HIGH-FIDELITY POWER AMPLIFIERS*

One of a series of articles on modern audio equipment. Power output and driver circuits are discussed here

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THE high quality of performance of modern high-fidelity equipment is due in large part to highly specialized and sometimes unique circuitry. The service technician who looks for the first time at the wiring diagrams of modern commercial hi-fi equipment is very likely to be puzzled and perhaps even shocked by some highly unorthodox and unfamiliar circuits. High-fidelity circuits can be divided into two general categories: those applying to power amplifiers; those applying to control units, preamplifiers and accessories.

Power amplifiers consist of three sections: the power output stage whose function is to deliver to the speakers anywhere from 10 to 50 watts of power with minimum distortion; the driver which must supply sufficient driving voltage to the output stage to drive it to maximum output; a phase inverter to convert a single-ended input signal to a push-pull signal, since almost all power amplifiers in high-fidelity equipment use push-pull parameters or an equivalent.

The classic power output circuit is shown in Fig. 1. Two triodes or pentodes are arranged with plates loaded and grids driven in push-pull. (Beam-power tetrodes are classed as pentodes in this article.) In older, inexpensive high-fidelity amplifiers, the circuit usually has 6V6 tubes as pentodes.

It is not easy to obtain high-power outputs with receiving type tubes. One of the first steps in the rapid progress of high-fidelity design in the past decade was the use of transmitting types in the output stages. There were two reasons for this:

First, these transmitting tubes require very little driving voltage even when used as triodes. Thus, where the 6B4 family requires 60 volts peak per grid of drive, transmitting pentodes of the 807 family used as triodes require only 40 volts.

Theoretically it should easily be possible to design drivers capable of delivering 60 volts peak with low distortion. In practice it is difficult to do so without increasing distortion to high levels. But 40 volts is easily supplied and at a distortion level very much lower.

Second, where receiving type tubes have to be driven into nonlinear operation to deliver 10 or 15 watts of output, transmitting tubes deliver this output over the most linear portion of their

* From the book *Maintaining Hi-Fi Equipment*, Gernsback Library.

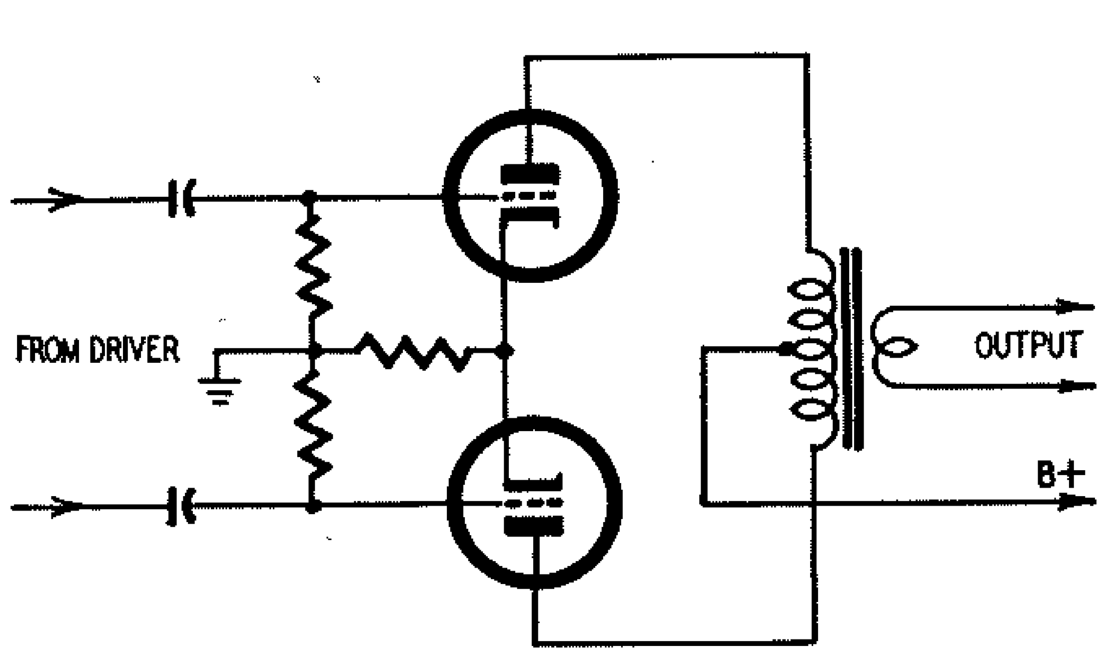


Fig. 1—The basic push-pull amplifier.

