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High-Power Audio Amplifiers

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As we increase the power output of an amplifier, we run into a whole new set of problems which are of importance to the designer and which must be solved properly and efficiently. Learn what these problems are and how they have been handled by one manufacturer.

THE CURRENT TREND toward more reserve power from high-fidelity audio amplifiers, has led to the need for the exertion of more care in the design of the power and output stages. Poor design can lead not only to electrical component or tube failure within the amplifier, but may result as well in tweeter-voice-coil burn-outs when an unchecked supersonic, audio, or parasitic oscillation is present at the output.

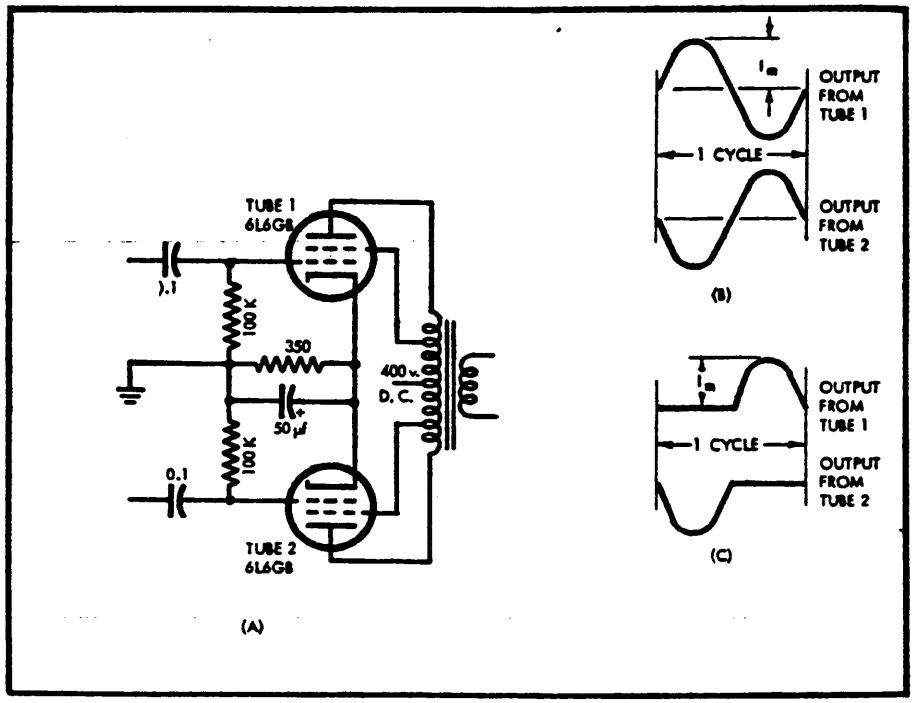

Fig. 1. (A) Schematic of typical Ultra-Linear push-pull output stage using 6L6GB tubes in Class AB. U-L tap is at 43% of turns from center on each side, or at 18.5% of total impedance. (B) Output over one cycle from each tube when biased for Class A operation. (C) Output from each tube if fixed bias is applied to obtain Class B operation.

Output Tube Efficiency

There are several tube types capable of high power output. The European EL-34/6CA7 can deliver as much as 100 watts in push-pull pentode operation. The Tung-Sol 6550 can do the same. However, the EL-34 is more efficient, dissipating less heat within the tube for specific power outputs, than does the 6550.

The efficiency of an output tube is defined as

$$\frac{\text{AC power delivered to the load}}{\text{plate} + \text{screen} + \text{heater power dissipations}} \times 100\%.$$

Table I compares the power dissipated at the quiescent conditions by both the EL-34 and the 6550, when operated so as to permit the delivery of 100 watts to the load. The EL-34 dissipates 26 per cent less power than does the 6550. Although both tubes are excellent and especially well designed for high power applications, economy in design tends to indicate the use of the EL-34 rather than the 6550.

