Pack some punch into your car hifi system

High-power car stereo amplifier

Give your car's sound system some real grunt with this high-power stereo amplifier. It boasts a total audio output of 100W (50W per channel), is easy to build and will cost you less than equivalent commercial units.

by ANDREW LEVIDO

Why put up with a Mickey Mouse 5W per channel car sound system? With this high-power stereo amplifier, you can enjoy real hifi sound in your car.

Some readers may think it unnecessary to install such a high-powered amplifier. After all, 50W is a heck of a lot of output and the listening area is really quite small. But there is more to it than that.

First, the ambient noise level in a car is far higher than in the typical lounge room. This means that the average listening level must be higher so that the music can be heard over the noise.

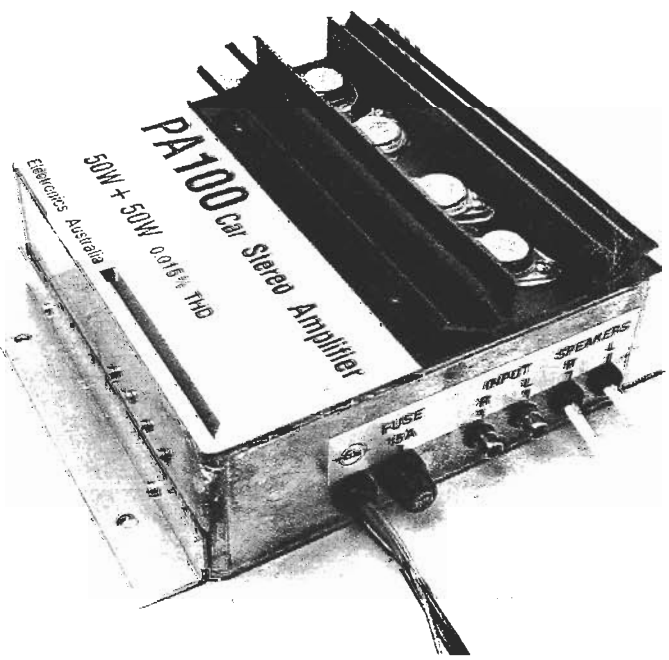
Second, a high-power amplifier is necessary to better exploit the wide dynamic range and wide bandwidth provided by the latest generation tuners and cassette decks. A high power amplifier is also desirable if you are thinking of installing a car compact disc player.

Finally, most so-called 5W car sound systems typically deliver their rated output at high distortion (often around 10%). The EA PA100 Car Stereo Amplifier is rated at a true 50W RMS per channel with just 0.5% distortion. And at 40W output, the distortion shrinks to a miniscule .015%.

These are excellent figures and are on a par with the very best commercial models. In particular, the unit should provide more than adequate drive for all foreseeable applications while keeping the drain on the car's electrical system within reasonable bounds.

Full specifications will be published next month.

The amplifier is housed in a sturdy metal diecast case which provides heatsinking.



Main features

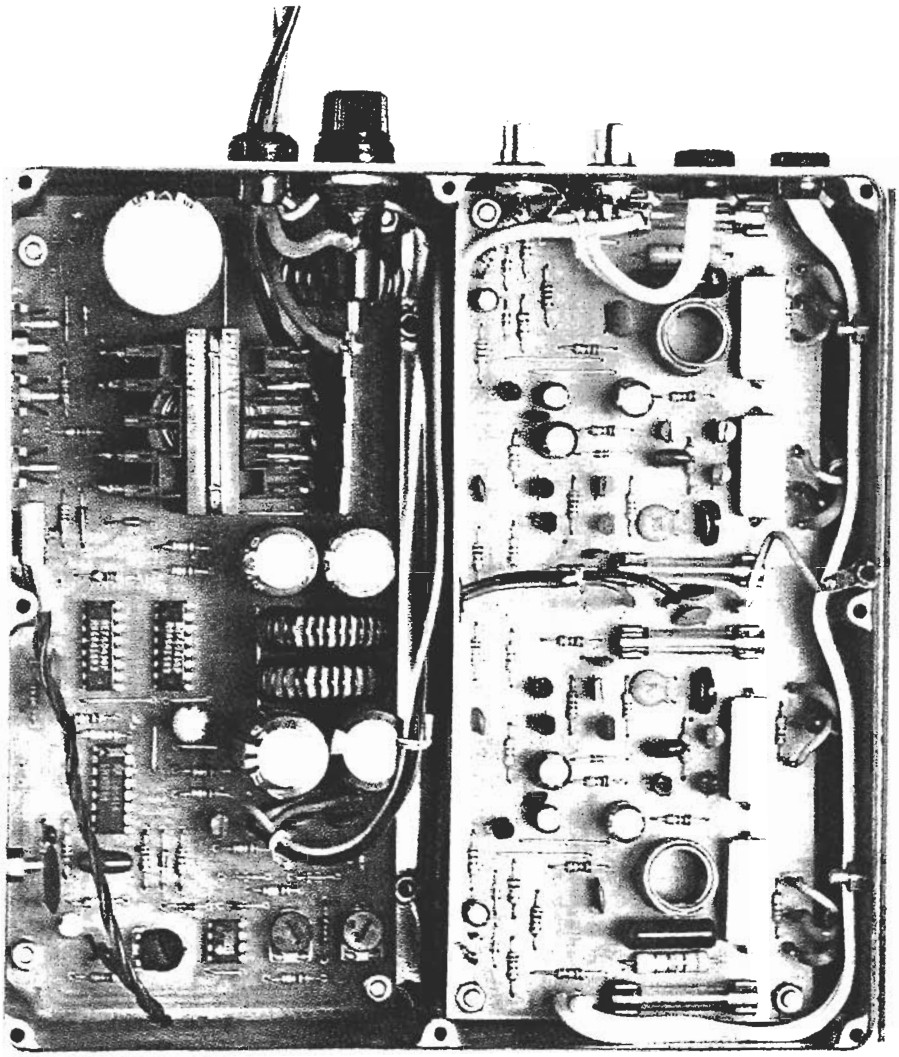
The PA100 amplifier is designed for mounting in the boot of the car or under a seat. Installation is relatively straightforward. The inputs are connected to the output of the signal source (car radio/cassette deck or CD player), while the speakers are connected to the amplifier. Power is derived directly from the car battery and the unit is switched on and off by means of a control lead connected to the signal source.