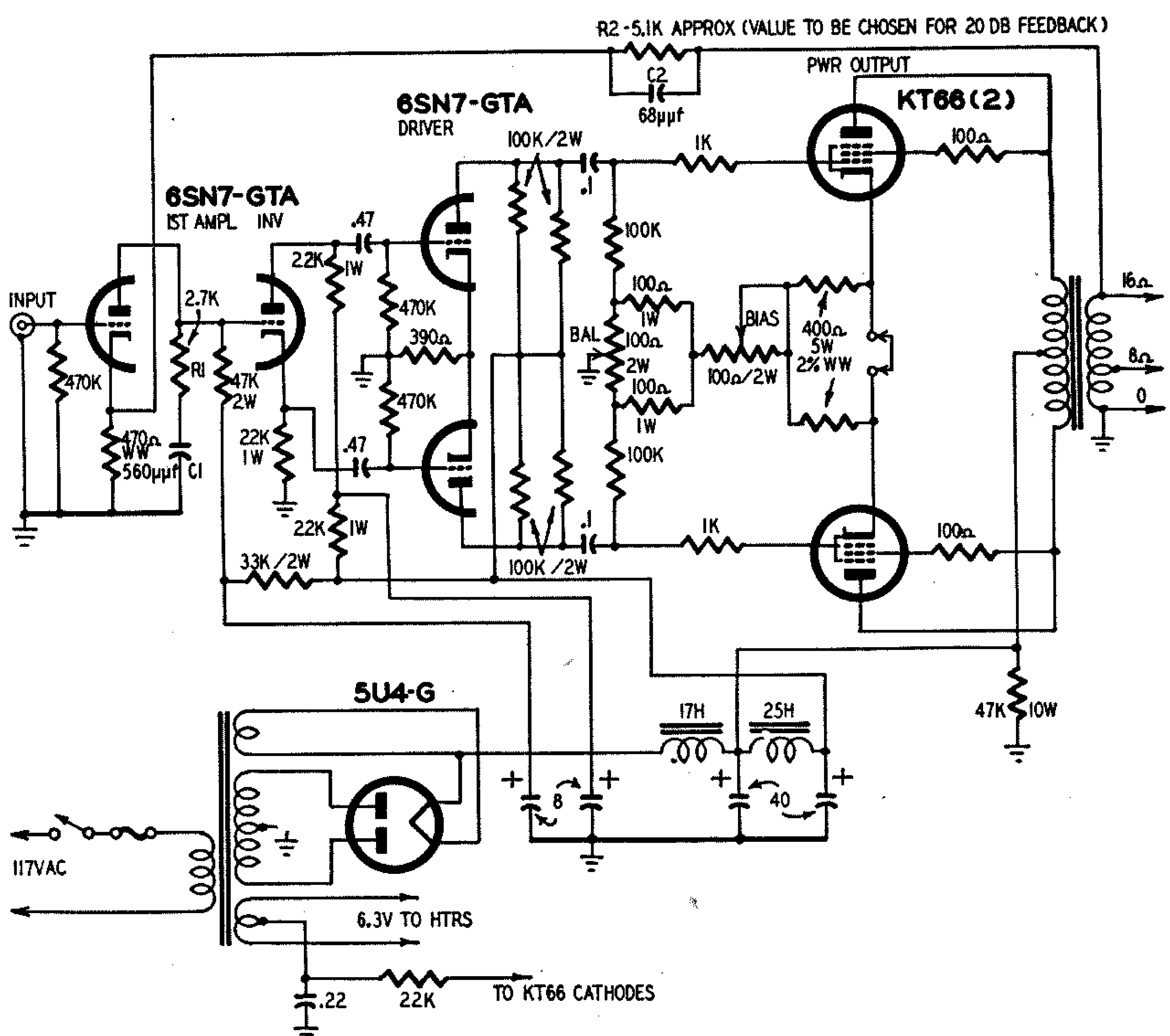


Fig. 2—Craftsmen C-500, typical Williamson amplifier using triodes.

curves, operating at only a small fraction of their maximum capabilities and strictly class A. Thus, distortion can be reduced to a small fraction of that with receiving type tubes. By this time it had become very clear that low distortion was the primary consideration and that a wide bandwidth was tolerable only when distortion was reduced to insignificant levels. The use of transmitting tubes provided a simple means of obtaining the desired low distortion.

The Williamson amplifier

This trend found its most notable expression in the amplifier named after D. T. N. Williamson, engineer of the British firm, Ferranti. The Williamson circuit not only used transmitting type tubes, but used them with highly refined circuitry for drivers and inverters. It was one of the most successful audio designs in electronic history. Even now, most commercial amplifiers use either some modification of the Williamson circuit or portions of it.

There is nothing very remarkable about the circuit. The original used two transmitting pentodes connected as triodes and loaded with an output transformer of hitherto unprecedented bandwidth, low distortion and very large size. The biasing arrangement was complex but permitted excellent balance and precise bias adjustment. The first amplifier–inverter used direct coupling to minimize phase shift at the low-frequency end. (See Fig. 2.)

A number of improvements were made as the circuit was applied to commercial equipment. One modification is that of splitting the self-bias resistors of the output tubes. About half the bias for each tube is developed in an independent unbypassed cathode resistor. This provides some current feedback to reduce distortion further.

As output transformers were improved and bandwidth extended to 100,000 cycles and beyond, it became more difficult to maintain stability in the feedback loop at the extremes, particularly at the resonant peak of the output transformer which fell usually in the region around 100 kc. One expedient was to include within the loop, a bypass network affecting only the frequencies around and above 100 kc. This took the form of a resistor and a capacitor in series (R1 and C1, Fig. 2) in the plate circuit of the input tube which bypassed the unwanted ringing frequency. To minimize these troubles further, a phase-shifting capacitor (C2) was added in parallel with the feedback resistor. This network had a time constant which produced a phase shift opposite to that of the output transformer at the ringing frequency, or in that region.

Ultra-Linear operation

About 1952 David Hafler and Herb Keroes revived an unusual output tube circuit which had been patented some years before and which provided operation combining the best features of triode and tetrode or pentode operation. This Ultra-Linear configuration made only a very slight change in the normal push-pull circuit; the screen grids were connected to taps on the primary of the output transformer. There is some controversy about how this circuit actually operates but the general consensus is that connecting the screens in this way applies a certain amount of negative feedback.

In any event, the connection has some very great virtues. First, the operating curve is more linear than that of either triode or pentode operation. Second, the power output capabilities are about one-half those of pentode connection and about double those of the triode connection. Thus, with the same plate supply voltage and drive, the Ultra-Linear configuration doubles the output power over that of the triode Williamson. More important than this is the fact that distortion is decreased at low output levels. Finally, the tube capacitances are the same as in pentode operation. This eliminates, or at least greatly minimizes, the Miller effect at high frequencies. It not only makes possible an upward extension of the bandwidth, but—more important—reduces the phase shift in the region of 100 kc. It therefore permits the use of larger feedback factors for an equal degree of ringing.

The Ultra-Linear circuit was immediately applied to the Williamson design and a high proportion of today's commercial amplifiers are Ultra-Linear versions of the Williamson. A typical circuit is shown in Fig. 3.

Cathode loading

Meanwhile, considerable work was being done on cathode loading of power-output tubes. It was known that such loading produced high power with very low distortion, since cathode loading results in current feedback. Cathode loading also improves the high-frequency response greatly. This permits higher feedback with less risk of ringing or instability at the transformer resonant frequency. Unfortunately, cathode followers have no voltage gain; hence the drivers have to supply somewhere between 150 and 200 volts of drive per side. This is a serious problem

