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A NEW SYSTEM OF IMPACT EXCITATION OF CONTINUOUS ELECTRICAL OSCILLATIONS AND THEIR APPLICATION TO WIRELESS TELEPHONY.

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[During the development of radio-telegraphy and radio-telephony there have appeared many devices, including various forms of discharge gaps and arcs, for the production of high-frequency oscillations. The following contribution presents yet another method, which was discovered by the author, for the production of oscillatory currents of high frequency; an arrangement which at first sight may appear to differ but slightly from some hitherto known systems, but which, on closer study, will be seen to be new in electrical action. Besides being new, this system possesses some interesting characteristics and some advantages over the other systems, which render it useful. A brief study¹ of the system is given in the following pages, together with some notes on its successful application to wireless telephony.]

If an ordinary spark discharge of a condenser takes place in a primary circuit, which is coupled to a closed or open sec-

¹For a more detailed study see "A New Method of Impact Excitation of Undamped Oscillations and Their Analysis by Means of Braun-Tube Oscillographs," by E. L. Chaffee, *Proceedings American Academy of Arts and Sciences*, vol. xlvii, No. 9, Nov., 1911.

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dary circuit, there are produced in the two circuits oscillations of two periods. These two periods result from the interaction of the currents in the two circuits, causing the energy to be alternately interchanged from one circuit to the other. Since we are chiefly interested, in this discussion, in the conditions which give a maximum amplitude of current in the secondary circuit, the two circuits are to be considered as adjusted to the same natural period. Fig. 1 (*a*) shows the graph of the currents in the primary and secondary circuits for the case just considered.

The disadvantages of the ordinary spark-discharge system are obvious. The periodic return of energy into the primary circuit causes a useless dissipation of heat in the spark gap, and, aside from the wear and tear on the gap, the efficiency of the system is greatly reduced. The double periodicity of the oscillations is undesirable in wireless telegraphy not only because the energy is divided between the two periods, but because of the greater interference of signals.

A marked improvement over the ordinary spark-discharge system is found in the quenched-spark method of producing oscillations. The Lepel system² is an example of this class of generators. The success of this system depends upon the properties of certain, short, rapidly-cooled gaps which are characterized by a loss in conductivity as soon as the amplitude of the oscillations in the primary circuit becomes zero; but this loss in conductivity is, in general, *not* rapid enough to quench out the primary oscillations when the current alone becomes zero. After the primary circuit ceases to oscillate, the secondary circuit continues to vibrate in its natural period. The graphs of the oscillations for this system are shown at *b*, Fig. 1.

The secondary oscillations of the quenched-spark system are of three periods; namely, the two coupling periods when the primary is active, and the natural period of the secondary circuit after the primary oscillations have been quenched.

The diagrams given at *a* and *b* of Fig. 1 represent the conditions for only one oscillation train. In the case of the first system, the spark or train frequency is only a few hundred per

² Lepel, *Electrician* (London), 63, pp. 142, 157, 174, 345, 376 (1909); 64, pp. 153, 386 (1909-10); G. W. Nasmyth, *Phys. Rev.*, 32, No. 1, 103 (1911).

Peukert arc, *Electrician* (London), 64, 361, 550.

FIG. 1.

second, which means that, in general, the interval of time separating the successive trains is several hundred times longer than the time of duration of one train. The quenched-spark system allows of a spark frequency of several thousand per second. By the use of specially-constructed rotating gaps, the spark frequency can be pushed to 20,000 or 30,000 per second. Even with these highest frequencies, which are seldom if ever used in practice, there would be about twenty-five secondary oscillations of a wave length of 500 metres, between primary trains, provided the damping were not sufficient to reduce the oscillations to zero during the interval.

The new system, herein to be described, depends, in its action, upon the properties of a special discharge gap when working in conjunction with properly-adjusted circuits. The action of the system is disclosed by *c* of Fig. 1, which shows the marked difference in action of this system from that of the others. As will be seen, the primary circuit executes *rectified* impulses of approximately double the period of the secondary oscillation. Because of this fact, because of the particular shape of the primary impulses, and because of the fact that these impulses always occur automatically in the proper phase relation with the secondary oscillations, the latter are sinusoidal in form, are continuous, and, if the primary impulse frequency be sufficient, are constant in amplitude. The primary impulse frequency may be adjusted at will, but is usually several hundred thousand, and may be a million or more, per second. Fig. 1 shows the primary impulses occurring every two secondary oscillations. This is not always the case, for the conditions can be adjusted so that the impulses occur every three, four, etc., up to any number of secondary oscillations. Since the primary impulses are rectified, the secondary circuit returns practically no energy to the primary circuit, and the secondary circuit, therefore, oscillates with but one period, *i.e.*, its own free period.

Other details and interesting characteristics of this system will be considered below.

Although this system is not an arc system, yet the resulting oscillations possess the continuity of the arc oscillations, but with a greater constancy of wave length and an improvement of wave form. A more detailed comparison with the Poulsen-arc system will be found in the section on wireless telephony.

THE OSCILLATORY SYSTEM.

(1) *The Gap and Connections.*

The gap consists essentially of an aluminum cathode and an anode of some other metal, such as copper or silver, both water or air cooled and surrounded by an atmosphere of moist hydrogen. The active surfaces of the terminals are accurately parallel planes of one or two square centimetres area, and adjustable as to distance separating them, which, for the best results, is about

FIG. 2.

Air-cooled Cu-Al discharge gap. One-half natural size.

.07 mm. Large terminals are undesirable on account of the increased electrostatic capacity of the gap, which must be small in comparison with the main capacity of the circuit.

For the cathode, aluminum is the only metal which gives at all satisfactory results, and the gap should be constructed so that the terminals can be occasionally renewed. After the gap has been in operation for some time the aluminum becomes pitted and covered with a very hard oxide which is difficult to remove. One electrode was operated, however, for over one

hundred hours with fairly satisfactory results at the expiration of that time.

Several metals work well as anode, the latter apparently playing very little part in the action of the gap. It appears, however, that the denser metals of high cathode drop, such as copper and silver, are desirable. The anode, with occasional cleaning, will serve indefinitely.

Although the amount of heat produced in the gap is small, some method of cooling the terminals is necessary. Air cooling

FIG. 3.

Details of water-cooled *Cu-Al* gap. Two-fifths natural size.

by means of radiating vanes is to be preferred on account of convenience and simplicity. Fig. 2 gives the details of an air-cooled gap, the right-hand half in section. At *e* there is shown the *Al* electrode which is held by a taper-fit in the massive terminal *t*. Opposed to this *Al* electrode is a similarly shaped copper electrode held by taper-fit in a similar massive terminal. These terminals are threaded and engage in the side castings *c c*, and are provided with blackened metallic radiating vanes as shown. The side castings are separated by a thin slab of hard

rubber or asbestos board, which has a central circular hole to serve for the gap chamber h . Rubber handles rr are for use in adjustment. The inlet and outlet for the hydrogen are shown at i and o .

