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MATTERS RELATING TO
THE INSTITUTE OF RADIO ENGINEERS

TECHNICAL PAPERS AND DISCUSSIONS

EDITED BY
ALFRED N. GOLDSMITH, Ph.D.

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PROCEEDINGS OF THE BOSTON SECTION OF THE INSTITUTE OF RADIO ENGINEERS

On the evening of Thursday, October 29th, 1914, Professor George W. Pierce, Vice-President of the Institute, read a paper on "Gaseous Detectors" at the Jefferson Physical Laboratory, Harvard University.

On Thursday, December 3rd, 1914, a paper entitled "Radio Frequency Changers" by Dr. Alfred N. Goldsmith was read at the Jefferson Physical Laboratory.

On Thursday, January 28th, 1915, a paper entitled "Seasonal Variation in the Strength of Radiotelegraphic Signals" by Dr. Louis W. Austin was read at the Jefferson Physical Laboratory. A second paper: "Wooden Lattice Masts" by Mr. Cyril F. Elwell, was also read. Professor George W. Pierce gave an experimental demonstration of electric radiation at short wave lengths.

On Thursday, February 25th, 1915, Mr. Melville Eastham, Secretary of the Boston Section of the Institute, presented a paper on "Inductances and Oscillation Transformers," in the Cruft High Tension Laboratory, Harvard University.

On Thursday, March 25th, 1915, Mr. Fulton Cutting presented a paper dealing with "Data on Transformer Design in Radiotelegraphy"; and Professor Charles A. Culver read a paper entitled "Notes on Radio Transmission without Elevated Wires," in the Cruft High Tension Laboratory.

On Thursday, April 29th, 1915, Mr. C. Nusbaum presented a paper on "Eddy Current and Hysteresis Losses in Iron at High Frequencies" in the Cruft High Tension Laboratory. There was also read a paper by Mr. Edwin H. Armstrong entitled "Some Recent Developments in the Audion Receiver."

SOME RECENT DEVELOPMENTS IN THE AUDION RECEIVER[1]

BY

EDWIN H. ARMSTRONG

THE AUDION AS DETECTOR AND AMPLIFIER

The fundamental operating characteristic of the audion is the relation between the wing current and the potential of the grid with respect to the filament—say the negative terminal of the filament. Such a characteristic is shown in Figure 1, and from it we see that a positive charge placed on the grid produces an increase in the wing current, and that a negative charge placed on the grid produces a decrease in the wing current. When the audion is used as an amplifier, and an alternating e. m. f. is impressed between the grid and the filament, the continuous current of the wing circuit will be varied in accordance

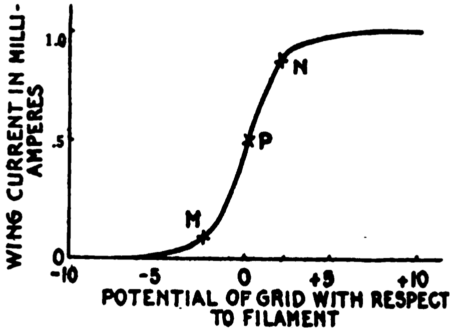

FIGURE 1

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[1] Delivered before The Institute of Radio Engineers, New York, March 3, 1915, and before the Boston Section, April 29, 1915.

(The introductory material of this paper was originally submitted as a discussion by letter on Haraden Pratt's paper, "Long Range Reception with Combined Crystal Rectifier and Audion Amplifier." The first six figures have been kindly lent by the "Electrical World"; the remaining figures and text are herewith published for the first time.)

with the characteristic of Figure 1, producing on the continuous current a superimposed a. c. wave in phase with and of the same frequency as the impressed e. m. f. Diagrammatically this action is shown in Figure 2.

The action of the audion as a detector of radio frequency oscillations is very different from its action as a simple amplifier. Some form of connection must be used, such that the effect of a group of radio frequency oscillations in the grid circuit of the audion is translated into a single audio frequency variation of the current in the telephones. The usual method is to make use of the valve action between the hot and cold electrodes at low pressures, and the connection used to do this is shown in Figure 3. In this method of connection there are two distinct actions; one rectifying and the other amplifying. The closed oscillation circuit: LC, filament, grid, and condenser C_2, behaves exactly as a Fleming valve receiver, the incoming oscillations being rectified between the grid and filament and the rectified current being used to charge the condenser C_2 (the side connected to the grid being of course negative). The negatively

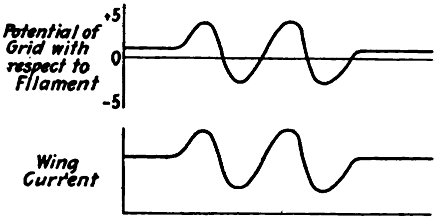

FIGURE 2

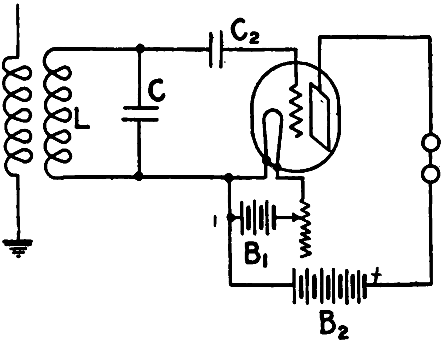

FIGURE 3

charged grid then exerts a relay action on the wing current, decreasing it; the wing current returning to its normal value as the charge in the grid condenser leaks off by way of the grid and the grid resumes its normal potential. If the audion is properly constructed, the relay action results in an amplification of the energy available for use in the telephones over that which would be available in a simple rectifier. Figure 4 indicates the features of the valve method of detection.

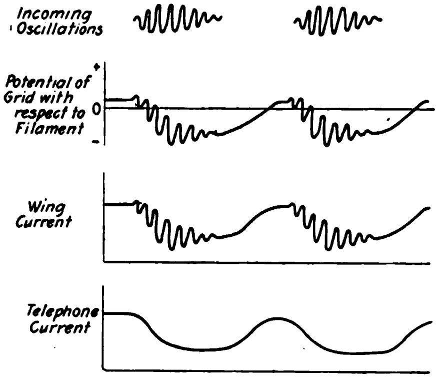

FIGURE 4

Working in conjunction with Professor Morecroft, I have recently secured oscillograms which confirm the explanations already advanced and these oscillograms and the means by which they were obtained are herewith shown in Figures 5, 6 and 7.

FIGURE 5

It will be seen, therefore, that using the audion as a detector of radio frequency oscillations, it has been shown that in addition to operating as a rectifier it simultaneously acts as a

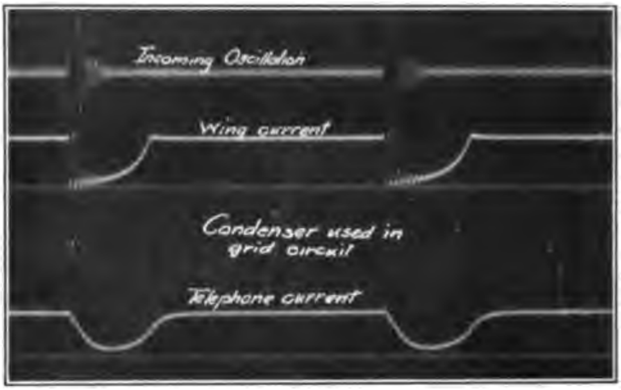

FIGURE 6

repeater of the radio frequencies; so that oscillations in the grid circuit set up oscillations of similar character in the wing circuit of the audion. In the ordinary detector system no use

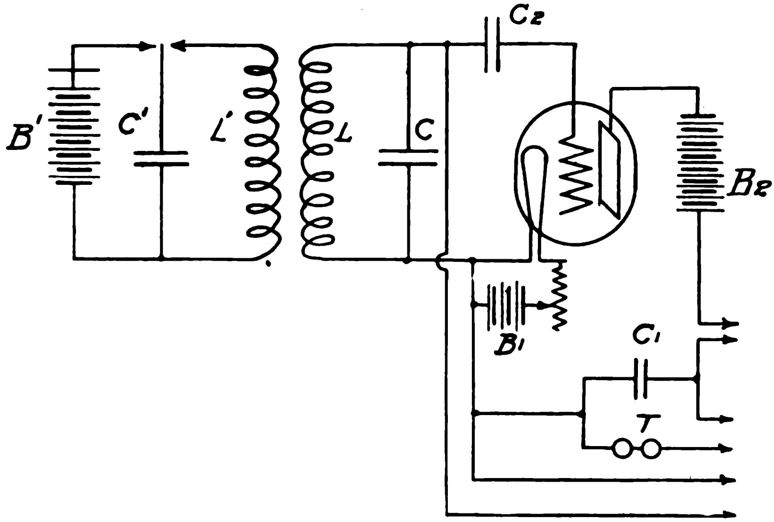

FIGURE 7

is made of the repeating action, and it is the purpose of the present paper to show that it may be turned to account to produce improvements in the reception of signals which completely overshadow any of the particular advantages of the audion when used as a simple detector. The ordinary detector circuit is illustrated by Figure 3 and the phenomena present therein may be summed up diagrammatically by the curves of Figure 4. It will be seen from these that the radio frequency oscillations present in the wing circuit of Figure 3 with the ordinary audion are necessarily small and also that they are of no value in producing a response in the telephones; but by providing means for increasing their amplitude and means for utilizing them to reinforce the oscillations of the grid circuit, it becomes possible to produce some very remarkable results.

REINFORCEMENT OF RADIO FREQUENCY OSCILLATIONS BY THE AUDION

There are two ways of reinforcing the oscillations of the grid circuit by means of those in the wing circuit. The simplest way perhaps is to couple the two circuits together in the manner shown in Figure 8. This is essentially the same as Figure 3, but modified by the introduction of the inductively coupled coils L_2 and L_3 in the grid and wing circuits respectively and by the condenser C_2 which forms a path of low impedance across the telephones for the radio frequencies. In such a system, incoming signals set up oscillations in the grid circuit which repeat into the wing circuit producing variations in the continuous current, the energy of which is supplied by the battery B_2. By means of the coupling M_2, some of this energy of the wing oscillations is transferred back to the grid circuit, and the

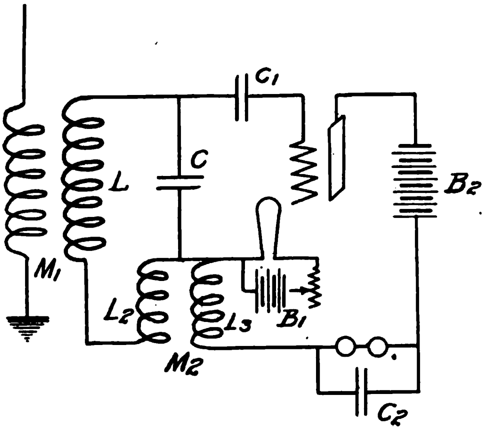

Figure 8

amplitude of the grid oscillations thereby increased. The amplified grid oscillations then react on the wing circuit by means of the grid to produce larger variations in the wing current, thus still further reinforcing the oscillations of the system. Simultaneously with this procedure the regular detecting action goes on; the condenser C_1 is charged in the usual way, but accumulates a charge which is proportional, not to the original signal strength but to the final amplitude of the oscillations in the grid circuit. The result is an increased response in the telephone proportional to the energy amplification of the original oscillations in the grid circuit. It will be observed from the operating characteristic (the relation between grid potential and wing current), that the amplitude of the variation in the wing current is directly dependent on the variation of the grid potential. This indicates that the grid circuit should be made up of large inductance and small capacity to obtain the maximum voltage which it is possible to impress on the grid. For moderate wave lengths the tuning condenser C of the grid circuit may be omitted altogether and the capacity of the audion alone used to tune the circuit. For long wave lengths, the distributed capacity of the grid circuit inductance becomes so high with respect to the capacity of the audion that better results are obtained by the use of a tuning condenser to fix definitely the points of maximum potential difference across the grid and filament of the audion.

In the second method of reinforcing the oscillations of the grid circuit the wing circuit of the audion is tuned by means of an inductance introduced as shown by Figure 9. This differs

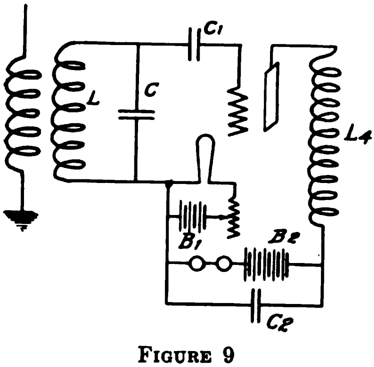

FIGURE 9

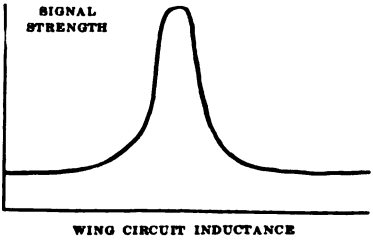

FIGURE 10

from the ordinary detector circuit of Figure 3 by the addition of the coil L_4 and the condenser C_2. The manner in which the grid oscillations are amplified may best be understood by the following analysis. With no oscillations in the system, the potential difference between filament and wing will be approximately the voltage of the battery B_2, but when oscillations are set up in the grid circuit, causing radio frequency variations of the wing current, the potential of the wing with respect to the filament varies as the reactance voltage of the wing inductance alternately adds to and subtracts from the voltage of the battery. When a negative capacity charge is placed on the grid, the wing current will be reduced and the direction of the reactance voltage of the wing inductance will therefore be the same as the voltage of the battery B_2. The reactance voltage will therefore add to the battery voltage and the difference of potential between wing and filament and also between wing and grid will be increased. Similarly when a positive charge is placed on the grid the wing current is increased and the reactance voltage of the wing inductance opposes the battery voltage, producing a decrease in the potential difference between grid and wing. Hence, supposing a negative capacity charge is placed on the grid, the tendency of the corresponding increase in the potential of the wing with respect to the grid will be to draw more electrons out on the grid, thereby increasing the charge in the condenser formed by the wing and grid, the energy for supplying this charge being drawn from the wing inductance as the wing current decreases. The increased negative charge on the grid tends to produce a still further decrease in the wing current and a further discharge of energy from the wing inductance into the grid circuit. On the other hand, when a positive charge is placed on the grid, the potential difference between grid and wing is reduced and some of the energy stored in the capacity formed by them is given back to the wing inductance. During this part of the cycle, electrons are being drawn into the grid from the surrounding space to charge the grid condenser in accordance with the well known valve action, and this, in effect, is a conduction current, so that a withdrawal of energy from the circuit takes place. In spite of this withdrawal of energy, however, a well defined resonance phenomena between the audion capacity and the wing inductance is to be expected and in the reception of signals such is found to be the case. When the wing inductance is properly adjusted at the resonance frequency, energy from the wing circuit is transferred freely to the grid circuit and oscillations build up therein and are rectified in the usual way.

A curve showing the general relation between signal strength and value of wing inductance is shown in Figure 10, the circuits used being those of Figure 9. As the capacity of the audion is the main means of transferring energy from the wing to the grid circuit, best results are obtained when the condenser C is very small. On account of the very small capacity of the audion, the effectiveness of this method of tuning is more pronounced at the higher frequencies, but by the use of a shunt condenser across the inductance of the wing circuit very good amplification is secured on frequencies as low as 30,000 cycles (10,000 meters wave length). The best results, however, are obtained with some combination of coupling and wing circuit tuning, as illustrated in Figure 11. Other methods of coupling may be employed between the grid and wing circuits, electrostatic and direct magnetic couplings being illustrated in Figures 12 and 13. The arrangement of Figure 13 operates in the same way as the system with the two coil coupling; but the electrostatic coupling

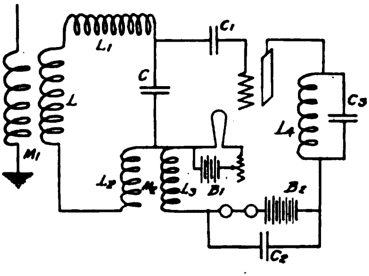

FIGURE 11

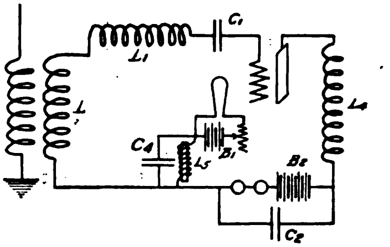

FIGURE 12

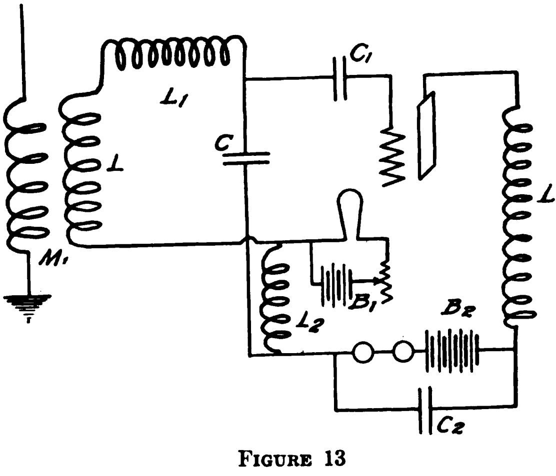

FIGURE 13

of Figure 12 works in an odd way. It is necessary, in this connection, to complete the wing circuit for the continuous current of the battery and this is done by shunting the coupling condenser C_4 by a coil of high inductance. The continuous current of the wing circuit flows thru this coil and C_4 provides a path of low impedance around this coil for the radio frequency oscillations of both grid and wing circuits. When a positive charge is placed on the grid, an increase in the wing current results, the alternating component of the wing current charging the condenser C_4 and the sum of the currents passing thru C_4 and L_4 equalling the current thru the audion. When a negative charge is placed on the grid the current thru the audion is reduced and the inductance L_5 discharged into the condenser shunted across it, charging it in the opposite way to that caused by the increase in the wing current. In both cases, C_4 then discharges thru the grid circuit reinforcing the oscillations therein.

AUDIO FREQUENCY AMPLIFICATION

It is possible to combine with any of these systems a system of audio frequency circuits which amplify the telephone current in exactly the same manner as the radio frequency oscillations are amplified, and such a system is shown in Figure 14. Here M_2 represents the coupling for the radio frequencies and the coils are of relatively small inductance. M_3 is the coupling for the audio frequencies, and the transformer is made up of coils having an inductance of the order of a henry or more. The condensers C_3 and

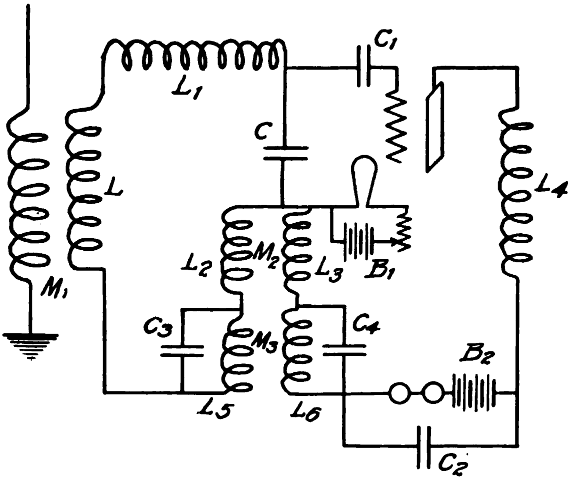

FIGURE 14

C_4 have the double purpose of tuning M_3 to the audio frequency, and of by-passing the radio frequencies. The total amplification of weak signals by this combination is about 100 times, with the ordinary audion bulb. On stronger signals, the amplification becomes smaller as the limit of the audion's response is reached.

THE AUDION AS A GENERATOR AND BEAT RECEIVER

Any repeater, which is also an energy amplifier, may be used to produce continuous oscillations by transferring part of the energy in the circuit containing the battery back to the controlling circuit to keep the latter continuously excited. By providing a close enough coupling between the grid and wing circuits, sufficient energy is supplied to the grid circuit to keep it in continuous oscillation, and as a consequence thereof oscillations of similar frequency exist in all parts of the system. The frequency of these oscillations is approximately that of the closed grid circuit if the tuning condenser of that circuit is large with respect to the capacity of the audion. If this capacity is small, then the wing circuit will exert a greater influence on the frequency of the system, and it will not approach that of the grid circuit so closely. When such a system of circuits is in oscillation, it has been found possible not only to receive continu-

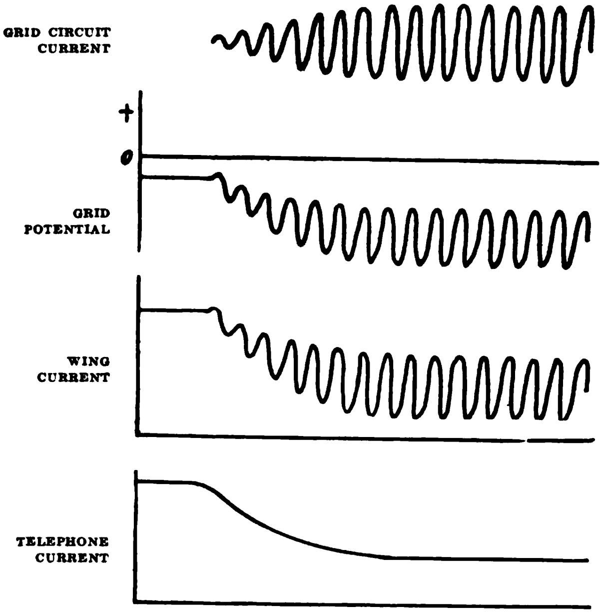

FIGURE 15

ous waves by means of the beat method but also very greatly to amplify them as well.

The phenomena involved may best be understood by reference to Figures 15 and 16, which show the relation between wing current and time at the beginning of oscillation. When the audion begins generating, the grid oscillations are continuously rectified to charge the grid condenser, and this charge continuously leaks off either by way of the grid or by means of a special high resistance placed in shunt with the condenser. As the negative charge builds up in the grid condenser, it decreases the average value of the continuous current component of the wing current and therefore limits the amplitude of the oscillations of the grid circuit until a point is finally reached where the rate at which electricity is supplied to the grid condenser is just equal to the rate at which it leaks off. Consider now the effect on the system of an incoming continuous wave having a frequency slightly different from the frequency of the local oscillations. The presence of the local oscillations will not in any way interfere with the amplifying powers of the system and the incoming oscillations will build up in exactly the same manner as for the

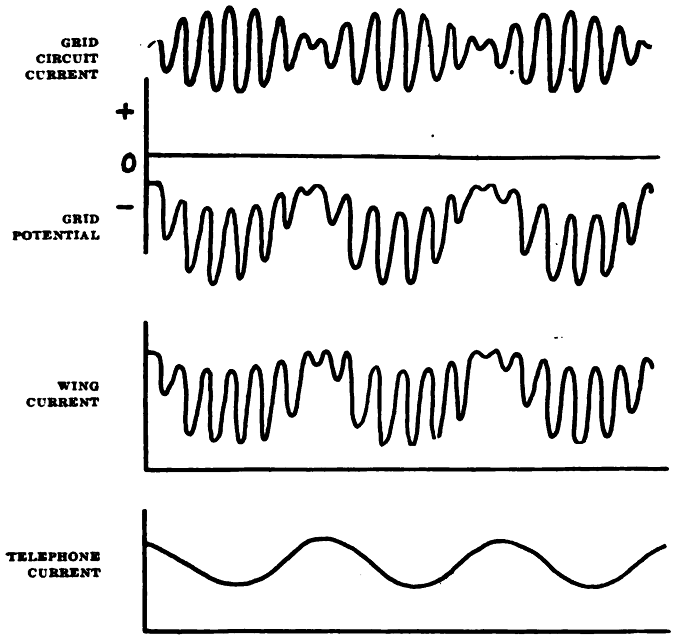

Figure 16

non-oscillating state but to a greater degree because of the closer grid and wing coupling. Simultaneously with the amplifying of the incoming wave, beats are produced between the local and the signalling currents, the effect being alternately to increase and decrease the amplitude of the oscillations in the system. From Figure 15 it will be apparent that when this steady state is reached an increase in the amplitude of the grid oscillations by any means whatever will increase the negative charge in the grid condenser, producing a decrease in the average value of the wing current and hence a decrease in the telephone current. On the other hand, a decrease in the amplitude of the oscillations will allow some of the negative charge in the grid condenser to leak off and thereby permit an increase in the telephone current. Hence, when incoming and local oscillations add up, the negative charge in the grid condenser is increased and a decrease in the telephone current results. When the two frequencies are opposed, some of the charge in the grid condenser leaks off and an increase in the telephone current occurs. The result is the production in the telephones of an alternating current having a frequency equal to the difference in the frequencies of the local and incoming oscillations and having the very important property of being almost simple harmonic. Figure 16 illustrates the characteristics of this method of reception. The complete phenomena may be summed up as follows. Incoming oscillations are simultaneously amplified and combined in the system to produce beats with a local oscillation continuously maintained by the audion. The radio frequency beats are then rectified by the audion to charge the grid and the grid condenser, and this charge varies the electron current to produce an amplifying action on the current in the telephones.

When the grid condenser is omitted, the beat phenomenon is slightly modified, and the audio frequency variation of the telephone current is produced according to the asymmetric action outlined in a previous publication dealing with the operating features of the audion. The system is more sensitive with the grid condenser, but the same general result is obtained by either method of reception.

PECULIAR FEATURES OF OSCILLATION

Some very interesting features of operation accompany the production of oscillations in the system. Suppose the audion is not oscillating, and the grid and wing coupling is fairly weak. As this coupling is increased, the point at which oscillations begin is indicated by a faint click in the telephones accompanied by a slight change in the character of the static. The oscillations produced are usually so high in frequency and constant in amplitude that they are entirely inaudible. As the coupling is still further increased, a rough note is heard in the telephones the pitch decreasing with increase of coupling. This note is produced by the breaking up of the oscillations into groups, and it occurs whenever electricity is supplied to the grid condenser at a greater rate than that at which it can leak off. The result is that the grid is periodically charged to a negative potential sufficient to cut off entirely the wing current, causing a stoppage of the local oscillations until the grid charge leaks off and the wing current re-establishes itself. The frequency of this interruption depends largely on the capacity of the grid condenser, the resistance of its leakage path, and the amplitude of the local oscillations; and it may be varied from several hundred down to one or less per second. This effect is sometimes troublesome in the reception of signals, especially with high vacuum tubes. It may be eliminated, however, by increasing the leak of the grid condenser by means of a high resistance shunt. The best coupling for receiving continuous waves lies somewhere between the point at which oscillations start and the point at which interruption begins, and can only be determined by trial. In this region, trouble is sometimes experienced by the appearance of a smooth musical note in the telephones. This occurs under certain critical conditions of coupling with the antenna when the grid circuit oscillates with two degrees of freedom. Two slightly different frequencies are therefore set up, producing beats which are rectified by the audion in the usual way. This effect is quite critical, and when it causes

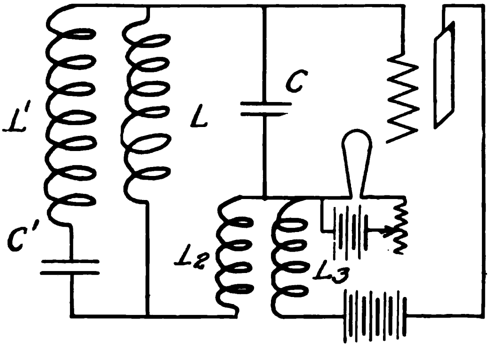

FIGURE 17

interference with signals, a slight readjustment of the circuits will usually make it disappear. It may, however, be made perfectly steady and reproduced at will by the system shown in Figure 17, where two grid circuits of different periods are provided. Two frequencies are therefore generated one having the frequency of the circuit LCL_2, and the other the frequency of the circuit $L'C'L_2C$. This arrangement may replace to advantage the ordinary buzzer for producing groups of oscillations. **The foregoing explanations refer to the audion only when it is used as an electron relay.* When there is an appreciable amount of gas, in the tube in the ionized state, disturbances of an entirely different character occur.**

AUDIO FREQUENCY TUNING

One of the very important advantages of the receiver when used for continuous waves is that the alternating current produced in the telephones is almost a pure sine wave. Only when the audio frequency is simple harmonic can selectivity be obtained by tuning the telephone circuit. A distorted wave such as that produced by spark signals possesses many harmonics and as each may be picked out by the tuned telephone circuit there is little chance of separating two spark signals by audio frequency tuning. With continuous waves, however, the pure wave produced by the beat method of reception makes it possible to obtain selectivity by the audio frequency tuning, resonance

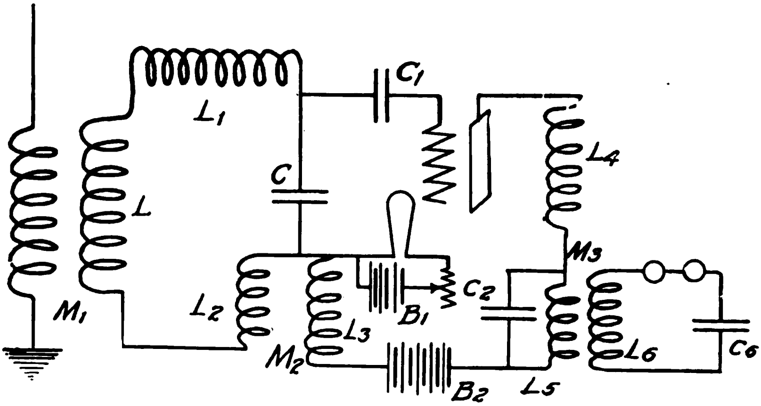

Figure 18

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* "Electrical World," December 12, 1914; and also discussion in "London Electrician," between Reisz and de Forest on the difference between electron and gas relays. (February 6, 1914, page 726; March 13, 1914, page 956; June 12, 1914, page 402; July 3, 1914, page 538; and July 31, 1914, page 702.—Editor.)

being fully as sharp as in the radio frequency circuits. Two methods of audio frequency tuning are shown in Figures 18 and 19. In Figure 18, the telephone is inductively connected to the wing circuit of the audion by means of a transformer the secondary of which includes besides the telephone a tuning condenser.

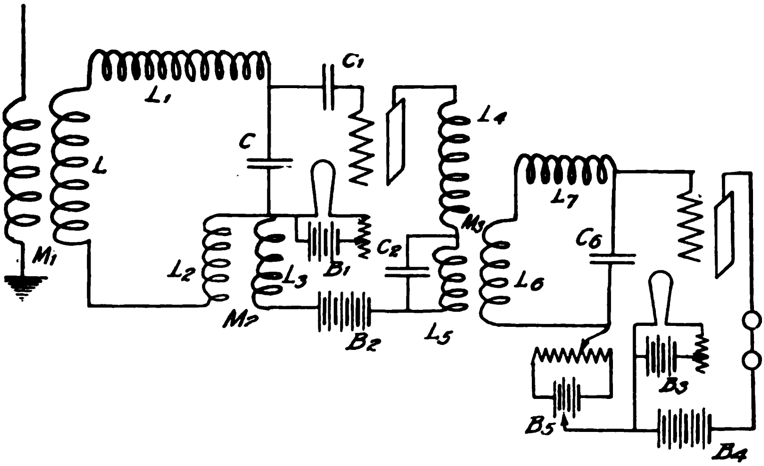

Figure 19

In this connection, the telephone, with a resistance of many thousand ohms, is placed directly in the tuned audio frequency circuit, and hence for good tuning the inductance of the coil L_6 must be made extremely large to secure the necessary ratio of the reactance of L_6 to the resistance of the circuit. This disadvantage is overcome in the system of Figure 19 by removing the telephones from the audio frequency circuit, and using the latter to operate a second audion. The telephones may then be placed in the wing circuit of this audion without adding appreciably to the damping of the circuit. The tuning of the circuit L_6C_6 may therefore be made very sharp with reasonable values of inductance simply by keeping the resistance low. In this case considerable amplification is obtained by the use of resonance in the transformer M_3 to increase the voltage impressed on the grid of the second audion. The great advantage of this kind of tuning is shown by the following example. Suppose the incoming signal has a frequency of 50,000 cycles, and the local frequency is 49,000 cycles. The differential frequency is 1,000, and the audio frequency circuit is tuned accordingly. An interfering wave 1 per cent. shorter than the signalling wave, or 49,500 cycles, will produce an audio frequency of 500 cycles per second, which will not appear at all in the wing circuit of the second audion unless it is many times stronger than the 1,000 cycle signal. This combination of radio and audio frequency tuning is too selective for use at the present time even when the sending station is equipped with an alternator, as the slight changes in frequency of the radiated wave produce changes in the beat frequency of the receiver which carry it out of range for the sharply tuned audio frequency circuit. A disadvantage of this method of tuning is that atmospheric disturbances produce a musical note due to shock excitation of the audio frequency system. Very loose coupling with the wing circuit of the first audion is a partial remedy for this. There are times, however, when interference is more troublesome than static and in such cases the method may be used to great advantages. If desired, both radio and audio frequency tuning can be carried out in the same audion as indicated in Figure 14. This combination is apt to be somewhat troublesome to operate as a cumulative amplification is obtained in the audio frequency as well as in the radio frequency system.

CASCADE SYSTEMS

Where a greater amplification than can be obtained with one audion is required, cascade working of the radio frequency systems may be resorted to by coupling together two or more audion systems, each connected as already described, in the manner indicated in Figure 19. The incoming oscillations in the first audion system are amplified in the usual manner and set up oscillations in the second system by means of the coupling M_3 (See Figure 20). The oscillations initially set up in the second system are again amplified, and then rectified in the second audion to produce audible response in the telephones.

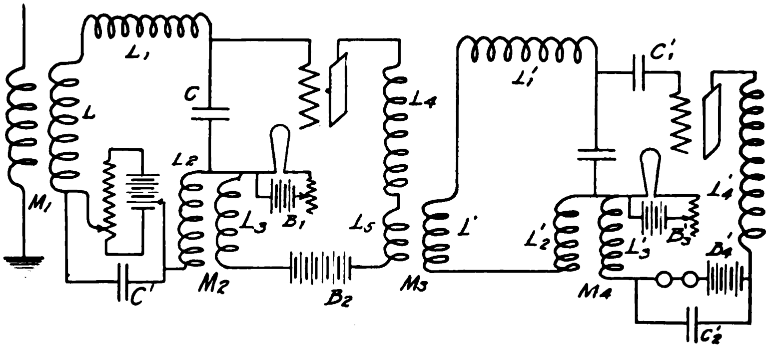

FIGURE 20

For the reception of spark signals, considerable adjustment is required to get the best results without causing one or the other or both of the systems to generate oscillations. It will be found that after the first circuit is adjusted to the point of oscillation and the second is coupled with it, the strength of signal in the first system will be reduced owing to the withdrawal of energy from it by the second system. The signals may then be again brought up in strength by increasing the coupling between the grid and wing circuits of the first audion until the appearance of the local oscillations indicates that the limit of amplification has been reached. By careful adjustment about a thousand times amplification and very sharp tuning can be obtained with two steps.

For continuous wave reception, there are several methods of operating cascade systems. It is possible to have either system generate oscillations, the other system acting simply as an amplifier or both systems may be made to generate in synchronism. It will generally be found that when both systems produce oscillations, beats will be produced, so that a continuous note is heard in the telephones; but by adjusting the frequency of one of the systems the pitch of this note will be reduced as the two systems approach synchronism, until finally at one or two hundred beats per second the two systems pull into step in much the same way as two alternators. The ability of the two systems to keep in step depends mainly on the value of the coupling between them, and the closer this is the better the two hold together. There is still another way of working this combination, and that is asynchronously. In this case beats are continuously produced in the system so that a continuous note is heard in the telephone, but the circuits may be so adjusted that the note is not loud enough to be troublesome or it may be tuned out of the telephone in the manner previously described. Incoming oscillations are combined in the system to produce beats with the beats already present so that a rather curious note is heard. Very good amplification is secured by this method though naturally the system is troublesome to operate.

It may be noted here that whenever a signal is too weak to read with one audion system and cascade operation becomes necessary, it is always better practice to use the cascade circuits for the radio frequencies, even if the regenerative circuits are not employed with each individual audion system. The frequency of the oscillations set up in the circuits by static are, under normal conditions, the same as those of the incoming signal; and the static is therefore never amplified more than the signal. Usually it is amplified to a somewhat lesser extent, especially if regenerative circuits are employed. In the cascade systems used for audio frequencies, a different condition exists. It is ordinary practice to connect the different stages by means of transformers, and this leads to conditions which cause the system to produce greater amplifications of the higher frequencies. The rate of change of the wing current of the detecting audion produced by static corresponds to a very high frequency, and as such is invariably amplified to a greater extent than the signal.

There is a second method of receiving continuous oscillations which makes use of the generating feature of the audion, but does not employ the beat phenomena. The amplifying ratio of the audion depends more or less directly on the value of the wing current, and by varying this current periodically there will be a corresponding periodic change in the amplifying power of the audion. Hence an audion arranged to repeat a continuous wave under such conditions will produce in its wing circuit oscillations which vary periodically in amplitude, and which may therefore be received by a simple audion system. The first audion may be arranged to produce the necessary variation in its amplifying power in the manner indicated in Figure 21, which also shows the complete circuits for carrying out this method of reception. Here $C_1L_1L_2C_2$ is an audio frequency system designed to produce audio frequency oscillations; and P is a potentiometer for adjusting the potential of the grid so that on the negative part of the oscillation in the wing circuit, the wing current is reduced practically to zero. The radio frequency

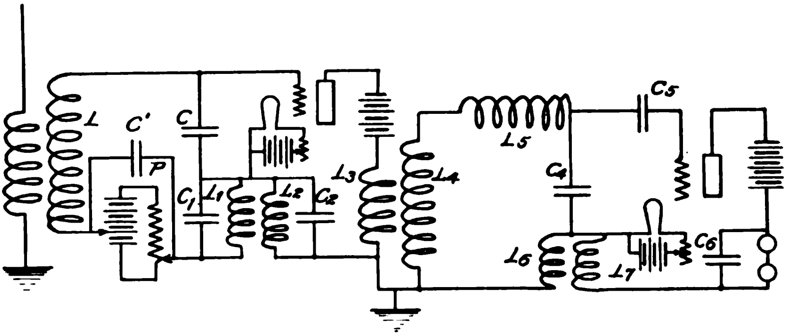

FIGURE 21

circuit $C'L\ C\ C_1$ is tuned to the oscillation frequency of the incoming wave. The radio frequency oscillations cannot be detected in the first audion system as the strong audio frequency current circulating in this system would produce a continuous note in the telephone receivers of such strength as to render inaudible all save very strong signals. By arranging to detect the oscillations in a second audion system coupled to the wing circuit of the first, interference of this sort is avoided; as the circuit $L_4\ C_4$ has a very high impedance for the audio frequency currents and the effect produced thru the magnetic coupling of L_3 and L_4 on the second system is negligible. The capacity current between these two coils thru the telephones to ground is, however, appreciable; and to avoid it it is advisable to ground their two adjacent ends as shown. The action of the system may be summed up as follows. The first audion system varies the amplitude of the incoming radio frequency oscillations at an audio frequency, and the second audion system amplifies and detects the radio frequency oscillations supplied to it by the first system. Diagrammatically, the phenomena occurring are as illustrated in Figure 22. The system gives about the same response as can be obtained with a single audion working with the beat method of reception. The advantages derived from the heterodyne method of amplification and the dependence of the audio frequency note in the receivers on the wave length are, of course, lacking; but for the reception of waves having a frequency higher than that at which beat reception is practicable, this method is of value.

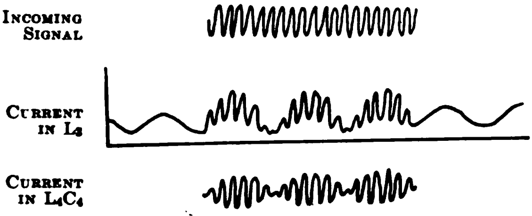

Figure 22

EFFECTS OF ATMOSPHERIC DISTURBANCES

A very interesting feature of these receiving systems is their behavior under conditions of severe atmospheric disturbances, particularly when used for receiving continuous waves. Their success under such conditions is due to the fact that they combine in addition to their inherent property of responding more readily to a sustained wave than to a strongly damped one, the characteristics of the two most effective static eliminators known; the balanced valve and the heterodyne receiver. The function of the balanced valve is a physiological one, as it simply provides a means to shield the ear from the loud crashes which temporarily impair its sensitiveness for the relatively weak signals. In effect, it puts a limit on the noise which can be produced in the telephone by a stray, regardless of its amplitude. Now the effect of the static on an audion is to build up a negative charge on the grid, reducing the wing current, and the limit of the response which can be produced in the telephones is reached when the wing current is reduced to zero. Under ordinary conditions, this limit is too great to do much good; but when the audion is generating it is possible, by proper adjustment of the amplitude of the local oscillations, to reduce the wing current to a point just above the lower bend in the operating characteristic so that the audion is rendered insensitive to a further increase in the negative charge on the grid. The strays which cause serious interference are of a much greater amplitude than the local frequency, so that no appreciable interaction between the two takes place, and the wing current is invariably decreased. Since the decrease in the wing current is not in proportion to the change in the grid potential, the response in the telephone and the effect on the ear of the operator are correspondingly reduced. Static of smaller amplitude than the local oscillations may interact with them to produce either an increase or a decrease in amplitude of the oscillations in the grid circuit and may therefore cause either a decrease or an increase in the wing current. The wing current can, of course, increase to a relatively large value, but as it is impossible for the wing current to increase faster than the charge in the grid condenser can leak off, the rate of increase is necessarily slow. The response in the telephones is therefore not so disturbing as would be caused by a decrease of similar value where the rate of change of current is usually large.

When the system is operated without an auxiliary leak around the grid condenser, a peculiar paralysis of the audion is frequently caused by heavy static, no sound of any kind being heard in the telephones for a considerable length of time. If the apparatus is not touched, the paralysis may last for many minutes, and then suddenly disappear and the former sensitiveness be restored. The effect is primarily caused by the charging of the grid condenser to a sufficient potential to cut off entirely the flow of electrons to the wing, thereby decreasing the wing current to zero. Now the way in which the negative charge in the grid condenser leaks off is chiefly by means of the positive ions in the tube, which are drawn into contact with the grid when it becomes negatively charged. These positive ions are the result of ionization by impact, and when the voltage of the wing battery is properly adjusted, they can be produced only in the region between the grid and the wing, since the velocity attained by the electrons between the filament and grid is very low. When the grid is charged to a high negative potential it keeps all the electrons between the grid and filament, thereby barring them from the region between grid and wing. Hence the production of positive ions must cease and the usual means of removing the negative charge from the grid vanishes. The resistance of the leakage path of the grid condenser must then be almost infinite, as is shown by the very long time taken for the charge to leak from a condenser of approximately 0.0001 microfarads capacity. The effect is naturally the more pronounced the higher the vacuum, as the number of positive ions present is correspondingly reduced. A resistance of several hundred thousand ohms placed across the grid condenser gives a leak which is independent of the value of the wing current and which effectually prevents trouble of this kind. With the very high vacua now obtainable by the use of a molecular pump, there are practically no positive ions present so that the auxiliary leak is always necessary. Under these conditions, it not only prevents paralysis by the static but it also removes from the grid condenser the excess of negative electricity which accumulates in it, thereby increasing the sensitiveness of the audion and the sharpness of the signals in the telephones. The very high potentials to which the grid condenser may be charged by the static when it is not provided with an auxiliary leak are surprising. These potentials may be measured in a very simple and accurate way, here described. After a stray has cut off the wing current, if we continuously increase the capacity of the grid condenser the potential across it, and hence the potential of the grid, with respect to the filament, will be decreased inversely as the capacity. A point will finally be reached where the grid potential is sufficiently reduced to allow the wing current to flow. When this occurs it indicates that the potential of the grid condenser is slightly less than that shown by the operating characteristic as necessary to reduce the wing current to zero. The potential to which the grid condenser was originally charged is equal to this voltage times the ratio of the capacity of the condenser at which the wing current began to flow to the original capacity. Voltages of over a hundred are not uncommonly reached by the grid; and as one volt represents a very strong signal, the difficulties of the static problem are very forcibly presented.

The fact that static of large amplitude produces almost invariably a decrease in the wing current while a signal (with beat reception) produces alternately an increase and decrease in the wing current is a circumstance of which it should be possible to take advantage. The circuits can be arranged to rectify the wing current in such a way that only the increases in this current are available to produce a response in the telephones, but in carrying this method out, trouble is experienced from a shifting zero. A better way of making use of the difference in response is the following one. Suppose that we arrange two complete receiving systems oscillating in step with each other, but so related to the antenna that the beat currents in the two systems are 180 degrees apart. The result of this will be that at the instant when the incoming signal is producing an increase of current thru the telephones in one receiver, it will be producing a decrease of current thru the telephones of the other receiver; so that the two telephone currents are 180 degrees out of phase. Static of large amplitude does not interact with the local frequencies, and will produce simultaneously in each receiver a decrease in the telephone current. These two currents are therefore in phase with each other. On replacing each telephone by the primary of a transformer, and connecting their secondaries thru a telephone in the proper phase, it is possible to balance out the static and at the same time secure an additive response of the signals from each receiver.

An arrangement of circuits by means of which this method can be carried out is shown in Figure 23. Here two oscillating receiving systems are kept in step by means of the circuits L_1 C_1 C_1' L_1'. L_1 C_1 and L_1' C_1' are identical, and each is tuned separately to the frequency to be received. When both audions are oscillating in step, the flow of current in these circuits as indicated by the vectors of Figure 23 will be alternately up on one side and down on the other. The point between the condenser C_1 and C_1' will be a node; and the antenna may be connected to this point without disturbing the conditions appreciably if a resistance R placed as indicated is included in the antenna. This resistance need not be large enough to interfere seriously with the signal strength; it need only be large with respect to the resistance of the circuit $L_1\ C_1\ C_1'\ L_1'$, which circuit has a very low resistance.

