

The diagram shows an operational amplifier (op-amp) configured as a current source. The non-inverting input (+) is connected to a voltage divider consisting of resistors Z_1 and Z_2 . The inverting input (-) is connected to the emitter of transistor T_{r1} . The op-amp's output is connected to the collector of T_{r1} and through resistor Z_3 to the common ground. Transistor T_{r2} has its base connected to the emitter of T_{r1} and its collector connected to the common ground. A load resistor Z_4 is connected between the collector of T_{r1} and the common ground. The current through Z_4 is labeled I_4 . The total current through the load is the sum of the op-amp output current I_3 and the current I_4 . The input voltage V_{in} is applied across the series combination of Z_1 and Z_2 . The voltage across Z_2 is $(V_{in} - I_4 Z_4) \frac{Z_2}{Z_1}$. The current I_3 is given by the equation:
$$I_3 = (V_{in} - I_4 Z_4) \frac{Z_2}{Z_1 Z_3} + \frac{V_{in}}{Z_3}$$
 The current in the load is:
$$\text{current in load} = I_3 + I_4 = \frac{V_{in}}{Z_3} + (V_{in} - I_4 Z_4) \frac{Z_2}{Z_1 Z_3} + I_4$$

It will help in visualising the operation if the impedances are assumed to be resistors of values $Z_1 = 1\text{ k}\Omega$; $Z_2 = 100\text{ k}\Omega$; $Z_3 = 100\text{ }\Omega$; and $Z_4 = 1\text{ }\Omega$. In the interest of simplicity we have assumed Z_4 to be negligibly small compared to Z_1 , and for the time being we will assume that the voltage output of amplifier A is completely defined by the external impedances.

With Tr_1 and Tr_2 turned off, amplifier A will deliver current to the load via Z_3 . The current with the values suggested will be 1.01 amps/volt because the second term in the brackets is zero (no I_4 current from the dumpers). When half a volt or thereabouts appears across Z_3 , one or other of the dumpers Tr_1 or Tr_2 will begin to turn on and pass some current I_4 into the load. We have selected resistor values such that $Z_4 Z_2 / Z_1 Z_3$ is unity so that the second term in the expression for the I_3 current is exactly equal and opposite to I_4 (this second term is the feed-forward error correction component). Currents I_3 and I_4 add in the load so that no matter what the magnitude of I_4 , the overall mutual conductance remains constant. We can

Two further changes are desirable. A practical amplifier is required to have an internal impedance small compared to the load at audio frequencies and stability requires that the internal loop gain falls with frequency. Both these conditions are met by the use of an inductor for Z_4 , a capacitor for Z_2 and resistors for Z_1 and Z_3 . The requirement for zero distortion from the dumpers is that $Z_4 Z_2 / Z_1 Z_3$ is unity at all frequencies of interest. This is achieved if $L = RRC$. Fig. 2 shows the circuit with the modifications carried out. (In order to keep the system operating at all frequencies it is necessary for a resistor in series with the inductor to have a conjugate match with a parallel resistor across the capacitor. This has been omitted for simplicity.)

Fig. 2 begins to look very familiar, in fact just like a conventional amplifier with the biasing removed and a small inductor added. Is this really all that is necessary to produce the perfect amplifier? The answer, of course, is no, not quite; the circuit is over-simplified. We have pushed all the problems back

into the class A stage and whilst the distortion would indeed be zero if the class A stage were perfect, this cannot be completely so in practice. We assumed in our analysis that amplifier A was completely controlled by the external impedances, that it had a perfect virtual earth at its input which implied perfect regulation at its output. The effect of departure from this ideal can be assessed by calculation from a deliberate unbalance of the four component bridge, whether this is due to tolerances of any of the components or to inadequate 'stiffness' at the output of amplifier A. With the values shown in Fig. 2, a 5% error in any component value will produce maximum intermodulation products of around $5\text{ }\mu\text{V}$ at 1 kHz ; maximum possible i.m. of 0.01%, the maximum absolute level of these components being some 140dB below full power. Although frequency dependent, it is clear that balance is by no means critical and standard tolerance fixed components can be used without adjusting facilities.

We have said that the dumpers have

say that any distortion in Tr_1 and Tr_2 produces perturbations in the current I_4 and since this causes the exactly equal and opposite perturbations in I_3 , no distortion appears in the load.