For clean, high power output, it is obvious to resort to push-pull operation. Maximum power considerations dictate the use of pentodes, but maximum curve linearity for the low distortion necessary in high-fidelity amplifiers would suggest triode operation. However, the best compromise is accomplished with true Ultra-Linear circuitry, (A) in *Fig.* 1, where linearity equal to or better than triodes is achieved while at the same time delivering power outputs comparable with that of the pentodes.

Tests that I have run indicate that this method of operation permits raising the screen voltage about 20 per cent above the manufacturer's specifications without any injury to the output tubes. However, this should not be done if the screen power dissipation ($E_{sc} \times i_{sc}$) or plate power dissipation ($E_{bb} \times i_b$) is higher than that recommended by the manufacturer. (Note: the above formulas for plate and screen dissipations are for fixed-bias applications only. When cathode bias is used, the plate and

TABLE I

COMPARISONS BETWEEN 6550 and EL-34

	6550	EL-34/6CA7
Plate Dissipation $E_{bb} \times i_b$ watts	$600 \times 50 \times 10^{-3} = 30$ watts	$800 \times 25 \times 10^{-3} = 20$ watts
Screen Dissipation $E_{sc} \times i_{sc}$ watts	$300 \times 1.5 \times 10^{-3} = 0.45$ watts	$400 \times 4 \times 10^{-3} = 1.6$ watts
Heater Power $E_f \times i_f$ watts	$6.3 \times 1.8 = 11.4$ watts	$6.3 \times 1.5 = 9.45$ watts
Total Dissipation per tube—watts	41.85 watts	31.05 watts

E_{bb} = plate supply voltage
E_{cc} = fixed cathode bias voltage
E_{sc} = screes supply voltage
E_f = filament voltage
i_b = zero signal plate current
i_{sc} = zero signal screen current
i_f = filament current

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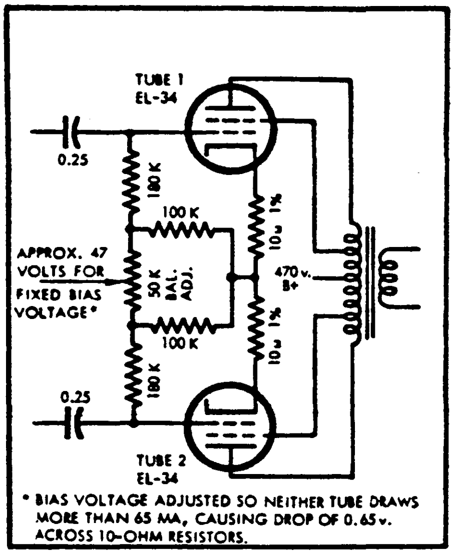

Fig. 2. Typical Class AB or Class B amplifier as used in EICO HF-50, HF-52, and HF-60 amplifiers. "Balance adjust" pot biases each tube properly for its individual curve variation.

screen dissipations become $(E_{bb} - E_{cc})i_b$ and $(E_{sc} - E_{cc})i_{sc}$ respectively.)

Two tubes, connected in push-pull circuitry and operated class A [each tube conducts through the complete cycle as in at (B) in *Fig.* 1] can deliver a specific amount of power before the plate and screen power dissipation ratings are exceeded. For more power output from the same pair of tubes without exceeding the ratings, they must be operated more efficiently.

This can be accomplished by decreasing the amount of plate and screen current the power supply must deliver per tube in each cycle—each tube would conduct for a shorter period of time per cycle, or for less than a complete cycle. The limit of this in audio work is class B, where each tube conducts for exactly one-half of each cycle, (C) in *Fig.* 1. The effective current per cycle that each tube takes from the power supply is low, for each tube conducts current only half the time—for one-half of each cycle.

