OSCILLATIONS DUE TO IONIZATION IN DIELECTRICS AND METHODS OF THEIR DETECTION AND MEASUREMENT

A REPORT OF AN INVESTIGATION

CONDUCTED BY

THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS

IN COOPERATION WITH

THE UTILITIES RESEARCH COMMISSION

BY

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I. INTRODUCTION

1. Necessity for Rational Methods of Testing Cables.—The growing application of high voltage cables for the transmission of electric energy and the wide extension in the use of condensers in the electric power industry as well as in communication engineering makes the reliability of the testing of appliances in which dielectrics are involved of great importance. Experience with cables and condensers has shown that their durability cannot be determined by the usual methods of testing. For the manufacturer and especially for the user of high voltage cables the question of how to increase durability and how to prevent breakdowns has become the more urgent the further the limits of applied high potentials has had to be pushed for the sake of economy. It is realized that progress in this direction depends on reliable methods of testing.

2. Object of Investigation.—The principal aim of this investigation was to develop a rational method of testing insulation as an aid to engineering practice in the manufacture and operation of cables. Searches for means of detecting early stages of deterioration in cable insulation were made in different directions. One of these is briefly described in the Appendix. Soon, however, it was realized that the scant knowledge of the processes which take place in dielectrics subjected to high electric potentials made it necessary that first of all one of the main problems be solved, which may be stated as follows:

It is known from every-day engineering experience that condensers and cables break down under the stress of high potentials and that the breakdown is caused by the deterioration of the insulating properties of dielectrics. Such deterioration occurs as the result of cumulative action of ionization in gaseous films and bubbles embedded within dielectrics. The degree to which a dielectric may be freed from such inhomogeneities would depend largely on the possibility of determining the starting point and intensity of ionization. It is necessary, therefore, to find reliable methods of detecting and measuring ionization in dielectrics.

3. Acknowledgments.—This study has been supported by funds contributed by the Utilities Research Commission, Inc., W. L. Abbott,
President. An Advisory Committee was appointed for this study as follows:

D. W. Roper, Chairman, Commonwealth Edison Co.
O. J. Bliss, Commonwealth Edison Co.
Herman Halperin, Commonwealth Edison Co.
G. W. Hamilton, Middle West Utilities Co.
C. A. Jaques, Public Service Co., of Northern Illinois
W. H. Knutz, Midland United Company

Numerous meetings of the Advisory Committee have been held at Urbana and at Chicago to consider the progress of the work.

The investigation has been carried on as part of the work of the Engineering Experiment Station under the general administrative direction of Dean M. S. Ketchum, Director of the Engineering Experiment Station. Acknowledgment is made of the services of M. C. Holmes, Special Research Assistant for this investigation, R. E. Tarpley, and W. A. Laning, Research Graduate Assistants, and A. E. Abel, Student in Electrical Engineering.

II. Principle and Methods

4. Basic Principle.—A number of arrangements were developed in an attempt to detect and measure ionization by means of the electric pulses or surges which are produced by ionization. They are all based on the idea that changes take place in the properties of insulating materials when subjected to electric potentials. Whatever the nature of these changes may be, chemical or physical, they produce variations in the dielectric constant and in the conductivity of the insulating material. The principle of the method of detecting ionization consists in utilizing these variations of dielectric properties which in the course of application of alternating potentials modify the original form of the charging current and produce oscillations.

5. Process of Modulating a Charging Current by Oscillations Due to Ionization.—There are a great number of ways by which charging currents from one source or from a combination of sources may be modulated by a varying dielectric. They may be represented by three typical diagrams (Fig. 1a, b, c). Figure 1a illustrates amplitude modulation by means of superimposed high-frequency currents. Figure 1b serves to explain the principle of frequency modulation also by means of super-position of high-frequency currents. Finally, the direct modulation of the charging current is shown in Fig. 1c. In all these figures the dielectric in the condenser, 1, is shown lami-
nated and the dots represent gas bubbles or voids detrimental to the operation of high-voltage condensers or cables.

When a poorly impregnated condenser which contains such voids or gas bubbles is subjected to an alternating high potential, the gas bubbles ionize and break down, disappearing suddenly from the system as pure dielectrics, and reappearing instead as semi-conductive dielectrics. The direct consequence of such a sudden change, and of the accompanying variations in the capacity and the conductivity of the condenser, is a redistribution of electric forces. Ripples of current arise in the form of pulses, surges, or damped oscillations. So small, however, is their magnitude that they cannot be measured directly without amplification.

The character of the ripples depends on the size of the bubbles, their chemical nature, and upon the surrounding conditions, whether they are located between metal electrodes, or imbedded within a good or poor dielectric. The wave form of the ripples depends not only on the circuit constants but also on the time and magnitude of the applied potential. So complex is the wave form that it is better described as a wave train. The number of such trains per unit time depends on the alternation of the voltage applied to the dielectric, usually 120 per second. Each wave train consists of about 10 to 20 wave groups of the relaxation type with an average periodicity of about 5000 per second. Finally, each such group includes a ripple of high-frequency damped oscillation, whose frequency depends entirely on the circuit constants, and may be deliberately varied up to 30 millions per second.

