THE DESIGN, CONSTRUCTION, AND TEST OF A SIMPLEX CARRIER CURRENT SYSTEM.

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I Introduction and Acknowledgments

Although this thesis is concerned primarily with carrier current telephony as applied to regular telephone toll service, it should be remembered that the fundamental principles involved also apply to the use of carrier current telephony and telegraphy on power transmission lines.

A systematic attempt to present all previous work in the field would entail a needless compilation of data which I have deleted.

"Anticipation of results, which often springs from prejudice or desire to secure evidence favoring a cherished belief or theory, is a stumbling block in scientific research work." I have endeavored to maintain an open-minded, unprejudiced attitude throughout the investigation.

I claim originality in the design of the circuit in that it was drawn previous to any reference work. From that point I made reference, as hereafter acknowledged, and altered the circuit to meet the extenuating conditions, holding throughout to the original ideas incorporated. A photostatic copy of the original circuit is included (Fig. 2) as well as a schematic diagram of the final systems (Fig. 1).

I acknowledge with thanks my indebtedness to Professors W. A. Murray and C. W. Hoilman, who gave me much helpful advice, enabling me to bring this work to a conclusion. I further acknowledge indebtedness to fellow classmates who assis-

ted in many ways. I am also deeply indebted to those workers incorporated in the accompanying bibliography.

II History

The complete history of carrier current telephony would necessarily start with the beginning of the telephone, which is in itself a carrier current device of a kind. Herein is included only the history of carrier current telephony proper.

The first successful experiments in carrier current telephony and telegraphy (also called Wired Radio, or Multiplex Telephony) were carried out in 1910 in the United States Signal Corps Laboratories under the direction of Major General G. O. Squier.

It is admitted that much valuable work was done abroad by such notables as: Gibbony, Stone, Pupin, la Blanc, and Ruhmer, but their investigations and findings did not materialize into a practical solution of the problem. The first commercial application of the idea was not made until 1912, when the engineers of the American Telephone and Telegraph Company realized the importance of relatively high frequency currents for the transmission of intelligence over wires. By 1918, carrier current telephony was installed in all of the important circuits of any length.

In 1920, the carrier current method of transmission of intelligence was tried over power lines. The first experimental equipment was installed by the American Gas and Electric Company between Atlantic City and Ocean City, New Jersey over an 11,000 volt transmission line. The results were so success-

ful that all power plants of any size now use this system for communication between the various plants and substations. In some cases the power companies have furnished the only means of communication between isolated districts and the rest of the world. Power transmission lines are so much more ruggedly built than telephone lines that the service is seldom interrupted by storms.

The advancement of carrier current telephony to its present state is due solely to the work of the Bell Telephone Company engineers. The first systems segregated the various bands by tuned circuits in the same manner that present day radio communications is accomplished. The Bell Laboratories, largely through the efforts of Dr. G. A. Campbell, developed the electrical device known as a wave filter. A wave filter consists of a network of pure inductive and capacitive reactances. By means of these wave filters the various bands can be segregated with greater precision, with a consequent increase in the number of messages that can be handled by any physical circuit.

The methods and systems have progressed from the stage where only three or four two-way telephone circuits were available per pair of line wires, to the stage where sixteen duplex circuits may be obtained from a single pair of an open wire lead.

III Fundamental Considerations

A. General

Carrier current telephony may be defined as a method by which intelligence is transmitted over wires by bands of frequencies which are above the voice frequency range. To accomplish this, the so called "carrier currents" of different frequencies are caused to vary in accordance with the intelligence to be transmitted. These various modulated carrier impulses may be transmitted simultaneously over the same physical circuit. At the receiving end the different frequencies must be separated by proper electrical wave filters, the impulses detected, or demodulated, and the signal components transmitted to the desired point.

From a consideration of the theory of modulation; which shows that if two different frequencies of voltage are impressed simultaneously upon a nonlinear impedance, the resultant current in the output will contain frequencies equal to the sum and the difference of the two impressed frequencies: the carrier current must obviously be of a frequency higher than the highest frequency present in the intelligence to be transmitted. There seems to be a difference of opinion as to the highest frequencies which may be used successfully. Up until a few years ago Bell technicians said that 30,000 cycles was the upper limit because of the increase in attenuation and cross talk, or inductive interference, at the higher frequen-

cies. However, the Army Signal Corps have tried frequencies as high as 600 kilocycles with great success. Their success with the use of such high frequencies is probably due to the fact that the Army ran tests on a single pair of line wires and therefore, were not hampered by cross talk which increases rapidly with an increase of frequency.

The earlier systems were little more than low frequency radio transmitters and receivers which were directly connected by a metallic circuit rather than by electromagnetic and electrostatic waves; the idea being that the energy transmitted would be guided by a channel, thereby reducing the power lost and at the same time offer the advantages of multiplexing.

In actual practive, several methods for transmission are employed. In some systems the carrier and one side band are transmitted. In other systems the carrier is suppressed, thereby reducing the line losses. When the carrier is suppressed, only one side band is transmitted and at the receiving end the carrier is reintroduced so that the intelligence may be demodulated. Usually, in this system, one of the carrier frequencies is transmitted continuously to provide a means of synchronizing the reintroduced carriers.

B. Technical

From the beginning engineers have had trouble with the greater attenuation and increased interference encountered at the higher frequencies. The transmission lines, which were good enough for voice frequency transmission, proved unsatisfactory for high frequency transmission. The engineers set to work; better lines were installed with improved insulators, transpositions for the line were recalculated and inserted with a high degree of accuracy, thus reducing cross talk to a minimum. However, even under the best of conditions, up until the last two or three years, the upper limit to the carrier frequency was 30,000 cycles.

Interference may be caused by electromagnetic or electrostatic fields. The open wire line is highly susceptible to inductive interference even though its capacity is low as compared with the capacity of cable circuits. Within recent years the capacity between circuits in an open wire line has been decreased by placing the wires of each pair closer together, thereby increasing the distance between adjacent circuits. Cable circuits have an advantage over open wire lines in that the lead sheath around the cable serves to shield the conductors from stray electric fields.

The high shunt capacity of a cable circuit greatly increases the attenuation per unit length of line; also, since the adjacent pairs in a cable are very close together, the

energy level must be kept much lower in the cable than in an open wire line in order to minimize cross talk. There fore, when repeatering a cable circuit, it is necessary to use approximately twice as many smaller gain repeaters as would be needed in the same length of open wire line.