In this way, the amplifier is automatically switched on and off by the signal source.

The PA100 draws a maximum of 15A but the typical current drain is around 1A to 2A, depending on the program and the sound level you consider to be "normal". An important safety feature is an under-voltage cutout circuit which shuts off the amplifier if the battery voltage drops below a preset level. This prevents the amplifier from excessively discharging the battery if the stereo is left on while the engine is not running.

In practice, the voltage cutout level is set so that the battery has sufficient capacity remaining to start the car.

The second safety feature we have incorporated is an over-temperature cutout. In order to understand why this is necessary, we need only consider that the ambient temperature inside a car can easily reach 60°C on a sunny summer's day. This high ambient temperature, coupled with poor air circulation, means



This internal view shows the inverter PCB at left and the amplifier PCB at right. Note the metal shield between the two boards.

that the amplifier could quickly overheat, even at moderate volume levels.

To prevent destruction of the semiconductors, the thermal cutout automatically shuts the amplifier down if the temperature becomes excessive. When the semiconductors have cooled down sufficiently, the amplifier automatically restarts. In practice, the thermal cutout should operate only on very hot days and then only if the car has been sitting in the sun for some time.

As shown in the photographs, the prototype was built into a sturdy metal diecast case. This provides both mechanical strength and a substantial degree of heatsinking for the circuit. An extruded aluminium heatsink provides additional heatsinking for the power amplifier output transistors.

Design considerations

Basically, there are three different ways of designing a power amplifier to run from the battery voltage in a car. The simplest method is to use a power amplifier which runs directly from the 12V rail. Because one side of the car supply is connected to chassis, a direct coupled amplifier is out of the question.

The maximum power output available from an amplifier of this type is severely restricted by the limited voltage swing available at the output. If we allow for a 2V drop across the output transistors, the most we can expect is about 3.2W RMS into a 4Ω load. If more power is required, lower impedance speakers must be used but, even with 2Ω speakers, the maximum power available is only about 6W.

Another approach is to use a bridge amplifier. This really consists of two power amplifiers operating 180° out of phase and connected so that they drive the loudspeaker in push-pull (ie, the loudspeaker is connected across the active outputs of the amplifiers). This results in twice the peak voltage across the speaker compared to the previous case and thus four times the output power.

Thus a bridge amplifier can produce a maximum of 12.5W into a 4Ω load and around 25W into a 2Ω load. The main drawbacks of this approach are the still limited power output and the need to provide two separate power amplifiers for each channel.

If even higher power outputs are required, the best solution is to use a DC-to-DC converter to generate high voltage supply rails. These are then used to power quite conventional power amplifier stages. It is usual to generate a balanced supply — that is, equal positive and negative supply rails referenced to ground — so that a direct coupled amplifier can be used.

This is the approach adopted for this design. It uses a DC-to-DC converter to generate positive and negative 27V rails. The result is a power amplifier stage

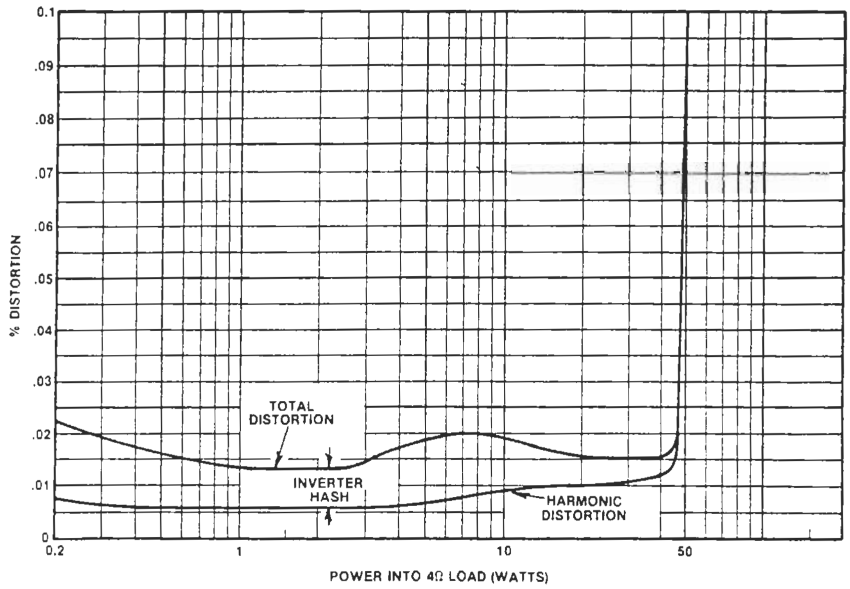


Fig.1: this graph plots the distortion and shows the very low level of inverter hash at the amplifier output.

100W Car Stereo Amplifier

capable of delivering the required 50W per channel into 4Ω loads.

Converter design

Quite a number of factors must be taken into consideration in the design of a DC-to-DC converter of this type. Because of the noise inherent in switching supplies, a switching frequency well outside the audio range is necessary. We chose 50kHz as a reasonable compromise. It keeps the switching noise inaudible and requires only a small transformer, without making the design unnecessarily complicated.