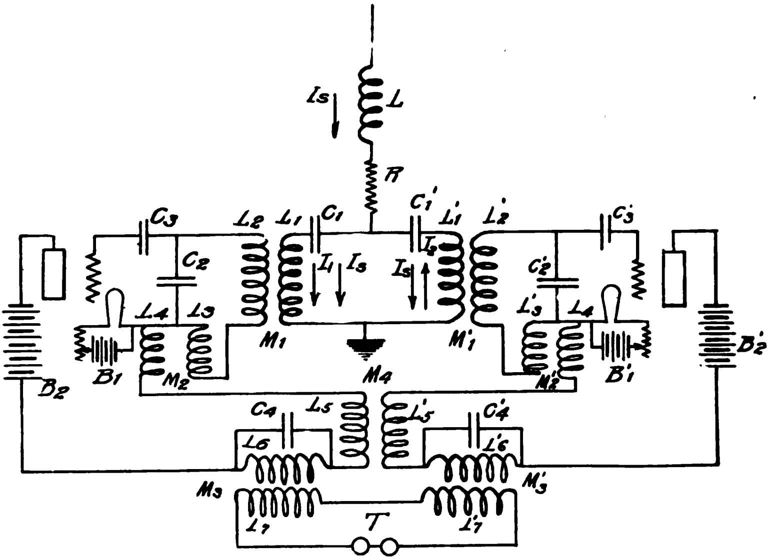

FIGURE 23

Incoming oscillations pass thru the divided circuit as indicated in the diagram, and therefore are in phase with the local oscillations of one receiver and 180 degrees out of phase with the local oscillations of the other. This produces the desired result in the currents thru the transformers of the circuit T which act in the manner already described.

It is found in practice that the oscillations set up in each system by the incoming signals tend to neutralize each other thru the circuit $L_1\ C_1\ C_1'\ L_1'$. This effect is avoided by introducing in the wing circuits a differential coupling arranged to neutralize the coupling between the two grid circuits. It is possible to do this, as it does not affect the coupling of either receiver with the antenna, and does not interfere with the local operation until the effective coupling between the two systems is reduced to a point below which they will no longer remain in step. There are other ways of securing the same result, but the system shown will illustrate the general procedure in carrying out this method of balancing.

The practical results obtainable with these receivers may perhaps be of interest. At the present time, signals from all high power stations from Eilvese (Germany) to Honolulu are heard day and night at Columbia University with a single audion receiver. Cascade systems give correspondingly better results, two stages being sufficient to make the night signals of Honolulu audible thruout the operating room. Interference with the signals from Nauen by the arc station at Newcastle, New Brunswick (Canada), is very easily eliminated by means of an audio frequency tuning circuit; and this is the most severe interference we have yet experienced, the two frequencies sometimes differing by less than 1 per cent. and the arc signals being much the stronger.

These receivers have been developed in the Research Laboratory of Electro-Mechanics, Columbia University; and are mainly the result of a proper understanding and interpretation of the key to the action of the audion; the grid potential-wing current curve. In conclusion, I want to point out that none of the methods of producing amplification or oscillation depend on a critical gas action; they depend solely on the relay action of the tube employed (electron or gas relay) and the proper arrangement of its controlling circuits.

SUMMARY: The action of the audion as a detector and simple amplifier is explained, with the method of verification of the theory by means of oscillograms. To reinforce the oscillations in the grid circuit two methods are employed: first, to couple the grid circuit to the wing circuit and arrange the latter to permit radio frequency currents to pass freely in it; and second, to use a large inductance in the wing circuit, thereby tuning it to the incoming frequency (in conjunction with the capacity between the filament and wing in the audion itself). Both methods may be used together. Various methods of coupling grid and wing circuits are shown. Methods of combined audio and radio frequency amplification are described.

The audion, being a generator of alternating current of any desired frequency, can be used as a beat receiver. A steady audion generator of regular groups of radio frequency oscillations is illustrated. Various methods of audio frequency tuning permitting high selectivity are possible. By the use of two audions in cascade, amplifications as high as 1,000 are attainable. The cascade systems can be arranged so as to operate both audions either synchronously or non-synchronously.

As an alternative to beat reception of sustained wave signals, an arrangement is explained wherein the amplifying ratio of a repeating audion is varied periodically at an audio frequency. Coupled to this system is a simple audion detector. Musical signals of any desired pitch are thus obtained.

It is found that static of large amplitude nearly always decreases the wing current, while a signal (with beat reception) alternately increases and decreases it. A system of circuits is described whereby this fact is taken advantage of in balancing out static while retaining an additive response to signals, thus effecting an elimination of static to a considerable extent.

Finally, instances of long distance stations received and interference overcome in practice are given.

DISCUSSION

Lee de Forest (by letter): Absence from New York and stress of business prevents my giving to Mr. Armstrong's paper the thoro discussion it merits from me.

Briefly, I must state that my investigation of the simple audion detector, the audion amplifier, and the "ultraudion" detector for undamped waves do not bear out completely the results and conclusions announced by that writer.

In the first place, anyone who has had considerable experience with numerous audion bulbs must admit that the behavior of different bulbs varies in many particulars, and to an astonishing degree. The wing potential-wing current curves for different bulbs, or even for the same bulb at different times, under differing conditions (filament temperature, etc.) vary widely.

What may appear to be a fixed law for one bulb may not hold for another.

Mr. Armstrong makes no mention of this well-known fact; nor does he even state that his grid potential-wing current curve may be quite otherwise than he has shown it with different applied "B" battery voltage, or filament temperatures.

He makes no mention of the fact, often demonstrated, that a continuous current indicating instrument, e.g., a micro-ammeter, may show a decrease in deflection, or practically no change in deflection either way when fairly strong radio frequency (or audio frequency) impulses are delivered to the grid even when the telephone receiver in the wing circuit gives strong response.

I have frequently proven that a *positive* charge applied to the grid, may decrease, rather than increase the "wing current." If I may say so, he treats the entire subject in much too cursory and cavalier a manner, even as he appears to be quite oblivious of the work of any other investigator or discoverer.

As I stated in an article in the "*Electrical World,*" February 20th, the *oscillating* quality of the audion was discovered by me several years ago.

I found that the complicated circuits Mr. Armstrong illustrates were quite unnecessary for producing the effects mentioned. In fact, the combination of oscillating and amplifying functions in the same bulb are obtained almost, if not quite, as efficiently, and far more simply by much simpler circuits.

The second method he shows for a combination tuning to radio and audio frequencies is ingenious and highly creditable. Unfortunately, as he truly points out, there is to-day no continuous wave generator of sufficiently constant frequency to permit full advantage being taken of this elegant method.

Edwin H. Armstrong: The condition in which a positive potential applied to the grid produces a decrease in the wing current is a remarkable one, in that it has been the cause of that mysterious atmosphere with which the audion has long been surrounded. The effect occurs under certain conditions which are very easily explained. Suppose there is an appreciable amount of gas in the tube and the difference of potential between the wing and filament is adjusted so that a considerable number of positive ions are produced. In such a state it frequently happens that the number of positive ions coming in contact with the grid is in excess of the number of negative ions. As a consequence of this the grid assumes a positive charge with respect to the filament. Suppose the potential to which the grid becomes charged is three volts positive with respect to the negative terminal of the filament. Under these conditions a battery of say one or two volts connected as shown in Figure 1 with its positive terminal connected to the grid will really change the potential of the grid in the negative sense. The natural result is a decrease in the wing current. The converse of this effect: the condition in which a negative potential applied to the grid produces an increase in the wing current, is invariably met with in high vacuum audions where the potential assumed by the grid is invariably negative. Both cases, however, can be explained on the same grounds. Figure 2 shows the potential assumed by the grid when a large number of positive ions are present.

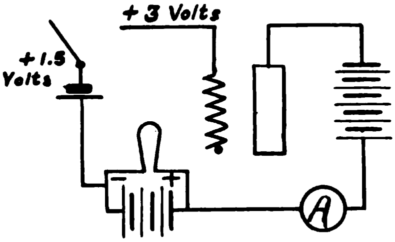

FIGURE 1

Edwin H. Armstrong (by letter): In replying to Dr. de Forest's communication, I want to point out that the paper was intended to deal with the application of circuits of a new type to the actuation of the audion. The fundamental operating features of the audion itself were outlined purely as a basis on which to explain the action of the circuits. A detailed explanation of the various phenomena involved in the audion as a detector and as a relay, radically different from that previously advanced by Dr. de Forest, was published by me some time ago in the "*Electrical World*," December 12th, 1914, and the columns of that paper, are, no doubt, still open to discussion of these elementary matters.

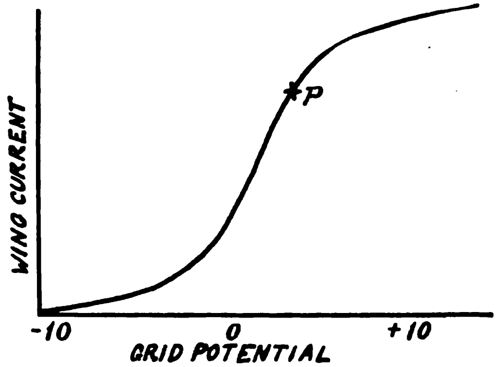

Figure 2

Dr. de Forest speaks of the great differences existing between the wing potential-wing current curves. It will be readily understood by those familiar with the laws of the conduction of electricity thru gases that such is bound to be the case where any considerable amount of gas is present in the bulb. The potential at which progressive ionization of the gas begins, is dependent, among other things, on the pressure; and hence the upper parts of the wing potential-wing current curves vary, but the lower parts, *the only place where the electron relay can be operated,* are invariably of the same general shape. With the modern methods now available, for producing very high vacua, it is a simple matter to construct audions whose characteristics are for all practical purposes identical. With these high vacuum bulbs, the astonishing differences of which Dr. de Forest speaks disappear to an astonishing extent.

The great differences which sometimes exist between the grid potential-wing current curves of different audions or for the same audion under different conditions of wing potential or filament temperature are again due to the residual gas, and are eliminated as before by the use of very high vacua. It will be evident, of course, that for each value of wing potential and filament temperature there will be a different grid potential-wing current curve; but for high vacuum bulbs these curves lie one above the other in an orderly manner and, barring minor differences, are of the same general shape.

For an explanation of the fact that a continuous current instrument in the wing circuit shows no change in deflection when an alternating e. m. f. of *audio* frequency is impressed on the grid even when a telephone in circuit with the meter gives a strong response, I want to call attention to Figures 2 and 5, of the original paper, together with a suggestion that a telephone perhaps is apt to respond somewhat more strongly to an alternating current than does a continuous current instrument! An explanation of the decrease of wing current which may occur will be found in the publication in the "*Electrical World,*" December 12th, 1914, with an accompanying oscillogram which shows the asymmetric effect in question. The circumstance stated by Dr. de Forest in which a *radio* frequency e. m. f. impressed on the grid produces a response in a telephone but not in a continuous current instrument is an impossible one. If the telephone responded, and there were no changes in the reading of the instrument, it would be an indication of an alternate and equal increase and decrease of the wing current at an audio frequency rate. This is an effect which *radio* frequency oscillations applied to the grid cannot produce. When a condenser is used in connection with the grid, radio frequency oscillations invariably produce a net decrease in the wing current and hence a decrease in the telephone current. Where use is made of the asymmetric relaying, which is possible because of the bends in the operating characteristic, either a net increase or net decrease may be produced in the wing current by radio frequencies applied to the grid, depending at which bend the audion is worked, but an increase and decrease can never be produced at the same time.

Dr. de Forest attempts to throw doubt on the validity of the operating characteristic, and hence on all explanations depending thereon, by stating that he has frequently proven that a positive charge applied to the grid may decrease rather than increase the wing current, a contention originally advanced by him in explanation of the relay and detecting action of the audion. In the discussion, I have pointed out the fallacy in this view and explained the seeming paradox which is found in low vacuum bulbs on the working part of the grid potential-wing current curve. There is another effect which may lead to incorrect conclusions concerning the action of the electron relay, which is due to effects found above the working part of the curve. As the potential of the grid is increased, it is possible that the wing current may reach a maximum and then fall off. This is due to the fact that a conduction current flows to the grid when it is positive with respect to the filament, and that under certain conditions, this current is subtracted from the wing current. The maximum current which can flow from filament to wing is limited to the number of electrons emitted by the filament, and if the condition of maximum current flow in the wing circuit is established before the grid potential becomes highly positive, then a further increase in the grid potential will increase the number of electrons absorbed by the grid and the result is a decrease in the wing current. The impossibility of working an electron relay on this part of the curve will be evident from the accompanying diagrams (Figure 3) which show how the effective resistance of the input side of the audion increases as

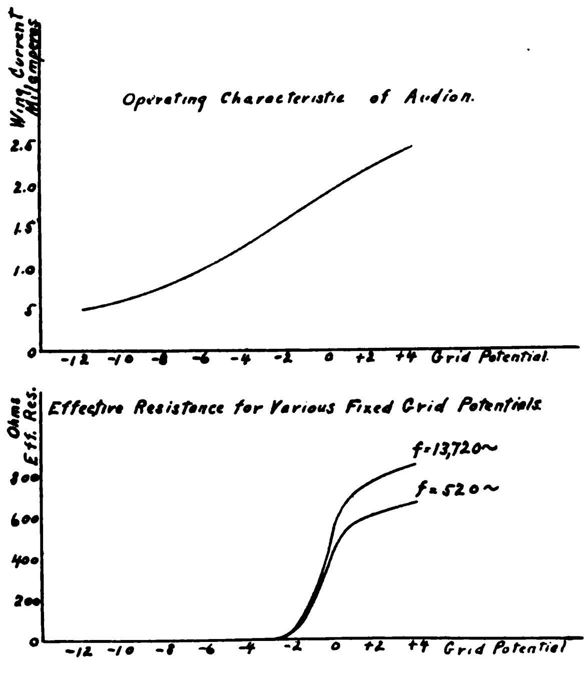

FIGURE 3

the potential of the grid is varied. Only when the grid is negative with respect to the filament can the full amplifying power of the audion be realized, as the input side consumes no energy. Herein lies the explanation of the great differences which exist in the amplifying powers of different bulbs when used in the customary fashion. It is usual to operate the audio frequency amplifier with the grid insulated from the filament for conduction currents so that the potential of the grid is determined solely by the characteristics of the audion. If it should chance to be sufficiently negative, the input side consumes no energy and the result is a good one; if it should be positive, then the input side consumes energy and the amplification is seriously impaired, the degree depending on the value of the positive charge. All this is clearly supported by the fact that when the potential of the grid of a good bulb is arbitrarily made positive, the amplification falls off. The curves shown in Figure 3 are additional confirmation, and in this connection it is interesting to note the agreement between the radio and audio frequency curves.

The statement by Dr. de Forest that he originally discovered the oscillating phenomenon and applied it to producing the effects described several years ago cannot be here discussed, because his priority in this matter will be contested shortly in another way.

Lee de Forest (by letter): While I cannot accept Mr. Armstrong's explanations of my observations as to the action of a positively charged grid on the wing current, they have at least more to recommend them than has his previous flat contradiction that such an effect as I have described existed at all.

What Mr. Armstrong states are "elementary matters" have not appeared so to associates and collaborators of Drs. Rutherford and Soddy with whom I have discussed them. These discussions, however, were prior to the appearance of Mr. Armstrong's paper.

In spite of Mr. Armstrong's explanations, we are left quite in the dark as to how high these consistent vacua are, and just what operating voltages he refers to. More quantitative explicitness and citations of the exact performances of scores of bulb would be more convincing than are the theories proposed as a basis for description of sundry complicated circuits.

If he is dealing with a type of tube which is quite distinct from the audion (on account of the degree of vacuum, the applied potentials, etc.), this should have been explicitly stated at the outset. This is my chief complaint. No essential data are given, but only general laws with attempted axioms. I assumed that we were dealing with phenomena in the audion as popularly known, operating on from 20 to 50 volts. With such, at least, there still remain some unexplained problems.

If he be unable to explain my observation that, using audio frequencies, certain bulbs show a decrease, others no perceptible change in deflection of a direct current micro-ammeter while a telephone receiver gives responses many times audibility—this fact should be frankly stated. I should also like to have his explanation as to why certain audions are distinctly more sensitive to low than to high spark frequencies while others show the exact reverse. Tho I have theories on this point, I have not yet proven them.

In connection with Mr. Armstrong's insistence on the value of his oscillograms which were taken at audio frequencies because audio and radio frequency phenomena are identical in nature, I should like to call attention to his statement that "This is an effect which radio (as distinguished from audio) frequency oscillations applied to the grid cannot produce."

Is it not perhaps possible that where successive strongly damped wave trains, of radio frequencies, have alternately positive and negative initial wave fronts, an alternating increase and decrease of wing current may occur which would, while giving loud signals in the telephone receiver, produce practically no change in deflection in a direct current micro-ammeter in series therewith?

As to Mr. Armstrong's closing remark, I had not before realized that he actually claimed broadly the discovery of the oscillating property of the audion. I think it can and will be established that this was discovered some time before his first work in this field. If any are still of the opinion that the oscillating quality of the audion awaited the discovery of the complicated circuits he describes, I would refer them to the article on "The Double Audion Type of Receiver," by Professor A. H. Taylor, in the "*Electrical World*" of March 13th, 1915.

Edwin H. Armstrong (by letter): Replying to Dr. de Forest's latest communication in regard to the effect of a charged grid on the wing current, I cannot but assume, from his failure to produce evidence to the contrary, that his observations may be explained by the residual positive charge on the grid. This applies to that type of tube in which so many "unexplained" phenomena are observed; "the audion, as popularly known, operating on from 20 to 50 volts."

Dr. de Forest's misapprehension as to the type of tube referred to in the paper rests entirely with himself. It was definitely stated in the article in the "*Electrical World*," and on the occasion of the presentation of this paper before the Institute of Radio Engineers that the vacuum of the bulbs was such that only thermionic currents existed. The methods used to obtain these vacua were those recently described by Dr. Irving Langmuir in a paper presented before the American Physical Society, and also in another paper presented before the Institute of Radio Engineers (See this issue of the PROCEEDINGS, together with the discussion on Dr. Langmuir's paper).

In explanation of Dr. de Forest's observation that audio frequencies applied to the grid may produce either a decrease or no change in the reading of a *direct* current micro-ammeter, while a telephone responds strongly, I have pointed out the oscillograms which fully explain both cases. It seems necessary to add that a *direct* current instrument of the type mentioned measures *average* values!

The question of the relative sensitiveness of an audion as a detector to high and low spark frequencies is entirely irrelevant to the present discussion. It has, however, some points which are of interest. The effect occurs only when the valve action of the audion is used to rectify the oscillations and a condenser is necessarily used in series with the grid. When there is a scarcity of positive ions, the rate of leak of the charge accumulated in the grid condenser from one group of oscillations may be so slow that the condenser fails to clear itself before the arrival of another group of oscillations. Under these conditions, a residual negative charge is continuously maintained in the grid condenser during the periods of signaling, and this charge interferes with the rectifying action between grid and filament. Obviously, this effect will be more pronounced at the higher spark frequencies, and the sensitiveness of the audion will be less impaired on the low spark frequencies. The phenomenon is an interesting one, but on the whole it is quite simple and elementary in character.

Dr. de Forest attempts to explain the circumstance which I have shown is impossible—the circumstance in which radio frequencies applied to the grid produce response in a telephone in the wing circuit but no change in the deflection of a continuous current instrument in series with the telephone. The explanation advanced is impossible. The effect described could be produced only by wave trains that were practically aperiodic. Needless to say, nothing remotely approaching this is in use in radio telegraphy at the present time.

In conclusion, I wish to point out that this discussion was originally begun by Dr. de Forest in an attempt to invalidate the explanations advanced to account for the various detecting, repeating, and oscillating phenomena. It is my opinion that the explanations given stand as correct.

Robert H. Marriott: It has been frequently charged that there has been a lack of research in radio engineering carried out in physical research laboratories. Mr. Armstrong deserves much praise in carrying out his highly interesting investigation, and it is to be hoped that further valuable results will be obtained under similar auspices.

(This discussion is herewith closed.—EDITOR.**)**

DEVELOPMENTS OF THE HETERODYNE RECEIVER[1]

By

JOHN L. HOGAN, Jr.

(Including a discussion on "Some Recent Developments in the Audion Receiver," by E. H. Armstrong.)

The comparatively recent development of the audion amplifier into the singing-relay form of radio-frequency oscillation generator has given a great impetus to heterodyne or electrical-beats receiving, since it has provided a cheap and satisfactory generator for such use. The further discovery that in the same audion bulb the triple functions of generation, rectification and amplification could be simultaneously carried on has additionally increased the use of heterodyne methods, altho the somewhat involved nature of the coincident phenomena has tended to obscure the true actions within the device. It is for this reason, in addition to his practical achievements, that Mr. Armstrong is to be congratulated for his painstaking work in the investigation of audion operation and for his clear and frank presentation of results. It may develop that I cannot agree with some of the conclusions he has drawn as to the relative commercial operating importance of some of these devices, but I do find his explanations of audion action in full agreement with my own observations and experiments.

It may be of interest to trace the development from the preferred form of beats receiver[2] shown in Figure 11 of my paper, "The Heterodyne Receiving System"[3] to the Armstrong arrangement, and to show some arrangements and give some results which have not as yet been published. To begin with, we must realize that a heterodyne receiver is one in which the incoming wave energy produces an effect at its own radio frequency, which effect is combined with a second effect occurring at a second (and usually slightly different) radio frequency so as to produce a "beat" phenomenon or resultant effect which is periodic and has a frequency equal to the difference in frequencies of the two

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[1] The diagrams and substance of this paper were presented before the Institute of Radio Engineers, New York, March 3, 1915.

[2] U. S. Patent to Lee and Hogan, No. 1141717 of June 1, 1915.

[3] PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, Volume 1, Part 3, page 75 *et seq.*, July, 1913.

component effects.† This resultant periodic action, which corresponds to the cyclic progression in phase difference between the components, is usually utilized by mechanically or electrically rectifying two "beating" radio frequency currents so as to produce a tonal indication. This operation is explained fully in the original paper referred to, but may be made sufficiently clear by reference to Figures 4 and 6 which are here reproduced.

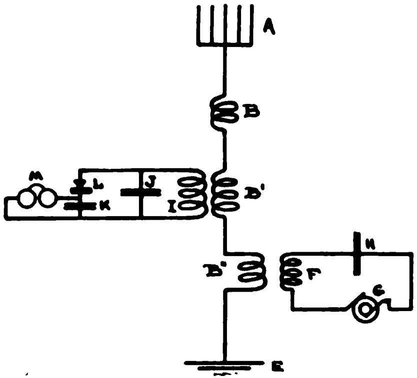

FIGURE 11
(OF ORIGINAL PAPER)

Figure 4 may be taken to represent on the A axis a sine wave voltage of frequency 250 per milli-second (or 250,000 per second). The B axis graph then represents a voltage of frequency 200 per milli-second. When these voltages act simultaneously on a circuit, the resultant takes the form shown by graph C, in which the "beat" or periodic change of amplitude is easily seen to occur at the rate of 50 per milli-second, or to correspond to the difference in fundamental frequencies. This voltage of course sets up in the circuit a corresponding current which is then rectified (graph D) and used to produce a final periodic effect such as shown by graph E. The frequencies 250,000 and 200,000 per second were chosen to permit graphs of several complete beats to be shown; the resulting beat frequency of 50,000 per second would of course be useless for producing directly an audible response in radio telegraphy. Ordinarily the frequencies would be, say, 250 and 249 per milli-second, giving a beat tone of 1,000 per second.

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† U. S. Patents to Fessenden, Nos. 1050441 and 1050728, January, 1913.

To define one type of heterodyne action still more specifically, let us consider Figure 11 of the original paper. Here the first radio frequency effect is the voltage across coils B, B′, B″ produced by the received wave in the usual way. The second

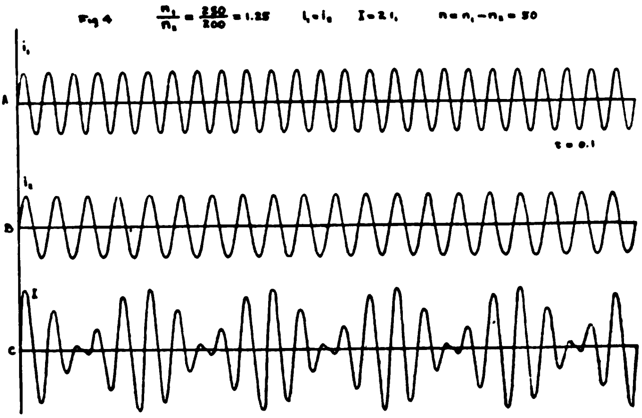

Figure 4
(of original paper)

is the radio frequency voltage across "B" produced by the local generator circuit FGH. These voltages correspond to graphs A and B, Figure 4, and result in a fluctuating current, such as graph C shows, tho in general the beat frequency will be of the order of

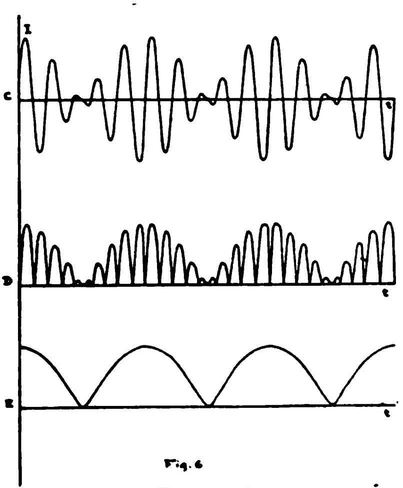

Figure 6
(of original paper)

1,000 per second. This fluctuating current is rectified by the combination LKM, as indicated by graph D, Figure 6 (in which each alternate half-wave should be dotted, to represent the return of its energy to the resonant circuit) and results in movement of the telephone diafram corresponding approximately to graph E. One cycle of sound will be produced for each complete "beat," and so the tone frequency may be changed at will by varying the difference between the component frequencies.

In practice, a large number of combinations of units to form a heterodyne receiver are possible. For example, the "local" oscillation generator may consist of a radio frequency alternator, an arc generator, a buzzer exciting circuit, a high frequency spark circuit, an oscillating audion, etc. Any one of the many circuits for radio frequency tuning may be used, and the local oscillator may, in general, be coupled to any tuned circuit of a series; nevertheless, beat formation with damped waves is best accomplished in circuits of low damping. With sustained waves full beats are, of course, formed in any circuit. Any form of non-polarized indicator may be used, such as a static or electrodynamic telephone or relay, or a rectifier and polarized (ordinary) telephone. Figure 5 shows a heterodyne receiver in which local oscillations generated by the direct current "arc" discharge gap D are transferred to the secondary tuning circuit L_3; L_4, C_1 and there interact with received-wave currents to form beats. As the audion rectifier-relay R introduces little damping into the secondary, full beat formation occurs. The arrangement is ex-

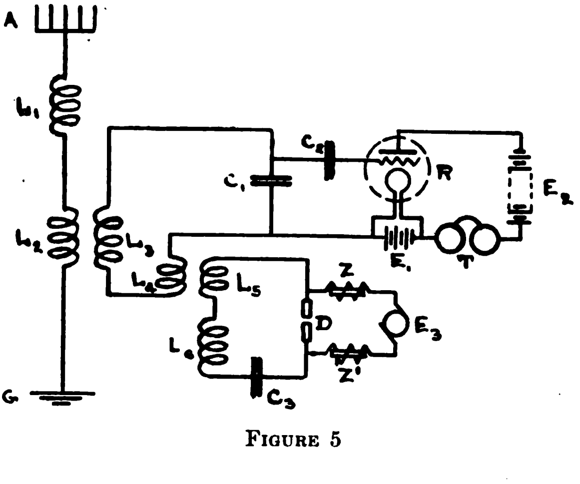

FIGURE 5

tremely sensitive, of course, and by selecting the proper coupling between L_4 and L_6 the normal delicacy of the audion to atmospherics and other intense momentary voltages may be somewhat reduced. The optimum power transferred from the local generator is rather critical for best amplification even with contact rectifiers, and with the audion the best adjustment for any given set of other conditions is very closely defined.

The extreme delicacy of the audion may be increased in heterodyne working exactly as in normal operation by the adoption of Mr. Armstrong's "regenerative" scheme. If the connection of Figure 8 (Armstrong's paper) is substituted for the simple audion arrangement of my Figure 5, the arc generator and antenna remaining unchanged, heterodyne reception with enhanced responsiveness will result. The coupling from local oscillator to secondary (or to antenna) circuit must be adjusted with great care, especially when the transformer M_2 (Armstrong's Figure 8) is coupled so closely that wing circuit radio frequency energy is transferred back to the grid circuit almost rapidly enough to maintain continuous oscillations. When the circuits are adjusted to the critical point of maximum amplification, the regenerative audion will be set into momentary sustained oscillation by each severe static discharge, so producing a brief singing beat tone and giving the sound effects of a sharply group-tuned telephone circuit. For the best results with so sensitive a rectifier-amplifier combination as the regenerating audion it is desirable to have as quiet an oscillator as possible,

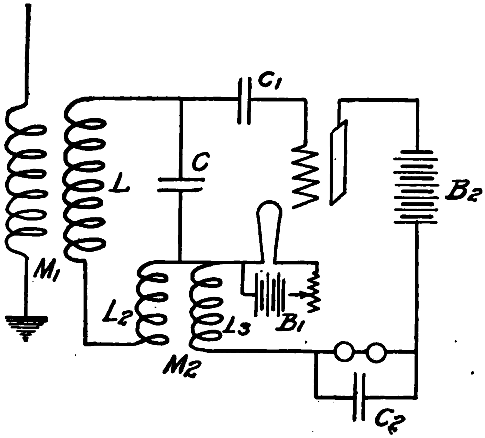

FIGURE 8 (Armstrong's Paper)

since when strays are light or absent it thus becomes possible to copy signals produced by absurdly small amounts of received sustained-wave power. Of course, when day-and-night transmission is required for week after week without interruption (as must be the case for radio to compete commercially with wire or cable signaling) the signal power must be sufficiently large to permit differentiating between it and irregular, impulsive disturbances in some one or more known ways; at the same time irregularities in the local oscillations for heterodyne working are made unobjectionable. Nevertheless, a quiet oscillator is a desirable and useful thing.

The most uniform and quiet radio frequency generator for very small powers I have ever handled is the regenerative audion relay. As has been known for some time, radio frequency oscillations can be produced by a simple two-electrode evacuated bulb, but my experience has been that steadier currents may be made by application of the singing telephone relay principle to the audion repeater. Mr. Armstrong has pointed out that any energy-amplifying telephone relay may be used as an oscillator by transferring part of the amplified energy back to the trigger circuit to keep the device in oscillation. It should be interesting to consider the frequency determining elements of such a circuit, and I have therefore shown in Figure 6 the analogous microphone relay arrangement. Here on closing the battery E circuit, a pulse of current is induced in L_1, via transformer L_3 L_2. If the winding direction of L_1 is properly selected with regard to the permanent magnet forming its core, the pulse will cause attraction of the diafram D, which will increase the resistance of microphone M and decrease the current in the battery circuit. The resulting fall in current induces a secondary pulse in L_2 in the opposite direction and repels the diafram, so reducing the microphone resistance, increasing the L_3 current and starting

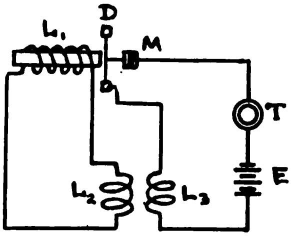

FIGURE 6

the cycle anew. If the magneto-microphonic relay L_1 DM is sufficiently sensitive, a comparatively large nearly sinusoidal current will be set up in L_3 DMTE, as may be evidenced by the tone emitted by telephone T in circuit. The period of the alternating current generated will be that of the mechanical system DM, which should be of self-resonant character (i.e., not highly damped). If the microphone-diafram combination be coupled by an air column between two diaframs, (one on the "receiver" L_1 and the other attached to the microphone M) which has its length so chosen as to resonate to the diafram frequency, the system will produce alternating current without requiring any exceptional delicacy as a repeater, as is shown by the familiar telephone hummer.

If one secures an efficient aperiodic repeater, such as that indicated by Figure 7, where the armature A takes the place of

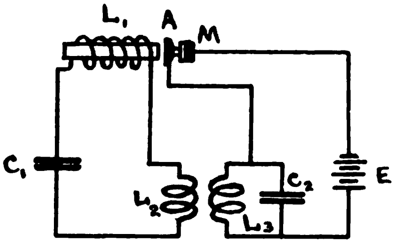

FIGURE 7

diafram D, the oscillation frequency may be determined electrically and may be shortened as far as the inertia of the repeater permits. Here the circuits $C_1(L_1 + L_2)$ and $C_2 L_3$ are tuned to the oscillation frequency desired; in both Figures 6 and 7, the coupled circuit L_1 L_2 represents the trigger which drives the relay and the circuit E L_3 carries the amplified current.

Until the audion repeater was developed there seems to have been no satisfactory telephone relay. Mono-periodic microphone repeaters were, however, quite efficient, and radio frequency currents could be generated by the methods suggested in Figures 6 and 7. The superior efficiency of the audion, however, and its freedom from inertia, at once indicated its suitability for this purpose. Mr. Armstrong's Figure 8, which constitutes an oscillator when transformer M_2 is rather closely coupled, may be compared with these simple singing microphonic repeater circuits and will be found to depend upon identical operating principles. The driving or grid circuit of the audion is connected for maximum resonant potential instead of current, since this favors its operation, and the device is of such sensitiveness that the driven or wing-B_2 circuit need not be tuned, tho to do so increases the available oscillation power. In Figure 8, the period of current is of course determined by the constants of the C, L, and L_2 circuit. The telephones and shunting condenser C_2 may be omitted and L_1 coupled to an antenna to set up beats with received energy therein, as shown by the right-hand half of my Figure 8. In this heterodyne arrangement the regenerative audion in non-oscillating condition is indicated as the rectifying and indicating element. The telephones T need not always be shunted by a condenser, since the effective capacity of their cords and windings is often sufficient to permit regenerative amplification.

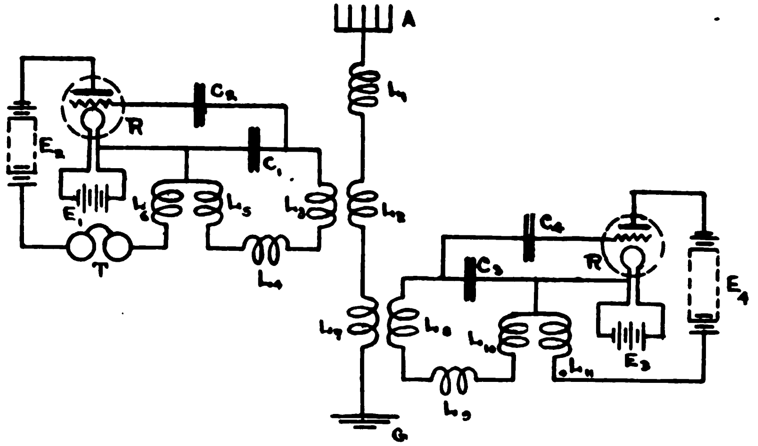

FIGURE 8

We thus have the heterodyne principle applied to large variety of receiver combinations. As Mr. Armstrong points out, the same bulb (with regenerative circuits) may be used simultaneously as a generator, rectifier and amplifier, then constituting an especially ingenious beats receiver. In practice, I have not found it possible to secure the full amplifying power of the regenerating audion relay when the bulb is oscillating, tho I have had both Mr. Armstrong's and Dr. de Forest's similar "ultraudion" arrangements demonstrated to me, and have often reproduced them in my laboratory. It appears that the critical optimum of the power-efficiency characteristic cannot be made use of when the same bulb is used as rectifier, amplifier and oscillator. The difficulty or impossibility of securing maximum response, however, may not prove an obstacle in commercial working, since the extreme delicacy of the "best" adjustment really prevents operation when static is present.

A brief summary of some of the heterodyne tests which I have conducted over the past year or so may be of interest as giving experimental data for the various beats receivers. At Brooklyn, we have two antennas, one a flat top having a natural wave length of 1,000 meters and effective height of about 250 feet, the other having a natural wave length of 250 meters and height of about 175 feet. With the regenerative audion heterodyne shown in my Figure 8, it is not difficult to read daylight signals from Nauen, Germany, over 4,000 miles, on a 10,000 meter wave, *on the small antenna.* On the large antenna, this same receiver arrangement gives responses to Nauen's daylight signals so loud that they may easily be read some fifty feet from the telephones, or transmitted over the telephone lines to considerable distances merely by holding the receiving head-phone close to the Bell transmitter. This almost unbelievable responsiveness can only be reached and maintained when strays are practically absent, however; as soon as atmospherics appear it becomes necessary to use a less sensitive receiver if messages are to be read.

On the large antenna, Nauen's daylight signals give an audibility factor of from 300 to 500 when the plain audion is used as a detector (see my Figure 5), with considerably greater freedom from stray disturbance. Even with this, however, the delicacy seems too great for reliable reception, and it is advisable to use still more rugged rectifiers. The ronescon detector, a special crystal combination having extreme permanence of adjustment and a normal sensitiveness about 80 per cent of the bare point electrolytic, gives heterodyne responses to Nauen of about 100 audibility. This arrangement gives the best continuous operating condition of all those tried, tho for very small received powers (such as intercepted on the Brooklyn antenna from Nauen, Eilvese, San Francisco and Honolulu) it is desirable that the local oscillator be very quiet in operation.

For a considerable period, the Nauen-Sayville transmission was monitored at Brooklyn, everything sent either way being copied so far as it was possible to do so thru atmospheric interference. When the ronescon heterodyne was used we found that our reception from Nauen was a trifle better than Sayville's, altho our antenna was far less effective in its ability to collect radio frequency energy arriving on waves of such great length than was that used at Sayville. The only difficulty experienced at Brooklyn or at Sayville (so far as could be determined) was from the apparent weakening of Nauen's signals in the presence of strays.

The evident conclusion is that heterodyne reception for consistent long distance working should be based on the use of rugged rectifiers having great overload capacity with small loss of conversion efficiency. Such reception of sustained wave signals has the following valuable characteristics, among others:

1. Signals produced as pure musical tones of regulable pitch, permitting
   a. Any degree of audio frequency tuning.
   b. Aural selection from static.
2. Selection by persistence of oscillation in addition to selection by wave frequency, since damped oscillations produce incomplete or decadent beats.
3. Ruggedness and ease of adjustment.
4. Stray minimization by virtue of the detector's overload characteristic (which may be equivalent to what Mr. Armstrong terms the "balanced valve" effect.)
5. Amplification of desired signal by heterodyne action, without proportionate increase of strays.
6. With signals of moderate strength, stray reduction by detuning antenna to coincide with frequency of local generator.

In spite of the present superiority for commercial work of such an arrangement as I have last outlined, however, the combined oscillator and amplifying rectifier and the regenerative audion used in non-oscillating condition for grouped-wave reception are useful and valuable devices. The work which Mr. Armstrong has done seems to me of great importance, and I wish again to thank him for his clear presentation of it.

New York, May 3, 1915.

SUMMARY: The heterodyne receiver is defined and explained. Various arrangements for heterodyne reception are discussed. The use of the "regenerative" or oscillating audion is then considered. It is shown how

any energy-amplifying relay can become an oscillation generator. Several instances are given. In connection with beat reception using the audion generator, it is stated that most satisfactory results are obtained in commercial service when it is used as a generator only, the detector being a rugged crystal combination. Examples of the extreme sensitiveness of the arrangements described are given.

THE PURE ELECTRON DISCHARGE

AND ITS APPLICATIONS IN RADIO TELEGRAPHY AND TELEPHONY

BY

IRVING LANGMUIR

HISTORICAL

It has been known for nearly two hundred years that air in the neighborhood of incandescent metals is a conductor of electricity. Elster and Geitel studied this phenomenon in great detail, and published the results of their investigations in a series of papers in "Wiedemann's Annalen" during the years 1882–1889.

In most of their experiments, they placed a metal plate close to a metallic filament within a glass bulb, and studied the charge acquired by the plate under various conditions of filament temperature and gas pressure. They found in most gases that the filament tended to give off positive electricity when it was at a red heat, but at very high temperatures it gave off negative electricity more easily than positive. When the vessel was exhausted as completely as was possible in those days, the tendency to give off positive electricity was much decreased and did not persist, whereas the tendency to emit negative electricity was apparently stronger than ever.

A similar discharge of negative electricity from the carbon filament of an incandescent lamp to an auxiliary electrode placed within the bulb was observed and studied by Edison and has since been known as the Edison effect. Fleming, in 1896 (Proc. Roy. Soc. **47**, 118, (1890) and Phil. Mag. **42**, 52 (1896)) investigated and described this effect in detail.

J. J. Thomson (Phil. Mag. **48**, 547 (1899)) showed that in the case of a carbon filament in hydrogen at very low pressures, the negative electricity is given off by the filament in the form of free electrons having a mass about 1/1800th of the mass of a hydrogen atom, and constituting in reality atoms of electricity.

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[*] Delivered before The Institute of Radio Engineers, New York, April 7, 1915.

Owen (Phil. Mag. 8, 230 (1904)) showed that a heated Nernst filament also gives off electrons, and Wehnelt (Ann. Phys. 14, 425 (1904)) proved that the electric current from a lime covered platinum cathode (Wehnelt cathode) is carried in the same manner.

Richardson (Phil. Trans. 201, 516 (1903)) applied the electron theory of metallic conduction to the electron emission from heated metals, and was thus able to develop a theory of this effect. In order to account for the conduction of heat and electricity by metals, Riecke and Drude had assumed that metals contain electrons which are free to move under the influence of an electric force and which are in constant vibratory motion similar to that of the molecules of a gas. Richardson assumed that these free electrons are ordinarily held within the metal by an electric force at the surface, just as the molecules of a liquid are prevented from escaping by a surface force related to the surface tension. If the velocity of an electron is sufficiently high, it may be able to overcome the surface force and escape. Since the average velocity of the vibratory motion increases with the temperature, the number of electrons which reach the necessary critical velocity to escape, will increase very rapidly with the temperature. These considerations are strictly analogous to those of the evaporation of a liquid, so that the number of electrons escaping should increase with the temperature according to the same laws as those governing the increase of the vapor pressure of a liquid as the temperature is raised.

It had already been shown that the vapor pressure (p) of a substance varies with the temperature (T) according to a relation of the form

$$p = A\sqrt{T}\,\varepsilon^{-\frac{\lambda}{2T}}$$

where A is a constant, λ is the latent heat of evaporation of the liquid (or solid), and ε is the base of the natural system of logarithms. Richardson was thus led to conclude that the current from an incandescent metal should increase according to an equation of a similar form, namely

$$i = a\sqrt{T}\,\varepsilon^{-\frac{b}{T}} \quad .$$

Here i is the current per square centimeter at the temperature T, and b is a constant which should be half the latent heat of evaporation of the electrons.

A curve showing the electron emission from heated tungsten, calculated with the use of appropriate constants from the above equation, is given in Figure 1.

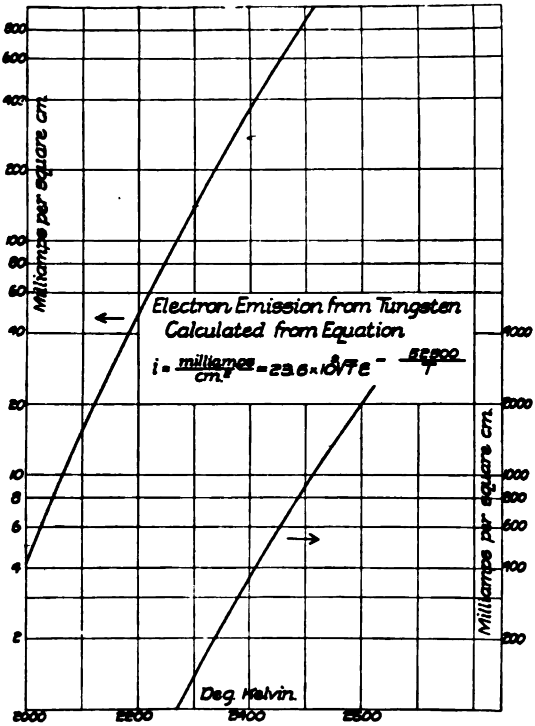


FIGURE 1—Electron Emission from Tungsten in a "Perfect" Vacuum

Richardson suggested that the currents obtained by the emission of electrons or ions from incandescent bodies should be called *thermionic* currents, a term which has since come into very general use.

According to Richardson's theory, an incandescent metal at a given temperature emits a certain number of electrons which is independent of the electric field around the heated body.

If a positively charged body is placed near the heated filament, the electrons will all be drawn away from the filament and will strike and be absorbed by the positively charged body. The motion of these electrons constitutes an electric current, the hot filament being the cathode and the positively charged body the anode of the discharge.

If, however, there is no electric field around the heated filament, or if a negatively charged body be placed near it, the electrons which are emitted from the filament return to it again and are re-absorbed, and therefore no current flows between the two electrodes.

According to this view-point, the electron emission is the same whether a thermionic current flows or not. As the potential of the cold electrode or anode is increased, a larger and larger proportion of the electrons emitted are drawn to the anode, so that the thermionic current increases. As the potential is further raised, a point is finally reached at which all the electrons emitted pass to the anode, so that a further increase in voltage causes no increase in current. The current is then said to be "saturated."