At the present time the top frequency for cable circuits is 60,000 cycles, giving twelve two way telephone circuits. The top frequency for open wire lines is now 140,000 cycles, providing sixteen duplex telephone channels. With the coaxial system between New York and Philadelphia, which is still in the experimental stage, 240 two way telephone circuits are obtained by using a frequency range up to one million cycles.

The coaxial system is of special interest in that it illustrates the advancement in the equipment used. Twenty bands of frequencies are available on this cable; each band consisting of twelve channels with a frequency width of 4,000 cycles. This sharp division between adjacent bands and channels is largely due to the developement of crystal filters which are much more selective than the ordinary reactor type filters. The quartz crystal, when properly cut, has the electrical properties of a reactive circuit with 100 times the "Q", or reactance-to-resistance ratio, that can be obtained with the best condensers and inductances now available.

In most telephone circuits, the gain per repeater is limited by the cross talk effects; in the coaxial system, the re-

peater gain is limited only by tube noises, resulting from the electric fields set up by the electron stream in the tube itself.

C. Economic

From an economic standpoint, the installation of carrier current equipment is justified only on long lines. Carrier current reduces the number of physical circuits necessary to supply the toll demand; however, offsetting this advantage is the fact that carrier current lines must be much more carefully constructed, insulated and balanced. Carrier current circuits, especially when cables are used, must be repeatered at much closer intervals. Any unbalance in the circuit is much more troublesome at carrier current frequencies.

Carrier current equipment is flexible, in that it can be connected into any line where there is too great a toll service demand to supply with the available physical circuits. Thus it may happen that a long distance call may be transmitted over several stages by voice frequency current and over several stages by carrier currents.

Other costs that must be considered are the heavy initial cost of the inside and outside plant, the cost of installation and the cost of maintenance. Maintenance costs include the cost of highly skilled labor as well as the cost of replacement materials.

IV Design and Construction

A. Oscillator

L. Design.

The oscillator decided upon was a modification of the series fed Hartley circuit.

Any amplifying circuit can be used as an AC generator under the following conditions:

(a). The output and the input circuit must be coupled so that a portion of the output energy is fed back into the input circuit. This feedback must be synchronized with the input. The engineers of the American Telephone and Telegraph Company say that the amount of energy fed back must be at least as great as the reciprocal of the energy amplification.

(b). Either the output or the input circuit should have a parallel resonant circuit to determine the frequency generated.

The feedback to the grid circuit was controlled by an adjustable tap from the coil to the cathode. Thus, since all of the plate current, both radio frequency and direct, flows through that portion of the oscillator coil between the cathode and the plate battery return (hence the name series fed), the amount of energy fed back to the grid can be controlled by adjustment of the cathode contact to the coil.

In the original design of the oscillator, the inductance

and capacity of the resonant circuit were calculated to give a maximum carrier frequency of 30,000 cycles by use of the formula:

$$f_r = \frac{1}{2\pi \sqrt{LC - \frac{R^2}{4Z^2}}}$$

and assuming that R was negligable.

A standard capacity was chosen and the necessary value of inductance to correspond was calculated.

In actual practice the oscillator coils used are constructed by using cores of powdered magnetic materials, such as. permalloy, with high permeability and low hysteresis. As the data for calculating and the material for constructing coils of this type was not available, large air-core coils had to be used.

The coil winding data was obtained by applying Nagoaka's chart.* The first coils were constructed by winding 400 turns of No. 26 enameled copper wire on a six-inch length of two-inch fiber tubing. When used in conjunction with a 0.1 mf. mica condenser, the original setup failed to oscillate because the resistance of the resonant circuit was too great. When this coil was used in conjunction with a 0.005 mf. mica condenser, oscillation setup, but the frequency was far too

*For information on inductance winding refer to Bulletin 74 of the Bureau of Standards, entitled "Radio Frequency Instruments and Measurements, or to the "Radio Handbook", by the Pacific Publishing Company.

high to be used on the artificial telephone line. However, this setup was used to test and akjust the remaining stages of the transmitting and receiving apparatus.

After the otherstages were put into operating condition, larger oscillator and detector coils were made. These coils consist of 300 turns of No. 22 enameled copper wire on a 9.5 inch coil form 5.5 inches in diameter. The original oscillator and detector coils were used as pick-up coils in the final set-up.

The schematic diagram of the oscillator is shown in Fig. 1 while the physical layout is shown in Fig. 4.

The oscillator condenser (C_2 & C_3) consists of a fixed 0.005 mf. mica condenser shunted by a 0.0005 mf. air condenser for tuning. The grid condenser (C_1) is a 0.00025 mf. mica condenser, and the grid resistor (R_1) is a 3 megohm grid-leak. The high frequency by-pass condenser (C_4) is a 0.5 mf. electrolytic condenser.

The tubes used throughout were Western Electric 245-A's. The 245-A is a screen-grid tube of the heater type, thus enabling the filaments to be supplied by either AC or DC. The maximum rating of the tube is given by the chart in the Appendix.

2. Operation and Test.

The oscillator stage is put into operation by adjusting the variable cathode tap until the observed plate current is a minimum. This is done with a low voltage on the plate. As soon as the circuit is oscillating, the plate voltage can be increased until the tube is passing its rated current. The oscillator was found to operate best with about 1/3 of the turns in the oscillator coil in the plate current circuit.

By using a high resistance AC voltmeter in conjunction with a 400 turn pick-up coil, comparative readings of AC output were taken for different values of plate voltage and plate current. The included curves (Fig. 9) show the results.

The oscillator output voltage was also viewed on an oscilloscope. The wave was practically a pure sine wave, showing that very few harmonics were generated in the oscillator. The large value of capacity in the by-pass condenser (C_4) is in a large measure responsible for the good wave shape. Other factors which contribute to good wave shape are: high "Q" resonant circuits, small L/C ratio, and operation of the tube on the linear portion of the characteristic curve. Strictly speaking however, it is impossible for a self-biased oscillator to stay on the linear portion of the curve, as the grid swings from very near the cut-off point to the saturation point of the curve.

B. Buffer Stages

Since the Hartley circuit is unstable with variation in load, and the carrier frequency output voltage was of too low a value for satisfactory modulation, two buffer stages were installed to amplify the voltage and to isolate the oscillator from the load.

The first buffer stage is coupled to the oscillator by a grid coil inserted within the oscillator coil. The second buffer is coupled to the first and the modulator is coupled to the second buffer through specially wound transformers (T_1). These high frequency transformers were constructed by winding 700 turns and 800 turns of No. 36 single cotton covered copper wire respectively on the primary and secondary. For better coupling the primary and secondary were wound in banks as shown in Fig. 7 The tuning condensers (C_3) are variable 0.0005 mf. air condensers.

