A New High-Efficiency Power Amplifier for Modulated Waves *

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THE use of increasingly higher power levels in broadcasting in the last few years has attached new importance to the matter of more efficient operation of the high-power stages in radio transmitters. The resulting reductions in cost of power, size of high-voltage transformers and rectifier, and water cooling requirements, are of particular importance in transmitters having outputs of 50 kilowatts or more.

The linear radio-frequency power amplifier, in the form in which it has been used extensively in broadcast transmission, may not be operated at a plate efficiency higher than about 33 per cent, if it is to supply the peak power required for amplifying a completely modulated wave. With this efficiency the d-c power input to a 50-kilowatt amplifier, for example, is 150 kilowatts, of which 100 kilowatts must be dissipated at the anodes of the water-cooled tubes.

This inherent weakness of the conventional linear amplifier has occasioned the development of certain other systems of amplification or modulation which permit a more economical use of power. Of these the high-level Class B modulation system[1] and the ingenious "outphasing modulation" scheme of Chireix[2] are most worthy of note.

A new form of linear power amplifier has been developed which removes the limitation of low efficiency inherent in the conventional circuit, permitting efficiencies of 60 to 65 per cent to be realized, while retaining the principal advantages associated with low-level modulation systems and linear amplifiers, namely, the absence of any high-power audio equipment, the ease of adding linear amplifiers to existing equipment to increase its power output, and the adaptability of such systems to types of transmission other than the carrier-and-double-side-band transmission most common at present.

Linear radio-frequency power amplifiers are ordinarily biased

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[1] Chambers, Jones, Fyler, Williamson, Leach, and Hutcheson, "The WLW 500-Kilowatt Broadcast Transmitter," *Proc. I. R. E.*, Vol. 22, p. 1151, October, 1934.

[2] Chireix, "High Power Outphasing Modulation," *Proc. I. R. E.*, Vol. 23, p. 1370, November, 1935.

nearly to the cut-off point so that the plate-current pulse width is approximately a half cycle. Under these conditions the plate efficiency is proportional to the amplitude of the radio-frequency plate voltage. It is possible to obtain large outputs from tubes with radio-frequency plate voltage amplitudes of 0.85 to 0.9 of the applied d-c potential, i.e., with the plate voltage swinging down to a minimum value as low as 10 to 15 per cent of the d-c potential. The corresponding plate efficiency for the tube and its tuned circuit is approximately 67 per cent. This condition, however, prevails only at the peak output of the amplifier, and since the amplitude of the plate voltage wave, in a transmitter capable of 100 per cent modulation, is only half as great for the unmodulated condition as for the peaks of modulation, the efficiency with zero modulation in the conventional amplifier does not exceed half this peak value, or about 33 per cent. Even during complete modulation the effective efficiency over the whole audio cycle is only 50 per cent, and for the average percentage modulation of broadcast programs the all-day efficiency is only slightly greater than the efficiency for unmodulated carrier.

In order to improve this situation it is necessary to devise a system in which the amplitude of the alternating plate voltage wave is high for the unmodulated condition, and in which the increased output required for the positive swings of modulation is obtained in some other manner than by an increase in this voltage.

A simple and fundamental means is available for achieving this result. One embodiment of the scheme is illustrated in Fig. 1. Each of the two tubes shown in this figure is designed to deliver a peak power of E^2/R watts into an impedance of R ohms. The total peak output of the two tubes being $2E^2/R$ watts, the tubes are suitable for use in an amplifier whose carrier output is one-fourth of this value, or $E^2/2R$ watts. If the tubes were to be connected in parallel in a conventional amplifier circuit the load impedance used would be $R/2$ ohms, and each tube would work effectively into R ohms by virtue of the presence of the other tube. The same load impedance $R/2$ is used in the new circuit, but between the load and one of the tubes

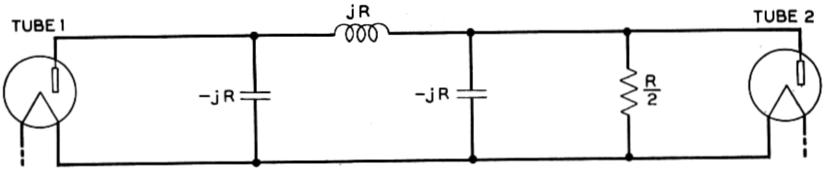

Fig. 1—Form of high-efficiency circuit.

