AMPLIPHASE . . . FOR ECONOMICAL SUPER-POWER AM TRANSMITTERS

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The development history of high-power, amplitude-modulated transmitters is most interesting. As the power-output requirements on AM transmitters increased, the difficulties encountered in obtaining performance and efficient operation became more complex. In order to keep the power capabilities of modulation circuits low, the linear-amplification system was used. This system, however, is inefficient and wasteful of primary power. This fact, in itself, made the linear-amplification system undesirable for high-power installation for, the higher the power, the more prohibitive the costs of the power lost in such a system. As a consequence, more efficient systems of high-power-AM systems became necessary and were developed.

A variation of a linear-power amplifier was devised by W. H. Doherty. This more efficient system, in its early days, also had limitations, mostly because of the difficulty encountered in attaining good system linearity.

The high-level, plate-modulated transmitter system became most popular in AM Broadcasting. This system, too, has deficiencies, particularly in high-power systems (50-kw and greater).

A third system, to which this article is devoted, has been developed and is in use in an increasing number of high-power-transmitter installations.

Ampliphase is a variation of—what is termed—"outphasing modulation" and, in general, improves on both of the preceding systems, particularly in high-power applications. It is the purpose of this article to describe the system, explain its operation and to discuss its application in high-power-AM transmitters.

"*Ampliphase*" is a word coined to describe phase-to-amplitude modulation and avoid the cumbersome group of words it replaces. RCA *Ampliphase* is a system technique whereby the amplitude modulation is formed across a single capacitive element, which is coupled directly to the transmitting antenna system. Several equipments using outphasing modulation have been developed by others with varying degrees of success. The French pioneer in this system, H. Chireix[1] created considerable interest on the European Continent and a number of equipments, mostly high-power types, were completed. On the North American Continent only one equipment was in commercial operation before RCA undertook its *Ampliphase* development program.

RCA's *Ampliphase* is a system in which a portion of the transmitter, outside of the active components, converts phase modulation into amplitude modulation. In order to fully appreciate the advantages of this system, a review of the fundamentals of amplitude modulation and the popular means of achieving high-power AM is presented here.

Take, for example, the properties contained in an amplitude-modulated r-f signal of a 50-kw radio transmitter. (See Fig. 1). With no modulation applied, r-f energy at one level (50 kilowatts) is produced. That same transmitter, heavily modulated with an audio signal, produces various r-f levels throughout the modulation cycle. At the negative modulation peak the r-f level is very low and the power produced is, likewise, very low. Conversely, at the positive peaks of modulation the r-f level is very high. At 100 per cent modulation, the r-f level is such that, at the positive-modulation peak (assuming no carrier shift with modulation) the peak power produced at this instant is four times the zero-modulation power or 200 kw from the 50 kw transmitter. All power levels between this peak and zero are produced over the range of the modulation envelope. With this in mind, let us examine the mechanics of achieving this variation of rf-output level in the three high-power-transmitter systems.

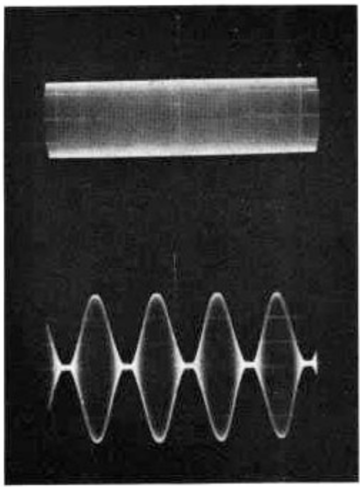

FIG. 1. Oscillogram of the output waveform of an AM transmitter with and without modulation.

The Linear Power Amplifier

First, in a linear system, the final-power amplifier reproduces, at its output, essentially the same signal present at its input. The reproduction faithfulness depends upon the tube, load and the proper adjustment of a number of critical parameters. Each stage of linear amplification distorts the signal to some extent as it raises the power level. The amplifier produces the value of *peak* power most efficiently. By nature, however, when the amplifier operates at carrier level, or any level below peak modulation value, the unused power (the power input to the stage is constant) is lost in the amplifier tube in the form of heat. This lost power is the greatest objection in the high-power, linear-amplifier system.