Richardson, in 1902, determined the relation between the saturation current from a heated platinum wire and a cylinder around it, and found that i varied with the temperature in accordance with the equation given above. For other substances also he found the relation to hold.

Since 1903, Richardson's theory of thermionic currents has been the subject of much investigation and discussion. H. A. Wilson (Phil. Trans. **202**, 243 (1903)) found that the electron emission from platinum at high temperature was decreased to 1–250,000 of its former value by a preliminary heating of the platinum in oxygen, or by boiling in nitric acid. The admission of a little hydrogen brought the current back to its former value.

Wehnelt (Ann. Phys. **14**, 425 (1904) and Phil. Mag. **10**, 80 1905)) discovered that platinum cathodes covered with lime emit vastly more electrons than platinum alone. He proposed using tubes containing such cathodes as rectifiers for alternating current of 100 or 200 volts, and described a Braun tube in which very soft cathode rays (100 to 1,000 volts) could be produced. Wehnelt worked usually with gas pressures ranging from 0.01 to 0.1 millimeter of mercury, the lowest pressure recorded being 0.005 millimeter. Under these conditions the paths of the cathode rays were visible, showing that there was strong ionization of the gas.

Soddy (Phys. Zeit. **9**, 8 (1908)) found that the large currents obtainable from a Wehnelt cathode stopped suddenly if the residual gases in the vacuum tube were absorbed by vaporizing some metallic calcium. This work of Soddy attracted considerable attention and made many investigators feel that thermionic currents in general were dependent on the presence of gas.

Lilienfeld (Physik. Zeitschr. 9, 193 (1908)), however, considered that Soddy's experiments did not show that the electron emission from the Wehnelt cathode had decreased, but suggested that the decrease in current might be caused by the building up of a negative charge in the vacuum because of the large number of electrons needed to carry the current.

Fredenhagen (Verh. deut. phys. Ges. 14, 384 (1912)) in 1912 studied the electron emission from sodium and potassium, two metals that Richardson had found particularly good sources of electrons, and concluded that the electrons are only emitted as a result of the presence of gas. He suggested that if a perfectly clean metallic surface could be obtained in a perfect vacuum the electron emission would cease entirely.

Pring and Parker (Phil. Mag. 23, 192 (1912)) in the same year measured the currents from incandescent carbon rods in a vacuum. They found that with progressive purification of the carbon and improvement in the vacuum, the currents decreased to extremely small values. They conclude that "the large currents hitherto obtained with heated carbon cannot be ascribed to the emission of electrons from carbon itself, but that they are probably due to some reaction at high temperatures between the carbon, or contained impurities, and the surrounding gases, which involves the emission of electrons."

More recently Pring (Proc. Roy. Soc. A 89, 344 (1913)) repeated these experiments under still better vacuum conditions and finds the former results confirmed. He concludes that "the thermal ionization ordinarily observed with carbon is to be attributed to chemical reaction between the carbon and the surrounding gas." "The small residual currents which are observed in high vacua after prolonged heating are not greater than would be anticipated when taking into account the great difficulty of removing the last traces of gas."

A similar feeling gradually arose in regard to the photoelectric effect, a phenomenon resembling the electron emission from incandescent metals, except that the electrons are emitted by the action of light—usually ultra-violet light, instead of heat.

Pohl and Pringsheim (Phys. Zeit. 14, 1112 (1913)) find that the photo-electric effect is very much decreased by improving the vacuum, and suggest that perhaps the whole effect is due to interaction between the gas and the metal. Wiedmann and Hallwachs (the latter the discoverer of the photo-electric effect) (Ber. d. Deut. Phys. Ges. 16, 107 (1914)) go further and state emphatically as a conclusion from experiments with potassium that "The presence of gas is a necessary condition for appreciable photo-electric electron emission."

Fredenhagen and Kuster (Phys. Zeit. **15**, 65 and 68 (1914)) conclude that the same is true for the photo-electric effect from zinc, and in a still later publication Fredenhagen (Verh. d. Deut. Phys. Ges. **16**, 201 (1914)) finds that both the photo-electric and thermionic electron emission from potassium are entirely dependent on the presence of gas.

We see, then, that there were the best of reasons for believing that it would be impossible to get any electric discharge thru a perfect vacuum, because one could not expect to get any electrons from the electrodes. In the operation of ordinary X-ray tubes it was well known that a certain amount of gas was necessary. Porter (Ann. Phys. **40**, 561 (1913)) studied the dynamic characteristics of the Wehnelt rectifier and found that with pressures as low as 0.001 millimeter there was a tendency for the current to become unstable, fluctuating periodically between zero and a higher value.

With higher pressures, this difficulty was avoided, but the characteristics clearly showed a sort of hysteresis loop, the current with ascending voltage being different from that obtained with descending voltage.

My active interest in thermionic currents began in connection with some experiments on electrical discharges occurring within tungsten lamps. According to Richardson's data on the electron emission from such metals as platinum and osmium, the currents that might exist across the evacuated space in a tungsten lamp would be very large; in fact, the current density, at temperatures close to the melting-point of tungsten, might be expected to be several hundred amperes per square centimeter. Of course it is evident at the outset that the current flowing from one part of a filament to the other thru the vacuum must actually be very small in any ordinary lamp. It was known that the vacuum in a tungsten lamp is extremely high, and measurements indicated that in well exhausted lamps after 100 hours life the pressure was probably less than one millionth of a millimeter of mercury. Taking these two facts in to account, the very existence of a tungsten lamp seems strong evidence that thermionic currents in high vacuum must be very small, if not entirely absent.

When this effect was studied in more detail, it was found that the smallness of the currents in a lamp was not due to any failure of the filament to emit electrons, but was due entirely to an inability of the space around the filaments to carry the currents with the potential available in the lamp.

In one case, two single loop tungsten filaments were mounted side by side in the bulb. After the bulb was exhausted in the best possible way and the filaments were thoroly aged and freed from gas, one of the filaments was heated while a positive potential was applied to the other thru a galvanometer. The hot filament thus served as cathode in the discharge occurring in the lamp. As the current thru the cathode was increased, the thermionic current as measured by the galvanometer increased at first, according to Richardson's equation as shown in Figure 1; but beyond a certain point, as indicated in Figure 2, the further increase in the temperature of the cathode produced no further increase in thermionic current.

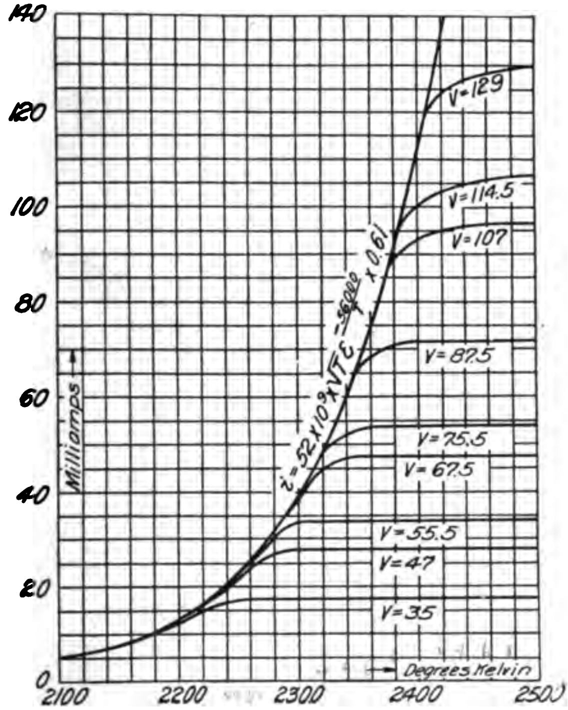


Figure 2—The Effect of Space Charge on the Thermionic Currents

The curve representing thermionic current as a function of temperature therefore consists essentially of two parts: first, a part in which Richardson's equation applies; second, a part in which the current is independent of the temperature. In the first part of the curve, it is found that the current is independent of the voltage, or shape and size of the anode, but in the second part of the curve the current is affected by both of these factors and may also be either increased or decreased by placing the lamp in a magnetic field. It is thus evident that the only reason that the current does not continue to increase, according to Richardson's equation, is that the space between the electrodes is capable of carrying only a certain current with a given temperature difference.

The explanation of this phenomena was found to be that the electrons carrying the current between the two electrodes constituted an electric charge in the space which repelled electrons escaping from the filament and caused some of them to return to the filament.

A further theoretical investigation on the effect of this space charge led to the following formulas by which the maximum current that can be carried thru a space (of certain symmetrical geometrical shapes) may be calculated.

In the case of parallel plates of large size, separated by the distance x, the maximum current per square centimeter, i, is

$$i = \frac{\sqrt{2}}{9\pi}\sqrt{\frac{e}{m}}\,\frac{V^{\frac{3}{2}}}{x^2} \qquad (1)$$

Here, e is the charge on an electron, m the mass of an electron, and V the potential difference between the plates. If we substitute the numerical value of $\frac{e}{m}$ and express i in amperes per square centimeter and V in volts, then this equation becomes

$$i = 2.33 \times 10^{-6}\,\frac{V^{\frac{3}{2}}}{x^2} \qquad (2)$$

In the case of a wire in the axis of a cylinder, the maximum current per centimeter of length from the wire is given by the equation

$$i = \frac{2\sqrt{2}}{9}\sqrt{\frac{e}{m}}\,\frac{V^{\frac{3}{2}}}{r} \qquad (3)$$

If we substitute numerical values as before, we find

$$i = 14.65 \times 10^{-6}\,\frac{V^{\frac{3}{2}}}{r} \qquad (4)$$

where i is the current in amperes per centimeter of length, and r is the radius of the cylinder in centimeters.

These equations have been found to agree accurately with experiments when the vacuum is so high that there is no appreciable positive ionization.

Extremely minute traces of gas, however, may lead to the formation of a sufficient number of positive ions to neutralize, to a large extent, the space charge of electrons and thus very greatly increase the current carrying capacity of the space. For example, a pressure of mercury vapor of about 1/100,000 millimeter has, under certain conditions, been found to eliminate completely the effect of space charge, so that a current of 0.1 ampere was obtained with only 25 volts on the anode, whereas, without this mercury vapor, over 200 volts were necessary to draw this current thru the space.

Besides this enormous effect on the current carrying capacity of the space, many gases have a great influence on the electron emission from the cathode. But in every case where the cathode is of pure tungsten, the effect of gas is to decrease, rather than increase, the electron emission. For example it is found that a millionth of a millimeter of oxygen, or of a gas containing oxygen, such as water vapor, will cut the electron emission down to a small fraction of that in high vacuum.

As a result of this work, we became firmly convinced that the electron emission from heated metals was a true property of the metals themselves and was not, as has so often been thought, a secondary effect, due to the presence of gas.

Further investigation showed that with the elimination of the gas effects, all of the irregularities which had previously been thought inherent in vacuum discharges from hot cathodes were found to disappear. In order to reach this condition, however, it was not sufficient to evacuate the vessel containing the electrodes to a high degree, but it was essential to free the electrodes so thoroly from gas that gas was not liberated from them during the operation of the device. It was also necessary to free the glass surfaces very much more thoroly from gas than had been thought necessary previously. The difficulty thus consists not in the production of the high vacuum, but in the maintenance of this vacuum during the use of the apparatus. As the voltage applied to the terminals was increased and as the current density in the discharge increased, the tendency for the gas residue to become ionized became very much more marked and the difficulties in maintaining a sufficiently high vacuum increased still further.

However, by special methods of exhaustion and by special methods of treating the electrodes, these difficulties have been overcome and it has thus been possible to construct apparatus in which a large current density can be obtained and potential differences of much more than 100,000 volts may be applied without obtaining effects attributable to positive ionization.

In previous devices which employed discharges thru vacuum, either with or without a hot cathode, there was always evidence of positive ionization if the current density was increased above an extremely low value, or if potentials over 50 or 100 volts were applied while a current of as much as a few milliamperes was flowing. The effects of this positive ionization manifested themselves in many ways. If the ionization was sufficiently intense, a glow thruout the tube was visible. For example, in the Braun tube, with a lime covered cathode, Wehnelt states that as high a vacuum as possible should be obtained, but he speaks of being able to see the path of the cathode rays. It has apparently always been assumed that cathode rays of sufficiently high intensity can always be seen, but of course such a luminosity is direct evidence of ionization of the gas. One of the most sensitive indications of the presence of positive ionization is the failure of the current to increase with the voltage in a regular manner, as shown in equations (2) and (4). If much gas is present, and by this I mean a pressure in the order of 1–10,000 millimeter, the current-voltage curve often shows decided kinks when the voltage is raised above 50 or 100 volts. In many cases the discharge is unstable and fluctuates periodically between two values. All these effects tend to be extremely erratic, since they vary with the composition and the pressure of the residual gases, and these, in turn, are altered by the discharge taking place thru them. For example, in the ordinary X-ray tube, the vacuum continually improves, and it is necessary, from time to time, to admit fresh portions of gas.

With the higher voltages, perhaps the most troublesome feature of positive ionization is its tendency to disintegrate the cathode. The positive ions, moving under the influence of the electric field, acquire high velocity, and when they strike the cathode cause rapid disintegration and ultimate destruction of the electrode. With a pure electron discharge, however, there is no disintegration of the electrode caused by the discharge and the filament lasts the same length of time as if no current passed thru the vacuum.

Another effect, produced by positive ionization, is the emission of electrons from the cathode under the influence of the positive ion bombardment. These electrons, which constitute the so-called delta rays, escape from the cathode with considerable initial velocity, and are therefore capable of charging up a third electrode in this space to a potential of ten or fifteen volts negative with respect to the cathode.

With the pure electron discharge, none of these effects are present. The cathode rays are entirely invisible, the current voltage curve is a smooth curve and follows the 3–2 power law, in case the filament temperature is sufficiently high and the shape of the electrodes is such that the small initial velocities of the electrons from the cathode do not play too large a role. It is possible to obtain a very high current density in this type of discharge, but in order to overcome the space charge effects, it is then necessary to use a very strong electric field close to the cathode.

DEVICES EMPLOYING A PURE ELECTRON DISCHARGE

Dr. Coolidge (Phys. Rev. 2, 409 (1913)) has used the pure electron discharge in the construction of a new type of X-ray tube. In this tube the cathode consists of a small, flat spiral of tungsten wire, surrounded by a small molybdenum cylinder which serves as a focussing device, while the anode, or target, consists of a massive piece of tungsten, placed near the center of the tube. With this tube it has been possible to use voltages as high as 200,000 volts in the production of X-rays. The current thru the tube is absolutely determined by the electron emission from the filament, which, in turn, depends on the temperature, in accordance with Richardson's equation.

The advantages of this tube over the ordinary X-ray tubes previously used are many. Perhaps the most important feature is that the current and voltage are under complete control at all times, the current being fixed by the temperature of the cathode while the voltage is simply that furnished by the transformer or induction coil used. The tube seems to have an almost unlimited life, the temperature of the filament being so low that no appreciable evaporation occurs and the absence of gas eliminating the cathodic disintegration usually characteristic of high voltage discharges in vacuum. The tube is entirely constant in its action and the erratic effects usually observed in X-ray tubes are eliminated.

Several other types of apparatus have also been developed making use of this pure electron discharge, and these devices possess the same advantages over apparatus formerly used as the Coolidge X-ray tube possesses over the ordinary X-ray tube.

In order to distinguish these devices from those containing gas and in most cases depending upon gas for their operation, the name "kenotron" has been adopted. This word is derived from the Greek *kenos*, signifying empty space (vacuum), and the ending, *tron*, used by the Greeks to denote an "instrument."

KENOTRON RECTIFIER

The Coolidge X-ray tube is, of course, a rectifier for high voltage alternating current, but it is not suitably designed for this purpose. In an X-ray tube, the voltage applied must be consumed in the tube itself, whereas in the rectifier the voltage in one direction should be consumed in the load in series with the rectifier, altho the voltage in the opposite direction should be taken wholly by the rectifier. In the X-ray tube, because of the great distance between anode and the cathode and the presence of a focusing device around the cathode, the space charge effects are very much exaggerated, so that it is necessary to apply several thousand volts, in order to get even 10 milliamperes of current. This voltage necessary to overcome the space charge, is completely lost when the tube is used as a rectifier.

To overcome this loss of voltage as far as possible, the anode and cathode in the kenotron are placed close together, and everything is avoided which might tend to screen the cathode from the field naturally produced by the anode. In this way it has been possible to build kenotrons which have supplied pure electron currents of over an ampere, with a voltage drop of about 200 volts. This current, however, requires large anodes and cathodes, so that it is usually more convenient to build kenotrons with a current capacity of not over 250 milliamperes, and if it is desired to rectify larger currents than this, to place several kenotrons in parallel.

There seems to be no upper limit to the voltage at which a kenotron can operate. A kenotron has been built capable of rectifying 250 milliamperes at 180,000 volts, and there seems to be every reason to think that kenotrons could be used at very much higher potentials if desired.

The design and the characteristics of kenotrons has recently been described in a paper by Dr. Dushman (General Electric

Review, Vol. 18, p. 156, 1915), and I will therefore only briefly describe these devices.

Figure 2 gives the characteristics of a typical kenotron designed for rather large currents. The curves show the current carried by the kenotron for different filament temperatures at given voltages between the electrodes. For example, if the temperature of the filament is 2,400 degrees the maximum current that can be obtained with any voltage is about 112 milliamperes. If, however, the resistance of the load is able to hold the current down to a value of say 54 milliamperes, then we see from the curves that the voltage drop in the kenotron would be 75.5 volts. The remaining voltage, which may be many thousands of volts, is consumed in the load in series with the kenotron.

Figures 3 and 4 illustrate two forms of kenotrons, one for voltages up to about 10,000, and the other one suitable for use up to 50,000 volts. With voltages higher than about 12,000 to 15,000 volts, the kenotron of the type shown in Figure 3 is apt to fail, because the electrostatic attraction of the anode pulls out the helically wound filament and short circuits the device. At the higher voltages, therefore, it is necessary to support the filament and to balance, as far as possible, the electrostatic forces acting on it.

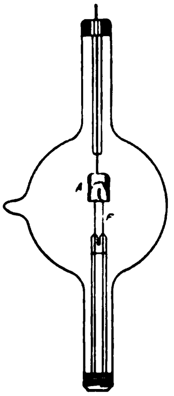


FIGURE 3—Molybdenum Cap Type of Kenotron

The characteristics of the kenotron are such that the current flowing thru it is always perfectly stable, so that several kenotrons can be run in parallel and each one will take its proper share of the current. This is in marked contrast with the behavior of mercury arc rectifiers, which have negative characteristics and therefore, if several are placed in parallel, one of them takes the whole of the current.

Owing to the absence of gas effects, the kenotron is a perfect rectifier, in that no measurable current flows in the reverse direction, even when voltages of 100,000 volts or more are applied. For similar reasons, it is capable of rectifying radio frequency currents, as well as audio frequency, there being not the slightest sign of any lag effects.

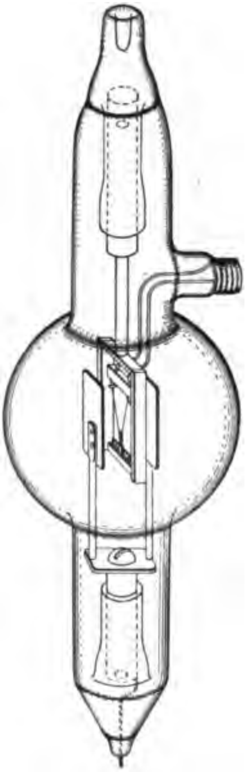


FIGURE 4—Kenotron with Filament Between Two Parallel Plates

AMPLIFYING OR CONTROLLING DEVICES: PLIOTRONS

In a pure electron discharge, as the temperature of the filament is raised, a point is always reached where the current becomes limited by the space charged between the electrodes. Under these conditions, only a small fraction of the electrons escaping from the cathode reach the anode, whereas the majority of them are repelled by the electrons in the space and therefore return to and are absorbed by the cathode. From this viewpoint it is evident that if a negatively charged body is brought into the space between the anode and cathode, the number of electrons which then return to the cathode will increase, so that the current to the anode will decrease. On the other hand, if a positively charged body is brought near the cathode, it will largely neutralize the negative charges on the electrons in the space and will therefore allow a larger current to flow from the cathode. In this way it is possible to control the current flowing between anode and cathode by an electrostatic potential on any body placed in proximity to the two electrodes. This controlling effect may be best attained by having this controlling member in the form of a fine wire mesh, or grid, placed between the electrodes.

The term "pliotron" has been adopted to designate a kenotron in which a third electrode has been added for the purpose of controlling the current flowing between the anode and cathode. This word is derived from the Greek "*pleion*" signifying "more." A pliotron is thus an "instrument for giving more" or an amplifier. A similar use of the prefix "plio" occurs in the geological term "pliocene."

The three elements, hot filament cathode, grid, and anode, are, of course, similar to the elements of the de Forest audion. However, the operation of the audion is in many ways quite different from that of the pure electron device operating in the way I have described above.

In the audion, as in the Lieben-Reisz relay, the amplifying action appears to be largely dependent on gas ionization, even when the device operates well below the point at which blue glow occurs. The action is probably somewhat as follows. There is normally present a small amount of gas ionization, due to the passage of the electrons between cathode and anode. The presence of the positive ions partly neutralizes the space charge which limits the current flowing between the electrodes. If a small positive potential is applied to the grid, the velocity of the electrons passing by it is somewhat increased, and they therefore produce more ions in the gas. Besides this, as the potential on the grid is increased, the number of electrons passing the grid is increased, and this again tends to increase the amount of ionization. A very slight increase in the amount of ionization brought about in this way very greatly reduces the space charge, and therefore largely increases the current that can flow between the electrodes. In this way, with a given construction of grid, filament, and plate, the relaying action may be very greatly increased beyond that which would occur if no gas were present. The amount of gas ionization which is necessary, in order to eliminate practically completely the effects of space charge, is often much too small to produce a visible glow in the gas.

If too much gas is present, or if the potential on the plate or the current flowing to the plate is too large, then the amount of positive ionization may reach such values as to neutralize almost entirely the space charge and thus allow a large current to flow. Under these conditions, the relaying action of the audion is lost. This is the case, for example, when the audion gives a blue glow. In the border land between these two conditions, there is a region of instability in which the sensitiveness of the audion may be enormously great, but it is usually not found very practicable to operate the device in this region because of the difficulties in maintaining adjustment, for any lack of adjustment may cause the audion to go over into a condition of blue glow.

The audion is often used with a condenser in series with the grid. Under these conditions, the audion requires the presence of a certain amount of gas ionization so that the positive ions formed may prevent the accumulation of too large a negative potential on the grid. With the pliotron, owing to the absence of positive ions, if it is desired to use a condenser in series with the grid, this condenser must be shunted by a high resistance and often a source of potential must be placed in series with the high resistance, in order to supply positive electricity to the grid as rapidly as this tends to be taken up from the electrons given off by the filament.

CONSTRUCTION OF PLIOTRONS

In the construction of pliotrons, it has been found desirable to make the wires constituting the grid of as small cross-section as possible. In this way, even when a positive potential is applied to the grid, the current that flows to the grid may be made extremely small. The use of very fine wire is made possible by using a frame of glass, metal, or other suitable material, to support the grid. Thus, in Figures 5 and 6, the filament is mounted in the center of a frame made of glass rods, on which the fine grid wire is wound by means of a lathe. The grid may thus consist of tungsten wires of a diameter as small as 0.01 millimeter and these may be spaced as close as 100 turns per centimeter, or even more.

In Figures 5 and 6 are shown two types of pliotron. Figure 5 shows a pliotron such as is used for amplifying radio signals in a receiving station. Figure 6 shows a large pliotron which may be used for controlling as much as 1 kilowatt of energy for radio telephony.

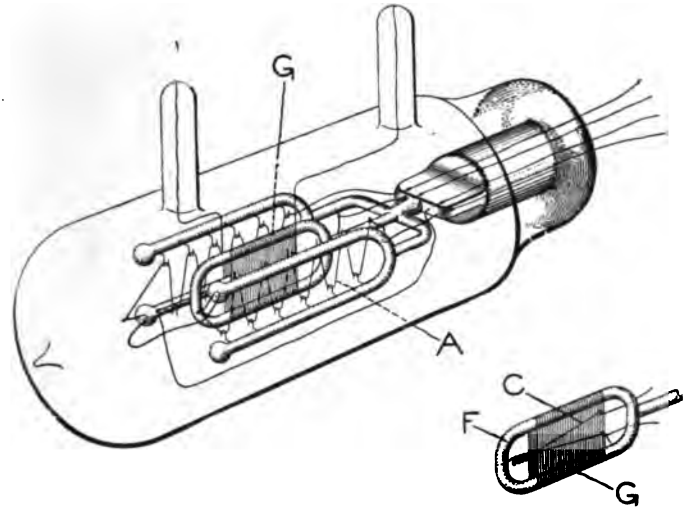


Figure 5—Small Pliotron

The characteristics of the pliotron depend upon the length of filament used, the distance between filament and grid, spacing between the grid wires, diameter of the grid wires, the distance between grid and anode, and the size and shape of the anode. The important elements in the characteristics of a pliotron are:

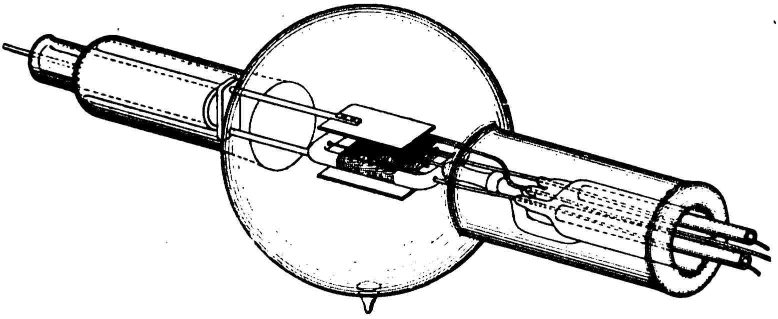


Figure 6—Large Pliotron

first, the relation between the current flowing between anode and cathode as a function of the potential on the anode and of that on the grid; second, the current flowing to the grid, as a function of the potential of the grid and the potential of the anode.

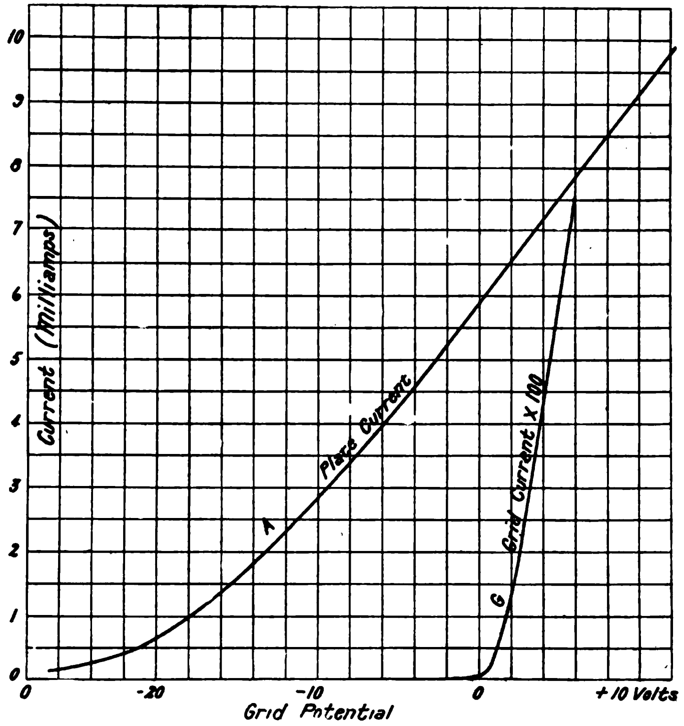


FIGURE 7—Characteristics of Small Pliotron

Figure 7 gives the characteristics of a small pliotron such as that shown in Figure 5. Curve A gives the current flowing to the anode for different grid potentials, while the potential of the anode is maintained constant at 220 volts. Curve G gives the current flowing to the grid under the same conditions. For different anode potentials, these curves are shifted vertically, by amounts proportional to the change in anode potential. In fact, it is found that these curves can be represented with fair approximation by a function of the form

$$i = A\,(V_a + k\,V_g)^{\frac{3}{2}}$$

where i is the current flowing to the anode, V_a is the voltage on the anode, V_g the voltage on the grid, and k the constant which depends on the relative shapes and positions of the electrodes.

Figure 8 gives similar characteristics for a large pliotron like that shown in Figure 6. In this case, the anode potential was 8,500 volts. Since the grid is at a negative potential, no perceptible current flows in the grid circuit.

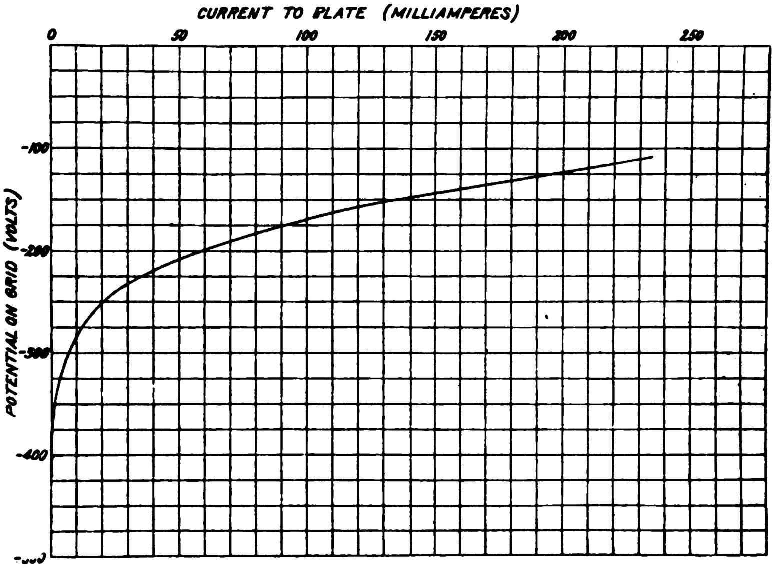


FIGURE 8—Characteristics of Large Pliotron

By using a fine grid, the current to the anode can be stopped entirely by even a very slight negative potential on the grid. On the other hand, a rather low positive potential will then be sufficient to draw a large current to the anode. The amount of current taken by the grid would be only a very small fraction of that flowing to the anode, in case the diameter of the grid wires is small compared to the distance between them. On the other hand, with a coarse grid, that is, a grid in which the spacing is large, a rather large negative potential may be necessary, in order to stop the current flowing to the anode. Similar results to those obtained by changing the spacing of the anode, may be obtained by changing the relative distances between the electrodes. The effects produced in this way may be expressed approximately by means of the constant k in the above equation; the effect of fine spacing thus being to increase the value of k, while coarse spacing decreases it.

By using a fairly coarse grid, consisting of fine wire, it is possible to obtain a control of the current to the anode, always using a negative potential on the grid. Under these conditions, since there are no positive ions present, no current flows to the grid, except that necessary to charge it electrostatically to the required potential. It thus becomes possible to control very large amounts of energy in the anode circuit, by means of extremely minute quantities of energy in the grid circuit.

There does not seem to be any upper limit to the voltages that may be used in the pliotrons. With voltages over 30,000 volts, it is often necessary to space the electrodes further apart and to use heavier wires for the grid, in order to reduce the danger of breakage of the parts by the large electrostatic forces which then occur.

The current carrying capacity of the pliotron is limited only by the size of cathodes that it is found convenient to use and by the voltage available. Large currents cannot be readily obtained with low voltages because of the space charge effect described previously. With voltages above 500 volts, however, it is found practicable to use currents of 300 or 400 milliamperes for a pliotron of the type shown in Figure 6. With high potentials, there is no difficulty in using currents as large as this, provided the energy is consumed in some device in series with the pliotron. On the other hand, if the full voltage is applied to the anode while the current is flowing to the anode, the energy liberated in the form of heat may be so great as to volatilize the anode or cause it to radiate so much heat that the glass parts of the apparatus are softened. In a pliotron with a 5-inch (12.7 cm.) bulb the amount of energy that may be so consumed within the pliotron is about 1 kilowatt. Still larger amounts of power may be dissipated if the bulb is immersed in oil and if the grid frame is made of quartz, or other heat resisting material.

It is evident from the characteristics of the pliotron that any number of these devices may be placed in parallel and that in this way, very large amounts of power may be controlled.

PLIOTRONS IN A RADIO RECEIVING STATION

PLIOTRON AS A DETECTOR

If the antenna of a receiving set is coupled directly to the grid of a pliotron and a telephone receiver is placed in series with the anode, signals may be readily detected, but the results obtained in this way are usually very poor. Under these conditions, the sensitiveness of the arrangement is proportional to the curvature of the curve A, Figure 7 (or, more accurately, proportional to the second derivative of the anode current with respect to the grid potential). This curvature may be somewhat increased by applying a negative potential to the grid, but even under these conditions the sensitiveness of the arrangement is usually not very high.

If it is attempted to use a condenser in series with the grid and thus use the pliotron in the way that the audion is often used (as described, for example, by Armstrong, "Electrical World," December 12, 1914; also this issue of the PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS), it is found necessary to shunt the condenser with the resistance and often to place a battery of a few volts in series with the resistance, in order to prevent a large negative charge from accumulating on the grid.

It has been found, however, by Mr. White, that a very minute trace of certain gases may very greatly increase the sensitiveness of this device as a detector. For example, by placing within the bulb a small quantity of an amalgam of mercury and silver, the characteristics of the tube show a kink, as indicated in Figure 9. With a detector of this sort, if the grid potential is adjusted so that its average value is approximately that at which the kink occurs, there is a very marked increase in sensitiveness. This is due to the fact that under these conditions either an increase or a decrease in the grid potential causes a decrease in the anode current. The sensitiveness of this detector is then very high. The quantities of mercury vapor necessary to give this effect are so low that anode voltages of 200 volts or more may be used without any indication of glow discharge.

PLIOTRON AS AMPLIFIER

The value of a pliotron as an amplifier is dependent primarily on the slope of the curve between anode current and grid potential; for example, curve A, Figure 7. A second factor of importance is the magnitude of the current taken by the grid. In order to get the greatest amplifying effect it is desirable to have this current as low as possible. In a pliotron of the type shown in Figure 5, the current to the anode increases at the rate of about 1 milliampere per volt change in the grid potential.

By using larger anode potentials, the slope of the curve can be made very much greater, since it becomes possible to use grids of finer mesh. For example, in Figure 8 it is seen that the slope of the curve corresponds to about 1.9 milliamperes increase in anode current per volt change in grid potentials.

It has been found that there is no sluggishness in the characteristics of the pliotron, even at the highest frequencies.

By connecting the pliotron as an amplifier, as shown in Figure 10, the high frequency currents received from the grid may be amplified from 100- to 600-fold. In this arrangement, it is the high frequency or radio frequency that is amplified, and not the audio frequency. This amplification of the radio frequency possesses the marked advantage that the detector circuit may be tuned to the same frequency as the amplifier

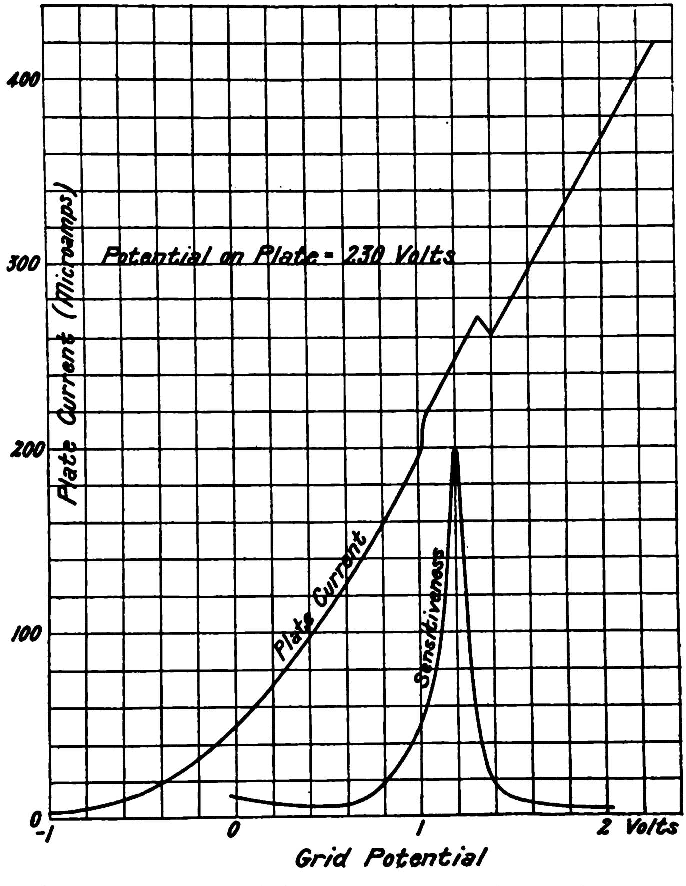


Figure 9—Characteristics of Detector Containing a Trace of Mercury Vapor

circuit, and in this way a very marked increase in selectivity is obtained. In fact, it has been shown by Mr. Alexanderson that the resonance curve of an outfit consisting of amplifier and detector, both tuned to the radio frequency as shown in Figure 10, may be obtained from the resonance curve for the detector alone, by squaring the ordinates. For example, if with a single detector, the signals from one station (*A*) are received 100 times as strongly as those from another station (*B*), then, with the above arrangement with the amplifier, the signals from *A* will be received 100 times more strongly, or 10,000 times as strong as those from station *B*. If two amplifiers be used in this way, the signals from station *A* could be obtained 1,000,000 (or 100^3) times as strong as those from station *B*.

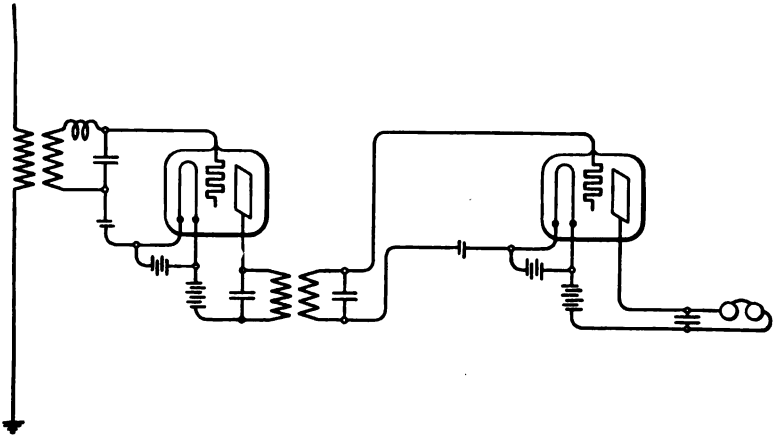


FIGURE 10—Arrangement of Two Pliotrons In Cascade, Employing "Tuning In Geometrical Progression"

In practice, this arrangement has been found to give a wonderfully high degree of selectivity.

Of course, a pliotron may also be used for amplifying the audio frequency, coupling the circuits together by means of an iron core transformer. A single pliotron, under these conditions, gives an amplification of current of several hundred-fold, when voltages of from 100 to 200 volts are used on the anode.

PLIOTRON AS OSCILLATOR

By placing inductance and capacity in the grid and plate circuits and coupling these two circuits together, it is possible to use the pliotron as a source of continuous oscillations. Small pliotrons of the type shown in Figure 5 may produce oscillations of a power up to a few watts, and these may be used in a receiving station, according to the heterodyne principle, for receiving continuous oscillations. One pliotron may be used both for amplifying or detecting, and for producing oscillations.

With the larger pliotrons, using voltages of a few thousand volts, up to a kilowatt of radio frequency oscillations may readily be produced by a single tube.

USE OF THE PLIOTRON IN RADIO TELEPHONY

By means of a single large pliotron, it has been found possible to control about 2 kilowatts of energy in an antenna by means of the currents obtained from an ordinary telephone transmitter. There are many arrangements by which this may be accomplished. For example, a 2 kilowatt Alexanderson alternator (100,000 cycles) may be loosely coupled to the antenna and the anode of the pliotron may be connected to a point on the antenna where the potential is normally high. So long as the potential on the grid of the pliotron is strongly negative, no current flows to the pliotron and therefore the full energy is radiated by the antenna. If, however, the negative potential on the grid is decreased, a sufficient current may be drawn from the antenna strongly to damp the oscillations and thus greatly to decrease the energy radiated. With sufficiently high potential on the grid, practically the whole of the energy may be diverted from the antenna.

It is thus possible to control the output of the antenna by varying the negative potential on the grid of the pliotron. Since the grid is always negative, no current flows between filament and grid, and therefore practically no energy, is required to maintain the charge on the grid. In this way, therefore, by connecting the secondary of a transformer between the grid and filament, and placing the primary of the transformer in series with a telephone transmitter, it is possible by means of the variations in the currents from the telephone transmitter to obtain potentials on the grid of several hundred volts and thus to control the output of the antenna.

Instead of using an arc or alternator as a source of radio frequency current, the pliotron may also be used as a generator of the oscillations. One pliotron may be used both for producing the oscillations and for controlling the amplitude of the oscillations, in accordance with the variation of pitch and amplitude of the sound waves acting on the telephone transmitter. It is usually preferable, however, to use a large pliotron for producing the oscillations, and to connect a small pliotron in the grid circuit of the large pliotron for controlling the output of the latter.

With the above arrangement an extremely simple and efficient radio telephone outfit can be made. Since the pliotron for producing oscillations requires comparatively high direct current voltages, it has been found convenient to combine the pliotron oscillator with a kenotron rectifier. Two types of apparatus of this type have been in use a considerable time, and it will be of interest to describe these in some detail.

In the first outfit, which is a small outfit having a capacity of about 20 watts in the antenna, the source of power is the local city supply, which is 118 volts, 60 cycle alternating current. This is connected with the primary of a small transformer, having two secondary windings. One of the secondaries is designed to give about 5 volts and furnishes the current used for heating the filaments of the kenotrons and pliotrons. The other secondary of the transformer is wound to furnish a potential of about 800 volts. This is rectified by means of a kenotron and serves to charge a condenser of about 6 microfarads. In this way a source of high voltage, direct current is obtained in a very simple manner. The plate of the pliotron oscillator is then connected to one of the terminals of the condenser, while the filament is connected to the other. The plate of the second pliotron is connected to the grid of the first, while the grid of the second is coupled by means of a second small transformer to the microphone circuit. With this small outfit, both pliotrons may be relatively small, and in order to obtain an energy of about 20 watts in the antenna, it is found that the current drawn from the condenser is so small that the potential supplied by it does not vary sufficiently to be audible in the signals sent out by this outfit. The different parts of this apparatus may be made very compact and no adjustments are found necessary in operating the system unless it is desired to change the wave length. In this case, it is only necessary to change the inductance or capacity.

In the second outfit, which is suitable for use up to 500 watts or more, the high voltage direct current is obtained from a small, 2,000 cycle generator. The current from this is transformed up to about 5,000 volts, rectified by kenotrons, and smoothed out by means of condensers. By the use of 2,000 cycle alternating current instead of 60 cycle, it is possible to store up large quantities of energy and thus obtain as much as a kilowatt or more of power in the form of direct current with condensers of moderate size. This high voltage direct current is then used, as before, to operate a pliotron oscillator, the output of which is controlled by means of a small pliotron connected to the telephone transmitter.

By means of this system of control the amount of energy in the telephone transmitter circuit need be no larger than that commonly used in standard telephone circuits. It has thus been found possible to connect up this radio telephone outfit with the regular telephone lines so that conversation may be carried on between two people, both of whom are connected with the radio stations by means of the regular land lines. It has also been found possible to communicate both ways over these lines.

SUMMARY: The thermionic current produced by the emission of free negative electrons from the surface of heated metals is described in detail. Its theoretical magnitude is calculated for certain definite cases. The limitation of thermionic currents by space charges around the cathode (in high vacua) is explained. In reviewing the bibliography of the subject, it is shown that the preponderance of opinion before the most recent and careful experiments was to the effect the thermionic currents could not be obtained in a pure vacuum. The incorrectness of this conclusion is experimentally proven. The degree of cleanliness of the electrodes and the completeness of exhaustion required to produce these thermionic currents in regular fashion is unusual. With true thermionic currents, the cathode does not disintegrate, and there is no blue glow in the path of the cathode rays even at the highest voltages. An X-ray tube using thermionic currents is described. A rectifier for high voltage alternating current ("kenotron") is considered, its operating characteristics being given. By inserting a third fine wire grid electrode in a kenotron, an amplifying device ("pliotron") is obtained. Its theory, construction and characteristics are given. Its use in radio receiving stations as a detector or amplifier is described. The "exponential" method of tuning, involving the use of radio frequency pliotron amplifiers in cascade, is shown to have given remarkable selectivity. The pliotron may also be used as a powerful generator of radio frequency energy; or for the modulation or control of such energy. A 20-watt radio telephone transmitter, and a 500-watt radio telephone outfit are each described in detail.

DISCUSSION

Alfred N. Goldsmith: The material presented by Dr. Langmuir to the Institute of Radio Engineers constitutes one of the important contributions to the knowledge of thermionic phenomena in high vacua which have been worked out in the Schenectady laboratory. It may be that certain facts presented in the earlier papers will be of interest.

