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High-Efficiency R. F. Amplifiers

By the Engineering Department, Aerovox Corporation

THE principal advantage of the class-B linear r.f. amplifier, shown in Figure 1, is the ease with which it may be applied to a radio transmitter to amplify a modulated signal. An output amplifier of this type enables modulation to be carried out in one of the lower-powered stages, where less audio power is required, and provides a simple means of increasing the power output of an existing transmitter.

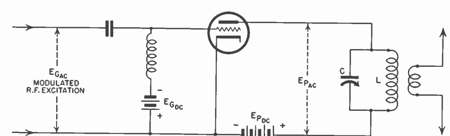
The principal advantage of the grid-modulated r.f. amplifier is likewise its economy of audio power. The modulating voltage being applied, in this case in series with the d.c. bias and r.f. excitation voltages, the audio power required for complete modulation is negligible compared to that required for complete plate modulation of the same amplifier.

The principal disadvantage of both types of amplifier has been the reduced power output resulting from the conventional methods of operation. To understand the reasons for this reduction in output, let us investigate the manner in which the linear amplifier is generally operated.

CLASS-B OPERATION

The grids of the class-B r.f. tubes are biased approximately to cut-off, since it is at this particular point of operation along the Eg-Ip characteristic that the fundamental component of r.f. plate current is closely proportional to the r.f. grid voltage, a condition necessary for high-quality amplification. The plate current wave is then in phase with the r.f. grid voltage. The r.f. component of plate voltage, on the other hand, describes a wave, the half cycles of which extend above and below a line established by the d.c. plate voltage value, and is 180° out of phase with the r.f. grid voltage. The plate voltage phase is determined by the tuned coupling circuit which is anti-resonant at the fundamental operating frequency. The plate current flows only during positive half-cycles of r.f. grid voltage as a result of the adjustment of the bias voltage to cut-off. These relations are shown in Figure 2.

Because of the phase relationships between r.f. plate voltage and r.f. plate current, maximum plate current is seen to flow at the instant of minimum plate voltage. Conversely, plate current is zero when the plate voltage wave is at its peak. Large amplitudes of the plate voltage wave mean low negative swings. The lower these negative peaks, the lower will be the product EpIp, expressing the plate power loss in the tubes, and the higher will be the amplifier efficiency. The efficiency of the conventional class-B linear amplifier is thus very closely proportional to the r.f. plate voltage amplitude, and it is evident that instantaneous increases in plate voltage level during amplitude modulation give rise to increased efficiencies.



CLASS-B LINEAR AMPLIFIER

Tube views tuned coupling circuit as pure resistance when L-C is tuned to antenna. L-C combination has maximum impedance in carrier channel; low impedance for higher and lower frequencies. Hence $E_{P_{AC}}$ is very nearly sinusoidal.

FIG. 1

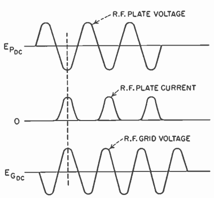


FIG. 2

The process of amplitude modulation may produce large plate voltage amplitudes with negative peaks far enough below the zero axis for instantaneous efficiencies between 60 and 70 percent, when the grid excitation voltage is modulated. For 100% modulation, however, the unmodulated plate voltage amplitude must not exceed one half the modulated amplitude. The unmodulated efficiency of the amplifier is consequently only half the theoretical possible value, or 30 to 35 percent. Even under these conditions, the *effective efficiency* taken over the entire modulation cycle has been found to be only fifty percent or thereabouts.

In the class-B r.f. amplifier, the unmodulated amplitude of r.f. plate voltage is reduced to half the modulated value by lowering the r.f. grid voltage to 50% of the value required for maximum antenna current (or maximum r.f. plate voltage). At this point, the power output is one fourth of the theoretical maximum.

