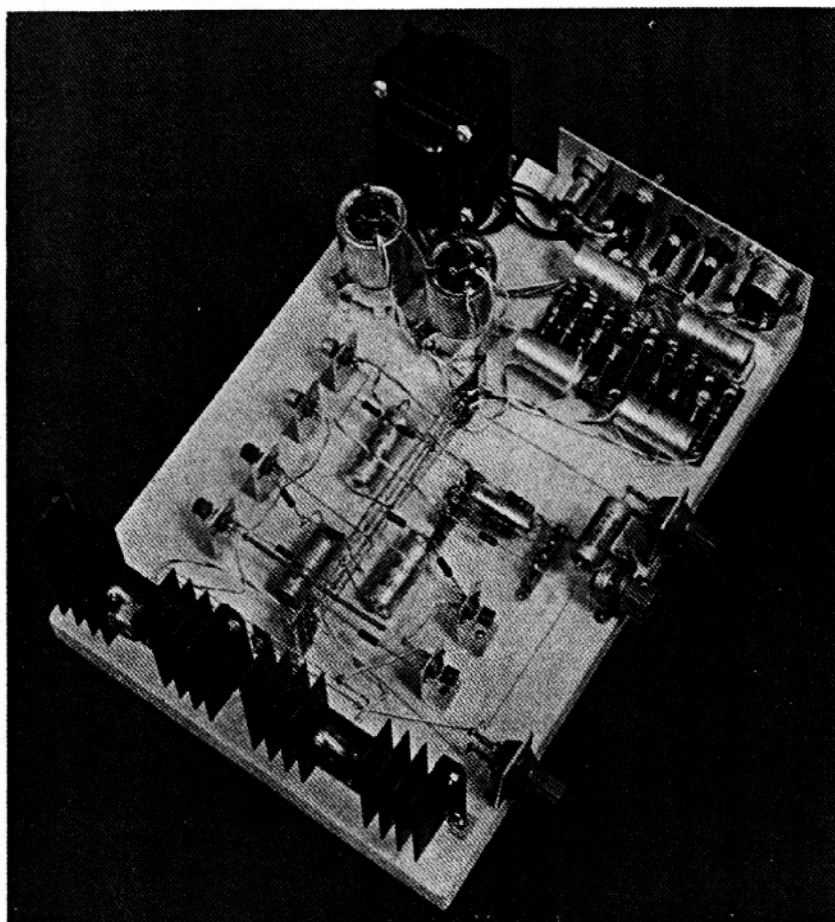


High-Impedance Drive for the Elimination of Crossover Distortion*

J. J. FARAN, JR.[†], SENIOR MEMBER, IRE, AND R. G. FULKS[†], MEMBER, IRE



Breadboard of a 20-watt class B power amplifier making use of complementary symmetry.

Summary—Crossover distortion in a class B transistor power amplifier can be greatly reduced by driving the output stage from a high-impedance source. Doing this capitalizes upon the fact that the current-to-current gain characteristic of a class B stage is much more linear in the crossover region than the voltage-to-current gain. High-impedance drive can be most easily applied to a complementary output stage, but can also be applied to two transistors of the same polarity if a driver transformer is used. In circuits of this type, no temperature-compensated bias arrangements are necessary, and “thermal runaway” is virtually impossible, as only one of the output transistors can be biased on at a time. Moreover, reverse bias is applied to the “off” transistor, reducing its turn-off time and minimizing the increase in power supply drain at high signal frequencies. Amplifiers designed according to this principle have operated with very low distortion and have exhibited unequalled thermal stability.

INTRODUCTION

IN A push-pull class B amplifier, one output transistor ideally conducts current only when the input signal is positive and the other conducts only when the input signal is negative. Class B amplifiers operate with significantly greater power efficiency than class A amplifiers. The class B amplifier, furthermore, has negligible power consumption when there is no input signal. For these reasons, and because transistors are especially vulnerable to heat, class B circuits are extensively used in transistor power amplifiers.