We also chose to use power Mosfets as the switching devices in the converter. There are three main reasons for our decision to use these unusual components.

First, the on resistance of a power Mosfet has a positive termperature coefficient. Thus, they can be paralleled without the need for wasteful current sharing resistors. This is important because of the low battery voltage available. At 15A, the voltage lost across a 0.1Ω resistor is 1.5V or 12.5% of the available voltage.

Second, power Mosfets are very fast, with low switching losses. This leads to a more efficient design which dissipates little power and is therefore more reliable.

Finally, power Mosfets are very easy to use. Mosfets are transconductance devices, which means that the drain-source current is controlled by a voltage at the gate. The result is a much simpler drive circuit than would be possible if conventional bipolar transistors had been used for the inverter.

To explain, the gate of a power Mosfet appears as a 1500pF capacitance, irrespective of drain current. It is simply necessary to charge and discharge this capacitance to switch the transistor on and off. A quick glance at the circuit diagram will show that a low cost CMOS IC (4049) has been used to drive the Mosfets directly.

The car battery voltage is notoriously variable, ranging from below 11V to above 15V in some cases. This represents a variation of plus and minus 15% over the mean value. This range of variation in the amplifier supply could not be tolerated, so some form of regulation is necessary.

We chose to use an LM3524 pulse width modulating regulator IC as used in the Busker amplifier described in February 1985.

How it works

Having discussed some of the design considerations involved in the development of the DC-to-DC converter, we turn now to a more detailed description of the circuitry.

The positive side of the battery supply is connected via a 15A fuse and inductor L1 to the centre tap of the converter transformer. The purpose of the fuse is self evident while the inductor serves to attenuate any switching noise on the supply lines. This measure is to prevent interference to the car radio due to switching noise.

The power to the rest of the circuit is switched by Q2, which in turn is controlled by Q1. Q1 is driven by the remote control line and so turns the inverter on and off using a control signal from the tuner or cassette deck. D1 and D2 prevent damage to Q1 by high voltage transients which may appear on the control line.

If the control input is low, there will be no power supply to the circuit, so all the switching transistors will be off. The current drain of the circuit in this situation will only be the leakage in the Mosfets. This was measured to be less than 500μA in the prototype.

The LM3524 contains all the control circuitry required for the inverter. The internal oscillator frequency is set by the components connected to pins 6 and 7 and the values shown give a nominal switching frequency of 50kHz.

In practice, the actual frequency may vary somewhat from the nominal value but this is of no consequence (the measured frequency of the prototype was actually 44kHz). Note that the LM3524's internal oscillator must operate at twice the switching frequency because of an internal divide by two function.

The 1.5kΩ resistor and the 0.1μF capacitor connected to pin 9 compensate the internal voltage regulating op amp at the frequency of the pole of the output filter. Diode D3, the 100kΩ resistor and the 2.2μF capacitor provide a soft start function to the inverter. This works as follows.

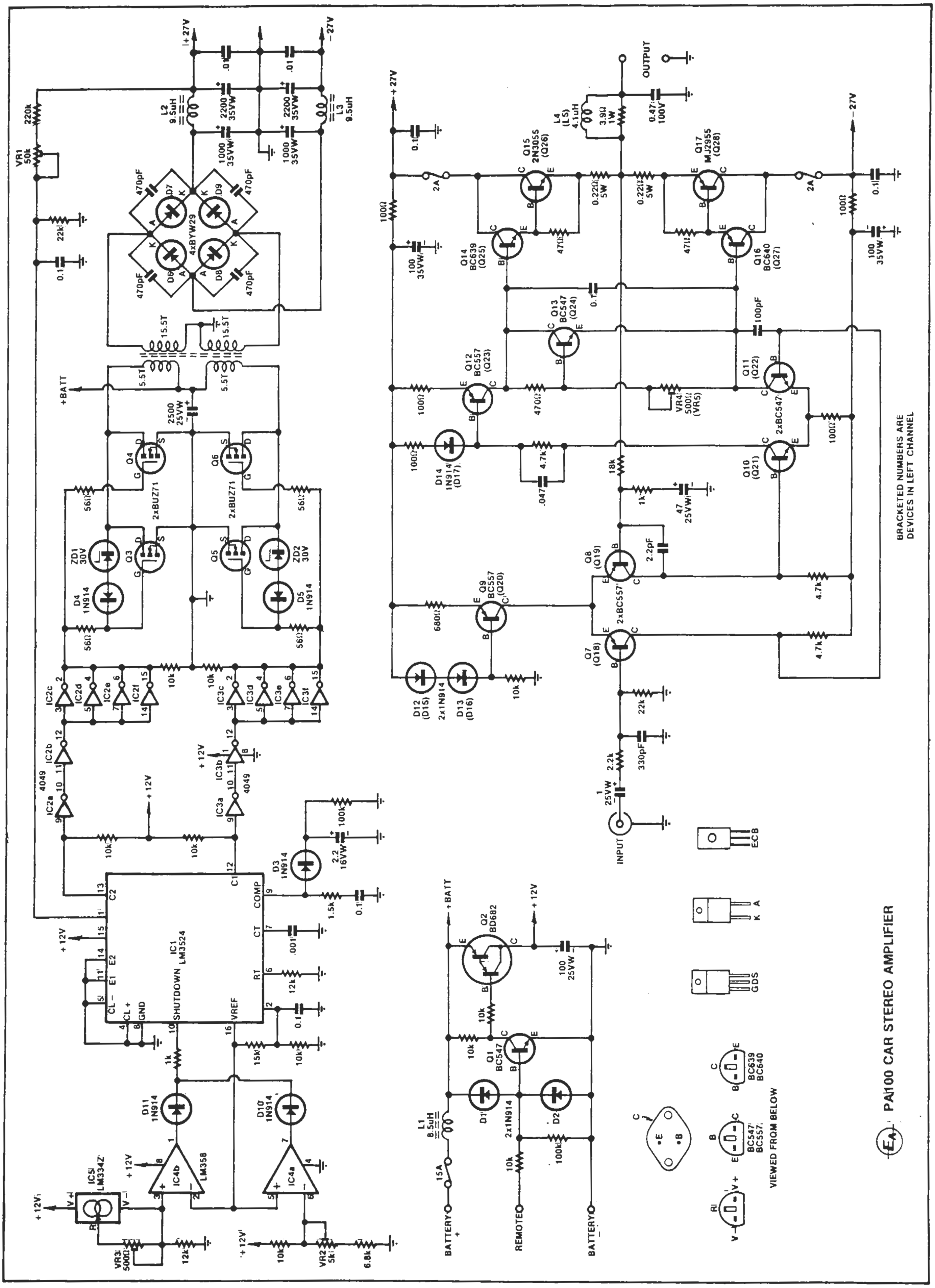
When the inverter is turned off, the capacitor is discharged via the 100kΩ resistor. When the inverter is subsequently turned on, the voltage at pin 9 will be low. This voltage will rise, as the capacitor charges up via D3, until it reaches the normal operating level.