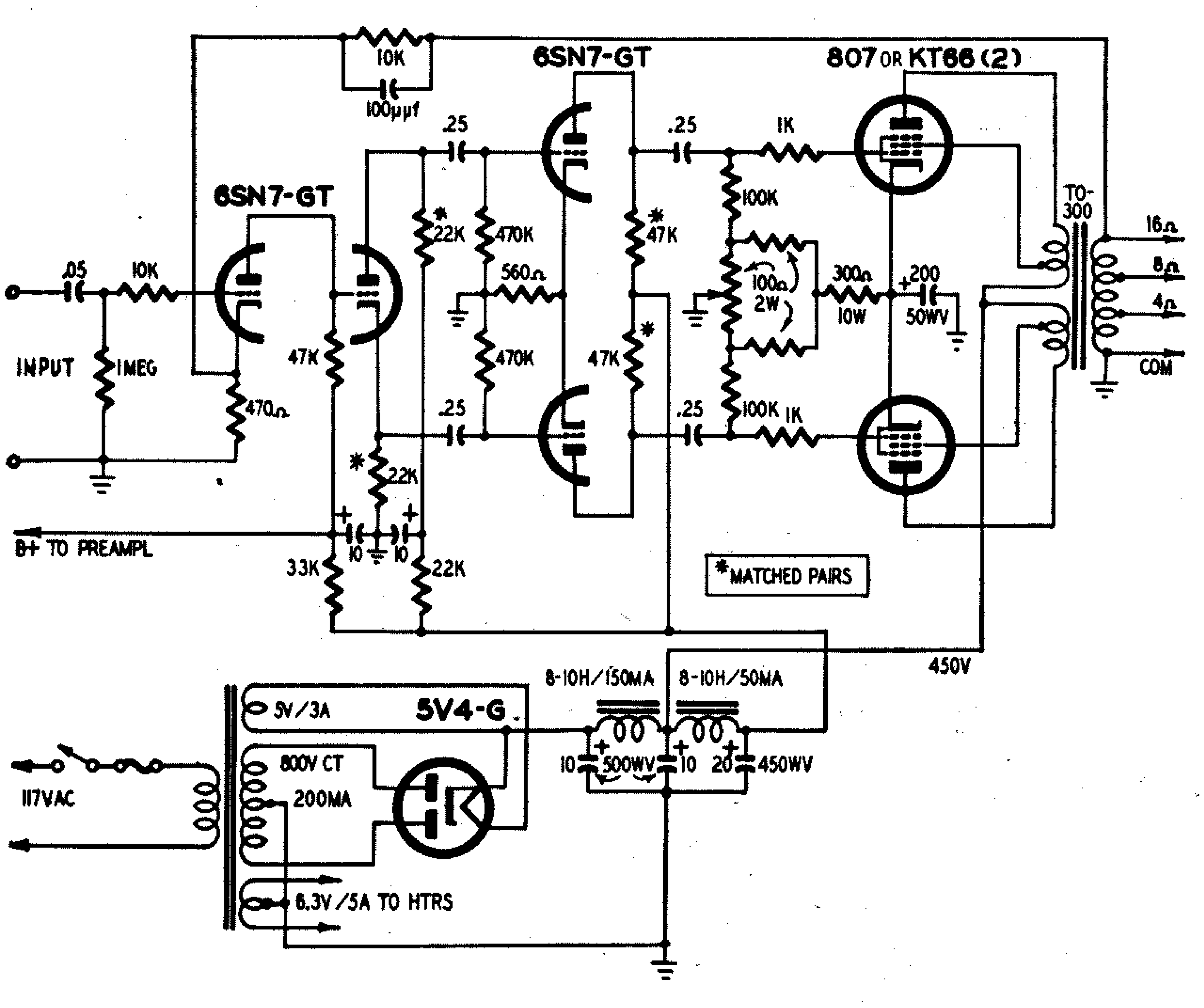


Fig. 3—Typical Williamson amplifier designed for Ultra-Linear operation.

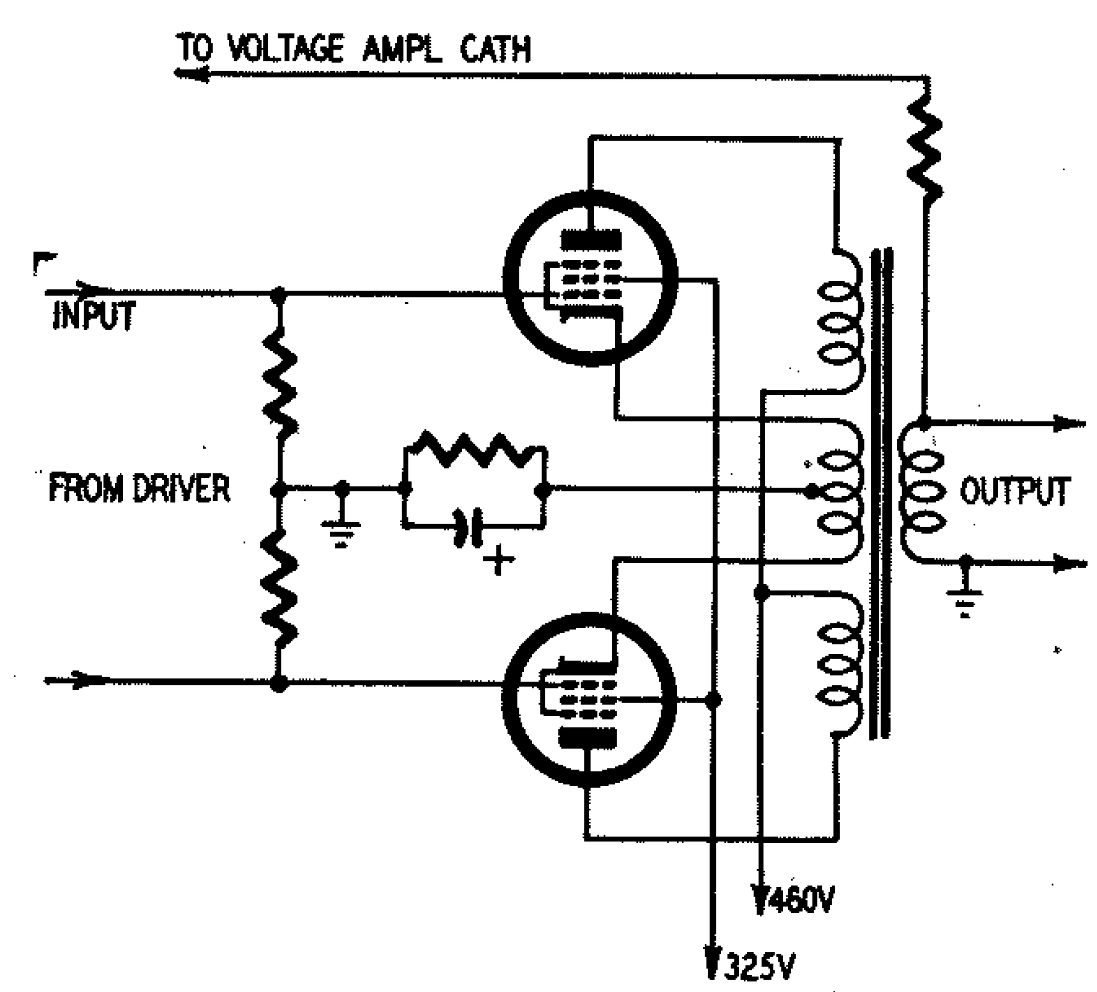


Fig. 4—Cathode-loaded output circuit.