(Tube 1) there is interposed a network which simulates a quarter-wave transmission line at the frequency at which the amplifier is operated.

It is a well-known property of quarter-wave transmission lines and their equivalent networks that their input impedance is inversely proportional to the terminating impedance. The network of Fig. 1, in particular, presents to Tube 1 an impedance of R ohms when its effective terminating impedance is also R ohms, that is, when half of the power in the load is being furnished by Tube 2; but should Tube 2 be removed from the circuit, or prevented from contributing to the output, the terminating impedance of the network would be reduced to $R/2$ ohms, with a consequent increase in the impedance presented to Tube 1 from R to $2R$ ohms. Under this condition Tube 1 could deliver the carrier power $E^2/2R$ at its maximum alternating plate voltage E and consequently at high efficiency.

The operation of the amplifier over the modulation cycle is as follows: The grids of both tubes are excited by the modulated output of the preceding amplifier stage, but for all instantaneous outputs from zero up to the carrier level Tube 2 is prevented by a high grid bias from contributing to the output, and the power is obtained entirely from Tube 1, which is working into $2R$ ohms, twice the impedance into which it is to work when delivering its peak output. In consequence, the radio-frequency plate voltage on this tube at the carrier output is nearly as high as is permissible and the efficiency is correspondingly high. Beyond this point the dynamic characteristic of Tube 1, unassisted, would flatten off very quickly because the plate voltage swing could not be appreciably increased. Tube 2, however, is permitted to come into play as the instantaneous excitation increases beyond the carrier point. In coming into play Tube 2 not only delivers power of itself, but through the action of the impedance-inverting network causes an effective lowering of the impedance into which Tube 1 works, so that Tube 1 may increase its power output without increasing its plate voltage swing, which was already a maximum at the carrier point. At the peak of a 100-per-cent modulated wave each tube is working for an instant into the impedance R most favorable to large output and delivering E^2/R watts, twice the carrier power, so that the total instantaneous output is the required value of four times the carrier power. Thus the required tube capacity is the same as in a conventional linear power amplifier.

Since it is usually desirable in power amplifiers to provide low-impedance paths for the harmonic components of the radio-frequency plate current wave, the reactive elements designated $-jR$ in a practical circuit ordinarily consist of a considerably larger capacity shunted by a coil, and in the tuning process either the coil or the condenser is adjusted so that the impedance of the combination is the required value of $-jR$ ohms. The effective shunt load $R/2$ is then usually obtained by coupling the radiating system of the transmitter to the necessary extent into the parallel circuit associated with Tube 2.

The presence of a quarter-wave network in the output circuit of the amplifier causes the plate potentials on the two tubes to be 90 degrees apart in phase. This requires that the voltages impressed on the two grids be 90 degrees apart in order that each may be opposite in phase to the related plate potential, as is necessary in any power amplifier. In addition to this phase requirement, there arises from the variation in load impedance for Tube 1 the requirement that the excitation on this tube shall rise considerably less than 100 per cent on the positive peaks of modulation. Without some limiting action on this excitation the grid current in Tube 1 would be excessive and would result in a diminution of its output at modulation peaks.

