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Analyzing the Power Amplifier

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By D. E. Harnett

Engineering Dept., Pacent Electric Company

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Analyzing the Power Amplifier

How Oscillograms Help to Indicate the Transient Voltages and Currents in the Circuits—A Radio Club of America Paper

By D. E. HARNETT

Engineering Dept., Pacent Electric Company

THE commercial need for high-quality reproduction has lately focused the attention, not only of engineers, but of the whole radio world, on the audio-frequency circuits of radio receivers. Selectivity and sensitivity for a number of years received much attention, but during that time, those engineers who realized how much better broadcast receiver reproduction could be, were trying to persuade the public to recognize good quality and to prefer it. Their efforts have finally met with success. The modern radio set has a much better amplifier than was the case a year and a half ago.

One of the lessons learned from the extensive experimenting on audio circuits is that it is necessary to have the loud speaker driven by a tube which can develop considerably more power than is required from the other tubes in the set. This means that the B-battery supply must furnish much more power to the output tube than was previously thought necessary. As a result, the B socket-power device, which operates from the a. c. house mains, has become very popular. The superiority of this type of socket-power device over the type which operates from some other source, such as a d. c. house-lighting circuit, is that it is possible to maintain the voltage by a suitable transformer at practically any desired value. The limiting factors are the safe operating voltage of the rectifier and the insulation in the device, particularly the insulation in the condensers. These factors are, of course, economic, for it is possible to build rectifying tubes for practically any voltages and to insulate properly for these voltages.

The device under discussion is the "Powerformer." It is a combination power amplifier and B socket-power device. The device was developed by a group of engineers under the direction of Mr. L. G. Pacent.

It is desirable to have all that wiring which connects with a high-voltage circuit (such as the plate circuit of the power amplifier tube) confined within a metal case, in order to eliminate danger of injury to the broadcast listener. The rectifier tube is capable of rectifying considerably more current than is required for the power tube. This excess current is supplied to a potentiometer from which the plate potentials for the different tubes in the receiver are drawn. These different plate potentials—of the order of 150 volts, or less—are brought out to binding posts, which connect to the plate circuit of the radio receiver. The audio circuit connects through the jacks. The schematic diagram is shown in Fig. 1.

The operation of the separate parts of this circuit has been studied by a good many engineers and reported before the Radio Club of America and before the Institute of Radio Engineers. When, however, these different units are combined into one circuit, certain complications arise. It has been found that the actual functioning of the different parts of this circuit is not generally understood.

The principal object of this device is to enable the broadcast listener to have good quality reproduction, with a fair amount of volume. In order to obtain this result, an amplifier tube must be employed which is capable of delivering about one watt without distortion. The audio transformers must be properly designed so that they will not distort the signal. This means that they must have a high primary inductance, a high mutual impedance, and a ratio which is somewhat lower than was thought best three or four years ago. With the use of ordinary magnetic materials, this necessitates a large core and a winding employing from two to three times the copper used in the average transformer of the past.