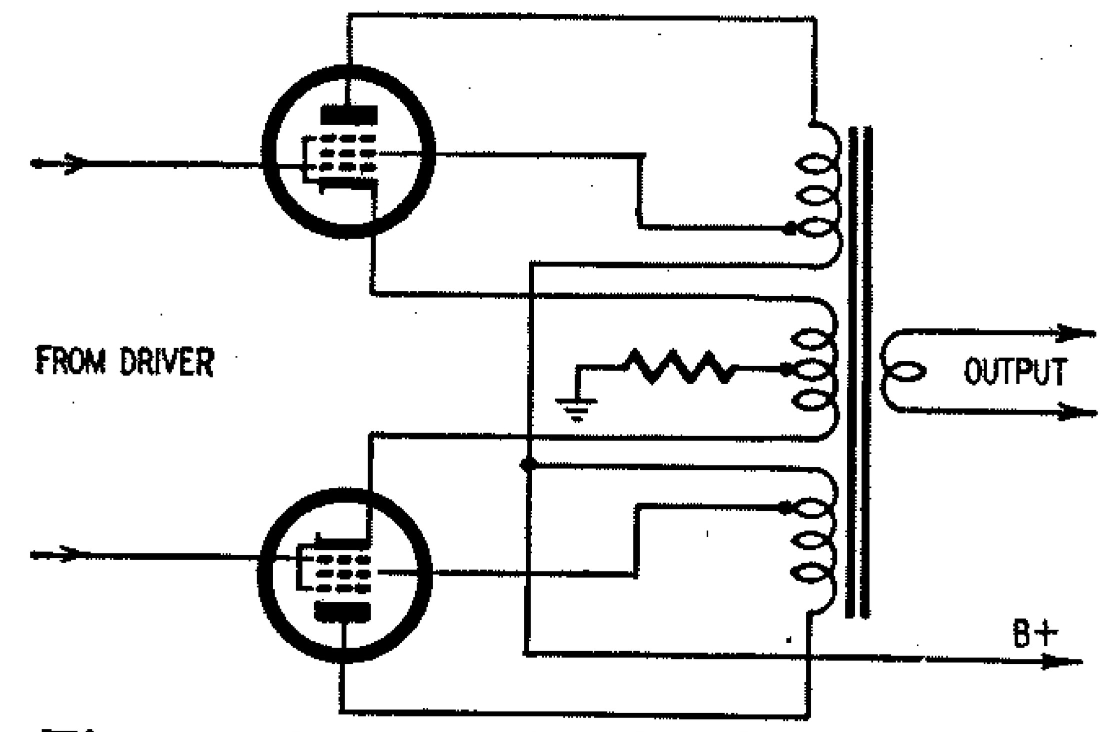


Fig. 5—Output circuit shows Ultra-Linear design with cathode loading.

since, as mentioned before, it is difficult enough to supply 60 volts of drive with low distortion.

Though complete cathode loading poses too many problems, it was quickly perceived that partial cathode loading would provide a good degree of current feedback without raising the driving requirements out of practical reach. Several circuits of this type were developed, differing in the ratio of plate-to-cathode loading. Typical examples are the British Quad amplifier and the American Bogen DB15G. (A simplified circuit is shown in Fig. 4.)

Both of these use pentode operation, obtaining a low output impedance by combining current feedback via the partial cathode loading and voltage feedback of an overall loop. Since pentodes are far more sensitive than triodes, a simpler driver can be used. The Bogen uses merely the first two stages of the Williamson front end; the Quad uses a pair of pentodes in the paraphase phase-inverting circuit.

It is possible to combine the Ultra-Linear configuration with partial cathode loading and this was done in the Fisher 70A (Fig. 5) amplifier.

An arrangement which looks rather similar is that of the McIntosh amplifiers. (See "Circuit Features of High-Fidelity Power Amplifiers," August, 1955.) In this, bifilar windings are used for the plate and cathode portions of the transformer primary and the screens are cross-coupled to the opposite plates. This arrangement permits class-B operation with very low distortion and without the switching transients normally produced by such operation. Thus a pair of 6V6's can deliver outputs in excess of 20 watts. Fig. 6 shows a simplified version of the output of the McIntosh amplifier.

I mentioned switching transients in the preceding paragraph. These occur when output tubes are driven to and beyond cutoff. The transient is produced by leakage reactance of the output transformer which results in collapsing currents at the cutoff point and produces parasitic oscillation, audible in the output as a very annoying thump, which tears up the signal. Because these transients occur at cutoff or beyond, high-fidelity power stages avoided such operation. That meant, in practice, they were limited to class-A or -AB_1 operation. Unfortunately, this operation is inefficient and it is difficult to obtain high-power output with it. Much design thought has therefore been expended on means of obtaining class-AB_2 or -B operation without switching transients.

Before going into that we might mention two expedients for obtaining high-power outputs with class-A operation. One is a style of operation called A_2. In this the tubes are never cut off but they are driven into the grid-current region. This produces higher distortion, but its effects can be minimized by careful balancing and high feedback factors.

The first commercial amplifier to employ this mode of operation was the Brook unit designed by Lincoln Walsh which was the first great postwar high-fidelity amplifier. It has since been used also in the Fisher Laboratory model 50A. In this type of operation the grids draw considerable current, consequently the grid impedance must be very low. The driver is therefore a cathode follower with transformer coupling to the output tubes; even the low resistance of a cathode follower with resistor loads would be too great for A_2 operation. The transformer also has capacitor coupling to extend the low-frequency response. This results in something intermediate between transformer and double-impedance coupling (Fig. 7).

Another possible arrangement (Fig. 8), not used at present in a commercial amplifier, is *extended* class-A operation. Here four identical tubes are used, one pair operating as triodes, the other as pentodes. At low levels the pentodes are cut off and do not contribute anything. At a certain point in the dynamic range, however, as the driving voltage increases and reduces the effective bias,

