitably drilled aluminium (use the pcb as a template) strip on the pcb, putting greaseless semiconductor insulators on top of the aluminium strip, and putting the horizontally mounted transistors on top of the insulators. The transistors, aluminium strip, and pcb are then fixed together with 3 mm nuts and bolts. Finally the transistors are soldered to the pcb. The aluminium strip is not a heatsink, as the driver transistors only get barely warm even at high power outputs.

There are various possibilities for Tr4 and Tr5; the cheapest and most readily available are the MJE340/MJE350 complementary pair which have reasonable h_{FE} but fairly low f_T; whilst the less readily available, and slightly more expensive, 2SA968/2SC2238 pair have similar h_{FE} but much higher f_T, which leads to better high frequency performance. Using a matched pair of driver transistors will give the best performance, but once again there is only a very small penalty for using randomly chosen pairs. If you use the MJE340/MJE350 pair (TO126) then they need to be mounted on the pcb with their metal face up, followed by the insulating pads and then the aluminium strip on top of the pads. On the other hand if you use the 2SA968/2SC2238 pair (TO220) then the aluminium strip goes on the pcb first, followed by the insulating pads, and then the transistors metal side down. These different arrangements are necessary to accomodate the different pinouts of the TO126 (ecb) and TO220 (bce) transistors.

Tr2 does not really need to be a power transistor, I simply used one because it was the easiest way to ensure good thermal contact between Tr2, Tr4, and Tr5. If you wish you can use just about any small signal npn plastic transistor (e.g. BC184L flat face down) and use epoxy adhesive to glue it onto the aluminium strip between Tr4 and Tr5.

L1 is made by wrapping 17 turns of 0.9mm enamelled copper wire around the body of a 3W wirewound resistor (the square cross section, white ceramic body variety) and soldering each end of the wire to the corresponding resistor lead.

If you intend to drive low impedance loads, such as 4Ω loudspeakers, at high levels with this power amplifier then it might be better to use Exicon ECF20N16/ECF20P16 power mosfets with their 250W dissipation capacity rather than the 125W ECF10N16/ECF10P16 pair specified. There are undoubtedly other power mosfets which would work reasonably well in this design (e.g. BUZ900/BUZ905) but I have never been tempted to try them because none of them have specifications as good as the Exicon parts, and all are invariably more expensive. Exicon mosfets are designed and manufactured in the UK specifically for hi-fi audio power amplifiers.

The power mosfets are bolted onto a pcb mounting, thermal transfer bracket which is then bolted onto the heatsink proper (usually with the case back panel in between). I would recommend enlarging the holes used to fix the thermal transfer bracket to the heatsink so that they take M5 nuts and bolts. Insert the central, locating M3 nut and bolt first when mounting the power mosfets onto the thermal transfer bracket and pcb. Then insert the power mosfets on top of their greaseless insulating pads and bolt them loosely to the thermal transfer bracket and pcb with M3 nuts and bolts; put an ordinary washer (not a lock washer, they'll chew up the pcb) under each nut on the pcb side. At this point check that the power mosfet cases and pins are not in electrical contact with the thermal transfer bracket. This shouldn't be a problem if you are using a pcb, but care is required with a stripboard layout. In the latter case use the thermal transfer bracket as a drilling template. When the power mosfets are properly seated all of the nuts and bolts can be tightened up. I usually then solder the nuts in place on the bolts; they usually need a bit of scraping before they will take solder. This ensures that the nuts and bolts don't work loose due to the inevitable thermal cycling of the power mosfets and thermal transfer bracket. If you ever need to remove the power mosfets the solder on the nuts and bolts can be removed with a solder sucker or solder wicking braid. Use heat transfer grease between the thermal transfer bracket and heatsink, or between the thermal transfer bracket and case back panel as well as between the case back panel and heatsink, when finally bolting the power amplifier to the heatsink or case back panel/heatsink. Photograph 1 shows a completed power amplifier built on a manufactured pcb.