Both of these requirements concerning the input to the amplifier are satisfied by the use of the input circuit shown in Fig. 2. With the output of the previous stage applied directly to the grid of Tube 2, the resulting excitation E_1 on Tube 1 is proportional to the terminating resistance R_1 of the quarter-wave network. With a suitable value of R_1 the input conductance of Tube 1 arising from the flow of grid current at high excitations causes an effective lowering of R_1 which gives the desired limiting action on the excitation. At the same time the input impedance X^2/R_1 of the quarter-wave network is increased, compensating to a large extent for the shunting effect of the grid current in Tube 2, so that the previous stage is assisted in maintaining the proper excitation on the amplifier.

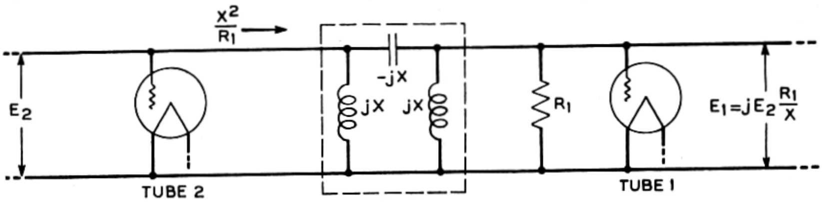

Fig. 2—Input circuit for a high-efficiency amplifier.

In a preliminary study of the behavior of an amplifier under these new conditions of operation, the results shown in Fig. 3 were obtained with a pair of small tubes. The radio-frequency plate potential of Tube 2 is the potential across the load circuit and is required to be linear with excitation. The short dotted portion halfway up on this characteristic shows the curvature that would be obtained if Tube 2 were not allowed to come into action. With proper adjustment of the bias and relative excitation on Tube 2 this effect is eliminated and the characteristic continues to rise up to the desired peak amplitude.

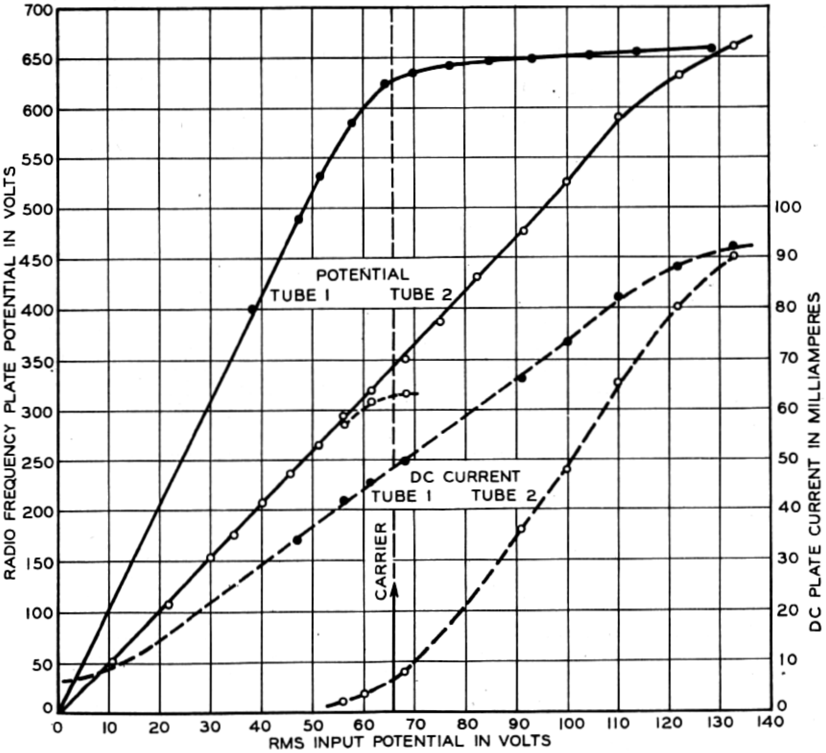

Fig. 3—Dynamic characteristics of an experimental low-power high-efficiency amplifier.

The radio-frequency plate voltage of Tube 1 is seen to be twice that of Tube 2 up to the point where curvature begins, and then to increase only slightly between the carrier output and peak output. The plate current of Tube 2 commences just before the carrier point is reached and rises twice as rapidly as the plate current of Tube 1. The equality of plate currents and radio-frequency plate potentials on the two tubes at the peak of modulation indicates that the tubes are contributing about equally to the instantaneous output at this point.