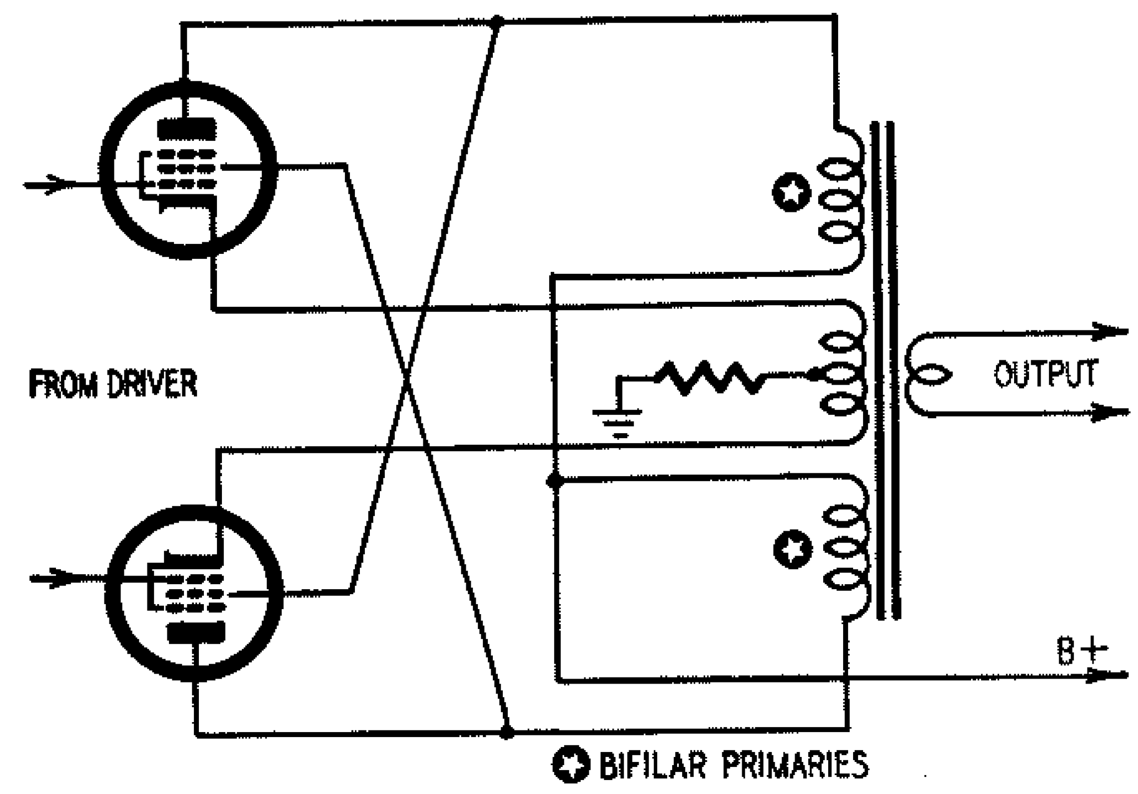


Fig. 6—McIntosh output circuit.

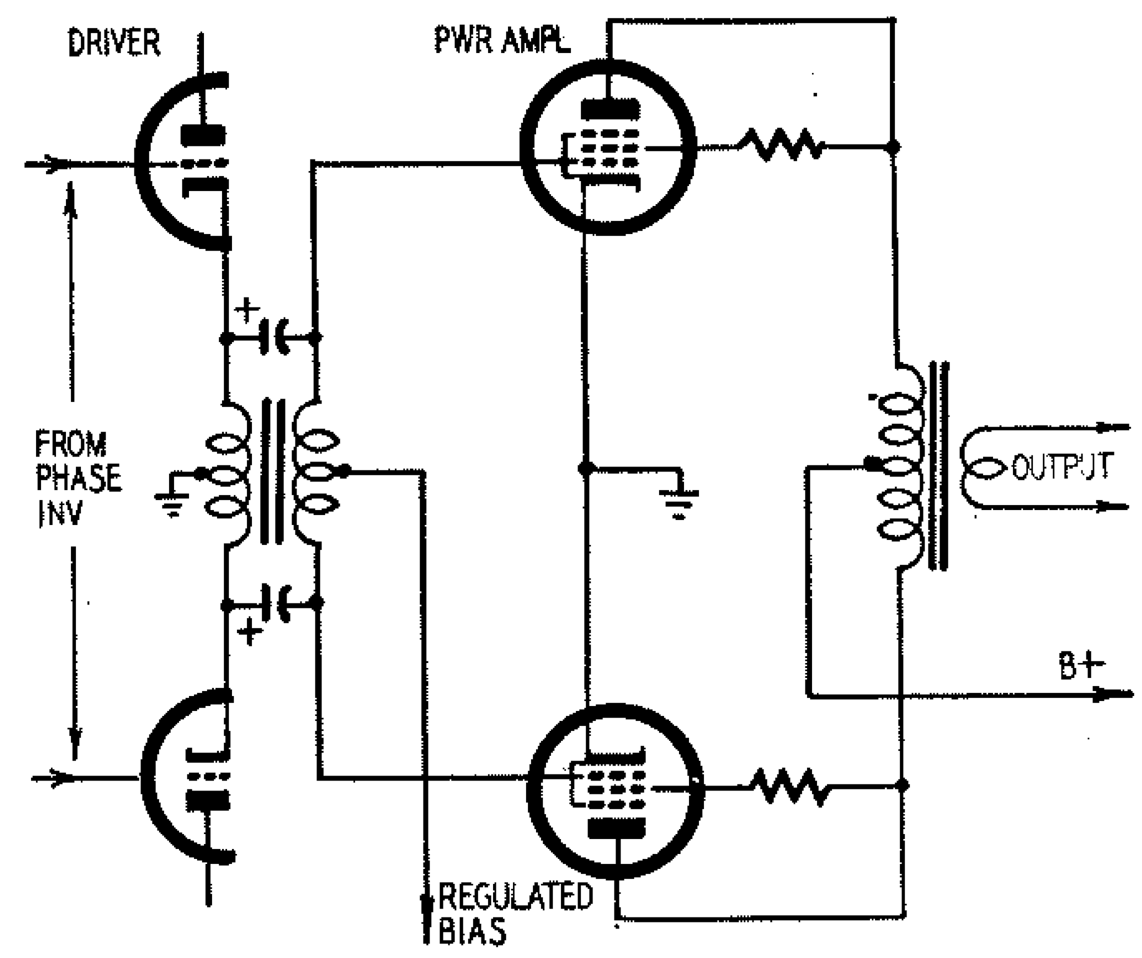


Fig. 7—Circuit for class-A_2 operation.