The 1st buffer stage was biased so that the grid would draw no current, thereby eleminating the chance of varying the load on the oscillator and therefore the carrier frequency.

In operation, once the buffer stages are adjusted to operate at the carrier frequency, there is no need to tune the coupling circuits unless the carrier frequency is changed.

The schematic diagram of the buffer stages is given in Fig. 1. The layout of the two buffer stages together with the oscillator is shown in Fig. 4.

C. Modulation

Modulation is difficult to define other than mathematically; however, it may be said that modulation occurs at any time that the output current of any impedance contains components which are proportional to the product of the input voltages.

One way of analyzing modulation by a vacuum tube is to assume that, since the slope of the characteristic curve is not constant, the amplification, and there fore the output current, can not be regarded as constant, but varies as a function of the input voltage itself.

If a uniform carrier voltage is applied to the grid of a vacuum tube, a certain degree of amplification will result, depending in amount on the particular portion of the grid voltage-plate current curve over which the action is taking place, the amplification becoming greater when the input voltage is operating in the region of greater slope. If a voice frequency voltage is now applied to the input of the vacuum tube, the action may be superficially considered as one of varying the portion of the characteristic curve on which the amplification of the carrier current is taking place; that is, during the time that the voice frequency voltage is low the amplification of the carrier voltage is low, and during the time that the voice frequency voltage is increasing the amplification of the carrier voltage is increasing. In other words, we may look upon the impressed low frequency voltage as a varying bias which contin-

uously alters the degree of amplification of the high frequency carrier voltage. Refer to Fig. 8 for pictorial illustration.

A brief mathematical analysis of modulation will show the resultant output current when voltages of two different frequencies are impressed upon a non-linear impedance.

When a vacuum tube is operated over the lower parabolic section of the grid voltage-plate current characteristic curve, the relationship between the plate current and the grid voltage is given by the formula:

$$i_p = ae_g + be_g^2 \qquad (1)$$

If the impressed grid voltage consists of two sine wave voltages, one of a high frequency $p/2\pi$ and one of low frequency $q/2\pi$; that is:

$$e_g = E_1 \operatorname{Sin} pt + E_2 \operatorname{Sin} qt. \qquad (2)$$

Substituting this value of grid voltage in the equation for plate current gives:

$$i_p = aE_1 \operatorname{Sin} pt + aE_2 \operatorname{Sin} qt + bE_1^2 \operatorname{Sin}^2 pt + bE_2^2 \operatorname{Sin}^2 qt + 2bE_1E_2 \operatorname{Sin} pt \operatorname{Sin} qt. \qquad (3)$$

Substituting in (3) the following trigonometric relations:

$$\tfrac{1}{2}\operatorname{Cos}(p-q)t - \tfrac{1}{2}\operatorname{Cos}(p+q)t = \operatorname{Sin} pt \operatorname{Sin} qt$$

$$\tfrac{1}{2} - \tfrac{1}{2}\operatorname{Cos}2pt = \operatorname{Sin}^2 pt$$

$$\tfrac{1}{2} - \tfrac{1}{2}\operatorname{Cos}2qt = \operatorname{Sin}^2 qt$$

$$i_p = aE_1 \operatorname{Sin} pt + aE_2 \operatorname{Sin} qt + bE_1^2(\tfrac{1}{2} - \tfrac{1}{2}\operatorname{Cos}2pt) + bE_2^2(\tfrac{1}{2} - \tfrac{1}{2}\operatorname{Cos}2qt) + 2bE_1E_2\ \tfrac{1}{2}\operatorname{Cos}(p-q)t - \tfrac{1}{2}\operatorname{Cos}(p+q)t$$

Neglecting the double frequency terms, the modulating fre-

quency term and the constant term, the plate current can be expressed by:

$$I_p = aE_1 \sin pt + bE_1E_2\cos(p-q)t + bE_1E_2\cos(p+q)t.$$

This analysis shows that the resultant output current contains, amongst other terms, frequencies equal to the sum and the difference of the impressed frequencies. These so called "upper and lower side bands" contain the intelligence being transmitted.

For detection, or demodulation, only one side band and the carrier frequency are necessary. By filtering out one side band, the number of available circuits per pair of conductors is doubled.

Grid modulation is used in this system; that is, the modulation is carried on in grid circuit of the modulation tube. Fig. 1 shows the schematic diagram of the modulator stage. Fig. 5 shows the physical layout. In this system, both the carrier input and the audio frequency input voltages are controlable; two 50,000 ohm potentiometer rheostates (R_2) are used for this purpose. The audio frequency control is in the grid circuit of the one stage audio frequency amplifier which is transformer coupled to the modulating stage. The carrier frequency amplitude control is directly connected to the grid circuit of the modulating tube.

The high frequency by-pass condenser (C_4) shunted around the audio frequency transformer (T_1) provides grid return of the carrier frequency with a low impedance path, otherwise the high impedance of the audio transformer would choke out the carrier

component of the output of the modulating stage.

It is in this stage that the carrier is sometimes purposely suppressed, for a different type of transmission.

A push-pull circuit is used to accomplish this carrier frequency suppression. The high frequency voltage is impressed on the grids of the two tubes at the same instant, therefore the resultant high frequency currents in the plate circuit are the same. If the output transformer is connected correctly, and if the number of turns in each plate circuit is the same, the flux set up by the high frequency currents in the transformer will be in opposition and cancel each other, therefore no voltage of carrier frequency will be induced in the secondary of the output transformer, Any signal impressed upon the signal frequency transformer will be impressed upon the two grids 180° out of phase, therefore the flux set up in the output transformer by the resulting plate current will be additive and the signal frequency appears at the output. At the same time, modulation takes place in each of the tubes and the side band frequencies generated also set up additive fluxes in the core of the output transformer which induce the side band frequency voltages in the output.

In testing the system it was found that unless the carrier voltage impressed upon the grid of the modulator tube was at least as great as the voltage of the impressed intelligence waves, a serious distortion in the demodulated signal was introduced.

The only meter available for making this test was a high resistance rectifier type AC voltmeter, which is very inaccurate at high frequencies. If a vacuum tube voltmeter were available, it would be possible to determine at what degree of overmodulation distortion is introduced.

The investigator suggests that a beat frequency oscillator and detector would give a much more satisfactory carrier current generator and demodulator. The reasons are several: the frequency range would be vastly increased, and the tuned resonant circuits could be designed to oscillate at much higher frequencies, thereby reducing the size of the inductances and condensers necessary.