The Doherty System

A more efficient, linear system is the Class "BC" or "Doherty" system. In this "modified-linear" system, two amplifier tubes are employed. The main, or, "carrier" tube is operated with its most efficient operation point at carrier level. Power above carrier level is supplied by the carrier

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[1] "High-Power Outphasing Modulation," by H. Chireix, *Proceedings of the I.R.E.*, Vol. 23, Nov. 1935, pp. 1370-1392.

and a second, "peak" tube. Here, again, the reproduction faithfulness of the output signal depends not only on tube characteristics but also the proper adjustment of a large number of circuit parameters.

It was noted that, in the more efficient "Doherty" version of the linear system, the efficient output was achieved by utilizing the carrier tube at its full capability with a minimum of unused power. This leads us to the second method of producing modulated r-f energy: high-level modulation, a system in which the rf-amplifier tube always operates at maximum efficiency.

High-Level Modulation

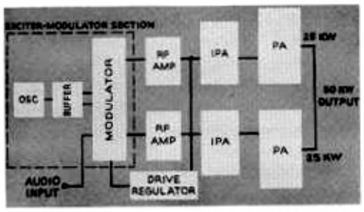
In this modulation method, the plate voltage on the final amplifier is raised and lowered as dictated by the modulating intelligence which is supplied by high-power-audio amplifiers. At carrier level, the plate voltage is at a given value; at high-modulation peaks, the plate voltage is nearly double that given value and at negative-modulation peaks, nearly zero. The plate voltage is constantly changing, in step with the modulating intelligence, thus producing the differing rf-output levels.

Faithful reproduction of the input signal in the system is heavily dependent upon the tube-linearity characteristics of the high-power-audio stages. A certain amount of feedback is incorporated in the system to correct for deficiencies in the linearity. Performance of this system is limited at low modulating frequencies by the iron content of the modulation transformer (which controls the varying power-amplifier plate voltage). Other limitations lie in the losses encountered in other modulation components. In very high power systems, care must be exercised to avoid lengthy periods of maximum modulation to prevent the power dissipated within the modulation transformer from permanently damaging the transformer.

The Ampliphase System

In the third method of producing high-power, amplitude modulation, the final-amplifier plate voltage remains constant while the current delivered to the load varies in accordance with the modulating waveform. In addition, the amplifier operates at full r-f voltage output from carrier level up through full peak-power output. This results in high efficiency at these various levels. This is the *Ampliphase* system.

FIG. 2. Block Diagram of the "Ampliphase" System.



$$Z_T = 2R\cos^2\theta/2 \pm jR\sin\theta$$

Where

Z_T = Impedance at tube

θ = Angle between r-f voltages of the two channels

R = The effective combining point load

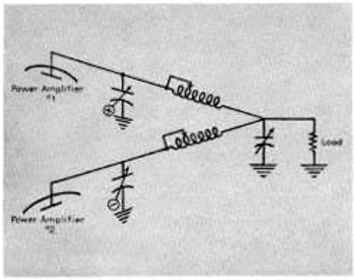
FIG. 3. Equation for Calculating Power Amplifier Plate Impedance.

Ampliphase Theory

The *Ampliphase* system is, basically, two paralleled, continuous-wave transmitters, using conventional Class "C" amplifiers—with their attendant high efficiency—as the final-power amplifiers. (See Fig. 2) Tube-plate voltages are constant throughout the modulation cycle and radio-frequency energy is amplified by conventional means. It is at the output ends of the two high-power amplification channels where the key to the *Ampliphase* system lies.

The modulation information is imposed at the low-power end of the transmitter and the modulation is realized at the high-power end. During amplification the information is in the form of phase modulation and depends only slightly on r-f amplifier-tube characteristics for faithful reproduction.