Unfortunately, crossover distortion is a characteristic of nearly all class B amplifiers. It occurs because of failure to accomplish a smooth transition from conduction in one output transistor to conduction in the other. Consider, for example, the complementary class B output stage of Fig. 1. A plot of its output voltage

* Received April 2, 1962. Revised manuscript received, April 16, 1962. Reprinted with permission from the *Solid State Journal*, August, 1961.

[†] General Radio Co., West Concord, Mass.

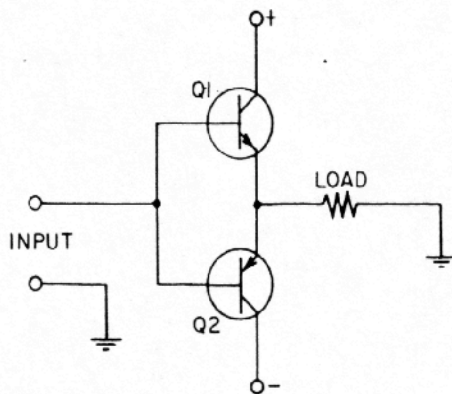


Fig. 1—A complementary class B emitter-follower power amplifier output stage.

against input voltage is shown in Fig. 2. It can be seen that there is a region of input voltage around the zero level for which the output voltage is very small. This produces crossover distortion in a sine-wave input signal as illustrated in Fig. 3. This is a strong source of harmonic distortion as well as an almost complete loss of gain for small signals—a serious defect, for example, in servo amplifiers.

Various remedies have been devised for eliminating crossover distortion. One of these is simply to enclose the class B output stage in a loop with enough feedback to reduce the distortion to an acceptable level. However, this distortion is composed of frequencies much higher than that of the signal being amplified, so this method requires that the frequency response around the feedback loop be flat far above the highest frequency at which the amplifier is intended to operate. Another method is to apply a bias voltage to the base of each transistor to cause it to conduct slightly even when there is no input signal. This is a very effective method of preventing crossover distortion, but it creates another problem. The "standby" current in each transistor is strongly dependent upon temperature, increasing at higher temperatures. There is, therefore, serious danger of thermal runaway, in which further increases in current cause further increases in temperature, and so forth, until the transistors are permanently damaged. To prevent this, temperature-sensitive elements such as diodes or thermistors can be included in the base bias network to change the bias voltage in such a way as to hold the standby current constant. This method can correct satisfactorily for ambient temperature changes, but the temperature-sensitive element cannot instantaneously follow the temperature of the junctions of the transistors and there is danger that a suddenly-applied signal may heat up the transistors before the bias voltage is corrected. In such systems, although crossover distortion is eliminated, there is introduced the danger of thermal runaway.

HIGH-IMPEDANCE DRIVE

A method of operating a class B output stage so that

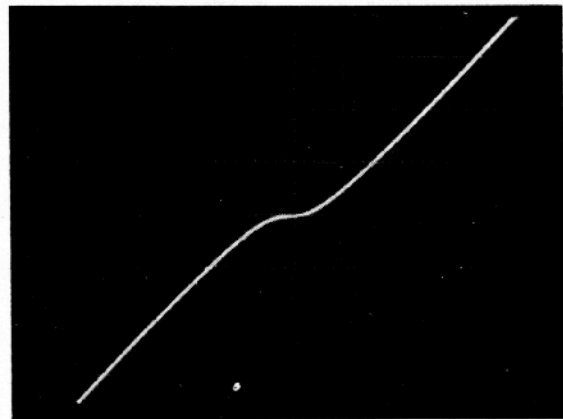


Fig. 2—Output voltage (vertical) vs input voltage (horizontal) of the output stage of Fig. 1. Q1, 2N1218; Q2, 2N176; load, 10 ohms. Both scales, 0.2 v per major division.