In a paper by Coolidge (Phys. Rev., December, 1913, page 409) the usual defects of X-ray tubes are given. They apply, in general, to tubes in which cathode rays pass. They are a gradual increase in the vacuum as the tube is operated, rapid and erratic changes in the pressure, heating of the electrodes with consequent evolution of gas, deposition of the electrode metal on the tube, the difficulty of obtaining satisfactory pressure regulators, and the dissimilar characteristics of two apparently identical tubes. If, however, the tube be exhausted to a pressure less than 0.000,03 millimeter (and certain other conditions are fulfilled), the above defects can be eliminated. Coolidge used for the cathode a spiral of thin tungsten wire electrically welded to molybdenum supports. The molybdenum was sealed in the tube using a special glass having the same coefficient of expansion. The remainder of the tube was of a German glass. The tungsten filament was heated by a storage battery, well insulated from the ground. Before exhausting the tube, the electrodes were fired in a tungsten vacuum furnace. This latter was a tungsten tube 1 inch (2.5 cm.) inside diameter and 12 inches (30 cm.) long. This was placed in a water cooled metal cylinder and exhausted to a few thousandths of a millimeter pressure. The tungsten tube was then connected to a 100 kilowatt transformer. For exhausting the tube, a Gaede molecular pump was used, connected to the tube thru a short large piece of tubing. During exhaustion, the tube was heated to about 470° C. At the same time, heavy high voltage discharges were passed thru the tube. This procedure was continued for several days. A liquid air trap was used between the Gaede pump and the tube to condense vapors. In the last stages of the exhaustion, very heavy discharge currents were passed thru the tube which was air cooled by the use of a fan.

Inasmuch as sufficiently low pressures to obtain the effects Dr. Langmuir describes can hardly be obtained without the use of a molecular pump, a brief description of this latter is not out of place. This pump is not of the piston type (which cannot pump out vapors) but depends on gas friction. In the figure, the rotating disc is shown. As a consequence of its rotation, the difference of pressures on the two sides will be constant; that is, $p_1 - p_2$ = constant. The constant is proportional to the speed of rotation of the disc and the internal friction of the gas. This latter has been shown to be constant at all pressures by Maxwell (theoretically). It will be seen that starting at a small pressure, it is theoretically possible to reach an absolute zero of pressure. Actually this cannot be realized since at very low pressures not $(p_1 - p_2)$ but $p_1 \div p_2$ is a constant. It is obvious that an auxiliary pump must be used to begin with. In practice, the peripheral velocity of the disc is high, namely not far from the molecular velocity. The disc rotates at 8,000 to 12,000 R. P. M. With pumps of this type, a 6 liter container can be exhausted to a pressure of 0.000,002 millimeter in 4 minutes.

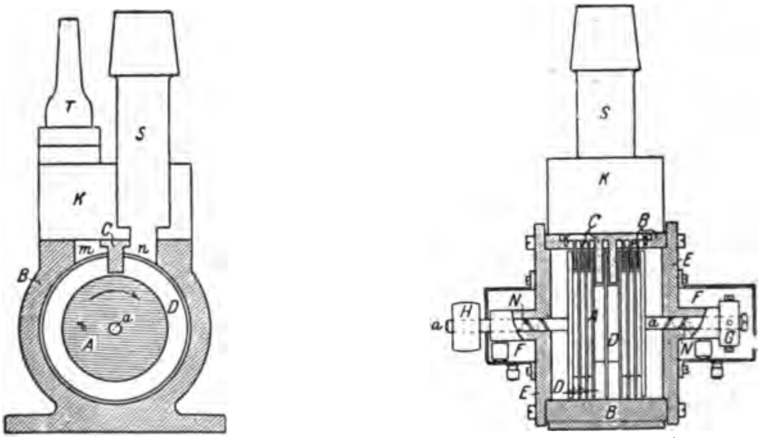


FIGURE 1

Dr. Langmuir has worked out an ingenious pressure gauge for very low pressures based on similar principles. (Phys. Rev., April, 1913, page 337, also S. Dushman, Phys. Rev., March, 1915, page 212.) Inside the gauge is placed a thin aluminum disc attached to a steel or tungsten shaft and carrying a magnetic needle, shown in Figures 2 and 3 (from the "Physical Review"). Outside the tube, but in the plane of the needle, is a Gramme ring which is supplied with current cyclically at six points by means of a motor-driven commutator. The aluminum disc is therefore caused to rotate rapidly. Above it is suspended a very thin mica disc, hanging on a quartz fiber which carries a small mirror. The gas drag resulting from the rotation of the lower disc twists the upper disc thru an angle which is proportional to the pressure of the gas, the number of R. P. M. of the lower disc, and the square root of the molecular weight of the gas. It is, however, practically independent of the distance between the discs. This gauge is of use at pressures below 0.01 millimeter. Its sensitiveness is high. A light beam reflected from the mirror moves 1 millimeter on a scale 60 centimeters (2 feet) away, when the lower disc rotates at 10,000 R. P. M. and the pressure is 0.000,000,25 millimeters.

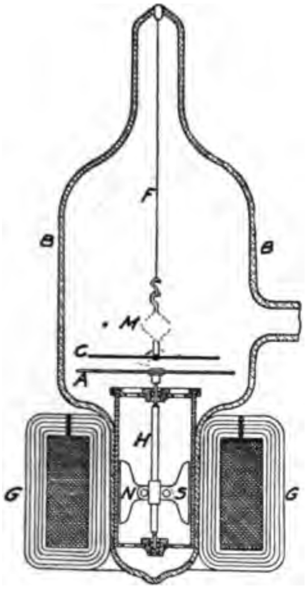


FIGURE 2

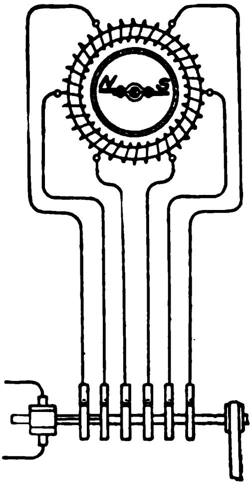


FIGURE 3

In another paper Dr. Langmuir (Phys. Rev., December, 1913, page 450) draws certain important conclusions as to the methods and degree of exhaustion of tubes which are to show pure and reproducible thermionic currents. They are,

1. An extremely high vacuum is necessary: less than 0.000,1 millimeter. No oxygen, water vapor, carbon dioxide or hydrocarbons may be present. During exhaustion all glass parts must be immersed in liquid air, or be heated to 360° C., for an hour or more.

2. Large anodes are to be avoided. The anode should be heated to 2,000° C. or more *in vacuo*, or else a heavy high voltage discharge should be passed to it during exhaustion. In passing this discharge, the pressure should be so low that no glow is seen (except possibly when inert gases only are present). The electrodes are preferably tungsten which has been heated to 2,500° for 10 minutes in the apparatus.

3. By properly placing the electrodes, the space charge (which limits the thermionic currents) may be kept small. If a cylindrical anode is used, it should be charged to several thousand volts and the filament temperature raised until the thermionic current is 50 to 200 milliamperes.

Dr. Saul Dushman has also given some valuable data in relation to the construction of such tubes (Phys. Rev., August, 1914). In his work, tubes with molybdenum anodes were used. Platinum leading-in wires were employed. From the vacuum tube, a large bore glass tube ran to the liquid air trap, and thence to the Gaede molecular pump, which latter was connected to a "box" pump connected to a 1 centimeter "rough" vacuum line. A McLeod gauge was placed between the molecular and box pumps. There was also an outlet whereby air dried by passage over phosphorus pentoxid could be admitted to the apparatus. During the exhaustion, an electric oven kept the tube at a temperature of 350 degrees. It was at a temperature of more than 300 degrees for at least an hour. The vacuum was certainly less than 0.000,000,2 millimeter. The electrodes were freed from occluded gases and volatile oxids by applying an alternating electromotive force of from 1,000 to 5,000 volts, the thermionic current being 50 to 200 milliamperes. The temperature of the anode was 1,000° C. or more. The blue glow gradually disappeared, and the thermionic currents increased. When the anode was finally brought to a white heat, the high voltage discharge was stopped. The temperature of the tungsten cathode was calculated from the following formula, where T is the temperature (in degrees Kelvin), and H is the intrinsic brilliancy of the filament in international candles per square centimeter of projected area:

$$T = \frac{11{,}230}{7.029 - \log_{10} H}$$

In a recent article (*"General Electric Review"*, March, 1915), Dr. Dushman gives the details of the design of the kenotron. In particular, the important questions of proportioning the electrodes to the current-carrying capacity, of keeping the internal loss in the kenotron low, and of preventing excessive electrostatic strain on the electrodes are considered.

Passing to the question of the advantage of the kenotron over the mercury arc rectifier in that several of the former may be safely operated in parallel, the criterion for such stable operation is easily expressed. If i is the current passing thru a kenotron, a small change in terminal voltage e must cause a change of the same sign in i.

That is, $$\frac{di}{de} > 0.$$

But for the kenotron, it has been shown that

$$i = k e^{3/2}$$

where k is a constant. Therefore,

$$\frac{di}{de} = \frac{3k}{2} e^{1/2} > 0.$$

Also, it can be similarly shown that if two or more kenotrons are operated in parallel, a small change in terminal voltage of all of them will produce changes of current in each of them proportional only to the corresponding constant k of each kenotron.

By reference to Figure 7 of the paper, it will be seen that the amplification produced by the small pliotron even when the grid is at a positive potential is considerable. Thus a change of grid potential from $+2$ to $+4$ volts causes in a change of power in the grid circuit of $1.46(10)^{-4}$ watts, but as a result there is a change of power of $1.4(10)^{-1}$ watts in the plate circuit. The amplification is therefore roughly 1,000. At lower grid potentials, and especially at negative grid potentials, this must be enormously increased; and especially at lower frequencies.

Lee de Forest: Naturally Dr. Langmuir's paper is to me one of the most interesting ever presented before the Institute. It is a tribute to the exhaustive thoroness and scientific care with which such a resourceful corporation as the General Electric Company can attack any problem in which it may become interested.

Philologists, fully as much as physicists or radio engineers, are indebted to Drs. Langmuir and Dushman for coining two fresh new words to add to our modern Greek mythology, along with such contributions as "Cymoscope," "Cymometer," etc.

That the two devices thus designated possess a novelty of nomenclature no one can deny. As to just wherein the "Kenotron" differs in principle from the Edison-Wehnelt-Fleming "vacuum valves," or the "Pliotron" from the audion amplifier and oscillating audion is a somewhat more debatable question.

It is certainly not self-evident that when a large audion is exhausted to a higher degree of vacuum than heretofore, so that conductivity by means of gas carriers enters less and that by thermions enters more into phenomena otherwise identical, long ago discovered, and thoroly characteristic—it becomes (except by an ingenious name) a new device.

Increased utility naturally follows upon enlarged dimensions, increased life, and ability to transform larger amounts of power.

I believe, however, that Dr. Langmuir has, by working into these extremely high vacua and the high potentials necessitated thereby, pursued the less promising of two paths of research.

It is well to remember in this connection that to-day arc generators developing 75 kilowatts of radio energy are in operation on voltages of less than 1,000 volts.

An arrangement for controlling the amplitudes of radiated waves by means of an audion side-path to earth, the latter in turn controlled by a microphone, was used by myself as early as 1909. It was found that, with the amount of power I was then experimenting with, the complication of circuits and necessary additional apparatus involved, rendered this method less advantageous than the simple microphone-in-earth-lead connection.

Where however large powers are to be voice-controlled an arrangement operating on this principle offers certain important advantages.

Sewall Cabot: I should like to ask Dr. Langmuir to give us some idea as to the constancy of adjustment in using the pliotron as a receiver. In using the audion we have had much trouble in obtaining and holding the voltage at the anode at its proper value, and in keeping the temperature of the filament steady. The pliotron, having no gas in it, and using higher potentials would seem to be a more constant device.

Irving Langmuir: The most advantageous feature of the pliotron seems to be its constancy. Even the form using a slight amount of mercury vapor is extremely constant in action. The anode voltage may be increased from 70 volts to more than 200 or 300, and as the voltage is increased, the sensitiveness of the device gradually rises. We have had no difficulty whatever in receiving signals using the regular city supply line to supply the plate or anode voltage. This cannot be done with the audion which is too sensitive to slight changes in the voltage of that circuit. The slight fluctuations which occur in the voltage of the city supply line cause, however, no effect at all in the pliotron.

In order to get the greatest sensitiveness in the use of this detector, the potential of the grid is so adjusted that we work on the flat part of the current-voltage curve, thus rendering it possible greatly to increase the current by a slight change in the grid voltage. In fact, the pliotron is always used by us in such a way that most of the electrons emitted from the filament return to the filament when no signals are coming in.

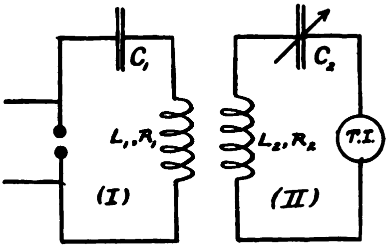
A DERIVATION OF THE BJERKNES LOGARITHMIC DECREMENT FORMULA

By

Louis Cohen

It is the purpose of this paper to present a new derivation of the well-known Bjerknes logarithmic decrement formula. The author believes that the method and the mathematical treatment of the problem as given here is simpler and easier to follow than the original work of Bjerknes; and it may therefore be of interest to radio engineers.

The Bjerknes method consists essentially in coupling loosely an oscillatory circuit, which includes also a thermo-indicating instrument, to the exciting circuit, and noting the readings on the instrument in the oscillatory circuit when that circuit is exactly in resonance with the exciting circuit, and when it is slightly off resonance. The arrangement of circuits is shown schematically in the accompanying diagram; we denote the exciting circuit by (I) and the resonance circuit by (II). If the coupling is very weak, the current induced in circuit (II) is small, and its inductive reaction on circuit (I) is negligible. In that case we may consider that circuit (I) acts merely as a source of e. m. f. for circuit (II) thru the mutual inductance between them. The e.m.f. induced in circuit (II) is of the same frequency and the same damping as the current in circuit (I), and we have then



the following differential equation for the e.m.f.'s acting in circuit (II):*

$$L_2 \frac{dI}{dt} + R_2 I + \frac{1}{C_2}\int I_2\, dt = E\, \varepsilon^{(j\omega_1 - a_1)t} \qquad (1)$$

where $\omega_1 = \frac{1}{\sqrt{L_1 C_1}}$, and $a_1 = \frac{R_1}{2 L_1}$;

the frequency constant and damping factor of circuit (I).

The e. m. f. acting on circuit (II) generates a current in it of the same frequency and the same damping as that of the e. m. f. In addition to this, however, we also have a transient current in circuit (II), which is due to the fact that an inductive circuit does not respond instantly to the impressed e. m. f.; it requires a certain time interval before the permanent condition is established. Since, however, in this case the e. m. f. acting on circuit (II) is itself intermittent, when a spark discharge is used, for instance, in circuit (I), the permanent condition is never reached. The transient current comes into play every time the e. m. f. begins to act on circuit (II), which means at every spark discharge in circuit (I). The transient current in circuit (II) is also of a damped oscillatory character.

We have then for the total current in circuit (II),

$$I = I_1 + I_2, \qquad (2)$$

where I_1 may be considered as the forced current, and I_2 the transient or free oscillatory current.

Since I_1 is of the same frequency and the same damping as the impressed e. m. f., we have

$$I_1 \propto \varepsilon^{(j\omega_1 - a_1)t} \text{ and}$$

$$\frac{dI_1}{dt} = (j\,\omega_1 - a_1)\, I_1, \quad \int I_1\, dt = \frac{1}{j\,\omega_1 - a_1} I_1.$$

---

*(Radio engineers are reminded of de Moivre's theorem; namely $\varepsilon^{j\theta} = \cos\theta + j\sin\theta$, where $j = \sqrt{-1}$. As a matter of symbolic notation, and for ease of mathematical manipulation, $\varepsilon^{j\theta}$ is carried thru all calculations, the understanding being that only its real part, $\cos\theta$ shall be retained in the final results.

Remembering this convention, the right hand member of equation (1) becomes

$$E\,\varepsilon^{j\omega_1 t}\varepsilon^{-a_1 t} = E\,\varepsilon^{-a_1 t}(\cos\omega_1 t + j\sin\omega_1 t).$$

Passing to the real part, this stands for

$$E\,\varepsilon^{-a_1 t}\cos\omega_1 t.$$

This is merely the mathematical expression for the statement directly preceding equation (1) in the text.—EDITOR.)

Equation (1) may therefore be written in the following form:

$$\left\{L_2 (j\,\omega_1 - \alpha_1) + R_2 + \frac{1}{C_2 (j\,\omega_1 - \alpha_1)}\right\} I_1 = E\varepsilon^{(j\,\omega_1 - \alpha_1)\,t},$$

and

$$I_1 = \frac{E\,\varepsilon^{(j\,\omega_1 - \alpha_1)\,t}}{L_2 (j\,\omega_1 - \alpha_1) + R_2 + \dfrac{1}{C_2 (j\,\omega_1 - \alpha_1)}}. \qquad (3)$$

Putting $\alpha_2 = \frac{R_2}{2\,L_2}$, and $\omega_2^2 + \alpha_2^2 = \frac{1}{L_2 C_2}$, and rearranging, equation (3) takes the form

$$I_1 = \frac{E\,(j\,\omega_1 - \alpha_1)\,\varepsilon^{(j\,\omega_1 - \alpha_1)\,t}}{L_2 \left\{\omega_2^2 - \omega_1^2 + (\alpha_2 - \alpha_1)^2 + 2\,j\,\omega_1 (\alpha_2 - \alpha_1)\right\}}. \qquad (4)$$

The potential across the condenser C_2 due to charging current I_1 is,

$$V_1 = \frac{1}{C_2}\int I_2\,d\,t = \frac{E\,\varepsilon^{(j\,\omega_1 - \alpha_1)\,t}}{L_2 C_2 \left\{\omega_2^2 - \omega_1^2 + (\alpha_2 - \alpha_1)^2 + 2\,j\,(\alpha_2 - \alpha_1)\right\}}. \qquad (5)$$

Taking only the real parts of I_1 and V_1 we have*

$$I_1 = K\sqrt{\omega_1^2 + \alpha_1^2}\,\varepsilon^{-\alpha_1 t} \cos(\omega_1 t + \phi + \psi), \qquad (6)$$

$$V_1 = \frac{K}{C_2}\,\varepsilon^{-\alpha_1 t} \sin(\omega_1\,t + \phi), \qquad (7)$$

$$\left.\begin{aligned} \text{where } K &= \frac{E}{L_2 \sqrt{\left\{\omega_2^2 - \omega_1^2 + (\alpha_2 - \alpha_1)^2\right\}^2 + 4\,\omega_1^2 (\alpha_2 - \alpha_1)^2}}, \\ \tan\phi &= \frac{\omega_2^2 - \omega_1^2 + (\alpha_2 - \alpha_1)^2}{2\,\omega_1 (\alpha_2 - \alpha_1)}, \\ \tan\psi &= \frac{\alpha_1}{\omega_1}. \end{aligned}\right\} (8)$$

For the transient terms I_2 and V_2, it is only necessary to consider the character of the free current in a circuit of inductance L_2, capacity C_2, and resistance R_2. The solution of the problem

* (It is to be noted that the *real* part of $\frac{A + B\,j}{X + Y\,j}$ obtained by multiplying numerator and denominator by the conjugate imaginary, $X - Y\,j$, and simplifying, is $\frac{A\,X + B\,Y}{X^2 + Y^2}$.

The modulus, or phase angle of $P + Q\,j$ is θ where $\tan\theta = \frac{Q}{P}$. For the fraction above, it is $\tan\theta = \frac{B\,X - A\,Y}{A\,X + B\,Y}$.—Editor.)

is well known; we shall therefore give here the final equations only, we have

$$I_2 = D_1 \varepsilon^{-a_2 t} \cos \omega_2 t - D_2 \varepsilon^{-a_2 t} \sin \omega_2 t, \tag{9}$$

$$V_2 = \varepsilon^{-a_2 t} \sqrt{\frac{L_2}{C_2}} \left\{ D_1 \cos (\omega_2 t - \gamma) - D_2 \sin (\omega_2 t - \gamma) \right\}, \tag{10}$$

$$\tan \gamma = \frac{\omega_2}{a_2}.$$

The constants D_1 and D_2 are to be determined from the initial conditions of the problem.

We shall consider now separately the two cases: first when the electrical constants of circuit (II) are adjusted for resonance to circuit (I), and second when slightly out of resonance.

Resonance condition, $\omega_2 = \omega_1$.

The total current in circuit (II) is

$$\left.\begin{aligned} I_r = I_1 + I_2 = \omega_1 K_r \varepsilon^{-a_1 t} \cos (\omega_1 t + \phi + \psi) + \\ \varepsilon^{-a_2 t} (D_1 \cos \omega_1 t - D_2 \sin \omega_1 t), \\ V_r = V_1 + V_2 = \frac{K_r}{C_2} \varepsilon^{-a_1 t} \sin (\omega_1 t + \phi) + \\ \varepsilon^{-a_2 t} \sqrt{\frac{L_2}{C_2}} \left\{ D_1 \cos (\omega_1 t - \gamma) - D_2 \sin (\omega_1 t - \gamma). \right. \end{aligned}\right\} \tag{11}$$

$$\begin{aligned} K_r &= \frac{E}{L_2 (a_2 - a_1) \sqrt{(a_2 - a_1)^2 + 4 \omega_1^2}}, \\ &= \frac{E}{2 L_2 \omega_1 (a_2 - a_1)}. \end{aligned} \tag{12}$$

In the above and subsequent equations a^2 is neglected in comparison with ω^2, $\frac{a^2}{\omega^2}$ is very small in comparison with unity.

The angle ψ is very small, and for the resonance condition the angle ϕ is also very small, hence we may put $\psi = \phi = 0$. Also since $\frac{\omega}{a}$ is a large quantity, $\gamma = 90°$ approximately. Equations (II) reduce then to the following:

$$\left.\begin{aligned} I_r &= K_r \omega_1 \varepsilon^{-a_1 t} \cos \omega_1 t + \varepsilon^{-a_2 t} (D_1 \cos \omega_1 t - D_2 \sin \omega_1 t) \\ V_r &= \frac{K_r}{C_2} \varepsilon^{-a_1 t} \sin \omega_1 t + \varepsilon^{-a_2 t} \sqrt{\frac{L_2}{C_2}} \left\{ D_1 \sin \omega_1 t + D_2 \cos \omega_1 t \right\} \end{aligned}\right\}. \tag{13}$$

To determine the constants D_1 and D_2, we note that for $t = 0$, $I = 0$ and $V = 0$. We have then,

$$K_r \omega_1 + D_1 = 0,$$

$$D_2 = 0,$$

$$\therefore \qquad D_1 = - K_r \omega_1,$$

and

$$I_r = K_r \omega_1 \cos \omega_1 t \, (\varepsilon^{-a_1 t} - \varepsilon^{-a_2 t}). \tag{14}$$

The integrated effect of the square of the current for a complete train of oscillations is,

$$J_r^2 = \int_0^\infty I_r^2 \, dt = K_r^2 \omega_1^2 \int_0^\infty \cos^2 \omega_1 t \, (\varepsilon^{-a_1 t} - \varepsilon^{-a_2 t})^2 \, dt. \tag{15}$$

The above integral is well known (see Peirce's "Table of Integrals"), and we get

$$J_r^2 = K_r^2 \omega_1^2 \left(\frac{1}{4 a_1} + \frac{1}{4 a_2} - \frac{1}{a_1 + a_2} \right)$$

$$= \frac{K_r^2 \omega_1^2 (a_1 - a_2)^2}{4 a_1 a_2 (a_1 + a_2)}. \tag{16}$$

Non-resonance condition.

In this case $\tan \phi$ is very large and $\phi = 90°$ approximately. The total current in the circuit and the potential across the condenser are given by the following expressions:

$$\left.\begin{aligned} I = I_1 + I_2 &= - K \omega_1 \varepsilon^{-a_1 t} \sin \omega_1 t + \varepsilon^{-a_2 t} (D_1 \cos \omega_2 t - \\ &\qquad D_2 \sin \omega_2 t) \\ V = V_1 + V_2 &= \frac{K}{C_2} \varepsilon^{-a_1 t} \cos \omega_1 t + \varepsilon^{-a_2 t} \sqrt{\frac{L_2}{C_2}} \{ D_1 \sin \omega_2 t + \\ &\qquad D_2 \cos \omega_2 t \} \end{aligned}\right\} \tag{17}$$

where the value of K is given by (8).

For $t = 0$, we have $I = 0$ and $V = 0$, hence

$$D_1 = 0,$$

$$\frac{K}{C_2} + \sqrt{\frac{L_2}{C_2}} L_2 = 0.$$

Therefore

$$D_2 = - \frac{K}{C_2} \sqrt{\frac{C_2}{L_2}} = - \frac{K}{\sqrt{L_2 C_2}} = K \omega_2. \tag{18}$$

Substituting above value of D_2 in (17) we get,

$$I = - K \omega_1 \varepsilon^{-a_1 t} \sin \omega_1 t + K \omega_2 \varepsilon^{-a_2 t} \sin \omega_2 t. \tag{19}$$

The integrated effect of the square of the current is,

$$J^2 = \int_0^\infty I^2 dt = K^2 \int_0^\infty \{\omega_2 \varepsilon^{-a_2 t} \sin \omega_2 t - \omega_1 \varepsilon^{-a_1 t} \sin \omega_1 t\}^2 dt. \tag{20}$$

The above integral can be separated into three parts. We have

$$\int_0^\infty \varepsilon^{-2a_2 t} \sin^2 \omega_2 t\, dt = \frac{\omega_2^2}{4\alpha_2(\alpha_2^2 + \omega_2^2)} = \frac{1}{4\alpha_2},$$

$$\int_0^\infty \varepsilon^{-2a_1 t} \sin^2 \omega_1 t\, dt = \frac{\omega_1^2}{4\alpha_1(\alpha_1^2 + \omega_1^2)} = \frac{1}{4\alpha_1}$$

$$\int_0^\infty \varepsilon^{-(a_1 + a_2) t} \sin \omega_1 t \sin \omega_2 t\, dt$$

$$= \frac{1}{2}\int_0^\infty \varepsilon^{-(a_1 + a_2) t} \{\cos(\omega_1 - \omega_2) t - \cos(\omega_1 + \omega_2) t\}\, dt$$

$$\frac{1}{2}\int_0^\infty \varepsilon^{-(a_1 + a_2) t} \cos(\omega_1 - \omega_2) t\, dt$$

$$= \frac{1}{2}\,\frac{1}{(\alpha_1+\alpha_2)^2 + (\omega_1 - \omega_2)^2}\Big[-(\alpha_1 + \alpha_2)\cos(\omega_1 - \omega_2) t$$

$$+ (\omega_1 - \omega_2)\sin(\omega_1 - \omega_2) t\Big]\varepsilon^{-(a_1 + a_2) t}\Big/_0^\infty$$

$$= \frac{1}{2}\,\frac{\alpha_1 + \alpha_2}{(\alpha_1+\alpha_2)^2 + (\omega_1 - \omega_2)^2}$$

Similarly

$$\frac{1}{2}\int_0^\infty \varepsilon^{-(a_1 + a_2) t} \cos(\omega_1 + \omega_2) t\, dt = \frac{1}{2}\,\frac{\alpha_1 + \alpha_2}{(\alpha_1 + \alpha_2)^2 + (\omega_1 + \omega_2)^2}.$$

Combining the results from the above integrals, we get

$$J^2 = \int_0^\infty I^2 dt = K^2 \left\{ \frac{\omega_1^2}{4\alpha_1} + \frac{\omega_2^2}{4\alpha_2} - \frac{\omega_1 \omega_2 (\alpha_1 + \alpha_2)}{(\alpha_1 + \alpha_2)^2 + (\omega_1 - \omega_2)^2} - \frac{\omega_1 \omega_2 (\alpha_1 + \alpha_2)}{(\alpha_1 + \alpha_2)^2 + (\omega_1 + \omega_2)^2} \right\}. \tag{21}$$

The last term in the above equation is negligibly small in comparison with the other terms, hence

$$J^2 = K^2 \left\{ \frac{\omega_1^2}{4\alpha_1} + \frac{\omega_2^2}{4\alpha_2} - \frac{\omega_1 \omega_2 (\alpha_1 + \alpha_2)}{(\alpha_1+\alpha_2)^2 + (\omega_1 - \omega_2)^2} \right\} \tag{22}$$

$$= \frac{K^2}{4}\left\{ \frac{(\omega_1^2 \alpha_2 + \omega_2^2 \alpha_1)\{(\alpha_1 + \alpha_2)^2 + (\omega_1 - \omega_2)^2\} - 4\alpha_1 \alpha_2 \omega_1 \omega_2 (\alpha_1 + \alpha_2)}{4\alpha_1 \alpha_2 \{(\alpha_1 + \alpha_2)^2 + (\omega_1 - \omega_2)^2\}} \right\}.$$

Since the difference in the values of ω_1 and ω_2 is small, we may write $\omega_1^2 \alpha_2 + \omega_2^2 \alpha_1 = \omega_1^2 (\alpha_1 + \alpha_2)$ and

$$4\omega_1 \omega_2 \alpha_1 \alpha_2 (\alpha_1 + \alpha_2) = 4\omega_1^2 \alpha_1 \alpha_2 (\alpha_1 + \alpha_2),$$

and in using the final formula we must bear in mind the approximation thus introduced; that is, to obtain accurate results, the difference in the values of ω_2 and ω_1 must be made small.

With this approximation, formula (22) simplifies to the following:

$$J^2 = \frac{K^2\omega_1^2}{4}\left\{\frac{(\alpha_1+\alpha_2)\left\{(\alpha_1-\alpha_2)^2+(\omega_1-\omega_2)^2\right\}}{4\alpha_1\alpha_2\left\{(\alpha_1+\alpha_2)^2+(\omega_1-\omega_2)^2\right\}}\right\}. \qquad (23)$$

Introducing the value of K^2 from (8), we get

$$J^2 = \frac{E^2\omega_1^2(\alpha_1+\alpha_2)\left\{(\alpha_1-\alpha_2)^2+(\omega_1-\omega_2)^2\right\}}{4L_2^2\alpha_1\alpha_2\left\{(\alpha_1+\alpha_2)^2+(\omega_1-\omega_2)^2\right\}\left\{\left[(\alpha_2-\alpha_1)^2+\omega_2^2-\omega_1^2\right]^2+4\omega_1^2(\alpha_2-\alpha_1)^2\right\}} \qquad (24)$$

The second factor in the denominator can be put in the following form:

$$\begin{aligned}\left\{(\alpha_2-\alpha_1)^2+(\omega_2-\omega_1)^2\right\}^2+4\omega_1^2(\alpha_2-\alpha_1)^2 &= (\alpha_2-\alpha_1)^4\\ &+2(\alpha_2-\alpha_1)^2(\omega_2^2-\omega_1^2)+(\omega_2^2-\omega_1^2)^2+4\omega_1^2(\alpha_2-\alpha_1)^2\\ &=(\alpha_2-\alpha_1)^4+2(\alpha_2-\alpha_1)^2(\omega_2^2+\omega_1^2)+(\omega_2+\omega_1)^2(\omega_2-\omega_1)^2\end{aligned}$$

Neglecting the term $(\alpha_2-\alpha_1)^4$, and introducing the same approximation used before, the above reduces to,

$$4\omega_1^2\left\{(\alpha_2-\alpha_1)^2+(\omega_2-\omega_1)^2\right\}.$$

Substituting this in (24), we get

$$J^2 = \frac{E^2(\alpha_1+\alpha_2)}{16L_2^2\alpha_1\alpha_2\left\{(\alpha_1+\alpha_2)^2+(\omega_1-\omega_2)^2\right\}}. \qquad (25)$$

For resonance condition we have by combining (16) and (12),

$$J_r^2 = \frac{E^2}{16L_2^2\alpha_1\alpha_2(\alpha_1+\alpha_2)}. \qquad (26)$$

From (25) and (26) we get by division,

$$\frac{J_r^2}{J^2} = \frac{(\alpha_1+\alpha_2)^2+(\omega_1-\omega_2)^2}{(\alpha_1+\alpha_2)^2}, \qquad (27)$$

and

$$\frac{J_r^2-J^2}{J^2} = \frac{(\omega_1-\omega_2)^2}{(\alpha_1+\alpha_2)^2}. \qquad (28)$$

Hence

$$\alpha_1+\alpha_2 = (\omega_1-\omega_2)\sqrt{\frac{J^2}{J_r^2-J^2}}. \qquad (29)$$

If δ_1 and δ_2 are the logarithmic decrements per semi-period of circuits (I) and (II) respectively, then $\alpha_1 = 2n_1\delta_1$ and $\alpha_2 = 2n_2\delta_2$. Introducing these values in (29), and assuming that the frequencies are nearly the same, equation (29) becomes,

$$\delta_1+\delta_2 = \pi\left(1-\frac{n_2}{n_1}\right)\frac{J}{\sqrt{J_r^2-J^2}}, \qquad (30)$$

which is the well known logarithmic decrement formula given in all text books on radio engineering.

SUMMARY: The Bjerknes method of determining the logarithmic decrement of a circuit consists in coupling loosely to it an oscillatory circuit containing a thermo indicator; the latter circuit having known constants. From the resonance curve obtained by detuning the latter circuit, the logarithmic decrement of the unknown circuit is calculable by formula (30) above.

The current in the resonant circuit is the sum of two component currents; one forced (and of the same decrement and frequency as the exciting current) and one a transient or free oscillatory current. Using the convenient mathematical method of imaginary symbolic operators, the differential equation of the excited current is set up and solved for the resonance condition and for non-resonant conditions. The integrated effect of the square of the current is obtained for each case. Proceeding on the assumption that the detuning of the circuits is not large, the usual formula for obtaining the logarithmic decrement is derived.

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It is with deep regret that the Institute of Radio Engineers announces the death of

Mr. N. H. C. Taylor

He was the radio operator on board the steamship "Marowijne," which foundered with all on board during a hurricane on the Caribbean Sea on August 14, 1915. Mr. Taylor, who was an Associate Member of the Institute, was in the employ of the Tropical Radio Telegraph Company at the time of his death.

The heroic steadfastness required by the radio operator in stress and storm is shown by this catastrophe.

THE TRAINING OF THE RADIO OPERATOR*

By

M. E. Packman

In contra-distinction to the advance that has been made by the scientific and commercial development of radio telegraphy, the operator problem stands much as it did in the earliest days. While radio equipment has undergone many improvements, traffic departments have accomplished much in the organization and collection of business, and the number of equipments has greatly increased, little has been done to increase the efficiency of the operating staff. In former days the only question asked of a man applying for a position as wireless operator was; "Are you an operator?" Since the advent of the Government License it has been changed to "Have you a license?" An affirmative answer was and is, in the majority of cases, all that is required to secure the applicant his position. In some cases, this was necessary; and it will undoubtedly continue to be so inasmuch as it is not always possible to obtain a competent man at the particular moment that an operator is needed. It seems, however, that if the question of the training and selection of operators for radio service were handled in a manner more in accord with that followed by railroads, the deplorable condition that exists in some land and ship stations would be greatly improved. As all persons acquainted with the commercial development of radio communication in this country well know, a very chaotic state of affairs existed prior to the time that the Department of Commerce placed certain restrictions on radio equipment, operators, and methods of operating. After the matter of wave length restrictions has been more nearly adjusted to meet present conditions, I think it will be possible to say that as a whole conditions have been much improved.

As far as the operators are concerned, the Government examinations have weeded out many undesirable men from the service and consequently have raised the standard a little higher, but it must be borne in mind that the Department of Com-

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* Presented before The Institute of Radio Engineers, New York, October 6th, 1915.

merce looks at the efficiency of the operator from a different point of view than should the commercial company if it is seeking the most suitable men. The requirements of the department are only a part of what good commercial service demands, tho in many cases a first grade license is all that is required or asked for.

As one man of my acquaintance, who employs a great many operators every year has stated in referring to the operators on his ships, "Some of these men cannot send, some of them cannot receive, some of them cannot adjust a detector, and some of them cannot tune." Such men as he refers to, that do little else than ride back and forth on the ships, are common in the radio service everywhere; and the excuse is made that it is difficult to find men who are good telegraphers and at the same time are capable of handling a radio set to the greatest advantage. This condition is the natural result of attempting to get efficiency out of men who have had no telegraphic experience or who have had no training in the use of commercial radio apparatus. I have known men whose highest aim in life was to be so expert a telegrapher that they could sit down and work any telegraph circuit at which they might be placed. On the other hand, there are radio operators who are interested only in the handling of the instruments; and again there are men who have no particular interest in any phase of the business, other than its outside attractions. Obviously none of these classes of men completely fill the requirements of a "good" operator, but this list includes practically all the available men, with few exceptions, who have not been specially trained.

A question then arises: what are the qualifications of a "good" operator. In the first place, he should be capable of transmitting signals clearly, accurately, and rapidly in either American Morse or Continental Morse. He should understand that any communication not only has to be sent but also to be received; and realizing this, he will space his characters and words so that they will be easily understood by the receiving operator. He should know when to repeat and when it is unnecessary, when to send slowly and when he may send faster. In receiving, he should be able to read almost any kind of sending, and to make a neat copy with either pen or typewriter regardless of whether he has interference to contend with or not. If he is capable of getting the most out of his instruments he must thoroly understand the principles which underlie their design. This knowledge must be so perfect and of so practical a nature that he will know instantly what is needed in case of emergency or disaster. He must have a comprehensive knowledge of telegraphic tariffs, traffic, methods of routing, the location of various radio and telegraphic stations, etc., so that he can quickly determine in what way a message can be handled with the greatest dispatch and least expense. This will not only be an aid to him in procuring business but it will be of benefit to the general public with whom he deals. He must be ready and willing to perform the functions of his office at all times; and in every case he must be a gentleman.

Some of the qualifications enumerated involve inborn personal characteristics that are apart from any training that a school can give. Experience has shown that one phase of the work will appeal more strongly to one man than another and that it is seldom the case that a man of his own initiative becomes proficient in all the things essential to his work. I think it can be said, however, that given a man with average intelligence, willingness, and six months training in a well organized school; a proficient radio operator can be developed.

The object of this paper is briefly to outline the course in "Radio Telegraphy" as given at Dodge's Institute of Telegraphy at Valparaiso in Indiana, and to show some of the methods that are used in an effort to meet the requirements of a comprehensive training for radio operators or other persons interested in the art of radio communication. More than one-third of the students entering the school are enrolled in the Radio Department, and of this number about two-thirds also take the work in the Morse Department, thus familiarizing themselves with both codes. Aside from the special work in each of these departments all students are required to take a half hour's work in penmanship, under a competent instructor, each day. To anyone familiar with telegraphic work, the importance of this is apparent. The school is also equipped with a large number of typewriters so that the student may become proficient in copying directly from the circuits by this means. The greater portion of the students completing the course in Radio Telegraphy enter the service of the Marconi Wireless Telegraph Company with which company we have a working arrangement. Others of these students enter other commercial or government service.

As might be expected in an institution of this kind the student body is made up of all classes. The students are of all ages, and they come from all parts of the United States; many of them come even from foreign countries. Some of those who enroll in the Radio Department, especially, are college graduates; many are high school graduates, while some of them have very meagre education. Altho we have no regular entrance requirements, as far as education is concerned, it is frequently the case that we are compelled to refuse the applicant because of his lack of elementary education. The average student is between eighteen and twenty years of age and has had two years of high school training. This is, of course, a desirable qualification, and I have found that those students who have had amateur experience together with the high school work are the most apt in mastering the radio work. This is due, of course, to their great interest in the radio field. Another class of men that invariably develop into excellent radio operators is drawn from the commercial and railroad fields. There is also a great variance in the ulterior motives of the different students. The majority of them, of course, expect to prepare themselves for service as commercial radio operators. However, we have many special students with entirely different objects in view. Among these are men from the armies and navies of foreign countries as well as some from the United States government service. We have other students who are interested in the subject from a scientific standpoint only, some who expect to teach the subject in other schools and colleges, and so on.

In arranging a course that will meet these varied conditions, numerous points had to be considered. In the first place, it is impossible in most cases for the student to remain in school for a period exceeding six months. This means that all the work relating to the subject must be covered within this time at most. In the second place, owing to the lack of preparatory training in electrical science, it is necessary to begin with the very principles of electricity; and considering the extent of such electrical knowledge that an operator should have, and the complexity of some electrical ideas, it requires a very careful selection of the subject matter in order that the course be made as comprehensive as possible. Many of the theories which underlie the working of radio apparatus, involve the principles of alternating currents, a subject which is usually taken up in the third or fourth year in engineering courses; and altho simple to an electrical engineer is very complex and difficult of explanation to a student who has no foundation for such work. Nevertheless, these ideas have to be covered in order that the student is eventually able to reason out many of the problems and questions that may present themselves sooner or later. In our work the students are not shown lists of questions, the answers to which can be memorized, and their examinations are the result of actual knowledge of radio apparatus, its uses, merits, and failings. This, it appears, is the only possible manner in which a "good" operator can be trained so far as theory and manipulation of apparatus are concerned.*

In general, the theory, adjustment and operation of radio equipment is given in a series of lectures associated with laboratory work, which occupies three hours each forenoon, five days per week. The beginning class is held between 11 and 12, an intermediate class between 9 and 10, and the advanced class between 8 and 9. The hour between 10 and 11 is devoted to code practice. Other code classes are held from 1.30 to 3 P. M., 4 to 5 P. M., and 7 to 8 P. M. The penmanship class is held between 3.30 and 4 P. M. During the summer months, the evening session is discontinued. In describing the various parts of the course, I shall take up the code work first.

At the time the Department of Radio Telegraphy was established, the American Morse code was used almost exclusively in the radio service in this country, the South Wellfleet station being the only one that used Continental Morse extensively, so far as I am informed. With this condition existing, it was a simple matter to train a Morse operator to receive the same code thru telephone receivers. In the Morse Department of the school, there was and is every facility for training a student in Morse receiving where there are a great variety of speeds. A new student is started on a circuit where an instructor makes the characters of a letter and the student pronounces the letter; and as he becomes familiar with the combinations forming all the letters, he is advanced to a circuit on which short words are sent, which he calls off as he recognizes them. In this way a student is advanced from one circuit to another until he is receiving at a speed of twenty-five to thirty words per minute. On the more advanced circuits in the commercial and railway department, the instruction consists of commercial and railway messages or train orders. Examinations are held from time to

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*One method of preparing a man for a government license, which I have been informed is used, is to furnish the student with a list of questions, such as are used by the inspectors in examining applicants for operators' licenses, together with the correct answer to each question. With such a list of questions and answers, it is a simple matter for a telegrapher to pass the examination as given by the Department of Commerce, provided he does not write down answer six for question five. Such a man is of course worthless in actual radio service altho he has nevertheless passed the requirements of the Department of Commerce.

time and the students making the fewest mistakes in their copies, which are marked with care, are advanced to higher circuits.

After a student who had enrolled in the radio course had progressed to the point where he could receive eighteen to twenty words per minute from a sounder, he was transferred to the radio code work. All such students were supplied with practice sets including a single slide tuning coil, detector, fixed condenser, head telephone receiver, and sufficient aluminum wire to construct an indoor antenna, as well as a key and buzzer mounted on a base board. An operator at the radio station in the school sent press matter at a speed of about fifteen words per minute for a period of an hour and a half or so, and at a faster speed for an equal period. Students, supplied with the small receiving sets which they had installed in their rooms, were supposed to spend the afternoon in copying these signals. This method was very good, in some respects, where the total number of students was small and where they were all able to receive ordinary Morse signals at a fair speed. They not only had the benefit of the code practice but they also had some practical experience in the adjustment of detectors and in tuning, which is, of course, a valuable part of an operator's training. On the other hand where students are depended upon to get their own practice in this way, they are very apt to waste a great deal of time and their progress is slow.

In the spring of 1913, the Department of Commerce regulations went into effect, calling for Continental code and examinations for licenses. It was evident that numerous changes would have to be made in the course of instruction in order that the students might receive the necessary and proper training. As a result a complete reorganization of the department was inaugurated. The Continental code is now taught exclusively in the Radio Department and the system used for many years in the Morse work is followed with the exception, of course, that all receiving is done with telephone receivers instead of by means of a sounder.

Ten code circuits, operated at various speeds, are used at the present time. On circuits 8, 9, and 10, which are the beginners' circuits open buzzers are used. An instructor sends letters singly on the lowest of these, and the student calls out the letter as he recognizes it. The student is not permitted to copy on paper at the start as it is found that he then invariably loses interest before he has accomplished anything. There is always a little rivalry among the members of a group of new students as to which one will be the first to call off the letters as they are sent; and this urges them to use increased energy in mastering the first few days' work. As they become familiar with all the letters, figures, and characters prescribed for radio signaling the students are advanced to a higher circuit where they pronounce words. Inside of a few weeks or less, they are able to receive words sent at a rate of four or five per minute. The length of time required, of course, depends upon the natural aptitude of the student, and his application.