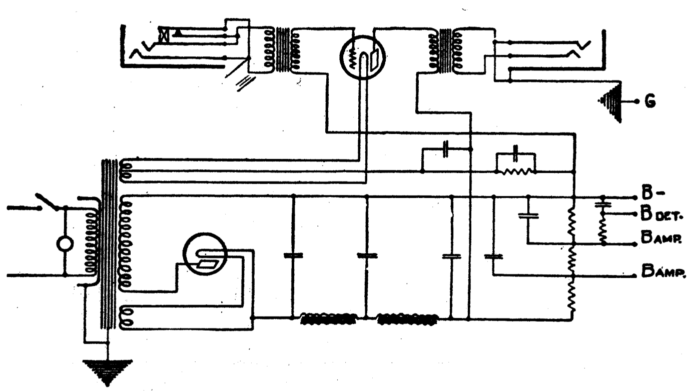

FIG. 1

Consider first the rectifier circuit—here a 60-cycle transformer is operated with the primary on a 110-volt lighting circuit. There are three other windings besides the primary. One of these operates the filament of the rectifier tube; the second, the filament of the amplifier tube; the third supplies the rectifier with high voltage, that is, it supplies the power for operating the plate circuits of the amplifier tube and those of the other tubes of the broadcast receiver. The current and voltages in the transformer are shown in Fig. 2. In Figs. 2 and 3, the arrow indicates the direction of travel in the film. In other words, the head of the arrow indicates an earlier time than the stem of the arrow. In the later photographs, the arrow indicates the direction of time; in other words, the meaning of the arrow is reversed. It will be noticed that the device is supplying the rectified current during approximately one third of the cycle; that is, instead of rectifying during all of the half cycle, which has the proper polarity for rectification, it is rectifying only during the portion of the cycle during which the transformer voltage exceeds the voltage across the first condenser in the filter circuit. Abrupt changes in the impedance of the transformer load introduce a large number of harmonics in the high-voltage winding which are reflected in the primary, giving the wave shape shown at the top of the photograph. Naturally, the direct-current component of this secondary current cannot be reflected through the transformer. This is shown by the fact that the area of the top half of the primary wave is equal to the area of the lower half. The power factor of this device is approximately 70 per cent.

$$\text{Power Factor} = \frac{\text{Power}}{EI}$$

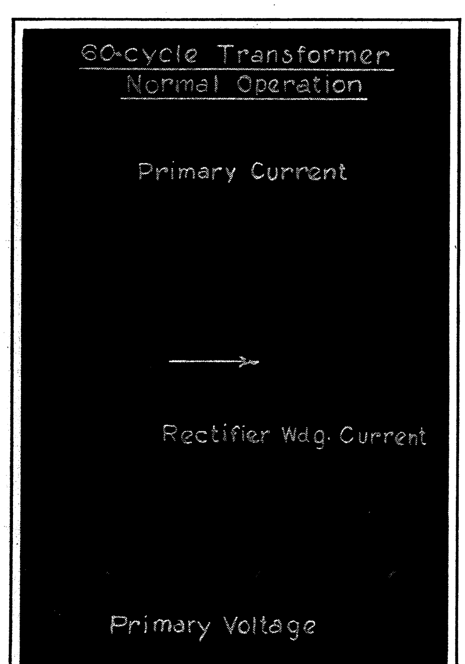

FIG. 2

The power is the product of primary voltage, the 60-cycle component of primary current, and the cosine of the angle between them. E is the primary voltage, and I is the r. m. s. value of primary current; that is, r. m. s. value of 60-cycle primary current and all of the harmonic currents. Thus there are two effects tending to decrease the power factor—the phase difference between the primary voltage and current, and the presence of the harmonics in the primary. The current in the other two secondary windings is a sine wave working into a resistive load, that is, into the tube filaments. Approximately two thirds of the power drawn from the transformer is supplied to the rectifying circuit; the remaining one third is used to light the tube filaments. Fig. 3 shows the effect of the rectifier winding on the primary current much more clearly than does Fig. 2. In Fig. 2, the presence of the harmonics appearing in the primary current wave is partially obscured by the presence of the power current which supplies the power to the tube filaments. In Fig. 3 the transformer was operated with the tube filament windings open-circuited, that is, the tube filaments were supplied by a separate transformer. Consequently, the primary current is the sum of the magnetiz-

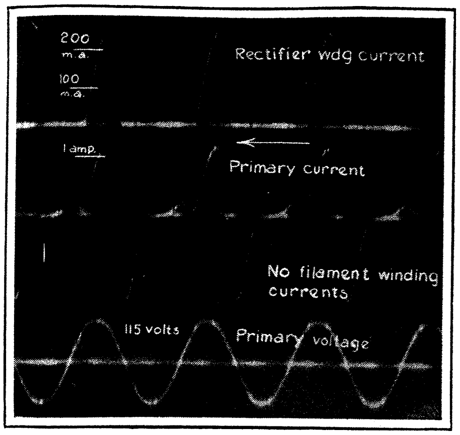

FIG. 3

ing current and the rectifier winding current reflected through the transformer.

THE FILTERING CIRCUIT

THE operation of the filtering circuit is shown in Fig. 4. The lower curve shows the current through the first condenser, and the upper curve shows the current through the first of the two chokes. It has been observed that the ratio of the r. m. s. value of the current of this first condenser to the direct-current rectified output is approximately constant, and lies between 1.8 and 2. 2. for normal loads. It is practically independent of the capacity of this first condenser. The current through the second of the two chokes has very little ripple in it.