The methods of ionization measurements which were developed may be divided into three classes. One class includes methods which make use of the inaudible high-frequency ripples as well as the audible group-frequency. The second class includes methods in which only the inaudible high-frequency pulses are utilized. The third class includes methods which apply exclusively the audible group-frequency pulses.

6. Typical Methods of Modulation.—In order to detect the existence of the bubbles, the condenser which is to be tested, 1 in Fig. 1, may be made a part of an oscillatory circuit, 3, with its inductances, 4 and 5, and a condenser, 6. The latter serves to block the passage of the testing 60-cycle alternating current from the source, 2, while chokes, 7 and 8, prevent the higher frequencies of circuit, 3, penetrating to the source, 2. A continuous wave oscillator, 9, induces, by means of the coil, 10, currents of higher frequencies in the tuned circuit, 3. An am-
Methods of Modulating the Charging Current

(a) Amplitude Modulation by Means of Superimposed High Frequency Currents

(b) Frequency Modulation by Means of Superimposed High Frequency Currents

Methods for Separating Surges Due to Ionization from the Main Charging Current

(d) Transformation at High Frequency

(e) Balanced Bridge

FIG. 1. DIAGRAM SHOWING PRINCIPLE OF DETECTING OSCILLATIONS DUE TO IONIZATION IN A DIELECTRIC

A amplifier and receiver, 11, coupled by means of the coils, 12 and 5, is tuned to the frequency of both the oscillator 9, and the circuit 3. This receiver serves to measure, by means of the indicator, 13, any variations in the amplitude of the induced high-frequency current due to a change in the capacity and conductivity of the condenser 1, when
subjected to a voltage at which ionization sets in. Starting from this critical voltage the indicator 13 shows larger and larger deflections the higher the voltage applied at 2. The magnitude of these deflections is a function of the amount of ionization which is produced in the cable by the applied voltage.

In Fig. 1b, the same principle is applied with the exception that circuit 3 is made a part of the oscillator, the former being directly connected to the oscillator tube, 16, fed by the power supply, 14. This arrangement is especially adapted to the detection of variations of frequency in circuit 3, due to variations of capacity of condenser 1. For this purpose another oscillator, 15, serves to produce beats as soon as the frequency of circuit 3 varies as a consequence of ionization in the overstrained condenser 1. By means of the amplifier and detector 11, the beats are rectified and indicated by the instrument 13.

In both of these arrangements use is made of the variation of the electric properties of the dielectric, 1, which modulates the charging current supplied by an auxiliary source, 9, in Fig. 1a, or by two heterodyne sources, 14 and 15, in Fig. 1b. It was found, however, that the charging current of the source of high potential 2, which supplies the power for testing the condenser 1, may also serve as a carrier of characteristic ripples produced by ionization in the condenser. How these ripples are utilized for the detection of ionization is shown in Fig. 1c. By means of choking coils, 7 and 8, the sudden current variations produced by ionization in the dielectric of condenser 1 are restricted in their propagation, and are forced to excite the circuit 3 into oscillation. Coil 4, coupled to coil 10, transmits these oscillations to the amplifier and detector of the receiver 11. The rectified average amplitude, or the thermic effect of the oscillations as indicated by a suitable instrument 13, gives a relative measure of ionization.

Arrangements shown in Figs. 1a and 1b are better adapted to detect frequency variations, while that of Fig. 1c is more suitable for the detection of amplitude variations in circuit 3.

7. Role of a Cable in Oscillating Circuit; Standing Waves and Quasi-stationary Conditions.—If the condenser 1 in Fig. 1c is replaced by a long cable (Fig. 1d) additional phenomena arise in connection with the ripples. A cable represents a system of uniformly distributed capacitance and inductance. The time necessary for an impulse to travel along the cable and return to the source when the impulse is reflected from the ends of the cable has to be considered; also the value of the resistance of the circuit, especially at the terminals of the cable, becomes important. A ripple originating by ionization at any place
in the cable may be propagated towards both cable ends in the form of a single traveling wave. When a wave reaches the cable end it may be absorbed entirely by a terminal resistance, or, at suitable values of this resistance, reflections may take place. In the latter case every surge or ripple will give rise to a series of traveling waves which ultimately form a more or less pronounced standing wave. A pronounced stationary wave, as indicated in Fig. 1d by the current distribution curve $L_s$, is produced when two principal conditions are satisfied: first, the resistance of the circuit must be small; secondly, the constants which determine the frequency $f$ of the circuit must be chosen in accordance with the cable length $l$, which enters as part of this circuit so that

$$fl = n\frac{v}{4}$$

where $v$ is the velocity of wave propagation in the cable and $n$ is an odd number denoting how many quarter-waves are to be distributed along the cable. In all other cases quasi-stationary conditions prevail with more or less uniform distribution of current and voltage, as indicated by the curve $I_u$ in Fig. 1d.