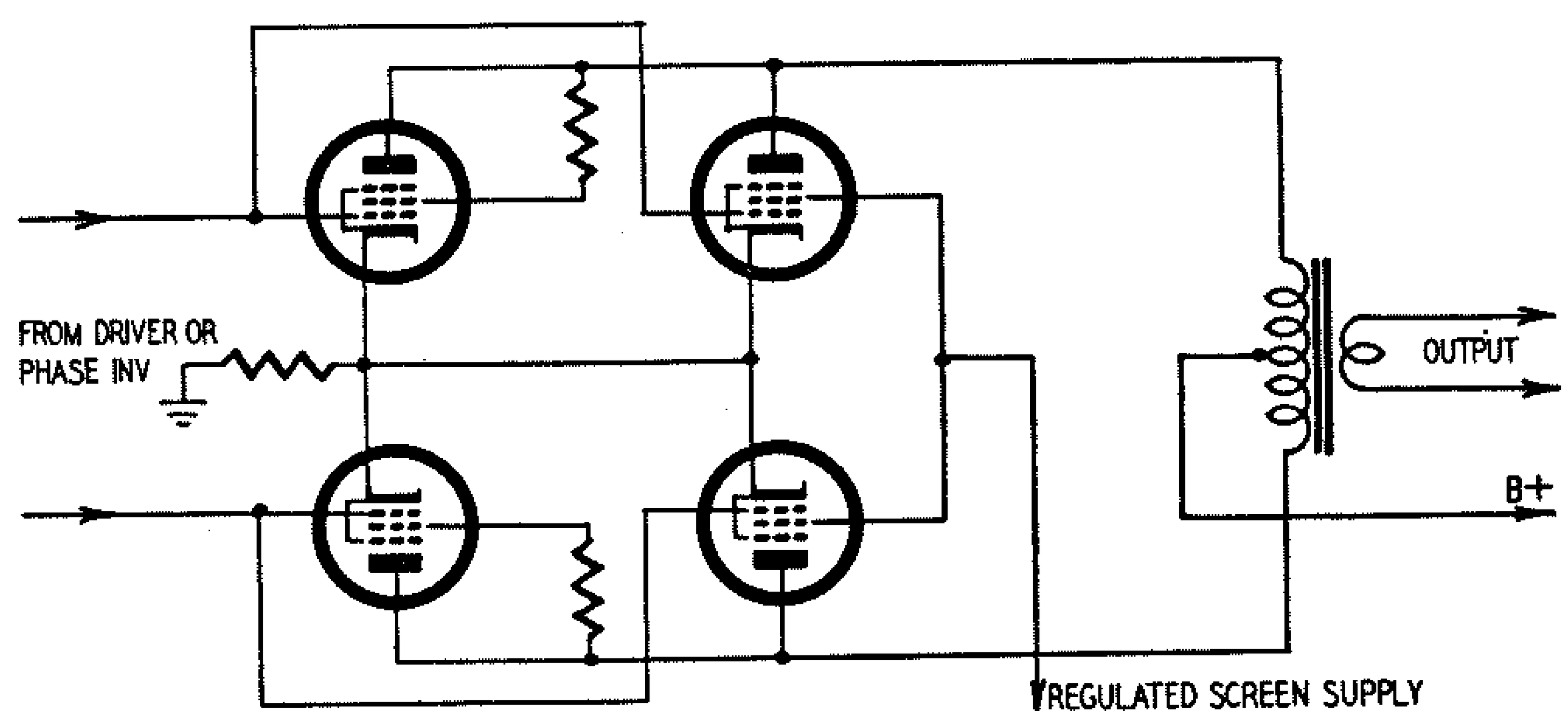
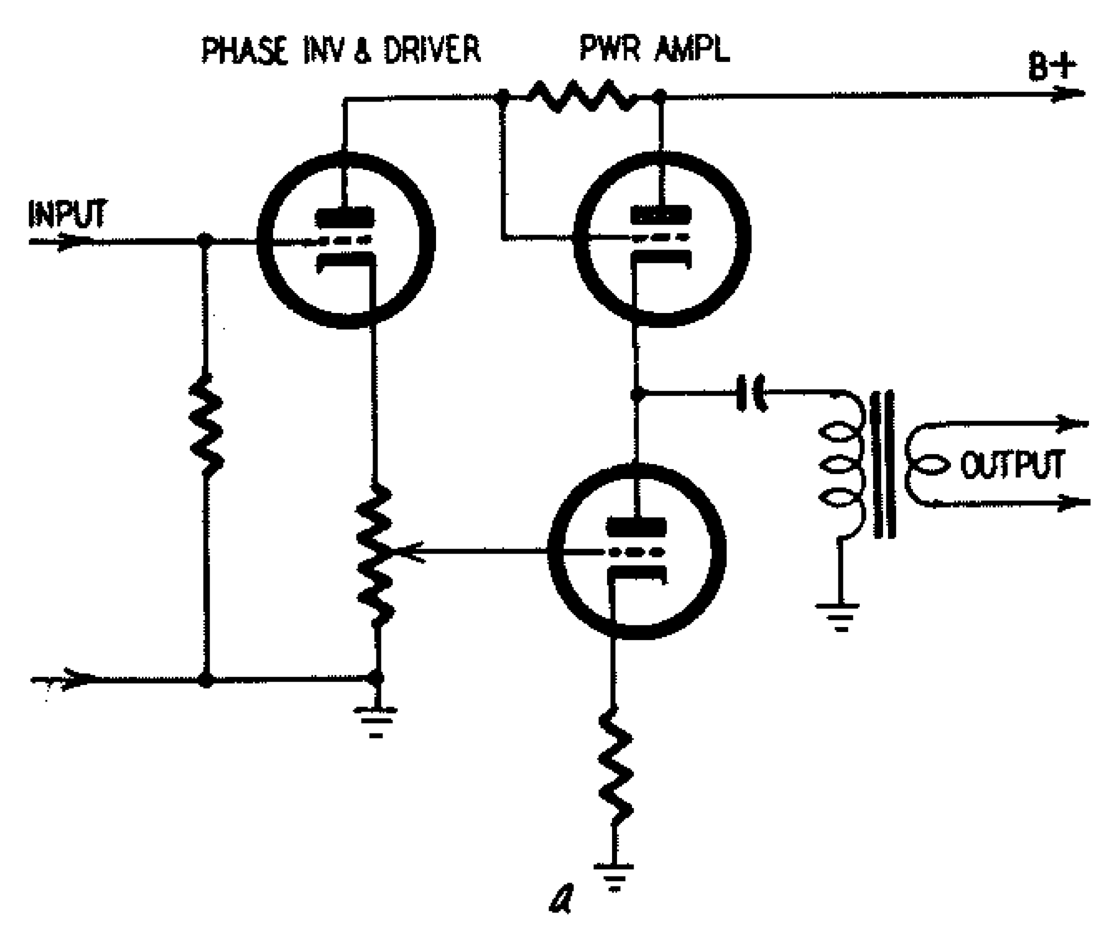
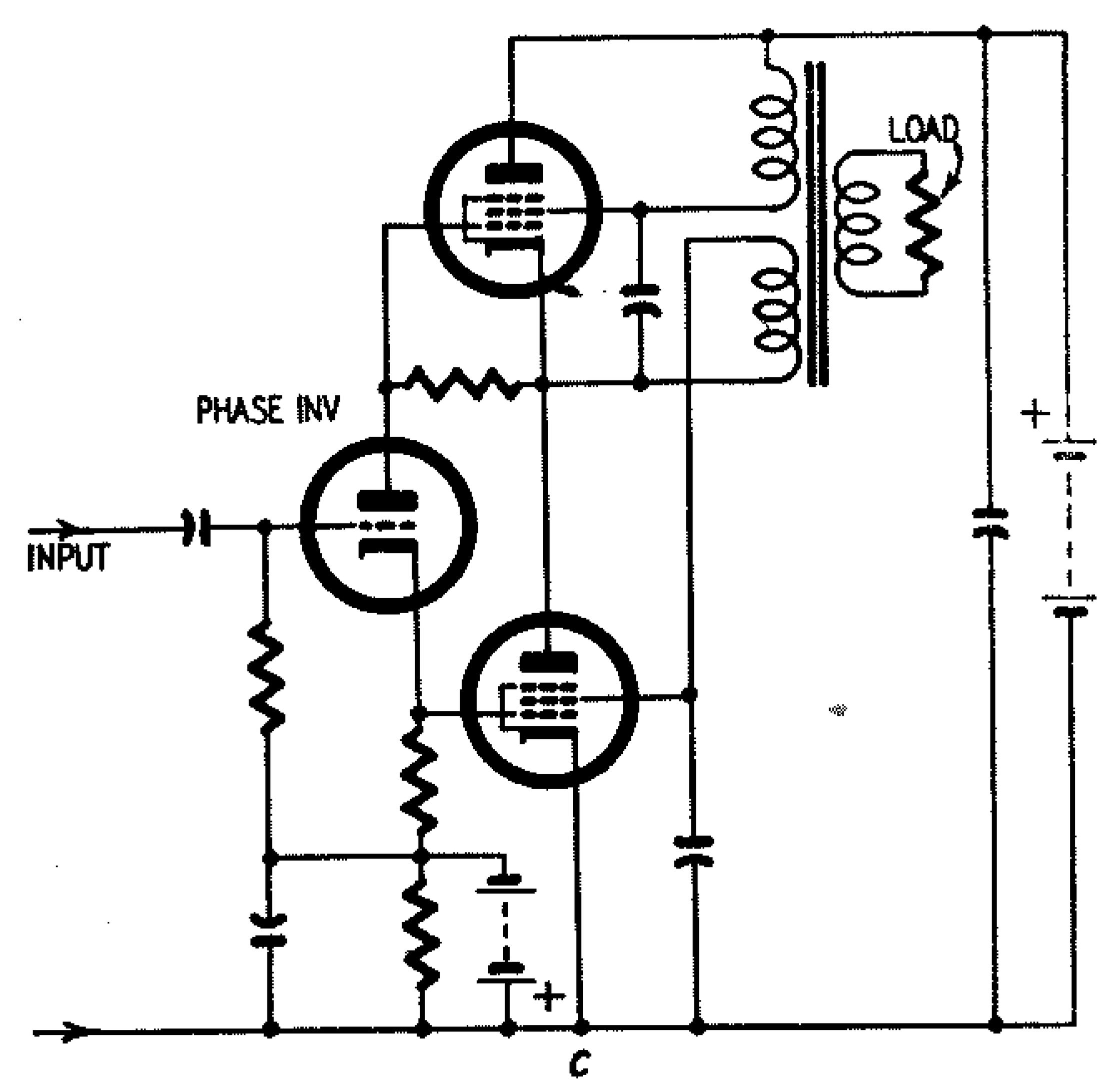