The power mosfets can be mounted directly onto a heatsink and connected to the pcb by wires which are kept as short as possible, if desired. Although not quite as elegant as using the thermal transfer bracket, direct mounting probably provides better heatsinking. The heatsinks are usually chosen to fit in with the power amplifier casing, which is a matter of individual taste, but should be rated at no more than 2.0EC/W for domestic use or no more than 1.3EC/W for continuous sinewave use.

I used a 2U high 19" rackmount case from Maplin (Order Code XM68Y) to house a stereo pair of power amplifiers together with their associated power supplies and protection circuitry (of which more later) in conjunction with 1.8EC/W heatsinks, for domestic use. I used white dry transfer paint lettering (available from most good art supply shops), followed by three coats of water based spray varnish, to annotate the power switch and indicator lights on the front panel.

One final point concerns the gain of the amplifier which was set to 23 in order to work with my relatively high output preamplifier. This may be a little low for some users and may be increased to 30 by reducing R5 from 100 to 75Ω, at the expense of a very slight increase in distortion.

Power supplies

The power amplifier needs a ±50V power supply and a suitable circuits are shown in Figure 6 for powering both a single or a pair of power amplifiers. For a single power amplifier the (preferably toroidal) transformer should be rated for at least 160VA (225 VA preferred), whilst a pair powered from one transformer requires a minimum rating of 300VA (500VA preferred). The smaller transformers will supply enough current to give around 100W/8 Ω and 130W/4Ω output from the power amplifiers, whilst the larger ones will supply enough current for 100W/8 Ω and 160W/4 Ω . The colours of the transformer leads shown in Figure 6 correspond to those supplied by Maplin; they may be different for transformers from other suppliers. Toroidal transformers from other suppliers or manufacturers , such as Airlink, Antrim, Farnell, ILP, and RS, with 35 - 42V secondaries are also suitable.

The mains input filters are not strictly necessary but do cut down on the possibility of switching and/or motor interference from heavy domestic appliances. I personally prefer to use IEC mains inlets which integrate the mains connector, fuse, switch, and filter in one housing; this cuts down on the amount of exposed mains wiring.

Ideally each power amplifier of a stereo pair should have its own independent power supply but this is an expensive option. A single transformer serving separate rectifiers and capacitor banks for each power amplifier is a good cost effective compromise. Be prepared for the fact that the power supply will cost more than the power amplifier itself, although it is often possible to pick up suitable transformers cheaply by scanning the surplus advertisements in ETI and other electronics magazines.

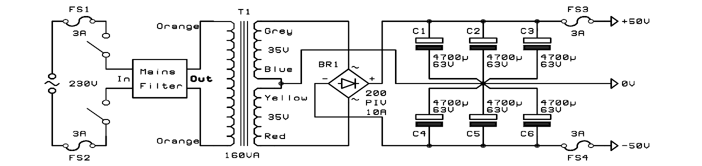


Figure 6a: Power supply for a single power amplifier

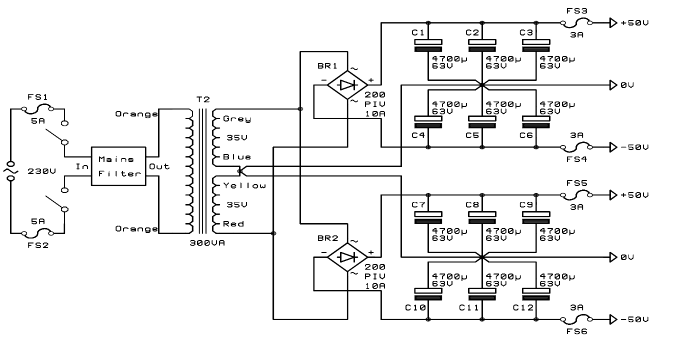


Figure 6b: Power supply for dual power amplifiers

It's better to use three smaller electrolytic capacitors, rather than one big one, to smooth each of the positive and negative supply lines, as shown in Figure 6. These capacitors will account for a significant part of the total cost of a power amp/psu combination, and it is possible to save money by using 3300µF parts whilst still getting perfectly satisfactory performance. Equally well using larger or better quality components will reduce ripple on the power supply lines and lead to better handling of bass transients, albeit at higher cost.