A water-cooled gap as shown in Fig. 3 was, however, used throughout this investigation. By reference to the drawing this gap is seen to consist of two hollow threaded electrodes capped with aluminum and copper, respectively, and each provided at the outside end with an inlet and outlet tube for the passage of the cooling water. The terminals are enclosed in a hard rubber casing provided with a circular glass front. Hard rubber disks attached to the electrodes serve for adjusting handles.

The general diagram of connections is shown in Fig. 4. S is a source of direct current of a few hundred volts. In the follow-

FIG. 4.

Diagram of connections.

ing experiments about 500 volts were used. I_0 is a D. C. ammeter which measures the current in the supply circuit. This circuit also contains the two inductances or choke coils L_0 L_0 , and a variable resistance R_0 , capable of reducing the current to about 0.2 ampere. In the following experiments L_0 L_0 are ordinary A. C. arc-light inductances, and R_0 is a resistance, adjustable in one-half ampere steps, in series with a variable copper-sulphate electrolytic resistance, for closer regulation of current. C_1 and C_2 are variable air condensers, G the gap, L_1 and L_2 the variable primary and secondary of the closely-coupled oscillation transformer, and I_2 a hot-wire ammeter. The secondary circuit is here shown as a closed circuit, but an open antenna circuit may be used.

(2) *Operation of Gap.*

The system will start on closing the switch if the distance between the terminals is not much greater than 0.1 mm. In appearance the discharge resembles a very minute arc, of an intense reddish-purple color, absolutely quiet and stationary. The discharge remains at one point on the electrodes for several minutes until the aluminum is slightly pitted, when it suddenly shifts to another point. When the discharge is examined by means of a spectroscope only the primary hydrogen spectrum appears with an occasional weak flashing-up of a few of the

FIG. 5.

Effect of changing length of gap.

$$\begin{aligned}
 I_0 &= .335 \text{ ampere.} \\
 \lambda_2 &= 106 \text{ meters.} \\
 C_1 &= 112 \times 10^{-6} \mu.f. \\
 C_2 &= 60 \times 10^{-5} \mu.f.
 \end{aligned}$$

aluminum lines. Plate 1b gives the discharge spectrum with an aluminum comparison spectrum. It is evident from the figure that the metals are not vaporized, and the indications are that the conduction is entirely by gaseous ionization.

In order to show the effect on the intensity of the secondary oscillations of varying the length of the gap, the curve shown in Fig. 5 was taken. It is seen that the intensity of the secondary current, as measured by the hot-wire ammeter, is roughly independent of the length of the gap. At 0.18 mm. the secondary current is a maximum, but at about this length of the gap the

discharge begins to hiss and become unsteady. For other values of the main current, I_0 , the curve would be slightly different, but, in general, the best results are obtained with a gap length of from .04 to .09 mm.

The effect of changing the pressure of the hydrogen was investigated. Apparently atmospheric pressure gives the most satisfactory results, although, for decreased pressure, the oscillations are possibly slightly more intense until the pressure of about 10 or 20 cm. is reached, when they rapidly become weaker. Increased pressure is decidedly detrimental.

The following is a brief review of the events during one cycle, the details of which will be considered more at length later. It is clearest, in tracing the sequence of phenomena, to begin at the instant after the system has been started, when the potential of the primary condenser C_1 (Fig. 4) has attained a value sufficient to break down the high resistance of the gap. The gap resistance rapidly falls to a very low value as the discharge of condenser C_1 and the main current I_0 , which was previously flowing into C_1 and which remains practically constant on account of the inductances L_0 , L_1 , rush across the gap and through the primary coil L_1 . This current rush takes place according to a definite positive loop of current with respect to time, the shape, amplitude, and duration of which depend upon the constants of the circuit, the rapidity of absorption of energy by the secondary circuit, and, to a slight extent, upon the conditions of the gap and strength of the main current I_0 . The condenser C_1 is discharged and charged somewhat in the opposite direction by this positive current rush. If conditions are right the discharge stops as soon as I_1 becomes zero, there being no inverse current. The secondary receives a certain increment of energy from this discharge, and continues to oscillate after the primary discharge stops.

This absence of inverse current above referred to is due to the combination of three conditions. First, and most important, is the practically instantaneous re-establishment of the high initial gap resistance when the current becomes zero, due probably to the formation of an insulating oxide film on the aluminum; second, the higher cathode drop of the anode metal; third, the absorption of energy by the secondary, although rectification usually takes place without this aid.

At the end of the above-mentioned current rush the current through the gap is zero and the condenser C_1 has an inverse charge. Since the main current must remain constant, it is now flowing into C_1 , it having been gradually shifted over to C_1 as I_1 decreased toward zero. The main current I_0 flows into C_1 at a practically constant rate, neutralizing the inverse charge and charging it in the initial direction. The potential difference of C_1 increases uniformly, attaining a much higher value than exists outside the choke coils. This uniform increase in potential of the primary condenser is very useful, as will appear later.

Impressed across the gap is the potential difference of the condenser C_1 plus the ripples induced in the primary circuit by the secondary current, these potential ripples serving as a trigger to start the primary discharge on a second cycle in the proper phase relation with the secondary oscillation.

It is evident from the above consideration that, on account of the inductances L , L_0 , the condenser C_1 can attain a much higher difference of potential than that of the source, the magnitude of this condenser potential being determined by the breaking-down potential of the gap. It is also clear that, if this breaking-down potential be assumed approximately constant, the number of discharges of C_1 per second depends upon the main current I_0 .

The duration of each primary discharge does not, as has been stated, depend upon the supply current, so that it is only the duration of the interval between primary discharges which changes with varying main current. The secondary continues to oscillate during these intervals with decreasing amplitude according to the damping of the secondary circuit. In what follows the number of secondary oscillations to one primary discharge and charge is spoken of as the "inverse charge frequency referred to the secondary oscillation" or simply I. C. F.

From what has been said it is clear that the secondary receives periodic impulses from the primary, the frequency of these impulses depending upon the main current and the capacity of the primary condenser. During the intervals of non-activity of the primary circuit the secondary circuit oscillates in its own free period and with damping determined solely by the conditions of the secondary circuit, such as resistance and radiation. As has been stated, the amplitude of the oscillation can, however,

be maintained practically constant by making the primary impulses occur every two or three secondary oscillations, and, if the damping in the secondary circuit be small, the resulting oscillations are then almost perfectly undamped and continuous.

(3) *The Syntony Conditions.*

In order that the maximum energy be transferred to the secondary circuit there are two conditions of syntony, as they may be termed, to be fulfilled. In the first place, the primary discharges must always occur in the proper phase relation with the secondary oscillation, or, in other words, the I. C. F. must be a whole number. In general the I. C. F. is between 5 and 16 or 20, and this first condition of syntony is automatically forced by the strong reaction of the secondary current upon the primary circuit, but when the I. C. F. is of the order of 2 or 3 the adjustment for this condition of syntony must be more carefully made.