In a circuit such as this filter circuit, it might seem that the presence of the chokes and condensers would cause rather large transient voltages when the device is connected to or disconnected from the line. Actually, there are probably no transient increases and certainly none which exceed about ten per cent. of the normal voltage. The transient occurring when the switch was shut off is shown in Fig. 5. In this particular case, the switch was shut off during the time interval when the condenser was being charged. This is indicated by the fact that the last charging current peak is lower than the others. Oscillograms which were taken when the switch was turned off during the part of the cycle when the device was not rectifying, do not show this decrease in the last of the charging current peaks. It will be noticed that the current through the condenser drops to zero within approximately one fiftieth of a second after the switch is turned off. During the same time interval, the current through the first choke drops to zero. At the time that the current through this first choke has dropped to zero, there is still a charge on this first condenser. The choke current drops to zero, however, since the charge on the second condenser is still appreciable, and is sufficiently greater than the charge on the first condenser to stop the current. The current through the second choke starts to drop off at about the time when the current through the first choke is reduced to one third of its normal value. This current then drops to approximately zero at the time when the voltage on the third filter condenser is sufficiently greater than the voltage on the second to stop the current. By this time, the voltage on the second condenser is so low that the remaining charge on the first condenser proceeds to discharge through the choke, giving the slight current through the first choke that is shown in the illustration. A close inspection of the original film will show a slight current through the condenser at this instant. The reason it does not show up in the photograph is due to the fact that the current scale for the choke current is approximately four times that for the condenser current. A very short time after this discharge in current, the charge on the final condenser has been dissipated through the resistance and consequently the remaining charge on the second condenser discharges through the second choke, giving the slight rise shown. These steps in the discharge transient do not, of course, completely discharge the condensers, and very small current can be seen on the original film which repeats the first two slight rises in the choke currents that are plainly distinguished on this film. Several oscillograms of this transient were taken and all of them verify the results shown in this photograph. The right-hand portion of the middle curve on this line shows the amount of ripple in the second choke current before the switch is turned off. Practically all of this ripple is by-passed through the third of the filter condensers. Fig. 6 is another oscillogram taken under the same conditions. The condenser current is not faithfully recorded in this photograph because the oscillograph element was loose. The other two oscillograph elements were working properly, so that the choke currents are faithfully recorded.

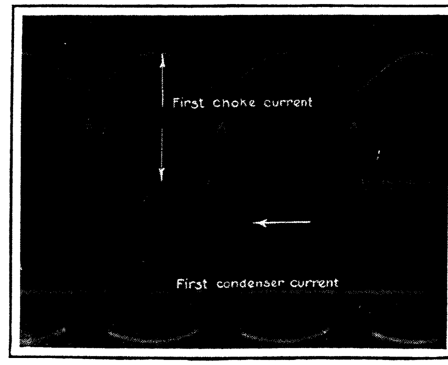

FIG. 4

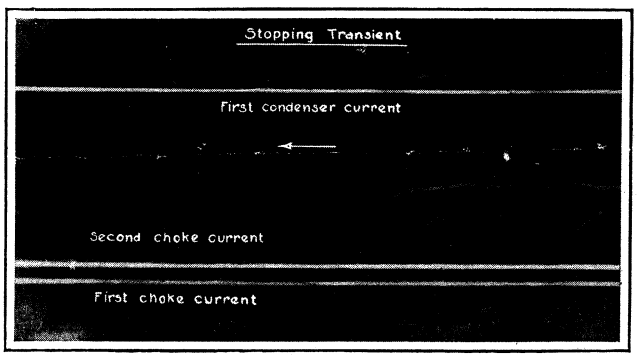

FIG. 5

In order to understand why the current drops to zero in pulses, consider the network as two separate circuits. The first is the circuit of the inductances, resistance, transformer, and rectifier in series. Assume the rectifier to act as a resistance. This is a reasonable assumption, since the direction of current flow is correct and the filament will remain hot for several cycles. The current in this circuit will decay logarithmically. The oscillatory discharge of the second circuit, inductances and condensers, will be superimposed on this discharge, giving the characteristics shown. This decay is shown even more clearly in Fig. 6.