Fig. 8—Circuit for extended class A.





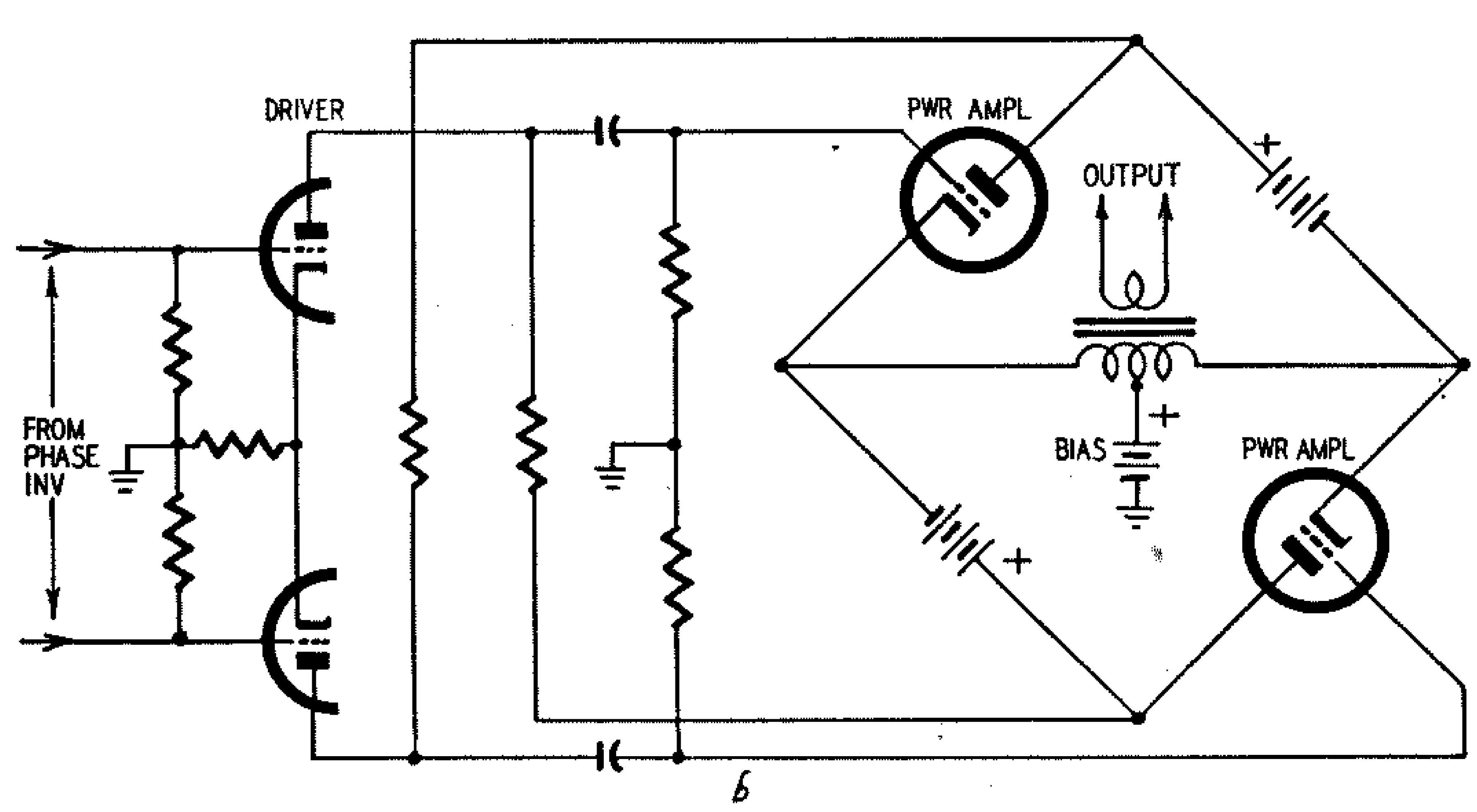


Fig. 9—Output circuit with plate of one tube and cathode of other loaded.

