A 200-Watt Solid-State Stereo Amplifier

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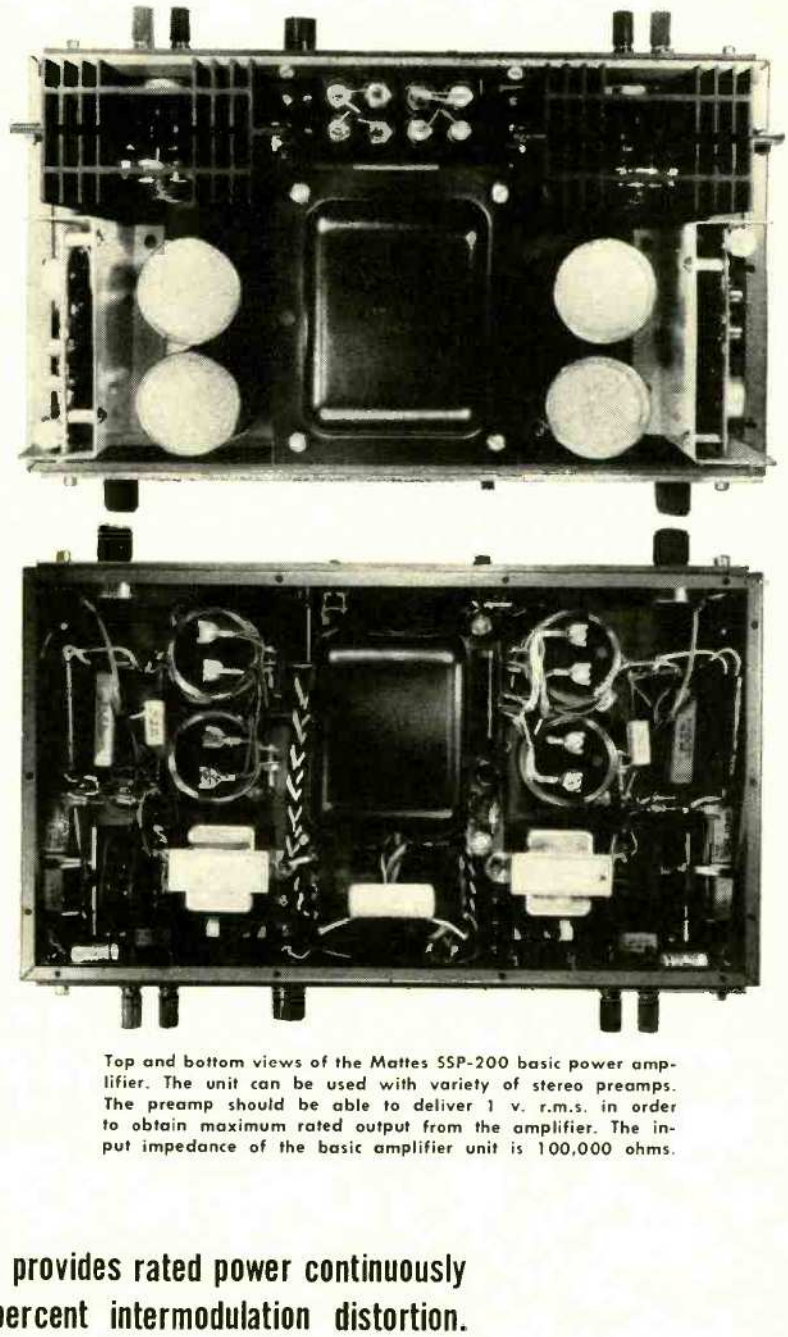


Top and bottom views of the Mattes SSP-200 basic power amplifier. The unit can be used with variety of stereo preamps. The preamp should be able to deliver 1 v. r.m.s. in order to obtain maximum rated output from the amplifier. The input impedance of the basic amplifier unit is 100,000 ohms.

New circuit advance provides rated power continuously at less than 0.1 percent intermodulation distortion.

WHEN transistor high-fidelity equipment first appeared a few years ago, high hopes were raised for the future of solid-state components. Transistor amplifiers would be small, powerful, deliver superb performance, and be inexpensive. Regular readers of ELECTRONICS WORLD need not be reminded that up to this time these hopes have not as yet been completely realized.