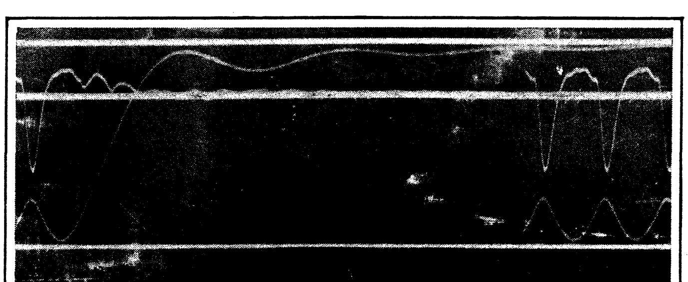

FIG. 6

In order that any considerable voltage will be built up across one of the condensers due to the switching transient, it would be necessary that the direction of the flow of energy in the steady state would be, for the moment, reversed. Since none of the photographs give any indication of the reversed current through the chokes, it follows that there can be no high voltage across any of the condensers during the discharging interval.

A moment's consideration of the energy stored in the filter circuit will show that it is very unlikely that a high-voltage transient across one of the condensers will occur. In this filter circuit we have two fifty-henry chokes in series with the high-voltage lead, with three 2-mfd. condensers connected across the line. See Fig. 7. Under normal conditions, the voltages across the condensers are 500, 375, and 350 volts respectively, 50 milliamperes of direct current flowing through each inductance. The energy stored in the first condenser will be $\frac{1}{2}$ CE^2, which is 0.25 joules. The other condensers store 0.14 and 0.112 joules. The energy stored in the chokes will be considerably less than this energy stored in the condensers. It is $\frac{1}{2}$ LI^2, or 0.0625 joules for each choke. The total stored energy in the circuit is then 0.637 joules. Thus we see that, even though the entire amount of this energy should by chance all pour into one of the condensers at once, the voltage across this condenser would be less than double the normal voltage across the first condenser. The solution is as follows:

$$\frac{1}{2} CE^2 = \frac{1}{2} \times 2 \times 10^{-6} \times E^2 = 0.637$$

Therefore, E=800 volts. But since the oscillogram shows that there is no reverse in the flow of energy, even this cannot occur, and there will be no increase in the voltage across any one of the condensers when the switch is turned off.

The starting transient is shown in Fig. 8. When the transformer is switched on to the line there may be a high secondary voltage transient if it is connected during a particular part of the cycle. In the device under consideration, this will have no effect except on the transformer itself. The reason is that the rectifier filament is cold, so the rectifier tube acts as an open circuit during the first few cycles, and therefore it separates the transformer from the filter. As the tube filament heats up, the tube rectifies and gradually builds up the necessary voltage to maintain the steady state. From the appearance of the oscillogram, it is evident that this voltage is built up gradually. If there were a transient voltage exceeding the normal, some of the charging current peaks would be slightly higher than the steady charging peaks. It will be noted that the area of the first few of these charging peaks is greater than the areas under the following discharging alternations of the condenser current. This is the interval during which the first condenser is accumulating its steady charge.

The drop in B voltage supplied by the "Powerformer" is directly proportional to the current drawn. The regulation curve for the high tap slopes down in a straight line from 175 volts, zero current, to zero volts, 37 milliamperes. The socket-power supply will give 20 milliamperes at 90 volts. The characteristic falls rapidly because it is impossible to use more than half the voltage at the output of the filter. The plate-circuit requirements of the power amplifier tube necessitate a high voltage at the filter output. The excess must be absorbed in a resistance. The scheme gives much poorer regulation than can be obtained from a good socket-power device where the voltage output of the filter is correct for the set. The power supply is ample for the usual two-step r. f. amplifier, detector, and one step audio amplifier. The second audio step is in the "Powerformer."

With the natural high impedance of socket-power devices, considerable trouble has been caused by the coupling between the audio plate circuits through the impedance of the socket device circuit. This trouble is entirely eliminated with this scheme. The detector plate circuit is completed through the 2-mfd. bypass condenser. The 30,000-ohm series resistance eliminates the coupling effects between the detector circuit and the two audio circuits.

The 7500-ohm sections of the potentiometer separate the two audio circuits so that each audio current goes through its proper bypassing condensers. Even at as low a frequency as 60 cycles, the condenser path for the audio component of the power amplifier plate current is only one thirtieth that of the potentiometer path.