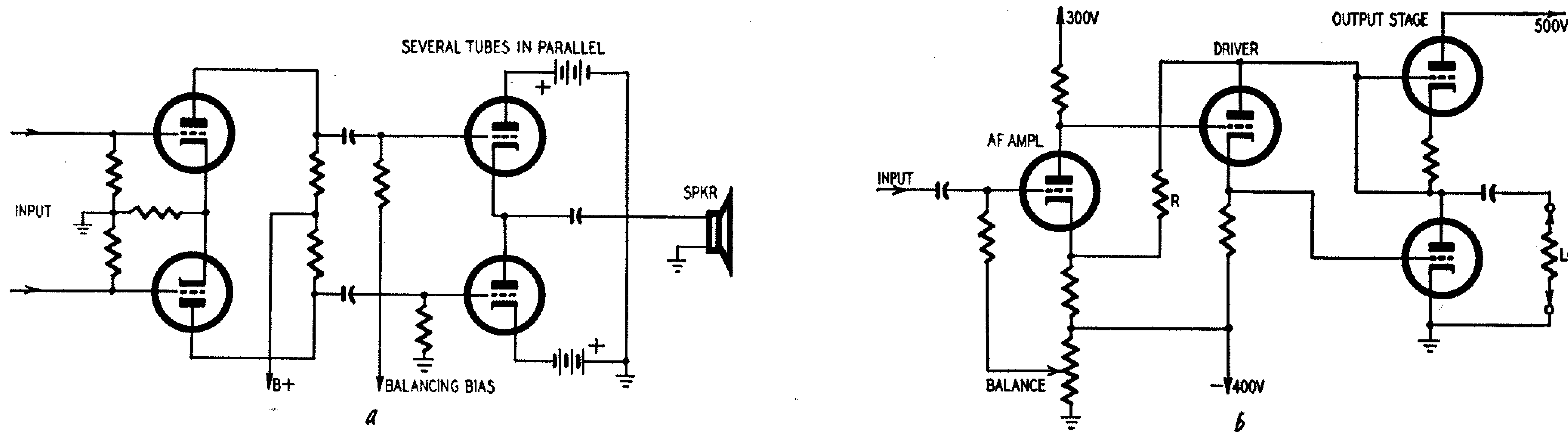


Fig. 10—Single-ended push-pull output.

they begin to contribute and at maximum output are the dominant developers of power. Operation is class A, but the amplifier output power is much higher.

One of the possible ways of using two tubes in a power stage is to load the cathode of one and the plate of the other tube. This appears in different forms in two commercial amplifiers: the National Unity-Coupled Horizon and the Electro-Voice Circlotron.

Since the circuit diagrams of these amplifiers do not make the operation clear, let us examine the circuit in simplified form. The general idea is expressed in the simple diagram of Fig. 9-a. Here we have, in effect, two tubes whose outputs are in series but whose inputs are in push-pull. The transformer is connected in the middle of the circuit at the point where the two tubes are connected in series. It is in the plate circuit of the lower tube, in the cathode circuit of the upper one. Push-pull operation results because the two grids are fed by out-of-phase voltages and therefore, as the plate current of one tube rises, the current of the other falls. The load for both sections is common, so all the distortion products cancel.

National and Electro-Voice have traveled two different paths to obtain a practical amplifier with this configuration. Electro-Voice turns the circuit into a bridge as indicated in Fig. 9-b. This requires two power supplies (indicated by batteries), but as long as the bridge is well balanced no dc can flow through the output transformer. This simplifies the design of a good output transformer; it also makes possible class-AB_2 operation approaching class B without switching transients. This in turn makes it possible to develop high power outputs with high efficiency. Triodes or pentodes can be used and, since the output impedance is very low, pentode operation in this mode produces as good or better damping factors than triode operation in conventional push-pull stages. Furthermore, the load resistance required is only one-fourth that required in plate loading. This makes the problem of producing a high-quality transformer considerably simpler.

Since the output stage has no gain, high driving voltages are required. To obtain them a "bootstrap" driver circuit has been developed. In this circuit (Fig. 9-b) the plate loads of the drivers are returned to the plates of the opposite output tubes. Their signal voltages add to the dc potential applied to the driver plates, effectively raising their plate supply voltage.

National avoids the need for two high-current power supplies by arranging the circuit as in Fig. 9-c. The output transformer has two primaries with unity coupling. One is connected in the plate circuit of one tube and the other in the cathode circuit of the other tube. The output tubes' screen grid and power-supply filter capacitor improve the coupling between plate and cathode windings. Not as much drive is required in this circuit and the preceding amplifier is simplified, consisting of a single twin-triode. For a more detailed discussion of this circuit, see "Circuit Features in Hi-Fi Power Amplifiers," September, 1955.

Another form of this so-called "single-ended push-pull" style has been used in one commercial amplifier (the Stephens OTL) and may be used in the future because it permits coupling 500-ohm speakers directly to the amplifier without an output transformer. Fig. 10-a gives a very simplified diagram of one form of this circuit. The two grids receive out-of-phase signals. Two power supplies are used and balance is achieved by returning one grid to an appropriate negative voltage. The output is taken off the junction of plate and cathode and the impedance can be made low enough by paralleling a number of tubes to match the low impedance of a 500- or even a 16-ohm speaker.

Various methods of driving and of supplying the various voltages can be used. Fig. 10-b is a simplification of the output and driver stages of the Stephens amplifier. This configuration permits class-B operation but has two serious disadvantages: It is extremely inefficient even in class-B operation, the power output ranging from 1 to 10% of the input power; there is no common load in which distortion can be canceled. However, the absence of an output transformer permits the use of 40 db or more of feedback, which compensates for the higher initial distortion. It is probable that this circuit will appear in additional amplifiers in the future.

The driver is a cathode follower direct-coupled to the grid of the lower output tube. The output tubes are in series across the 500-volt supply and they feed the load in parallel. Current flows from ground through the cathode-plate circuit of the lower triode and then through the plate and cathode circuits of the upper tube. Signal voltage for the upper tube is taken off the plate of the lower and grid bias is developed by the drop across the cathode resistor.

The upper tube sees the lower as a cathode resistance shunted by the load and the lower sees the upper one as a plate load resistor. In each case, the load is capacitance-coupled to the source. Resistor R between the driver plate and the voltage-amplifier cathode provides inverse feedback to stabilize the amplifier against possible voltage drift.

The internal resistance of the lower triode varies as the signal applied to its grid. This varies the current through the upper triode and develops a signal voltage across the load. At the same time, the change in current through the tubes develops a signal voltage on the upper triode grid that is equal to and in phase with that applied to the lower triode grid. The blocking capacitor prevents dc from flowing through the load. END