The r.f. plate voltage and antenna current increase linearly with the excitation voltage in a class-B r.f. amplifier until the tubes reach the point of saturation determined by their cathode emission. After this point is passed, both the r.f. plate voltage and antenna current depart from linearity, further increases in excitation voltage resulting in little, and finally no further increase in either plate voltage or antenna current. (See Figure 3). If the r.f. grid voltage has been adjusted to give an unmodulated r.f. plate voltage amplitude at or near the saturation value, and modulation is then applied, there can be no further increase in either the plate voltage or antenna current amplitudes, but a decrease (negative swing) may still be obtained on negative modulation peaks. As a result, positive peaks of the carrier current and voltage (and plate voltage) will be flattened off, or distorted, at the saturation level, while the negative peaks may remain quite normal in shape. A means of supplying the missing positive peaks would enable operation of the amplifier at high levels of zero-modulation efficiency and increased overall efficiency.

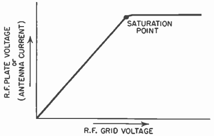


FIG. 3

THE DOHERTY HIGH-EFFICIENCY AMPLIFIER

In the circuit developed by W. H. Doherty of Bell Telephone Laboratories, two amplifier tubes are assigned different functions. One is operated at maximum efficiency to deliver a high value of resting carrier, while the other comes into operation automatically, as will be shown, to supply the r.f. plate voltage peaks which the first tube is incapable of developing. In consequence of their functions, these tubes are designated *carrier tube* and *peak tube*, respectively.

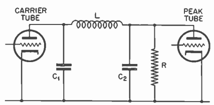


FIG. 4

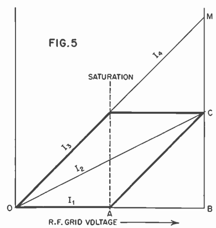
The skeleton circuit of Figure 4 shows the arrangement of components for accomplishing this action. The two tubes are assumed to have identical electrical characteristics and to receive r.f. excitation from a common source. The load impedance, represented by the pure resistance, R, diagrammatically represents the conventional tuned coupling circuit through which the amplifier delivers output power.

The peak tube works directly into the load impedance, while the carrier tube has a radio-frequency filter network (L-C_1-C_2) interposed between its plate and the load. This network is electrically identical with a *quarter-wave transmission line* and like that device possesses the property of impedance inversion. That is to say, the impedance exhibited at one end of the network is inversely proportional to that measured at the other end. Thus, if the load impedance is R ohms, the carrier tube plate "sees" 1/R ohms.

The d.c. grid bias of the peak tube is of high value, in order that plate current flow through that tube will be checked at all ordinary values of r.f. grid voltage. The carrier tube bias, on the other hand, is adjusted to cut-off so that that tube operates at maximum efficiency.

If the excitation is increased uniformly from zero, the carrier tube output delivered to R through the network will increase linearly until plate-circuit saturation is reached, whereupon it will level off at a constant value for any further increase in excitation. Meanwhile, a high value of bias has delayed operation of the peak tube. As excitation is increased beyond the point of carrier tube saturation, the effect of this bias is overcome, and the peak tube begins to deliver power to the load along with the carrier tube. The initiation of operation of the peak tube effectively increases the impedance terminating the network. Through the impedance-inverting property of the latter, the impedance presented to the plate of the carrier tube is decreased. This permits the power output of that tube to increase still further without any increase in its alternating plate voltage. Further increase in excitation causes the peak tube to contribute still more power to the load, at the same time permitting the carrier tube output to increase simultaneously. The final result of this action is that, at the instantaneous value of plate voltage amplitude corresponding to the modulation peak, the carrier tube delivers twice its original output power at no increase in output voltage. Half the power in the load is at that instant being furnished by the peak tube.

A graphical clarification of this action is given by Figure 5. As the r.f. grid voltage increases during the modulation cycle, the amplitude of r.f. current delivered by the carrier tube to the load through the network increases linearly from point O until the grid voltage reaches point A, corresponding to saturation. This is the resting carrier point. At this point, this current ceases to increase with the grid voltage and extends along a flat line to axis B at point C.