FIG. 4. Simplified Schematic, "Ampliphase" Combining Network.



This, then, leaves two areas in which to concentrate our attention. Since the output circuit is where the modulation is actually formed, we shall direct our attention there first.

Output or Combining Network

The heart of the *Ampliphase* system is the network across which the modulation is formed. Surprisingly enough, this is a very basic circuit. Several papers have been written on the mathematics of the conversion of phase modulation to amplitude modulation in an outphasing system. (See Fig. 3.) The development of the theory is not required in gaining an understanding of the *Ampliphase* system, only the general impedance equation of Fig. 3 need be cited.

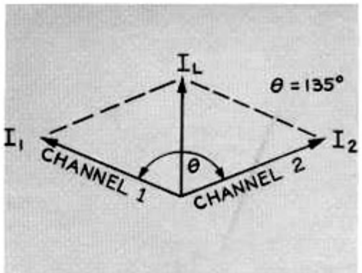
Ampliphase Modulation

In arriving at a suitable transmitter design, solutions of several points throughout the modulation cycle are computed. In the *Ampliphase* system, the points from carrier level upwards to the positive peak of output power are of prime interest. The secondary importance of those points *below* carrier level are revealed later in the discussion of drive requirements for the power-amplifier tubes.

The combining network is made up of two 90-degree *pi* (π) networks: one network couples each power amplifier to the common load. (See Fig. 4.) If the r-f energy from the two power amplifiers is fed in phase, the network acts as a simple paralleling device to couple the two amplifiers to the single load.

Feeding the two signals to the network in an out-of-phase condition produces less voltage at the output than in the "in-phase" condition. Further, since the impedance at

FIG. 5. Vector representation of the phase difference between the two r-f chains in an "Ampliphase" transmitter at zero modulation.



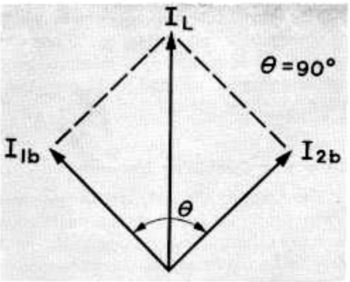


FIG. 6. Vector reprensentation of the phase difference between the two r-f chains in an "Ampliphase" transmitter at the peak of a 100-percent modulation envelope.

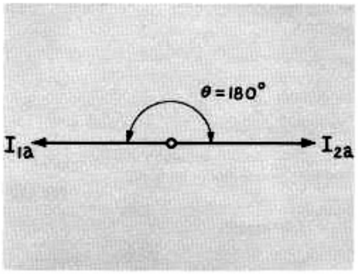


FIG. 7. Vector representation of the phase difference between the two r-f chains in an "Ampliphase" transmitter in the trough of a 100-percent modulation envelope.

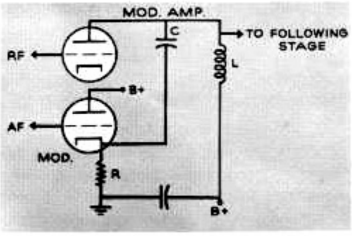


FIG. 8. Basic circuit: "Ampliphase" phase modulator.

the output of the combining network changes in the "out-of-phase" case (indicated by the lower voltage level), the network no longer appears as a tuned load to the power amplifiers. The amount of reactance present under this condition is contained in the last part of the impedance equation. (Fig. 3.) Note that equal amounts of reactance, differing only in sign, appear at each power amplifier. To provide resistive loads for the power tubes, the input element of each of the 90-degree networks is adjusted accordingly. The *pi* input capacitor on the power amplifier, experiencing inductive reactance, is increased to draw more capacitive current from the amplifier, thereby compensating for and providing the "real" load required for efficient amplifier operation. Likewise, in the power amplifier experiencing capacitive reactance, the input element is adjusted an equal amount in the opposite direction to provide amplifier its purely-resistive load at carrier level. (See Fig. 5.)