Figure 1 shows the general arrangement of the code and lecture room; the photograph, being taken from the instructor's desk does not, however, include the switch board and instruments

FIGURE 1

used in controlling the circuits. On circuits 1 to 7, all receiving is done thru double head telephone receivers similar to those used in commercial working. The transmitter or signal producing device used on all of these circuits consists of a buzzer, controlled by a telegraph key, having line wires connected to the terminals of the interrupter, a condenser being interposed in one or both of these. On circuits 3 to 7, there is one transmitter on each circuit, with telephone terminals bridged across the line wires for seven students. Circuits 1 and 2 are arranged in long lines along the side of the code room, and each is divided into eight stations all of which are equipped with a buzzer transmitter, condenser and transfer switch for changing from sending to receiving. All of these circuits are connected with a Western Union switch board at the instructor's desk by means of which any one of the circuits may be connected with any other or any transmitter on the instructor's desk can be instantly connected, by means of a loop pin with any circuit. Or, in the same manner, a telephone transmitter may be connected with any circuit. The code speeds on circuits 7 to 1 are gradual variations from five or six words per minute on 7 to the highest speeds on circuits 1 and 2 which usually are connected together. Each of the buzzers on these circuits is separately adjusted so as to give out as good a note as possible, and it always happens that there are as many different tones as there are buzzers inasmuch as it is difficult to obtain a perfect tone from all. This I consider to be an extreme advantage, however, over the system used in some schools where one master vibrator or other audio frequency generating device is used as a source of power to supply all circuits. It is possible for a student to become so familiar with one spark frequency, especially if it is absolutely regular, that he will have great difficulty in copying commercial stations which have sparks varying in a more or less degree from the perfect tone. With the individual buzzer method, however, an experienced operator, when listening in on our faster circuits to the interchange of radio messages will not fail to recognize its true ring. Some of these student stations emit a high musical spark resembling the 500-cycle stations, while there are others of varying pitch down to the rough irregular spark such as is emitted by the old low frequency sets of the Shoemaker type. In fact nearly every condition of arcing or other irregularity in a commercial transmitter is automatically met.

To some this may appear to be a deplorable way in which to teach a student to copy telegraph code, but on further consideration it is evident that the student not having had a perfect spark to copy from at all times, has accustomed himself to just the conditions of regular commercial service. Altho the tendency is toward a universal use of musical sparks and apparatus with which such sparks can be readily and easily maintained, it will undoubtedly be a long time before the difficulties of tone adjustment will be done away with. Again, the moral effect of an irregular or rough spark is impressed upon the mind of the student. Some students of their own accord endeavor to get and maintain a clear tone, while others are more or less indifferent. In any case, the advantages of the good tone are evident and a certain pride is ordinarily taken in maintaining such tones. (I have been told by old operators that our students can be recognized by the adjustment of their test buzzers.)

Another advantage of the individual buzzer arrangement is that the loudness of the different stations can be readily adjusted to any fixed value, assuming that the frequency of interruption is constant. As previously mentioned, a condenser is interposed between either one or both sides of the line and the buzzer, and by constructing these condensers so that they have different capacities, their impedences are different and hence different stations can be made to send out signals of different strengths. Some of the stations have adjustable condensers and hence have a ready means of "varying their power." At the instructor's desk, variable condensers are used so that the signal strength can be varied from just audibility to any desired value. Other methods of varying the signal strength in such circuits readily present themselves, but the method outlined above has proven to be the most satisfactory of any that I have tested. In any case it is exceedingly important that the practice signals be not too loud and it is desirable to have them of different strengths. It has been my experience that a student may become so proficient in the code work on the circuits, that he can copy the most complicated code and cipher messages from the fastest senders, but when placed in the radio receiving room he will be able to get but little of what is being sent. This is partly due to the fact that he may be practicing with too loud signals. Ability to read very faint signals from distant stations is largely a matter of ear training and for this reason it is desirable to have the practice signals quite weak. On the other hand, an operator who is accustomed to receiving such signals may become so confused by very loud signals that he will be unable to copy them.

Each station on circuits 1 and 2 is provided with four calls; that is, it represents four different ship or land stations and the operator at each of these places is expected to answer any one of these calls. Inasmuch as the international call letters assigned to commercial stations in this country, into the service of which most of our students go, are combinations beginning with W or K, each of the student stations has one call beginning with each of these letters. The two remaining calls are selected from those used in the United States Naval service or foreign stations, thus giving a wide variety of combinations. Some of these calls are selected on account of the difficulty encountered in transmitting them, or again there may be two that are easily confused or wrongly interpreted by a receiving operator. Others admit of a rhythmical swing which experienced operators develop. Among the different stations and ships represented on these circuits are those at the principal ports on our sea coasts and on the Great Lakes and the vessels which are likely to be in communication with them. The instructor's desk answers to or uses any call not assigned to one of the student stations. Occasionally the entire system of calls is changed. It is thought that such a system as this trains the student to be quick to recognize as well as to send difficult or uncommon calls.

Practically all the code work on these faster circuits consists of message work, and such other communications as are actually carried between ships and radio stations. Everything is carried over these circuits in accordance with the provisions of the London Convention, the Marconi traffic regulations, and good judgment. Students are not permitted to converse over the circuit nor to carry on any conversation except where the exigency of the case demands it. Messages are sent from one station to another with proper prefixes and service instructions, being relayed where necessary and filed for future reference. As might be expected, a student is often tempted to give an O. K. on a message addressed to his station when a goodly portion of it is missing rather than to ask for a repetition or to say that he had not received it, and in order to circumvent this, nearly all the messages sent out from the instructor's desk are messages that call for answers or must be relayed. This proves to be a very satisfactory method of insuring that the communication has been actually received and soon the student ceases to commit such offenses. Sometimes a wrong check is purposely affixed to determine if the student will note this. The various ship stations send in their "T R" reports and positions which must conform to the practice of commercial stations; in fact, everything is handled as nearly in conformity with actual conditions as possible. Very little press is sent over these circuits as it not only gives the student a fictitious idea of his ability, but really furnishes little practice. In fact, I am convinced that it has a tendency to make him "guess" more than anything else, which is, of course, one of the worst habits that an operator can acquire. In case such material is sent over the circuits, it is generally an article having in it many uncommon words. In some instances subjects in French, German or Spanish, or long lists of code or cipher words are sent in an endeavor to train the student to write down just what he receives, by sending such material that he is unable to form any advanced ideas.

Another failing common to many operators, which we have endeavored to overcome in our men, is the inability to read signals thru interference. There always has been more or less of this to contend with, but now that all commercial work is ordinarily carried on at the same wave length, or at best at a few wave lengths the confusion has become greater; and when severe atmospheric disturbances exist in addition, it taxes the ability of the operator to the utmost. The acquiring of ability or skill in reading signals under these conditions is a matter of patience and concentration of the mind on one particular tone; a faculty which can be developed by training. In order, in a measure, to duplicate the condition of interference and to bring out this faculty of copying under adverse conditions, I make it a practice at times to have an interfering transmitter, or possibly several, working on the same circuit at the same time the regular code practice is being carried on over this circuit. This is done an hour or so each day and the results are exceptional. Ordinarily an omnigraph or other automatic transmitter is used to operate the interfering buzzer, the strength of the signals being variable. However, at times two groups of students will be carrying on communication simultaneously on the same circuit.

For the regular code practice, no automatic transmitters or sending machines of any kind are used, altho we have a number of varieties; except that a day or two before the government inspector visits the school, the omnigraph is used in order that the applicant shall not be confused by its mechanical accuracy. Hand sending by expert radio operators is depended upon entirely. All students receive such instruction either one and a half or two hours per day depending upon which circuit they happen to be working and the state of their advancement. During such periods of the day as there is no instruction on the circuit the students send among themselves, each being assigned a certain part of an hour, the schedules being rigidly maintained.

It is generally considered that not all men can become expert senders, this being a natural qualification with some; but it has been our experience that nearly any person can become a good sender if he is taught the full arm "pump handle" movement and rigorously practices it. Slow sending, if heavy, distinct, and properly spaced is always better than light rapid sending in the case of a new man. After he has once become a good sender, he easily acquires the speed which is essential in many cases. Taking operators as they are ordinarily found, better speed can generally be made and more business transacted in the same time, by sending good distinct characters at a speed of twenty or twenty-two words per minute than can be done by transmitting at a speed of twenty-eight or thirty words per minute. There is always a tendency for new men to endeavor to "burn up" some other operator by rapid sending and if he is a poor sender at best, a great deal of time is lost as a result. Our code circuits are fitted with good telegraph keys, some Western Union keys, and some heavier keys similar to those frequently found in radio stations; and students are urged to practice a correct method of sending on these during all their spare moments. In cases where a man is especially stiffened in the muscles of his forearm from manual labor, or in other cases, we insist on an hour or so of continuous sending every day. After a student has practiced a correct method of sending until he has become sufficiently competent to transmit signals clearly, accurately and without "breaking," he is allowed to operate the school station on field days. Students are always anxious to do this but good sending on the practice circuits is pre-requisite. In most cases a good sender is the result.

In the technical or theoretical phase of the work the first part of the course consists of a study of the elements of electricity and magnetism, emphasizing such points as relate directly to radio apparatus and abreviating such matters as are not of first-hand importance. Following these more elementary subjects, the course is extended into a study of dynamo electric machinery, going only briefly into the theory of such apparatus, but giving special attention to the actual principles of the generation of current, the factors influencing the output, the function of the various parts, as well as the use, and care of such machines and methods of making tests and repairs. In connection with the study of alternating current machines the student is familiarized with terms common to alternating current operation (frequency, wave form, power factor, etc.), so that when the study of capacity and inductance has been taken up, the elements of alternating current problems will be less difficult. To facilitate the study of dynamo-electric machinery, the laboratory is equipped with a number of types of motor-generator sets used in radio service as well as various other A. C. and D. C. motors and generators of different capacities, together with starters, rheostats and other auxiliary apparatus. Figure 2 is a view of the general laboratory which shows some of this equipment. In the foreground is a direct current generator, belted to a three-phase induction motor, the set being used to supply direct current for operating the motor-generators and other direct current apparatus. The generator of this set is of very open construction and the terminals of all windings are brought to a connection block, making it a very convenient machine for demonstration work. Along the right hand side of the picture can be seen several radio transmitters, of different types, used for instruction and demonstration work. Along the wall to the left, not visible in the photograph, are cabinets containing various kinds of physical and electrical instruments, tuning devices, measuring instruments, and other apparatus useful in experimental work in radio telegraphy.

FIGURE 2

After completing that part of the work covering dynamo-electric machinery, a study of electro-magnetic induction is taken up, theoretically and experimentally. This is one subject upon which too much time cannot be spent and every effort is made to present the phenomena of inductance and self and mutual induction in such a manner that the student will get a clear conception of principles involved. The effects of self inductance are discussed in their relation to the primary circuits of induction coils and transformers. In the explanation of mutual induction I have found the use of audio frequency currents, generated by a buzzer, very helpful, using induction coils or coupling coils in which one of the coils can be rotated with respect to the other. Use is also made of coupling transformers of all types common to radio service, the result of which is that the student looks at the principle rather than any one form of construction. Many other schemes used by instructors in physics can be used to advantage. This part of the course is concluded with a study of the practical construction of commercial induction coils and transformers such as are used in radio installations, here as elsewhere, attention being drawn to methods of testing and making temporary or permanent repairs.

Following this work the next part of the radio set that is studied is the condenser, it being considered in its various forms and constructions. An effort is made to give the student a clear insight into the principles which are involved in certain important phenomena. Methods of calculating the approximate capacities of different types are shown, and then the means of obtaining any desired value of capacity, with definite dielectric strength, by the combination of standard units is demonstrated. Emphasis in this case is laid on the methods by which the proper capacity in the condenser of a radio set can be obtained by re-arranging the separate units of the condenser which has been injured, thru breakdown or puncture, and the precautions which must be taken in thus using it. Methods of charging condensers as used in the closed circuit of transmitters and the necessity for and function of the spark gap are demonstrated; which leads to a study of oscillatory discharges.

It has been my experience that unless the theoretical work is varied or made attractive by the interposition of actual radio telegraphing, thus giving an actual demonstration of some of these theories, it often happens that the student will lose interest, with the result that he fails to grasp the very things which are most essential. At this point, then, a horizontal aerial is strung up a short distance from the ground thus constituting a very apparent air condenser, and an induction coil is connected thereto forming a plain aerial transmitter. With this arrangement signals or messages are sent to portable stations. Altho this type of transmitter is generally known to the student, the experiment proves an interesting diversion in which many of the practical difficulties encountered in the operation of such sets with large induction coils, and their remedies, can be easily demonstrated and in a forcible manner.

Just at this point, when the student has in mind the oscillations of the current in this plain aerial transmitter and the radiation of electric waves, I have found it to be a very opportune time to go ahead with the explanation of the terms period and frequency, and their relation to wave length. With an aerial 100 feet long, all of which is visible, the student can be made almost to see the oscillation running out to the end of that wire and returning in a given time, and if the wire is longer that it will take a greater length of time for the complete oscillation.

After concluding the study of plain aerial transmitters, with stress laid on the limiting quantity of charge that can be converted into radio frequency energy in consequence of the small capacity of the aerial, the work naturally leads into the study of coupled transmitters wherein much larger capacities can be used. With an understanding of oscillatory currents already acquired, the effects of the constants of the closed circuit on the wave length are quite apparent. I have found that a study of wave lengths in a circuit which does not radiate waves, leads to much confusion and lack of understanding hence the reason for a consideration of wave length in connection with the plain aerial transmitter first.

During that part of the work covering closed circuits of the transmitter, I assume a circuit having a condenser of a certain capacity about which is shunted an inductance of some twenty turns. It is stated that the wave length using say two turns is 300 meters. The inductance of the helix per turn is then calculated, and the results tabulated. The student then calculates the wave length with the movable clip on each of the twenty turns and enters this data in his tabulation after which attention is invited to the fact that the wave length varies as the square of the number of turns. From this it is apparent that in case he was working on a ship and for any reason was required to change his wave length say from 300 to 600 meters the position of the clips would be instantly known, with fair approximation, without the use of a wave meter or other device. In like manner, the effect of the condenser capacity on the wave length is demonstrated; and cases are assumed wherein a portion of the condenser is damaged and the use of half of the condenser with a definite increase in the inductance will give the wave length required, this to be obtained without the use of measuring instruments. It is a well known fact that the majority of operators, after having once located a 600-meter adjustment on their receiving tuners, actually do very little tuning, and in case of accident to a ship or its radio equipment, it is very necessary that the operator on such a ship should be able to maintain his apparatus in such a condition that he can send on a wave very nearly 600 meters in length. In cases where the distance is great, this may be of extreme importance. Close coupling will not answer in all cases and hence an endeavor is made to give the student a knowledge of the best and quickest way in which to meet such conditions (to say nothing of the value which such information is to him at all other times). In order to verify the calculations and to bring the facts more emphatically to mind, the wave length at each adjustment is measured in the laboratory by means of a wave meter and the results are tabulated along with the calculated values in the note book which every student keeps. The results of such measurement are also reproduced in curves.

Following this work, means for transferring the oscillating energy to the radiating circuit and the conditions under which the greatest current is produced in the antenna are taken up and explained. Various methods are demonstrated in the laboratory for indicating the maximum antenna current, so that an operator will have some way of determining if his antenna is radiating the maximum amount of energy whether he has an approved hot wire ammeter or not. In the study of resonance between an oscillating circuit and an oscillating E. M. F., no attempt is made to avoid the actual alternating current principles which determine the strength of current that will flow in a circuit containing resistance, inductance and capacity. Once this idea is formed in the mind of a student a great many questions such as resonance phenomena in the audio frequency circuits, the use and proper capacity of telephone condensers in receivers, etc., are readily understood. In any case of this kind, the general theory is explained and then demonstrated by experiment. After demonstrating the tuning of the open and closed circuits in different ways the effects of re-transference of energy between them and the production of two wave lengths are brought out. Here, as in many other cases, it is necessary to exaggerate the fact in order to make the desired impression, and for this purpose we have some special apparatus with which it is possible to produce two wave lengths differing from each other by several hundred meters, with the two circuits tuned to an intermediate value.

At this point we take up the study of spark gaps especially the quenched gap which, when placed in the primary circuit of the above coupled system, serves to demonstrate the quenching action in a forcible manner. I have constructed a small quenched gap having ten sections which quenches perfectly operating on 60-cycle current in connection with a one-fourth kilowatt leakage transformer. An attempt to measure the wave length of the circuit in which it is contained shows a very flat wave having a decrement that is difficult to determine. This is shown mounted on a small panel set (Figure 2) which was built for some experimental work in transmitting on low antennas.

The work in transmitting sets is concluded with a study of several standard sets that are in commercial use, showing the inter-relation of the various parts and auxiliary apparatus such as meters, circuit breakers, antenna switches, etc. One of the sets that we have permanently installed in the school is a Marconi 2-kilowatt, 240-cycle set which was loaned to us thru the courtesy of Mr. John Bottomley. This set is complete with storage battery-induction coil auxiliary set, and receiver. Several other complete sets of composite type are also installed. Figure 3 is a view of the radio station showing the Marconi

Figure 3

2-kilowatt, 240-cycle transmitter, the storage battery auxiliary transmitter, switch boards, and various types of receiving apparatus.

During the course, about one week's time is spent on storage battery work in which are set forth the details of types common in radio service, their care, methods of charging, etc. Some circuits applicable to emergency ship lighting are also shown.

In taking up the study of receiving circuits and receiving apparatus, we begin with a review of the principles of resonance, again emphasizing the factors which determine the impedence; wherein it is seen that the alternating E. M. F. produced in the antenna by the passage of a wave train can only produce a maximum current in the antenna to earth circuit when the inductance and capacity of that circuit bear a definite relation to each other. Therefore, in order that this circuit shall be adjusted so as to have a low impedence, its capacity and inductance must be made variable by the insertion of a variable condenser and a tuning coil at its earthed end. Before progressing farther into the theory of tuning, it is necessary to consider the action of some detector, such as a crystal rectifier, stating its function and the actual reason for its use. After this has been done, a detector can be included in our antenna circuit and we have the elements of the simplest form of receiving circuit. It is shown experimentally and theoretically how this circuit can be so adjusted that it will respond to waves of widely differing length; and then how it can be further adjusted so that it will respond only to frequencies which are very near to that to which it is tuned. Such a receiver is then compared with a standard receiver as to selectivity and strength of signals, which readily demonstrates its disadvantages. The next improvement on this simple outfit, the close coupled tuner is taken up in the same manner, theoretically and experimentally. In connection with this type of receiver, reference is made to commercial tuners embodying this principle, such as the Type "D" tuner of the United Wireless Telegraph Company, many of which are still in use. Every student, tho generally much to his displeasure at first, is required to use one of these tuners in the radio receiving room until he becomes familiar with its use and possibilities.

After the study of closely coupled receiving sets, and the various methods involving a direct coupling, their advantages and disadvantages, loose or inductively coupled receivers are taken up; first in an elementary way, and then in connection with regular receiving sets. Our laboratory is well equipped with tuning apparatus of various kinds so that quite an opportunity is offered for setting up any standard circuit, or most special circuits. Specific instructions in the use of commercial tuners, such as are used by the commercial companies, follow the theoretical circuits. A great many operators in commercial service are incapable of getting the most out of their receiving sets; and especially is this true in the case of some of the more complicated receivers involving intermediate circuits or special tuning apparatus. In order to train the student to make the most of the facilities at hand and to give him an actual knowledge of the use of such apparatus, I have used the following scheme with success. The tuner or receiving circuit under test is connected to an antenna in the usual manner or to a dummy antenna in which are induced sharply tuned oscillations from a wave meter excited by a buzzer operated by an omnigraph. With the wave meter in operation, the student adjusts the receiver as broadly as possible, thus picking up the signals; after which he tunes for selectivity, and readjusts for the optimum results. After he has become familiar with the various adjustments several wave meter transmitters differing more or less in wave length are simultaneously operated, all being inductively related to the antenna or dummy antenna. A student will send with one of these transmitters while the one manipulating the receiver will endeavor to separate his signals from the interfering signals. In a short time the student becomes quite adept in tuning, and is able to meet many of the difficulties encountered in practice.

In the study of detectors, many of the common types are included, tho the most emphasis is laid on those of the crystal rectifying type inasmuch as they are the ones most used in commercial service at the present time. A great deal of stress is laid on the use of carborundum, which is probably more used and more reliable than any other detector. In much the same manner that a student becomes apathetic toward the Type "D" tuner, he becomes averse to the use of carborundum for reasons which are well known, but if he is supplied with a suitable potentiometer and a large collection of these crystals, he can generally be convinced that this form of detector has some merits. Every student, during the course, spends several hours testing crystals. The laboratory is equipped with a large number of detector stands, potentiometers, and tuners fitted for the use of these crystals, and in using these he gains an idea of the correct method of using such detectors, and eventually has more confidence in them.

One forenoon each week, a special class is held at which all students in the radio work are in attendance. This period is devoted to the discussion and study of radio law, the international regulations, traffic rates, method of computing charges, and similar matters. On some occasions, classes in geography are held at this hour, and maps of the radio districts are studied, steamship lines and routes pointed out, location of radio stations noted, and so on. Each student is required to learn the name of every passenger steamship line on the Great Lakes, the names of their vessels, their runs, call letters, and stations with which they are likely to be in communication. This information is of great value to a new operator, and requires very little time to learn. Some students take a great interest in this work.

Altho our station license is an experimental license and calls for no specific hours of service, we have certain hours during which we always have one or more men on duty in the receiving room, where they get a great deal of practical experience. The requirements as to the matter of maintaining a continuous watch during the time that is assigned to a student are strict, the result of which is that the man acquires a sense of duty so that he is much more apt to realize the importance of his position after he is actually in the service. A complete log is kept of everything that transpires, and all messages are copied and filed. These later are sorted out and entered on report blanks such as are used by the commercial companies and which are furnished by them for this purpose. In fact, the business of the station, in every particular, is handled by the students in a manner as nearly in conformity with commercial practice as is possible. In rating students for positions their record in the receiving room, and number and completeness of the messages copied are taken into consideration.

The receiving room is well equipped with commercial tuners and some special receivers and other receiving apparatus. In the laboratory we have apparatus for receiving undamped, continuous wave stations as well as spark stations, and tuning apparatus for waves as long as 14,000 meters. Most of the equipment in the receiving room is commercial apparatus, while the experimental apparatus is used in the laboratory station. Figure 4 is a photograph in the laboratory receiving room, showing some special receiving apparatus used in research work. At the right is seen a long wave receiving coupling and on the left is a continuous wave generator which was built for testing receivers for undamped waves. It can also be used as a generator for heterodyne receiving. A radio-telephone, with which some experimental work has been done, can be seen in the foreground on the left. Any transmitter in the laboratory can be controlled from this room.

For the regular station work, we have a standard six wire aerial, supported on a 100-foot (31 meter) steel tower, brought down to a mast on the building. In connection with the laboratory apparatus, we have a smaller four wire aerial and a long single wire antenna, used principally for long wave reception. With the arrangement of these different aerials and certain apparatus, it is possible to have several groups of students receiving simultaneously without mutual interference. Ordinarily we have two well-advanced operators on duty in the station from 8 A. M. until midnight; however, in case of severe storms over the lake region, a continuous watch is maintained.

FIGURE 4

Another interesting feature of the work in the radio course is the so-called "field work." One afternoon each week, when the weather conditions permit, the students are divided up into parties of four to eight and supplied with portable receiving sets or complete field sets which are taken out into the surrounding country and set up. Aerials are erected on poles provided for the purpose or put up on high trees. Occasionally a kite will be used to elevate an aluminum wire or a small boat on one of the nearby lakes will be equipped with a small sending and receiving set. Figure 5 shows a field station, in the charge of a group of students, with which they are in communication with the station at the school. As will be seen this set includes both transmitter and receiver, and when the aerial is elevated to a suitable height, it has a range of several miles. It can be used either as a "plain aerial" set or directly coupled, radiating about half an ampere either way when properly tuned.

FIGURE 5

Communication is established between these field stations and the school, where an operator is maintained. During the course of such work aerial construction, methods of quickly putting up an emergency aerial, and the importance of good earth connections are demonstrated in an interesting and forcible manner. I have also found this to be an excellent manner in which to combine practical detector adjustment, tuning and wiring up of apparatus. Many interesting experiments that can be performed in the open country readily present themselves, all of which are of advantage in an operator's training. The effects of broad and sharp waves, necessity of tuning, and the advantages of high spark frequencies and so on are readily set forth in an interesting manner.

For the benefit of special students or those who are particularly interested, we have a somewhat more advanced course in electrical and radio engineering subjects including radio telegraphic measurements and theories. The extent of this work, at the present time, is limited owing to a lack of necessary equipment, but at the same time it offers some advantages to those students who are ambitious and desirous of extending their knowledge of the art of radio communication.

During the coming fall it is our plan to erect a second steel tower 175 feet (54 meters) high at a distance of 400 feet (123 meters) from our present tower. It is also expected that we will add considerably to our electrical equipment at that time.

SUMMARY: The qualifications of a "good" operator are divided into inborn and acquired or teachable characteristics. A course of training for radio operators is then discussed in detail. The entrance requirements and objects of the students are considered, and the subject matter of the course is given.

1. OPERATING DIVISION. Students are taught to receive on buzzer-excited circuits, using head band telephone receivers. A number of circuits of gradually increasing speed and difficulty are provided. Different tones and intensities of signals are provided to accustom the student to actual conditions. All messages sent between student stations are in accordance with the radio laws and commercial practice. Messages must generally be checked and relayed by the student. Artificial interference is provided to teach reading of desired message thru such interference.

2. TECHNICAL DIVISION. The elementary principles of electricity and magnetism and the study of dynamo-electric machinery are given. Inductance, mutual inductance. capacity, wave length and frequency are studied, together with methods for their predetermination by calculation. Resonance phenomena are shown. Different types of commercial receivers and crystal detectors are tested. Field work is done with portable transmitting and receiving sets. Some facilities for research work are provided.

3. TRAFFIC DIVISION. The radio law, international regulations, geography and other material of value to operators are taught by lecture. Work in penmanship is obligatory.

DISCUSSION

Elmer E. Bucher: After careful consideration of Mr. Packman's contribution, I see that he recognizes the time-worn but desirable search for the "one hundred per cent perfect" employee. To a slight extent, I agree with him that in some respects the efficiency of the operating staff of commercial radio telegraph companies might be improved; but I must take complete exception to the allegation that the training of operators has suffered neglect, or that progress in this detail has not kept pace with general commercial radio development. The further reference to "deplorable conditions," assumed to exist in the operating staffs at certain commercial ship and shore stations, cannot carry weight without citations of specific instances of inability. It is useless to decry the service or personnel of an entire organization for the disability of a few, hence it may be of interest to give a brief outline of the method of instruction in vogue at the various radio schools maintained by the Marconi Wireless Telegraph Company, thereby disproving the assertion that radio telegraph operators have not been well trained.

It has been the practice of that Company since its inception to instruct its employees thoroly in the subject of radio telegraphy by the establishment of schools both here and abroad. In localities where the demand for operators has been insufficient to warrant the opening of a company-owned school, local telegraph schools have been subsidized or supplied with apparatus free of cost. In addition, these schools have had the free services in an advisory capacity of the Marconi officials and engineers, who have thereby assured themselves that the graduated students possess qualifications suitable to a proper standard. The foregoing policy has been adopted and rigidly adhered to thruout these years, and it is a fact that the courses given at privately owned institutions have been generally modelled after that given at the Marconi training schools.

In general, corporation-owned schools have the advantage over privately owned schools in that the former are in possession of a more complete radio equipment and are thus enabled to offer their pupils a more comprehensive course than is otherwise possible. Being in closer touch with commercial radio development and the demands of a well organized radio service, such companies are prepared to supply their students with the knowledge most necessary to their requirements, technically and commercially.

A particular problem which radio schools are compelled to meet is the varied degree of intelligence and ability manifested by the applicant for admission. In a university or college, before a student is enrolled on the roster, certain conditions must be met and complied with; consequently it is assured that the entrant is, in a large measure, fitted for the instruction he is about to receive. More clearly, such applicants have thru a number of successive years gradually fitted themselves for their more advanced work, and are therefore able to derive the fullest benefit of the instruction.

Obviously, in a radio telegraph school, such a long drawn out procedure is not possible: first, because the applicant has neither the inclination nor the financial means to support himself over an extended period of training; and second, because no commercial company would care to meet the financial drain imposed upon its treasury by carrying a student on the register for a great number of months. It may be of interest in this connection to remark that corporation-owned schools are not generally a financial success; yet companies are perfectly willing to stand the expense involved in order to maintain a high standard of service by the employment of a staff of well trained men, so important to its commercial success.

Therefore, in order that the student may receive a permanent assignment in the radio service with the least possible delay, it becomes the duty of the radio telegraph school to fill in the gaps in the student's knowledge of the art. In consequence, it is not always possible to inaugurate a definite course of procedure. In so far as possible, the mode of instruction must be varied to meet the individual needs of the pupils.

So far the best success has been achieved by first ascertaining the knowledge of the applicant in respect to the radio art in general and the fundamentals of elementary electricity and magnetism. This known, we are at once enabled to segregate the students into two classes. The missing links of the more advanced student's knowledge are then filled in by a number of general lectures on radio telegraphy, after which a series of experiments are made on the actual apparatus.

The student least informed on matters of electricity is placed in a separate class where he is given thoro instruction in the elements of electricity and magnetism. Slowly but surely, the supposed complexities of the art disappear, the pupil having formed a complete mental picture of the underlying action upon which the operation of radio telegraph apparatus is based.

In this work the instructor must exercise great patience, for it takes time to shape and mold the thought of a raw recruit in the right direction.

A similar procedure is adopted in respect to instruction in the telegraph code; *i. e.*, the student's ability is first ascertained, and then a division into classes made accordingly.

In the code classes artificial radio telegraph circuits are employed thruout, traffic being dispatched from individual to individual after the method employed at commercial ship and shore stations.

The foregoing instruction is followed up by a series of lectures on "Radio Traffic" in which the student is fully informed on the International, United States, and Navy regulations. Intricate problems which the student may encounter in dealing with various radio stations of foreign countries are discussed and solved, until it is certain that the pupil is thoroly familiarized with all possible future conditions which he may meet.

Contrary to the views expressed by the speaker of the evening, I am in favor of introducing a certain amount of automatic machine sending now and then in the code practice, for it has been observed to have a marked effect upon the student's sending. A good automatic Wheatstone sender, connected to a buzzer system, and operated at a speed suitable to the pupil's ability, will do wonders in impressing upon his mind the desirability and necessity of a uniform mode of sending. The ease of reception experienced impels the student to adopt a similar mode of formation more or less unconsciously, resulting in daily improvement.

I would lay down no hard and fast rule concerning the time required for a student to complete his tuition in radio telegraphy. I do not believe it possible to make an expert telegraphist from an absolute beginner in the space of six months, even tho I am aware that this condition has been approached in isolated instances. I do, however, maintain that by six months' study and close application a student is qualified to pass the U. S. Government examination and competent to take an assignment as junior operator at any ship or shore station.

It might be mentioned here that the Marconi Company uses every precaution in introducing a beginner into the commercial service. It is its custom to send a school graduate to sea as a junior operator, under the guidance of an experienced man. In this manner he is enabled to derive the full benefit of the senior operator's previous experience and all possibility of error thro lack of initiative on his own behalf is thereby eliminated.

In respect to training the student to read radio signals thru interference, a school located in a prominent seaboard city such as New York, does not require artificial "jamming" or interfering apparatus. A commercial receiver connected to a fair-sized aerial fulfills the requirements, the operator being enabled to separate interfering stations under actual commercial conditions. Obviously, no better method of training could be devised.

I note from Mr. Packman's contribution that certain pupils with whom he has come into contact possessed biased minds, even to the point perhaps of expressing their desires as to the type of apparatus they consider preferable! A student having pre-conceived notions in this respect is apt to possess proclivities along other lines not amenable to discipline. Hence I would lose no time, in extreme cases, for the good of the services, in eliminating his name from the records.

I contend that the profession of radio telegraphy requires young men of live and alert characteristics who are quickly capable of assimilating new ideas, progressive in their make-up and business-like in character. To secure a well-rounded employee, one equally proficient in several branches of a given art, is one of the problems of the hour; the natural result of this need has been an age of specialization which in many fields has been overdone.

A radio telegraphist cannot be a man of narrow vision. He must be broad enough to think in terms international for he comes in contact with peoples, business methods, and social customs, of all climes and races. Thru several years of experience I have not found it difficult to lay out a course of procedure that will fully fit the student in this respect; and I firmly believe that, in view of their previous training, the degree of proficiency attained by the average radio employee is remarkable, and that in no department of wire telegraphic or telephonic communication will there be found operatives of the attainments of the average telegraphist in charge of radio telegraph equipment to-day.

I think it will be found on investigation that as far as the Marconi Company is concerned, the training of radio operators has in nowise suffered neglect. Every possible available means has been brought to bear in the student's preliminary education so that he may be fully qualified to meet any emergency arising on his initial assignment to a ship or coast station.

David Sarnoff: I consider that the radio operator is one of the most important elements in radio communication. I agree, in some respects, with Mr. Bucher's refutation of the statement made by Mr. Packman regarding "the rather deplorable conditions which exist at present in the radio operating field." I believe there has been a marked tendency toward improvement in this direction during the past few years, and observation justifies the expectation that the improvement will continue.

The acquisition of the late United Wireless interests by the Marconi Company, thereby placing the large number of radio operators under the control of one organization, and the international requirements that a single code—continental—be universally employed, have helped matters considerably. By having all operators under the control of a single organization, antagonism and rivalry among operators otherwise employed by competing radio or steamship companies are removed and this is a very important factor. The advantages of a universal code are obvious in that it renders communication between operators of all nations more flexible.

Before operators are employed in the Marconi service, they are required to pass thru the Marconi School of Instruction where they are given thoro instruction in the principles and manipulation of the various types of radio equipment in general commercial use.

The procuring of a government radio license is not considered sufficient proof of the operator's ability and general fitness for the Marconi service. There are of course exceptional instances where deviation from this rule is imperative and under such conditions the choice of an operator must be governed by the exigencies of the moment.

I should like to say a word or two about the training of the radio operator, starting from the point where Messrs. Packman and Bucher leave the subject.

In my opinion the actual training of the operator commences after he leaves school and joins the operating staff. I have frequently thought that the present method of employing graduates from radio schools in the radio service is wrong; for the reason that at present their first positions are given them on shipboard whereas the better way would be to assign them first to coast stations, where they would obtain the benefit of the more skilled operators on shore, who are thoroly familiar with the proper methods of conducting radio traffic. Here also, the novices in the profession have a better opportunity of handling a larger amount of radio traffic, under the guidance and with the assistance of the more matured and trained coast station operators. The early Marconi operators, and those who now hold the more important positions in the organization, were thus trained.

Unfortunately, however, my theory is not possible of adoption by radio organizations at present, for the following reasons.

First. Because the number of coast stations now in operation, as compared with the number of ship stations, is proportionately very small.

Secondly. Because the majority of the coast stations are situated in out-of-the-way places where, by reason of existing circumstances, it is not practical to assign any but trained operators.

Thirdly. If a graduate from a school is sent to an important coast station and spends some time in becoming proficient, it is hardly to be expected that he would thereafter view with favor the assignment to a less important position on shipboard. Here, too, the difference in salaries paid at ship and shore stations would play an important part.

It is interesting to note from this evening's paper the different methods employed in training the student to become a proficient radio telegraphist, but experience has taught us that there is a marked difference shown by the young operator in transmitting or receiving messages in school, and in handling regular business at a commercial station. This is but natural, and a condition which must be expected. It is for this reason, however, that the disadvantages of placing a school graduate, even on an unimportant freight ship, are so apparent. One poor operator on shipboard, with even a weak radio equipment, can do more harm when in the vicinity of busy ship and shore stations, than can be undone by ten good operators, with an equal number of efficient sets.

In the paper on "Radio Traffic" which I delivered last year before the Institute, I dwelt at length on the importance of brevity in radio communication, and this all-important point cannot be impressed too strongly, especially on the young operator. Very often I have observed junior operators assigned to less important ship stations, transmitting a radiogram by the longest method possible, inserting unnecessary symbols and words, repeating where there is no need to do so, and thereby retarding the movement of traffic very seriously.

The young operator is often actuated by a desire to listen to himself sending. On ship stations where traffic is infrequent, the junior operator often indulges in quite a lot of unnecessary preliminaries and finishing touches, when transmitting or receiving a single message. While these matters may appear insignificant to some of those present, I submit that you need only consider the unfavorable conditions of static, or strays, interference, and frequently poor operating, to appreciate what it means to indulge in superfluities under such circumstances. On the other hand, the advantages of brevity under these conditions will likewise be apparent. Unfortunately, the government regulations pertaining to radio communication, are not adapted to the solution of these practical problems when they prescribe certain preambles and symbols in handling radio traffic. In my paper on the subject previously referred to, I gave examples of this condition.

I also reiterate my long-standing objection to the present wave length regulations enforced by international agreement. It avails us very little to produce transmitters of high radiating efficiency, and receivers capable of sharp tuning, when the majority of ship and shore stations employ 600 meters as their working wave length. I am aware, of course, that wave lengths below 600 meters may be used, and while this has been taken into consideration in the design of the more modern equipments, it fails entirely, nevertheless, to afford the measure of relief required.

In this connection I might say a word or two in admonition of the operators who fail to take full advantage of the opportunity afforded them by the latest Marconi equipments, which are provided with 300, 450 and 600 meter wave lengths, and with facilities for rapidly changing from one wave length to another, the change being effected by the throwing of a single switch. I have known operators who continue to struggle thru interference on 600 meters rather than change to 300 or 450 meters, and I have also observed others who do not even struggle. It is, however, not possible, under the present government regulations, to take full advantage of even the wave lengths mentioned; for the reason that by the rules of the London Convention it is required that when two stations communicate, both must employ the same wave length. Therefore, while it is feasible for a ship station equipped with the latest Marconi set to change quickly from 600 to 450 or 300 meters when communicating with another ship or coast station, it is not quite so feasible for the coast station to effect the same change. You will appreciate, therefore, the importance of reconsidering the whole subject of wave lengths and traffic regulations.

I would urge all of you who have opinions to express on this subject, to write the Institute.* It will be glad to accumulate and summarize all ideas so that a logical and comprehensive statement of facts and suggestions may be presented at the next International Convention, which is to be held at Washington, D. C. It may sound a trifle optimistic to talk of International Conventions in these days, but we are hopeful nevertheless.

In connection with the proper manipulation of radio equipments by operators; I have noticed during my experience that radio engineers are very often prone to criticize the operator for failure to obtain maximum efficiency, and I doubt not that the criticism is sometimes warranted; but on the other hand, something may be said about the radio engineer who, when designing radio equipment at the laboratory, fails to appreciate the operator's difficulty on shipboard. For instance, I have always felt that sufficient attention has not been paid by designing engineers to the subject of detectors. Sensitiveness seems to be the goal for which most engineers aim, but apparently stability is not given the same consideration. There is nothing more troublesome at radio stations than to handle a detector which is too frequently affected by vibration, induction from transmitting apparatus, or by the many other causes which disturb crystal detectors. Operators many times continue to call radio stations which promptly respond but are not heard because the detector at the calling station is temporarily out of adjustment. Every operator knows that this is a daily occurrence and the cause of unnecessary interference, repetition and consequent delay in the movement of traffic. I am of the opinion that some form of valve detector is probably most suitable for commercial operation at ship and shore stations, because the valve detector gives more promise of possessing the combination of the two important elements, namely, sensitiveness and stability.

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* A paper dealing with "The Inadvisibility of Wave Length Regulation" will be delivered by Messrs. Goldsmith and Hogan later in 1916. All members having views on this subject are strongly urged to communicate them to either of the authors in writing.

As regards commercial radio schools versus radio telegraph company-owned schools: It is preferable, of course, where a student can do so, to take up his course of training in a school of a large radio organization, because such a school is conducted with the object of training the men for the company's service and not for the profit derived from tuition fees. But there are many cases where, for good reasons, it is not possible for a young man to attend the company's school, and for this reason the commercial schools are performing a very important mission in the radio art. Men must be trained, and they should be trained properly. Many a boy living at or near Valparaiso, Indiana—where the Dodge Institute of Radio Telegraphy is located—might have been unable to take a course in a Marconi School situated elsewhere, and for that reason the Marconi Company lends its support to, and assists in every possible way, this School, as well as all other schools which show a desire to train operators as they should be trained.

Alfred N. Goldsmith: There is no doubt whatever that the question of wave length regulation, which has been brought up by Mr. Sarnoff, is worthy of the most careful consideration. It is further desirable that it be carefully considered *at length*, in view of the possibility of an International Convention on this subject within the next two years. It is not at present obvious that wave length regulation is at all a necessity, and certainly the matter is one for considerable discussion.

As an illustration of an undesirable state of affairs, attention may be called to the restriction of the important range of wave lengths between 600 and 1,600 meters to the use of the Government. It will be noted that most of the stations using these wave lengths are Navy stations, primarily intended for use in times of war, but not for commercial service in times of peace. Whenever one realizes that in times of war the enemy would hardly refrain thru courtesy from using wave lengths within the restricted range, the valid objection to closing this range to all commerical ship and shore stations, becomes evident. The ability to tune skilfully and read thru interference is well worth cultivation.

I feel further that amateurs have been unduly hampered by the wave length restrictions which are now current. This, however, is of comparatively small importance when contrasted with the really serious crippling of commercial traffic by the enforced rules concerning 600 meter transmission and the equality of wave lengths between ships and their corresponding shore stations.

I expect that in the near future a paper will be written by Mr. Hogan and myself dealing with the question of wave length regulation and considering critically whether any wave length regulation should be adopted, and furthermore what rules of radio traffic are most desirable. I am very desirous that all members of the Institute or others interested, should correspond with Mr. Hogan or myself, on this subject in order that we may have the broadest expression of opinion on which to base our own judgments.

Referring further to a possible part of the training of the radio operator which has not been clearly brought out, it seems to me that it would be well to give the students in radio operating some courses in reading messages thru atmospheric disturbances. It would be possible to imitate their effect in the laboratory and thus train the student, at least to some extent, in receiving thru such strays.

John L. Hogan, Jr.: I have been much interested both by Mr. Packman's paper and by Dr. Goldsmith's statement as to the problem of wave length restriction which has been before us for some years. It is so nearly a self-evident fact that the present Federal regulations as to radio wave lengths are of an unjust and ineffectual nature that their adoption seems a most surprising thing. The restriction of wave lengths between 600 and 1600 meters, which is the range best adapted for low and moderate power ship communication, to Government use is an act which has caused and is causing unfortunate delay in the development of the commercial radio art. The requirement that inter-communicating stations both use the same wave length, and the insistence that ships communicate always with the nearest land station, are also regrettable features of the present Convention rulings.

With reference to Mr. Packman's paper, I must agree with Mr. Bucher in his indication that the operating situation of commercial radio telegraphy is not entirely "deplorable." Nevertheless, there are a number of points upon which the vast majority of radio operators could be better trained.

One of these, which was mentioned incidentally by Mr. Packman, receives far less attention than it really deserves. This is the matter of operators' handwriting. It has been my experience that the "copy" of radio operators is as a rule much poorer than that of wire telegraphers. One reason for this is, of course, that the average age of the radio men is considerably below that of the line men, and that the penmanship of the radio operator is therefore likely to be in a formative stage. Another reason is that the traffic in many radio stations, on account of its small volume, puts no especial premium upon and offers no especial opportunities for clear smooth handwriting. It is a fact, nevertheless, that a radio operator is not likely to advance rapidly to better operating positions, and thereafter to executive positions, if his handwriting is of an uncertain and illegible type. It is not probable that too much emphasis can be laid upon the desirability of careful drill in helping to form the habit of clear and characteristic handwriting.

A second point is that radio operators in a commercial telegraph school should be trained to copy signals thru static interference strays. I have known men to be graduated from telegraph courses with the ability to read good buzzer signals, at fairly high speeds, and after securing their Government licenses, to fail utterly in attempts to read incoming radio messages thru even moderate static disturbance. Until an operator has become accustomed to concentration upon signal notes in the midst of harsh irregular noises from strays, he is likely to become excited and useless if he encounters unusual atmospheric interference. If it were difficult to give such training during the usual telegraph course, it might be expected that the operators would have to wait until they entered commercial service for this part of their training. However, it is not at all impracticable to combine practice in receiving thru strays with the ordinary daily code practice which all students of radio operating must be given.

Figure 1 shows a device which is simple and easily set up, yet which I do not believe has been used for this purpose except by the National Electric Signaling Company. In this diagram, X represents a weighted pivoted contact which drags upon the heavily and irregularly knurled surface of a slowly revolving metal wheel. Connected in series with this imperfect contact is a battery B_1 and potentiometer R_1. By suitably choosing the speed of the wheel and the weight of the contact at X, the strength of battery B_1, and the position of sliding contact on R_1, irregular impulses corresponding to almost any sort of static may be applied to the line wires L_1, L_2, thru the telephone transformer T_1. These irregular current impulses, transmitted from the line wires, are reproduced in receiving

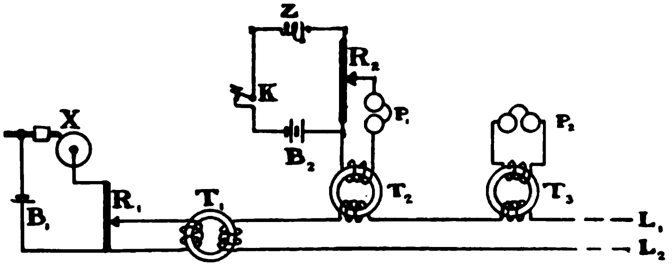

FIGURE 1

telephones P_2, thru the telephone transmitter T_3, as scratchy hissing sounds closely resembling those produced by atmospherics. A buzzer sender, consisting of a buzzer of any frequency Z, a key K and battery B_2, and a variable resistance R_2, may be associated with the line wires thru another telephone transformer T_2. By varying the potentiometers R_1 and R_2, the relative intensities of strays and signals can be made anything desired. It is, of course, obvious that additional transmitters of various frequencies and intensities can be associated with the same line wires, and that these wires may be used to conduct the signals to any reasonable number of student's receiving telephones, such as P_2. While many modifications of the device are obvious, the system as shown has proved very useful for such work as I suggest, and practice on it would form a desirable part of any radio operator's preliminary experience.