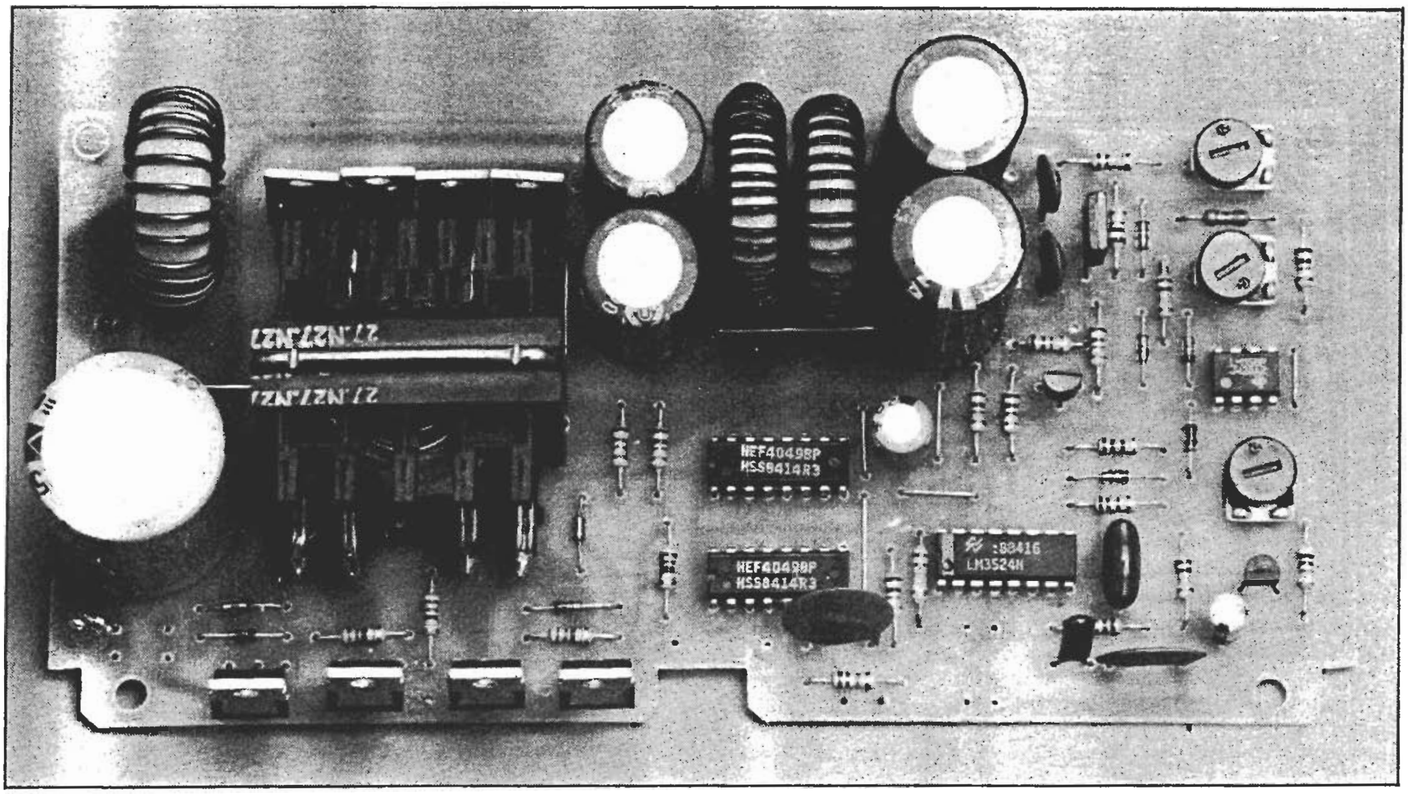
The output pulse width is proportional to the voltage on pin 9. Thus, the pulse width will increase gradually from zero to the normal operating level.

An error amplifier inside IC1 compares the output voltage of the inverter with a reference voltage, and controls the on time of the switching transistors. The reference voltage is derived from an internal regulated 5V source which is divided down to 2V by the 15kΩ and 10kΩ resistors. A 0.1μF capacitor decouples this 2V reference.

Another voltage divider, consisting of trimpot VR1 and the 220kΩ and 22kΩ resistors, reduces the converter output voltage to a similar level. The trimpot provides adjustment of the division ratio so that the output voltage can be set precisely to 27V. The divided output voltage is decoupled, again with a 0.1μF capacitor, and applied to the inverting input of the error emplifier.