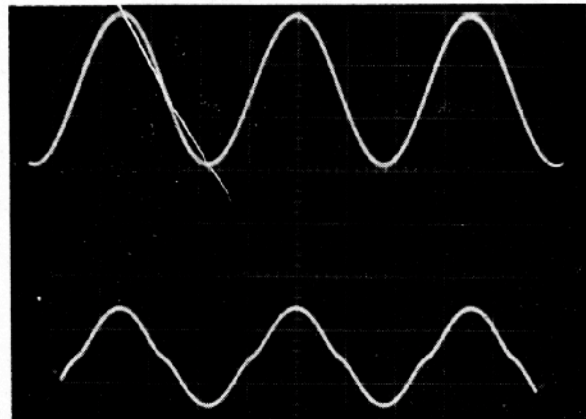


Fig. 3—Input voltage (upper) and output voltage (lower) of the output stage of Fig. 1 when driven from a low-impedance source. Q1, 2N1218; Q2, 2N176; load, 60 ohms. Both traces, 0.2 v per division.

crossover distortion is inherently eliminated is based on the discovery that the output voltage of the circuit of Fig. 1 much more closely reproduces the input current than the input voltage. To illustrate this, the output voltage of the circuit of Fig. 1 is plotted as a function of the input current in Fig. 4. By comparison with Fig. 2, it can be seen that the crossover distortion is no longer present. The residual nonlinearity visible near the crossover in Fig. 4 is due to the decrease of beta (h_{fe}) at very low current levels in each of the output transistors.

To reduce the crossover distortion, then, it is necessary to drive the circuit of Fig. 1 not with a voltage but with a current whose waveform is undistorted. Because the input impedance of the transistors becomes relatively high when the input voltage is near zero, the current must be supplied from a high-impedance source.¹ Then, at each axis-crossing of the input signal, the input voltage will "jump" from the voltage at which one transistor turns off to the voltage at which the other turns on. The input voltage is thereby auto-

¹ H. J. Woll, "Handbook of Semiconductor Electronics," McGraw-Hill Book Co., Inc., New York, N. Y., Section 11, pp. 11-33 ff.; 1956.

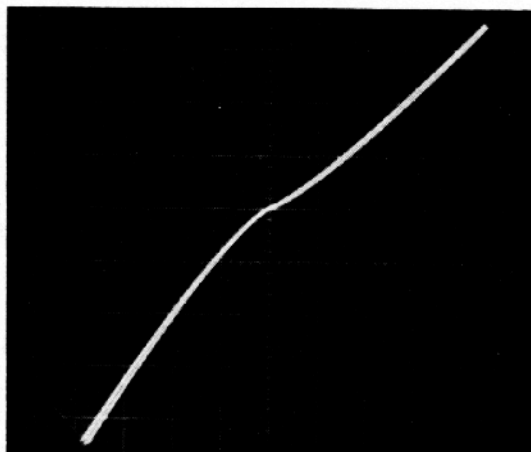


Fig. 4—Output voltage (vertical) vs input current (horizontal) of the output stage of Fig. 1. Q1, 2N1218; Q2, 2N176; load, 10 ohms. Vertical scale, 0.2 v per division; horizontal scale, 0.25 ma per division.

matically predistorted in such a way as to produce an output substantially free of crossover distortion. This system represents a sharp departure from the practice of driving emitter-follower circuits from low-impedance sources to take advantage of the inherent voltage feedback for reducing distortion due to nonlinearity of current gain.

It would appear that to drive this circuit from a very-high-impedance source would be the worst way to insure thermal stability. However, the interconnection of the two transistors itself provides the thermal protection. The most serious type of thermal runaway that might occur with the circuit of Fig. 1 would be current flow through the two transistors in series, from the positive power supply to the negative. With the bases and emitters tied together, however, if one transistor should become biased on (a necessary condition for thermal runaway), the other will be biased off by the same voltage. The runaway current path is very effectively interrupted by the transistor that is biased off, and so the thermal stability of this circuit is excellent.

A further advantage of the direct interconnection of the bases and emitters of the output transistors is that the reverse bias which is applied to the base of the "off" transistor comes from a relatively low-impedance source (the "on" base-emitter junction of the other transistor); this reduces the turn-off time of the transistor and lowers the current drain and power dissipation at high frequencies.

HIGH-SOURCE-IMPEDANCE DRIVER CIRCUITS

It is difficult to determine theoretically just how high the driving source impedance should be for any particular circuit. However, the following empirical formula can be used to estimate the magnitude of the crossover distortion:

$$d = \frac{KR_m}{R_s^2 I_{in}}$$

where

d is the total harmonic crossover distortion in per cent;

K is a constant found to be between 1 and 4 volts for germanium power transistors;

R_m is the maximum input resistance in the crossover region—on the order of 60 ohms for a common-base output stage and 2500 ohms for common-emitter and common-collector stages using germanium power transistors;

R_s is the source resistance; and

I_{in} is the input drive current in amperes.

