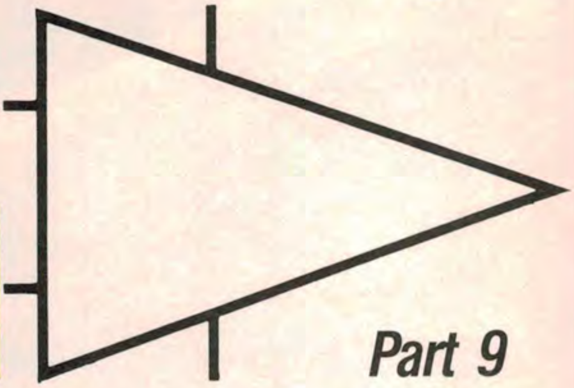
by BRYAN MAHER

OP AMPS Explained



Part 9

High voltage operational amplifiers may be built to any specification by combining ICs with transformers and transistors. Here we consider a number of practical circuits.

Most op amp applications generally familiar to us involve low-voltage signals, generally in the range 1mV to 10V. Stages which simply tailor or manipulate signals — for example volume controls, tone controls, and addition or integration sections — have the simple requirement that their output signal voltage be suitable as an input for the following stage; not too small and not too large. This requirement is generally easy to meet.

However, when we come to the final stage, which drives some external load, the situation is usually quite different. Our amplifier must provide an output signal voltage level which suits the requirements of the load — no matter what those requirements may be. So while we can choose the signal voltage level for the intermediate stages of our circuit, we do not have much say at all about the output signal voltage level.

Signal level choices

Being astute humans, we generally choose a nice easy signal level of about 1V for all intermediate stages. This allows us to simply rush to our nearest electronic supply counter and purchase economical integrated circuits, resistors and other electrotechnical paraphernalia, race home, construct something and have it working in short time. As we only want a signal level of about 1V, we can use nice low voltage power supplies, say ±9V, or ±12V, or even ±15V.

A slightly more subtle point may have escaped us: with very little effort on our part, the circuit will also probably achieve such desired properties as low noise, low drift, compact size and low cost. Before we take such widely-valued achievements for granted, let us acknowledge the fact that all these highly-prized attributes stem, in part, from the fact that the signal and power supply voltages are low.

Let's now face up to the output stage requirements. Notice we said *requirements*, not *choice*. It is the *load to be driven* (whatever that may be) that actually *demands* the voltage level here.

For example, to play records in the lounge room, a common 8Ω speaker at 1W power level must be driven by a signal level of 8V peak-to-peak. We have no choice if 1W is wanted and the speaker is 8Ω.

For 10 watts and the same speaker, 26V peak-to-peak is demanded and for 200 watts, 114V peak-to-peak. Obviously the amplifier output stage is also required to provide the appropriate current, which will be fairly high.

High voltages

We'll leave our discussion of high-current power amplifiers until the next chapter. For the time being, let's consider high voltage amplifiers for loads which, because of their high impedance, require very little current. There are more loads of this type around that may be at first thought. Domestic examples include electrostatic loudspeakers and the TV picture tube grid.

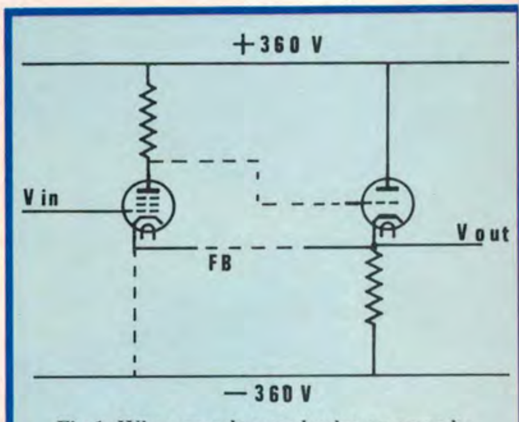


Fig 1: When grandpa used valve op amps he had no trouble producing outputs of ±100 volts or more. The dotted lines represent circuit details not shown.

DANGER NOTICE
VOLTAGES USED IN THESE AMPLIFIERS AND POWER SUPPLIES ARE HIGHLY DANGEROUS.