D. Demodulation

Demodulation may be considered in exactly the same way as modulation. Briefly, when two voltages---the side band frequency and the carrier frequency---are applied simultaneously to the input of a non-linear impedance, in this case the grid of a vacuum tube, just as in modulation, the output current contains frequencies equal to the sum and difference of the two impressed frequencies (aswell as the distortion frequencies which will not be considered). It can be seen that the difference of the two frequencies will be the frequency of the original intelligence impressed at the transmitter.

Suppose, for example, that the carrier frequency is 100 kc. and that the impressed intellegence contains frequencies between 1000 and 3000 cycles. The upper side band will contain frequencies from 101,000 cycles to 103,000 cycles and the lower side band will contain frequencies from 97,000 to 99,000 cycles. Suppose that only the upper side band and the carrier frequencies are transmitted and impressed upon the input of the demodulator circuit; the side band of frequencies from 101,000 cycles to 103,000 cycles and the carrier frequency will "beat" and set up two frequency bands, the upper inaudible band containing frequencies from 201,000 cycles to 203,000 cycles, and the lower band containg the intelligence frequencies from 1000 to 3000 cycles.

Fig. 1 shows a schematic diagram of the demodulator; Fig. 6 shows the physical layout of the demodulator and the one stage

audio frequency amplifier.

This demodulator is a modification of the ordinary regenerative detector. The feedback is controlled by the adjustable cathode tap. The inductance, tuning condensers, grid blocking condenser, grid leak, and high frequency by-pass condensers are of the same values as those used in the oscillator stage. The by-pass condenser shunted across the audio frequency transformer provides a low impedance path for the circulation of the regenerative feedback currents.

In actual operation the regeneration control proved to be very critical; for less critical feedback control it is suggested that an additional tuning condenser of 0.0005 mf. be shunted across that portion of the detector coil in the plate circuit.

As in the first buffer stage, the pickup coil for the detector consists of 400 turns of No. 26 enameled copper wire on a six inch length of two inch fiber tubing.

It was found necessary to add one stage of audio frequency amplification to build up the energy level. The volume control is a 50,000 ohm potentiometer shunted across the secondary of the audio transformer T_3.

E. Miscellaneous

1. The Tubes:

The Western Electric 245-A vacuum tube was chosen for two reasons: its amplification factor is much higher than the amplification factor of any other available tube; and the tube, having a screen grid, permitted a greater flexibility in testing various circuit variations.

It was found that, so long as a positive potential was kept on the screen grid, the value of the voltage was not very critical. Therefore, in order to reduce the number of B battery supplies to a minimum, the screen grids were electrically tied to the plates, thereby permitting the tubes to be used as ordinary triodes.

The tube characteristics are given in the Appendix.

2. The Metering Panel:

Since there are seven tubes in this system, seven milliammeters would be necessary to meter all of the plate currents, if separate meters were placed in each circuit. To reduce the number of meters necessary, the metering panel was designed and constructed. By use of this panel, the number of necessary meters is reduced to three: one 10 ma. DC milliammeter, one 300 volt DC voltmeter, and one three-volt AC Voltmeter.

Fig. 10 shows a schematic diagram of the method used to insert the milliammeter and the voltmeter, or just the voltmeter alone, in any of the plate circuits.

For example, to read the plate voltage on any tube, push the button in that circuit down and at the same time throw the two way key (on the same half of the panel as the button) upward. To read both the plate current and plate voltage, hold the same button down and throw the key downward.

With the panel as it is right now, the plate circuit is open for a short interval every time the buttons are pushed down. This is due to the fact that the switches break contact before the new contacts are made. By bending the contact supports slightly, a make-before-break switch can be made, thereby eliminating the interruption of the plate currents in the circuit being metered.

Discussion of Results

One of the main purposes of this investigation was to study the actual transmission of carrier current by using the equipment in conjunction with the available artificial telephone line. It was planned to study the attenuation at various carrier frequencies; to study the effects of different modulating frequencies upon the attenuation of a given carrier frequency; and the effect, if any, of the degree of modulation upon distortion and attenuation. However, the artificial line, which is a modified low-pass filter, has a cut off frequency which is too low to satisfactorily pass carrier current frequencies this high.

Therefore, the only possible tests that could be made with the system were the tests upon the individual stages of the system and the adjustment of these stages to give an optimum performance. These tests show that carrier current is the best solution for the problem of multiplexing telephone and telegraph circuits. No other method gives such a large number of channels.

Conclusions

In order to test carrier current equipment on the available artificial line, a lower carrier frequency must be used. It is suggested that the carrier frequency be around 15,000 cycles. With this carrier frequency, it is possible to test the system for the transmission of either telephone or telegraph signals. For telegraphy, it is probable that modulated continuous wave will give the most satisfactory results; the modulating frequency should be in the neighborhood of 800 cycles. For the telephonie transmission, this carrier frequency will prove more than ample to carry all intelligence frequencies which are, normally, between 200 and 3,000 cycles.

Unless low-loss high inductance coils are available, it is advised that beat-note oscillators be designed for both the generation and detection of the carrier frequency.

If a more thorough investigation is desired, several other refinements of the system are suggested: duplex , or two-way, operation; automatic gain control; and carrier suppression transmission, thereby enabling the use of a higher carrier frequency.

Summary

The original circuit diagram was drawn previous to any reference work on the subject; however, in the construction of the system it was found necessary to add to and subtract from the original circuit. For instance, in order to isolate the oscillator from the modulator and to amplify the carrier voltage it was necessary to add buffer amplifier stages; since only one system was built and since the system worked on the tuned detector principle, no filters were deemed necessary. Other circuit changes of minor importance are; the use of individual plate voltage supplies to minimize feed back between stages; the use of regenerative detection; and a variation in the obtaining of the oscillator output.