To some extent, the difficulties in designing high-quality power amplifiers with transistors have been due to inadequacies of the transistors available to the engineer; to some extent, the circuits used have imposed severe limitations. In this article, the authors will review the performance limits imposed by the problems inherent in designing power amplifiers with transistors, and introduce a new circuit design which largely overcomes these problems, while extending the state of the art of power-amplifier design.

Transistor Limitations

Although the design of a circuit usually begins with the establishment of performance requirements, it will be instructive to take as an example a good transistor and calculate the maximum performance which would be available from a pair of these used in a conventional circuit. The circuit chosen, for purposes of calculation, is a driver-transformer-coupled "totem-pole" class-B output stage using two transistors (Fig. 1A). The calculations are those to be found in any textbook on designing power-amplifiers using semiconductors.

For our transistor type let us take 2N3233 or 2N3055 silicon power transistors, which are readily available at low cost, and which because they may be operated at a higher junction temperature than germanium types, may allow us to draw more power from the circuit. Our answer works out to be approximately 50 watts per channel, using one 2-degree/watt heat sink for each transistor—about the practical limit in convection-cooled heat sinks of reasonable size.

It is important to point out that to achieve the 50-watt rating requires that the transistors be operated, under some conditions, at a junction temperature of exactly 200°C (392° F), and also that the maximum ambient temperature is 40°C (104°F), for the purposes of the example, although this maximum ambient rating is barely adequate for general consumer use.

Perhaps some engineers will be able to find ways to increase the continuous power rating beyond 50 watts, while others will wonder at our temerity. Let us say that the figure represents, in our opinion, a fair approximation of the maximum which can be expected when conventional circuits are used. Generally speaking, circuits without driver transformers will produce less power reliably. The use of non-linear biasing techniques might permit more than 50 watts, but at some cost in linearity. The major factor limiting the performance of a power amplifier using transistors is the change in characteristics which takes place with an increase in temperature, particularly the shifting of bias characteristics. These factors must be taken into account when the transistor dissipation calculations are made.

Principle of the New Circuit

If the need to bias the output transistors were eliminated, the calculations just performed would be somewhat simplified and would lead to a different result—about 125 watts continuous power per channel instead of 50. This is exactly the power output taken from a pair of 2N3055's in the circuit to be described which, in fact, eliminates the need to bias the output transistors. To accomplish this end, the circuit (upon which multiple U.S. and foreign patients are pending) employs two concepts which are new to high-fidelity solid-state power amplifier design. These are: (1) a power stage which is designed to operate with many of the characteristics of an Esaki (tunnel) diode, and (2) a system of latching diodes which serve a control function to be described below.

Due to its negative-input-impedance characteristics, a tunnel diode may be used as an amplifier with unity voltage gain but considerable power gain. Consider the combination of a low-power voltage amplifier, with very low distortion, coupled to a tunnel diode (Fig. 1B). With adequate feedback applied around the system, the result would be a linear power amplifier.

Many devices may be made to exhibit the negative-impedance characteristic shown by the tunnel diode. Such a device may also be simulated by a combination of more conventional components, an example of which is an oscillator that is just below its threshold of oscillation. Such a circuit, with its negative-impedance characteristics, has been used to make practical negative-impedance systems in which only current gain is desired, as in telephone repeater amplifiers and other specialized line amplifiers.

Assuming that the correct combination of components were employed for the purpose, the combination suggested above—the low-distortion voltage amplifier and the unity-gain negative-impedance stage—could be made to have high power and low distortion. Power would come to the load from the power supply through the negative-impedance device, while the signal voltage variation would be under the control of the highly linear voltage amplifier, which would also function as a driver amplifier.

The basic circuit of the new amplifier consists, then, of a low-distortion driver amplifier coupled both to the load and to a power oscillator, which is constantly on the brink of oscillation as its output is common to its input (Fig. 1C). The power oscillator is prevented from oscillating by making the driver amplifier of very low impedance so as to short-circuit the oscillator. The fact that the short-circuit is virtual, rather than real, is of no importance; the effect is the same.