Away from home we may meet such loads in radar tube applications; cathode ray oscilloscope blanking, Z modulation and deflection circuits; piezo-electric transducers; current sources; detonator firing systems; long signal cables; silicon controlled rectifier (SCR) firing circuits; electrophoresis, and more. In such sciences as neuropharmacology and biology we may meet microiontophoresis. Here the art of passing charged ions of exotic organic compounds through small-diameter, high-resistance microelectrodes demands a drive signal of a hundred or more volts.

Valves

In earlier years, when valves were used, high voltage signal requirements posed no problem. Electron tubes or valves were, by their very nature, high voltage devices. In fact, it was very difficult to manufacture a valve which was happy with low voltages. Mostly they operated from 150 to 300V supplies.

Some readers may be a little shocked at the idea that operational amplifiers could be anything else but integrated

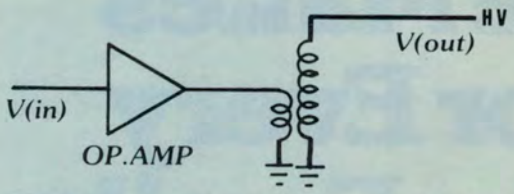


Fig 2: Using a small power op amp we can drive a transformer primary. If the secondary has a large number of turns a high output voltage will be produced. Problems will arise because the large back voltages generated by the transformer may damage the output stage of the amplifier.

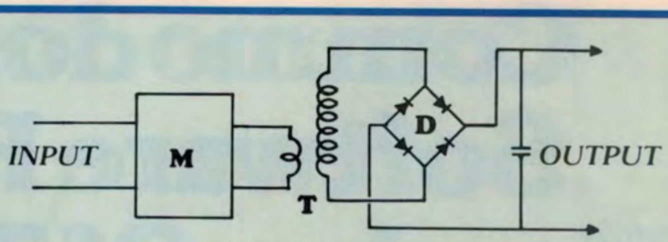


Fig 3: This is the circuit of a DC transformer. The input is either DC or long positive rectangular pulses. M is a feedback modulated RF oscillator, and T is an air cored RF transformer which produes a high voltage output. The output is rectified by the diode bridge D, which produces isolated DC or long positive pulses.