The modulation equation is of use over a fairly wide range of phase angles, but not over the entire modulating range. (See Fig. 6.) The loads deviate slightly from a unity-power factor toward the positive, in-phase, condition and especially in the negative, out-of-phase, condition. (See Fig. 7.)

The quite-definite departure from unity power-factor in the negative modulation region is of minimum importance because the drive-regulator system in the transmitter apportions drive to the amplifier tube as the depth of the negative-modulation peak dictates. The total result is that, when the load to the PA's is least "real" and, hence, provides for the least-efficient operation, the available drive is small. As a result, the inefficiencies of the system are minimized. Even more important, the linearity of the modulation system is improved, and both efficiency and faithful reproduction are gained. Drive regulation further provides the high value of drive necessary when the PA tubes are required to develop the high-power levels of the positive modulation peaks.

The combination of the regulated drive and the outphasing modulation leads to a highly-efficient and highly-linear system with a minimum of major components.

The characteristics of this combining network offer some very definite operating advantages over other transmitter systems. A particular advantage is that a change in load reactance does not detune the amplifier stages to any great extent, but serves only to adjust the proportion of the power contributed by each stage. The power delivered to the load and the efficiency of the system changes very little over a fairly wide range of reactance values.

This advantage is of great importance when the antenna load has highly reactive side-band impedances, for modulation linearity and efficiency are not greatly affected and the output capability is not limited by this condition.

Imparting the Modulation Information

After the consideration given the modulation and how it is formed at the output, let us now look briefly at the means of applying the phase modulation on two r-f channels of the RCA *Ampliphase* transmitter. Two types of simple phase modulators are in use presently on commercial *Ampliphase* transmitters. Both are highly acceptable and each is used to best satisfy the design requirements of the particular equipment. The modulator used on the medium-frequency AM line is a very stable device, highly linear in phase modulation. (See Fig. 8). This stage is a simple, tuned-rf amplifier with the tuned load formed by a parallel-resonant circuit in which a variable resistance (R) is placed in series with the capacitive element (C). The inductive element (L) is tuned so that its reactance is equal to twice the reactance of the capacitive element. At this point, varying the resistance changes only phase angle and not the magnitude of the impedance seen by its driving tube. The resistance variation in the audio phase-modulator is the cathode impedance of an audio cathode-follower stage. This is the circuit in which phase modulation at an audio rate is attained. The phase-modulation characteristic, complemented by a given transconductance characteristic of the cathode follower, produces linear phase modulation over a given range. The magnitude of phase modulation required for full amplitude modulation at the output of the transmitter is then attained by cascading the required number of stages. In practice, the amount of amplitude variation of the r-f output from this stage is very slight, when the modulator is properly tuned. This amplitude variation serves as a simple indicator to tune the stage and, in fact, the entire modulator. The capacitive element is a fixed value and the inductive element, a slug-tuned coil, is tuned for minimum audio "ripple" at the phase-modulator output.

The second type of modulator is a modified "Beleskas Phase Modulator"[2] circuit where the grid voltage of the phase-modulator stage is changed at an audio rate to thus control the amount of r-f through the tube. This adds, vectorially, with a fixed amount of energy feed, in quadrature, directly to the plate circuit. This stage produces some incidental amplitude modulation which must be removed in a subsequent limiter stage but it has the advantage of requiring no tuning. The *Beleskas*

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[2] "Phase Modulation Circuit," by S. M. Beleskas, *Proceedings of the National Electronics Conference*, Vol. 3, 1947, p. 654.

modulator lends itself to application in transmitters which change operating frequency quickly, with a minimum of retuning, such as short-wave transmitters operating in the high-frequency band between 3 and 30 mc. This modulator, however, is not readily cascaded.

It is appropriate to note here the role the modulator plays in the system. Since the modulator imparts the modulation intelligence at the low-level part of the system, and the linearity of the modulated information is not effected by r-f amplification, there is no practical limit to the extent to which this information can be amplified. The same modulator can be responsible for producing modulation on a 10-kw, 100-kw, or 1000-kw transmitter using the *Ampliphase* system. Hence, great futures exist for the *Ampliphase* system in very-high-power transmitter units where the inefficiencies and linearity difficulties of the linear amplification systems and the expense of high-power, plate-modulated systems make them undesirable for super-power transmitters.