Analysis of Operation

Analysis of circuits such as the one shown is rather lengthy, when rigor is required, but their operation is not really difficult to understand. While it leaves a great deal to be desired as a practical high-fidelity amplifier, let it be said at the outset that the schematic shown actually works. It is essentially the circuit used in the final commercial product, the *Mattes* SSP-200, although the SSP-200 also incorporates the latching-diode system to be described shortly. The easiest way to understand the operation of the circuit is to enumerate and consider the three different stages of operation during each cycle of signal.

1. At very low levels, the voltage across the secondaries of the driver transformer is insufficient to cause transistor action in the power transistors. Hence, the primary of the transformer and the power transistors are simply high impedances and do not affect signal flow. The driver amplifier drives the load entirely.

2. As the signal level increases, the power transistors begin to turn on and supply some current to the load. The driver continues to drive the load directly as well, although current is now drawn through the driver-transformer primary. The negative feedback loop adjusts the amount of drive to allow for current gain of the power transistors.

3. In the third stage of operation, the signal level has in-

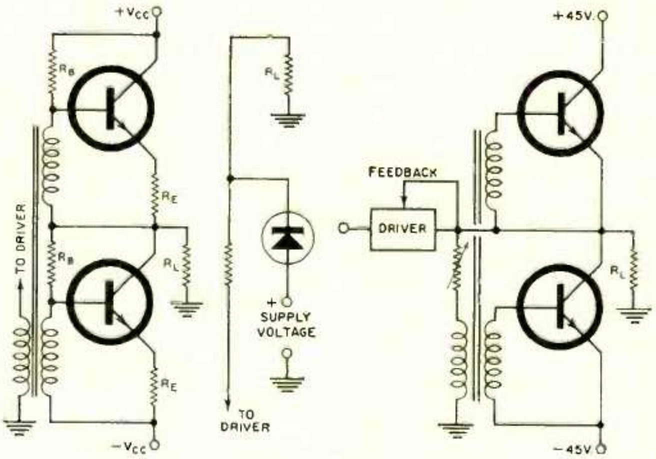
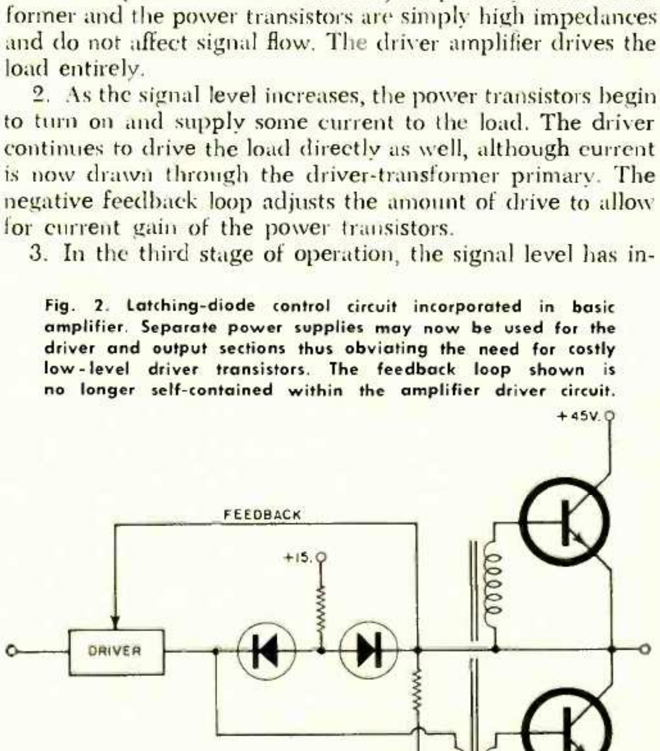


Fig. 1. (A) Typical transformer-driven output stage used in calculations. Emitter resistor value of 0.5 ohm is compromise between marginal stability and reduced efficiency. (B) Simplest form of tunnel-diode amplifier referred to in text. (C) Basic circuit of amplifier employing negative-impedance power-output stage. Negative-feedback loop is an integral part of driver amplifier; since output stage has one terminal for both input and output, feedback serves entire system.

Fig. 2. Latching-diode control circuit incorporated in basic amplifier. Separate power supplies may now be used for the driver and output sections thus obviating the need for costly low-level driver transistors. The feedback loop shown is no longer self-contained within the amplifier driver circuit.