It was realized at the very beginning of this investigation that such standing waves might be utilized for locating the position of a source of ionization in a cable. For this purpose standing waves are produced along the cable in sequent order of single, double, treble, etc., quarter wavelengths until maximum effect is observed on the indicating instrument 13. The other quasi-stationary forms of waves may be used for the detection and measurement of ionization wherever the source may happen to act. For both detecting and locating the sources of ionization any of the methods represented by Figs. 1a, 1b, 1c may be applied.

8. Means of Separating Minute Ripples from Main Charging Current.—In designing apparatus for the detection and measurement of ionization the problem of separating electrically the pulses and minute ripples due to ionization from the main charging current in a cable had to be considered. Two types of apparatus were developed which solve this problem. In the one type of experimental arrangement (Fig. 1d) the main charging current was eliminated by using transformation at high frequencies. The usual alternating current applied for testing cables has a frequency of 60 cycles, which is accompanied by harmonics reaching 660 cycles and more. In order to eliminate these frequencies from the measuring circuits, ionization in the dielectric
was made use of to produce ripples of a frequency hundreds or thousands times higher than the frequency of the charging current. These high-frequency ripples are readily transformed from the primary circuit, $A$, to the secondary circuit, $B$, by means of a coreless transformer, 4, 10, as shown in Fig. 1d, while the transformation of the low-frequency charging current remains comparatively weak. The higher the natural frequency of the cable circuit is made, the smaller becomes the induction of the low-frequency charging currents into the input circuit $B$ of the amplifier 11.

By this method tunable damped oscillations which are produced by ionization may be amplified and measured without interference of the charging currents.

In the other type of apparatus (Fig. 1e), the main charging current of 60 cycles and a large part of its harmonics are eliminated by the application of a balanced bridge connection. The latter consists of two branches $C$ and $D$. Branch $C$ includes the cable to be tested, 1, and a resistance, 15, while in the branch $D$ is inserted the balancing condenser, 6, and a resistance, 16, shunted by a variable condenser, 17. By adjusting the condenser 17, and resistances 15, 16, the charging current $I$ is divided in two parts which flow into the branches $C$ and $D$, respectively, so that the difference of potential between the points $E$ and $F$ is equal to zero. The ionization pulses, however, and also their transients are propagated along the cable 1 and throughout the circuit $A$. They produce at the points $E$, $F$ a difference of potential which is imparted by means of a transformer and filtering circuit $G$ to the input circuit $B$ of the amplifier 11. A detailed description of such a balanced bridge for detecting ionization is given in Section 25.

III. Application of Principle in Connection with Testing of Cables

9. Detection of Ionization by Its Effect on Superimposed Radio-Frequency Standing Wave in a Cable.—The first attempts to apply the method of superimposing radio-frequency currents on a cable subjected to high voltage alternating potentials were made according to the principle represented by Fig. 1a. Experiments were made with the view of influencing the amplitude of the radio-frequency current by the change of both the conductivity and the dielectric constant of the ionized region of the cable. The arrangement which was used for this purpose (Fig. 2) consisted of a set of three independent 5-watt oscillators, 9, supplied with thermionic tubes, 13, and interchangeable coils.
FIG. 2. DETECTION OF IONIZATION IN A CABLE BY SUPERIMPOSING RADIO-FREQUENCY CURRENTS

10. They covered a range of frequencies from 1500 to 20,000 kc. and served to excite high-frequency currents in the input cable circuit, 3', made up of the coupling coil, 4', two high-voltage condensers, 6', and the cable, 1. In the latter, high-frequency currents were transmitted to the cable output circuit, 3'', supplied with a similar arrangement of two condensers, 6'', and a coil, 4'', coupled to the receiver coil, 12. A thermocouple, 20, connected to the coil, 12, and to the microammeter, 21, served to measure the high-frequency current in the aperiodic receiver circuit, 22.

Whenever the frequency of the oscillator, 9, was made to correspond to the fundamental frequency, or to a harmonic of the combined circuit 3'-1-3'', a maximum deflection of the microammeter, 21, was obtained. The crucial test of these experiments consisted in finding out whether the deflection of the high-frequency measuring microammeter, 21, could be influenced by superposition of a high-voltage 60-cycle alternating current applied to the cable. For this purpose the terminal, 23', of one end of the cable conductor was connected to the high potential side of the secondary of a high-voltage transformer, 3, while the pothead, 26'', and sheath at the other cable end were connected to the grounded end of the secondary of the high-voltage transformer, 3. In order to protect the oscillator, 9, and the receiver, 22, from the high potential field of the cable circuit, glass plates, 24, were inserted between the coils, 10, 4', and 4'', 12, respectively. The choking coils, 25', 25'', served to prevent the high-frequency currents propagating out-
OSCILLATIONS DUE TO IONIZATION IN DIELECTRICS

side the circuits, 3' and 3''. For these experiments a cable 30.36 m, (110 ft.) long was used, which was known to possess spots of imperfect impregnation.