The power supply can be either hardwired, constructed on stripboard, or constructed on single sided glass fibre copper clad board. I recommend the latter option; simply drill the board to take the rectifier bridge, snap in capacitors, fuses and spade connectors and then cut the copper with a scalpel or burr to make the circuit. Don't use a snap in blade scalpel - the blades fly out when you're cutting - use one where the blade is retained by a screw up clamp. The power supply circuitry is so simple that its not worth etching a pcb. If you want a power on/off indicator I recommend a led in series with a 10 kΩ 2 W resistor connected between the +50V and -50V power lines of any of the power supply options.

The power amplifier should be connected to the power supply and input/output sockets as shown in Figure 7 for a mono system. For a dual mono system repeat everything from the mains inlet/filter/switch/fuses onwards; for a stereo system using a Figure 6b style power supply repeat everything from the power supply onwards. It is particularly important that the single point star earthing scheme is adhered to and that the input phono socket is insulated from the (metal) case. You should only use one of the 0V connections on the power amplifier pcb, it doesn't matter which, but the one which gives the shortest distance to the psu star earth in your particular layout is safest. If you use both connections you will create an earth loop, leading to possible problems with mains hum. The protective earth connection to the metal case MUST be made or the case could become live in the event of a fault or wiring error. It makes good sense from a safety standpoint to make sure that the mains inlet, preferably an IEC filtered type, is covered by a protective rubber "boot" and that any connections to the mains switch and mains fuse are impossible to touch and properly insulated. Using rocker switches and fuseholders with "Faston"/"Lucar" spade connectors makes good insulation straightforward if you use the soft plastic covers for the spade receptacles. This part of the project involves mains voltages, get a more experienced constructor to handle this part of the project for you if you are at all unhappy about working with mains voltages. Photograph 2 shows a completed mono power amplifier, built around a manufactured pcb, and power supply.

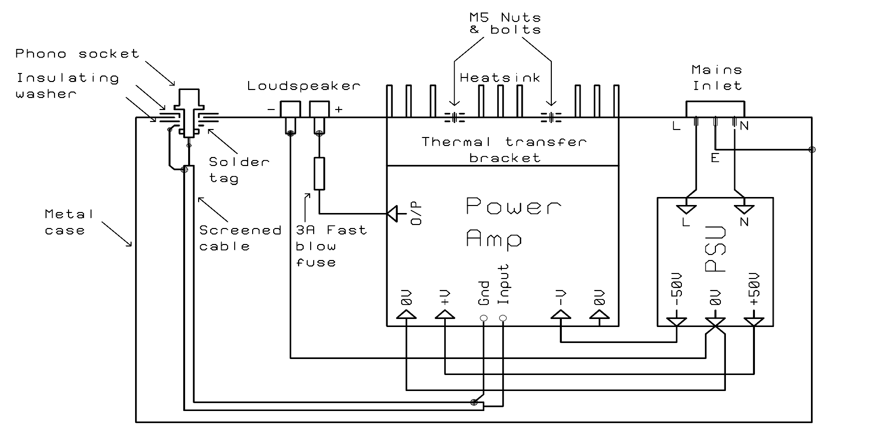


Figure 7: Power amplifier and psu wiring

Loudspeaker protection

Although the protective zener diodes and fuses will protect loudspeakers attached to the power amplifiers from most eventualities, a large sustained DC offset at the output caused by component failure could possibly wreck your expensive loudspeakers. This eventuality is mercifully remote, I've never had it happen to me in twenty years of fiddling with amplifiers and speakers, but it can happen. For added peace of mind, and particularly if your loudspeakers are expensive, it is best to add circuitry to protect against DC offsets.