A convenient rule of thumb is that the driving source impedance should be high compared to the maximum value of the input resistance in the crossover region.

Fortunately, it is possible to build a source using conventional transistors whose impedance is more than adequately high for most class B output stages. One of the possible configurations for such a circuit is used in the amplifier shown schematically in Fig. 5.² The high-impedance source for the output transistors is the junction of the collectors of Q3 and Q4. The impedance at this point is half the collector impedance of a grounded-base amplifier, and can easily be of the order of hundreds of kilohms. In order to maintain the voltage at this point at the correct dc level, it is necessary to use feedback. The feedback, however, cannot be taken directly from the junction of the collectors of Q3 and Q4 because a feedback resistor would itself lower the impedance at that point. Therefore, the feedback is taken directly from the output at the emitters of Q1 and Q2. In addition to maintaining the proper dc level at the output, the feedback is effective at signal frequencies for making the output impedance low and for reducing distortion from other sources such as beta nonlinearity and unequal betas in the output transistors. The voltage gain of the amplifier shown in Fig. 5 is approximately equal to the reciprocal of the voltage division of the feedback network, R1 and R2. This amplifier requires two positive and two negative power supplies. The lower voltage supplies, marked + and −, provide the high current for the output stage. The higher voltage supplies, marked ++ and −−, supply only the much smaller current required by the input and driver stages.

The average current in transistors Q3 and Q4 (which operate class A) must be at least equal to the peak base current required by the output transistors. Because they must conduct this much current steadily, the power dissipation in Q3 and Q4 may be considerable.

² J. J. Faran, Jr., "Elimination of crossover distortion in class-B transistor amplifiers," *Proc. IRE (Correspondence)*, vol. 49, pp. 834-835; April, 1961.

Fig. 7 is a detailed schematic diagram of a practical audio amplifier of this type and its power supply. The amplifier is designed to have a music-power rating of 20 watts and to work into an 8-ohm load.

An accidental short circuit on the output could ruin both output and transistors. The 1-ohm resistors are included to provide partial protection against such an occurrence. They limit the maximum sine-wave output

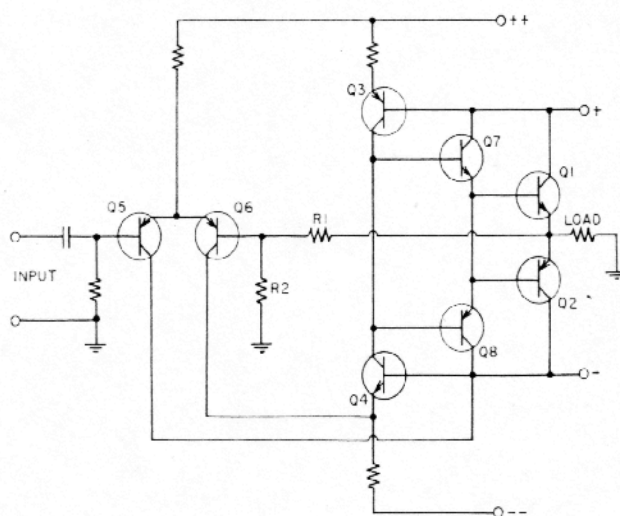


Fig. 6—The amplifier of Fig. 5 with additional class B drivers (Q7 and Q8) added.