The second condition of syntony is that the *shape* of the primary wave or current rush must be such that the resulting electromotive-force impulses in the secondary circuit, due to the different parts of the primary wave, bear the proper phase relation to the secondary wave. With a fixed secondary circuit the first condition can be obtained by varying the main current I_0 , or the primary capacity C_1 . The second condition of syntony can be established by changing the primary inductance L_1 .

The two conditions of syntony are illustrated by the curves of Figs. 6 and 7. In Fig. 6 the full line curve gives the variations of the secondary current, I_2 , plotted to an arbitrary scale, as the main current, I_0 , is varied, and shows maxima and minima of I_2 as the first condition of syntony is more or less perfectly fulfilled. The dotted disconnected lines give the maximum wave length readings of the wave meter, excited by the primary discharge, as ordinates plotted to the variable I_0 . The third dot-and-dash curve is the reading of the wave meter when set on the primary circuit, and when the secondary circuit is open.

In further explanation of Fig. 6 attention is called to the following facts. It is evident that if the potential to which the condenser is charged is practically the same under all conditions—and experiment shows that this is approximately the case—then with a given C_1 , the number of discharges per second in the primary circuit is roughly proportional to the current I_0 . This

actual spark frequency produces in the wave meter an effect corresponding to a wave of that frequency. This primary fundamental wave length, as it will be called, plotted to I_0 would give a curve of the general shape given by the dot-and-dash line in the figure. When, however, the secondary circuit is closed the secondary current exerts an equilibrating influence on the primary discharge, helping it to occur, as has been stated, at a definite time in relation to the secondary current, thereby forcing

FIG. 6.

Illustration of syntony to change frequency.

$$\begin{aligned}\lambda_2 &= 95 \text{ metres.} \\ C_1 &= 80 \times 10^{-5} \mu.f., \\ C_2 &= 60 \times 10^{-5} \mu.f.\end{aligned}$$

the primary circuit to operate according to the short horizontal lines. For instance, by reference to the figure it is seen that, for a supply current of 0.7 ampere, the unforced primary fundamental wave length is 350 metres. The frequency corresponding to this is about 860,000 per second, which means that there are that number of primary discharges occurring per second. When, however, the secondary circuit, having a natural wave length, $\lambda_2 = 95$ metres, is closed, conditions are different on account of

the absorption of energy by the secondary circuit, and the primary discharges at a rate corresponding to a wave length of about 280 metres. This is about three times λ_2 , showing that the I. C. F. is 3. As the supply current is decreased the primary is forced by the secondary to discharge at this rate until the current has become so small that the slower rates corresponding to I. C. F.'s of 4 or 5 are more stable. When conditions are least

FIG. 7.

Curve showing syntony to wave form.

$\lambda_2 = 86$ metres.
 $I_0 = .75$ ampere.
 $C_1 = 60 \times 10^{-5} \mu.f.$
 $C_2 = 40 \times 10^{-5} \mu.f.$

forced for these values of I. C. F. a maximum of secondary current is observed as shown at $I_0 = 0.46$ in the figure. It is seen that for the steep part of the dot-and-dash curve the I. C. F. jumps between several successive values. It is also now easy to understand that the maxima of secondary current naturally occur at values of I_0 where the I. C. F. is less forced.

The second condition of syntony, namely, the syntony of wave form, is represented in Fig. 7. In this case the hot-wire

ammeter reading was taken in the secondary circuit as an inductance, in series with the primary of the oscillation transformer, was varied, the abscissa scale being in turns of the coil. A variation of this inductance changes the natural period of the primary circuit, thus affecting the time of duration of the primary impulses without materially changing their frequency. The disconnected curve, marked λ_1 , represents the primary fundamental wave length plotted to turns of inductance. The curve of secondary current shows the marked maximum when, the I. C. F. remaining constant, the primary discharge loop has the best duration compared to the period of the secondary oscillation. The forcing by the secondary oscillation of the primary condenser to discharge at the frequency corresponding to a wave length of 138 meters is well shown by the λ_1 curve.

Several measurements were taken of the natural period of the primary circuit when adjusted to give maximum secondary current, for different secondary wave lengths, and it was found that this natural primary period divided by the corresponding secondary period was, in every case, within one or two per cent. of the quantity 1.71.

(4) *Power and Efficiency.*

The closeness of the coupling, or, what is of more importance, the mutual inductance between the primary and secondary circuits, should, for the best results, be adjusted according to the amount of power delivered by the secondary circuit. Various power and efficiency curves of the system have been taken and may be found in the more complete paper referred to above. Only a few general deductions will be given here.

The maximum power obtainable in the secondary circuit from one gap is about 40 to 50 watts.

The efficiency is generally between 30 per cent. and 40 per cent., but may be somewhat higher. The maximum efficiency is generally obtained when the supply current is from .3 to .8 ampere.

The curves of Fig. 8 are typical and show the effect on the efficiency of changing the supply current, I_0 . The secondary wave length was maintained constant at 100 metres. The full line curves show the variations in current in amperes in the secondary circuit for three values of secondary resistance, as the

main supply current, I_0 , is varied from 0 to 1.5 amperes. The dotted curves give the efficiencies for the three curves, plotted to the right hand scale.

If greater power is required, gaps can profitably be operated in series. Two gaps work perfectly and three gaps well on 500 volts, with much increased power output. Four gaps were satisfactorily run on 1000 volts, but in general there is a slight sacrifice of regularity of operation as the number of gaps in series is increased.

FIG. 8.

Secondary current and efficiency curves with changing current, [76].

$$\begin{aligned}\lambda_2 &= 100 \text{ metres.} \\ C_1 &= 175 \times 10^{-6} \mu.f. \\ C_2 &= 86 \times 10^{-6} \mu.f.\end{aligned}$$

The amount of power obtained, when gaps are operated in series with a definite supply current, is not directly proportional to the number of gaps. When two gaps are operated in series, the power output is almost twice that from one gap. When more gaps are connected in series, the gain in power is much less, the greater the number of gaps the less the gain in power output.

The average voltage across one gap ranges from 100 to 200. As the number of gaps in series is increased, the current being constant, the voltage across the series is practically proportional to the number of gaps.

The efficiency of the system, when gaps are operated in series, decreases as the number of gaps is increased.

The curves of Fig. 9 give an idea of the result of increasing the number of gaps in series. The values of the efficiency and power may be somewhat misleading as the adjustments were not for conditions of maximum power and efficiency. The general shape of the curves, however, may prove of interest.

FIG. 9.

STUDY OF THE OSCILLATIONS BY MEANS OF BRAUN-TUBE OSCILLOGRAPHS.