The output circuit of the LM3524 consists of a pair of transistors, whose


PA100 CAR STEREO AMPLIFIER
BRACKETED NUMBERS ARE DEVICES IN LEFT CHANNEL
VIEWED FROM BELOW
+27V
-27V
+BATT
+12V
OUTPUT
INPUT
BATTERY +
REMOTE
BATTERY -
IC1 LM3524
SHUTDOWN
VREF
COMP
IC4a
IC4b
LM358
IC5 LM334Z
4049
4xBYW29
2xBUZ71
2xBC557
2xBC547
2x1N914
Q2 BD682
Q1 BC547
Q15 2N3055 (Q26)
Q17 MJ2955 (Q28)
Q14 BC639 (Q25)
Q16 BC640 (Q27)
Q13 BC547 (Q24)
Q12 BC557 (Q23)
Q9 BC557 (Q20)
Q8 (Q19)
Q7 (Q18)
Q10 (Q21)
Q11 (Q22)
L1 8.5uH
L2 9.5uH
L3 9.5uH
L4 (L5) 4.1uH
VR1 50k
VR2 5k
VR3 500Ω
VR4 500Ω (VR5)
15.5T
5.5T
15A
2A
ECB
K A
GDS
BC639 BC640
BC547 BC557



Above: close-up view of the inverter PCB. Do not touch the leads of the Mosfet transistors with your fingers (see text).

collector and emitter terminals are available on pins 11 to 14. In this circuit, the emitters are connected to ground while 10kΩ pullup resistors are connected to the collectors. The output transistors drive 4049 CMOS inverters (IC2 and IC3) which, in turn, drive the Mosfet switching transistors (Q3, Q4, Q5 and Q6).

Note that four of the gates in each IC package are paralleled in order to provide sufficient drive for the Mosfets. CMOS gates are well suited to driving Mosfet transistors. They are cheap and they include protection diodes which would otherwise have to be included separately.

The gates of the Mosfets are driven via 56Ω resistors to ensure that parallel Mosfets switch simultaneously. Diodes ZD1, ZD2, D4 and D5 protect the Mosfets from excessive drain-gate voltages.

The secondary of the transformer is connected to a conventional diode bridge (D6-D9) which produces positive and negative DC rails about the secondary centre tap. The centre tap is connected to ground to reference the supply rails to the vehicle chassis.

Note that the bridge diodes are BWY29 types. These are 7A ultra-fast recovery rectifiers. The diodes used in the prototype were rated for a maximum reverse voltage of 200V, although diodes with a 100V rating should be equally suitable.

The reverse recovery time of the diodes is important. At a switching frequency of 50kHz, the use of slow recovery diodes would result in large power losses. Let's look at this in a little more detail.

When a diode switches from the conducting state to the blocking state, its characteristic is not ideal. The current through the diode does not immediately change from the forward current to a value very close to zero. Instead, a large reverse current flows for a short time, until the diode recovers its steady state properties.

This time is called the reverse recovery time. If this time is a significant proportion of the off time of the diode, the losses will be quite high. The BYW29 diode has a reverse recovery time of 25ns, putting the forward conduction losses well above the reverse recovery losses.

Unfortunately, very fast recovery diodes contribute to the switching noise in the system by virtue of their "snapping" in and out of conduction. To combat this, 470pF capacitors have been connected across each diode. These have negligible effect on the efficiency of the rectifier but attenuate the switching noise considerably.

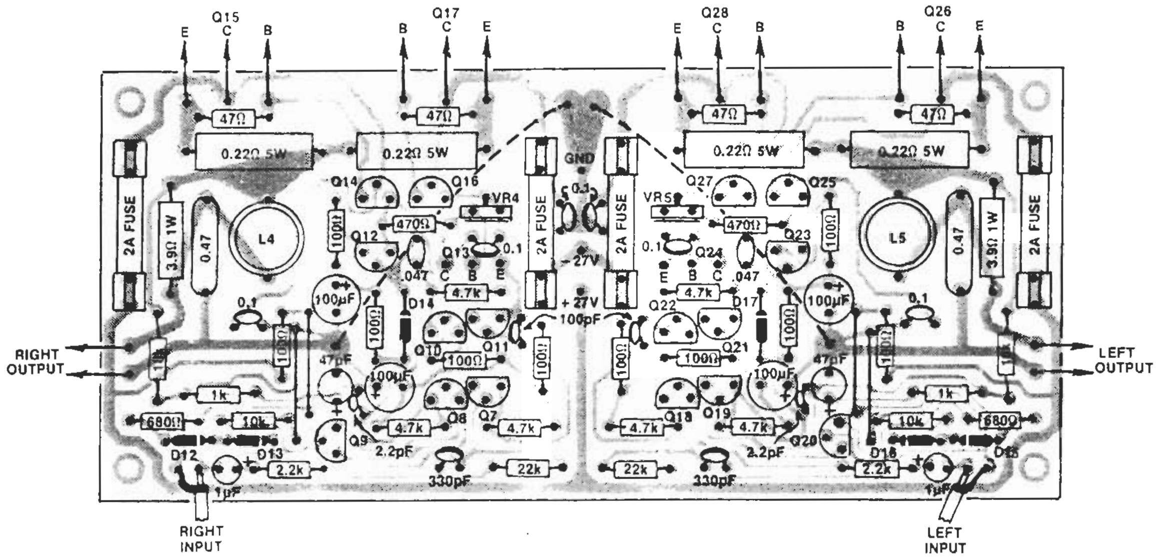
The rectified supply rails are filtered, first by a pair of 1000μF capacitors, and then by LC filters consisting of 9.5μH inductors (L2 and L3) and the 2200μF capacitors. The inductors are wound on Neosid iron powder cores, which are especially designed for RF interference suppression. The cores exhibit considerable losses at high frequencies and thus switching noise on the output is further attenuated.