I thought about designing suitable protection circuitry into the power amplifiers but this would have made the pcbs more expensive for those who don't want this facility, and in any case excellent stand-alone protection devices are available at low cost. I use the Vellman K4700 Loudspeaker protection kit which is available from Maplin (Order Code VE24B) and other suppliers. This device protects a stereo pair of power amplifiers by disconnecting the loudspeakers, using a relay, when more than ±1 V DC is detected on the output. It also eliminates switch on and off "thumps" in the loudspeakers. The antithump circuitry doesn't serve much purpose with this power amplifier because the soft start and decay of the led driven constant current sources, together with the very low output offset voltage, means that switch on and off is signalled by only the softest of barely audible "plops". The K4700 is very small and can easily be fitted inside the power amplifier enclosure.

Testing

If you constructed the power amplifier on stripboard now is a good time to check component values and locations as well as for unintended solder bridges between adjacent tracks and dry joints. If you made your own pcbs apply similar checks to those for stripboard and also check that there are no cracks or breaks in the tracks due to faulty resist or slight overetching. If you are using the manufactured pcbs the only likely error is inserting resistors in the wrong position. I misread a resistor value when building the stripboard prototype which resulted in 35 V on the gates of the power mosfets at power up! The fuses blew and, given that the datasheet quotes an absolute maximum of ±14V on the gates, I resigned myself to £10 worth of mosfets gone up in smoke (not literally!); but amazingly both survived! Either Exicon's figures are extremely conservative or they make very tough mosfets, but I wouldn't bank on being so lucky a second time.

Before commencing setup/testing make sure that VR1 is turned fully anticlockwise and that the power supply is turned off. Temporarily replace the power supply output fuses by 500mA fuses and connect the power amplifier to the power supply via an ammeter capable of reading at least 2A in the positive supply line. Switch on the power supply whilst watching the fuses. If the fuses blow or the meter reads more than 0.1 A turn off the power.

Blown fuses indicate a constructional error of some kind; check all of your power supply wiring and recheck your stripboard/pcb very carefully. A high current reading, assuming that VR1 really is turned fully anticlockwise, means that the amplifier is oscillating (my prototype drew about 0.4A when it was oscillating). Oscillation is almost invariably caused by overlong (i.e. longer than 300mm) power supply connections to the power amplifier, or overlong connections between the stripboard/pcb and separately heatsinked power mosfets.

If all is well gradually rotate VR1 until the quiescent current is around 100mA. Leave the power amplifier turned on for about 10-15min, during which time the quiescent current will rise to maybe 130mA and fall back again. Make a final adjustment of VR1 to set the quiescent current to 100mA. You'll find that setting the quiescent current requires a delicate touch on VR1. Turn off the power, replace the 500mA fuses with 3A fuses, and the power amplifier is ready for use.

Performance

The square wave performance of the power amplifier at 10kHz is shown in Photographs 3(a) - 3(g). Testing at lower frequencies represents a much less severe test of a power amplifier and so these results are not given here. For all of these tests the input filter was disabled by removing C4.

The input signal, Photograph 3(a), may be used for reference to illustrate the very slight hf rolloff with purely resistive 4 and 8Ω loads shown in Photographs 3(b) and 3(c) respectively; whilst the addition of 0.1μF in parallel with the load resistor "squares up" the 4Ω response but causes a very small overshoot in the 8Ω response as shown in Photographs 3(d) and 3(e) respectively. With a heavily capacitative load of 1.0μF in parallel with 4Ω the output shows a small amount of well controlled ringing as seen in Photograph 3(f), whilst with 1.0μF in parallel with 8Ω the ringing is more marked, but still under control, as can be seen in Photograph 3(g).