Intermediate Stages of Amplification

As indicated at the outset, the r-f power amplification system is conventional. The number of stages and power gain of each is of minimum importance to system performance. Drive regulation is applied at an intermediate-amplifier stage. In general, the ideal point to inject the drive regulation is on the grid of the driver amplifier. This is because of the low amount of modulating power required to produce the regulated drive.

To provide maximum phase stability and performance with feedback applied, the individual amplifiers have broadband loads. This eliminates the necessity of periodical re-adjustment of the amplifier tuning. In general, a check of amplifier resonance need be accomplished only when replacing tubes, and seldom then.

Ampliphase System Theory

Before we examine actual applications of the system, let us review the theory of the *Ampliphase* system (see Fig. 2).

The modulated-rf energy to the transmitter load is produced by two Class "C" power amplifiers working into a single load. The impedance of this load is changed by varying the phase angle of the rf into the power amplifiers in step with the audio intelligence. The simple output network is adjusted to produce a resistive impedance to the PA tubes at the carrier output level. Drive to the final amplifiers is regulated in accordance with their drive needs which, in turn, depend upon the power they are required to supply to the load at any given instant in the modulation cycle.

Unusually good linearity is attained in the system hence the transmitter operates with only small amounts of feedback, contributing to excellent stability. Inherent linearity is displayed by the fact that the standard 50-kw equipment meets all FCC station-performance requirements *without* system feedback whatsoever. A moderate amount of overall audio feedback is generally applied at the secondary of the audio input transformer to further improve low-frequency performance and reduce noise level.

An analysis of the *Ampliphase* system is not complete without discussing the operational aspects, for the proof of its performance capabilities lies in operation.

Tuning

To demonstrate operational tuning, take the example of the RCA 50-kw medium-frequency, *Ampliphase* transmitter, BTA-50H. These procedures apply, as well, to the 100-kw BTH-100B and the 250-kw BHF-250A transmitters because of the similarity of these transmitters to the 50-kw equipment. The general modulator alignment was covered earlier in this article.

The two *pi* networks in the output and combining network tune very simply. As a matter of fact, most of the tuning is done as part of neutralizing the power amplifiers. These circuits, as all others in the high power stages, are set up initially and need not be disturbed unless replacement of a component is required. The input-capacitive element is resonated with the series inductance of the *pi* network by grounding (short-circuiting) the combining point and operating the two r-f channels without plate voltage on the final PA's. Feed-through energy from the PA grid is used to tune the unloaded PA-plate-tank circuits to resonance. An oscilloscope or rf-detecting voltmeter may be used to indicate the build-up of energy in this circuit using the plate-voltage-sampling divider provided in the transmitter. The PA-neutralizing capacitor is then tuned for minimum feed-

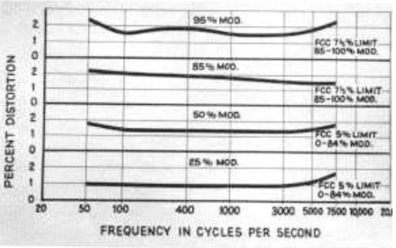
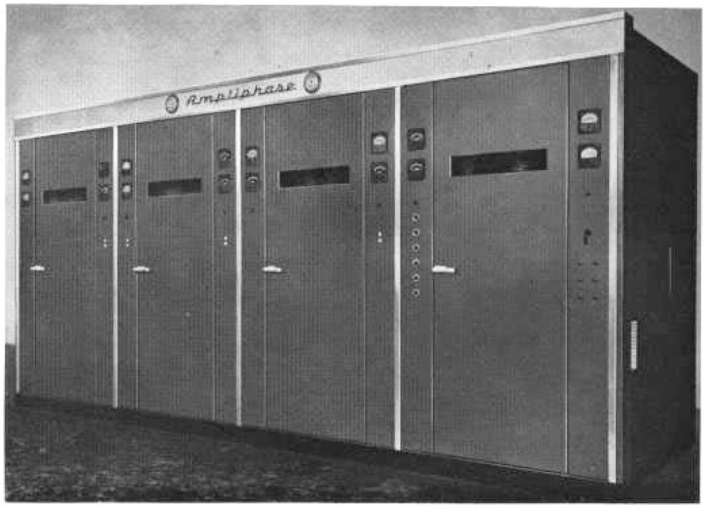