Power Dissipation

The power dissipated in the tube is proportional to the total current passing through each tube over a complete cycle, that is, the average current. For the same amount of power being delivered to the load, each tube will dissipate less plate and screen power in class B than would be the case for class-A operation. Since plate and screen currents are lower per cycle in class B, the voltage applied to these electrodes can then be increased until the maximum plate and screen d.c. power dissipations are once again reached. These permissible additional voltages permit a pair of tubes to deliver higher output powers.

Although class B is used when there is a need for greater efficiency, class A provides better linearity and lower distortion. The obvious course is to choose a condition between class A and class B for best operation, in which the tube conducts for more than one half the cycle, yet less than the complete cycle. This is known as class AB. For maximum power, it is best that the bias on the tube grids be adjusted so as to approach as closely to class B as is possible without introducing excess distortion.

Figure 2 shows a schematic of a power output stage which can be used in class AB operation. A d.c. balance control was included for lower hum, distortion and output tube protection. Fixed bias, a necessity for the cutoff conditions in class B, is used here in class AB to maintain constant operating conditions for the tubes.

When tubes are biased so as to operate close to class B, each tube works on a nonlinear portion of its individual plate characteristic curve, although the composite curve for the two tubes is reasonably linear. On a curved portion of the characteristic, only a substantial change in bias voltage can alter the amount of plate current each tube is conducting as shown in *Fig.* 3. Near cutoff, tube characteristics vary considerably from tube to tube due to curvature. Each tube must have its individual bias adjusted so as to control the individual tube currents. This can be accomplished with the balance control.

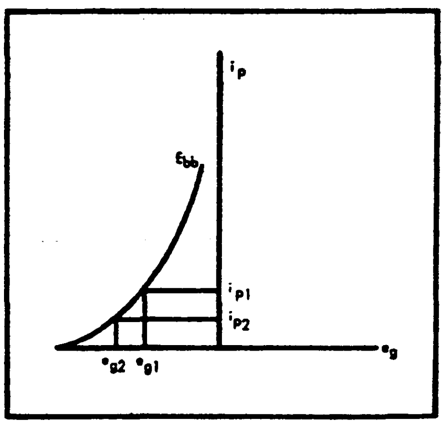

Fig. 3. Plate current variation with bias voltage.

Unbalance, resulting in excess current in one of the tubes, can damage it irreparably, for added current through the tube means added power dissipation by the tube. The d.c. balance control adjusts the bias on each tube just differently enough (consistent with its own peculiar plate characteristic) to allow each tube to conduct the same amount of current, even if each one must work at slightly different portions of their respective grid characteristic at quiescent conditions.

Under high signal conditions, the d.c. is slightly unbalanced despite the use of a balance control. This is because the different tube characteristic of each output tube near cutoff, as described. However, the tubes are protected. Much of the power that is dissipated in the plate and screen circuit in the quiescent state is dissipated by the output load when a signal is fed through a class AB amplifier.

The slight d.c. unbalance is also insignificant at high signal conditions, since any inequality in each curve is applied to a minute portion of the complete signal, thus not appearing as distortion. This condition, coupled with an excellent phase splitter (such as the Clare Cathode-Coupled type) makes an a.c. balance control unnecessary.

This balance adjustment can be checked in several different ways. It may be checked audibly by adjusting the control for a minimum hum condition. A more accurate method provides an accommodation to use a milliameter temporarily in each cathode. Here, the balance control is set to make the currents equal.

A simpler method is the addition of a small 1 per cent resistor in each cathode, as in *Fig.* 2. When the voltages across both resistors are equal, the currents through the tubes are equal $(E = IR)$.

The Output Transformer

A good output transformer is extremely important in high-power applications. An efficient unit will permit more of the power developed by the tubes to be delivered to the load.

Efficiency in a transformer is a function of the core losses (hysteresis) and the d.c. resistance of the winding. Since the magnetizing current through the transformer is low, efficiency is primarily dependent on copper losses—the winding resistance. The unit with lower primary and secondary resistance is thus the most efficient.