As a further measure, .01μF ceramic capacitors are connected across the 2200μF electrolytic capacitors to improve the decoupling at high frequencies. Electrolytic capacitors are notoriously poor performers at high frequencies because of their high self inductance.

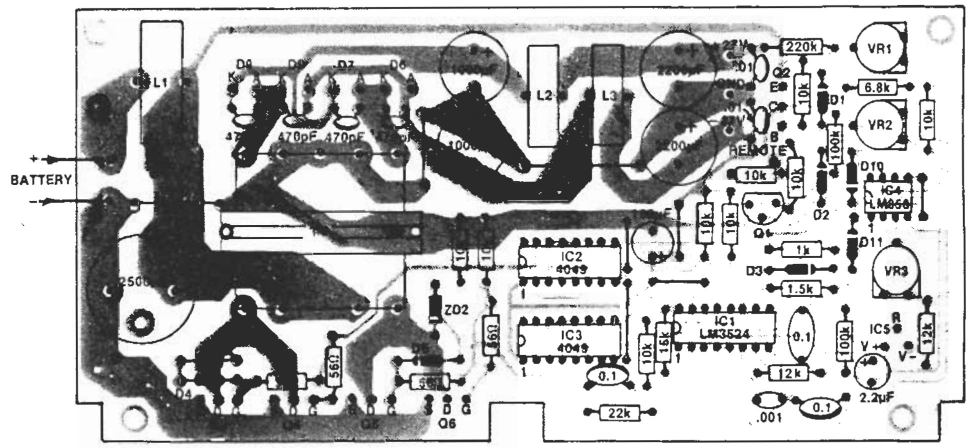
The only parts of the inverter yet to be described are the under-voltage and over-temperature cutout circuits. The under-voltage circuit is the simpler of the two. It is based on comparator IC4a, part of an LM3524 dual single supply op amp. The non-inverting input (pin 5) is connected to the 5V reference produced by IC1 while the inverting input (pin 6) is connected to the positive supply rail via an adjustable voltage divider.

If the voltage at the inverting input falls below the reference voltage on pin 6, the output of the comparator will go high and shut down the inverter. The divider has been designed so that the shut down voltage can be varied between 9.2V and 12.4V by trimpot VR2.

The over-temperature cutout is similarly based on comparator IC4b, which compares the reference voltage on pin 2 to the voltage applied to pin 3. In this case, the op amp is set up so that the inverter is switched off if the voltage



Parts layout for the amplifier PCB. Note that Q13 and Q24 are not mounted on the board.



Parts layout for the inverter PCB. The leads to the car battery must be capable of carrying at least 15A.

applied to the non-inverting input rises above the reference voltage.

The temperature sensing element is IC5 which is an LM334Z current source. This IC produces a current that is directly proportional to its absolute temperature. This current flows through the series 12kΩ resistor and the resultant voltage monitored by the comparator.

Trimpot VR3 allows the cutout temperature to be varied over a wide range. We set up the prototype to cut out when the case temperature of the switching transistors reached 95°C. Detailed instructions on setting this adjustment will be published in Part 2 next month.

Power amplifiers

The two power amplifiers are identical, so a description of the right channel only will be given.

The input signal is coupled into the first differential stage via a 1μF DC blocking capacitor and a 2.2kΩ "stopper" resistor. The 330pF capacitor shunts any RF present on the input to ground.

Transistor Q9 functions as a constant current tail for the input differential pair, Q7 and Q8. It supplies about 1mA to the differential pair, the current being shared equally between the two transistors.

The main advantage obtained by using a constant current source over a simple resistor is that of increased power supply rejection. This was of particular concern in the design of this amplifier because of the nature of the power supply. The effectiveness of the design is demonstrated by Fig. 1 which shows the level of switching noise present at the amplifier output.

The balanced outputs of the first stage are taken from the 4.7kΩ load resistors and fed to the inputs of a second differential stage. This stage, consisting of transistors Q10 and Q11, has a simple resistor "tail" and a current mirror load. The current mirror is formed by D14, Q12 and associated resistors.

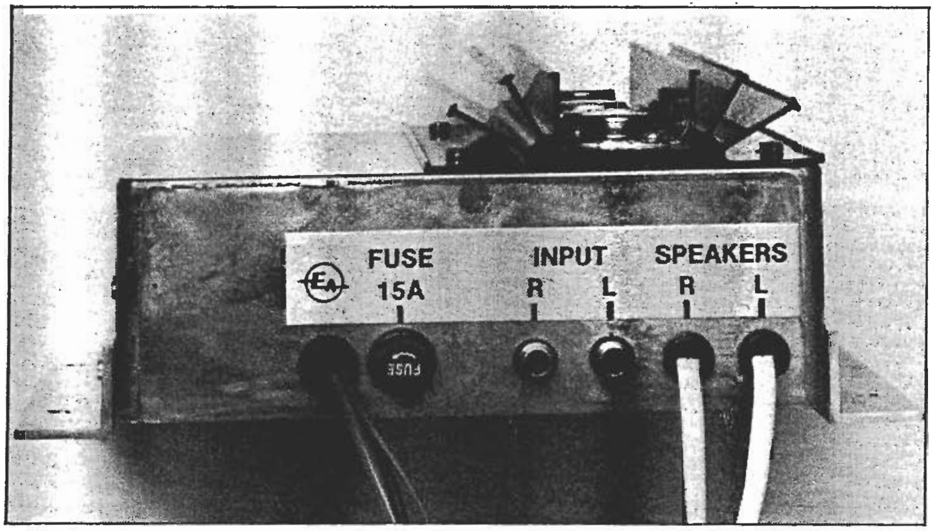
The current mirror has a very high dynamic resistance and ensures equal current through each side of the differential stage. The advantages of this configuration are high voltage gain, good linearity and wide voltage swing.