FIG. 9. Audio Distortion at various modulation levels. Type BTA-50H "Ampliphase" Transmitter.

FIG. 10. The RCA Ampliphase Transmitter serves more than 30 broadcast stations in daily operation.



through energy, thus neutralizing the amplifier. The other channel is neutralized in an identical manner.

The short circuit at the combining point is removed and the input-shunt elements of the two power-amplifier output networks are offset from resonance by an equal amount which is pre-determined by that required to produce normal efficient operation when plate voltage is applied. A chart provided in the transmitter instruction book indicates the proper offset at any given operating frequency.

The zero-modulation phase-difference between the two channels is adjusted to give proper power output at carrier level. Modulation is then applied and the drive-regulator gain adjusted to give sufficient drive for positive-modulation peaks and normal carrier-shift under modulation. A nominal amount of feedback is then applied and the transmitter is ready for duty.

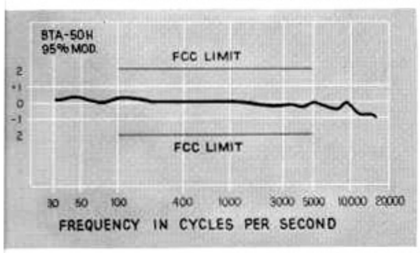
Operation and Maintenance

Operation consists of observing the usual amplifier-meter readings. Unbalance in the final-amplifier-plate currents indicates a change in load reactance. Considerable change in this reactance can be readily compensated for by readjustment of the capacitance at the combining point, thus returning the PA-plate-current balance.

Modulator performance is readily checked by observation of the usual tube currents, through the convenient metering provided in the transmitter and by monitoring the amount of incidental-amplitude modulation produced by the modulated stages during normal modulation percentages. This modulator check may be accomplished without disturbing normal transmitter operation.

Any operational deficiencies in the intermediate-amplifier stages are indicated by the metering of conventional parameters in each amplifier stage. If trouble occurs in either channel, the transmitter can quickly be reduced to two parallel CW channels by removing the final-plate voltage. This allows comparison of the like amplifiers of the two channels which readily indicates the defective circuit. Having identical components in the two channels aids in correcting difficulty. Direct substitution or the "trading" of suspect components leads to rapid location of the difficulty, in the event it ever arises. Thus, the nature of the system of identical and parallel channels is a great aid in rapid servicing of the transmitter system.

FIG. 15. Typical audio-frequency response of the BTA-50H Transmitter at 95 percent modulation. You can hear the difference on a good receiver.



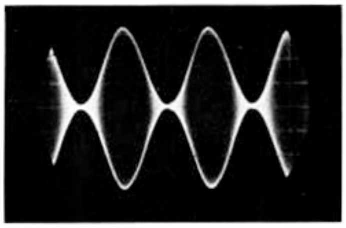


FIG. 11. Output waveform BTA-50H: 30 cps @ 100% modulation. (Distortion 2.3%)

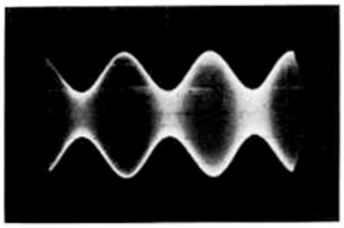


FIG. 12. BTA-50H: 30 cps @ 50% modulation. (Distortion 1.3%)