Tr_1 and Tr_2 have only one function to perform and that is to dump current into the load sufficiently accurately and sufficiently fast to come to the rescue of the class A amplifier and prevent it from overloading. If this is achieved then the class A amplifier, although it may have considerable gymnastics to perform, will be in complete control of the load current at all times.

Fig. 1 does not look like a practical hi-fi amplifier since its output is constant current and the input is floating relative to the power supply. Nevertheless it is obvious that if the input is returned to the other end of the load all the unique properties of Fig. 1 will still apply though perhaps a little less simple to visualise. This done, we have an amplifier whose output source impedance is Z_4 and Z_3 in parallel.

Fig. 2. Basic diagram of principal elements.

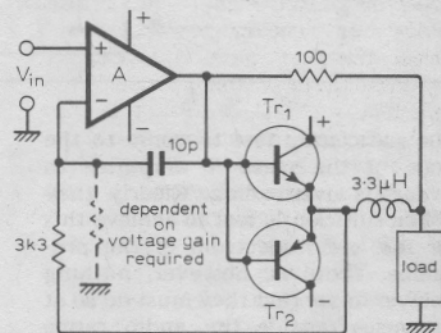
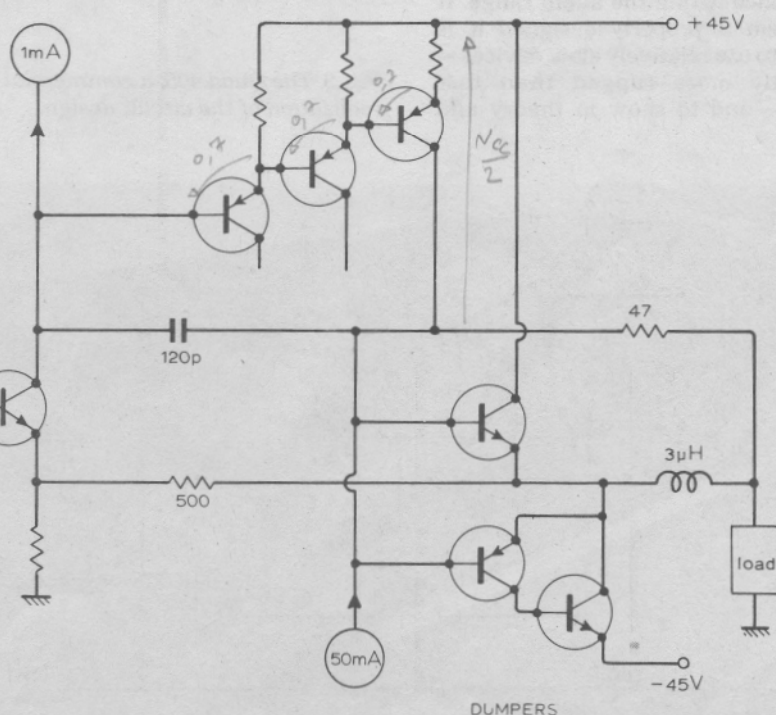
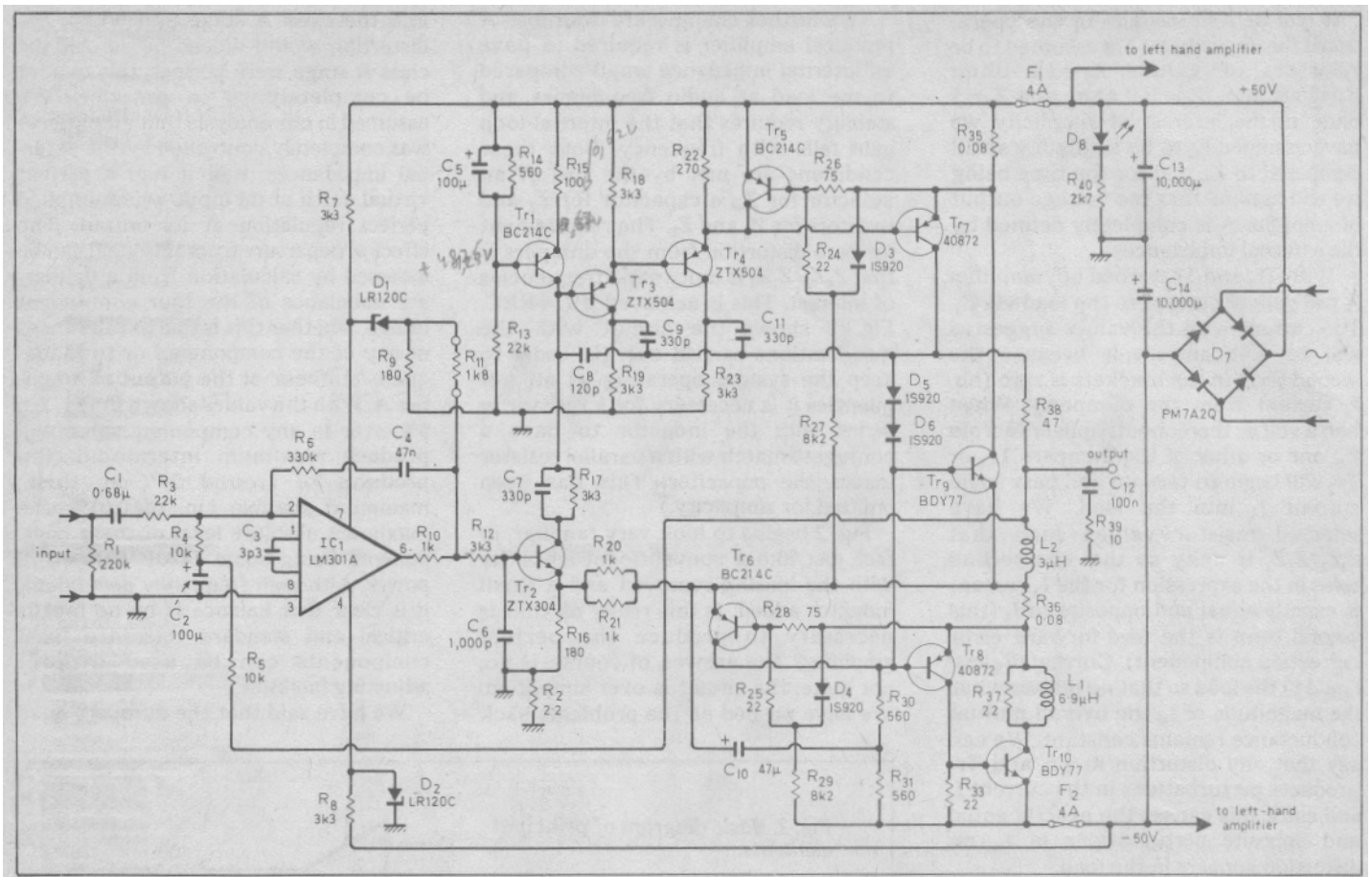