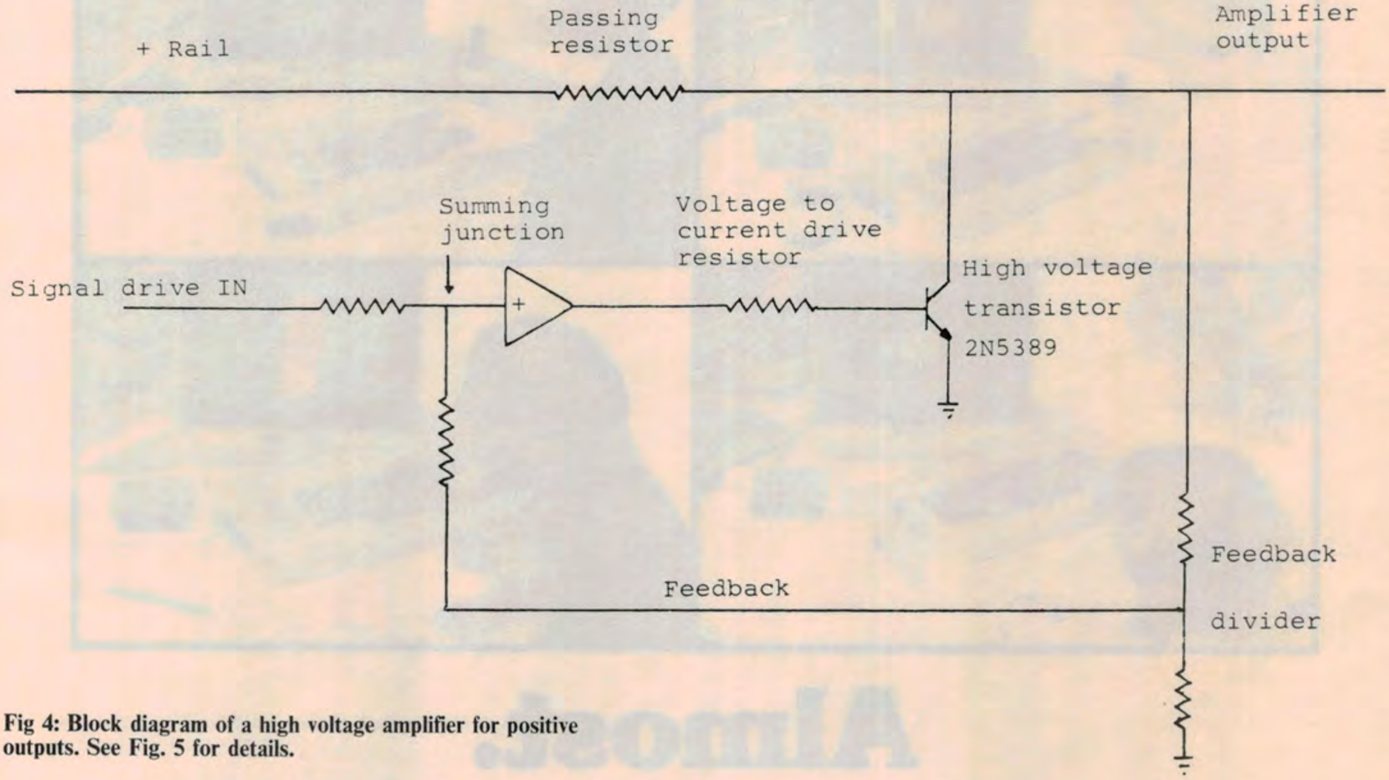


Fig 4: Block diagram of a high voltage amplifier for positive outputs. See Fig. 5 for details.

solid state circuits! Sorry to disillusion you, but operational amplifiers were first invented using valve technology (eg, the Tektronix Operational Amplifier Type O).

Consider Fig. 1. This shows a once popular valve operational amplifier circuit, wherein the provision of a 100V swing at the output was no trouble at all. Now that all valves (except large transmitting types) have been cast out in disdain, what shall we do for those occasional applications where the load demands a high-voltage, low-current drive?

FETS and transformers

If we had field effect transistors (FETs) of sufficiently high voltage rating, we could implement Fig. 1 by directly substituting FETs for valves. If we did we would be giving credence to the saying of a wise circuit designer: "It is only circuit ideas that really matter — the technology used is a mere detail". But such FETs are rarely available, so we probably would not take that step.

Fig. 2 shows a way out if the signals are nice and "rounded", like sine waves. An ordinary step-up transformer driven by a low voltage solid state amplifier could provide high voltage output signals. Four points would need due attention if we used such a design.

(1). Even though the load is high impedance, the amplifier still needs to be a high-power type because of transformer magnetising current requirements.

(2). Strict precautions against repetitive or occasional high-voltage spikes caused by the inductive nature of the transformer are mandatory. Recall that an inductor produces a voltage that is proportional to the rate of change of current. Such spikes are notorious for their ability to damage transistors and integrated circuits. Just because you vow to always use signals with slow rise times does not preclude spikes caused by sudden changes. Remember that switching a circuit on or off can also generate voltage spikes.

(3). The foregoing and the limited frequency response of most transformers makes the reproduction of fast rise square pulses difficult.