A third point upon which many radio operators are weak lies in the adjustment of their receiving tuners. Inductively coupled receiving apparatus, having variable primary and secondary inductances, and a tuning condenser directly connected across the secondary coil, represent the best practice of the commercial radio service to-day. This apparatus, simple as it is, is capable of giving widely different results in the hands of operators of different degrees of experience. Setting aside for the moment those men who are really able to handle an inductively coupled receiver properly, the remaining radio operators may perhaps be divided into two groups. The first of these, which we may call the "primary men," do all their adjusting by altering the inductance of the primary circuit and at the same time leave the secondary inductance and capacity at some average setting which gives fairly satisfactory results, so long as no interference is encountered, The second group, or "secondary men," have a great aversion to changing the settings of their primary coils and tune only with the secondary variable condenser. It is obvious that an operator who is in either of these classes will be certain to get only mediocre results from even the most carefully designed receiver. It is highly essential that all radio operators should appreciate that with an inductively coupled tuner they will secure maximum loudness of signals with maximum freedom from interference when their primary and secondary are both tuned to the wave length they desire to receive, and when the coupling between primary and secondary coils is properly adjusted. It requires a considerable amount of actual practice with inductively coupled tuners to learn just how the four variables (primary, secondary, inductive coupling, and secondary capacity) are inter-related and how compensating adjustments in each must be made as the others are changed.

In order that beginners may have training of this sort, they are usually given short periods of listening at an operating receiving radio station. It is manifestly impossible to handle a large class in this way, giving each one of them enough practice in tuning to be of much value to him. In order that radio schools may deal with this point in a way comparable with its importance, I suggest the circuit arrangements shown in Figure 2.

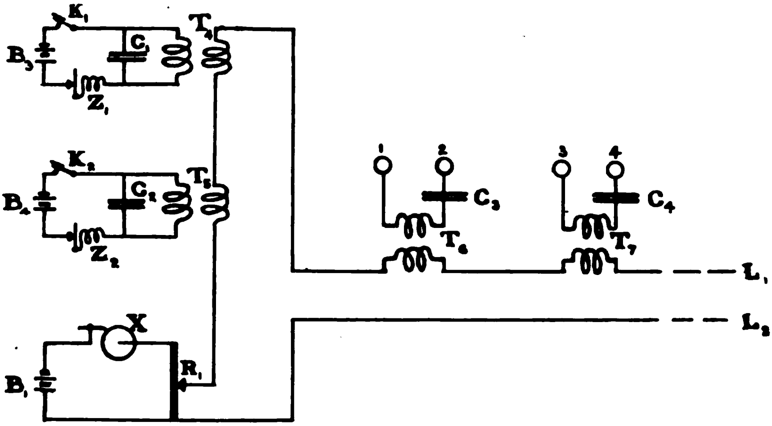

FIGURE 2

In this diagram, buzzer exciters producing radio frequency currents of any desired intensity and group frequency, and corresponding to waves of any length and decrement encountered in practice, are associated with the line wires L_1, L_2. The buzzer Z is connected with battery B, key K, capacity C, and the primary air core transformer T as shown. With the same line wires a static exciter such as that described in connection with Figure 1 may also be connected. At each student's desk, the line wire is connected thru a transformer, such as T_6, which has its terminals connected to binding posts such as 1 and 2, thru a condenser, as C_3. The radio frequency currents set up by the buzzer exciters impress forced radio frequency voltages upon the terminals 1, 2, and if the capacity C_3 and inductance of T_6 are chosen so as to represent properly an average antenna, any radio receiving set may be connected to the two binding posts exactly as it would be connected to antenna and ground in a radio station. By tuning the receiving sets so connected, signals from any of the buzzer exciters may be selected, as signals from outside stations may be selected in practice. The difficulties of eliminating highly damped disturbances, such as those of strays, may also be experienced in this way, since the impulse maker X will shock the primary circuit of each receiving tuner into oscillation of whatever period it has, exactly as static would in an ordinary receiving station. For tuning to damped waves, one or more of the buzzer exciters may have resistance inserted in their oscillation circuits, so as to increase the decrement of the current impulses there generated.

Simple modifications of Figure 2 which will permit students to inter-communicate under conditions very closely approximating those of actual radio practice may easily be devised by following the principles just outlined. It is certain that training of this sort would go far toward increasing the traffic handling ability of any operator who has not reached a point of high efficiency in the manipulation of his instruments.

By these comments, I do not wish to be understood as inplying that radio operators in general suffer from inability in these several directions. There are many men in the field of whom their respective service executives may well be proud. There are, nevertheless, many inexperienced telegraphers who would be greatly benefited by thoro drill in the three matters I have discussed. It is my hope that future courses of training in radio telegraphy will give beginners greater opportunities for thoro understanding of commercial radio conditions.

M. E. Packman: In reference to Mr. Hogan's scheme of using many commercial receiving sets, which, of course, is highly desirable, he apparently fails to appreciate the fact that it would require about 25 to 30 receiving sets, costing from two hundred and fifty dollars up. Such expense is not possible for commercial institutions.

The work with elaborate artificial antennas in receiving has been turned over to the more advanced students.

In reference to Mr. Bucher's and Mr. Sarnoff's remarks in connection with the deplorable conditions I referred to, I think that they are both considering the service on the Atlantic Coast which is indeed better than it is in other parts of the Marconi service. I am more or less familiar with Mr. Bucher's school and know that his training is very comprehensive but the point is that the demand is far greater than the school can supply. I have known men in service who have first grade licenses and who are actually unable to receive anything. I have known men in my own school who get thru the commercial examinations with no trouble who are practically worthless as far as commercial service is concerned. This condition has been the case for a good many years in the part of the work with which I am familiar, tho it has been improving from time to time. Many operators have been employed who have practically very little knowledge as compared with what they should have.

On the Great Lakes, it must be considered that the time of navigation does not exceed over nine months and that out of 60 or 80 ships, there are only 15 or 20 which run the whole year round. This means that there will be 40 or 50 operators required at the beginning of the season. Some of the old ones return, but only very few, and the first men that call at the office are the ones that secure the positions, regardless of their ability. The point to be noted is that they are employed without knowledge of the chief operator as to their ability. This condition does not exist in the East to this extent.

(Further material received from Mr. Packman too late for insertion in this issue of the PROCEEDINGS will appear in an early issue.—EDITOR.)

SUSTAINED RADIO FREQUENCY HIGH VOLTAGE DISCHARGES*

By

HARRIS J. RYAN AND ROLAND G. MARX

INTRODUCTION

In high voltage work, discharges thru the air between conductors and over and thru insulators can be prevented only with the aid of ample knowledge of their characteristics. Discharges produced by low (audio) cycle voltages for given conditions are now fairly generally understood. In radio telegraphy, high (radio) frequency damped and sustained high voltage waves are employed. Accidents, including lightning, produce in high voltage power circuits, in the long run, almost every conceivable high voltage transient. Such transients may vary from a simple over-voltage at normal frequency thru all possible impulses and damped oscillations to perhaps a briefly sustained high frequency high voltage wave train. Little is known as yet of the relation between discharge distances and voltages of the various sorts just specified. The evidence so far accumulated indicates that for given values of maximum voltage, the discharge distances are almost *independent* of the characteristic variation of the voltage whenever the critical corona voltage is higher than the discharge voltage. It indicates, too, that the discharge distances are *dependent* upon the characteristic variation of the voltage whenever the critical corona voltage is below the discharge voltage. In regard to the latter condition, this evidence indicates further that the discharge distance will be longest when the voltage source or transient is most sustained, or when its frequency is the highest or when both of these characteristics are present. It follows that discharge distances should be found a minimum for low frequency high voltages and a maximum for sustained high (or radio) frequency high voltages. It thus appears that voltages which can be formed by accident may discharge thru

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* A paper presented before a joint meeting of The Institute of Radio Engineers and The American Institute of Electrical Engineers, San Francisco, September 16th, 1915.

greater distances and do more damage than the same values of voltages as used in most commercial work. The following experiments were undertaken as a reconnaissance in this region of high voltage phenomena.

DISCHARGE INTO THE ATMOSPHERE FROM A SINGLE ELECTRODE

One terminal of a sustained high frequency high voltage source[1] was grounded, the other was a 1-inch (2.5 cm.) copper tube capped with a hollow copper sphere 2 inches (5 cm.) in diameter. This spherical end of the high voltage terminal was mounted properly remote from all grounded objects. When a voltage of 50,000 at 88,000 sustained cycles was applied, a dry redwood stick was brought near to the sphere and then removed. A spark passed from the sphere to the stick and immediately grew into a heavy brush discharge. See Figure 1. It consisted essentially of an active mass of darting streamers. The character of this mass varied from that of a combustion flame at the base to the familiar static discharge at the extremities. We have been able to determine with a fair degree of approximation (by measurement correct to within ten per cent.) that the rate of energy supply in the discharge from the electrode, illustrated in Figure 1, was about one kilowatt. It is charac-

FIGURE 1

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[1] Described in "*Sphere Gap Discharge Voltages at High Frequencies,*" by J. Cameron Clark and Harris J. Ryan, "Proceedings of the Am. Inst. Elec. Eng'rs," June, 1914, Vol. XXXIII, page 937.

teristic of this high voltage, radio frequency discharge, that it consumes a large amount of power; and if that power is not available, a discharge will not develop. It may start to develop and one may see some brush momentarily, but not the actual discharge. No "flashing-over" effect will be produced unless plenty of power is available. The discharge averaged about 10 inches (25 cm.) in length, was rather bright, produced a hissing, roaring sound, and was not accompanied by the familiar odor of ozone that is formed by the less violent audio frequency or intermittent radio frequency discharges. It is easily blown about by air currents. It may be blown by the breath from place to place on the ball. It can be fanned with a hat from the ball back along the 1-inch (2.5 cm.) conductor, and put out as it is driven into the region of lower capacity in the vicinity of the conductor, that is, where the fields are less intense and where the energy cannot be delivered at the rate that the flame or the discharge requires.

A modification of the above experiment was arranged to enhance the flame-like portion of this discharge, and to eliminate most of the "brush" part. A circular metal disk 16 inches (40 cm.) in diameter, provided with a 3-inch (7.5 cm.) hole at its center, and with ¼-inch (0.6 cm.) guard tubing facing all edges, was hung centrally over, and about 3 inches (7.5 cm.) above the 2-inch sphere (5 cm.) terminal by means of nonconducting supports. Figure 2 is a photograph of the steady flame-like discharge that occurred from the sphere to the plate. This photograph was naturally obtained by a legitimate artifice. In the laboratory, everything was dark when the first exposure was made and the flame photographed; and then by using some flash-light powder, all the apparatus was illuminated so that it could be photographed also. The flame, tho very strong, gives off no great amount of luminous radiation. The voltage and frequency were the same as before, viz., 50,000 and 88,000. The temperature of this flame was high. It melted quartz, rapidly disintegrated a tungsten lamp filament, and formed a bead on the end of a Nernst lamp filament. The metal of the electrodes was not greatly heated, and little or no metallic vapor appeared to enter the arc stream.

This flame discharge is not stable under all conditions. For example when the inductance and capacity of the disk were increased by placing in contact with it one end of an insulated 1-inch (2.5 cm.) copper tube 4 feet (1.2 meter) long, the flame discharge was no longer quiet and stable, but became noisy and snappy, tending to develop into an intermittent disruptive discharge. The flame became unstable also when the electrode gap length of the arc generator was too short in adjustment. It appeared to be identical with the flame-like portion of the heavy brush discharge of Figure 1. Time did not permit a study of the extent to which the combustion of nitrogen was taking place in the flame. It seems as tho something of the sort is occurring for the reason that ozone is not in evidence when this discharge occurs.

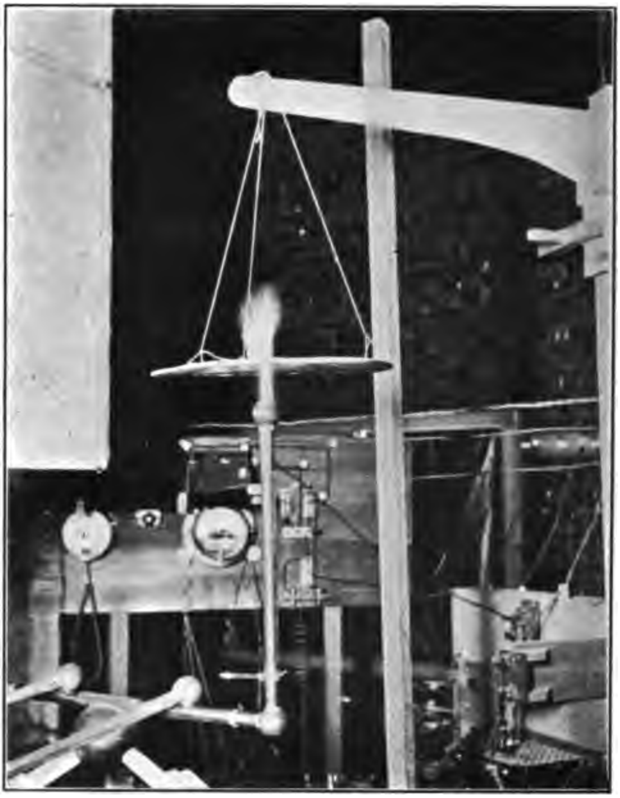

FIGURE 2

The ability of the radio frequency brush to produce thermionic conduction thru glass, porcelain, quartz and all similar refractory insulations is perhaps its most remarkable property. This is illustrated by bringing any mass of high grade electrical porcelain near to or in contact with the sustained radio frequency electrode. In an actual case, the electrode was a ½-inch (1.2 cm.) aluminium tube laid in the top groove of a 33 kilovolt porcelain line insulator that was itself placed on an insulating support and mounted remote from all objects of opposite or ground potential. On the application of 35 kilovolts at 200,000 cycles, the air between the tube and insulator was overstressed, small flame discharges conducted the insulator charging currents to the porcelain surface where one or more brilliant hot spots would appear in about 30 seconds. Further study developed the fact that these hot spots were the heads of corresponding hot conducting cores that extended into the depth of the porcelain, thus establishing by conduction new routes for the delivery of the charging currents taken by the porcelain mass. No insulation that supports a conductor charged with high voltage at sustained high frequencies can endure, unless it is so designed that not a particle of air or other gas in contact with it is overstressed under actual working conditions. The Fortescue and Farnsworth principle can be employed in the design of such supporting insulators so as to suppress all overstress of air adjacent to the porcelain or other solid dielectric.[1]

SUSTAINED RADIO FREQUENCY CORONA ABOUT A WIRE

The general arrangement of the equipment employed for the sustained radio frequency corona study is shown in the diagram of Figure 3; and a photograph thereof in Figure 4. The corona was formed around a number 19, B. & S. gauge clean copper wire* held axially in a galvanized iron cylinder, 15 inches (38.1 cm.) in diameter and 35 inches (88.9 cm.) long. Twelve (12) inches (30 cm.) of the wire at the center of the cylinder were normally left clear, and the remainder was shielded by two brass tubes 7-16 inch (1.1 cm.) in diameter. A third tube ½ inch (1.2 cm.) in diameter was arranged to slip over the central portion of the wire, and shield that too when desired. In this manner the corona could be suppressed, or it could be allowed to develop by removing the copper tube from the wire, and thus greatly increasing the stress on the atmosphere adjacent to the wire (because of the smallness of the wire circumference). We could thus check up the accuracy of the cathode ray power measuring meter.

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[1] "*Air as an Insulator when in the Presence of Insulating Bodies of Higher Specific Inductive Capacity,*" C. L. Fortescue and S. W. Farnsworth, "Trans. Am. Inst. Elec. Eng'rs," 1913, Vol. XXXII, page 893.

* Diameter of wire = 0.036 inch = 0.092 cm.

Various voltages up to about 30 kilovolts, (root-mean-square), were impressed on the wire at sustained radio frequencies of 88,000 and 188,000 cycles per second; also at 60 cycles per second for comparisons. The appearance of the coronas at radio and audio frequencies differed greatly, while those at the two radio frequencies differed only slightly. That is to say, the enormous difference in corona at radio frequencies and at audio frequencies such as 60 cycles, is a difference that has come about perhaps gradually on the way up from 60 cycles to some such value as 50,000 cycles. At all events, to double, or a little more than double the frequencies when one is operating at a frequency of as high as 80,000 cycles, produces very little effect on the character of the phenomenon. The radio frequency corona appeared very active, it was quite brilliant and noisy and gave off an appreciable amount of heat. At 30 kilovolts the average diameter of the radio frequency corona was about 2 inches (5 cm.) whereas that at the audio frequency appeared to be less than 1-8 inch (0.3 cm.). A photograph of these coronas is reproduced in Figure 5. Two exposures were

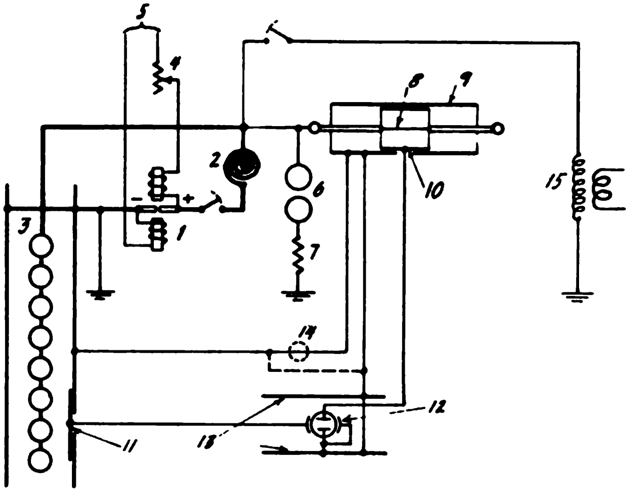

FIGURE 3—Diagram of Connections for Sustained Radio Frequency Corona Investigation

1—Arc Generator
2—Air Inductance
3—Air Condenser
4—Resistance
5—To 1200 Volt D. C. Supply
6—Sphere Gap Voltmeter
7—Carborundum Resistance
8—Corona Wire
9—Cylinder
10—Potential Tapping Cylinder
11—Potential Tapping Plate
12—Cyclograph Quadrants
13—Guard Plates
14—Carbon Lamp Resistance
15—60 Cycle High Voltage Transformer

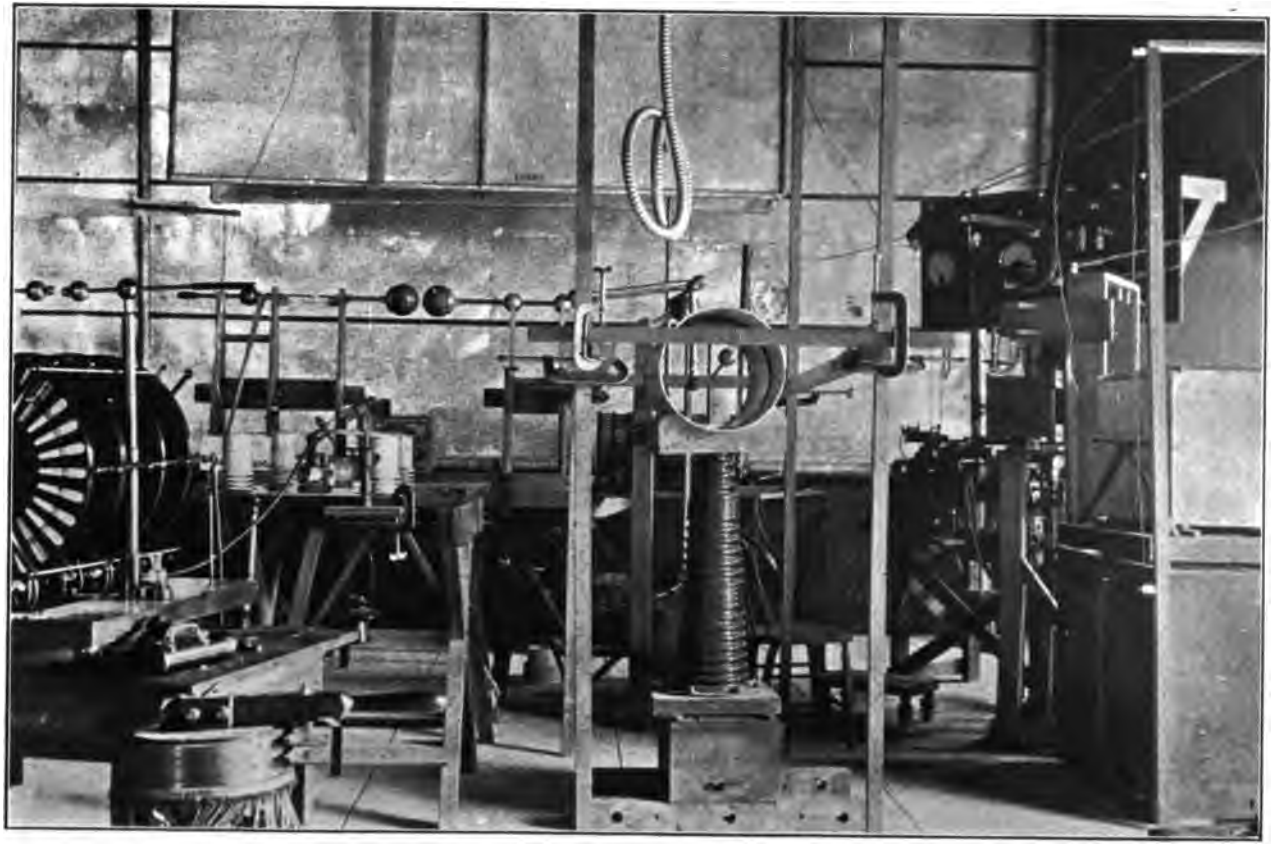

FIGURE 4

made on the same film; on the left is a 1-second exposure to the corona about the wire at 19.5 kilovolts and 188,000 cycles, while on the right is a 120-second exposure to the corresponding corona formed at the same voltage and 60 cycles. The camera was moved so as to separate the two images. In the original photograph the difference is very striking. Not only was the exposure 120 times as large, but the result was very nearly as many times less. The action is therefore a vastly more intense one.

FIGURE 5

Some observations were made to determine the relative values of the voltages required to start corona about the wire at 188,000 cycles and at 60 cycles. All voltages were determined with the same 5-inch (12.7 cm.) spherical gap.* Attention is called to the lack of information that we have as yet in regard

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* Little has been published as yet in regard to the standardization of the sphere-gap for the measurement of radio frequency voltage. It appears likely that not much more than a beginning has been made. Until such standardizations are available, the spherical gap will serve quite well as a radio frequency voltage gauge for purposes of record and comparison. The working scale for the 5-inch (12.7 cm.) spherical gap used herein was arbitrarily chosen as the one determined at radio frequencies for a 7-inch (17.8 cm.) spherical gap with the neutral of the voltage source grounded. *Loc. Cit.* No. 1; also "Dielectric Phenomena in High Voltage Engineering," by F. W. Peek, Jr., page 107.

to the standardization of these gaps. Our work has indicated very closely that there is little difference between the indications that a sphere electrode gap will give for given values of voltage at radio and at audio frequencies. However, for the exact interpretation of the result as given here, the footnote will be helpful. The density of the atmosphere was that due to ordinary temperatures near sea level. Twelve and seven-tenths (12.7) kilovolts were required to start the corona at 188,000 cycles and 13.2 kilovolts correspondingly at 60 cycles. The indications of the sphere gap were here assumed to be independent of changes in frequency.

Cyclograms were taken of the energy consumed per cycle in the corona about the wire at 60, 88,000 and 188,000 cycles and at voltages ranging from 15,000 to 20,000 to determine the relative power factors and the wave forms of the currents flowing from the wire. The cathode ray tube was used in taking these cyclograms. The details of the method used have been given in the "Transactions of the American Institute of Electrical Engineers."[1] The actual arrangement of the cyclograph with its voltage and current condensers as used in the present work is given in the diagram of Figure 3. Various trials were made to determine that the cyclograph gave true indications within its limits of action when high frequency high voltage was used. These trials were as follows. When the wire at number 8, Figure 3, was screened from corona formation by sliding the ½-inch (1.2 cm.) brass tube over it, the cyclogram would close up into a right line loop without area. Thus arranged, by inserting an ordinary incandescent lamp at number 14 the cyclogram would open so as to enclose a large elliptical area. Again using the radio frequency high voltage, the effect in the results due to the hysteresis or other loss in the glass of the cathode ray tube was found to be negligible by noting that a no-area cyclogram obtained with all four quadrants mounted on the exterior wall of the tube remained as such when all conditions continued the same except that one pair of quadrants was mounted within the tube.

In Figure 6 sample cyclograms are reproduced. With the aid of the lantern, enlarged images of these cyclograms were thrown upon a sketching board and tracings carefully made. Figure 7 was engraved from these tracings. The distortion noted is due to the fact that the only suitable tube available

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[1] "*A Power Diagram Indicator,*" Harris J. Ryan, "Trans. Am. Inst. Elec. Engin'rs," 1911, Vol. XXX, pages 1089–1113.

for this sort of work was one of small size. To obtain sizeable cyclograms, it was necessary to permit some distortion in their lower portions. They are instructive, however, for they show that the radio frequency corona current wave suffers less distortion than the corresponding audio frequency corona current wave. They also show, under the conditions present, that the power factor of the radio frequency corona current was about *one-quarter* of the power factor of the corresponding audio frequency corona current. The present work, however, as stated in the introduction, is merely a reconnaissance of these interesting phenomena. It will be profitable to have them studied broadly and with great care, especially so with ample and suitable facilities.

FIGURE 6

DISCHARGE BETWEEN BLUNT POINT AND PLATE

A needle point is promptly melted and burned by radio frequency brush discharges. Only blunt points can be used, therefore, to determine the radio frequency high voltages required to discharge given distances when one electrode is or both electrodes are in corona. The scheme employed in this set of determinations is diagrammed in Figure 8 for the radio frequency or audio frequency discharges, and in Figure 10 for combined audio and radio frequency discharges. A photograph of the electrodes and the sustained radio frequency discharge between them is reproduced in Figure 9.

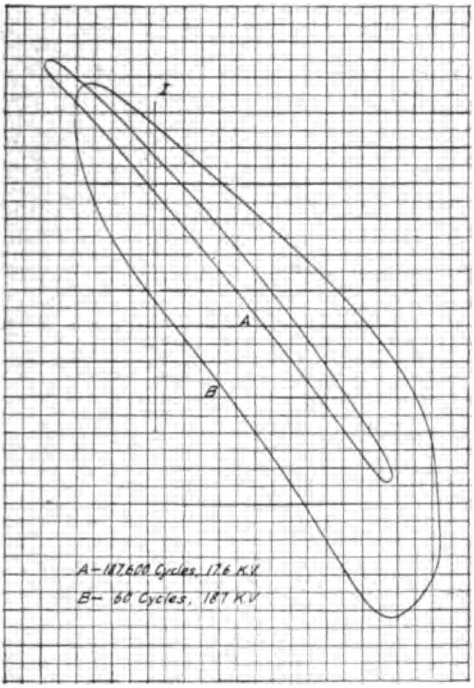

FIGURE 7

The blunt pointed electrode connected to the high frequency source was a square ended piece of number 12, B. & S. gauge copper wire,* projecting axially from the main radio frequency high voltage electrode, constituted as before of a 1-inch (2.5 cm.) copper tube ended with a 2-inch (5 cm.) copper sphere. A galvanized iron sheet, 3 feet (91.4 cm.) square, was used as the grounded electrode. Carborundum resistances (see number 5, Figure 8), were employed at strategic points to avoid short-circuiting the machines that supplied the arc generator with continuous current. The 5-inch (12.7 cm.) sphere gap at number 4, Figure 8, was used to measure all voltages. The sustained radio

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* Diameter of number 12 wire = 0.081 inch = 0.21 cm.

frequency voltages that produced discharges between the point and plate also produced at slightly lower values heavy brushes that extended from the blunt point most of the distance to the plate. In fact, the discharges seemed to occur only when the brushes appeared to have fully bridged the space between the

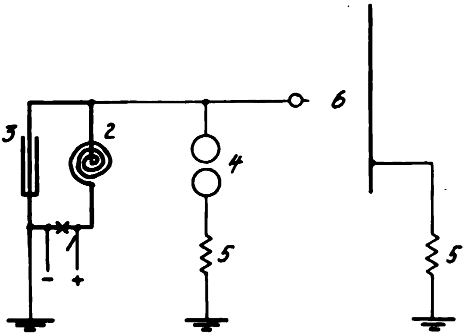

FIGURE 8—Diagram of Connections for Point to Plate Discharge

1—Arc Generator
2—Air Inductance
3—Air Condenser
4—Sphere Gap Voltmeter
5—Carborundum Resistance
6—Point to Plate Gap

FIGURE 9

electrodes. Facilities were lacking for the measurement of the large amounts of power that were evidently consumed in these brushes.

The 60-cycle voltage source was substituted for the arc generator in this sustained radio frequency point to plate discharge equipment diagrammed in Figure 8; and voltage discharge distance measurements were then made to compare with the corresponding sustained radio frequency discharge distance measurements. Likewise for comparison a few determinations were made of the radio and audio cycle voltages required to discharge from the same blunt point to a similar blunt point in lieu of the galvanized iron plate.

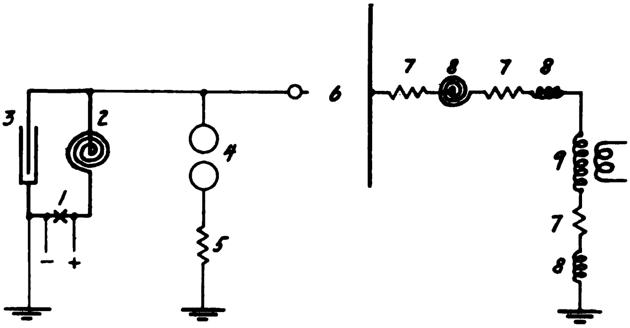

FIGURE 10—Diagram of Connections for Discharge with Combined Radio and Audio Frequency Voltage

1—Arc Generator
2—Air Inductance
3—Air Condenser
4—Sphere Gap Voltmeter
5—Carborundum Resistance
6—Point to Plate Gap
7—Carborundum Protective Resistance
8—Protective Air Inductance
9—60 Cycle High Voltage Transformer

The results obtained for the audio and radio frequency discharges are charted in Figure 11; and for the composite discharge values produced by the simultaneous application of sustained radio frequency voltage from earth to the blunt point and of 60-cycle voltage from earth to the plate are given in Table I. Two forms of discharge occurred and are designated "spark" and "arc" discharge. The former occurred at a somewhat lower voltage than the latter. The spark functioned to discharge the main condenser of the radio frequency generator and the arc to short circuit the 60-cycle and 1,200-volt direct current sources. The sums, equivalents and differences recorded also in Table I, and the values at corresponding differences charted in Figure 12 assist one to understand the parts that each voltage took in forming the composite discharges.

It is of interest to note (see Figure 11), that whereas 135 kilovolts at 60 cycles were required to discharge 16 inches (40.6 cm.) from the blunt point to the plate only 46.2 kilovolts were required correspondingly at 88,000 cycles. An increase of 7.5 kilovolts at 60 cycles was required by an increase of 1 inch (2.5 cm.) in the 15-inch (38.1 cm.) discharge gap while the corresponding increase at 88,000 cycles was only 1.5 kilovolts. In other words, as the length of a 15-inch (38.1 cm.) point to plate gap is increased the amount of increase of 88,000 cycle discharge voltage is *one-fifth* of that required at 60 cycles.

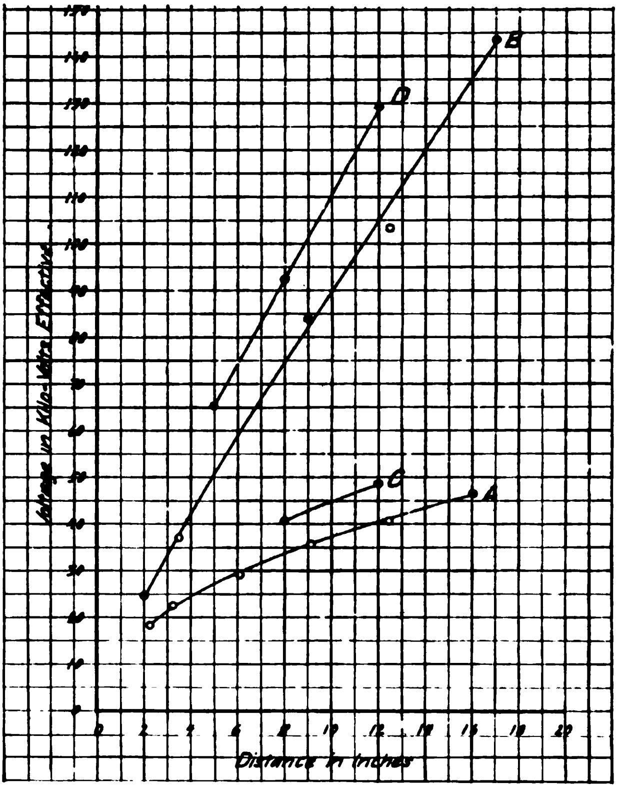

FIGURE 11—Point Discharge

A—Point to Plate, 88,000 Cycles
B—Point to Plate, 60 Cycles
C—Points, 88,000 Cycles
D—Points, 60 Cycles

NOTE—Radio Frequency Sphere Gap Voltmeter Calibration Used in all Cases.

The composite discharge distances due to the combination of audio and radio frequency voltages are virtually the sum of the distances thru which the individual voltages discharge. In Table I, column 2, the radio frequency voltages alone would have discharged the distances given in column 6[1], which when subtracted from the actual discharge distances in column 1, give the distances in column 7 as the added discharge distances due to the audio frequency voltages in column 4. These audio frequency voltages and the added discharge distances they caused are charted in Figure 12. For comparison the A. I. E. E. standard

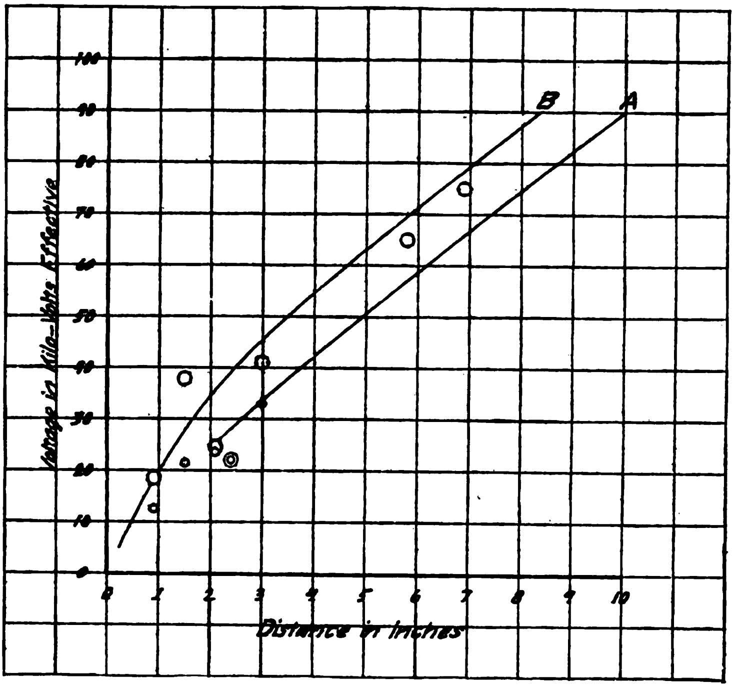

Figure 12—Plot to Accompany Table 1

For points marked thus—o Abscissas Represent Values in Column 7, Ordinates in Column 3
For points marked thus—O Abscissas Represent Values in Column 7, Ordinates in Column 4
A—Curve B of Figure 11
B—A. I. E. E. STANDARD Needle Gap Curve

needle gap voltage discharge curve and the 60-cycle point to plate discharge curve of Figure 11 are also charted as curves "B" and "A" in Figure 12. It is thus seen that the added dis-

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[1] These distances were observed for the conditions shown in Figure 10, and are not identical with distances for corresponding voltages observed for the conditions in Figure 8 and charted in curve A, Figure 11.

charge distances due to the superimposed audio frequency voltage are practically the same as the corresponding discharge distances produced by the identical audio frequency voltages acting alone. In making this comparison, one must hold in mind the fact that the added discharge distance caused by the superposition of the 60-cycle voltage should naturally be somewhat greater than the discharge distance produced by such audio cycle voltage acting alone; because in the former case, no initial voltage is required to start corona at the blunt point; such corona is started by the sustained radio frequency voltage.

The authors desire to acknowledge herewith the valuable assistance rendered by their departmental co-worker Professor J. C. Clark.

SUMMARY: 1. Sustained radio frequency corona brushes or flames once started are maintained at much lower voltages than those required to start them by overstressing and ionizing the atmosphere. They quickly destroy even the most refractory insulations by their heating and ionizing properties.

2. The power factor of the charging current of a conductor in corona due to the application of sustained radio frequency high voltage is decidedly lower than the corresponding power factor at audio frequencies. Nevertheless, because of the high values of the currents that produce the radio frequency coronas, the losses they cause may be hundreds of times the corresponding audio frequency losses.

3. The sustained radio frequency voltage required to discharge between corona-forming electrodes may be as low as one-third of the corresponding audio frequency voltage. At higher voltages this ratio will probably be found to be less than one-third.

4. Sustained radio frequency and audio frequency voltages when combined, discharge thru distances between corona-forming electrodes that are substantially the sum of the distances thru which such voltages would discharge when acting alone, due account being taken of their mutual aid in starting the corona at one or both of the electrodes, as the case may be.

TABLE I

Combined Radio Frequency and Audio Frequency Voltages; Point to Plate Discharge

1 Gap Distance in Inches	2 Radio Frequency Voltage in Kilovolts	3 Audio Frequency Voltage for Spark Discharge	4 Audio Frequency Voltage for Arc Discharge	5 Sum of the R. F. and A. F. Voltages	6 Discharge Gap Equivalent to Radio Frequency Voltage	7 Difference, Column 6 Subtracted from Column 1
5	28.7	....	....	....	....	...
5	....	....	51	....	....	...
5	21.2	22	....	43	2.6	2.4
5	21.2	....	22	43	2.6	2.4
5	22.4	23.5	....	46	2.9	2.1
5	22.4	....	24.5	47	2.9	2.1
5	26.4	12.5	....	37	4.1	.9
5	26.4	....	18.5	45	4.1	.9
12	42.9	....	....	....	....	...
12	....	....	105	....	....	...
12	29	....	75	104	5.1	6.9
12	31.8	....	65	97	6.2	5.8
12	37.5	33	....	70.5	9.0	3.0
12	37.5	....	41	78.5	9.0	3.0
12	40.3	21.5	....	62	10.5	1.5
12	40.3	....	38	73	10.5	1.5

Radio Frequency Voltages at 88,000 cycles. All voltages in terms of five inch (12.7 cm.) gap; the calibration being taken as Kilovolts (effective) = 2 + 45.5 × (Gap Distance in inches) = 2 + 17.9 × (Gap Distance in cm.).

DISCUSSION

Robert B. Woolverton (Chairman): On behalf of The Institute of Radio Engineers, I wish to acknowledge the great courtesy of the American Institute of Electrical Engineers in the arrangements it has made for this joint session.

As the advantages of the use of long wave lengths in radio communication become more and more evident, it has become apparent to radio engineers that they are limited quite strikingly in the use of these long waves at high power by the formation of corona on the antenna. It is obvious, therefore, that any light that can be thrown on the subject of corona is of intense value to radio engineers.

Robert H. Marriott: As Mr. Woolverton has pointed out, a paper of this kind should enable us to anticipate what may be expected in the way of corona on high power station antennas, and in that way we can keep down costs. It will be remembered that the matter of antenna insulation has always been one of the important things in radio work.

Haraden Pratt: Does the resistance used in connection with direct current arc generator circuits vary with frequency? Another matter which arises in connection with this paper deals with harmonics produced in the working circuits. Taking a circuit of 100,000 cycles, I have been able to observe as many as 62 harmonics, some more or less strong than others. In the event that some parts of the apparatus subjected to the high potentials, such as the concentric brass tubes mentioned in this paper, should have a capacity that would reinforce one or more of these harmonics, might not the added steepness of the very high frequency wave affect the character of the corona ?

Harris J. Ryan: I have had no experience with the variation in the resistance of the carborundum rods with frequency. I understand that their resistance does vary with frequency. We were compelled to use these rods as a matter of strategy in preventing short circuit currents. Otherwise, it would have been disastrous for our apparatus. The values of the resistance, however, were so low that the results were not affected by the presence of these rods. We are confident of that. We made tests and assured ourselves of the fact that we were not using too much resistance.

Unavoidably harmonics are produced in the driving voltage of the Poulsen arc generator. However, in generating high voltage, the inductance of the oscillating circuit must be made relatively large and the capacitance relatively small. The harmonics in the arc voltage do not, as a consequence, drive corresponding currents in appreciable amounts thru the whole of such inductance. These currents penetrate only a few of the outer turns of the inductance whence they are shunted by the local capacitance of such turns; thus it comes about that the harmonic voltages are not impressed thru the entire inductance and do not reach the main electrode in appreciable amounts. This we have demonstrated conclusively by means of the cathode ray voltage oscillograph.

Ellery W. Stone: In the paper (on page 353), it is stated that "Further study developed the fact that these hot spots were the heads of corresponding hot conducting cores that extended into the depth of the porcelain." I should be interested in having Professor Ryan explain how the hot conducting cores in the porcelain were detected.

Harris J. Ryan: We have within the last two years again and again applied these sustained radio frequency high voltage discharges to porcelain insulators of many different patterns and sorts. We know that a molten conducting core is formed, because when a high voltage of radio frequency is applied in the manner indicated in the paper in the immediate neighborhood of the insulator, there is at first quite a corona display for a few moments due to the breakdown of the air near the electrode. This disappears immediately when a bright hot spot forms under or near the electrode, and this bright spot is of a yellowish white incandescence. As soon as such bright spot appears the charging current need no longer be furnished thru the outside conducting air (corona); but, since there is a conductor thru the porcelain, the charging current passes to it laterally thru the porcelain.

As regards the molten condition of this core, the discharge can be driven to the point that there is actual plasticity. In fact, if an opposing electrode is placed under the porcelain, so that directive forces are present, the conducting core is driven thru the porcelain from one electrode to the other. This experiment has been performed with porcelain one-half inch (1.27 cm.) thick, but there is no reason why it should not be performed with thicker porcelain. In these experiments, the hot spot has appeared at each side, and the corona has simultaneously disappeared. Upon stopping the application of the high voltage, the core promptly cools and solidifies. If the porcelain is broken apart thru the core it is found to be smooth grained, brittle and glass-like. Left mechanically undisturbed it is often, tho not always, found to have regained most of its original dielectric strength; i.e., it will endure the application of audio frequency voltage to the flash-over point. Renewed application of the radio frequency high voltage without change in the position of the electrodes will generally, tho not always, re-establish the hot conducting core in the former position.

An interesting variation in this experiment may be made to demonstrate the powerful mechanical drive that exists in the path of an electric spark. When a hot core thru the porcelain has been produced the main electrode is drawn away from the porcelain, say 3 to 5 inches (7.5 to 12.5 centimeters). This will stop the current flowing conductively thru the porcelain hot core and reactively thru the rest of the porcelain. Simultaneously the radio frequency voltage is raised to the value whereat the air between the main electrode and the hot core in the porcelain is ruptured. A spark is thus set up. It discharges the main condenser of the radio (high) frequency source thru the hot, plastic core in the porcelain. This spark stops the generation of the radio frequency high voltage. By the recovery of the generating action of the source in an obvious manner, such voltage is quickly renewed so that several sparks per second follow one another. When a few sparks have passed, the high voltage is turned off and the specimen is allowed to cool. It is then broken open whereupon one will often find that a clear hole of small calibre, diameter one-fiftieth of an inch (one-half millimeter), or thereabouts, has been made thru the porcelain core by the blast of the spark. There is here some evidence of the electro-physical manner in which a real open puncture is formed thru a refractory dielectric.

In a paper presented to the American Institute of Electrical Engineers before another section here to-day, Mr. F. W. Peek, Jr., demonstrates that it requires a much shorter time to build up and to produce under high voltage a discharge between spherical electrodes than between pointed, sharp or even blunt electrodes, as long as the "sharp" electrodes are not so blunt as to prevent corona from being formed in advance of the discharge. This is in contradistinction to an arrangement where spherical electrodes are employed and they are not widely separated, so that the corona is not formed in advance of the discharge. This is a matter of great practical importance in dealing with the question of arranging properly static arresters and reliefs. Incidentally, evidence related hereto was produced by the following experiment at sustained radio frequency high voltages. Near the main helix of the arc generator, a companion helix was mounted. Connected in series therewith was a high voltage adjustable condenser, so that one might easily, by turning the handle of that condenser, pass thru such a capacity value as to bring about resonance in the circuit thus formed. The detached helix was four or five feet away from the arc helix and the oscillating circuit of the generator, and was connected to nothing save the adjustable condenser. In order to ascertain when the circuit was in tune for the frequency of oscillation of the generator, there was connected across the terminals of the condenser a needle gap set at about an inch (2.5 cm.) length. As one passed thru the exact value for the capacity required to produce completely effective tuning, an arc would be set up between the needle points. They were promptly melted, because of the rather large amount of power present. Then it was noticed that unless one passed thru the correct capacity value slowly, the discharge did not have time to build up between the needle points. It was necessary to pass thru the resonance value very deliberately. To build up the discharge between the points required appreciable time because it required the absorption of considerable energy. Prolific ionization had to be produced to bring about the discharge.