So long as the cable was subjected to voltages below 20 kv. no variation in the thermocouple current was indicated by the microammeter, 21. For higher potentials 20-35 kv. one to three per cent variations of the high-frequency current could be observed which were, however, so erratic that a definite relation between applied voltage and these high-frequency current variations could not be established.

The thermocouple was replaced then by a regular radio receiving apparatus. Three types of irregular sounds were detected by listening to the loudspeaker.

One type was traced to interference from running electric machinery in different parts of the laboratory building. This noise was heard at a cable voltage below 2000, and its intensity did not increase with increased voltage. The second type of sound was obtained only at voltages above 15-20 kv. whenever the oscillator, 9, was operating. Its origin was due to the interaction between the continuous oscillator wave and the damped wave produced by ionization. The third type of sound was heard at voltages above 10 kv. when the oscillator, 9, was disconnected. It was ascertained by consecutive experiments that this latter type of sound was characteristic of high-frequency damped oscillations which set in whenever ionization took place in form of corona-like discharges.

For the first type of sound the adjustment of the frequency of the oscillator, 9, and of the cable circuit, 3, did not change appreciably the intensity of the sound, if only the receiver was in tune with the cable circuit. For the second type the cable circuit and the receiver had to be adjusted to resonance with the oscillator, but the latter had a number of harmonic frequency settings at which response was obtained. As to the third type of sound, the oscillator, 9, could be detuned entirely, or even altogether disconnected, and still the sound was heard. Also the natural frequency of the cable circuit, 3' and 3'', could be varied over a wide range. The only condition which was essential for the production of this characteristic sound was that the receiver should be tuned to the natural frequency of the cable circuit.

While the first type of sound had to be dealt with as a disturbance and was to a large extent overcome by proper shielding, the other two types were utilized for detecting ionization. They were the result of the effect of two physical processes, operating within one arrange-
ment of apparatus. By producing variations of conductivity and per-
mitivity, ionization gives rise to the following oscillatory processes:

(a) Superposition of high-frequency damped oscillations upon
the charging current. Rectification of these oscillations in the de-
tecting circuit produces group-frequency pulses which are audible
by the loudspeaker as a crackling noise.

(b) Heterodyning of high-frequency damped oscillations with
the continuous oscillations induced by the oscillator 9. Irregular
beats are thus produced which likewise become audible as a mushy
noise.

10. Measurement of Ionization Discharges by Means of Oscilla-
tions They Produce.—For the development of a quantitative method
of detecting ionization it was necessary to modify the apparatus so
that only one of the enumerated processes is made use of at a time.
The first of the processes appeared the most promising, and therefore
was chosen as the basis for a method of detection of and of relative
measurement of ionization discharges in a cable. This principle was
described in connection with Figs. 1c and 1d. It can be briefly stated
thus: Every spot in a cable dielectric where ionization sets in becomes
a source of a disturbance, which travels towards both ends of the cable.
Modified by the constants of the cable and terminal circuits, each
disturbance gives rise to a ripple of damped high-frequency oscilla-
tion whose effective amplitude and frequency can be measured. The
number of such disturbances per second is determined by the group
frequency.

As shown in Fig. 3, the actual set up consisted of the a.c. 60-cycle
high voltage transformer, 2, whose high potential lead was connected
to the cable conductor, 27, through a radio-frequency coreless choke,
7, while the sheath, 28, of the cable, 1, was grounded. The radio-
frequency cable circuit, 3, included the cable, 1, two mica condensers,
6, in series, each of 300 mmf. capacity, and an inductance coil, 4, of 8 turns 5 in. in diameter. The latter was inductively coupled to the amplifier, 35, by means of an aperiodic circuit supplied with two coils, 29 and 30. The role of this circuit was to protect the amplifiers from electrostatic stray fields originating at the cable terminal and condensers, 6. The circuit was grounded through the shield, 32, and also at a point half way between the coils through a resistance, 31, of 0.1 megohm. The coupling with the amplifier was effected by the variocoupler coil, 10, placed in a copper shielding box, 33, and connected by a shielded cable, 34. A Western Electric 6-tube Superheterodyne Type 6D receiver, 35, and a two-stage audio amplifier served to convert weak radio-frequency surges produced by ionization in the cable into strong audio frequency oscillations. The primary, 36, of a step-down transformer Model-UP414 was inserted in the last stage of the audio amplifier, and the two secondaries, 37 and 38, were connected either with a loudspeaker, 39, or with a Weston radio-frequency ammeter, 12. In this way the total oscillatory effect of the ionization discharges, the radio-frequency part as well as the group-frequency, was utilized for energizing the indicating ammeter. When the voltage applied to the cable was below 2-3 kv. the indication of the ammeter, 12, was too small to be read, although by means of the loudspeaker, 39, background noises could be heard. With increasing applied
potentials the indications of the meter, 12, increased slowly at first, but when a certain critical value of the applied potential was exceeded a much greater rate of current increase followed.