THE AMPLIFIER

WE NOW consider the amplifier portion of the circuit. If we are to get fair reproduction, it is necessary that the current through the secondary of the output transformer, when connected to a normal load, will have the same wave shape as the signal voltage impressed across the primary of the input transformer. In other

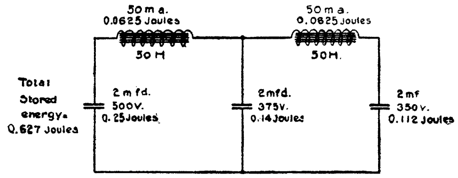

FIG. 7

words, the condition illustrated in Fig. 9 should obtain. The wave forms of the input voltage plate current and output transformer current are shown. The signal voltage is 4.22 volts r. m. s., corresponding to 6 volts peak signal or 18 on the grid through the 3:1 step-up transformer. The bottom curve represents the plate current of the tube. The zero of this current is above the curve

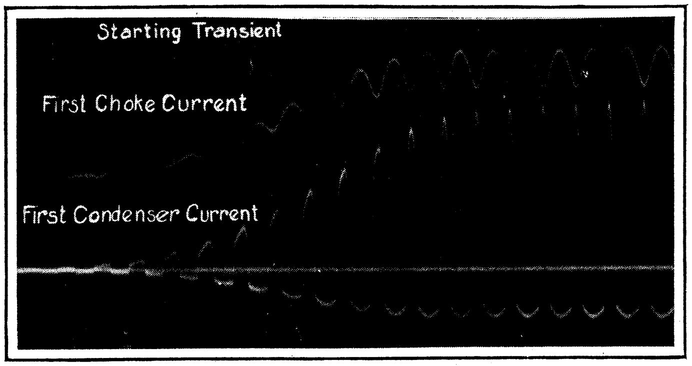

FIG. 8

shown. The center curve shows the current through the secondary of the output transformer working into a 5000-ohm resistive load used to simulate a loud speaker load. It will be noticed that the output current has about the same wave shape as the input signal voltage. The plate voltage was 390 volts; the grid bias 27 volts; the direct-current component of the plate current—34 milliamperes. This, and the succeeding oscillograms, were taken with a 60-cycle signal. The amplifier stage was connected to a more flexible battery supply than the rectifier and filter circuit we have been discussing. We used the separate battery supply so that it could be easily adjusted to illustrate the effect of having improper B and C voltages on the tubes. Fig. 10 shows the effect of using too small a C battery in this circuit. The signal voltage is still approximately $4\frac{1}{2}$ volts. The plate voltage is 400 volts. The C bias has been reduced to 10 volts, giving a plate current of 77 milliamperes. This condition obtains as the grid signal swings positive enough to draw current. The IZ drop of the current flowing through the high impedance of the transformer secondary will absorb practically all of the voltage induced in the secondary winding; consequently, the grid potential will remain approximately constant during the positive half of the grid signal, as shown in the photograph. When there is no alternating current in the plate circuit, the current through the output transformer secondary will, of course, fall off, just as any current decays when the potential across an inductance is removed and the inductance is discharged through a resistance. This gives the wave form shown in the center curve of the film. It will be noticed that the signal voltage shown at the top of the curve is no longer a sine wave. This is due to the fact that this particular curve was taken at 12:35 A. M. at Columbia University, using the United Service for the alternating current supply. It was noticed during that evening, as well as on other evenings, that the wave shape of the supply was much poorer after midnight than it was earlier in the evening. Fig. 11 is another curve representing approximately the same condition. The difference in this case is that another output transformer was substituted for the standard one. This output transformer has a large step-down ratio of the type which is adaptable to certain of the moving coil type loud speakers. In this case the signal voltage was considerably lower, that is, $\frac{3}{4}$ volt instead of $4\frac{1}{4}$ volts, accounting for the change in the plate current and the output transformer current. Since the output transformer secondary was much lower in inductance, the current decays more rapidly than in the other case.