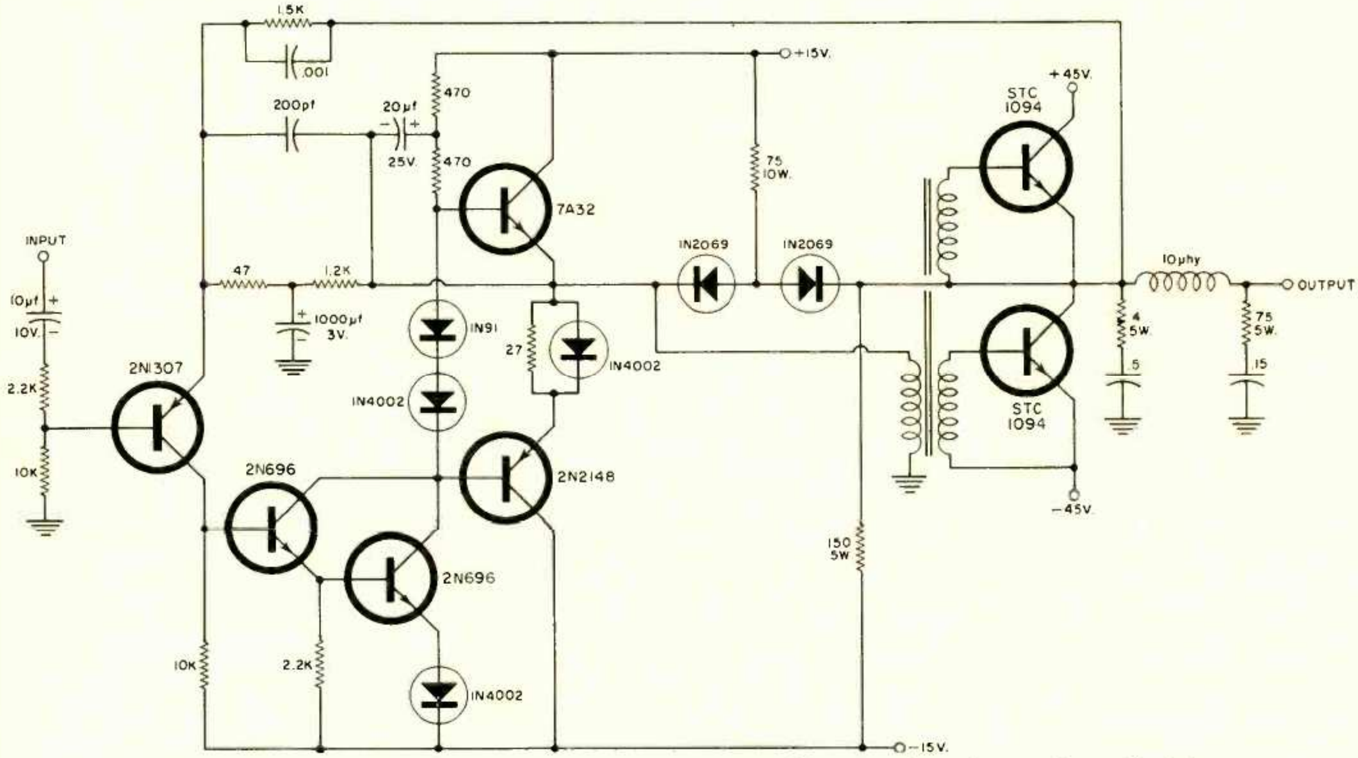


Fig. 3. Complete schematic of practical 100-watt-per-channel power amplifier. Note that only one of two identical stereo channels is shown and that the power-supply circuit has not been illustrated. Incidentally, the resale price of the output transistors shown is around $23 each, while the 2N3055 or 2N3233 mentioned in the text cost about $5 each. Because of the use of special, custom-built driver transformers and special wiring techniques, home construction is not recommended.

creased further, the power transistors are operating fully, and are supplying all the current to the load. Furthermore, current from the output stage is actually helping supply its own input, while the driver supplies no power to speak of, only a voltage control signal. As current comes backward toward the driver from the power stage, the apparent impedance of the load rises enormously. As a result, the driver, which would have been limited to the delivery of a volt or two across the low-impedance load, is now able to swing the full extent of the power supply, as it is not called upon to supply power to the load.