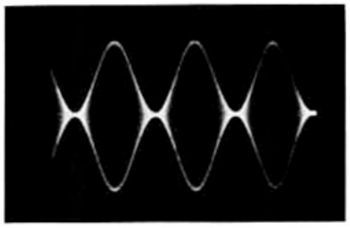


FIG. 13. BTA-50H: 1000 cps @ 100% modulation. (Distortion 0.85%)

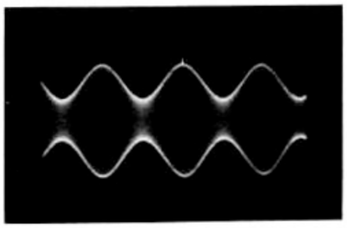


FIG. 14. BTA-50H: 1000 cps @ 50% modulation. (Distortion 0.55%)

As pointed out earlier, changes in power tubes have little effect on modulation performance until reduced emission results in insufficient r-f level to drive the power amplifiers properly. This, too, is readily indicated by the meter readings. It is well to note that the power amplifier tubes, which represent the greatest investment inside the transmitter, operate equally in each channel, providing equal power upon demand by the modulation level. At carrier level on the 50-kw transmitter the power-amplifier tubes dissipate only 7 kilowatts in each PA. Under average modulation percentages, each tube dissipates approximately 13 kw. Ordinarily, a tube capable of plate dissipation between 30 to 35 kw is used in this service. Under constant plate-voltage and only sufficient emission reserve for positive modulation peaks, this design leads to extended tube life.

Typical Ampliphase Transmitter Performance

Having discussed operation and maintenance of the system, the remaining item of the system application is the typical performance.

To evaluate the system, let us examine the typical performance of the latest *Ampliphase* design. The performance data found in Fig. 9 were taken on the first unit of the newest 50-kw, medium-frequency transmitter, the BTA-50H broadcast transmitter. (See Fig. 10.) It should be noted

FIG. 16. Typical IM distortion, Type BTA-50H transmitter, at 95 percent modulation. Rarely published for AM transmitters, this characteristic proves the quality of "Ampliphase" transmitters.

TYPICAL IM DISTORTION—TYPE BTA-50H

Low Frequency (CPS)	High Frequency (CPS)		
	2000	7000	10,000
40	2.0%	2.6%	2.7%
60	2.2%	2.6%	2.7%
100	2.3%	3.0%	3.0%

Intermodulation Signal Ratio 1 : 1
Carrier Frequency: 1090 kc, 54 kw output
Modulation Percentage: 95%

that in the *Ampliphase* system, the absence of high values of system feedback permits good high-audio-frequency performance. By the same token, low-frequency performance is not limited by the amount or quality of the iron in modulation components. (See Figs. 11, 12, 13 and 14.) The audio frequency response of the system is excellent as demonstrated by Fig. 15.

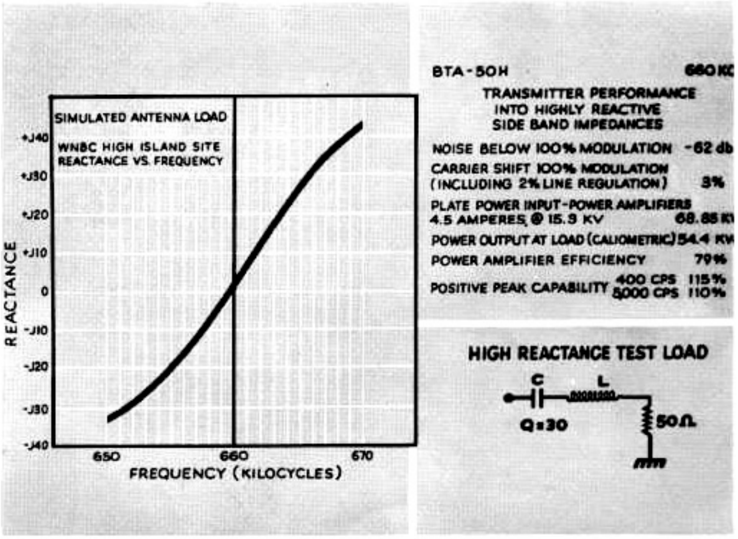
This performance is typical and demonstrates the superior system performance of the BTA-50H. Further demonstration of this performance is illustrated in the chart of intermodulation distortion performance obtained from this same transmitter. (See Fig. 16.