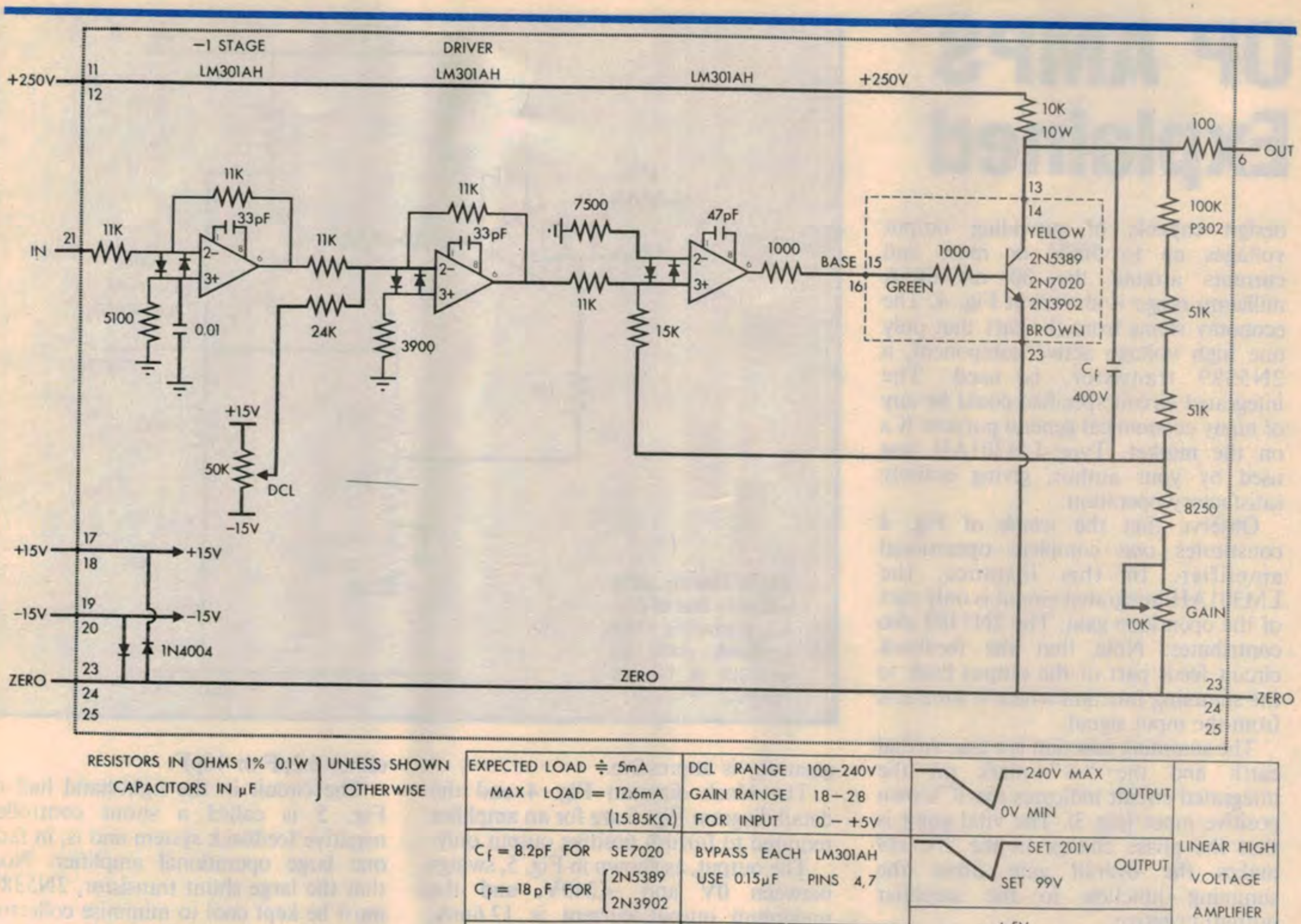


Fig. 5: Detailed circuit diagram of a positive, linear, high voltage amplifier. See also block diagram, Fig. 4.

OP AMPS Explained

(4). Low frequency square waves pose a different problem due to insufficient inductance in the transformer. The limiting case, DC, is of course utterly impossible. On low frequency signals, transformer coupling results in voltage depression below the baseline. This means that, as with coupling capacitors, the output is forced to assume equal positive and negative areas under the waveform (see Part 4, June 1984).

Despite its difficulties, the transformer-coupled scheme does have some uses. Two favourite applications are 600Ω audio lines, as in multiple public address loudspeaker systems, and SCR gate triggering circuits. Both instances, though very different, may need signals measured in hundreds of volts. Note one automatic (and desirable) property of transformer coupling: circuit isolation.

DC transformers

When low frequency square waves are required or where isolation is also a requirement, the scheme shown in Fig. 3 is occasionally used wherein the signal is used to modulate a high frequency carrier. The system shown here provides a simple method of coupling long, strictly positive, pulses. More complex arrangements are needed if a double-sided (bipolar) output is wanted. Fig. 3 is sometimes called an FM transformer or, alternatively, a DC transformer.

As long as circuit isolation is not a requirement, wouldn't it be nice to have a simple operational amplifier capable of directly providing the required high voltage output. Then the waveform could be any shape, slow or fast, or even DC. Of course such amplifiers would have to operate from high voltage rails.

High-voltage op amps

There are only a few high-voltage op amps on the market and, of these, only a couple are capable of working from rails of 100V or more. Because such voltages mean that a fair amount of power has to be dissipated, it is difficult to integrate the circuit onto one chip.