Although not practical, for reasons soon to be explained, the circuit just discussed does have several intriguing properties. One is that a short-circuit of the output terminals is actually a short-circuit of the driver, which immediately gives all of its power to the short-circuit, leaving the power transistors intact. Since the driver is power-limited, it is unharmed.

At low levels, the circuit is d.c.-coupled, permitting the application of d.c. feedback, thus stablizing the d.c. level at the output terminals. On the other hand, high-level signals are transformer-coupled, affording the design engineer a chance to eat his cake and have it too. The circuit is d.c.-stabilized by feedback, yet can be made to roll off at any desired low-frequency point by proper design of the driver transformer. Since there is no bias circuit to adjust, fluctuations in the power supply to the output transistors will have no effect upon distortion, but only upon maximum power output. Moreover, the output transistors may be switched from *p-n-p-* to *n-p-n* or one of each, at will, provided only that they are connected with proper polarity; there are no bias circuit adjustments to be made, since there is no bias.

There is one serious drawback, however. The maximum voltage swing across the load is determined by the driver transistor voltage ratings, not the ratings of the power transistors. This is because the gain of the power stage is unity, making the voltage swing across the driver and output terminals the same. Therefore, the driver transistors must have the same voltage rating as the power-stage transistors. Consequently, either costly low-level transistors must be employed to achieve high power output, or one must be content with the low power levels resulting from the use of reasonably priced driver transistors. To eliminate this difficulty, we operate the power stage from its own high-voltage supply, which requires a means of isolating the two halves of the amplifier—but only for part of the time.

Latching-Diode Control Circuit

The controlled isolation of the power stage of the amplifier from the driver is accomplished by the addition to the circuit of two diodes and two resistors, in the configuration shown in Fig. 2.

The operation described earlier takes place as stated. The new circuit comes into play when the voltage gain of the power transistors causes the voltage across the load to swing out-

Fig. 4. Intermodulation distortion with 8-ohm loads. At power levels from about 10 watts to beyond 100 watts per channel, the intermodulation distortion is below 0.1%

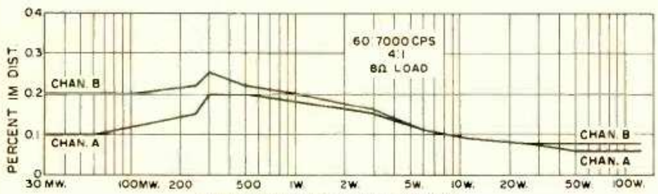
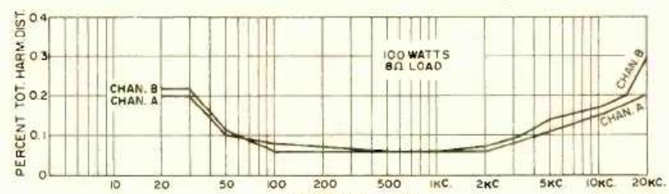


Fig. 5. Total harmonic distortion as measured at 100 watts output, 8-ohm loads. Over much of the range, the total harmonic distortion is below the 0.1 percent level.