The system works satisfactorily, but is very critical; this is largely due to the fact that regenerative detection is used. Once the system is adjusted for quiet distortionless operation, it is found that an increase in modulating potential sufficient to over modulate the carrier introduces distortion. This is probably due to the fact that the tube is not operating on a parabolic portion of the grid voltage plate current characteristic curve during a large portion of each cycle, thus introducing third order, fourth order, fifth order, and n th order distortion terms.*

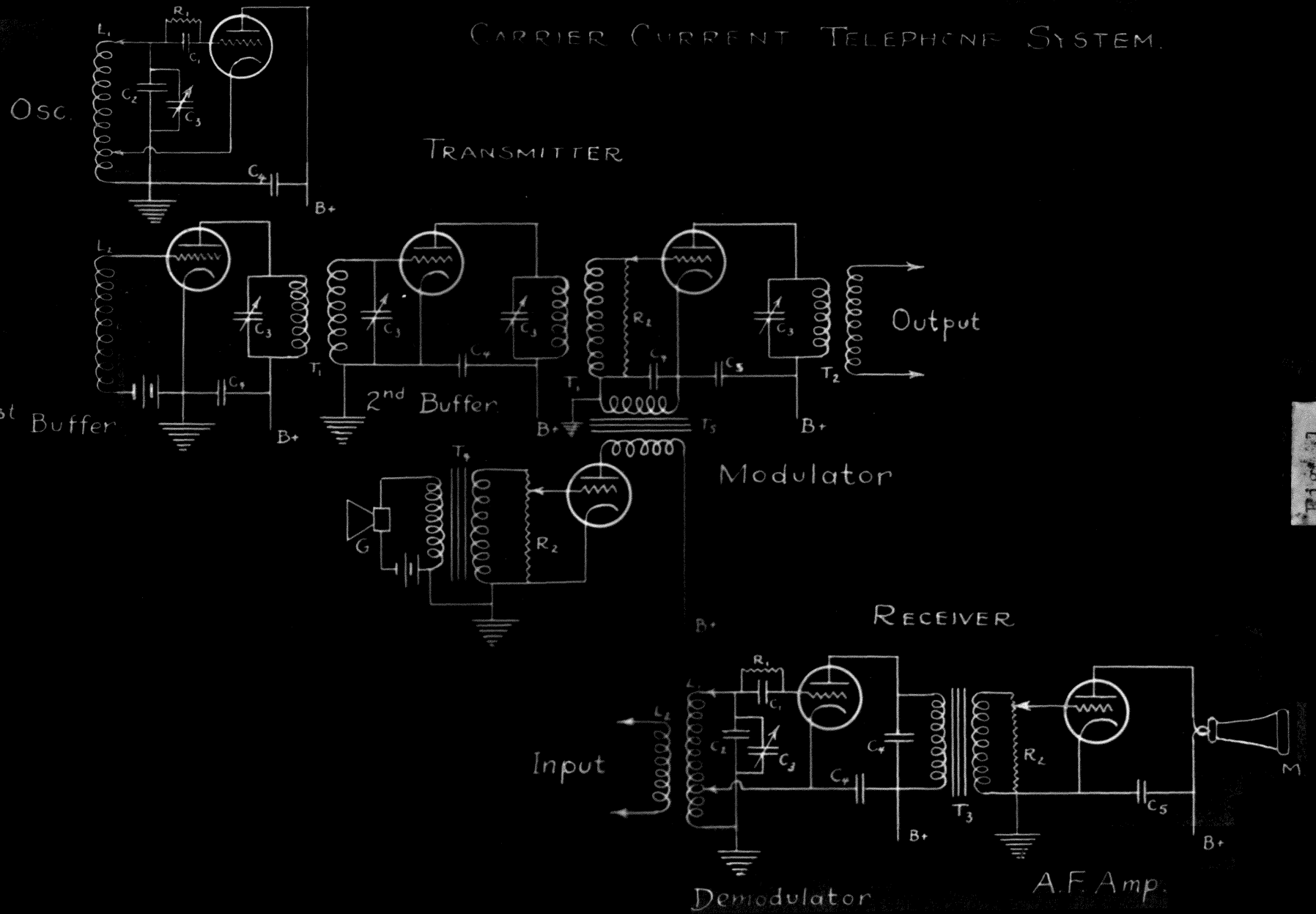
---

* It is to be remembered that the plate current can be expressed as a power series of n terms of the grid voltage, i.e. ---

$$i_p = a_1 e_g + a_2 e_g^2 + a_3 e_g^3 + \ldots\ldots\ldots\ldots a_n e_g^n.$$

The number of terms depends upon the portion of the curve over which the tube is operating; thus, for "square-law" or second order modulation, which occurs over the parabolic portion of the characteristic curve, n = 2; for third order modulation, n = 3; etc.

Schematic Diagram Of A One Way Carrier Current Telephone System.



Code for Figure 1.

Inductances:

L_1 -- Oscillator and Demodulator coils with 300 turns of No. 22 enameled copper wire on 9.5 inch coil forms 5.5 inches in diameter.

L_2 -- Coupling coils with 400 turns of No. 26 enameled copper wire on six inch coil forms two inches in diameter.

T_1 -- High Frequency transformers (See Buffer Data for details).

T_2 -- General Radio R. F. transformer

T_3, T_4, T_5 -- Audio frequency transformers

Condensers:

C_1 -- Grid condensers, capacity 250 mmf.

C_2 -- Oscillator and Demodulator condensers, capacity 0.005 mf. (Used in parallel with C_3).

C_3 -- 500 mmf. tuning condensers.

C_4 -- High frequency by-pass condensers capacity 0.1 mf.

C_5 -- Audio frequency by-pass condensers capacity 0.5 mf.

Resistances:

R_1 -- 3 megohm grid-leak resistors.

R_2 -- 50,000 ohm potentiometer reostates.

Miscellaneous:

G. Telephone Transmitter (for testing and adjustment of apparatus, the output of the laboratory oscillator was used).

M. Telephone Receiver.

Tubes -- Western Electric 245-A's.