In Fig. 4 a typical curve is shown which was obtained by applying to a 500,000 cir. mils single conductor cable 32.8 m. long potentials from 0 to 39.5 kv. The receiver was tuned to the fundamental frequency of the cable circuit $f = 789$ kc. ($\lambda = 380$ m). Up to 16 kv. a background noise of constant intensity was heard in the loudspeaker. When the thermic milliammeter was connected a corresponding current of 75 ma. was measured, which slightly increased as the applied voltage was further increased. Starting at a critical voltage of about 22 kv. the instrument showed a sudden increase of current at a rate of about 20 ma. for each additional applied kilovolt.

The following experiments served to verify the assumption that the indications of the instrument were due to oscillations produced by the application of 60-cycle high potentials to the dielectric of the cable: First, by detuning the receiver the indication of the milliammeter could be made to decrease to zero. Maximum current was obtained by setting the receiver at resonance with the fundamental frequency of the cable circuit. Second, by replacing the cable with brass tubing 1 in. in diameter and readjusting the receiver to a new resonance setting no current above 50 ma. was obtained for the entire range of 0 to 40 kv. applied potentials.

11. Precautions Against Interference.—That such oscillations may also originate by ionization along adjacent conductors and dielectrics outside the cable was shown by the following experiments:

First, by attaching at any point of the brass tubing a short piece of No. 22 copper wire a sudden increase of the indications of the instrument was produced at potentials slightly below the voltages at which visible corona and brush discharges appeared on the end of the thin wire.

Second, a spark gap connected across one of the condensers of the cable circuit produced oscillations at much lower voltages (2 kv.). The curves which resulted by gradually increasing the voltage were similar in character to Fig. 4.

The last two experiments demonstrated the necessity of discerning between the oscillations due to ionization in the cable itself and those disturbances which are due to ionization in the adjacent circuits.

Oscillations are produced wherever the potential gradient exceeds the value at which ionization takes place in the form of corona or
brush discharges. Thin connecting wires, kinks in transformer windings, wires and coils placed too closely to grounded bodies, overstrained condensers, etc., often have proved to be the source of oscillations, which interfere with measurements. These stray oscillations may be avoided by selecting properly designed transformers and condensers, by providing spherical surfaces at all binding posts and pot-heads, and by choosing connections of proper dimensions. Not only must these local sources of interference be avoided, but also electromagnetic surges, which propagate through space and radiate from faulty collectors, automatic switching devices and relays, must be suppressed. Shielding of the detecting and measuring apparatus is imperative. Much better results were obtained working in a room which was shielded throughout by lining the walls, ceilings and floor with cooper sheathing.

12. Comparison of Cable Samples by Radio-Frequency Method.—The curves in Fig. 5 represent typical examples of the results of tests obtained by the radio-frequency method. Three samples, each 14 ft. long, of a 22 kv., 500 000 cir. mils, one-conductor cable were chosen for the test. One of the samples, a, was cut from an old cable which previously had been repeatedly overloaded, another sample, b, from an entirely new cable.

The procedure was as follows: The natural frequency of the cable circuit, 3, Fig. 3, was determined by the resonance method. In this
Fig. 6. Characteristic loops showing effect of a cycle of increasing and decreasing values of applied voltage on ionization in cable samples

In the particular case the frequency was 789 kc. (λ = 380 m). The coupling of the cable circuit with the receiver, 35, was then adjusted by the variocoupler, 30, 10, so that when the receiver was tuned into resonance with the cable circuit, the background noises were hardly audible. At resonance the background noises were usually loudest, so that in most cases the resonance position of the calibrated tuning condenser of the receiver checked the predetermined frequency of the cable circuit. The applied voltage was then gradually increased until a feeble crackling sound characteristic of ionization discharges in cable was heard. At this stage the receiver was tuned in accurately until the maximum of sound intensity was obtained. Finally, the ionization indicating ammeter, 12, was switched in instead of the loudspeaker. From this moment on the voltage applied to the cable was gradually increased by steps and the readings of the ammeter, 12, were taken for each step.

From the shape of the curves (Fig. 5) it was inferred that the oscillations due to ionization might serve to determine the magnitude of the voltage at which ionization sets in at each particular case. So curve a, which represents the result of testing a cable sample which had been often overloaded, shows a characteristic bend at about 12 kv. Curve b represents the result of testing a sample of the same cable which had never been overloaded. The characteristic bend in this curve appears at 25 kv., a voltage about twice as large as was ob-
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Oscillations due to ionization in dielectrics obtained for the first sample. The slope of the curves is also characteristic; it is greater for the old overloaded sample than for the new sample. By repeating the measurements it was found that the characteristic bend for the old sample, \(a\), remained fairly constant. As to the new sample, \(b\), it was noticed that every repeated application of voltage higher than the normal shifted the characteristic bend towards lower voltages. Finally the characteristics of the two samples became approximately alike as shown by the curves \(a_2\) and \(b_2\).