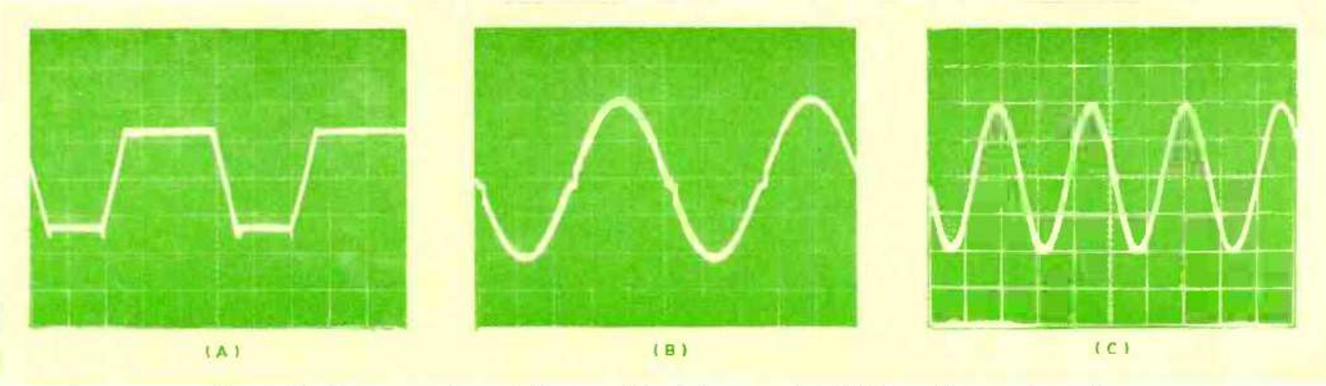


Fig. 6. (A) Output waveform of driver-amplifier during operation. (B) Output of power stage with latching diodes removed shows crossover-distortion notches. (C) With diodes inserted there is no discontinuity in the output waveform, which now measures less than 0.1 % total harmonic distortion.

side the domain of the driver power supply, which in this version is considerably less than that of the power stage. Under these conditions, the diodes appear as a high impedance, since they are reverse biased. This accomplishes the purpose of isolating the driver amplifier from the power transistors when this isolation is needed, while permitting the system to operate as the basic circuit, the rest of the time.

Complete Schematic

The complete schematic (Fig. 3) incorporates a few additional features which are worth explaining. One is the low-pass filter at the output. This has been used to remove very high frequency components from the signal which cannot be eliminated by feedback, due to the transit-time effects present in any power transistor. It has no audible or measurable effect upon performance.

The winding ratio chosen for the driver transformer is conventional—three to one. However, to take full advantage of the circuit's possibilities, the coupling must be extremely tight and the secondary windings must have as low a d.c. resistance as possible in order to achieve good transformer efficiency.

The circuit of the driver amplifier is relatively conventional and can be further simplified if higher distortion is tolerable. Its essential properties are very low output impedance, adequate power capability to drive the load through the crossover region when the power transistors are not yet conducting, as well as to drive the output transistors through the transformer, and d.c. coupling to allow feedback to minimize d.c. drift from input to output terminals.

Advantages of the Circuit

The most obvious advantage of the circuit is its ability to provide exceptionally high power at very low distortion across the entire band from 20 to 20,000 cps. See Figs. 4 through 6. The actual continuous power of 100 watts per channel is more than that of any other hi-fi amplifier of which we know.

The cost of such a circuit is not high, and makes possible the manufacture of high-quality power amplifiers at lower cost than has been possible until now. Accidental short-circuit of the output terminals during operation has no other effect than to turn off the signal to the loudspeakers until the short-circuit is removed. This is done without use of thermistors, light bulbs, relays, or special circuitry.

The efficiency of the power stage actually exceeds, by a small amount, the theoretical maximum of 78% usually cited by class-B circuits, since some of the power to the load (less than a watt) comes directly from the driver. No matched components are used at all—and no resistors are closer in tolerance than 10%. Except for the transformers and circuit boards, which are usually custom-made for any amplifier, all parts can be bought from electronic parts distributors' shelves without selection.

The power transistors chosen for the output stage must, however, be rated at 15 amperes collector current or higher, if the short-circuit-proof feature of the design is to be retained (Fig. 7). Otherwise, type 2N3233 transistors (*Silicon Transistor Corporation*) or type 2N3055 transistors (*RCA*) may be used.

At very low levels, distortion remains low, unlike many other solid-state amplifier circuits, because the load is driven by the driver-amplifier, which has enough gain to permit negative feedback to correct distortion. Usually, the low gain of power transistors at low currents renders the feedback less effective at these levels. All adjustments have been eliminated, as may be seen from the schematic. Having dispensed with adjustments, it is possible to dispense with the meters provided to monitor these adjustments.

Final Note

Engineers interested in power stages operating without bias will probably find it interesting to read about an entirely different means to this end in a paper available as a reprint from *General Radio Company*, West Concord, Mass. The title of the paper, which originally appeared in *Solid State Journal*, December, 1961, is "High Impedance Drive for the Elimination of Crossover Distortion" by James J. Faran, Jr. and R. G. Fulks.

Readers are again reminded of the proprietary nature of the circuit discussed in this article, and its coverage in patent applications. ▲

Fig. 7. Scope record of amplifier behavior when output is short-circuited. The portion of the waveform at the left shows the 1-kc., 100-watt output of the amplifier. Then the output is shorted and output drops to zero. After about 10 sec., short is removed. Note that full output is restored immediately after brief starting transient.