For this reason, some manufacturers prefer high-voltage op amp modules made up from discrete transistors. The parts are usually mounted on a small PC board and then encapsulated in an epoxy resin compound to ensure good thermal coupling. These modules are generally fairly expensive.

Other manufacturers produce integrated amplifiers with voltage ratings up to ±40V, such as the Harris type HA2640/2645 and the Motorola type MC1536. These are capable of giving up to 70V output voltage swings, meaning that the HA2640 output can swing anywhere from −35V to +35V. Load currents up to 15 milliamps and open loop gains up to 500,000 are part of their specifications.

The final approach is to build our own operational amplifier. This particularly applies if we require an output voltage swing greater than 100V.

A basic idea for a simple, low-cost

OP AMPS Explained

design capable of providing output voltages up to 500V or more and currents around the 30 or 40mA milliamp range is shown in Fig. 4. The economy stems from the fact that only one high voltage active component, a 2N5389 transistor, is used. The integrated circuit specified could be any of many economical general purpose ICs on the market. Type LM301AH was used by your author, giving entirely satisfactory operation.

Observe that the *whole* of Fig. 4 constitutes *one* complete operational amplifier. In this instance, the LM301AH integrated circuit is only part of the open loop gain. The 2N5389 also contributes. Note that the feedback circuit feeds part of the output back to the summing junction where it subtracts from the input signal.

The summing junction is a true virtual earth and the "+" mark on the integrated circuit indicates the IC's own positive input (pin 3). The vital point is that the phase change in the 2N5389 makes the overall gain (from the summing junction to the amplifier output) negative.

This is a good example of the drum your beloved author is fond of beating — that an integrated circuit of itself is not an operational amplifier!! Only a complete circuit with negative open loop gain and a closed negative feedback loop constitutes an op amp. With such high open loop gain [A_o = (gain of LM301)×(gain of 2N5389)], the circuit accuracy is impressive.

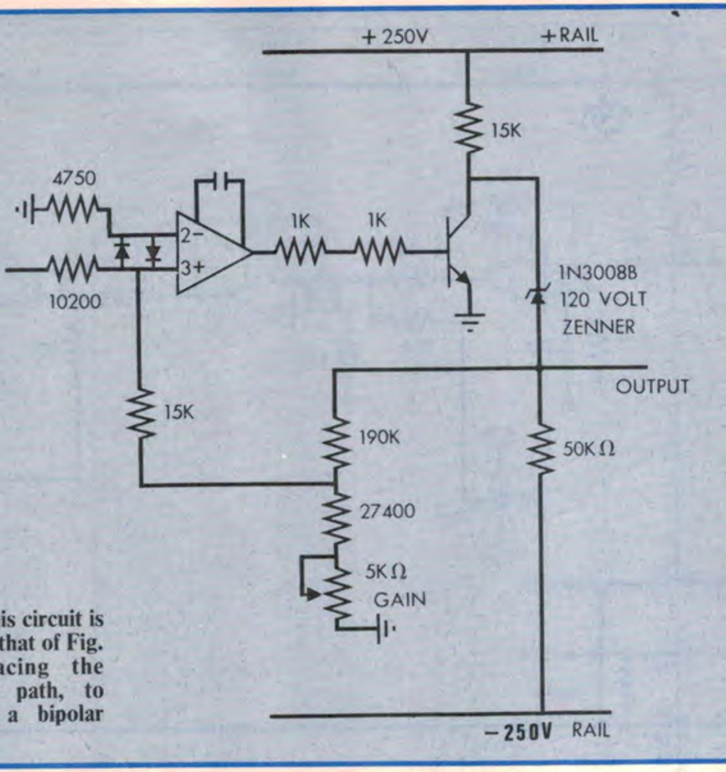


Fig 6: This circuit is added to that of Fig. 5, replacing the feedback path, to produce a bipolar output.

The block diagram Fig. 4 and the detail diagram Fig. 5 are for an amplifier required to furnish positive output only.

The output, as shown in Fig. 5, swings between 0V and +240V, and the maximum output current is 12.6mA. Negative feedback is provided by the four resistors and the potentiometer from the output to zero, together with the 15kΩ resistor between the virtual earth (pin 3) of the right hand LM301AH. Feedback capacitor C_f is chosen for the particular transistor type used, (any one of the 2N5389, 2N3902 or SE7020). As shown in Fig. 5, C_f is either 8.2pF or 18pF.