These photographs show that the power amplifier is unconditionally stable, in contrast to some well regarded commercial power amplifier modules that I subjected to the same regime. The remainder of the performance is summarized in the table below (IC1 = OPA604, 160VA toroidal transformer, C4 removed).

Input sensitivity	1.2 V rms (full output into Ω)
Input impedance	47 kΩ
Output Power (continuous)	100W rms into 8Ω (1kHz sinewave)
	130W rms into 4Ω (kHz sinewave)
Output offset voltage	0. mV
Full power bandwidth	15Hz - 125kHz (-3 dB)
Slew rate	25V/μs
Damping factor	>400 (8Ω load)
Noise	-95dB (input shorted)
Total harmonic distortion (thd)	100Hz 0.004 %
(1 - 60 W into 8 Ω)	500Hz 0.004 %
	1 kHz below noise
	10kHz 0.038 %

These are worst case figures because the noise and thd measurements are not bandwidth limited and therefore contain contributions from mains hum and wideband noise. Also the apparent rise in distortion at higher frequencies owes more to input/output cross coupling , which becomes more significant with increasing frequency, in my fairly rudimentary home-made distortion analyzer than any non-linearities in the power amplifier. The power amplifier measures well when compared with the vast majority of commercially available power amplifiers and modules, with their invariably optimistic rather than pessimistic performance figures, including some very expensive ones! The power amplifiers give much more solid bass, a faster attack in the treble, and an overall feeling of being in greater control when compared with my Blomley's. This project has been well worth the effort for me; if you build one or more of these power amplifiers I hope that you'll agree. Enjoy!

Printed circuit boards

I have designed a single-sided printed circuit board for this project and the foils are given at the back of the magazine, as usual, for those of you who prefer to make your own printed circuit boards. Power amplifiers usually have a long lifetime; so if you do make your own pcbs I would recommend sealing the copper side of the completed pcb with a spray on conformal coating (e.g. Maplin YB75S) to prevent corrosion of the copper tracks. Better still you can tin plate the newly etched pcb by dipping it into a tin plating solution for half an hour. Unfortunately tin plating crystals do not seem to be available in small quantities, and a 450 g pack from Farnell costs around £40!

However for ease of component location, solderability, freedom from solder bridges, and long-term reliability I prefer, wherever possible, to use manufactured pcbs with silk screened component locations, tin plated tracks, and solder masking. Obviously this is not economic for one or two pcbs so I have had a batch of pcbs manufactured..

Please note that the photographs mentioned in the text have not yet been added to this article. Quite a few of the parts listed with Maplin part numbers are no longer available from the company. The latest versions of the power amplifier described in this article are the MOS125 and MOS250 for which pcbs, kits of parts, and assembled and tested modules are available from White Noise.

Parts list

Code numbers after the component values are Maplin order codes, but equivalent parts from other suppliers are equally acceptable.

Power Amplifier

	Resistors	Maplin Part No.
R1	2. kΩ	M2K2
R2	47kΩ	M47K
R3	2.2kΩ 2 W	D2K2
R4	2.2kΩ 2 W	D2K2
R5	100Ω	M100R
R6	330Ω	M330R
R7	470Ω	M470R
R8	470Ω	M470R
R9	330Ω	M330R
R10	15kΩ	M15K
R11	2.2kΩ	M2K2
R12	15kΩ	M15K
R13	1kΩ	M1K0
R14	10Ω	M10R
R15	10Ω	M10R
R16	1kΩ	M1K0
R17	2.2kΩ 2 W	D2K2
R18	100Ω	M100R
R19	2.2kΩ 2 W	D2K2
R20	470Ω	M470R
R21	100Ω	M100R
R22	10Ω 3W	W10R