The next oscillogram, Fig. 12, shows the amplifier tube operating with too large a C battery. The signal voltage in this case was $4\frac{1}{4}$ volts; B voltage—400 volts; the C voltage—44 volts; 14 milliamperes flowing in the plate circuit. This signal carried the grid so far negative that the curvature on the lower end of the tube characteristic distorted the signal. This distortion which appears both in the plate current curve (the top curve in the photograph), and the output transformer curve (the middle curve), is very similar to the distortion introduced when the grid swings too far positive, where the poor regulation of the high impedance grid circuit causes the peaks of the wave to be cut off. Fig. 13 illustrates the case where the signal voltage is too high, or the B voltage is too low. In this case, the signal voltage was $4\frac{1}{4}$ volts; the plate voltage—175 volts; the C bias—15 volts. This C bias was found to be about the best adjustment for 175 volts B voltage. The plate current was 14 milliamperes. It will be seen that this signal carried the grid down near the cut off point, giving distortion at the lower end, and also carried it sufficiently positive to cause

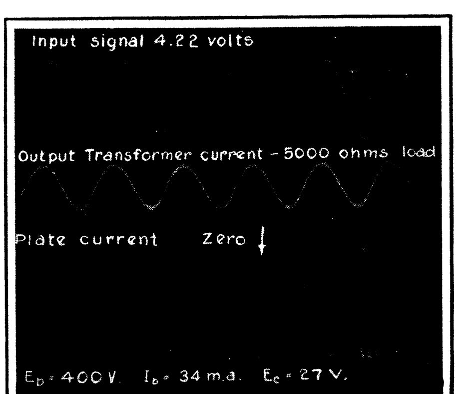

FIG. 9

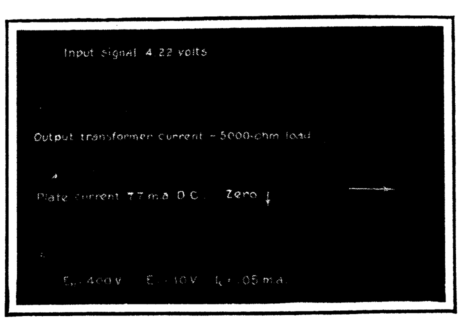

FIG. 10

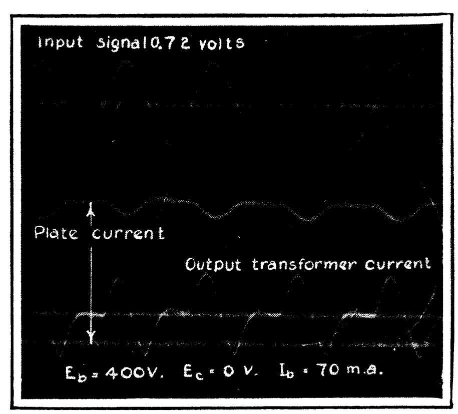

FIG. 11

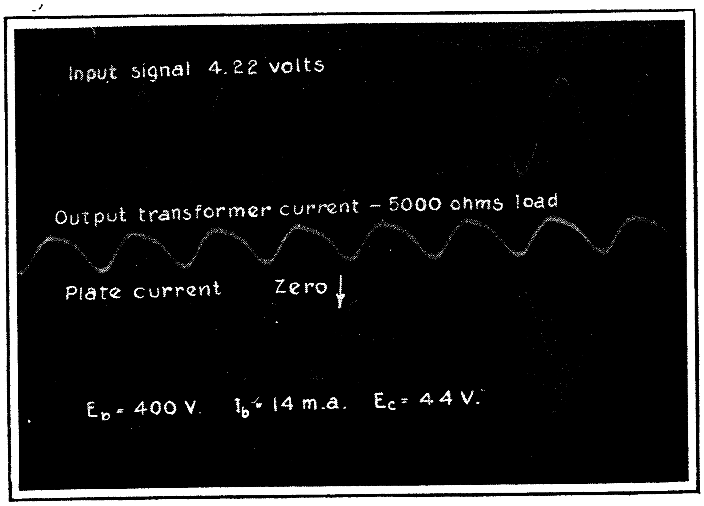

FIG. 12

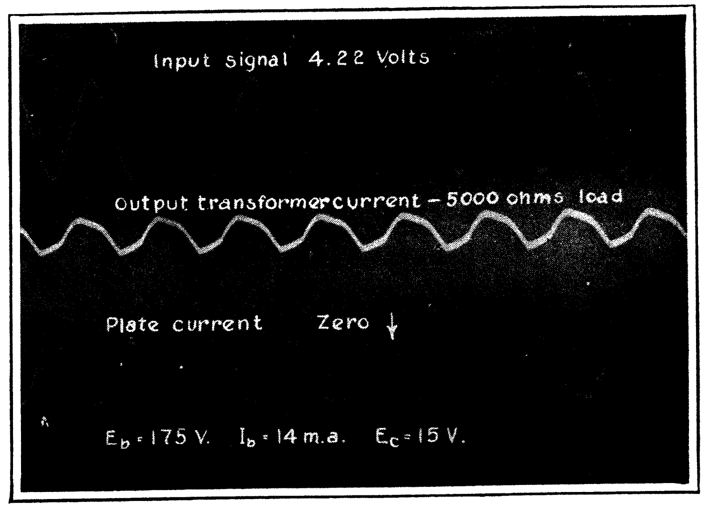

FIG. 13

similar distortion at the positive end of the cycle. This distortion appears in both the plate current curve and in the output transformer current curve.

Observations were made in several homes to find out how much signal voltage the average broadcast listener desires for what he would call normal volume. It was found that 6 volts peak audio-frequency voltage on the primary of the input transformer to the power stage was about the proper value. This corresponds to approximately 150 to 185 volts on the loud speaker. This value of 6 volts would of course be changed were a different transformer ratio to be used, or were a tube having a different amplification factor to be substituted. This power amplifier will take about 8 volts peak signal before the signal will suffer any distortion. It will take up to 12 volts on occasional peaks with such a small amount of distortion that the average broadcast listener will not notice it. If the plate voltage is reduced much below 300 volts, it will be found that the average broadcast listener will tune-in the signal so that there will be very objectionable tube overloading.