(1) *The Braun Tubes.*

The general appearance of the Braun tubes,³ which were used in this part of the work, is given in Fig. 10. The usual aluminum diaphragms were found unsuitable and were replaced by glass diaphragms having the shape of a truncated cone, the apertures being about .5 to .7 mm. in diameter.

Braun tubes making use of electrostatic deflection of the cathode beam were also used in parts of the experiment. They are essentially the same as those just described with the addition of the two electrostatic deflecting plates. These plates are about 8 by 2.5 cm. in dimensions, and are sealed inside the tubes about 2.5 cm. apart.

The tubes were operated on from 10,000 to 20,000 volts

³ F. Braun, *Wied. Ann.*, 60, 552 (1897); *Elektrot. Ztschr.*, 19, 204 (1898).
Zenneck, *Ann. d. Physik.*, 9, 497 (1902).

J. M. Varley, *Phil. Mag.*, 3, 500 (1902).

Varley and Murdock, *Electrician* (London), 55, 335 (1905).

direct current, derived from Professor Trowbridge's 40,000-volt secondary battery. A large resistance, composed of tubes of running water, was placed in series with the tubes in order to control the current should the vacuum change.

The tubes were in connection with a Gaede mercury pump in order to maintain the pressure in the tubes at just the right value.

In order to eliminate the deflection of the beam by the earth's magnetic field, the tubes were mounted with their axes parallel to the earth's magnetic force, which mounting gave the tubes an inclination of about 70° with the horizontal. The camera, for photographing the oscillographs, was directed downward, viewing the upper or front surface of the fluorescent screen. Plate 1 *a*, shows the general arrangement of apparatus.

FIG. 10.

Braun tube and deflecting coil.

The deflecting coils which were used in this investigation for the magnetic deflection of the cathode beam, were composed of from two to sixteen rectangular turns of copper wire, .325 cm. in diameter, half of the turns being on either side of the tube. The turns were about 7 or 8 cm. in width, and from 10 to 12 cm. in length. A nearly uniform field within the coil is secured by making the width of the rectangular turns $\sqrt{2}$ times the distance between the planes of the two parts of the coil.

When using high frequencies, the difference in potential between two parts of the same coil, due to inductance, is sufficient to cause very large electrostatic deflections of the cathode beam. This disturbance is most effectually eliminated by surrounding the tube, inside the coil, by a split solenoid of fine insulated copper wire wound on a paper tube. This device completely shields the cathode beam from electrostatic disturbances, but allows the magnetic forces to pass undiminished.

When the Braun tube is used for alternating currents of commercial frequencies, or for phenomena taking place in a few

hundredths of a second, the velocity of the luminous spot over the screen is small enough to give a visible streak of light even if the phenomenon lasts for only one cycle.

When high frequency currents are used, however, the velocity of deflection of the cathode beam is so great that it is necessary that the luminous spot travel over the same path thousands of times a second in order that even a visible effect may be observed, and many more times if a photographic record is to be taken with a reasonable exposure.

It is then apparent that, if a sequence of instantaneous phenomena is to be delineated by causing the cathode beam to trace out a pattern on the fluorescent screen of the Braun tube, the cycle of events must repeat many hundreds of thousands of times a second, and with such regularity that the spot of light will, each cycle, travel over exactly the same path.

When using the Braun tube for studying electrical oscillations, this is usually more or less of a difficult condition to attain on account of the uncertain and variable action of most forms of discharge gaps. The gap and system under consideration is, however, so regular and constant that it is not at all difficult to obtain photographs of patterns representing cyclic changes, many of which recur three million times a second with practically no variation.

Plates 1-7 are a few of over fifteen dozen photographs taken representing various conditions, and give unmistakable evidence of the remarkable regularity and continuity of the oscillations of the *Cu-Al* gap. The photographs were taken on Seed's Gilt Edge No. 27 plates, and exposures of from 3 to 30 seconds were made. The figures are practically natural size.

(2) *The Primary Wave.*

The observations for determining the shape and phase, with respect to the secondary oscillation, of the primary current rush were obtained by leading the primary and secondary currents each through a 4-turn deflecting coil about the Braun tube, the two coils making an angle of 90° with each other. The arrangement is diagrammatically shown in Fig. 11, where the letters have the before-mentioned significance. There is obtained on the fluorescent screen by this arrangement a perfectly definite and well defined pattern, which gives the corresponding instantaneous values of the primary and secondary currents. Plate 1 c,

is one of many photographs of such a pattern, taken with an exposure of about 15 to 30 seconds, and represents the conditions when adjustments are made for maximum energy in the secondary circuit.

Knowing, as will be adequately proved later, that the secondary oscillation is sinusoidal, the primary current, plotted to time, and its phase relation to the secondary current, can readily be derived from the patterns mentioned above. In *c* of Plate I the vertical distance d_1 to the primary loop above, from any point on the horizontal line distant d_2 from the centre or undeflected spot, gives the instantaneous primary current, i_1 , and the simul-

FIG. 11.

taneously secondary current, i_2 . A sine curve of amplitude represented by the secondary deflection is drawn, and the time coördinate for any corresponding values of i_1 and i_2 is the time, obtained from the sine curve, at which the current coördinate is i_2 . The direction of the spot of light is indicated by the arrows. The curve marked I_1 , in Fig. 12, shows the development of two figures, both reduced to the same scale for better comparison. I_2 , in the figure, is the secondary current. Seven such developments were made representing entirely different conditions, but in each case the phase of I_1 with respect to I_2 was the same as is shown in Fig. 12, and the shapes of the I_1 curves differed so slightly that, to save confusion, they are not reproduced.

Examination of the photograph and of the developments show, as has been stated, that there is *no* inverse current. Although the primary wave appears to have twice the period of the secondary oscillation, if the slope of the curve, or $\frac{di_2}{dt}$, which is proportional to the resulting induced electromotive force in the

secondary circuit, be plotted, a curve of the *same* period as I_2 is obtained. This e. m. f. curve is shown at E in Fig. 12.

If, now, the ordinates of the e. m. f. curve be multiplied by the corresponding values of the secondary current, a quantity proportional to the instantaneous rate at which energy is being transferred to the secondary is obtained, and if plotted, gives the curve marked W in Fig. 12. The portions of the curve below the axis of time are negative, and represent a return of energy to the primary circuit. The algebraic sum of the areas under the four loops is proportional to the total energy permanently deliv-

FIG. 12.

- I_1Primary discharge wave.
 I_2Secondary wave.
 EElectromotive force due to I_1 .
 WPower delivered to secondary circuit.

ered to the secondary circuit in one cycle. It is apparent that very little energy is returned to the primary circuit, and that the second half of the primary loop gives the greater amount of energy to the secondary circuit, the first part of the primary discharge being more or less irregular on account of the sudden breaking down of the high initial gap resistance and the superposed higher harmonics resulting from the sudden shock to the system.