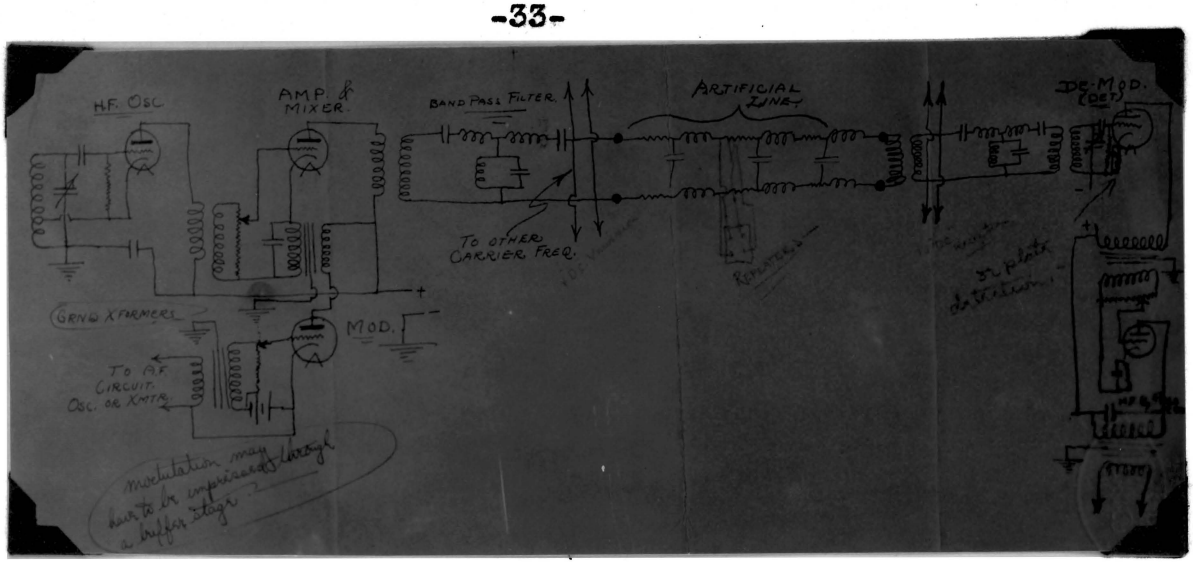


Fig. 2 The Original Circuit Diagram.

Fig. 3 The Final Setup of the Apparatus.

Left to right: Oscillator, two buffer stages, A. F. Amplifier, Modulator, Meters and Metering-panel, and Demodulator and A. F. Amplifier.

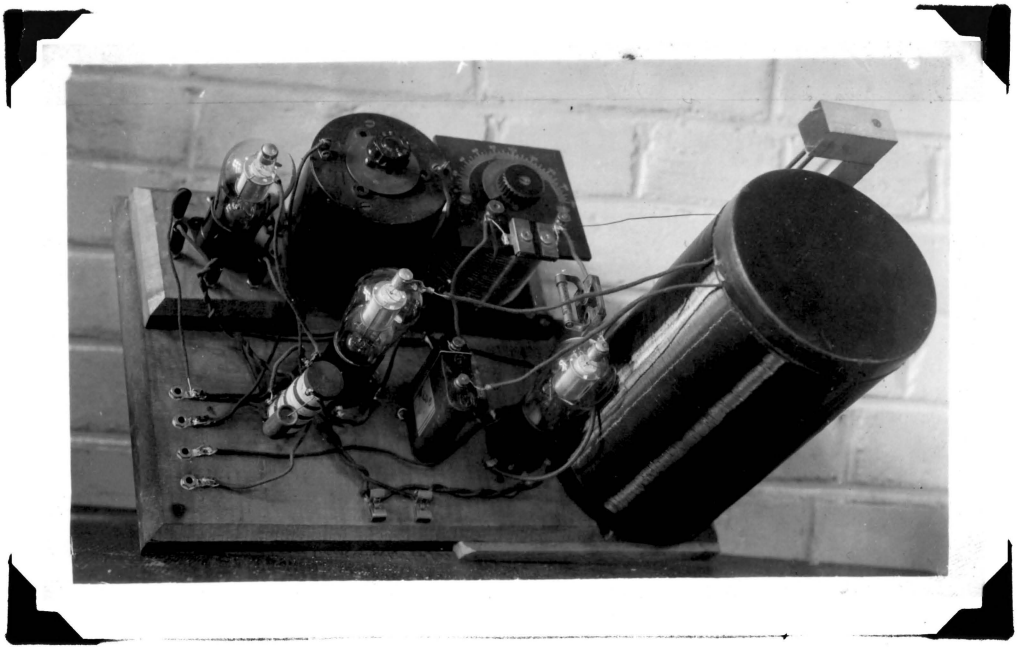


Fig. 4 The Oscillator and Two Buffer Stages.

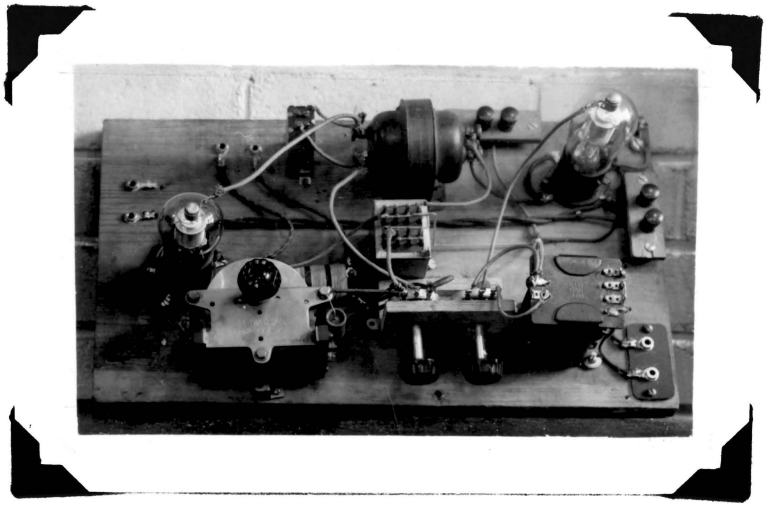


Fig. 5 A. F. Amplifier and Modulator Stages

Fig. 6 The Demodulator and A. F. Amplifier.

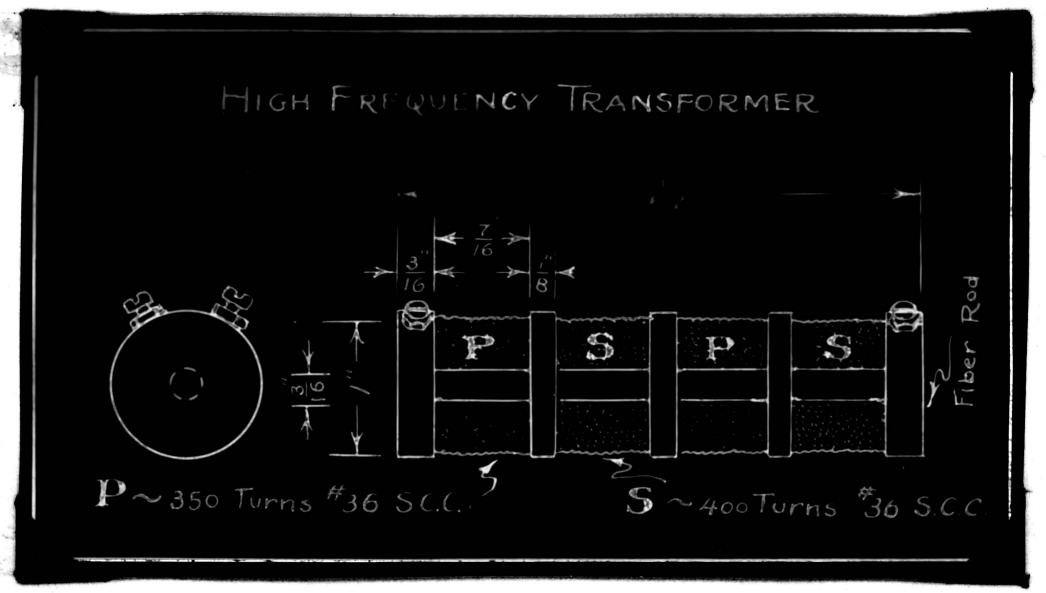


Fig. 7 Transformer used for coupling Buffer Stages.