It is well known that the maximum power delivered to any type of load, is at its peak when the source impedance is equal to the load impedance. However, for minimum distortion, the impedance the output tubes must "see" is different from their actual internal (source) impedance. When the EL-34 "sees" 4000 ohms, the best compromise between maximum power and minimum distortion is achieved.

A speaker—usually about 16 ohms—is the actual final load impedance. For maximum undistorted power to be delivered to the speaker, the output transformer should match the 4000 ohms to the 16-ohm speaker accurately.

Transformers used in high-power applications should have additional turns ratios to accommodate 4- and 8-ohm speakers. Many high-quality speakers have 8-ohm impedances. A 4-ohm impedance is necessary for use with several

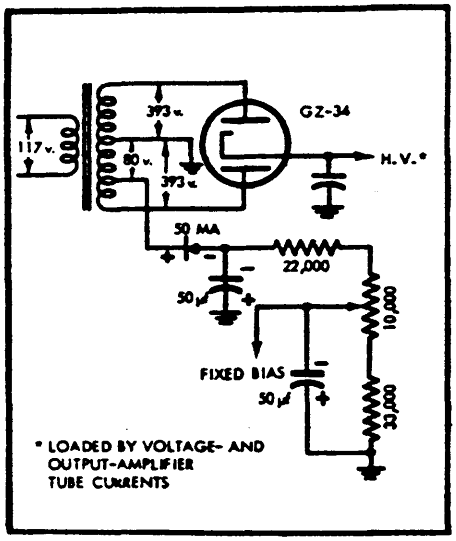

Fig. 4. Fixed bias supply voltage as used in amplifiers of Fig. 2. "Bias" pot adjusts bias voltage—for EL-34's, plate current should be 65 ma in this circuit.

of the excellent but low-efficiency speakers now on the market. To provide these additional impedances, the secondary of the transformer is tapped at points providing appropriate impedance ratios. Transformer manufacturers indicate in their specifications the impedance ratios supplied in their units.

The transformer used should also be capable of a wide-band flat frequency response to provide for stability in feedback circuits, as well as fidelity. The primary inductance must be high enough to prevent a rolloff of the low frequencies while the leakage inductance (theoretical equivalent inductance between the primary and secondary) must be low, not to allow rolloff at the high end of the audio-frequency spectrum. There must be sufficient high-grade steel laminations to permit a full-output power response down to the lowest audible frequency.

Power Supply

The power supply affects the response as well as the power output. The fixed bias (necessary in class B or class AB when operated close to class B) as well as the high voltage must provide good regulation. These voltages must remain reasonably constant over a large range of current variations to keep the output tubes working at their prescribed conditions for maximum output. Low rectifier and power-transformer-winding resistances help maintain the regulation. This same low impedance is necessary to retain the high output power at the low end of the audio spectrum.

There are many methods of obtaining the fixed bias. Manufacturers of amplifiers can have a transformer made with an extra winding for this purpose. The voltage at this winding is rectified, well filtered, and applied to the grids of the output tubes. Some commercial high power amplifiers tap the high voltage winding as shown in *Fig.* 4.

Another method frequently used when special tapped transformers are not available employs a filament transformer in reverse. The 6.3-volt winding is connected across the filament winding on the main power transformer. Approximately 110 volts will then appear across the primary of the filament transformer. This 110 volts is rectified, filtered, and used to supply the bias for the output tubes as shown in *Fig.* 5. Although expensive, this method can be used by the

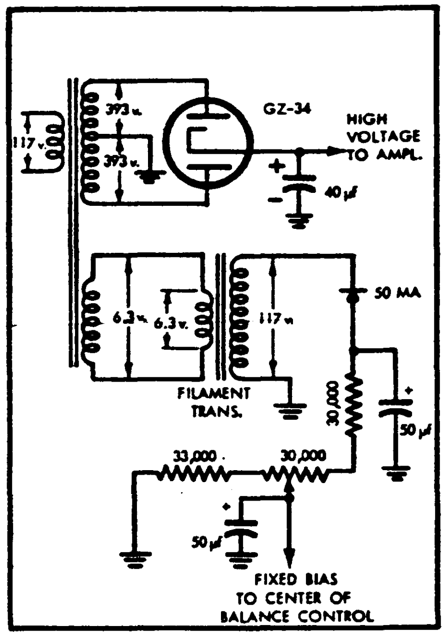

Fig. 5. Fixed bias supply using standard components.

amplifier builder without access to special transformers.