It has been stated that the primary current loops occur every two or more secondary oscillations. In this case the primary wave, considered as an intermittent function, can be analyzed

into harmonics. Such an analysis has been made for several values of I.C.F. One result only will be given here; namely, the development for an I.C.F. of 2.

$$e_2 = E \left[.43 \sin 2\pi \left(\frac{n}{2} \right) t + .50 \sin 2\pi n t + .26 \sin 2\pi \left(\frac{3n}{2} \right) t \right. \\ \left. - .061 \sin 2\pi \left(\frac{5n}{2} \right) t + .028 \sin 2\pi \left(\frac{7n}{2} \right) t - .017 \sin 2\pi \left(\frac{9n}{2} \right) t + \dots \right]$$

A beautiful way of demonstrating the existence of the harmonics is by the following experiment. Two secondary circuits are arranged so that they can be excited by the same primary circuit. Each of the secondary circuits includes a deflecting coil about the Braun tube, these coils being so placed as to produce deflections at right angles to each other. It is then possible to tune the two secondary circuits to the various harmonics, and to obtain, when the harmonics are in simple ratios, the Lissajou's figures shown on Plates 1 and 2. Cuts *d* and *e* of Plate 1 and *a* and *b* of Plate 2 were taken when there was placed about the tube an extra coil, which was traversed by the primary current, and produced a deflection in a horizontal direction in addition to the deflection given by one of the secondary coils. This arrangement gives, in three of the cuts mentioned, an extra loop when the primary is active.

(3) *The Resistance of the Gap.*

The shape of the primary wave form, which has just been considered, is determined principally by the changes in resistance which take place in the gap. If there were no change in resistance, and the influence of the secondary current were negligible, the form of the primary current rush would be given by the familiar equation

$$i_1 = \frac{Q_0}{\sqrt{R_1^2 C_1^2 - 4L_1 C_1}} (e^{-at} - e^{-\beta t}),$$

where

$$a = \frac{R_1 C_1 + \sqrt{R_1^2 C_1^2 - 4L_1 C_1}}{2L_1 C_1}$$

and

$$\beta = \frac{R_1 C_1 - \sqrt{R_1^2 C_1^2 - 4L_1 C_1}}{2L_1 C_1}.$$

Q_0 is the initial charge in the primary condenser C_1 , and L_1 and R_1 are the inductance and resistance in the primary circuit. The curve, which represents this equation, is, as is well known, a rise and fall of current with respect to time, and is aperiodic or oscillatory according as R_1^2 is greater or less than $4L_1/C_1$. The critical resistance above which the discharge is non-oscillatory is, for the circuits which were used in this investigation, of the magnitude of 100 ohms. As will be seen later, the average resistance of the gap is so low compared to this quantity that the existence of no inverse current cannot be attributed solely to the aperiodic nature of a discharge through a high resistance. Moreover, if the average resistance were high enough to cause the discharge to be aperiodic, the end of the discharge would be asymptotic to the time axis, which is not the case.

The change of resistance of the gap can be obtained experimentally by use of a Braun tube provided with electrostatic deflecting plates. These electrostatic plates are connected directly across the gap, causing a deflection perpendicular to that caused by the total current through the gap. In this way a trace of the voltage-current characteristic curve is obtained from which can be derived the resistance corresponding to any current.

Cuts *a-e* of Plate 3 are photographs of $E-I$ characteristic curves as above described. Cut *a* represents the conditions for a very long gap. The path of the spot of light, in tracing this figure, may be understood from the following. As the condenser charges there is no current through the gap, and hence no current deflection, but the potential of the condenser increases to a certain value determined by the breaking-down potential of the gap. This charging is represented in the photograph by a movement of the luminous spot from *A*, its undeflected position, to *B*, the potential at which the gap breaks down, which in magnitude, in this case, is equal to about 450 volts. The instant that the gap breaks down the potential drops, and the current through the gap increases giving the curve from *B* to *C*, roughly resembling a hyperbola. As the current decreases, represented by the line *CA* in the photograph, the potential remains practically zero, showing that after the gap has been once ionized the resistance remains low until the current becomes zero. The current does not increase in the negative direction for reasons previously given. During the passage of the primary current the capacity, C_1 , has

been completely discharged and charged in the reverse direction so that, as soon as the current stops, the full potential of the reversed condenser is brought to bear across the gap. This is represented by the point *D*. Current is now, however, flowing into C_1 at a constant rate, causing the fluorescent spot to move along the voltage axis from *D* to *B* to begin a new cycle.

The same kind of diagram is shown in cuts *b* and *c* of Plate 3 for shorter gaps. It is evident, as would be expected, that as the gap is shortened, the *E-I* curve closes in toward the two axes.

It is also seen that with a very short gap the current increase is oscillatory. These oscillations are very rapid, having a wave length of the magnitude of four or five meters, and on account of the extremely high frequency, cause the large potential oscillations shown by the blurred space in cut *d* of Plate 3.

Cut *e* of Plate 3 is a photograph taken when, on account of the dryness of the hydrogen, practically nothing but a glow discharge could be obtained. The gap in this particular case was traversed by a high frequency current. The photograph is introduced only for the small curved point at the right hand end of the potential deflection, which is the characteristic of the glow discharge.

Cut *f* of Plate 3 was taken in the same manner as the pictures just described except for the addition of a secondary deflection coil parallel to the primary coil about the tube. In this way there is obtained a spreading out of the diagram, and a clearer view of the actual path of the luminescent spot. The helical path from right to left results from the secondary current oscillation, and superposed primary potential oscillations due to the influence of the secondary vibrations on the primary circuit, both occurring during the charging of the primary condenser. The abrupt end represents the point at which the gap breaks down and the spot moves very rapidly, at first, over the primary discharge loop.

The change in resistance with changing current, derived from these *E-I* characteristics, gives curves of the general shape shown by the full line curves of Fig. 13. The curve marked *L* was derived from cut *a* of Plate 3, and represents the change in resistance of a very long gap. The other two full-line curves are for shorter gaps, and, in the extreme corner, is suggested the condition for decreasing current which completes the cyclic resistance changes.

The dotted curve of Fig. 13 is a resistance curve derived from the differential equations of the circuit by assuming an

approximate expression for the primary wave form. It agrees well in shape with the experimental curves (heavy lines).

The scales of the curves serve only to give an approximate idea of the magnitudes of the resistances at different currents, for the position of the curves depends upon the arc length and undoubtedly upon the period of discharge. It is worthy of note

FIG. 13.

Resistance curves of Cu-Al gap.

- G Glow discharge.
 L Discharge with very long gap.
 S Discharge with very short gap.
 Dotted curve calculated.

that the resistance at zero current is very high, thus admitting of a high initial charge in the primary condenser before the gap breaks down. The resistance curves are very steep, being much steeper than the corresponding curves for the Poulsen arc. It is, in part, this steepness which adapts the gap to the production of very high frequency oscillations. The very rapid reestablish-

ment of the high resistance is also of primary importance in the action of the gap with high frequencies.