Q13 forms a Vbe multiplier or "amplified diode" which sets the bias conditions for the output transistors. This transistor is mounted on the external heatsink, next to the output transistors. This is done so that the bias automatically changes to compensate for temperature induced variations in the base-emitter voltages of the output transistors.

VR4 is included so that the bias can be adjusted to the optimum level. A 0.1μF ceramic capacitor is connected across the Vbe multiplier to ensure stability.

The output stage consists of Darlington transistor pairs Q14, Q15,

100W Car Stereo Amplifier



This view shows the input RCA sockets, speaker leads, fuseholder and power supply leads.

Q16 and Q17. These are wired as emitter follower stages and provide current gain only. The 0.22Ω emitter resistors prevent thermal runaway by reducing the drive to the transistors as the collector current increases.

As a further precaution, 2A fuses have been included between the collectors of the output transistors and the supply rails. These serve two purposes: (1) they protect the output devices against output short circuits; and (2) they protect the load if one of the output devices breaks down.

The voltage gain of the power amplifier is set to 18 by means of the 18kΩ and 1kΩ feedback resistors at the base of Q8. The 47μF capacitor sets the lower cutoff frequency of the amplifier to about 5Hz.

Double pole lag frequency compensation is applied by the 2.2pF and 100pF capacitors on Q8 and Q11 respectively. These render the amplifier stable with overall negative feedback applied. Power supply decoupling is provided by the 0.1μF ceramic capacitors, the 100Ω resistors and the 100μF capacitors.

A final refinement involves the RLC Zobel network in the output circuit. This network renders the amplifier unconditionally stable. Note that air cored inductors are specified here because of the distortion introduced by ferrite cored inductors.

Construction

The PA100 Car Stereo Amplifier is assembled on two printed circuit boards. One accommodates the DC-to-DC converter and the other the two power amplifiers. Each board is fitted into one half of the diecast case with an aluminium shield between them.

The shield is necessary to prevent high frequency radiation from the converter into the low level circuitry of the power amplifier stages.

The inverter board is coded 85cs8b and measures 175 x 84mm. Before commencing construction of this board three notches must be cut out of one edge. These are to clear the pillars inside the diecast box and are marked on the copper side of the board. Having done this, position the board inside the case and mark the mounting holes.

Begin assembly of the board by installing the seven wire links, followed by the resistors, capacitors and semiconductors. Note carefully the orientation of the polarity conscious components. The power Mosfets are quite sensitive to static electricity. Do not handle them with your fingers.

We found it best to carefully insert each one using a pair of pliers. Solder them in position so that about 1mm of lead protrudes through the copper side of the board. This puts them at about the right height to be screwed to the case for heatsinking.

The next step is to wind the toroidal inductors. Begin with L1. This is wound on the slightly smaller, fatter core. Take about 1.5m of 1.25mm enamelled copper wire and thread half of it through the core. Begin winding with one end, pulling the wire fairly tightly through the core. Stop when about half the core is covered.

This done, return to the other end of the wire and wind the other half of the core. Completely cover the core with windings, so that the two ends emerge from the core at the same point. The whole core should have about 27 turns on it. If there are a few more or less, don't worry; it will make little difference to the operation of the circuit.

Trim the leads to about 10mm, clean away the enamel and insert the coil in the appropriate spot on the board. Push it down firmly onto the board before soldering.

Follow the same procedure with the other two inductors (L2 and L3), this time using 1mm wire and the larger cores. Each coil requires about 2m of wire and should have about 37 turns.

Now for the transformer. The primary is wound first using four lengths of 1.25mm enamelled copper wire. Cut each piece to about 350mm and begin at the 4-pin side of the coil, as shown in the accompanying diagram (Fig.2). Wind on five and a half turns, finishing on the same side of the coil. Cover the winding with a layer or two of masking tape to hold it in place.

Strip the enamel off all eight wires and terminate the starts as shown. This done, use your multimeter to determine the finish of each winding and terminate these also. Finally, check that there are no short circuits between the two half primary windings.

The secondary is wound using two lengths of 1.25mm enamelled copper wire. This winding begins and ends on the opposite side to the primary and consists of 15½ turns. Cover this winding with a layer or two of tape also.

Strip and tin the ends of this winding as before and terminate the starts as shown in the diagram. Once again, use your multimeter to determine the finish of each winding and terminate these as well. Give all the windings a final check and the transformer is ready to assemble.

The photographs show how the transformer is mounted. Do not overtighten the nuts underneath the board or you may crack the ferrite cores. Solder the transformer pins to the copper track after the nuts have been tightened.

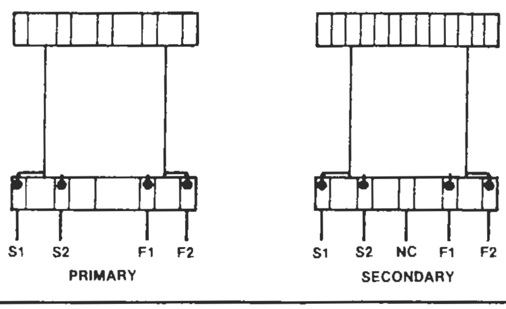


Fig. 2: this diagram shows how the leads for the inverter transformer are terminated. Do not confuse the start (S) and finish (F) ends of the windings otherwise the inverter will not work.