The high d.c. voltage shown in *Figs.* 4 and 5 is secured from a rectifier tube with a separate, rather than a filamentary type cathode. There is an important reason for this.

The filter capacitor used in this type of amplifier must be of the electrolytic type to conserve space. Oil-filled capacitors would require about six times the chassis area, providing no true advantage. Unfortunately, electrolytic capacitors are rated only at 500 working volts, with instantaneous peaks up to 575 volts. For longer life, the voltage applied to the capacitor should be kept within 500 volts. It should also be noted that the high voltage to be applied to the output tubes (such as the EL-34 under Ultra-Linear operation) is 470.

To fully understand why this requires the use of a rectifier with a separately heated cathode, it is only necessary to draw the equivalent circuit of a power supply. In *Fig.* 6, (A) shows the secondary of a power transformer supplying an a.c. voltage to the rectifier tube, which transforms the voltage into pulsating d.c. This in turn, is filtered to a smooth voltage by the electrolytic capacitor, *C*, and applied to the load, R_l.

(B) shows the equivalent of the circuit in (A), with the transformer drawn as an inductance, *L*, and the applied a.c. voltage in series with the transformer winding resistance, R_t. The rectifier tube is shown as a unidirectional element in series with the plate resistance, R_p, of the tube. Since these resistive elements are in series with the rectifier, the equivalent circuit can take the form of (C) in *Fig.* 6.

As a theoretical example, let the rectified voltage, $E_{dc} = 550$ volts, $R_t = 100$ ohms, $R_p = 200$ ohms, and the load resistance, $R_l = 1720$ ohms. When this total resistance, $R_t + R_p + R_l = 2020$ ohms is connected across the rectified d.c. voltage, E_{dc}, the current flowing is 550 volts/2020 ohms, or 250 ma ($I = E/R$). When this current flows through R_t and R_p, the voltage drop through these resistors is 250 ma × (100 + 200 ohms) = 75 volts. The voltage remaining across the load resistor, R_l, is then the total d.c. voltage, less the drop through R_t and R_p, or 550 − 75 = 475 volts. Since the load is

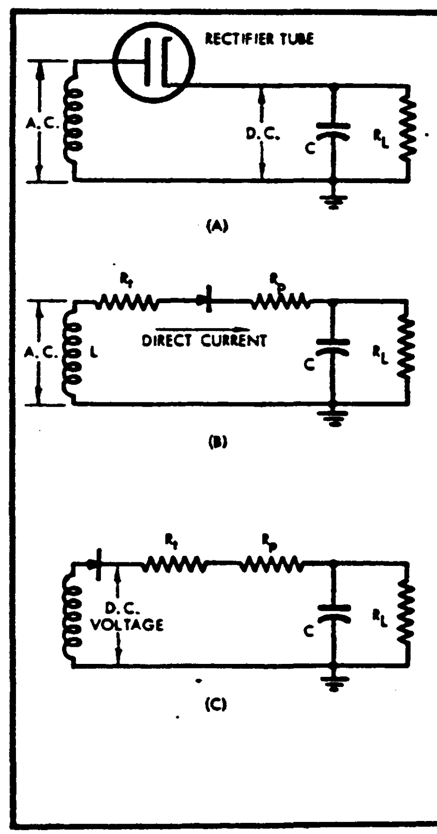

Fig. 6. (A) Power supply schematic. (B) Equivalent of (A), with transformer replaced by L and R_t, tube replaced by unidirectional element and plate resistance, R_p. (C) Positions of R_t and rectifier reversed, a permissible operation in a series circuit. When R_t is connected, direct current flow causes voltage drop in R_t and R_p.

in parallel with the filter capacitor, C, this 475 volts also appears across this capacitor. If the capacitor is rated at 500 volts, it will not break down.