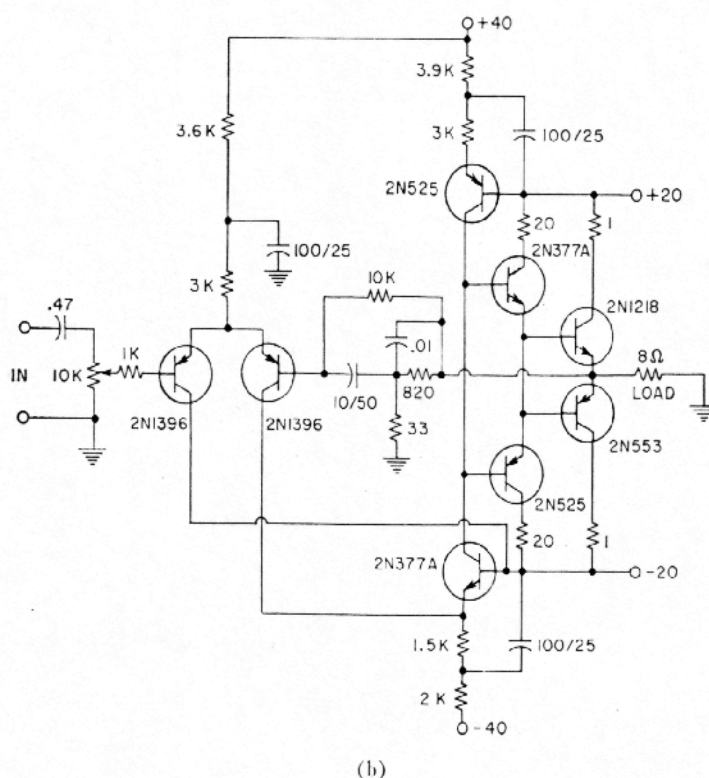


Fig. 7—Schematic diagram of (b) 20-w audio amplifier and (a) its power supply.

power to about 12 watts but the "music power" rating is still about 20 watts.

For lowest distortion, as in hi-fi applications, the current gains of the output transistors and of the two driver transistors should be closely matched. The power supplies do not require complicated regulation. The circuit is arranged so that ripple on the power-supply voltage does not cause any serious problem.

An audio amplifier of the type shown in Fig. 7 has produced 16-watt output into an 8-ohm resistive load with less than 0.03 per cent total harmonic distortion. There was approximately 34-db reduction in gain due to feedback. To achieve this performance, the output transistors were selected to have nearly equal current gains. This figure is quoted, however, to demonstrate the virtual elimination of crossover distortion. The distortion did not increase at lower output power levels.

OTHER COMPLEMENTARY OUTPUT STAGES

The class B output stage which we have considered in some detail above can be classified as the common-collector type. If we drive a similar circuit through a transformer whose secondary is connected as shown in Fig. 8, the transistors will be operated effectively common-emitter, with the possible advantage that the input impedance will be independent of the load impedance. This circuit is just as well protected against thermal runaway as the common-collector circuit, since only one of the transistors can be turned on at any time. The circuit will operate without crossover distortion if the transformer is driven from a high impedance. In addition, the transformer must have sufficient inductance that it does not lower the effective impedance of the driving source beyond an acceptable limit.

Another interesting output stage results when the transistors are connected in a common-base configuration as shown in Fig. 9. Although the current gain in the output transistors is only unity, this circuit has the advantage of much higher frequency response than either of the other two types discussed above. Its greatest advantage, however, is that when crossover distortion is eliminated by the use of high-impedance drive, the residual distortion due to variations in beta at both low and high current levels is almost entirely absent. This is so because fairly large changes in beta correspond to only very small changes in alpha (h_{fb}). In Fig. 10 the output voltage for the circuit of Fig. 9 is plotted against the input current. This is a very linear relationship, and comparison with Fig. 4 shows the great reduction in distortion which is brought about by common-base operation. Input and output voltage waveforms for a sine-wave input current applied to the common-base circuit are shown in Fig. 11. The input emitter-base voltage is characterized by steep vertical transitions at the crossover region where the input impedance is high, but no distortion is visible in the output voltage. Because the current gain in the tran-

sistors is only unity, the driver stage must be able to provide current equal to the peak output current. The steady current in the driver stage can be reduced by making use of the current gain of the transformer. The highest peak current is then generated at a lower current level (where beta is more constant) in the driver transistors. The thermal protection of the common-base output stage is again the same as for the other complementary circuits discussed above. The advantages of the common-base output stage, higher frequency response and lower distortion, are obtained at the expense of lower power gain and higher standby power consumption (in the driver stage).