Roy E. Thompson: Another explanation occurs to me, however. If two such circuits are coupled, in general (for electrical reasons) the second circuit will not follow the first one rapidly enough to admit of Morse signals in the first circuit being clearly indicated in the second. The "building up" of current takes too long in the second circuit, and detuning may occur thru reaction on the first circuit. Might this not be the explanation here also?

Harris J. Ryan: The point is well taken. If there is any effect in connection with these coupled circuits which throws one out of tune as the other is tuned to resonance when the action is performed rapidly but not when it is performed slowly, then this would be an explanation of the time required for the discharge to culminate. This is a matter which must be studied with great care to prevent arrival at erroneous conclusions.

Roy R. Thompson: If there were a means for controlling the energy of the primary circuit, it would be possible to note whether the discharge took place immediately after closing the primary circuit. The retardation due to variation of the secondary condenser could then be separately studied.

THE EFFECTIVENESS OF THE GROUND ANTENNA IN LONG DISTANCE RECEPTION*

By

R. B. Woolverton

The subject of this paper was suggested in October, 1914, when resonance curves were being taken by the writer at Eccles, Cal., on waves emitted by the various high powered commercial stations situated in the vicinity of San Francisco, at a distance of approximately 100 miles. The antenna used in taking these resonance curves consisted of the top wire of a 5-foot (1.6 meter) fence extending in a northwesterly direction for a distance of approximately 4,000 feet (1,300 meters). Altho the antenna so used was quite aperiodic, as might be expected, the received energy in the secondary circuit was remarkably large, signals being heard from stations in the Hawaiian Islands and Alaska. By using the ordinary crystal detector, full scale deflection was obtained on a Leeds & Northrup portable galvanometer when taking resonance curve data on the wave emitted by the high powered Marconi station at Bolinas, Cal.

In view of the results obtained at Eccles, the writer conducted on October 9th and 10th, 1915, experiments of a somewhat more quantitative character at the Palmer B. Hewlett ranch, situated 90 miles (140 kilometers) south by east of San Francisco. The receiving apparatus was of the de Forest "ultraudion" type (oscillating audion), using a second step amplifier audion bulb, and the audibilities were read on a "Wireless Specialty" audibility meter.† The connections are shown in detail in Figure 1.

It will be noted that two pairs of telephone receivers are connected in series, thus reducing the audibilities nearly 50 per cent., but it was found that the audion circuit would not oscillate when but one pair of receivers was used, with the audibility meter shunted about it.

Before beginning the experiments, it was thought that a com-

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*Presented before The Institute of Radio Engineers, New York, November 3, 1915.

(†A variable multi-contact resistance, graduated directly in "times audibility" for use with a definite telephone receiver of the Pickard type.—Editor.)

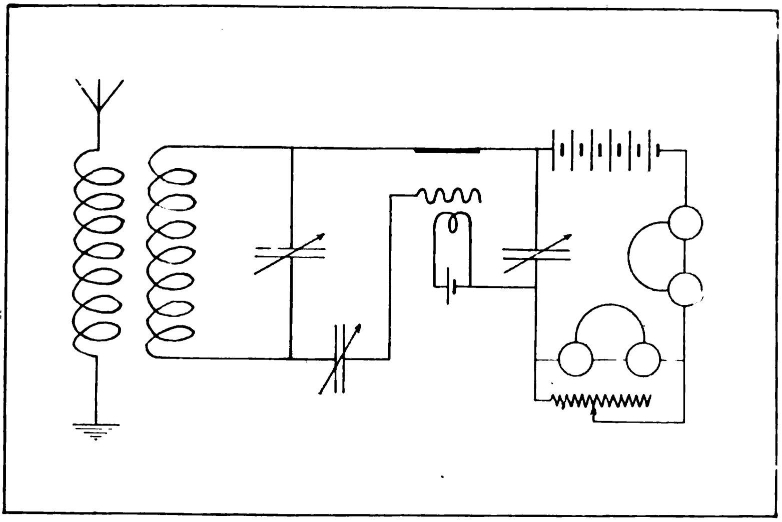

Figure 1—Diagram of Connections

paratively long single wire antenna would be so directional in effect that it was decided to confine the readings to one particular station; and Sayville, Long Island, was chosen, the antenna being made as nearly directional toward that station as possible. Buildings slightly interfered with this plan, however, and the antenna's true direction from the receiving apparatus was west-southwest, instead of more nearly west. As soon as readings were begun, it became apparent that this directional effect did not exist, as will readily be seen from the Honolulu audibilities in the "Audibility Table," Figure 2, and the "Direction and Range Chart," Figure 3. The two antennas consisted of 500-foot (160 meters) and 1,000-foot (320 meters) lengths respectively of a single Number 28 B. & S., cotton covered, magnet wire,* laid on dry earth without support at any point. The audibilities for the four transmitting stations are shown in Figure 2.

It will be noted that in the case of each station received from, the signal strength is more than sufficient for reliable communication, particularly when it is realized that the audibility of atmospherics was unity in each case. Atmospheric audibilities taken during the period of the tests, on a five-wire antenna, 45 feet high and 300 feet long, averaged 100.

Figure 3 shows the direction of the antenna with respect

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* Diameter of Number 28 wire = 0.0126 inch = 0.0320 centimeter

ANTENNA	SAYVILLE	HONOLULU	ARLINGTON-ARC	ARLINGTON-SPARK
500 FEET	50	100	60	100
1000 FEET	80	160	80	160

FIGURE 2—Table of Audibilities

to the stations received from, with the distances of the stations plotted to scale; and it immediately suggests experiments to determine the most effective design of a ground antenna. These experiments will shortly be undertaken by the writer, using various lengths, heights from the earth, and high potential ends both open and earthed. In view of the comparatively high ohmic resistance of the antenna wire used in the above tests, the use of a larger wire should give considerably greater audibilities. If such should be the case, and sufficiently high audibilities are obtained for daylight reception, it would seem that the ground antenna may be the solution of the serious problem of eliminating atmospheric interference, not to mention the difference in cost of the construction and maintenance of such an antenna, as compared with that of the present type.

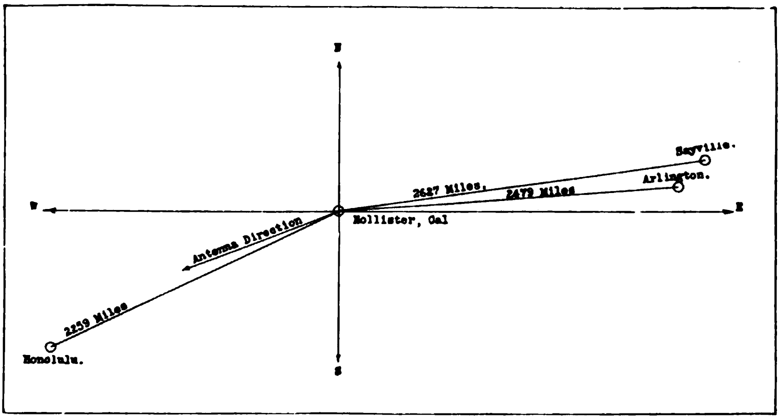

FIGURE 3—Direction and Range Chart

In closing the writer wishes to express his appreciation for the courtesy and valuable assistance rendered by Mr. Palmer B. Hewlett, of Hollister, Cal.

SUMMARY: Using an antenna several hundred meters long stretched on the ground, signals of an audibility up to more than one hundred are received from sustained wave stations 4,000 kilometers away. Atmospheric disturbances are found by the experimenter to be less troublesome relatively than when using a normal antenna. A further series of development experiments are outlined and will be undertaken.

DISCUSSION

Alfred N. Goldsmith: In presenting this paper to the New York membership of the Institute, it is to be noted that the paper gives only preliminary experiments and that Mr. Woolverton is carrying on further experiments and will lay the results of these experiments before the Institute. The paper is merely an introduction. It is further to be noted that Mr. Woolverton is well aware of the previous work done in this field by Messrs. Marconi, Braun, Zenneck, Kiebitz, Taylor and others.

Lester L. Israel: So far as the ground antenna is concerned, it has been worked with very largely without much success in the past. In Cuba particularly, a ground wire 1000 feet (300 meters) long was used and signals were received with about the same intensity as on an antenna 100 feet (30 meters) high. So far as atmospheric disturbances were concerned, the results were anything but satisfactory. It must be mentioned that if any advantages were obtained by Mr. Woolverton in the use of the ground antenna, the ground conditions in the neighborhood where the experiments were tried would be largely responsible.

Alfred N. Goldsmith: In reading thru a number of papers on this topic by Kiebitz, it was found that this experimenter claimed that he found no change in the ratio of signals to atmospheric disturbances of reception by using the ground antenna, as compared with the ratio for an ordinary antenna.

Lester L. Israel: In experimenting with ground antenna, Mr. Hill found that an antenna grounded at one end could be tuned but in cases where it was entirely ungrounded, tuning was practically impossible.

Roy A. Weagant: From the statements which have been made so far, it is not very clear whether Mr. Woolverton was working in the immediate vicinity of the elevated aerial or not. I believe that Mr. Woolverton referred to an aerial about 45 feet (15 meters) high. The influence of such an aerial on reception by means of a wire stretched on the ground would be very great.

We are not able to judge completely as to the efficacy of the ground antenna in eliminating atmospheric disturbances, because Mr. Woolverton gives the strength of atmospheric disturbances and signals on his ground antenna and the strength of atmospheric disturbances on the elevated antenna, but he does not give the necessary data as to the strength of signals of the elevated antenna. Such information should be sent.

So far as my own experiments are concerned, I do not know if there is any advantage in using the ground antenna. It seems that the ratio between signal strength and disturbance strength is constant regardless of the type of antenna used. Sometimes advantages which are obtained with low aerials are due to the fact that the receiver used, for example the audion, has an upper limit of response. If it is struck by a stray impulse of more than a certain strength, it is simply temporarily paralyzed, and no further immediate response is obtained.

Alfred N. Goldsmith: In connection with the experiments which Mr. Woolverton is carrying out, any suggestions addressed to Mr. R. B. Woolverton, Custom House, San Francisco, Cal., will be welcomed by Mr. Woolverton, who is interested in obtaining the widest possible expressions of opinion relative to experiments of this type.

Robert B. Woolverton: Every effort was made to prevent the elevated antenna from affecting the results on the ground antenna. The elevated antenna circuit was kept wide open, and in addition its direction was exactly at right angles to the ground antenna. However, in future experiments, the elevated antenna will be taken down.

Every effort was made to keep the sensitiveness of the ultraudion constant. The Los Angeles station of the Federal Telegraph Company provided signals used as a reference constant before reading audibilities on other stations. Furthermore, the de Forest bulb used in all the tests was an especially good one, and practically no difficulty was experienced in keeping its sensitiveness constant.

THE DESIGN OF THE AUDIO FREQUENCY CIRCUIT OF QUENCHED SPARK TRANSMITTERS

By

Julius Weinberger

(Including a Supplementary Discussion of "Resonance Phenomena in the Low Frequency Circuit," by H. E. Hallborg, Proceedings of the Institute of Radio Engineers, Volume 3, Part 2, 1915, page 107.)

A large number of contributions to the literature of radiotelegraphy have been made upon the subject of the so-called "resonance transformer." These have been both experimental and theoretical. The experimental contributions, as a general rule, have been investigations of the resonance transformer under actual operating conditions (that is, with the secondary condenser discharging periodically thru a spark gap), while the theoretical contributions have generally assumed a steady state of affairs (the secondary condenser *not* being discharged); in this case the method of treatment has been that employed for two coupled circuits.

In actual practice, such as in the operation of quenched gap sets, the requirement of a clear note involves the discharge of the secondary condenser at the peak of the wave each half cycle. It would seem, therefore, that the *transient* phenomena in the circuit would be the determining factors of voltage and current, rather than those of the steady state of affairs; that is, conditions would never assume the steady state.

To investigate these conditions, we can reduce the whole resonance transformer circuit to that of a simple inductance, capacity and resistance in series (Figure 1), as has been shown by Mr. Hallborg. The inductance **L** includes all the inductances in the circuit—generator inductance, transformer leakage inductance, inductance of any series choke coils, and so on. The condenser **C** is the secondary condenser reduced to the primary circuit by multiplication by the square of the ratio of transformer voltages. The resistance **R** includes resistances in the primary circuit and resistances in the secondary circuit reduced to the primary by division by the square of the ratio of transformer voltages.

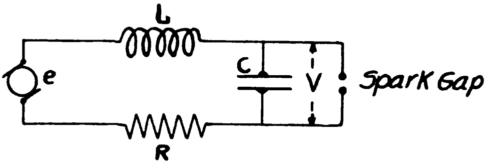

FIGURE 1

The differential equation for such a circuit is

$$e = E\cos(\theta - \theta_0) = Ri + x\frac{di}{d\theta} + x_c\int i\,d\theta$$

where

E = maximum generated * voltage

x_c = condenser reactance

x = inductive "

$\theta = \omega t$

θ_0 = an angle to be subtracted from θ if e is not zero for $t = 0$.

The potential difference across the condenser terminals can be found from

$$V = x_c\int i\,d\theta$$

when equation (1) has been solved for **i**.

Since we are mainly concerned with this **V**, we will omit writing the solution for i, but give that for **V** immediately:

$$V = \frac{E x_c}{Z}\sin(\theta - \theta_0 - \gamma) + \frac{E x_c}{Z}\varepsilon^{-\frac{R}{2x}\theta}\left\{\sin(\theta_0 + \gamma)\cos\frac{q}{2x}\theta + \left[\frac{R}{q}\sin(\theta_0 + \gamma) - \frac{2x}{q}\cos(\theta_0 + \gamma)\right]\sin\frac{q}{2x}\theta\right\} + \varepsilon^{-\frac{R}{2x}\theta}\left\{e_0\cos\frac{q}{2x}\theta + \frac{2Re_0 + 4xx_ci_0}{2q}\sin\frac{q}{2x}\theta\right\}$$

where

Z = impedance,

γ = phase difference between generated e. m. f and i

$q = \sqrt{4xx_c - R^2}$

e_0 = value of potential difference across condenser terminals at the time $t = 0$

i_0 = value of current thru the circuit at the time $t = 0$.

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* This is *not* the voltage across the generator terminals. If the generator armature has appreciable inductance (in comparison with the rest of the circuit) there will be a drop in voltage inside of the armature and a very much higher voltage will actually be *generated* than that which is measured at the terminals.

Consider the conditions introduced in the circuit immediately after the condenser has sparked over, at one peak of a cycle, and the spark has ceased. This is the moment for which we take $t = 0$. The important thing to be determined is:—what will be the voltage across the condenser for $\theta = \pi$ (that is, at the next peak of the cycle)? Will it rise to a sufficient value to cause another discharge? Or, rather, will it rise to a value equal to that, at least, at which the previous discharge took place? If not, the requirements of a clear note, of twice the generator frequency, will not be fulfilled. Also, it is this discharge voltage which determines the energy absorbed by the condenser.

Taking the equation given for V, we can introduce the following simplifications:

(1) Since we will consider the circuit as being resonant, we have $x_c = x$, and shall substitute x for x_c accordingly, thruout.

(2) Since the circuit is resonant, the current and generated voltage are in phase, hence $\gamma = 0$.

(3) When the condenser discharges, the potential difference between its plates is reduced to zero. Hence. at the moment we are considering, $e_o = 0$

(4) The spark occurs when the generated voltage is zero. Since i_o is in phase with e_o, $i_o = 0$.

(5) Since the circuit is resonant, $Z = R$.

(6) R^2 can usually be neglected as compared with $4\,x\,x_c$.

Hence $\qquad q = 2\sqrt{x\,x_c}$

Or, since $\qquad x = x_c$

$\qquad q = 2x$

(7) In our case, $\qquad \theta_o = \frac{\pi}{2}$

Substituting these conditions, we obtain

$$V = \frac{Ex}{R}\sin\left(\theta - \frac{\pi}{2}\right) + \frac{Ex}{R}\varepsilon^{-\frac{R}{2x}\theta}\left\{\cos\theta + \frac{R}{2x}\sin\theta\right\}$$

$$= \frac{Ex}{R}(-\cos\theta) + \frac{Ex}{R}\varepsilon^{-\frac{R}{2x}\theta}\left\{\cos\theta + \frac{R}{2x}\sin\theta\right\}$$

To show the general shape of this curve, which gives the voltage across the condenser at any moment after the time $t = 0$, it has been calculated for a specific case ($C = 20$ microfarads and $R = 1$ ohm), and is shown in Figure 2. In the same figure the curve of generated voltage (a sine wave), is given for comparison.

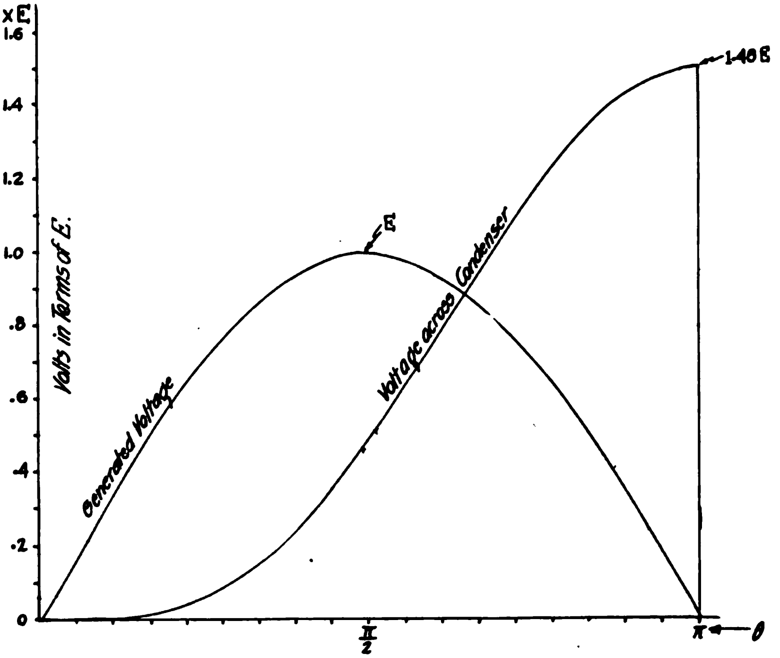

FIGURE 2

This condenser voltage, V, will reach its maximum for $\theta = \pi$. It will then be

$$V_{max} = \frac{E\,x}{R} - \frac{E\,x}{R}\varepsilon^{-\frac{\pi R}{2x}}$$

$$= \frac{E\,x}{R}\left(1 - \varepsilon^{-\frac{\pi R}{2x}}\right)$$

This, then, is the potential at which our "reduced" condenser will discharge. The actual condenser, across the transformer secondary, will, of course, discharge at a voltage which is simply this V_{max} multiplied by the transformer ratio. In Figure 3, curves are given for V_{max} in terms of E (the maximum generated voltage). It will be seen that for ordinary conditions of resistance (that is, R between zero and 1 ohm), $V = 1.5$ E is a good average value.

To find the R. M. S., or effective value of V is desirable, since this is the voltage that a voltmeter placed across the transformer primary will read, and this is also the voltage for which the transformer primary must be designed when the equation $V_{eff} = 4.44\,A\,B\,n\,f \cdot 10^{-8}$

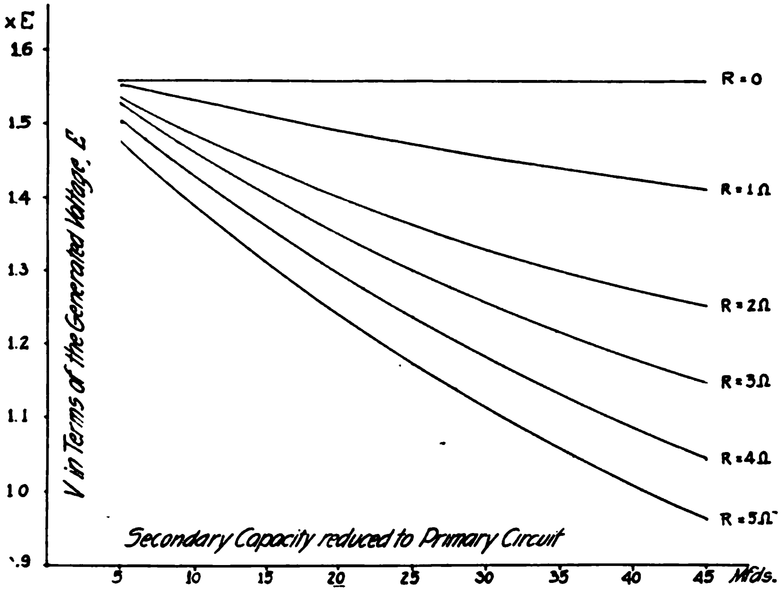

FIGURE 3

is used, where

V_{eff} = R. M. S. volts across transformer primary
A = cross sectional area of core in square cms.
B = flux density, in lines per square cm.
N = number of turns of primary winding.
f = supply frequency.

This effective value of **V** is

$$V_{eff} = \sqrt{\frac{1}{\pi}\int_0^\pi \left(- \frac{E\,x}{R}\cos\theta + \frac{E\,x}{R}\,\varepsilon^{-\frac{R}{2x}\theta}\left\{\cos\theta + \frac{R}{2x}\sin\theta\right\}\right)^2}$$

It is found* that

$$V_{eff} = 0.504\ V_{max}.$$

The design of a quenched gap set to operate under resonance conditions becomes a relatively simple matter. Let us take a numerical example for a 500-cycle, 1 kilowatt set, operating with a 110-volt generator (154 volts maximum).

We shall first find the equivalent primary condenser (i. e. the secondary condenser reduced to the primary circuit), required to absorb 1,000 watts, from

$$W = n\,C\,V^2$$

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*This value was determined graphically, the integration being done by measuring the area of the squared curve with a planimeter.

Since $V = 1.5\,E = (1.5)\,(110)\sqrt{2} = 233$ volts.

Hence $1000 = 500\,C\,(233)^2,$

$C = 37$ microfarads.

To tune to 500 cycles with this capacity, an inductance of 2.5 millihenrys is required. This can be made up partly from the generator armature inductance (usually this is between 1 and 5 millihenrys for a 1 kilowatt, 110-volt machine), and the rest obtained either by a transformer having this amount of leakage inductance, or else from a transformer with no appreciable leakage and series choke coils. I believe the latter method to be preferable as it admits of greater flexibility.

The value of the equivalent primary condenser (or rather, the "reduced" secondary condenser, as I have called it), being now fixed, the actual secondary condenser is determined by deciding on a suitable transformer ratio. The value of this secondary condenser is usually limited by conditions of wave length and also by the discharge current which the quenched gap in use will stand. A large condenser means heavy currents and considerable heating in the gap, while a high discharge voltage and a small condenser would require many gap sections and cause insulation difficulties. It is, I believe, common practice to employ about 0.006 microfarads as a secondary condenser for this type of set.

Having thus determined the ratio of primary to secondary capacities, the transformer ratio is of course fixed; and it is only necessary to design a transformer of the ratio desired—a simple matter with a closed core transformer of negligible leakage. Note should be taken of the fact previously mentioned that when the usual transformer formulas are used, the effective value of V (that is $0.504\ V_{max}$) should be used as the voltage across the primary.

Practically, the operation of quenched gap sets is at a point slightly "off" resonance. However, it is hardly necessary to operate with a condenser as much as 20 per cent larger than the resonance capacity. The foregoing results can, therefore, be applied as very good approximations to actual practice; and have been found to be quite satisfactory for this purpose.

[Since the above was written I have become aware of an article by L. B. Turner* upon the same subject. Following a somewhat different procedure, Turner reaches practically the

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*L. B. Turner: "Electrician," Vol. 69, 1912, page 694; "Der Schwingungskreis niedriger Frequenz in der Funkentelegraphie," "Jahrb. d. Drahtl Tel.," Volume 9, Heft 2, page 141.

same results as given above, with the exception that he neglects the resistance of the circuit. As Figure 3 shows, however, this would lead to considerable inaccuracies, for large resistances, and is strictly correct only for R = 0. Turner obtains the result

$$V = \frac{\pi}{2} E. \Big]$$

WASHINGTON, D. C., July 1, 1915.

SUMMARY: The paper gives the operating theory of the power transformer and alternator circuit of quenched spark gap transmitters. The secondary of the transformer and its loading capacity are reduced in the usual way to equivalent primary inductance and capacity. The theory of the transient phenomena occurring at the sudden discharge of the condenser is then developed. It is shown that under ordinary conditions the maximum condenser voltage (reduced to the primary circuit), is 1.5 times the maximum voltage generated in the alternator. The effective (or R. M. S.) condenser voltage, reduced to the primary, is found to be 0.504 times the maximum primary voltage. It is this R. M. S. voltage which is used in the usual transformer design. The theory is clearly illustrated for the case of a 500 cycle 1 K. W. set.

THE PUPIN THEORY OF ASYMMETRICAL ROTORS IN UNIDIRECTIONAL FIELDS

WITH SPECIAL REFERENCE TO THE GOLDSCHMIDT ALTERNATOR.*

By

BENJAMIN LIEBOWITZ

Since its advent, the radio-frequency generator of Professor Rudolph Goldschmidt has been the subject of much discussion, and several theories of its action have been advanced. The theory of the Goldschmidt alternator, however, is but a special case of the general theory of asymmetrical rotors in unidirectional magnetic fields, which latter has been developed by Professor Pupin, and on which he has been lecturing during the past seven or eight years. The Pupin theory, therefore, antedates the Goldschmidt alternator by several years, but is little known except to those who have attended his lectures. The object of this paper is to give the theory its due publicity.

CIRCUIT HAVING VARIABLE INDUCTANCE AND NO RESISTANCE

It will be helpful, perhaps, before considering Pupin's problem, to take up a simple, hypothetical case first, viz., a circuit having a periodically varied self-induction and no resistance. Imagine a circuit made up of two coils connected in series, the one having inductance L_1, the other inductance L_2, and let M be the maximum value of the mutual inductance between the coils. When they make an angle θ with each other, the mutual inductance between the coils is $M \cos \theta$. (See Figure 1.) Let the circuit be supplied with a source of constant e. m. f., E (e. g., a battery), and let R be the resistance. If one of the coils is continuously rotated with angular velocity ω, the total self-induction of the circuit will vary periodically in accordance with the equation

$$L = L_1 + L_2 + 2 M \cos \omega t.$$

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* Delivered before the Institute of Radio Engineers, New York, May 5, 1915.

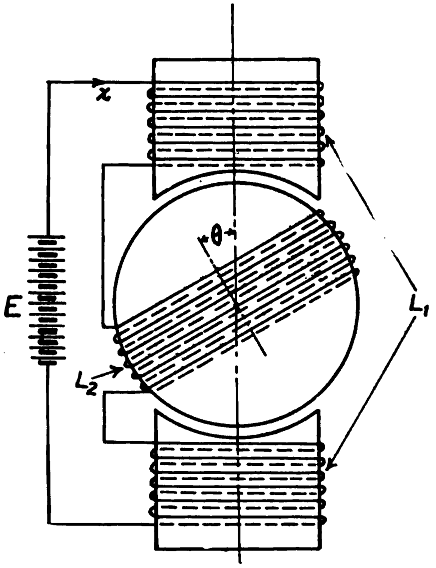

FIGURE 1

The inductance reaction will therefore be

$$\frac{d}{dt}\Big[(L_1 + L_2 + 2M\cos\omega t)\,x\Big],$$

where x is the current in the circuit at any instant. For brevity, put

$$L_1 + L_2 = \lambda,\;\; 2M = \mu,$$

and the inductance reaction becomes $\frac{d}{dt}\Big[(\lambda + \mu\cos\omega t)\,x\Big]$. The resistance reaction is Rx, hence the equation of reactions is:

$$\frac{d}{dt}\Big[(\lambda + \mu\cos\omega t)\,x\Big] + Rx = E.$$

This equation, as it stands, comes under Pupin's problem; what we are interested in for the moment is the simplification which results when the resistance R is assumed to be vanishingly small. We must assume, of course, that E also becomes vanishingly small, altho the ratio $E/R = X$ is to be regarded as finite. With these assumptions the equation of reactions becomes

$$\frac{d}{dt}\Big[(\lambda + \mu\cos\omega t)\,x\Big] = 0,$$

the solution of which is

$$(\lambda + \mu\cos\omega t)\,x = K,$$

whence $$x = \frac{K}{\lambda + \mu \cos \omega t}.$$

K is a constant of integration, depending on the initial conditions. If we assume, for example, that

$$x = X \text{ when } t = 0,$$

then $$K = (\lambda + \mu)\, X = (\lambda + \mu) \frac{E}{R}.$$

Therefore $$x = \frac{(\lambda + \mu)\, X}{\lambda + \mu \cos \omega t}.$$

This equation shows how the current varies in a circuit having a periodically varied self-induction, an initial current, and no resistance. Its graph is given in Figure 2 for the case

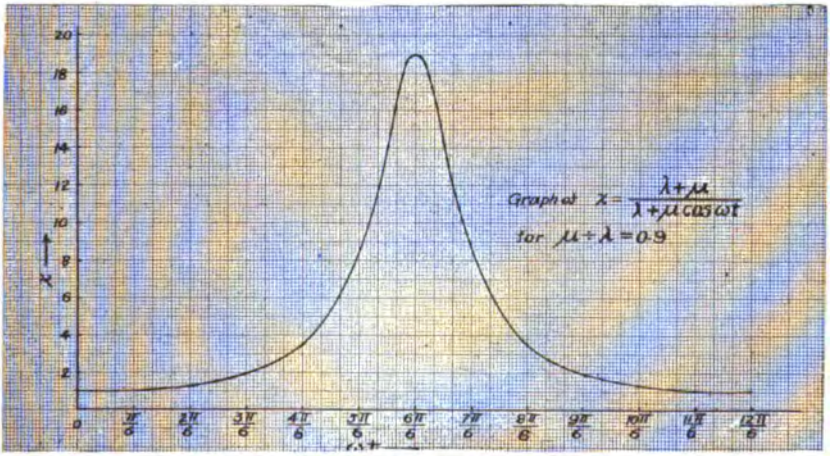

FIGURE 2

where $X = 1$, $\lambda = 1$, $\mu = 0.9$. Since it is an even function, it is developable into a series of cosines. Carrying out the development we obtain

$$x = \frac{(\lambda + \mu)\, X}{\lambda + \mu \cos \omega t} = 2\, X \sqrt{\frac{\lambda + \mu}{\lambda - \mu}} \left(\frac{1}{2} + B \cos \omega t + B^2 \cos 2\, \omega t + B^3 \cos 3\, \omega t + \ldots \ldots \right),$$

where $B = \sqrt{\left(\frac{\lambda}{\mu}\right)^2 - 1} - \frac{\lambda}{\mu} = \frac{\lambda}{\mu}\left(\sqrt{1 - \frac{\mu^2}{\lambda^2}} - 1\right).$

Now, the inductance of a circuit without capacity can never become negative, hence

$$L_1 + L_2 + 2M\cos\omega t > 0,$$
$$\therefore \quad L_1 + L_2 > 2M \text{ and } \lambda > \mu.$$

Hence B is a negative quantity whose absolute value lies between 0 and 1. B is 0 when M is 0, and $B = -1$ when $L_1 + L_2 = 2M$; i. e., when $\lambda = \mu$. This can never happen, but if it did, we see that the amplitudes of all the harmonics of x would be equal but would alternate in sign, and the series would not be convergent. In all other cases we see that the amplitudes of the higher harmonics *decrease in geometric progression*, and that they alternate in sign as before. Obviously the series is convergent.

The case just considered is a purely hypothetical one, of course, but I have worked it out in some detail because of the light it throws on the difficult problem presented by the actual circuits.

For the benefit of those who are not familiar with the theory of transformation of equations, a few words on this topic may be said. Suppose we have an equation of any nature whatever, in any number of variables. To fix the ideas, let there be two variables, x and y, and let the equation be given by

$$f(x, y) = 0.$$

To aid in solving this equation we may substitute for x any legitimate function in any number of new variables, and likewise for y. Suppose these transformations involve 2n new variables; upon $(2n - 2)$ of them we may impose any conditions we please; this leaves two variables, the relation between which must be determined from the original equation, $f(x, y) = 0$.

CIRCUITS HAVING INDUCTANCE, RESISTANCE, AND VARIABLE MUTUAL INDUCTANCE

Turning now to Pupin's theory, we consider first the case of a circuit having resistance R, inductance L, and a constant impressed e. m. f., E.; in the field of this circuit is rotated another circuit having resistance S and inductance N. For any angle θ between the coils, the mutual inductance is given by $M\cos\theta$. (See Figure 3.) In the first circuit, the reactions are the inductance reaction $L\frac{dx}{dt}$, the resistance reaction Rx, and the e. m. f., $M\frac{d}{dt}(y\cos\omega t)$ due to the presence of the rotating circuit. In this latter the reactions are the inductance reaction

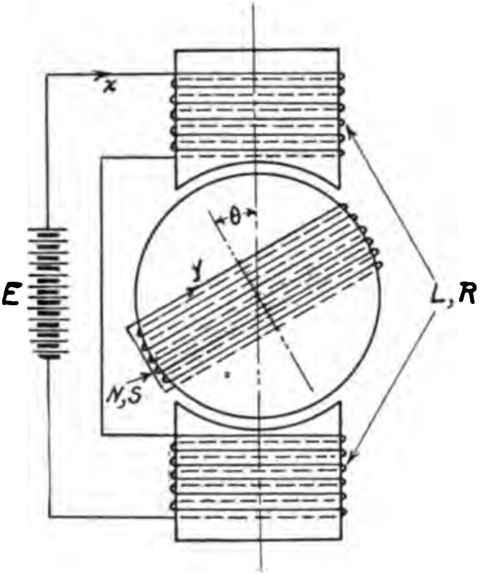

FIGURE 3

$N\frac{dy}{dt}$, the resistance reaction Sy, and the e. m. f. due to the presence of the stator circuit, $M\frac{d}{dt}(x\cos\omega t)$. (Thruout this paper, x shall denote the current in the stator, y the current in the rotor, and ω the angular velocity of rotation.) The equations of reactions therefore are:

$$(1)\begin{cases} L\frac{dx}{dt} + Rx + M\frac{d}{dt}(y\cos\omega t) = E, \\ N\frac{dy}{dt} + Sy + M\frac{d}{dt}(x\cos\omega t) = 0. \end{cases}$$

Pupin's rigorous solution of these equations is the backbone of his theory. Having once obtained the solution of these equations, it is a relatively simple matter to extend the theory to more complicated cases, e. g., with condensers in one or both circuits, impressed e. m. f.'s varying periodically with the time, etc. We shall treat in some detail, therefore, the case now under consideration.

To equations (1) apply the transformations:

$$(2)\begin{cases} x = x_0 + x_2 + x_4 + x_6 + \dots\dots\dots\dots, \\ y = y_1 + y_3 + y_5 + y_7 + \dots\dots\dots\dots, \end{cases}$$

getting:

$$
(3)\left\{\begin{array}{l}
L\frac{d\,x_0}{d\,t} + R\,x_0 \\
+ L\frac{d\,x_2}{d\,t} + R\,x_2 + M\frac{d}{d\,t}(y_1 \cos \omega\, t) \\
+ L\frac{d\,x_4}{d\,t} + R\,x_4 + M\frac{d}{d\,t}(y_3 \cos \omega\, t) \\
+ L\frac{d\,x_6}{d\,t} + R\,x_6 + M\frac{d}{d\,t}(y_5 \cos \omega\, t) \\
+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\
+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot = E, \\
N\frac{d\,y_1}{d\,t} + S\,y_1 + M\frac{d}{d\,t}(x_0 \cos \omega\, t) \\
+ N\frac{d\,y_3}{d\,t} + S\,y_3 + M\frac{d}{d\,t}(x_2 \cos \omega\, t) \\
+ N\frac{d\,y_5}{d\,t} + S\,y_5 + M\frac{d}{d\,t}(x_4 \cos \omega\, t) \\
+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\
+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot = 0.
\end{array}\right.
$$

We may regard this transformation as one involving the $2n + 2$ variables:

$$x_0, x_2, x_4, \ldots\ldots x_{2n};\ y_1, y_3, y_5 \ldots\ldots y_{2n+1};$$

where n is made to approach infinity. The transformation is therefore an infinite one, and we may impose an infinite number of arbitrary conditions; the only requirements to be fulfilled are that the sums $x_0 + x_2 + x_4 + \ldots\ldots$ and $y_1 + y_3 + y_5 + \ldots\ldots$ shall satisfy their respective equations and that they shall be convergent.

Impose on $x_0, y_1, x_2, y_3, x_4 \ldots\ldots$ the following conditions:

$$
(4)\left\{\begin{array}{ll}
(a) & L\frac{d\,x_0}{d\,t} + R\,x_0 = E \\
(b) & N\frac{d\,y_1}{d\,t} + S\,y_1 + M\frac{d}{d\,t}(x_0 \cos \omega\, t) = 0 \\
(c) & L\frac{d\,x_2}{d\,t} + R\,x_2 + M\frac{d}{d\,t}(y_1 \cos \omega\, t) = 0 \\
(c) & N\frac{d\,y_3}{d\,t} + S\,y_3 + M\frac{d}{d\,t}(x_2 \cos \omega\, t) = 0 \\
(d) & L\frac{d\,x_4}{d\,t} + R\,x_4 + M\frac{d}{d\,t}(y_3 \cos \omega\, t) = 0 \\
(d) & N\frac{d\,y_5}{d\,t} + S\,y_5 + M\frac{d}{d\,t}(x_4 \cos \omega\, t) = .0 \\
 & \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\
 & \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot
\end{array}\right.
$$

These conditions obviously satisfy the transformed equations (3) for they make each part of the left-hand members of (3) vanish separately; hence they satisfy the original equations (1). Furthermore, these conditions lead to a convergent result, as will presently be shown.*

The result of the transformations (2) is to break up the original equations (1) into an infinite series of equations (4), each of which can be solved if those preceding it are solved first.

Disregarding transient states thruout, the solution of (4a) is:

$$x_0 = \frac{E}{R}. \tag{5a}$$

Substituting this in (4b) gives

$$\begin{aligned} N\frac{d\,y_1}{d\,t} + S\,y_1 &= -M\,x_0\frac{d}{d\,t}(\cos\omega t) \\ &= \omega M\,x_0 \sin\omega t. \end{aligned}$$

The solution of this is:

$$y_1 = \frac{\omega M\,x_0}{Z_1}\sin(\omega t - \theta_1)$$

$$\text{where } Z_1 = \sqrt{(\omega N)^2 + S^2} \text{ and } \theta_1 = \tan^{-1}\frac{\omega N}{S}. \tag{5b}$$

Substituting this in (4c) gives:

$$\begin{aligned} L\frac{d\,x_2}{d\,t} + R\,x_2 &= -\frac{\omega M^2 x_0}{Z_1}\frac{d}{d\,t}\left[\frac{1}{2}\left(\sin(2\omega t - \theta_1) - \sin\theta_1\right)\right] \\ &= -\frac{(\omega M)^2 x_0}{Z_1}\cos(2\omega t - \theta_1)\cdot \end{aligned}$$

The solution of this is:

$$\left.\begin{aligned} x_2 &= -\frac{(\omega M)^2 x_0}{Z_1 Z_2}\cos(2\omega t - \theta_1 - \theta_2), \\ &\text{where } Z_2 = \sqrt{(2\omega L)^2 + R^2} \text{ and } \theta_2 = \tan^{-1}\frac{2\omega L}{R}. \end{aligned}\right\} \tag{5c}$$

Substituting this in (4d) gives:

$$\begin{aligned} N\frac{d\,y_3}{d\,t} + S\,y_3 &= \frac{\omega^2 M^3 x_0}{Z_1 Z_2}\frac{d}{d\,t}\left[\frac{1}{2}\cos(3\omega t - \theta_1 - \theta_2) + \frac{1}{2}\cos(\omega t - \theta_1 - \theta_2)\right] \\ &= -\frac{(\omega M)^3 x_0}{Z_1 Z_2}\left[\frac{3}{2}\sin(3\omega t - \theta_1 - \theta_2) + \frac{1}{2}\sin(\omega t - \theta_1 - \theta_2)\right]. \end{aligned}$$

---

* Later we shall deal with a case where the series are divergent, but it will be shown that even in this case Pupin's transformation is justified by the physical phenomena.

The solution of this is:

$$
\text{(5d)}\left\{
\begin{aligned}
&y_3 = -\frac{(\omega M)^3 x_0}{Z_1 Z_2}\left[\frac{3}{2 Z_3}\sin(3\omega t - \theta_1 - \theta_2 - \theta_3)\right.\\
&\qquad\qquad\qquad\qquad\left. + \frac{1}{2 Z_1}\sin(\omega t - 2\theta_1 - \theta_2)\right],\\
&\quad\text{where } Z_3 = \sqrt{(3\omega N)^2 + S^2} \text{ and } \theta_3 = \tan^{-1}\frac{3\omega N}{S}.
\end{aligned}
\right.
$$

We may continue in precisely the same manner to get $x_4, y_5, x_6, y_7, \ldots$ in turn. The complications multiply very rapidly, however, so I shall merely write down the values for a few more terms.

$$
\text{(5e)}\left\{
\begin{aligned}
&x_4 = \frac{(\omega M)^4}{Z_1 Z_2} x_0\left[\frac{3}{Z_3 Z_4}\cos(4\omega t - \theta_1 - \theta_2 - \theta_3 - \theta_4)\right.\\
&\quad + \frac{3}{2 Z_2 Z_3}\cos(2\omega t - \theta_1 - 2\theta_2 - \theta_3)\\
&\quad\left. + \frac{1}{2 Z_1 Z_2}\cos(2\omega t - 2\theta_1 - 2\theta_2)\right],\\
&\text{where } Z_4 = \sqrt{(4\omega L)^2 + R^2} \text{ and } \theta_4 = \tan^{-1}\frac{4\omega L}{R}.
\end{aligned}
\right.
$$

$$
\text{(5f)}\left\{
\begin{aligned}
&y_5 = \frac{(\omega M)^5 x_0}{Z_1 Z_2}\left[\frac{15}{2 Z_3 Z_4 Z_5}\sin(5\omega t - \theta_1 - \theta_2 - \theta_3 - \theta_4 - \theta_5)\right.\\
&\qquad\qquad\qquad\qquad + \frac{9}{2 Z_3^2 Z_4}\sin(3\omega t - \theta_1 - \theta_2 - 2\theta_3 - \theta_4)\\
&+ \frac{9}{4 Z_2 Z_3^2}\sin(3\omega t - \theta_1 - 2\theta_2 - 2\theta_3)\\
&\qquad\qquad\qquad\qquad + \frac{3}{4 Z_1 Z_2 Z_3}\sin(3\omega t - 2\theta_1 - 2\theta_2 - \theta_3)\\
&+ \frac{3}{4 Z_1 Z_2 Z_3}\sin(\omega t - 2\theta_1 - 2\theta_2 - \theta_3)\\
&\qquad\qquad\qquad\qquad\left. + \frac{1}{4 Z_1^2 Z_2}\sin(\omega t - 3\theta_1 - 2\theta_2)\right],\\
&\text{where } Z_5 = \sqrt{(5\omega N)^2 + S^2} \text{ and } \theta_5 = \tan^{-1}\frac{5\omega N}{S}.
\end{aligned}
\right.
$$

$$(5g)\quad\left\{\begin{aligned}
x_6 = & -\frac{(\omega M)^6 x_o}{Z_1 Z_2}\Bigg[\frac{45}{2 Z_3 Z_4 Z_5 Z_6}\cos(6\omega t-\theta_1-\theta_2-\theta_3-\theta_4 \\
& -\theta_5-\theta_6)+\frac{15}{Z_3 Z_4^2 Z_5}\cos(4\omega t-\theta_1-\theta_2-\theta_3-2\theta_4-\theta_5) \\
& +\frac{9}{Z_3^2 Z_4^2}\cos(4\omega t-\theta_1-\theta_2-2\theta_3-2\theta_4) \\
& \qquad +\frac{9}{2 Z_2 Z_3^2 Z_4}\cos(4\omega t-\theta_1-2\theta_2-2\theta_3-\theta_4) \\
& +\frac{3}{2 Z_1 Z_2 Z_3 Z_4}\cos(4\omega t-2\theta_1-2\theta_2-\theta_3-\theta_4) \\
& \qquad +\frac{9}{2 Z_2 Z_3^2 Z_4}\cos(2\omega t-\theta_1-2\theta_2-2\theta_3-\theta_4) \\
& +\frac{9}{4 Z_2^2 Z_3^2}\cos(2\omega t-\theta_1-3\theta_2-2\theta_3) \\
& \qquad +\frac{3}{2 Z_1 Z_2^2 Z_3}\cos(2\omega t-2\theta_1-3\theta_2-\theta_3) \\
& +\frac{1}{4 Z_1^2 Z_2^2}\cos(2\omega t-3\theta_1-3\theta_2)\Bigg], \\
& \text{where } Z_6=\sqrt{(6\omega L)^2+R^2} \text{ and } \theta_6=\tan^{-1}\frac{6\omega L}{R}.
\end{aligned}\right.$$

We see, therefore, that the current y_1 contains the frequency $\frac{\omega}{2\pi}$, the current x_2 the frequency $\frac{2\omega}{2\pi}$, the current· y_3 the frequencies $\frac{3\omega}{2\pi}$ and $\frac{\omega}{2\pi}$, the current x_4 the frequencies $\frac{4\omega}{2\pi}$ and $\frac{2\omega}{2\pi}$, the current y_5 the frequencies $\frac{5\omega}{2\pi}$, $\frac{3\omega}{2\pi}$ and $\frac{\omega}{2\pi}$; etc. That is, the current y_{2n+1} contains all the odd frequencies from $(2n+1)\frac{\omega}{2\pi}$ down to $\frac{\omega}{2\pi}$, and the current x_{2n} all the even frequencies from $\frac{2n\omega}{2\pi}$ down to $\frac{2\omega}{2\pi}$. If we collect all the terms of frequency $\frac{\omega}{2\pi}$ and denote the result by η_1, those of frequency $\frac{2\omega}{2\pi}$ and denote the result by ξ_2, etc., we get:

$$(6a)\quad \begin{aligned}
\eta_1 = & \frac{\omega M x_o}{Z_1}\sin(\omega t-\theta_1)-\frac{(\omega M)^3 x_o}{2 Z_1^2 Z_2}\sin(\omega t-2\theta_1-\theta_2) \\
& +\frac{3(\omega M)^5 x_o}{4 Z_1^2 Z_2^2 Z_3}\sin(\omega t-2\theta_1-2\theta_2-\theta_3) \\
& \qquad +\frac{(\omega M)^5 x_o}{4 Z_1^3 Z_2^2}\sin(\omega t-3\theta_1-2\theta_2)
\end{aligned}$$

$$-\frac{9(\omega M)^7 x_0}{4Z_1^2Z_2^2Z_3^2Z_4}\sin(\omega t-2\theta_1-2\theta_2-2\theta_3-\theta_4)$$

$$-\frac{9(\omega M)^7 x_0}{8Z_1^2Z_2^3Z_3^2}\sin(\omega t-2\theta_1-3\theta_2-2\theta_3)$$

$$-\frac{3(\omega M)^7 x_0}{4Z_1^3Z_2^3Z_3}\sin(\omega t-3\theta_1-3\theta_2-\theta_3)$$

$$-\frac{(\omega M)^7 x_0}{8Z_1^4Z_2^3}\sin(\omega t-4\theta_1-3\theta_2)$$

+ . . . .