Further observations were made by extending the foregoing procedure by the following additional testing operation. By gradual increments the applied potential was made about twice the critical value; these were followed by a series of decrements of the voltage in equal steps until the potential dropped to zero. At the same time readings of the indicating milliammeter, 12, were taken. In this way characteristic loops were obtained as shown in Fig. 6. The loop \(a_3\) was obtained by measurements on sample \(a\). Starting from 31.5 kv. the potential was decreased by steps until zero, and then likewise increased to the original value. Loop \(b_3\) was obtained with sample \(b\) subjected to potentials which started from zero and were gradually increased. When the potential reached 24 kv. it was decreased to zero. Similarly another sample, \(c\), was tested with the result shown by the loop \(c_3\).

The shape of the loops of Fig. 6 depends on the duration of voltage application at each step. The smaller the duration of voltage application at each step the smaller becomes the area enclosed by the loops. Curves of this type bring out the influence of time on the ionization. They show that the dielectric of a cable subjected to electric stresses is stable only below a certain characteristic voltage. Above the potential at which ionization sets in the cable is undergoing changes. The time necessary for the establishment of a new stable condition varies for different cables and depends also on the applied voltage.

Strictly speaking, all these curves, Figs. 5 and 6, represent the relation between the potential applied to the cable and the effective values of oscillations produced by ionization in the dielectric. Considering, however, that ionization is a phenomenon which accompanies the operation of cables and influences their durability, it was found useful to correlate the intensity of the oscillations with those properties of the cables which give rise to ionization. The factors which determine such properties of cables are the degree of impregnation, the rate of evolution of gases, and also the structural and chemical changes.
taking place in the dielectric materials. The following characteristics of the cable samples may be deduced from the shape of the curves:

(a) A bending zone appears on the curve at a voltage which determines the starting point of oscillations due to discharges in the cable dielectrics.

(b) The slope of the curve indicates the influence of applied voltage on the rate of increase both of the intensity of the oscillations and of the number of oscillation sources distributed along the cable.

(c) The difference between the ordinates for decreasing values of applied voltage and those for increasing values, also the areas enclosed within the ascending and descending branches of the curves are characteristic of the stability of the ionization as a function of the duration of the applied cyclic process of increasing and decreasing the applied voltage. These areas are useful for showing time effects.

---In the method described in the preceding sections (Fig. 3) the oscillations had to undergo a number of transformations before they were measured. So two stages of radio-frequency amplification, heterodyning by means of an auxiliary oscillator, two stages of group-frequency amplification, rectification by means of a detector tube, and, finally, step-down transformation were applied in order to obtain effects of about 300 ma. measured with a thermomilliammeter. In many cases so large a sensitiveness was not required. A simple commercial radio receiving apparatus, Fig. 7, was therefore so reconstructed that it permitted the measurement of the effective values of the oscillations due to ionization in the cable directly at any one of the three stages of radio amplification. For this purpose radio-fre-
quency currents from the cable circuit, 3, were fed by means of a step-up radio transformer, 4, to the first aperiodic amplifying circuit, 5. Each of the next three stages of radio amplification was supplied with terminals to allow the insertion of a thermocouple whose radio-frequency heating effect was indicated by a microammeter, 10. The complication of detection, heterodyning and of group-frequency amplification could thus be avoided.

For the testing of cable samples with which ionization started at comparative low voltages this proved quite sufficient. In order to extend whenever necessary the range of sensitiveness a detector, 11, and two stages of audio-frequency amplification, 12, were provided. For quantitative measurements a thermionic voltmeter, 13, was used whose impedance was matched with the output of the amplifier, 12, by means of three step-up transformers so that all the primaries were parallel-connected, while all the secondaries were in series. For preliminary adjustments a loudspeaker, 15, was used. The change from loudspeaker to thermionic voltmeter was made by means of a double-pole switch, 16. The change to direct radio-frequency measurements was made by plugging the thermocouple in the secondary of one of the radio-frequency transformers which served to translate radio-frequency oscillations from one stage of amplification to another. With this arrangement it was also possible to measure simultaneously the radio-frequency oscillations with the thermocouple and the audible group-frequency with the thermionic voltmeter. The range of frequencies included the entire radio broadcasting spectrum of \( f = 550 \) to 1500 kc. Many of the usual types of radio receivers can be thus adapted for detection and measurement of oscillations produced by ionization in dielectrics.

During the course of experiments it happened occasionally that the local University broadcasting station would disturb the measurements. In such cases the interference was usually obviated by setting the inductance of the cable circuit 3 for another frequency, and retuning the receiver condenser accordingly. More serious proved to be the interference due to sparking of faulty commutators and induction coils used in the laboratories located in the same building. Often selection from a larger range of frequencies was required to free the measurements from disturbances of this kind.