NONCOMPLEMENTARY OUTPUT STAGES

All of the circuits discussed above depend for their thermal stability upon the use of complementary symmetry. *n-p-n* germanium power transistors, however, are still few and expensive. Those that are presently available have neither the current ratings, the power capacity, nor the frequency response of readily-available, reasonably-priced *p-n-p* germanium power transistors. It is therefore desirable in certain cases, particularly that of very high power output, to use two transistors of the same type in class B output stages. High-impedance drive can be applied to a "noncomplementary" output stage without jeopardizing the thermal safety by simply using a driver transformer with two secondary windings. A schematic diagram of a common-emitter output stage using two *p-n-p* transistors is shown in Fig. 12. The thermal stability of this circuit is not provided automatically as in the circuits discussed above, but can be made quite good by making the resistances of the secondary windings very low. They can readily be made less than an ohm, which is some orders of magnitude less than the resistance of a temperature-compensated bias network. Again, as with the complementary circuits, whenever one transistor is driven on, the other is driven off by a voltage of the same magnitude. Tight coupling in the transformer is necessary because current flows only half the time in each secondary, and there is the possibility of the generation of undesirable transients in the leakage inductance. It is not difficult in practice, however, to design transformers which have adequately high inductance, low resistance, and tight coupling, since the power level is relatively low and the required turns ratio is not large.

An amplifier using an output stage of the form of Fig. 12 has produced 200 watts in a resistive load with less than 1 per cent total harmonic distortion. At lower power levels, the distortion is considerably less.

The common-base output stage can also be constructed of transistors of the same polarity as shown in Fig. 13. Input impedance, gain, and frequency response considerations are the same as for the complementary common-base output stage. Protection against thermal runaway is again achieved by making the resistances of the secondary windings very low.

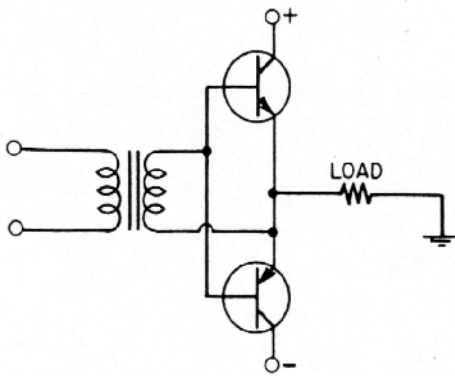


Fig. 8—A complementary common-emitter class B power amplifier output stage.

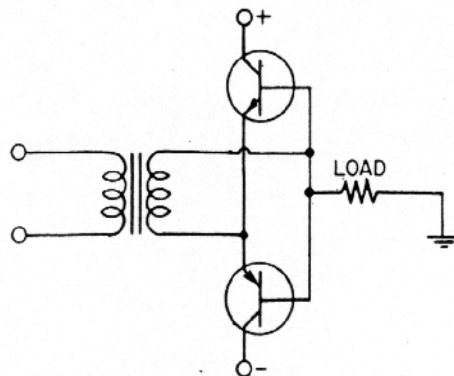


Fig. 9—A complementary common-base class B power amplifier output stage.

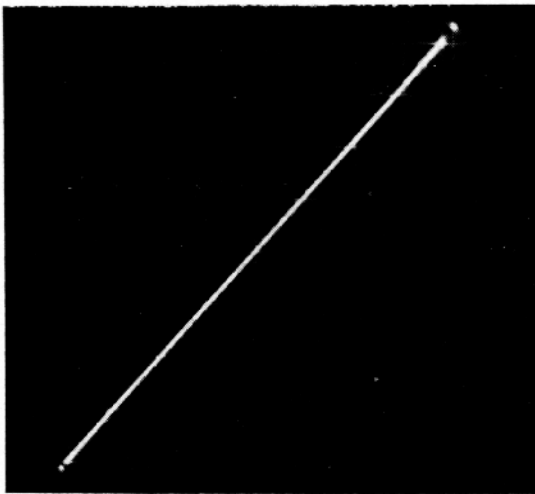


Fig. 10—Output voltage (vertical) vs input (base) current (horizontal) for output stage of Fig. 9. Q1, 2N1218; Q2, 2N176; load, 100 ohms. Vertical scale, 0.2 v per division; horizontal scale, 2 ma per division.