The *Ampliphase* modulation system is inherently stable in many respects. As shown earlier in this article, reasonable changes in load impedance have little effect on system performance. To demonstrate the range of sideband-impedance variation into which the *Ampliphase* modulation combining point may normally work, a 50-kw transmitter was set up to work into a dummy load which offers a flat characteristic at all modulating frequencies. The transmitter output was fed through a high-impedance, series-resonant circuit that produces a 38-ohm reactance at 10,000 cycles above and below carrier frequency. Under these conditions, the performance remained quite typical as indicated in the upper right-hand corner of Fig. 17 and the series of distortion curves in Fig. 18.

Summary

The *Ampliphase* system provides a new high in transmitter efficiency, performance and stability in high-power, AM transmission. The high efficiency of the amplifying and modulating system employs only a minimum of unused primary power. Modulating components do not represent large investments in iron and copper as they do in high-level modulation systems. Inherent system linearity means minimum feedback, and this means ease in attaining and maintaining performance.

Changes in high-power-tube characteristics do not, radically, affect the system linearity. By its very nature, the system is insensitive to unusual load-impedance characteristics. Audio fidelity of the system is exceptional in the high- and low-modulating frequencies assuring high-fidelity performance in very-high-power transmission systems. The combination of these features both in the theory and the demonstrated performance make the *Ampliphase* system most desirable for use in high-power-AM and super-power-AM applications.



BTA-50H 660 KC

TRANSMITTER PERFORMANCE
INTO HIGHLY REACTIVE
SIDE BAND IMPEDANCES

NOISE BELOW 100% MODULATION -62 db

CARRIER SHIFT 100% MODULATION
(INCLUDING 2% LINE REGULATION) 3%

PLATE POWER INPUT-POWER AMPLIFIERS
4.5 AMPERES, @ 15.9 KV 68.85 K

POWER OUTPUT AT LOAD (CALIOMETRIC) 54.4 K

POWER AMPLIFIER EFFICIENCY 79%

POSITIVE PEAK CAPABILITY 400 CPS 115%
5000 CPS 110%

FIG. 17. Typical BTA-50H performance when working into a load with highly reactive sideband impedances.

PERFORMANCE INTO HIGHLY REACTIVE SIDEBAND IMPEDANCES

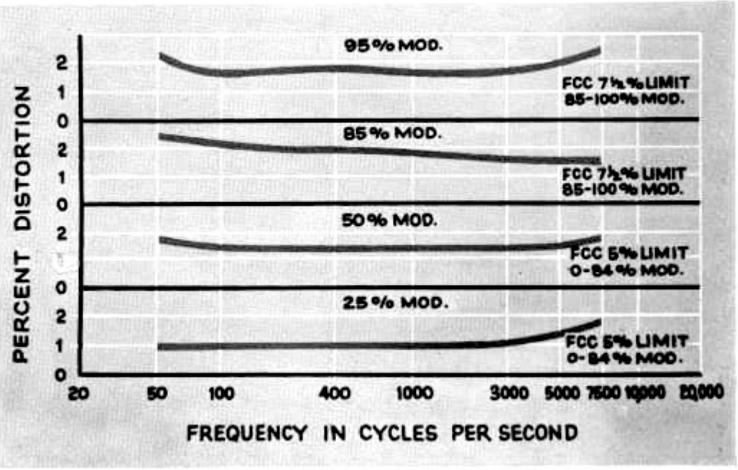


FIG. 18. Typical audio-frequency distortion characteristics of a Type BTA-50H Ampliphase transmitter when operating into a load with highly-reactive sideband impedances.