14. Description of Long-Wave Receiver.—In order to provide for such wider scale of frequencies and to explore the possibilities of utilizing for ionization measurements frequencies which extend below the
broadcasting band, an improved receiving apparatus was designed for a range of wave lengths from $\lambda = 330$ to 2800 m.

The general view of the receiver is shown in Fig. 8. It is mounted in a wooden box, divided into three compartments, each shielded separately by copper sheets. The central compartment is occupied by eight units of apparatus, each mounted in aluminum boxes. Units 1, 2, 3, 4, and 5 contain the five stages of radio amplification; $D$ is the detector unit; $A_1$ holds the first stage of audio amplification and $A_2$ the second stage of push-pull audio amplification.

In the left as well as in the right compartment are placed radio coupling transformers $L_1$, $L_2$ which serve for translating to the first stage of the amplifier the oscillations produced in the cables by ionization. By means of the handles $K$ the distance between the coils $L_1$ and $L_2$ could be changed for the purpose of varying the coupling. Of the five stages of radio amplification the first two stages were seldom applied. The remaining three stages were amply sufficient for all measurements. The sensitivity of these three stages was such that at a wavelength $\lambda = 1460$ m. ($f = 205.4$ kc.) an input of 450 microvolts produced an output of 2 volts. This corresponds to an amplification factor $\mu = 2 \times 10^6/450 = 4450$. Oscillations of as small an amplitude as 100 microvolts could still be measured. The output of each stage of radio-frequency amplification, starting from the second stage, may be connected to a thermocouple or to a thermionic voltmeter while the output of the audio group frequency may be measured by a thermionic or by an electrostatic voltmeter.
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(a) - Receiver Circuit

(b) - Two-Stage, Audio-Frequency Amplifier

The diagram Fig. 9a shows the details of the five stages of radio-frequency amplification, including the detector circuit. The first two stages were similar to the third stage and were therefore omitted in the diagram. Figure 9b gives the diagram of connections for the two-stage audio amplifier.

In the operation of the receiver the methods of varying the sensitivity and the frequency differ somewhat from that of the usual radio receiving sets and should therefore be mentioned.

Three ways of varying the sensitivity were provided. The one which affected all stages of amplification consisted in operating the knob, K, which controlled the coupling between the coils $L_1$ and $L_2$ of the input radio transformer, Fig. 8. The second way was by excluding from use as many stages of amplification as was desirable under the circumstances involved in the process of measuring ionization. For this purpose three of the five stages of radio amplification were supplied with switches $S_2$, Fig. 9a, which allowed the opening of the
input circuit of the preceding unused stage. The input was then applied to the terminals, \( T \), of the particular stage to be used. The third way of varying the sensitivity was applied when the last two stages of group-frequency amplification were used, and consisted in controlling the input voltage at the grid of the first audio stage by means of a potentiometer.

For the variation of frequency each stage was supplied with a variable condenser of 350 m mf. capacity and a set of four interchangeable coils. While the condensers were all mechanically coupled in a common unit operated by a knob of a Vernier reducing gear, the coils had to be interchanged in passing from one range of frequencies to another. The entire frequency spectrum of wavelengths 330 to 2815 m. was divided into four overlapping regions by four interchangeable coils.

\[
\begin{align*}
(1) \lambda &= 330 \text{ to } 630 \text{ m. with coil } A \\
(2) \lambda &= 550 \text{ to } 1050 \text{ m. with coil } C \\
(3) \lambda &= 900 \text{ to } 1750 \text{ m. with coil } D \\
(4) \lambda &= 1340 \text{ to } 2815 \text{ m. with coil } E
\end{align*}
\]

By insertion of thermocouples into the plug holes \( T \), Fig. 9a, the inductance of the tuned circuits was increased. In order to prevent the frequency calibration of the circuits from being disturbed a small compensating condenser \( C_2 \) was included in the circuits. Whenever a thermocouple was inserted, the short-circuiting switch \( S_2 \) had to be opened, and the condenser \( C_2 \) to be readjusted.

On the other hand the connection of a thermionic voltmeter to the binding posts \( V \), Fig. 9a, increased the capacity of the tuned circuits of the particular stage. Compensation was taken care of by means of fixed condensers which were added at \( V \)-points of all the other radio-frequency stages wherever the voltmeter was removed.

Whenever a thermionic voltmeter was to be used for measurements of radio-frequency exclusively it was necessary to open switch \( S_1 \) of the stage in use so as to disconnect it from the succeeding stages.

The receiver was constructed as a universal instrument for convenient adaptation to the varied conditions which were met in the course of investigating various methods of detecting the presence of ionization and measuring its intensity. For all practical purposes, however, 3 or 4 stages of radio amplification with a thermionic voltmeter as indicator proved sufficient.