PARTS LIST FOR CAR STEREO AMPLIFIER

1 diecast aluminium case, 185 x 185 x 65mm
1 heatsink, extruded fin, 185mm long x 75mm wide
2 aluminium brackets, 25 x 25 x 180mm
1 piece of aluminium sheet, 170 x 70mm, 1mm thick
1 Scotchcal label, 185 x 80mm
1 printed circuit board, code 85cs8a, 178 x 79mm
1 printed circuit board, code 85cs8b, 176 x 84mm
2 Neosid 17-137-10 iron powder ring cores
1 Neosid 17-131-10 iron powder ring core
2 Siemens ferrite cores, B66339-G-X127 (100121)
1 Siemens former, B66274-B1011-T1 (100260)
1 Siemens mounting kit, B66274-B2002-X (100311)
8 PC-mounting fuse clips
1 panel mounting fuseholder
4 2A fuses
1 15A fuse
2 panel mounting RCA sockets
3 rubber grommets
3 cable clamp grommets
1 solder lug
4 TO-220 mica washers
4 TO-3 mica washers
12 insulating bushes
23 PC stakes
4 35mm x 4BA countersunk screws
4 15mm x 4BA countersunk screws
4 10mm x 4BA roundhead screws
4 6mm x 4BA roundhead screws
4 10mm x 6BA roundhead screws
24 4BA nuts
4 6BA nuts
20 shakeproof washers
4 25mm spacers

Semiconductors
1 LM3524 PWM regulator IC
2 4049 hex CMOS inverter ICs
1 LM358 dual op amp
1 LM334Z temperature dependent current source
2 2N3055 NPN power transistors
2 MJ2955 PNP power transistors
8 BC557 PNP transistors
7 BC547 NPN transistors
1 BD682 Darlington transistor
2 BC639 NPN transistors
2 BC640 PNP transistors
4 BUZ71 Sipmos power FETs
4 BYW29 100V ultra fast rectifier diodes
13 1N914 diodes
2 30V 400mW zener diodes

Capacitors
1 2500µF 35VW PC electrolytic, RP type
2 2200µF 35VW PC electrolytic
2 1000µF 35VW PC electrolytic
5 100µF 35VW PC electrolytic
2 47µF 25VW PC electrolytic
1 2.2µF 25VW PC electrolytic
2 1µF 25VW PC electrolytic
2 0.47µF 100V polyester
1 0.1µF 100V polyester
8 0.1µF 50V ceramic
2 .01µF 50V ceramic
1 .001µF 100V polyester
4 470pF ceramic
2 330pF ceramic
2 100pF ceramic
2 2.2pF ceramic

Resistors (5%, 0.25W unless stated)
1 x 220kΩ, 2 x 100kΩ, 3 x 22kΩ, 2 x 18kΩ, 1 x 15kΩ, 2 x 12kΩ, 10 x 10kΩ, 1 x 6.8kΩ, 6 x 4.7kΩ, 2 x 2.2kΩ, 1 x 1.5kΩ, 3 x 1kΩ, 2 x 680Ω, 2 x 470Ω, 12 x 190Ω, 4 x 56Ω, 4 x 47Ω, 2 x 3.9Ω 1W, 4 x 0.22Ω 5W

Trimpots
1 50kΩ horizontal cermet
1 5kΩ horizontal cermet
1 500Ω horizontal cermet
2 500Ω vertical cermet

Wire and cable
7m 1.25mm enamelled copper wire
4m 1.00mm enamelled copper wire
4m 240VAC figure-8 cable (for speaker leads)
6m 15A figure-8 cable (for power supply leads)
400mm shielded cable
1m light-duty hookup wire
6m medium-duty hookup wire

Miscellaneous
Machine screws and nuts, shakeproof washers, silastic, heatsink compound, scrap aluminium.

Finally, a number of flying leads can be soldered to the inverter board. First, solder three 100mm lengths of thin hookup wire for the temperature sensor. This done, suitable lengths of medium-duty hookup wire can be installed for the supply lead connections and for the control leads. The supply leads should be about 200mm long while the length of the control lead will depend on just where you intend to mount the amplifier.

The leads to the car battery must be capable of handling at least 15A on a continuous basis. Use the thickest wire you can lay your hands on (within reason). The negative lead must be made quite long while the positive lead can be trimmed to a length of 50mm. This wire only has to connect to the fuse holder.

Amplifier board

The amplifier board is coded 85cs8a and measures 177 x 79mm. This board mounts in the other half of the case and should be used as a template to mark the mounting holes as before.

PC pins are used to terminate for all external connections to this board and these should be installed first. The fuse clips should likewise be installed at this early stage.

This done, the remaining parts (except for Q13 and Q24) can be installed according to the layout diagram. Note that there are four wire links on this board. The two 4.1µH inductors have to be wound by hand. This is not a difficult process although it does require some care.

The first step is to locate a suitable former. This needs to be a cylindrical object with a diameter of about 11mm. A drill bit or a piece of dowel rod could be used (we actually used a marker pen). The coils are wound using 1.25mm enamelled copper wire and a 1m length should be more than sufficient for both coils.

Begin by taping about 40mm of one end of the wire along the former, then wind on 13 turns. Each turn should touch the previous one. After the requisite number of turns has been made, cover the whole winding with a layer of ordinary adhesive tape to prevent the coil unwinding.

Now wind another 12 turns over the top of the previous winding, heading back towards the start. Stop on the opposite side of the former from the start (effectively wind another half turn) and secure the whole coil with a couple of layers of tape. The coil can now be removed from the former.

Finally, clean the ends of the leads and mount the coil on the PCB. Repeat this process for the other coil.

That's all for now. Next month, we shall give the final assembly details and describe the setting up and installation procedures.