The circuit in the right-hand half of Fig. 5 is called a shunt controlled negative feedback system and is, in fact, one large operational amplifier. Note that the large shunt transistor, 2N5389, must be kept cool to minimise collector-base leakage, i_{CBO}, while working in linear mode on such high voltages. It should therefore be mounted on a large, finned heatsink.

The feed resistor to the transistor base consists of two 1000Ω units in series, one of which is mounted directly at the transistor base to suppress parasitic-oscillation. This resistor must not be

OP AMPS Explained

wire-wound; ie it must not be inductive.

The preceding stages consist of two LM301AH units, each acting as independent unity gain op amps. The one marked "driver" sets the DC level of the output and, as readers will see, is actually a "level shifter" or "voltage-adder-translator stage" (big name for a small stage, eh?). The chosen DC level is set by the potentiometer marked DCL, and shifts up to 242V are possible.

The first stage, on the extreme left, simply provides phase-reversal. Note that all LM301AH integrated circuits should operate from well-regulated ± 15 volt supplies, bypassed at each IC using $0.15\mu F$ ceramic capacitors. The high voltage supply to the output transistor stage is +250V.

The overall gain is set by the 10kΩ potentiometer marked "gain" in the feedback chain, and may be set to any value in the range 18 to 28. This range could be extended by changing resistor values, but such a step would require a different C value and would modify the system bandwidth and perhaps drift rate.

The complete amplifier has a bandwidth from DC to 20kHz and rise and fall times of less than $22\mu s$. The amplifier is linear to at least 0.1%, while the measured drift rate is less than 2mV per day (at a constant room temperature).

Spin-offs

Another amplifier was constructed whose circuit is the "mirror image" of Fig. 5; that is, a PNP power transistor was substituted in the output stage and a −250V high voltage supply was used. Changes to the DCL potentiometer circuit were only minor. The characteristics of this amplier are similar to the previous version except that the output now swings between 0V and −240V.

A third amplifier was implemented for output signals swinging both positive and negative, the high voltage supply being ±250V. This is easily achieved by the "add-on" shown in Fig. 6. The circuit has low drift and features a measured bandwidth of DC to 24kHz.