	Capacitors	Maplin Part No.
C1	4 x 1µF polyester layer	WW53H
C2	100µF 63 V electrolytic	AT81C
C3	100nF polyester film	DT98G
C4	680pF polystyrene	BX34M
C5	220µF 50 V HF electrolytic	JL51F
C6	100nF polyester film	DT98G
C7	100µF 63 V electrolytic	AT81C
C8	100nF polyester film	DT98G
C9	100µF 25 V electrolytic	AT48C
C10	100µF 25 V electrolytic	AT48C
C11	100µF 25 V electrolytic	AT48C
C12	100nF polyester film	DT98G
C13	100µF 25 V electrolytic	AT48C

C14	22 pF polystyrene	BX24B
C15	-	
C16	100µF 63 V electrolytic	AT81C
C17	100nF polyester film	DT98G
C18	100nF polyester film	DT98G
C19	100µF 63 V electrolytic	AT81C
C20	100nF polyester film	DT98G

	Semiconductors	Maplin Part No.
IC1	OPA604/627	*
Tr1	2N5401	UL37S
Tr2	2N3704	QR28F
Tr3	2N5551	UL36P
Tr4	2SC2911	*
Tr5	2SA1209	*
Tr6	ECF10P16	*
Tr7	ECF10N16	*
LD1	3 mm red led	WL32K
LD2	3 mm red led	WL32K
ZD1	15 V 1.3 W	QF57M
ZD2	15 V 1.3 W	QF57M
ZD3	8.2 V 1.3 W	QF51F
ZD4	8.2 V 1.3 W	QF51F

Miscellaneous	Maplin Part No.
L1 10Ω 3W W/W (see text)	W10R
VR1 5 kΩ cermet trimpot	WR41U
Heat transfer bracket	*
TO3 semiconductor insulators	CH04E
Vertical pcb spade tabs	AS33L
Lucar push on receptacle	HF10L
Push on recptacle covers	FE65V
Pcb 2 way latching plug	RK65V
Pcb latching socket housing	HB59P
Pcb terminals	YW25C
Enamelled copper wire	BL26D
Heatsinks	*

	Single Power Supply	Maplin Part No.
T1	2 x 35V 160VA toroidal mains transforme	*
BR1	200piv 10A bridge rectifier	AR83E
C1	4700µF 63V snap-in radial electrolytic	*
C2	4700µF 63V snap-in radial electrolytic	*
C3	4700µF 63V snap-in radial electrolyti	*
C4	4700µF 63V snap-in radial electrolytic	*
C5	4700µF 63V snap-in radial electrolytic	*
C6	4700µF 63V snap-in radial electrolytic	*
Double pole switched and fused mains inlet filter		CT82D
FS1	20mm 3.15A time delay glass fuse	GL64U
FS2	20mm 3.15A time delay glass fuse	GL64U
Chassis mounting 20mm fuseholder		KC01B
Chassis mounting 20mm fuseholder		KC01B
FS3	20mm 3.15A fast acting glass fuse	GJ94C
FS4	20mm 3.15A fast acting glass fuse	GJ94C

Dual Power Supply

T2	2 x 35V 300VA toroidal mains transformer	*
FS1	20mm 5A time delay glass fuse	GL65V
FS2	20mm 5A time delay glass fuse	GL65V

All other parts as per single power supply

* These parts are either only available from White Noise or the White Noise parts offer the best value.

Legends to photographs

Photograph 1: The power amplifier built on a manufactured printed circuit board.
Photograph 2: A cased mono power amplifier showing power supply and heatsink.
Photograph 3a: The 1 kHz input to the power amplifier (1V / cm).
Photograph 3b: The power amplifier output into a 4Ω load (5V / cm).
Photograph 3c: The power amplifier output into a 8Ω load (5V / cm).
Photograph 3d: The power amplifier output into a 4Ω||0.1µF load (5 V / cm).
Photograph 3e: The power amplifier output into a 8Ω ||0.1µF load (5 V / cm).
Photograph 3f: The power amplifier output into a 4Ω||1.0µF load (5 V / cm).
Photograph 3g: The power amplifier output into a 8Ω||1.0µF load (5 V / cm).