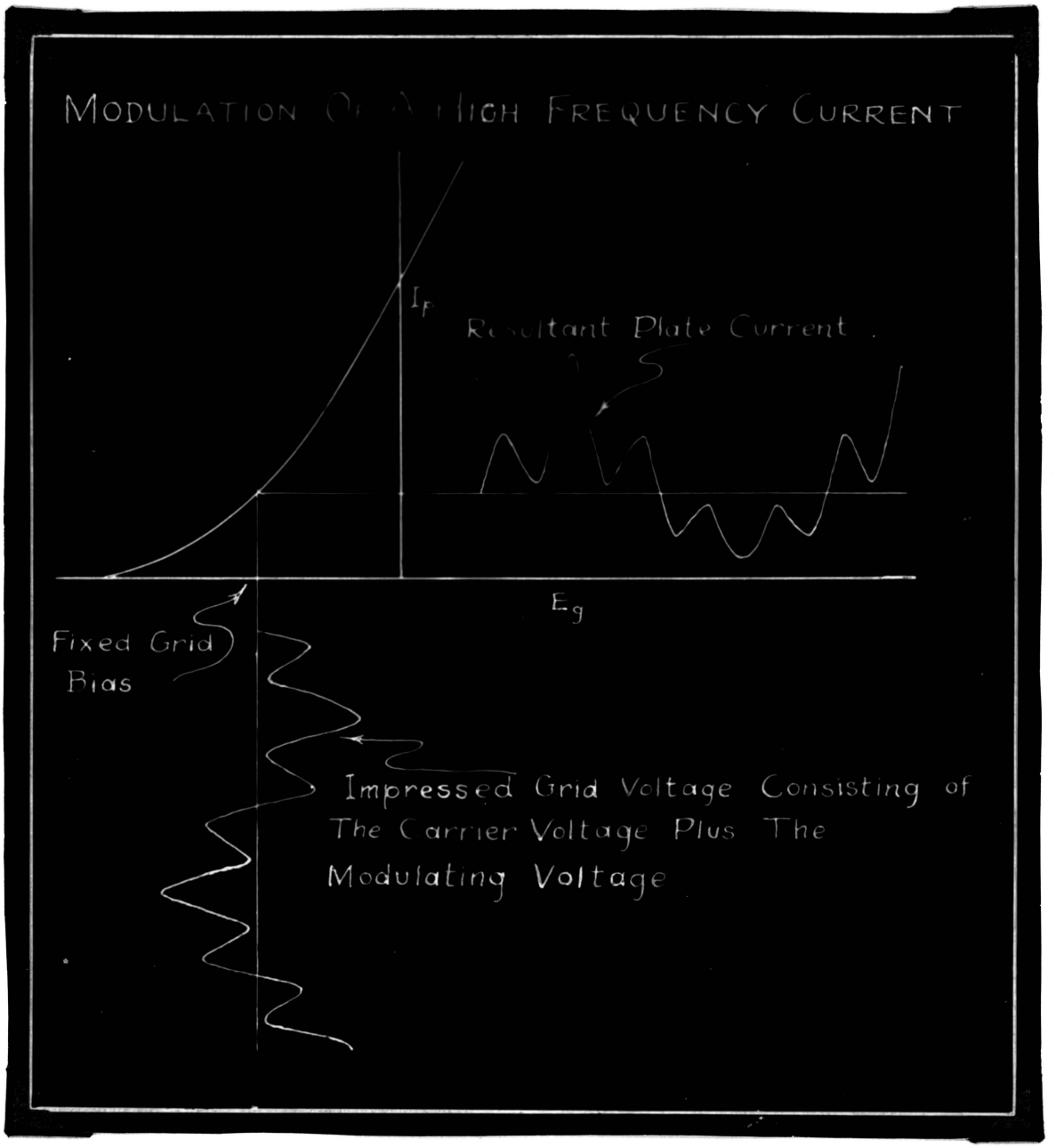


Fig. 8 Modulation of a High Frequency Current.