Fig. 3. Simplified diagram showing Class A stage, current dumpers and bridge components.

CLASS A OUTPUT





to be sufficiently fast to come to the rescue of the class A amplifier to prevent its overloading. Clearly they must be sufficiently fast to achieve this over the audio spectrum of the programme. There is, however, nothing whatever to say that they must do so at frequencies outside the audio range provided that steps are taken in the design of the whole amplifier to ensure that any such frequencies that may be present do not embarrass the amplifier performance within the audio range. If the system is properly designed it is possible to use relatively slow devices inherently more rugged than fast devices - and to show in theory and

Fig. 4. Full circuit diagram. Resistor R_2 is a protective connection *provided* to ensure earth continuity in the event that Tr_2 and its associated component panel are disconnected from the common earth chassis.

Fig. 5. The Quad 405, a commercial realization of the circuit design.

practice that they will never fail to come to the rescue of the low powered amplifier to any programme. If, however, the criteria are thought to be response to step functions, square waves and other factors not relevant to programme, then of course faster dumpers must be used commensurate with the rise times involved.

Fig. 4 shows a commercial amplifier circuit (the Quad 405) developed along these lines, Fig. 3 being a simplified diagram to indicate the relevant areas. The class A amplifier serves also as the driver for the top dumper. To counter this extra burden, the class A amplifier is a triple to give a very effective virtual earth. The mid frequency distortion of this amplifier measures about 0.005%, a region where slight component nonlinearities etc. tend to deprive such measurements of any true meaning.

An extremely attractive feature of the technique is the complete absence of adjustments or alignment requirements and no thermal problems. Nothing to set up in manufacture and nothing to go out of adjustment during life. One may expect that after several years there will be far less variation, set to set, than is presently realised with most conventional circuits.

References

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