The upper dot-and-dash curve is for the curved point at the end of the potential deflection in cut *e* of Plate 3 just mentioned, and represents the conditions for glow discharge.

(4) *The Inverse Charge Frequency (I. C. F.).*

Reference has often been made to the I. C. F., the value of which, as was stated, depends upon the wave length of the secondary oscillation, the size of the primary condenser C_1 , and the value of the supply current I_0 . In order to show that the I. C. F. has, under most conditions, a perfectly definite value, and at the same time, to illustrate some other points concerning the system, the photographs of Plate 4 were taken.

The arrangement of circuits, for the figures under discussion, was as follows: Two parallel deflecting coils were placed about the Braun tube, and so situated as to deviate the cathode beam in a direction perpendicular to the electrostatic deflection. One of these coils was connected in the primary circuit and the other in the secondary circuit. The electrostatic deflecting plates were connected to the terminals of the primary condenser C_1 .

The oscillograms of Plate 4 represent, therefore, the sum of the primary and secondary currents by deflections in the vertical direction, and the potential of C_1 , by deflections in the horizontal direction. In all of the cuts the lower portion results from the secondary oscillation during the charging of C_1 , when the gap current is zero.

The explanation of cut *b* will serve for all of the pictures of Plate 4. At point *A* the condenser C_1 is charged to a potential sufficient to jump across the gap. When the primary discharge begins, the spot of light moves very rapidly at first over the loop *ABC*. This discharge starts or maintains the secondary oscillation, so that the vertical deflection is due to the primary current plus the simultaneous secondary current. During the discharge the potential of the primary condenser falls and increases in the opposite direction, so that, at the end of the discharge, represented at *C*, the condenser potential is reversed. At point *C* the primary discharge is completed. The rest of the diagram from *C* to *A* is due to the secondary oscillation, which causes the vertical deflection, and the uniformly changing poten-

tial of the primary condenser while charging, which causes the horizontal deflection from C to A .

The number of secondary oscillations taking place during one primary cycle, and which has been called the I. C. F., is clearly shown by the photographs. In the case of cut b , the secondary completes one period during the primary discharge, and three complete secondary periods during charging from C to A , so that the I. C. F. is 4.

The instant at which the primary discharge begins and ends with reference to the secondary wave, is shown to be the same as was derived in the section on the primary wave. The high harmonic oscillations in the primary which occur, as has been mentioned, after the high resistance of the gap is broken down, are apparent in the beaded appearance of the upper loops of the oscillograms.

In cuts $a-e$ of Plate 4 the spot travelled over the patterns in an anti-clockwise direction. The I. C. F.'s are respectively 3, 4, and 6. In cuts a and b the undeflected position of the spot is shown, and the relative magnitudes of the direct and inverse potentials of the primary condenser can be noted.

The beats, shown in cuts $c-f$ of Plate 4, are due to the interference of two oscillations in a doubly-periodic secondary system employed in this case. The second-secondary oscillation is due to the vibration of an helix, a few turns of which were included in the secondary circuit. The luminous spot in cut d travelled in a clockwise direction.

(5) *Resistance Damping.*

In order to obtain an oscillogram of a variable which is a function of time, it is necessary to use some device which will give a uniform time axis to the figure. For instance, if it is desired to obtain an oscillograph of the commercial alternating current, one passes the current through the deflecting coil about the Braun tube. There appears on the screen a straight line, which results from the to-and-fro movements of the luminous spot over the same straight path. In order to see the current wave developed with respect to time, it is necessary to observe the line deflection in a revolving mirror, its axis being parallel to the line deflection. If a photograph is to be taken, it is further necessary to drive the mirror by some synchronous device so that

the image of the developed figure may be stationary on the photographic plate for a time sufficient to make the exposure. This synchronizing device is not difficult to arrange when using commercial alternating currents, but when it is desired to take an oscillogram of a high frequency current or condenser discharge, it is usually impossible to make the necessary synchronization. When using high frequency currents, the velocity of the spot of light on the fluorescent screen is so great that, in order to obtain a photograph, it is necessary that the cycle of changes, as shown by the pattern on the screen, be repeated many hundred thousand times with such regularity and certainty that the image is always in exactly the same position. The requirements of both the acting system and the synchronizing device are very rigid.

The development of the time axis can be most effectually accomplished, with the system under discussion, by the very simple connection which was used in the last section. The electrostatic plates, which cause a deflection perpendicular to the current coils, are connected to the terminals of the primary condenser C_1 . During the interval between primary discharges, when the primary condenser is charging, the primary current is zero, and the main or charging current is almost perfectly constant on account of the large inductances in the mains. This uniform charging causes a uniform increase in potential of the condenser C_1 , and hence a uniformly developed time axis on the fluorescent screen. The oscillations of the secondary, or any effect started by the primary discharge, is thereby developed, as is shown by the lower portions of the cuts of Plate 4.

This arrangement for the development of current or potential deflection with respect to time is of the greatest use in many ways. Its application will be illustrated here by showing the damping curves with oscillations of a frequency of two million or more per second.

Cuts *a* and *b* of Plate 5 represent the damping of the secondary oscillations due to the addition of resistance in the secondary circuit. The primary capacity and supply current were so adjusted as to give large values of the I. C. F. in order that as many secondary oscillations as possible might appear in the damped oscillation trains shown. The adjustments for the pictures of Plate 5 were so made that each oscillation train is just completed before the beginning of the next. The trains, therefore, succeed

each other with no intervals of rest. By adjustments of the supply current or primary capacity it is possible to lengthen or shorten the interval between the primary discharges, and by varying the resistance in the secondary circuit the number of oscillations in one train or the damping can be varied at will. The damping is evidently exponential in fulfilment of the familiar theory.

Cuts *c-f* of Plate 5 and cut *a* of Plate 6 are the results of adding to the arrangement of circuits just considered a second secondary circuit, excited by the primary discharge. There results, therefore, a doubly-periodic secondary system having two secondary circuits inductively coupled together. The doubly-periodic secondary oscillation gives the beats and curious figures shown. Cuts *c* and *d* are due to the addition of two oscillations differing widely in frequency. As will be seen from the description of the figures, the second oscillation is in one case over twice and in the other case almost three times the frequency of the main secondary oscillation.

Cut *a* of Plate 6 shows beats taken with almost undamped oscillations. The wave lengths are not recorded, but they were probably of the magnitude of 100 meters.

(6) *Damping in a Circuit Containing a Spark Gap.*

When the dissipation of energy in an oscillatory circuit is proportional to the square of the current, as is the case in a constant resistance, the damping is exponential. If, however, the resistance is a function of the current the energy dissipation is no longer proportional to the square of the current, and the damping no longer exponential. For instance, the resistance of a spark gap or arc is a function of the current, the resistance being greater the smaller the current through the gap.