There is one other possible source of distortion, namely, the effect of the direct current flowing through the primary of the input transformer in saturating the core and so causing distortion. This form of distortion will not be encountered in the output transformer, since a small air gap is provided to prevent core saturation. There are two forms of distortion which might be expected from core saturation in the input transformer. One would be that form where the iron is operated so high up on the magnetization curve that the effect of the part of the signal cycle which would tend to carry it a little further up, would not be as effective in changing the flux as the part which tends to reduce the flux in the iron. This would give an unbalanced effect, destroying the symmetry between the two halves of the output voltage. This effect does not exist in the type of amplifier we are considering, for the reason that the signal voltage causes such an extremely small change in the flux density in the iron that the difference in the slope of the magnetization curve in different parts of the cycle is inappreciable. Fig. 14 shows this effect. The smaller of the two curves shows the signal current flowing through the secondary of the output transformer into a 5000-ohm resistive load when a sine wave is impressed on the primary of the first transformer. For the larger of the two curves, the same conditions were repeated with the change that 31 milliamperes of direct current were flowing through the primary of the input transformer. The change in magnitude of the wave is of no significance since it is due to a change in magnitude of the impressed signal voltage. It will be noted that this direct current, 31 milliamperes, is far in excess of any current that would flow through the primary of this transformer in a normal circuit. It will be noticed that the two wave forms are similar, showing that even this large direct current had no effect as far as introducing this particular type of distortion is concerned.