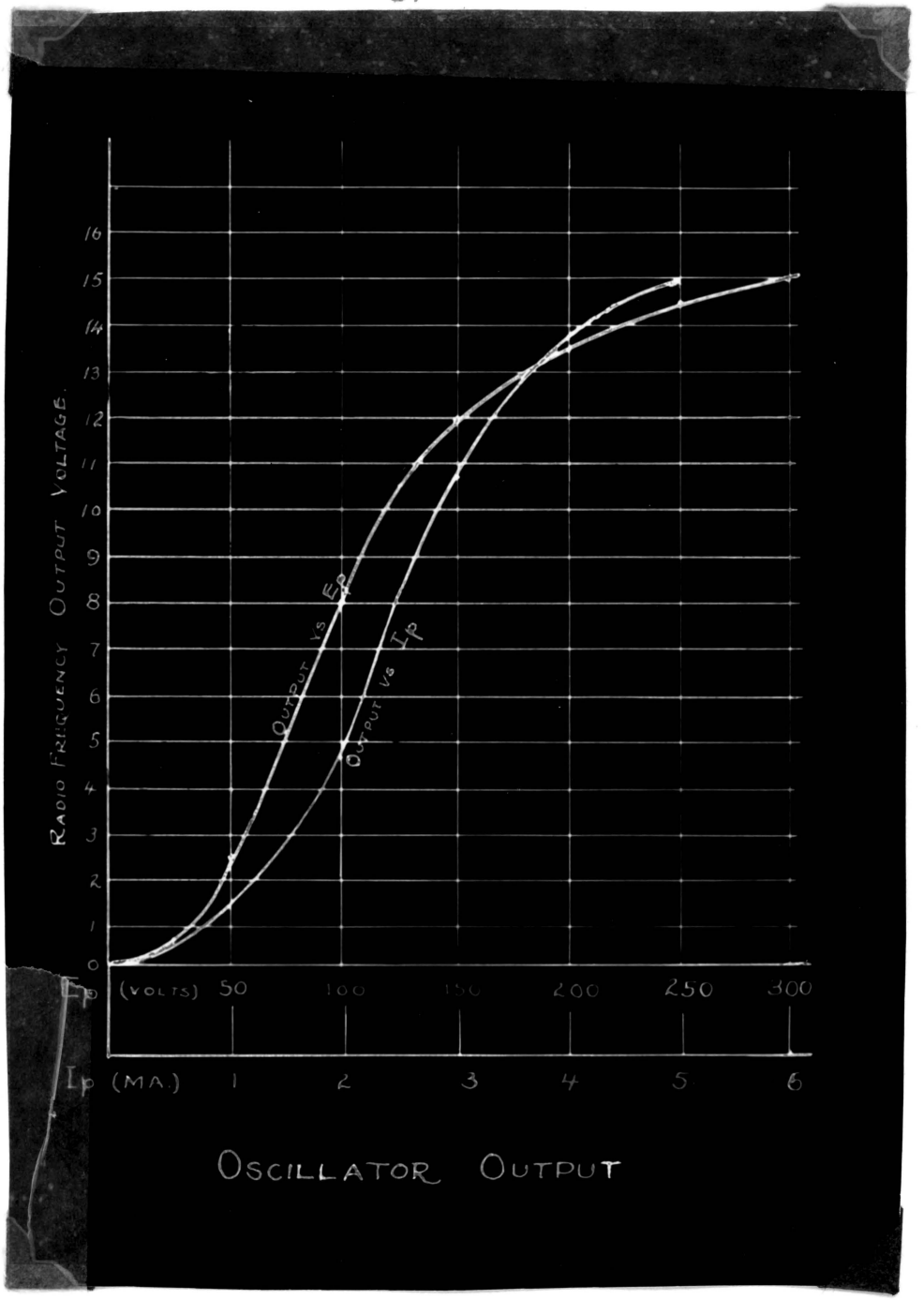
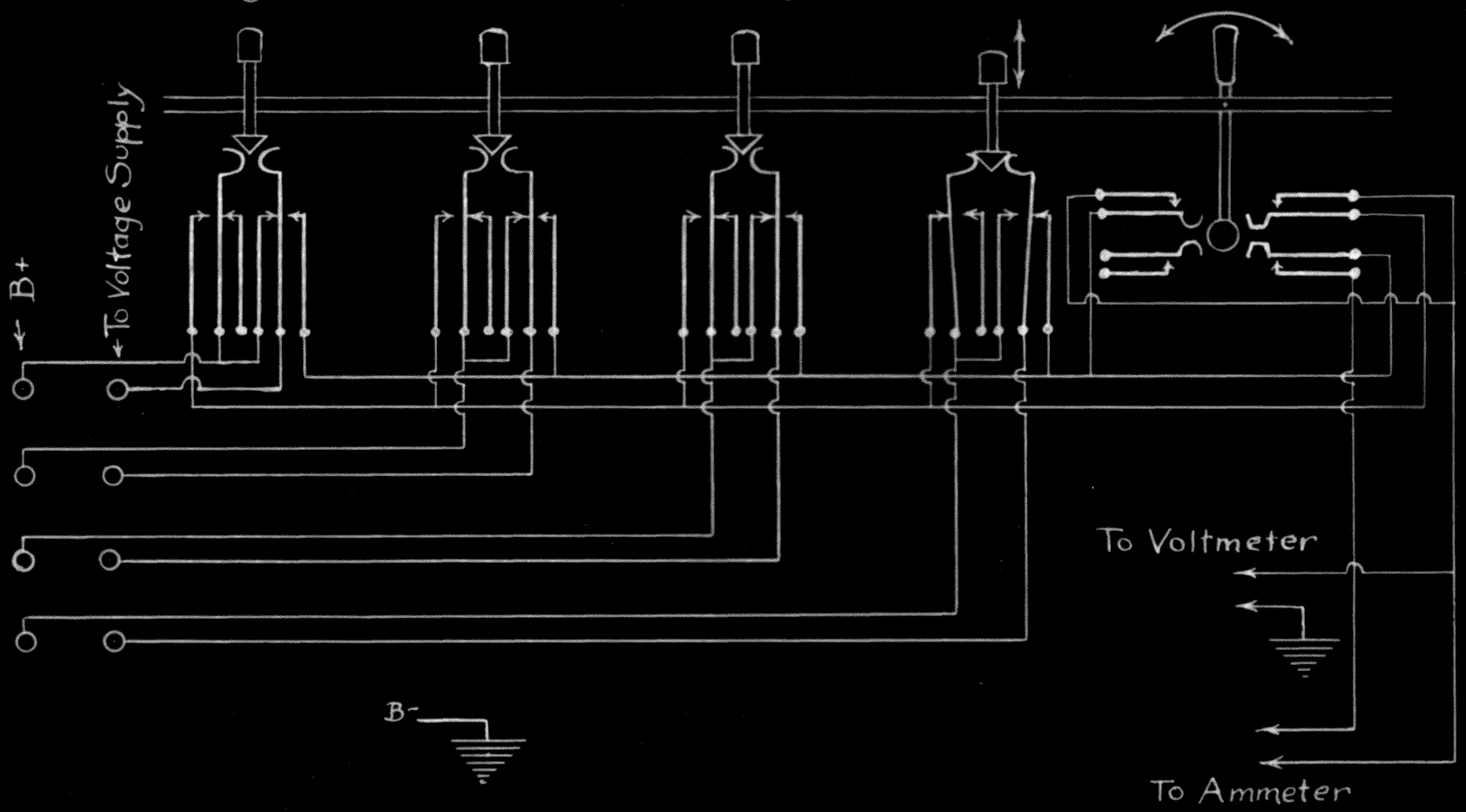


Fig. 9 Curves Showing Relationship between Oscillator Output and Plate-voltage and Plate-current.

Schematic Diagram Of Metering Switchboard

Showing One Of The Two Similar Sets Of Keys



Appendix

Maximum rating of the Western Electric Vacuum Tube--type 245-A.

Plate voltage	180 volts
Screen-grid voltage	67.5 volts
Control grid bias	-4.5 volts
Plate current	6.7 ma.
Screen-grid current	2.4 ma.
Amplification factor	85
Plate resistance	110,000 ohms
Transconductance	780 micromhos
Heater voltage	2 volts
Heater current	1.6 amperes

For further information on the operating characteristics of this tube refer to: The Western Electric Company---

V. T. Data Sheet 245-A.....Issue 1.

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