Richarz and Ziegler⁴ in 1900 observed, in a revolving mirror, the straight line deflection which is produced in a Braun tube when a condenser is rapidly discharged across a spark gap and through the deflecting coil. The frequency of the oscillations was very low. On account of the impossibility of taking a photograph, we have only their description of the phenomenon as seen in the revolving mirror. In appearance the figure resembled the backbone of a fish, or, in other words, a long straight line,

⁴ F. Richarz u. W. Ziegler, *Ann. d. Phys.*, 1, 468 (1900).

due to the undeflected spot, and at intervals along the line, pairs of equally inclined short straight lines, as one would indicate an arrow point. The short lines were due to the more intense maximum deflections during a train of oscillations, the separate oscillations being entirely undiscernible. The results showed that the damping due to a spark gap is not exponential but approximately linear.

Zenneck,⁵ in 1904, obtained further experimental proof of the approximately linear damping due to a spark gap. He photographed the line deflection, and by a process of projection from the several brighter spots, due to the decreasing amplitudes of the oscillations, derived the damping curves. Frequencies up to 1800 per second were used by him.

Heydweiller,⁶ in 1906, showed that the results obtained by the above-mentioned experimenters can be deduced theoretically. Heydweiller assumes, in deducing the linear damping, that the gap has a characteristic expressible in the form

$$e = a + \frac{b}{i}$$

where e and i are the voltage across and current through the gap, respectively, and a and b are constants. He further assumes that b is negligible, which reduces the conditions to the assumption of a constant voltage across the gap. Solving the differential equation for the discharge of a condenser across a constant-potential gap, he obtained rectilinear damping.

If a discharge gap be substituted for the secondary resistance in the arrangement of circuits which was used in the last section for obtaining plain resistance damping, very clear oscillograms can be obtained of the oscillation trains when the damping is caused by a gap. Although the inherent irregularity of some metallic gaps, when used in the secondary circuit, causes some irregularity of the oscillographs, yet good photographic records can be obtained, as is shown by the cuts of Plates 6 and 7. In order to obtain a potential sufficient to maintain the discharge across the secondary gap, it was necessary to use a large primary condenser and supply current, and to make the ratio, $\frac{n_2}{n_1}$, of the secondary to primary turns on the helix large.

⁵ J. Zenneck, *Ann. d. Phys.*, 13, 822 (1904).

⁶ R. Heydweiller, *Ann. d. Physik.*, 19, 646 (1906).

Cuts *b* and *c* of Plate 6 show two of the pictures first taken, and illustrate well the linear damping. The gap length was very short; the terminals were of aluminum.

Further investigation showed that the oscillation train took on entirely different aspects according as the discharge could be classed as a *pure arc*, or a *spark discharge*. When the discharge is a pure arc, the separate oscillations are regular and practically sinusoidal, and the damping is still linear. If the discharge is classed as a spark discharge, although the damping is linear, the separate oscillation loops are distorted as will appear presently.

Cut *d* of Plate 6 represents the condition when the discharge terminals of the secondary gap are carbon. The discharge was quiet and very brilliant, resembling, as indeed it was, the pure carbon arc operating, however, at a frequency of 5.7×10^5 oscillations per second.

Cut *e* of Plate 6 gives the appearance of the oscillogram when the terminals are of aluminum in air. The discharge in this case, as well as for cuts *b* and *c*, was probably a pure arc due to the carbon and other impurities in the aluminum. In appearance, the discharge was brilliant and similar to the carbon arc.

Magnesium terminals usually give the pure-arc discharge-form of damping curve, due probably to the large amount of magnesium vapor present in the discharge, or possibly to the burning of the magnesium into the oxide.

Cut *f* of Plate 6 and the pictures of Plate 7 represent the appearance of the *spark-discharge* oscillograms. When the temperature of the discharge is kept low, the conductivity of the gap is not maintained over the interval of zero current by the presence of incandescent metallic or carbon vapor, and the high resistance of the gap is partially established at each crossing of the axis by the current curve. This necessitates a reionization of the gas at the beginning of each current loop, or the breaking down of a possible oxide film, thereby distorting the wave in the neighborhood of the axis, as is shown by the figures.

The general form of the curve for spark damping, which is indicated in the photographs, was at times momentarily clearly outlined on the fluorescent screen and is shown by the drawing of Fig. 14. Apparently, in some of the photographs, the loops begin, in point of time, before the ending of the previous loop. This apparent paradox is due to the slight shift in the time axis

.resulting from the reaction of the strong secondary discharges upon the potential of the primary condenser.

The oscillogram photographs of spark damping here shown were taken for aluminum terminals because of the greater regularity of the discharge between terminals of that metal. Many other metals were tried, such as copper, cadmium, zinc, etc., and in practically every case in which the discharge was a spark discharge, the oscillations took the same form as is shown in Fig. 14.

Fig. 14.

Form of spark-gap damping curve.

When one of the terminals is carbon or magnesium, the current loops on one side of the time axis are of the pure-arc form, while those on the other side are of the spark-discharge form.

If the terminals are dissimilar, there is usually evidence of a rectifying effect. Particularly is this so if one terminal is of aluminum and the other of copper or iron. Cut *d* of Plate 7 shows this rectification.

The effect of hydrogen on the discharge is indicated by cuts *e*

and f of Plate 7, which were taken under the same conditions except for the H surrounding the gap terminals in the case of cut f . The hydrogen serves, in this case, principally to ensure a spark rather than an arc discharge, and probably increases the damping.

The outward appearance of the discharge is in no way an indication as to whether the oscillogram takes the arc or spark form. The form of the oscillogram serves conveniently to differentiate between the pure-arc and the spark discharges, when the terms arc and spark are applied to discharges operating on alternating currents. The discharge of the *Cu-Al* oscillation gap, which has been studied in this investigation, cannot, according to this definition, be called an arc, but is a spark discharge.

The photographs here shown of gap damping furnish in no way a complete discussion of the subject, but are presented to give additional proof of the existence of linear damping in a circuit containing a spark gap, and to show that there are two distinct forms of the oscillation trains according to the nature of the gap.

(7) *Notes Concerning the Mechanism of Conduction in the Cu-Al Gap.*

Very little can at present be given concerning the exact nature of the conduction which takes place in the gap under discussion and the office of the necessary hydrogen. No oscillations can be obtained unless the gap is immersed in some gas rich in hydrogen, but the latter alone gives by far the best results. In any case the gas must be moist. As was shown early in the paper, the absence of metallic vapor indicates that the conduction is probably affected entirely by the ionization of the surrounding gas. Since, as was also observed, the metal used for the anode makes little difference in the operation of the gap, and since aluminum is the only metal which works at all well as cathode, it is safe to say that it is the aluminum cathode, working in conjunction with the hydrogen, which gives the characteristic properties of the oscillation gap which has been partially studied in the foregoing pages. It might be mentioned here that magnesium acts to some extent as cathode, but, on account of its low vaporizing point, works very irregularly and unsatisfactorily. The discharge, in this case, is intensely green, showing vaporization.