I_1 = Peak tube-to-load current.
I_2 = Carrier tube-to-network current.
I_3 = Network-to-load current.
I_4 = Total load current.

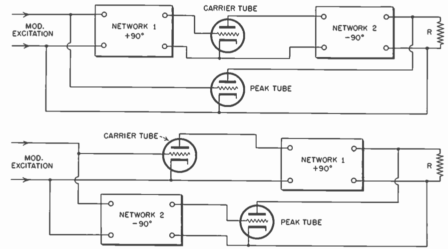


FIG. 6

Meanwhile, the peak tube has been inoperative for all values of r.f. grid voltage up to point A. After the excitation voltage has passed this point, however, (such as during the modulation cycle), the amplitude of current delivered to the load by the peak tube then increases linearly, as indicated by the lowermost curve, extending uniformly to line B at point C.

The current delivered to the load by the peak tube thus increases from zero at the resting carrier point to a value beyond the carrier amplitude equal to the network-to-load current. This condition of peak amplitude equal to twice the resting carrier amplitude is given by the total length of the curve OM and is the well-known condition of 100 percent modulation.

A by-product of the network action is the introduction of a 90° phase shift. This is not aimed at in the design but is an inherent property of the network as an impedance-inverting device. It is necessary to take this phase shift into account when a high-efficiency amplifier is laid out, since both tubes are to be driven from the same r.f. exciter. A second network must be introduced into the grid circuit of either one of the tubes, as shown in the alternative schemes in Figure 6. to secure the proper plate and grid phase relationships.

Doherty has given 62 percent as the overall efficiency of an experimental high-efficiency amplifier designed for a 1-kilowatt carrier.

TERMAN-WOODYARD AMPLIFIER

F. E. Terman and J. R. Woodyard have made use of the impedance-inverting network just described in their development of a high-efficiency grid-modulated amplifier operating along the same lines.

In this amplifier, carrier and peak tubes are employed in the same functions as in the Doherty circuit. A network equivalent to a quarter-wave line (see L-C_1-C_2 in Figure 7), together with the peak tube, acts as a variable impedance into which the carrier tube operates. With this arrangement, as with the high-efficiency linear amplifier, the r.f. voltage of the carrier tube is allowed to remain constant while antenna voltage and plate current are permitted to vary. In addition to this function, the peak tube also supplies additional power during positive modulation peaks in the manner already described for the high-efficiency linear amplifier.

The two tubes are separately biased. Eg_1 and Eg_2 are so chosen in magnitude that both carrier and peak tubes operate as class-C amplifiers with high plate-circuit efficiency. However, the peak tube bias is maintained at a higher level than that of the carrier tube. so that the former tube is inoperative between zero and maximum resting carrier level. The peak tube is automatically brought into operation when the carrier tube has reached maximum carrier output level; and then delivers its full output to the load, at the same time increasing the apparent load resistance presented to the network output. The alteration of the load resistance simultaneously permits the carrier tube to deliver still further output power to the load.

In the high-efficiency grid-modulated amplifier, modulating voltage of the same phase is applied to both grids, as shown in Figure 7. However, the voltage applied to the peak tube must, because of the high bias on this tube, be of a larger order of magnitude than that applied to the carrier tube. It has been recommended that this double-voltage audio driving be accomplished simply by supplying the separate tubes from taps on the audio coupling transformer.

The presence of the impedance-inverting network in the plate circuit of the carrier tube introduces here as well a 90° phase shift and, as a result, an auxiliary network of similar electrical characteristics must be inserted into one of the grid circuits to correct the phase of the unmodulated r.f. excitation voltage.

The designers of the high-efficiency grid-modulated circuit state 65 to 80 percent as efficiencies obtainable with this arrangement during both modulated and unmodulated intervals.

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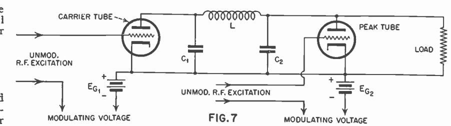

FIG. 7