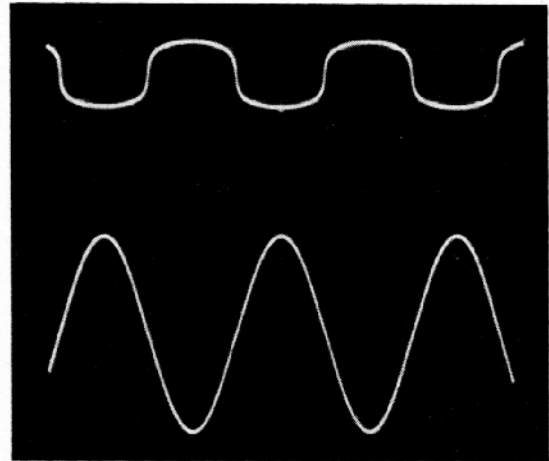


Fig. 11—Input (emitter-to-base) voltage (upper) and output voltage (lower) for sine-wave input current applied to the output stage of Fig. 9. Q1, 2N1218; Q2, 2N176; load, 100 ohms. Upper trace, 0.2 v per division; lower trace, 0.5 v per division.

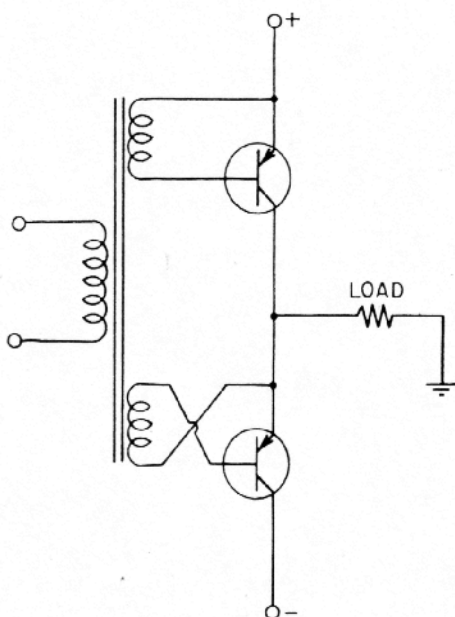


Fig. 12—A noncomplementary common-emitter class B power amplifier output stage.

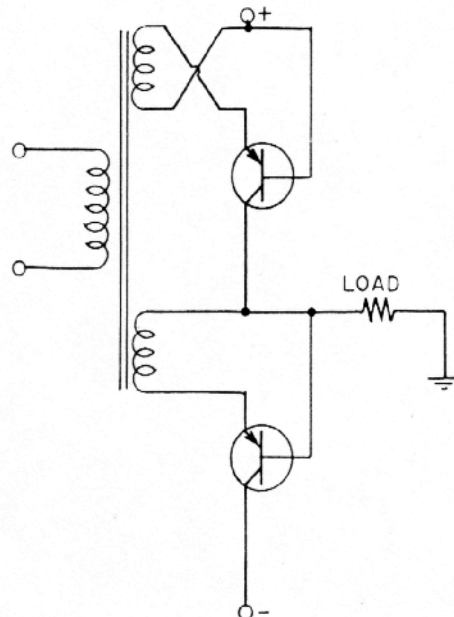


Fig. 13—A noncomplementary common-base class B power amplifier output stage.

CONCLUSIONS

The principle of high-impedance drive for eliminating crossover distortion in class B transistor amplifiers can be applied to circuits having the highest possible degree of protection against thermal runaway. This can be accomplished most easily with complementary output transistors, but examples have also been given of how this can effectively be done with two transistors of the same type.

Several high-impedance-drive amplifiers have been constructed to date, and they exhibit very low distortion without the use of bias networks in the output stage.

They have a few disadvantages, one of which is that it is not possible to take advantage of the transconductance linearity at high current levels which can be realized if the transistors are driven from a low impedance. It has been found, however, perfectly possible to reduce the distortion due to beta nonlinearity to a negligible amount by the use of simple feedback arrangements. Circuits employing high-impedance drive do show significant reduction of crossover distortion and possess unequaled thermal stability. For these reasons, circuits of this type appear to be by far the most satisfactory for class B amplifiers.