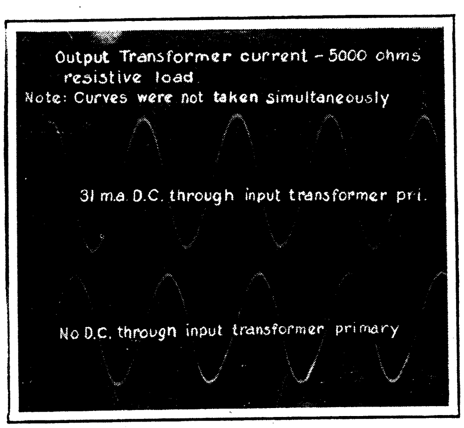

FIG. 14

There is still another type of distortion to be considered. When the direct current is flowing through the primary, that is, when the iron is worked higher up on the magnetization curve, the impedance of the transformer primary will be reduced. This acts to reduce the amplification of low frequencies when the signal is impressed through a high series resistance, such as the plate circuit of the tube. Fig. 15 illustrates an exaggerated example of this effect. In the larger of the two curves, the 60-cycle voltage was impressed on the primary of the transformer through a 27,000 ohms. Under these circumstances, the transformer is operating under more unfavorable conditions than is usually the case. The departure from the sine wave is due to the better amplification of the harmonics of the signal than of the fundamental. The fluctuation in the height of the peaks of the same wave was due to the fluctuation in the B-potential supply. The smaller of the two curves shows the effect of 20 milliamperes flowing through the primary while the signal is impressed across the primary through a 27,000-ohm series resistance. It will be noticed that the magnitude of the output signal has decreased, due to the reduction in the primary impedance. The harmonics are also more pronounced than they are in the upper curve. The conclusion to be drawn from these two photographs is that the effect of the direct current flowing through the primary of the transformer is to tend to cut off the lower frequencies. From experimental data which were taken in addition to these two oscillograms, it seems that a current of 5 milliamperes has very little effect in reducing the effectiveness of the transformer at the lower frequencies.

In conclusion, I wish to thank Dr. S. L. Quimby for his assistance in taking the oscillograms, and for his helpful suggestions. I also wish to thank Mr. Goudy, Mr. Brown, Mr. Corbett, and Mr. Lundahl, of the Pacent Electric Company's engineering department, for making this paper possible.

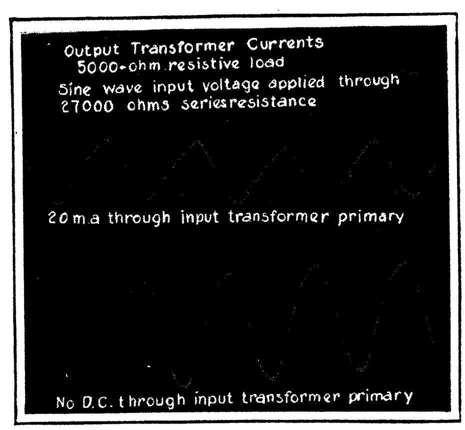

FIG. 15

More Life Membership Dues Paid

The Club Treasurer has received from Mr. George E. Burghard a check for One Hundred Dollars in settlement of Annual Dues for life membership.

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Mitchell, Irving H., 115 West 16th St., New York, N. Y. .... Member
Morgan, John T., c|o Charleston Electrical Supply Co., Charleston, W. Va. ...... Member
Nichols, William E., 38 Court St., White Plains, N. Y. .... Member
Palmer, George E., c|o Dubilier Condenser Corp.,
4377 Bronx Blvd., New York, N. Y. ..... Member
Rhodes, Howard E., c|o Doubleday, Page & Co., Garden City, N. Y. .... Member
Simpson, Frederick H., Jr., Box 208, Kingston, Ontario, Canada .... Member
Srebroff, Charles M., 186-24 Jordon Ave., Hollis, L. I., N. Y. .... Member
Whiting, Sherman E., 118 Wall St., Bridgeport, Conn. .... Member

Deceased

Wilbur F. Bingham	April 21st, 1927
LeRoy Clark	April 18th, 1927
Akira Tsubouchi	Japanese Earthquake Victims
Shin-Ichi Yokachi	Japanese Earthquake Victims

Annual Banquet at McAlpin

Nearly 200 members and guests of the Club were present at the second annual banquet held Thursday evening, May 12, at the Hotel McAlpin in New York City. This event was probably the most successful affair of its kind held by the Club since its formation, 18 years ago, and clearly demonstrated the tremendous enthusiasm and support which the Club enjoys.

Mr. George F. McClelland, Vice President and General Manager of the National Broadcasting Company, was the principal speaker of the evening. He spoke of the development of chain broadcasting on a national scale and pointed to the steady improvement of broadcast programs in point of quality and consistency of rendition.

Other speakers were Mr. David Sarnoff, Vice President and General Manager of the Radio Corporation of America; Mr. George Clark, the "Will Rogers of Radio"; Mr. R. H. Marriott; Mr. Lloyd Espenschied, of the American Telephone and Telegraph Co.; Mr. Harry Sadenwater of NC-1 fame, and at present in charge of transmission of the General Electric Company's broadcasting activities, was the toastmaster.

L. G. Pacent
Chairman Committee on Papers
91 Seventh Ave., New York, N. Y.

Pierre Boucheron
Chairman Committee on Publications
Room 2040, 233 Broadway, New York, N. Y.