Next, assume the same circuit as at (C) in *Fig.* 6; this time the load resistor, R_L, is omitted. Since there is no completed d.c. circuit, no d.c. current flows; no flowing current means no voltage drop across R_t and R_p. Therefore the entire 550 volts appears across the filter capacitor, C, the open circuit for d.c. This 550 volts can easily damage a capacitor rated at 500 volts if kept there for a long period of time or applied frequently.

This is exactly what happens when there is no separately heated cathode in the rectifier tube.

A rectifier with a filament type cathode, such as the 5Y3G or the 5U4GB conducts at the moment the amplifier is turned on. The output tubes have not had the time to heat their cathodes so as to start conducting. Since there is no current being drawn from the high-voltage power supply for the first half to three-quarters of a minute, (while the output-tube cathodes are warming up) there is no current flowing through the power supply and rectifier tube. No flowing current means no voltage drop in the rectifier tube and power transformer (*Fig.* 6). All the high voltage then appears across the electrolytic capacitor, and this may damage it.

The solution to this problem is to prevent the rectifier from heating up fast and setting up a high voltage before the output tubes start conducting. A slow-heating, separate cathode will provide this necessary time delay to protect the electrolytic capacitors, while the output tube cathodes are heating up. This will prevent the initial excess voltage surge, protecting the capacitor.

Tubes like the 5V4G provide this feature. However, for higher current applications, as in high power amplifiers, either two 5V4G's are necessary or the European GZ-34 made by Mullard and Amperex, may be used.

Mechanical Considerations

There are several layout factors which must be carefully considered for a successful and durable amplifier.

The internal volume of tubes such as the EL-34 is small. It thus needs a large ventilating area outside of the tube bulb to conduct away the excess heat. Tube manufacturers claim that the tube life of this (and any other tube) is an inverse function of the bulb temperature. They recommend that the maximum bulb temperature of 250° C should not be exceeded. (The bulbs of the tubes used in two EICO units were measured with Tempilac and did not exceed 230° C. under any enclosed conditions.)

To accomplish this, Mullard recommends as a rough approximation a distance of 40 millimeters or 1 9/16 in. between two tube bulbs and 30 millimeters or 1⅜ in. between any tube bulb and any other component mounted on the chassis. These temperature specs should be carefully observed when using these or any other output tubes, although the distances between different types may vary. A good rule-of-thumb is one bulb diameter of space between tubes. However, this can vary considerably as in the case of the 6L6GB, 6550 and EL-84.

Power transformers should not be mounted close to the hot tubes. Although the transformer itself may have a low temperature, being placed too close to these tubes can raise the ambient temperature to such a degree that when added to the transformer's own temperature rise, the insulation can break down.

Another important consideration for a successful amplifier is the electrolytic capacitor. These components must run cool. At high temperatures (above 85° C. in some cases and above 65° C. in most instances) these capacitors may become excessively leaky. They may short out entirely, or ruin the rectifier tube. Electrolytic capacitors should not be mounted near hot components such as power output tubes and power transformers.

Ventilating slits or holes between and around hot tubes and transformers is a good method for cooling the components. These slits will provide a chimney effect, affording excellent ventilation. The bottom plate on the chassis should have similar holes and be raised from the actual mounting shelf to permit cool air to rise into the chassis. If a protective cover is used, this too should have enough open spaces to provide good ventilation. It should, however, be noted that good ventilation is no substitute for proper spacing of components. Æ