The fact that moisture in the hydrogen is necessary indicates

that an oxidation of the aluminum plays some part in the operation. The necessity of an hydrogen atmosphere leads one to believe that perhaps a reduction of the ever-present aluminum oxide film at some time during the cycle may take place, there possibly being a cyclic change of oxidation and reduction of the aluminum determined by the temperature at various instants during one primary discharge. For instance, it may be that some action such as follows takes place. At the beginning of the discharge, the thin oxide film makes necessary a high breaking-down potential in order to start a discharge. As soon, however, as the discharge is started, H ions are conveyed to the aluminum cathode, and, since the atmosphere about the terminal is H, reduce the oxide film. The free surface of the aluminum is thereby exposed, and the resistance drops to a low value. This reduction would be the greater the larger the current, and there would result the very rapid drop in resistance which is shown in the curves of Fig. 16. As soon as the discharge stops, the aluminum is partially reoxidized by the O ions which were freed by the first process, and the initial high resistance of the gap is re-established.

It is probable that the regularity of the gap is partly due to the fact that the discharge takes place for some time at one definite point on the aluminum, this confinement of the discharge to one place resulting possibly from the protecting oxide film over the rest of the surface.

WIRELESS TELEPHONY.

The experiments in connection with the application of this new oscillation system to wireless telephony have been carried on in conjunction with Professor G. W. Pierce, who has offered many valuable suggestions and done a great deal for the development of this application of the system. ,

A detailed description of the experiments which have been in progress for over a year cannot here be given; they will be the subject of a later article. A brief description of the method of operation, with some general statements concerning results, may, however, be of interest.

First, what are the essentials of a practical system of wireless telephony? In an ideal system of any form of telephony, the only audible effects at the receiving station should be the vibrations of

the telephone diaphragm synchronous with and proportional to the sound vibrations which are impressed at the transmitting station. This is quite successfully accomplished in the ordinary line telephony in the familiar manner. An electric current is the transmitting agent, and a sound is heard in the receiver *only* when this current is modified or varied. In wireless telephony transmission is obtained by means of electromagnetic-waves, and there should be no appreciable sound at the receiving station except when these waves are modified in some manner, as by the human voice. It is clear that this necessitates the emission, by the transmitter, of a perfectly steady, continuous stream of electromagnetic waves, of a frequency above the limit of audibility (about 35,000 per second). If the waves are not continuous, the train frequency must be above this limit. These waves must be capable of being modified by a telephone transmitter in such a manner that the envelope of the wave train, as it changes in amplitude, is the wave form of the sound vibrations which are impressed upon the transmitter diaphragm. The frequency of the waves should be high enough for efficient electric-wave transmission, or from 300,000 to 1,000,000 oscillations per second. Consequently, during one sound vibration there would be several hundred electrical vibrations.

In addition to the requirements stated above, the system, in order to be of practical value, should emit efficiently an electric wave of unvarying length. And, still more important, from a practical point of view, the system should be simple, reliable, and capable of being easily operated without the necessity of continual adjustment.

High-frequency alternators and the Poulsen arc, with its modifications, have been used for wireless telephony during the last few years with some success. The greatest faults of the alternator system are its great expense and its inefficiency. The Poulsen-arc ⁷ system is complicated, and requires continual adjustment, which makes it difficult to operate. Further, it emits waves which vary in length as the arc length and supply current change, an inherent characteristic of the system.

The connections for the transmitting station, which is now to be described, are shown in Fig. 15. The connections of the

⁷ V. Poulsen, British Patent Specifications, 15,599 of 1903.

supply and primary circuits, as may be seen in the figure, are identical with the corresponding connections described earlier in the paper. G represents the gap, and C is a small variable air or oil condenser. T is a closely-coupled, and preferably variable,

FIG. 15.

oscillation transformer. The telephone transmitter is shown connected in the ground lead. The hot-wire ammeter in the antenna, and the throw-over switch to change from sending to receiving, are not shown.

A variable condenser of the semi-circular plate type, designed as an air condenser, was filled with castor oil (with dielectric constant 4.5) and used with one set of apparatus as the primary condenser. Its maximum capacity was about $.009 \mu f$. The oil was used not to increase the dielectric strength, for that is unnecessary on account of the low potentials, but to increase the capacity. A small variable mica condenser was also used in another case. Such a condenser can be made very small.

Various methods of connecting the telephone transmitter have been tried, but the connection shown has so far proved most satisfactory. The ordinary Bell high-resistance microphone transmitter has been used with good success, although the large overload in current causes some deterioration. We have, however, used them on an antenna current of an ampere or more for several months without a serious loss in efficiency.

The potential of no part of the apparatus, except possibly the top of the antenna, rises over 1,000 volts. No great caution, therefore, need be taken to insulate the various parts of the system, and small switches, having very small gaps when open, can be used. For instance, the antenna current can be broken by separating contacts by only the thickness of a thin piece of paper.

The switch, to throw from transmitting to receiving and *vice versa*, may be a small key having several leaves which make certain contacts when in both positions. By the one operation of pressing the key, the antenna is transferred from the receiving apparatus to the transmitting apparatus; the detector is short-circuited; and a short circuit about the gap is broken. The gap immediately functions without the necessity of any adjustment, and continues to operate until the gap is again short-circuited by releasing the key.

For telephony the gap operates best on from .2 to .5 ampere direct current.

Most of the tests have been carried out between a station at the home of Dr. Pierce and the Jefferson Laboratory, a distance of about a mile. These two stations have been permanently installed for over a year, and are used not only for experimental purposes, but as a means of easy and practical communication with the laboratory.

When the transmitting station is properly tuned, there is practically no sound at the receiving station other than the voice.

The slight hum or hiss which is present to a more or less degree, according to the adjustments, is usually not at all objectionable and may be tuned out. The articulation is very good, and communication is easily maintained between the two stations for hours at a time with the loss of hardly a word, and, what is practically of great importance, without the slightest adjustment.

No definite statement can now be given as to the distance to which it is possible to talk. Our conversation has been reported as being understood at a distance of about forty miles, and it is very probable that the speech could be heard at a somewhat greater distance, even while employing only one gap.

Two gaps operated in series give much more power, but no experiments have been made to determine the maximum distance over which communication can be maintained.

By interposing into the antenna circuit a small battery buzzer, the continuous radiation of waves can be periodically interrupted and a very satisfactory telegraph system is obtained, which is difficult to distinguish from a high-frequency alternator or a rotating gap system.

No attempt has been made to give a complete discussion of the application of this oscillation system to wireless telephony, but enough has been given to enable one to see that the system does possess, to a greater extent than do the other systems, many of the essentials of a practical system of wireless telephony.