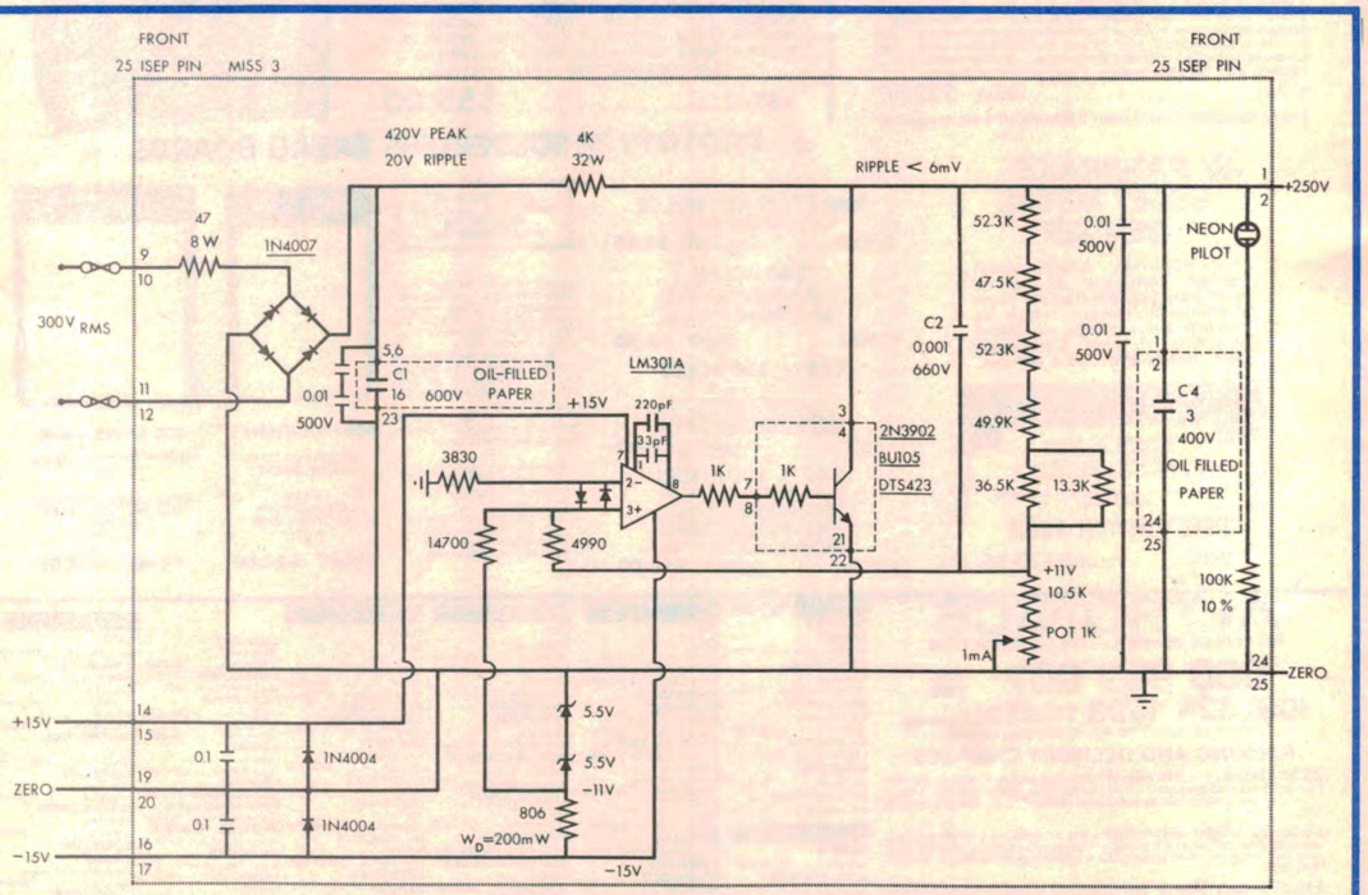
But, gentle reader, that's not the end of the possible evolution of "spin-offs" from Fig. 5. Yet another amplifier was built to supply an output signal swinging between +1V and +400V, from a high voltage supply of +430V. To achieve this, several resistor values were changed, giving gain of up to 41 and a measured bandwidth from DC to 14kHz.

Power supplies

By now, you are probably blinking your eyes and wondering just where your so-and-so author got all those high-voltage regulated power supplies. Do not fret, it is not that difficult really. Look closely again at Fig. 5. If the input is held constant, then the output will also remain constant, ie, the circuit will behave as a regulated, high-voltage DC supply. Fig. 7 shows a practical regulator circuit.

Fed from a 300V RMS winding on a mains transformer, the diode bridge rectifier provides an unregulated, filtered

Continued on page 122



RESISTORS IN OHMS 1% 0.1W } UNLESS SHOWN
CAPACITORS IN μF } OTHERWISE

Z_0	BU105	MAX LOAD	+ 250 VOLT
< 0.1Ω	$I_b = 1.5mA$ for $I_c = 10mA$	30mA	REGULATOR

Fig 7: Here is the circuit diagram of a 250 volt, 30 miliamp, linear regulated voltage supply.

Op amps explained

... ctd from p90

400V DC supply. The rest of the circuit acts as one big operational amplifier with a constant −11V input to pin 3 of the LM301A provided by two 5.5V zener diodes in series. Pin 3 is the virtual earth point and the circuit description is similar to that of Fig. 5 except that the output voltage is higher at +250V DC constant. The capacitors used are hermetically-sealed, steel can, oil-filled paper dielectrics of 600 or 400V rating. These are much more reliable than electrolytics at high voltages.

The 1kΩ gain potentiometer provides fine adjustment of the output voltage. With the values shown, adjustment between +246V and +253V DC is possible.

This +250V supply is capable of load currents up to 30mA. Its output drifts only 18mV per day at constant room temperature and load, the measured output resistance is 60mΩ, and the output ripple is 6mV. It makes a very satisfactory voltage regulator and is eminently suitable for driving our high voltage amplifiers. A mirror image version was also built to provide a −250V supply, while a third version using different component values was constructed to supply +400V DC.

That's it for now. Next month we will consider audio amplifier circuits.