The high radio-frequency plate potential of Tube 1 at the carrier amplitude results in an efficiency of 63 per cent, and by integrating the d-c plate currents of Fig. 3 over a complete cycle of modulation it is found that the effective average efficiency at 100 per cent modulation is also 63 per cent. The d-c plate current of the amplifier therefore rises 50 per cent with full modulation, as does the output power.

The necessity for careful adjustment of the relative excitation and bias on Tube 2, to obtain a linear characteristic in the amplifier, is eliminated when the feedback principle[3] due to Black is employed. Negative feedback may be used in radio transmitters at either radio frequency or audio frequency. The resulting improvements in linearity are useful in noise reduction as well as in distortion correction.

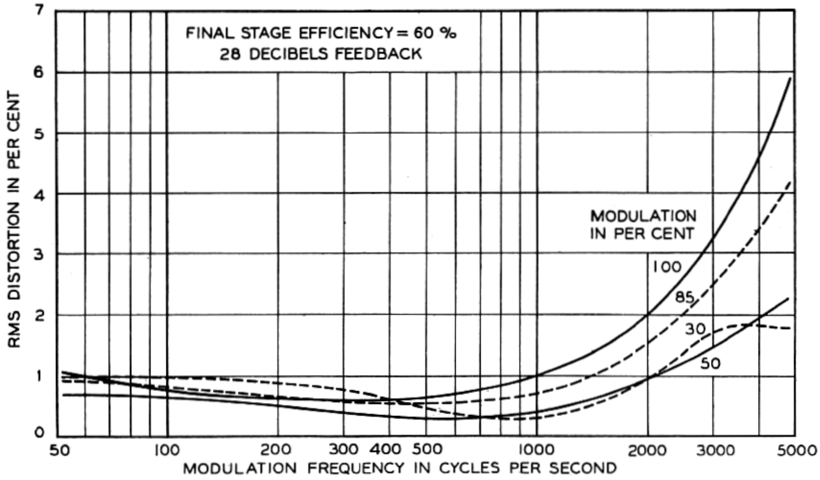

Fig. 4—Distortion measurements on a 50-kilowatt transmitter.

Figure 4 gives the results of distortion measurements on a complete 50-kilowatt transmitter built in the Laboratories and operating at a plate circuit efficiency for the final stage of 60 per cent. The use of 28 db of audio-frequency feedback, besides permitting alternating-current filament heating for all of the tubes, resulted in a distortion level less than 1 per cent at any frequency between 50 and 1000 cycles. At the higher audio frequencies the feedback is less effective because of the cumulative phase shifts in the various stages. The percentage modulation actually occurring in a broadcast program at these high frequencies, however, is so small that the distortion measured at high percentages of modulation is not of practical significance. The test, moreover, was made at the low-frequency end of the broadcast

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[3] H. S. Black, "Stabilized Feedback Amplifiers," *Electrical Engineering*, January, 1934; *Bell Sys. Tech. Jour.*, January, 1934.

spectrum, where the effect is most pronounced because of the smaller band width.

The power required by this transmitter, including all auxiliary equipment, was 135 kilowatts with normal program modulation, as compared with approximately 230 kilowatts required in the usual 50-kilowatt installation.

High-efficiency operation, in addition to affording a large saving in the plate power supply, reduces the plate dissipation by a factor of three or four, with a resulting economy in the cooling system and an improvement in tube life.

The absence of any such requisites as the complicated driving stages of the Chireix system or the large audio equipment involved in high-level modulation gives the new circuit an important advantage over other high-efficiency systems in cost of apparatus and simplicity of design. The new amplifier, moreover, is operated at a plate voltage consistent with safety to the tubes, and is therefore not subject to the operating difficulties encountered at the high peak plate voltages required in high-level modulation.