+ . . . .

(6b) $$\xi_2 = -\frac{(\omega M)^2 x_0}{Z_1Z_2}\cos(2\omega t-\theta_1-\theta_2)$$

$$+\frac{3(\omega M)^4 x_0}{2Z_1Z_2^2Z_3}\cos(2\omega t-\theta_1-2\theta_2-\theta_3)$$

$$+\frac{(\omega M)^4 x_0}{2Z_1^2Z_2^2}\cos(2\omega t-2\theta_1-2\theta_2)$$

$$-\frac{9(\omega M)^6 x_0}{2Z_1Z_2^2Z_3^2Z_4}\cos(2\omega t-\theta_1-2\theta_2-2\theta_3-\theta_4)$$

$$-\frac{9(\omega M)^6 x_0}{4Z_1Z_2^3Z_3^2}\cos(2\omega t-\theta_1-3\theta_2-2\theta_3)$$

$$-\frac{3(\omega M)^6 x_0}{2Z_1^2Z_2^3Z_3}\cos(2\omega t-2\theta_1-3\theta_2-\theta_3)$$

$$-\frac{(\omega M)^6 x_0}{4Z_1^3Z_2^3}\cos(2\omega t-3\theta_1-3\theta_2)+ \quad . \quad .$$

+ . . . . . .

(6c) $$\eta_3 = -\frac{3(\omega M)^3 x_0}{2Z_1Z_2Z_3}\sin(3\omega t-\theta_1-\theta_2-\theta_3)$$

$$+\frac{9(\omega M)^5 x_0}{2Z_1Z_2Z_3^2Z_4}\sin(3\omega t-\theta_1-\theta_2-2\theta_3-\theta_4)$$

$$+\frac{9(\omega M)^5 x_0}{4Z_1Z_2^2Z_3^2}\sin(3\omega t-\theta_1-2\theta_2-2\theta_3)$$

$$+\frac{3(\omega M)^5 x_0}{4Z_1^2Z_2^2Z_3}\sin(3\omega t-2\theta_1-2\theta_2-\theta_3)$$

$$-\frac{45(\omega M)^7 x_0}{2Z_1Z_2Z_3^2Z_4^2Z_5}\sin(3\omega t-\theta_1-\theta_2-2\theta_3-2\theta_4-\theta_5)$$

$$-\frac{27(\omega M)^7 x_0}{2Z_1Z_2Z_3^3Z_4^2}\sin(3\omega t-\theta_1-\theta_2-3\theta_3-2\theta_4)$$

$$- \frac{27\,(\omega M)^7\,x_o}{2\,Z_1\,Z_2^2\,Z_3^3\,Z_4} \sin\,(3\,\omega t - \theta_1 - 2\,\theta_2 - 3\,\theta_3 - \theta_4)$$

$$- \frac{9\,(\omega M)^7\,x_o}{4\,Z_1^2\,Z_2^2\,Z_3^2\,Z_4} \sin\,(3\,\omega t - 2\,\theta_1 - 2\,\theta_2 - 2\,\theta_3 - \theta_4)$$

$$- \frac{27\,(\omega M)^7\,x_o}{8\,Z_1\,Z_2^3\,Z_3^3} \sin\,(3\,\omega t - \theta_1 - 3\,\theta_2 - 3\,\theta_3)$$

$$- \frac{9\,(\omega M)^7\,x_o}{4\,Z_1^2\,Z_2^3\,Z_3^2} \sin\,(3\,\omega t - 2\,\theta_1 - 3\,\theta_2 - 2\,\theta_3)$$

$$- \frac{3\,(\omega M)^7\,x_o}{8\,Z_1^3\,Z_2^3\,Z_3} \sin\,(3\,\omega t - 3\,\theta_1 - 3\,\theta_2 - \theta_3)$$

$$+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\text{(6d)} \quad \xi_4 = \frac{3\,(\omega M)^4\,x_o}{Z_1\,Z_2\,Z_3\,Z_4} \cos\,(4\,\omega t - \theta_1 - \theta_2 - \theta_3 - \theta_4)$$

$$- \frac{15\,(\omega M)^6\,x_o}{Z_1\,Z_2\,Z_3\,Z_4^2\,Z_5} \cos\,(4\,\omega t - \theta_1 - \theta_2 - \theta_3 - 2\,\theta_4 - \theta_5)$$

$$- \frac{9\,(\omega M)^6\,x_o}{Z_1\,Z_2\,Z_3^2\,Z_4^2} \cos\,(4\,\omega t - \theta_1 - \theta_2 - 2\,\theta_3 - 2\,\theta_4)$$

$$- \frac{9\,(\omega M)^6\,x_o}{2\,Z_1\,Z_2^2\,Z_3^2\,Z_4} \cos\,(4\,\omega t - \theta_1 - 2\,\theta_2 - 2\,\theta_3 - \theta_4)$$

$$- \frac{3\,(\omega M)^6\,x_o}{2\,Z_1^2\,Z_2^2\,Z_3\,Z_4} \cos\,(4\,\omega t - 2\,\theta_1 - 2\,\theta_2 - \theta_3 - \theta_4)$$

$$+ \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$\text{(6e)} \quad \eta_5 = \frac{15\,(\omega M)^5\,x_o}{2\,Z_1\,Z_2\,Z_3\,Z_4\,Z_5} \sin\,(5\,\omega t - \theta_1 - \theta_2 - \theta_3 - \theta_4 - \theta_5)$$

$$- \frac{225\,(\omega M)^7\,x_o}{4\,Z_1 Z_2 Z_3 Z_4 Z_5^2 Z_6} \sin\,(5\omega t - \theta_1 - \theta_2 - \theta_3 - \theta_4 - 2\,\theta_5 - \theta_6)$$

$$- \frac{75\,(\omega M)^7\,x_o}{2\,Z_1\,Z_2\,Z_3\,Z_4^2\,Z_5^2} \sin\,(5\,\omega t - \theta_1 - \theta_2 - \theta_3 - 2\,\theta_4 - 2\,\theta_5)$$

$$- \frac{45\,(\omega M)^7\,x_o}{2\,Z_1\,Z_2\,Z_3^2\,Z_4^2\,Z_5} \sin\,(5\,\omega t - \theta_1 - \theta_2 - 2\,\theta_3 - 2\,\theta_4 - \theta_5)$$

$$- \frac{45\,(\omega M)^7\,x_o}{4\,Z_1\,Z_2^2\,Z_3^2\,Z_4\,Z_5} \sin\,(5\,\omega t - \theta_1 - 2\,\theta_2 - 2\,\theta_3 - \theta_4 - \theta_5)$$

$$- \frac{15\,(\omega M)^7\,x_o}{4\,Z_1^2\,Z_2^2\,Z_3\,Z_4\,Z_5} \sin\,(5\,\omega t - 2\,\theta_1 - 2\,\theta_2 - \theta_3 - \theta_4 - \theta_5)$$

$$+ \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

$$(6f)\quad \xi_6 = -\frac{45\,(\omega M)^6\,x_o}{2\,Z_1\,Z_2\,Z_3\,Z_4\,Z_5\,Z_6}\cos\left(6\,\omega t - \theta_1 - \theta_2 - \theta_3 - \theta_4 - \theta_5 - \theta_6\right) + \ldots$$

$$(6g)\quad \eta_7 = -\frac{7\times 45\,(\omega M)^7\,x_o}{4\,Z_1\,Z_2\,Z_3\,Z_4\,Z_5\,Z_6\,Z_7}\sin\left(7\,\omega t - \theta_1 - \theta_2 - \theta_3 - \theta_4 - \theta_5 - \theta_6 - \theta_7\right) + \ldots$$

. . . .

. . . .

Finally

$$(7)\quad \begin{aligned} x &= x_o + \xi_2 + \xi_4 + \xi_6 + \xi_8 + \ldots \\ y &= \quad\ \ \eta_1 + \eta_3 + \eta_5 + \eta_7 + \ldots \end{aligned}$$

These series are Pupin's solution of the fundamental differential equations (1). They are, in effect, Fourier's series, each amplitude of which is an infinite series. Their physical significance is most easily brought out after their convergence has been demonstrated.

PROOF OF CONVERGENCE WITH VANISHINGLY SMALL RESISTANCES

I have found a relatively simple proof of the convergence by first letting the resistances become vanishingly small, which leads us to series that are obviously convergent, and then showing that the re-introduction of finite resistances does not affect the convergence.

When $R = S = 0$, $\theta_1 = \theta_2 = \theta_3 = \ldots = \frac{\pi}{2}$,

and $Z_1 = \omega N$, $Z_2 = 2\,\omega L$, $Z_3 = 3\,\omega N$, $Z_4 = 4\,\omega L, \ldots$

Hence η_1 becomes

$$\begin{aligned} \eta_1 = x_o\frac{M}{N}\Bigg\{ &\sin\left(\omega t - \frac{\pi}{2}\right) - \frac{M^2}{4\,L\,N}\sin\left(\omega t - \frac{3\,\pi}{2}\right) \\ &+ \frac{3}{4\times 4\times 3}\left(\frac{M^2}{L\,N}\right)^2\sin\left(\omega t - \frac{5\,\pi}{2}\right) + \frac{1}{4\times 4}\left(\frac{M^2}{L\,N}\right)^2\sin\left(\omega t - \frac{5\,\pi}{2}\right) \\ &- \frac{9}{4\times 4\times 9\times 4}\left(\frac{M^2}{L\,N}\right)^3\sin\left(\omega t - \frac{7\,\pi}{2}\right) \\ &\qquad\qquad - \frac{9}{8\times 8\times 9}\left(\frac{M^2}{L\,N}\right)^3\sin\left(\omega t - \frac{7\,\pi}{2}\right) \\ &- \frac{3}{4\times 8\times 3}\left(\frac{M^2}{L\,N}\right)^3\sin\left(\omega t - \frac{7\,\pi}{2}\right) - \frac{1}{8\times 8}\left(\frac{M^2}{L\,N}\right)^3\sin\left(\omega t - \frac{7\,\pi}{2}\right) \\ &+ \ldots \Bigg\} \end{aligned}$$

Hence:

$$
(8)\left\{\begin{aligned}
\eta_1 &= -\,x_0\frac{M}{N}\cos\omega t\left\{1+\frac{1}{2^2}\left(\frac{M^2}{LN}\right)+\frac{2}{2^4}\left(\frac{M^2}{LN}\right)^2+\frac{5}{2^6}\left(\frac{M^2}{LN}\right)^3\right.\\
&\qquad\left.+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\right\}\\
&\text{Similarly}\\
\xi_2 &= \frac{x_0}{2}\left(\frac{M^2}{LN}\right)\cos 2\,\omega t\left\{1+\frac{2}{2^2}\left(\frac{M^2}{LN}\right)+\frac{5}{2^4}\left(\frac{M^2}{LN}\right)^2+\frac{14}{2^6}\left(\frac{M^2}{LN}\right)^3\right.\\
&\qquad\left.+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\right\}\\
\eta_3 &= -\,\frac{x_0}{2^2}\frac{M}{N}\left(\frac{M^2}{LN}\right)\cos 3\,\omega t\left\{1+\frac{3}{2^2}\left(\frac{M^2}{LN}\right)+\frac{9}{2^4}\left(\frac{M^2}{LN}\right)^2\right.\\
&\qquad\left.+\frac{28}{2^6}\left(\frac{M^2}{LN}\right)^3+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\right\}\\
\xi_4 &= \frac{x_0}{2^3}\left(\frac{M^2}{LN}\right)^2\cos 4\,\omega t\left\{1+\frac{4}{2^2}\left(\frac{M^2}{LN}\right)+\frac{14}{2^4}\left(\frac{M^2}{LN}\right)^2\right.\\
&\qquad\left.+\frac{48}{2^6}\left(\frac{M^2}{LN}\right)^3+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\right\}\\
\eta_5 &= -\,\frac{x_0}{2^4}\frac{M}{N}\left(\frac{M^2}{LN}\right)^2\cos 5\,\omega t\left\{1+\frac{5}{2^2}\left(\frac{M^2}{LN}\right)+\frac{20}{2^4}\left(\frac{M^2}{LN}\right)^2\right.\\
&\qquad\left.+\frac{75}{2^6}\left(\frac{M^2}{LN}\right)^3+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\right\}\\
\xi_6 &= \frac{x_0}{2^5}\left(\frac{M^2}{LN}\right)^3\cos 6\,\omega t\left\{1+\frac{6}{2^2}\left(\frac{M^2}{LN}\right)\right.\\
&\qquad\left.+\cdot\;.\;.\;.\;.\right\}\\
&.\;.\;.\;.\;.\;.\;.\;.\;.
\end{aligned}\right.
$$

Now, by expansion in power series we find:

$$
(9)\left\{\begin{aligned}
\left(1-\sqrt{1-\frac{M^2}{LN}}\right) &= \frac{1}{2}\left(\frac{M^2}{LN}\right)\left\{1+\frac{1}{2^2}\left(\frac{M^2}{LN}\right)+\frac{2}{2^4}\left(\frac{M^2}{LN}\right)^2\right.\\
&\qquad\left.+\frac{5}{2^6}\left(\frac{M^2}{LN}\right)^3+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\right.\\
\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^2 &= \frac{1}{2^2}\left(\frac{M^2}{LN}\right)^2\left\{1+\frac{2}{2^2}\left(\frac{M^2}{LN}\right)+\frac{5}{2^4}\left(\frac{M^2}{LN}\right)^2\right.\\
&\qquad\left.+\frac{14}{2^6}\left(\frac{M^2}{LN}\right)^3+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\right\}\\
\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^3 &= \frac{1}{2^3}\left(\frac{M^2}{LN}\right)^3\left\{1+\frac{3}{2^2}\left(\frac{M^2}{LN}\right)+\frac{9}{2^4}\left(\frac{M^2}{LN}\right)^2\right.\\
&\qquad\left.+\frac{28}{2^6}\left(\frac{M^2}{LN}\right)^3+\cdot\;.\;.\;.\;.\;.\;.\;.\;.\;.\right\}
\end{aligned}\right.
$$

$$\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^4 = \frac{1}{2^4}\left(\frac{M^2}{LN}\right)^4\left\{1+\frac{4}{2^2}\left(\frac{M^2}{LN}\right)+\frac{14}{2^4}\left(\frac{M^2}{LN}\right)^2 + \frac{48}{2^6}\left(\frac{M^2}{LN}\right)^3 + \cdots\cdots\right\}$$

. . . .

From (8) and (9) there results:

$$\eta_1 = -2x_0\frac{L}{M}\left(1-\sqrt{1-\frac{M^2}{LN}}\right)\cos\omega t$$

$$\xi_2 = 2x_0\frac{LN}{M^2}\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^2\cos 2\omega t$$

$$\eta_3 = -2x_0\frac{L}{M}\left(\frac{LN}{M^2}\right)\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^3\cos 3\omega t$$

$$\xi_4 = 2x_0\left(\frac{LN}{M^2}\right)^2\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^4\cos 4\omega t$$

$$\eta_5 = -2x_0\frac{L}{M}\left(\frac{LN}{M^2}\right)^2\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^5\cos 5\omega t$$

. . . .

. . . .

Hence, putting for brevity:

$$\left(\frac{LN}{M^2}\right)\left(1-\sqrt{1-\frac{M^2}{LN}}\right)^2 = \phi$$

we get

$$(10)\quad \begin{cases} x = x_0 + 2x_0\left\{\phi\cos 2\omega t + \phi^2\cos 4\omega t + \phi^3\cos 6\omega t + \cdots\cdots\right\} \\ y = -2x_0\frac{L}{M}\left(1-\sqrt{1-\frac{M^2}{LN}}\right)\left\{\cos\omega t + \phi\cos 3\omega t + \phi^2\cos 5\omega t + \phi^3\cos 7\omega t + \cdots\cdots\right\}. \end{cases}$$

Hence Pupin's series reduce to Fourier's series, the amplitudes of which are proportional to integral powers of ϕ. This is what we should expect from the simple case treated above of a single circuit with no resistance and a periodically varied self-induction. In fact, if we had chosen in the case first treated, a pair of circuits with periodically varied mutual inductance and no resistance, instead of a single circuit with periodically varied self-inductance, we should have arrived immediately at equations (10).

The quantity ϕ takes the form $\infty \times 0$ when $M = 0$, and so does the quantity $\frac{L}{M}\left(1 - \sqrt{1 - \frac{M^2}{LN}}\right)$. It may readily be shown, however, that

$$\operatorname*{Lim}_{M \doteq 0} \phi = 0$$

$$\text{and that } \operatorname*{Lim}_{M \doteq 0} \frac{L}{M}\left(1 - \sqrt{1 - \frac{M^2}{LN}}\right) = 0$$

Hence, when $M = 0$, the only current which exists is $x_0 = E/R$, which, of course, must be the case. Further, $\frac{M^2}{LN}$ is the coupling factor of the two circuits, and this must always be less than unity, and positive, of course. With these limitations on $\frac{M_2}{LN}$, it is clear that the quantities ϕ and $\left(1 - \sqrt{1 - \frac{M^2}{LN}}\right)$ can never reach unity. Therefore

$$0 < \phi < 1 \text{ and } 0 < \left(1 - \sqrt{1 - \frac{M^2}{LN}}\right) < 1\cdot$$

Hence the amplitudes of equations (10) are power series whose ratio is less than unity in absolute value, therefore the series are absolutely convergent.

PROOF OF CONVERGENCE WITH FINITE RESISTANCES

This result will now be extended to the practical case where the resistances are finite. In order to pass from equations (10) back to equations (7) and (6), we go through the following steps: (1), expand each expression $2\phi^n$ and $2\frac{L}{M}\left(1 - \sqrt{1 - \frac{M^2}{LN}}\right)\phi^n$ into power series in $\left(\frac{M^2}{LN}\right)$; (2), break up each term $h\left(\frac{M^2}{LN}\right)^k$ of the resulting series into a number of smaller terms

$$a_1\left(\frac{M^2}{LN}\right)^k + a_2\left(\frac{M^2}{LN}\right)^k + a_3\left(\frac{M^2}{LN}\right)^k + \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot$$

where a_1, a_2, a_3, . . . all have the same sign as the original term $h\left(\frac{M^2}{LN}\right)^k$; (it is important to note that in forming equations (8), the terms which were combined into single terms all had the same sign); (3), split up each term $a_i\left(\frac{M^2}{LN}\right)^k \cos m\omega t$ into two terms, viz.,

$$a_i\left(\frac{M^2}{LN}\right)^k \sin\Theta \cos m\omega t \text{ and } a_i\left(\frac{M^2}{LN}\right)^k \cos\Theta \sin m\omega t,$$

each of which is smaller than the term from which it is derived. In this way each of the series in equations (10) is converted into two series, one in sines, the other in cosines, in each of which the amplitudes are infinite series. That is, we pass from the convergent series of (10) to Pupin's series (8) by a number of steps *which cannot alter the convergence.* Hence it is proved that Pupin's series are convergent, and therefore that the Pupin theory is entirely rigorous.

PHYSICAL INTERPRETATION OF THE SOLUTION

Turning now to the physical interpretation of equations (6) and (7), we see that whenever an asymetrical rotor is revolved in the field of a stator on which is impressed a constant e. m. f., there are generated an infinite number of harmonics in both the stator and the rotor. The harmonics in the rotor are all odd, in the stator they are all even. If the resistances are small in comparison with the inductances, the amplitudes of the harmonics decrease approximately according to integral powers of a quantity ϕ whose absolute value is less than unity. If the resistances are not small, it is obvious that amplitudes must decrease more rapidly. The smaller the coupling coefficient the smaller is the quantity ϕ, and hence the more rapidly do the amplitudes decrease. The wave distortion in single phase alternators is an example; if the air gap is small, the coupling $\frac{M^2}{LN}$ will not be very small, and the amplitudes of the odd harmonics in the rotor will not fall off very rapidly. The presence of these odd harmonics constitutes at least part of the distortion. If a large uncoupled inductance is connected in series with the field of a single phase alternator, the coupling $\frac{M^2}{LN}$ will be reduced, and the distortion consequently diminished. This might be of practical importance, for example, in enabling single phase alternators to be constructed with smaller air gaps and thereby reducing the amount of copper required in the field coils. The case of polyphase alternators with unbalanced load is precisely similar, of course.

In ordinary alternating current machinery, the harmonics are suppressed as far as possible; in the Goldschmidt alternator, on the other hand, the harmonics are encouraged by the use of condensers, the object being to get as much energy as possible into a single predetermined overtone. In his lectures, Professor Pupin indicated how the theory could be extended to include condensers in the stator and rotor circuits. This extension will now be carried out in detail.

CIRCUITS HAVING RESISTANCE, INDUCTANCE, CAPACITY AND VARIABLE MUTUAL INDUCTANCE

Suppose that the rotor and stator circuits include any arbitrary arrangement of inductances and capacities. At a given frequency $\frac{2n\omega}{2\pi}$, the stator circuit will have a definite effective resistance, which we may denote by R_{2n}, and a definite effective inductance, which we may denote by L_{2n}. Similarly, at a given frequency $\frac{(2n+1)\omega}{2\pi}$, the rotor circuit will have an effective resistance S_{2n+1} and inductance N_{2n+1}. That is, the quantities R, S, L, N are no longer constants, but are functions of the frequency. R_{2n} and S_{2n+1} must always be positive, but L_{2n} and N_{2n+1} may be positive, negative or zero. If $L_{2n} = 0$, it means that the stator circuit is tuned to the frequency $\frac{2n\omega}{2\pi}$; similarly, if $N_{2n+1} = 0$, the rotor circuit is tuned to the frequency $\frac{(2n+1)\omega}{2\pi}$.

It is clear, therefore, that the fundamental differential equations (1) hold for the present case as well as for the previous case, provided that we consider steady states only, the only difference being that R, S, L and N are now functions of ω. Bearing this in mind we may proceed exactly in the same manner as before, arriving at equations (4). The solutions of these equations are of the same form as in the previous case, i. e., of the same form as equations (5); but now, Z_1, Z_2, Z_3, Z_4 . . . . and $\theta_1, \theta_2, \theta_3, \theta_4$, ... are given by:

$$Z_1^2 = (\omega N_1)^2 + S_1^2 \qquad \theta_1 = \tan^{-1}\frac{\omega N_1}{S_1}$$

$$Z_2^2 = (2\omega L_2)^2 + R_2^2 \qquad \theta_2 = \tan^{-1}\frac{2\omega L_2}{R_2}$$

$$Z_3^2 = (3\omega N_3)^2 + S_3^2 \qquad \theta_3 = \tan^{-1}\frac{3\omega N_3}{S_3}$$

$$Z_4^2 = (4\,\omega L_4)^2 + R_4^2 \qquad\qquad \theta_4 = \tan^{-1}\frac{4\,\omega L_4}{R_4}$$

$$\cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot\qquad\qquad\qquad\cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot$$

It is clear, therefore, that the solutions as given by equations (6) and (7) hold for all cases, provided that the proper meanings be attached to the Z's and the θ's.

We proceed now to investigate what happens to Pupin's series when the rotor circuit is tuned to a definite number of frequencies $\frac{\omega}{2\pi}, \frac{3\,\omega}{2\pi} \cdot\cdot\cdot\cdot$, and the stator circuit to the frequencies $\frac{2\,\omega}{2\pi}, \frac{4\,\omega}{2\pi}, \cdot\cdot\cdot\cdot$ To fix the ideas, let the rotor be tuned to the single frequency $\frac{\omega}{2\pi}$, and the stator to the single frequency $\frac{2\,\omega}{2\pi}$. Then Z_1 becomes simply S_1, and Z_2 becomes R_2. We assume, furthermore, that the effective resistances for these frequencies, i. e., S_1 and R_2, are small. Then the quantities $\frac{\omega M}{Z_1}$ and $\frac{\omega M}{Z_2}$, which now become $\frac{\omega M}{S_1}$ and $\frac{\omega M}{R_2}$, are very large.

It will be observed that the current η_1 contains the amplitudes:

$$\frac{\omega M x_0}{Z_1},\ \left(\frac{\omega M}{Z_1}\right)^2\left(\frac{\omega M}{2Z_2}\right)x_0,\ \left(\frac{\omega M}{Z_1}\right)^3\left(\frac{\omega M}{2Z_2}\right)^2x_0,\ \left(\frac{\omega M}{Z_1}\right)^4\left(\frac{\omega M}{2Z_2}\right)^3x_0$$
$$\left(\frac{\omega M}{Z_1}\right)^5\left(\frac{\omega M}{2Z_2}\right)^4x_0, \cdot\quad\cdot\quad\cdot\quad\cdot$$

Likewise, the current ξ_2 contains the amplitudes:

$$2x_0\left(\frac{\omega M}{Z_1}\right)\left(\frac{\omega M}{2Z_2}\right),\quad 2x_0\left(\frac{\omega M}{Z_1}\right)^2\left(\frac{\omega M}{2Z_2}\right)^2,\quad 2x_0\left(\frac{\omega M}{Z_1}\right)^3\left(\frac{\omega M}{2Z_2}\right)^3.$$
$$2x_0\left(\frac{\omega M}{Z_1}\right)^4\left(\frac{\omega M}{2Z_2}\right)^4, \cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot$$

and η_3 contains the amplitudes:

$$\frac{3\,\omega M x_0}{Z_3}\left(\frac{\omega M}{Z_1}\right)\left(\frac{\omega M}{2Z_2}\right),\quad \frac{3\,\omega M x_0}{Z_3}\left(\frac{\omega M}{Z_1}\right)^2\left(\frac{\omega M}{2Z_2}\right)^2,$$
$$\frac{3\,\omega M x_0}{Z_3}\left(\frac{\omega M}{Z_1}\right)^3\left(\frac{\omega M}{2Z_2}\right)^3, \cdot\quad\cdot\quad\cdot\quad\cdot\quad\cdot$$

and ξ_4 contains the amplitudes:

$$\frac{6\,(\omega M)^2x_0}{Z_3Z_4}\left(\frac{\omega M}{Z_1}\right)\left(\frac{\omega M}{2Z_2}\right),\quad \frac{6\,(\omega M)^2x_0}{Z_3Z_4}\left(\frac{\omega M}{Z_1}\right)^2\left(\frac{\omega M}{2Z_2}\right)^2$$

$$\cdot\qquad\cdot\qquad\cdot\qquad\cdot\qquad\cdot\qquad\cdot\qquad\cdot\qquad\cdot$$

We see, therefore, that every current contains amplitudes which are power series in $\left(\frac{\omega M}{Z_1}\right)\left(\frac{\omega M}{2 Z_2}\right)$; and if the circuits are tuned so as to reduce Z_1 to S_1 and Z_2 to R_2, and if these resistances are small, it follows that *all* the series of equations (6) *diverge,* and therefore that *all the amplitudes tend towards infinity.* A complete discussion of the convergence or divergence of these series is not very simple, but in the given case it is clear that if the resistances R_2 and S_1, are small, the higher powers of $\left(\frac{\omega M}{Z_1}\right)\left(\frac{\omega M}{2 Z_2}\right)$ which occur in all the amplitudes soon become so large as to make all the other terms in the amplitudes negligibly small, and the divergence of all the amplitudes is therefore assured.

EXPLANATION OF LIMITATION OF ROTOR AND STATOR CURRENTS IN PRACTICE

The question now arises, does the Pupin theory break down when tuned condenser circuits of low resistance are employed, or is the theory still justified by the physical phenomena? And if the theory is justified how can the operation of the Goldschmidt alternator be accounted for?

The answer to both of these questions is, I think, not far to seek. It does not require an elaborate theory to show that if the stator and rotor circuits are tuned, let us say to the frequencies $\frac{2\omega}{2\pi}$ and $\frac{\omega}{2\pi}$ respectively, the currents all tend toward infinity in an ideal machine of low resistance. For, suppose a current x_0 is flowing in the stator; this will give rise to a current $\frac{\omega M x_0}{S}\sin\omega t$ in the tuned rotor circuit; this in turn will give rise to a current $-\frac{(\omega M)^2 x_0}{R S}\cos 2\omega t$ in the tuned stator circuit (leaving out of account the other currents generated): this stator current in turn will give rise to a current $-\frac{(\omega M)^3 x_0}{2 R S^2}\sin\omega t$ in the tuned rotor circuit, which is opposite in phase to the first current $\frac{\omega M x_0}{S}\sin\omega t$ but is very much larger than the same if the resistances are small. In this way, each new current of frequency $\frac{\omega}{2\pi}$ in the rotor will give rise to a much larger current of frequency $\frac{2\omega}{2\pi}$ in the stator, and this in turn to a still larger current of frequency $\frac{\omega}{2\pi}$ in the rotor, and so forth. Physical reasoning shows, therefore, that the currents to which the circuits are tuned tend toward infinity in ideal machines of low resistance. But obviously, if one of the currents becomes infinite, they all must become infinite, hence the Pupin theory as applied to the case of tuned condenser circuits is entirely in accord with the phenomena which would exist in an ideal machine. The correctness of the Pupin theory in all cases is therefore established.

As regards the practical operation of the Goldschmidt alternator, this is readily accounted for by the variable permeability of the iron. As the rotor and stator currents become larger and larger, the permeability of the iron becomes smaller and smaller, hence the circuits *automatically detune themselves* and thereby keep down the currents. At the same time, the losses in the iron increase rapidly as the currents become larger, hence the effective resistances also become larger, and this also tends to limit the values of the current. It is a physical impossibility, therefore, to keep the circuits in tune or to keep the resistances very low; the practical operation of the Goldschmidt alternator is thus accounted for.

The Pupin theory shows that by suitably controlling the impedances Z_1, Z_2, Z_3, ... it should be possible to make any given amplitude larger than the others, but it also shows that to make the given amplitude large, the neighboring amplitudes must also be large. Professor Pupin long ago pointed out the possibilities in this method of generating radio frequency currents, but in his opinion the difficulties and disadvantages outweighed the advantages to such an extent that he did not attempt to develop the method for practical purposes.

Thruout this paper, attention has been confined to the case of a constant e. m. f. impressed on the stator. It should be mentioned, however, that the Pupin theory includes the case where the impressed e. m. f. is any function of the time. In conclusion it should also be mentioned that Professor Pupin showed his solution of the fundamental differential equations to Professor Moulton of Chicago University, and that the latter has since applied the method to the general theory of linear differential equations with harmonic coefficients.

SUMMARY: The case of a simple circuit having periodically varying inductance is first examined. The solution shows that the current has a constant component and an infinite series of convergently diminishing higher harmonics. Circuits having inductance, resistance, and variable mutual inductance are next considered. To solve the equations obtained, an infinite transformation is carried out, each variable being replaced by the sum of an infinite series of new variables, thus enabling an infinite number of arbitrary conditions to be imposed. As a result, an infinite series of equations is obtained, each of which can be solved if those preceding it have been solved. The solutions are worked out to the fourth harmonic in one circuit and the third in the other. In one circuit, only odd frequencies appear; in the other, only even. The general solutions are in the form of a Fourier's series, each amplitude of which is an infinite series. The convergence of the solutions is completely established. The solutions are then extended to the case where rotor and stator circuits contain capacities.

It is shown that according to Pupin's theory, all currents in low resistance rotors and stators tend toward infinity if these circuits are appropriately tuned. This apparent discrepancy from practice is explained on the ground that the variable permeability of the iron in the Goldschmidt alternators automatically detunes the circuits and that the increasing losses of the iron tend further to limit all currents.

DISCUSSION

Louis Cohen (by letter): Aside from the interesting solution of the problem that the paper deals with relating to radio frequency alternators, the great importance of the paper consists in the general method that Professor Pupin has given us for solving differential equations having variable coefficients. I believe the method will prove of great value in the solution of many other problems in electrotechnics.

I recall that I have discussed this problem with Professor Pupin about six years ago, and he told me then that he had marked out the general solution of the problem, but reserved its publication for some future time. We ought to be grateful to Mr. Liebowitz for having put it in shape for publication and presenting it before the Institute.

As an illustration of the applicability of the method developed in the paper to the solution of other problems, it may be of interest to mark out the problem of the microphone circuit.

We have in this case an inductance, a variable resistance and a continuous e. m. f. in the circuit, and the circuit equation is,

$$L\frac{dI}{dt} + RI + rI\cos\omega t = E, \tag{1}$$

where R+r is the total resistance of the circuit in stationary condition.*

As far as I know the complete solution of this problem has never been given. Following, however, the method developed by Professor Pupin, we can readily obtain the solution of the problem.

Put $$I = I_0 + I_1 + I_2 + I_3 + \ldots\ldots + I_n, \tag{2}$$

and make the substitution in equation (1), we get

$$\left.\begin{aligned} & L\frac{dI_0}{dt} + RI_0 + rI_0\cos\omega t \\ & + L\frac{dI_1}{dt} + RI_1 + rI_1\cos\omega t \\ & + L\frac{dI_2}{dt} + RI_2 + rI_2\cos\omega t \\ & + \cdots\cdots\cdots\cdots \\ & + L\frac{dI_n}{dt} + RI_n + rI_n\cos\omega t = E \end{aligned}\right\} \tag{3}$$

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* (R is the constant resistance of the external circuit; the resistance of the microphone, which varies periodically under the influence of a sound of frequency $\frac{\omega}{2\pi}$, is $r\cos\omega t$. The term $I\,(r\cos\omega t)$ in equation (1) is therefore the drop of potential at time t across the microphone.—EDITOR.)

In accordance with the method given in the paper, we can break up equation (3) into a number of independent equations, as follows:

$$\left.\begin{aligned}
&\text{(a)}\quad L\frac{dI_0}{dt} + RI_0 = E \\
&\text{(b)}\quad L\frac{dI_1}{dt} + RI_1 + rI_0\cos\omega t = 0 \\
&\text{(c)}\quad L\frac{dI_2}{dt} + RI_2 + rI_1\cos\omega t = 0 \\
&\text{(d)}\quad L\frac{dI_3}{dt} + RI_3 + rI_2\cos\omega t = 0 \\
&\qquad\quad \cdots\cdots\cdots\cdots \\
&\qquad\quad \cdots\cdots\cdots\cdots
\end{aligned}\right\} \tag{4}$$

Disregarding the transients, we have for the solution of (4a),

$$I_0 = \frac{E}{R}. \tag{5}$$

Substituting the value of I_0 from (5) into (4b), we get

$$L\frac{dI_1}{dt} + RI_1 = -\frac{Er}{R}\cos\omega t \tag{6}$$

and

$$I_1 = -\frac{Er}{RZ_1}\cos(\omega t - \theta_1) \tag{7}$$

$$Z = \sqrt{L^2\omega^2 + R^2}, \quad \theta_1 = \tan^{-1}\frac{L\omega}{R}.$$

Substituting the value of I_1 into (4c), we have

$$\begin{aligned}
L\frac{dI_2}{dt} + RI_2 &= \frac{Er^2}{RZ_1}\cos(\omega t - \theta_1)\cos\omega t \\
&= \frac{Er^2}{2RZ_1}\left\{\cos(2\omega t - \theta_1) + \cos\theta_1\right\}
\end{aligned}$$

and

$$I_2 = \frac{Er^2}{2RZ_1Z_2}\cos(2\omega t - \theta_1 - \theta_2) + \frac{Er^2\cos\theta_1}{2R^2Z_1}. \tag{8}$$

Repeating the operation, we find in a similar manner,

$$\begin{aligned}
I_3 = &-\frac{Er^3}{4RZ_1Z_2Z_3}\cos(3\omega t - \theta_1 - \theta_2 - \theta_3) \\
&-\frac{Er^3}{4RZ_1^2Z_2}\cos(\omega t - 2\theta_1 - \theta_2) \\
&-\frac{Er^3}{2R^2Z_1^2}\cos\theta_1\cos(\omega t - \theta_1)
\end{aligned} \tag{9}$$

$$\left.\begin{aligned} I_4 = {} & \frac{E\,r^4}{8\,R\,Z_1\,Z_2\,Z_3\,Z_4}\cos(4\,\omega\,t - \theta_1 - \theta_2 - \theta_3 - \theta_4) \\ & + \frac{E\,r^4}{8\,R\,Z_1 Z_2^2 Z_3}\cos(2\,\omega\,t - \theta_1 - 2\,\theta_2 - \theta_3) \\ & + \frac{E\,r^4}{8\,R\,Z_1^2 Z_2^2}\cos(2\,\omega\,t - 2\,\theta_1 - 2\,\theta_2) \\ & + \frac{E\,r^4}{8\,R^2\,Z_1^2\,Z_2}\cos(2\,\theta_1 + \theta_2) \\ & + \frac{E\,r^4}{4\,R^2\,Z_1^2\,Z_2}\cos(2\,\omega\,t - \theta_1 - \theta_2) + \frac{E r^4 \cos^2\theta_1}{4\,R^3\,Z_1^2}. \end{aligned}\right\} \quad (10)$$

and similarly for the other components.

If we collect separately the terms of the same frequency, and denote the results by η_0, η_1, η_2, etc., respectively, we get

$$\begin{aligned} \eta_0 = {} & \frac{E}{R} + \frac{E\,r^2\cos\theta_1}{2\,R^2\,Z_1} + \frac{E\,r^4}{8\,R^2\,Z_1^2\,Z_2}\cos(2\,\theta_1 + \theta_2) \\ & + \frac{E\,r^4\cos^2\theta_1}{4\,R^3\,Z_1^2} + \cdots\cdots \\ = {} & \frac{E}{R}\left\{1 + \frac{r^2}{2\,R\,Z_1}\cos\theta_1 + \frac{r^4}{8\,R\,Z_1^2\,Z_2}\cos(2\,\theta_1 + \theta_2) \right. \\ & \left. + \frac{r^4\cos^2\theta_1}{4\,R^2\,Z_1^2} + \cdots\cdots\right\} \quad (11) \end{aligned}$$

$$\begin{aligned} -\eta_1 = {} & \frac{E\,r}{R\,Z_1}\left\{\cos(\omega\,t - \theta_1) + \frac{r^2}{4\,Z_1\,Z_2}\cos(\omega\,t - 2\,\theta_1 - \theta_2) \right. \\ & \left. + \frac{r^2}{2\,R\,Z_1}\cos\theta_1\cos(\omega\,t - \theta_1) + \cdots\cdots\right\} \quad (12) \end{aligned}$$

$$\begin{aligned} \eta_2 = {} & \frac{E\,r^2}{2\,R\,Z_1\,Z_2}\left\{\cos(2\,\omega t - \theta_1 - \theta_2) + \frac{r^2}{4\,Z_2 Z_3}\cos(2\omega t - \theta_1 - 2\theta_2 - \theta_3) \right. \\ & + \frac{r^2}{4\,Z_1\,Z_2}\cos(2\,\omega\,t - 2\,\theta_1 - 2\,\theta_2) \\ & \left. + \frac{r^2}{2\,R\,Z_1}\cos(2\,\omega\,t - \theta_1 - \theta_2) + \cdots\cdots\right\} \quad (13) \end{aligned}$$

. . . .

The total current in the circuit is

$$I = \eta_0 + \eta_1 + \eta_2 + \cdots\cdots \quad (14)$$

It is seen therefore that the current is of a complex character, having a continuous current component, and currents of frequencies $\frac{\omega}{2\pi}$, $\frac{2\,\omega}{2\pi}$, etc. It is also to be noted that the amplitudes of the different components decrease as the frequencies increase.

As a partial proof we may consider the case when there is no inductance in the circuit, $L = 0$, we have then

$$\theta_1 = \theta_2 = \theta_3 = \cdots\cdots = 0$$

$$Z_1 = Z_2 = Z_3 = \cdots\cdots = R.$$

Equations (11), (12), and (13) reduce to

$$\begin{aligned} \gamma_0 &= \frac{E}{R}\left\{1+\frac{r^2}{2R^2}+\frac{r^4}{8R_4}+\frac{r^4}{4R^4}+\cdots\cdots\right\} \\ -\gamma_1 &= \frac{Er}{R^2}\cos\omega t\left\{1+\frac{r^2}{4R^2}+\frac{r^2}{2R^2}+\cdots\cdots\right\} \end{aligned} \qquad (15)$$

. . . .

If we put L = 0 in equation (1) we get

$$I = \frac{E}{R + r\cos\omega t} = \frac{E}{R}\left\{1+\frac{r}{R}\cos\omega t\right\}^{-1}. \qquad (16)$$

Expanding the above by the binomial theorem, we have

$$I = \frac{E}{R}\left\{1-\frac{r}{R}\cos\omega t+\frac{r^2}{R^2}\cos^2\omega t-\frac{r^3}{R^3}\cos^3\omega t+\cdots\cdots\right\} \qquad (17)$$

$$\cos^2\omega t = \frac{1}{2}+\frac{1}{2}\cos 2\omega t$$

$$\cos^3\omega t = \frac{1}{2}\cos\omega t+\frac{1}{4}\cos\omega t+\frac{1}{4}\cos 3\omega t$$

$$\cos^4\omega t = \frac{1}{4}+\frac{1}{2}\cos 2\omega t+\frac{1}{8}+\frac{1}{8}\cos 4\omega t$$

. . . .

Making these substitutions, we get

$$\begin{aligned} \because\ I = {} & \frac{E}{R}\left\{1+\frac{r^2}{2R^2}+\frac{r^4}{4R^4}+\frac{r^4}{8R^4}+\cdots\cdots\right\} \\ & -\frac{Er}{R^2}\cos\omega t\left\{1+\frac{1}{2}\frac{r^2}{R^2}+\frac{1}{4}\frac{r^2}{R^2}+\cdots\cdots\right\} \\ & + \cdots\cdots\cdots\cdots \end{aligned} \qquad (18)$$

The results by the two methods are in exact agreement.

Benjamin Liebowitz (by letter): Owing to the fact that Pupin's series diverge when tuned condenser circuits of low resistance are employed, great care must be exercised in interpreting the theory as applied to the Goldschmidt alternator. The theory shows that if a current of a given frequency is large, the currents of neighboring frequencies must also be large; but it also shows that by properly controlling the impedances (detuning some of the circuits, if necessary) *the series for a given frequency can be made to diverge more rapidly than any other.* There is nothing in the theory, therefore, which says that a high efficiency is impossible. On the other hand, a high efficiency would hardly be expected, owing to the inevitable large losses in the iron, and in practice the efficiency is not more than fifty-four per cent., according to Mr. Mayer.

It has been remarked that the currents of frequency $\frac{2\omega}{2\pi}$, for example, generated in the stator by successive "reflection" from the rotor, being of opposite signs, tend to neutralize each other. It must be borne in mind, however, that any power series whose ratio is greater than unity is divergent, even if the signs alternate. Therefore, all the currents tend toward infinity in an ideal machine, in spite of the differences in sign of successive amplitudes. The series will begin to converge only when the ratios $\frac{\omega M}{Z}$ become sufficiently small, and in tuned condenser circuits this cannot happen until the currents attain sufficiently large values to produce detuning, a decrease in M, and increases in the effective resistances, by the approach of saturation.

Lester L. Israel (by letter): From the theory developed in this paper it appears that currents of lower frequency due to reactions of the higher harmonics become increasingly large.

Since in practice the Goldschmidt alternator is quite efficient, this can hardly be so. Perhaps the apparent discrepancy may be accounted for by the fact that these induced lower harmonics are opposed in phase, together with a limitation or modification of the series representing them arising from the high energy absorption at one of the higher harmonics.

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All references to any individual, company, or radio station are fully listed in this index. Answers to points brought out in the Discussions will be listed under the name of the questioner. With the exception of the names of companies, all topics will be listed in general under the *noun* referred to. The numbers correspond to pages in the text. The following abbreviations are used: r. f.—radio frequency; a. f.—audio frequency; l. v.—low voltage; h. v.—high voltage.