15. Application of Long-Wave Receiver to Ionization Measurements of a Cable.—A 22-kv. single conductor, 500 000 cir. mils cable 7 m. in length was chosen for testing the radio-frequency method of
measuring ionization. The constants of the cable circuit were selected so that ionization in the cable might produce frequencies from 100-900 kc. The diagram of connections is shown in Fig. 10. The cable ends were supplied with the usual oil-filled potheads. The conductor terminated at both ends with hollow aluminum spheres, $Q_A$ and $Q_B$ made up of two halves. Inside each sphere were placed two chokes, one of which was an air core coil, $L_r$, wound on a bakelite tube, and connected in series with the latter was an iron-cored choke, $L_a$. The outside ends of $L_r$ were connected to brass rods insulated from the spheres by bakelite bushings and joined together in a sleeve, $S$. The sleeve $S$ served as a binding post for connection with a 50 000-volt 60-cycle transformer. The object of this arrangement was to protect the receiver from line disturbances, and to limit the high frequency current, produced by ionization within the cable, to the radio-frequency cable circuits $A$ and $B$. Each of these circuits consisted of two 3000 mmf. mica condensers $C$, connected in series, and the inductance coils $L_c$. The latter were made up of a fixed part and a variable part, supplied with taps for varying the wavelength of the cable circuits by steps. They served as primaries of radio transformers $T_A$ and $T_B$. 

**Fig. 10. Radio-Frequency Method of Detecting Cable Discharges Due to Ionization**
FIG. 11. ARRANGEMENT OF APPARATUS FOR RADIO-FREQUENCY METHOD OF MEASURING IONIZATION IN CABLES
The secondary coils were wound on a bakelite cylinder. They were
guided on glass rods and could be moved axially by strings and wind-
llasses operated by knobs $K$, Fig. 8. The terminals of the secondary
coils were connected to switches $S_1$ and $S_2$, respectively, for the pur-
pose of connecting each core alternately, or both in series, to the input
of the receiver.

For the detection of ionization it was not essential to couple both
cable circuits $A$ and $B$ with the receiver at the same time. By doing so
an increase of about 40 percent in the indications of the output meters
was obtained as compared with those obtained with the use of only
one of the cable circuits at a time. Provision for two circuits at each
end of the cable was made solely for the study of methods of locating
the source of ionization and eliminating charging currents and other
disturbances. With the available amplification the use of only one cir-
cuit was quite sufficient.

The entire arrangement of the apparatus in connection with the
cable under test is illustrated in Fig. 11. In the background is visible
the cable sample $C$ with potheads, $P$, at each end supported on wooden
stands, $W$. Aluminum spheres, $Q_A$ and $Q_B$, terminate each cable end.
Next to the front appear the high-voltage condensers, $C_A$ and $C_B$,
arranged in pairs one above the other. Each pair belongs to a cable
circuit $A$ and $B$ respectively. The long-wave receiver $M$ follows with
the radio-coupling transformer $T_A$, controlling knob $K$ and the loud-
speaker $S_p$. At the front on the table is seen the thermionic voltmeter
$T_h$. A metal box, $B$, underneath the table contains all the batteries
which feed the receiver vacuum tubes.

The following measurements were selected to bring out character-
istic properties of the oscillation method of measuring ionization in a
cable. The object of the measurements was to investigate:

(a) The range of frequencies which may be produced by ion-
ization.

(b) The influence of outside interference.

(c) The effect of radio-frequency amplification combined with
group-frequency amplification.

(d) The effect of pure radio-frequency amplification.

(e) The relative advantages of the thermoelectric and thermi-
onic indicating instruments.

(f) The time effect of ionization as a function of applied volt-
age.

16. Range of Frequencies Investigated.—Measurements have
established that ionization produces ripples of oscillations whose basic
frequency, as distinguished from the group frequency, depends solely on the constants of the cable circuit $A$ and $B$, and may be deliberately varied by choosing proper values for the inductances of the coils and for the capacities of the condensers in accordance with Thompson's formula. Two cases may be considered. In case $A$, Fig. 10, one end only of the cable, with a capacity of $C_c$, has attached to it an oscillation circuit with a capacity $C$ and inductance $L$; in case $A-B$ both ends have attached similar circuits with similar $C$ and $L$.

Assuming a quasi-stationary distribution of current and voltage, which holds for all practical cases when the frequency of the oscillation is much lower than the fundamental frequency of the cable itself, we obtain for case $A$

$$f_A = \frac{1}{2\pi} \sqrt{\frac{C + C_c}{LCC_c}}$$

Case $A-B$ represents two coupled circuits with an e.m.f. of oscillation acting within the cable. The capacity of the latter $C_c$ is common to both circuits and serves as the coupling member of the oscillating system whose component parts $A$ and $B$ oscillate in phase. Accordingly we obtain for this case a frequency

$$f_{AB} = \frac{1}{2\pi} \sqrt{\frac{2C + C_c}{2CC_c}}$$

By dividing $f_{AB}$ by $f_A$ we obtain the ratio

$$\frac{f_{AB}}{f_A} = \sqrt{\frac{1 + 2C/C_c}{1 + C/C_c}}$$

For the particular case described the capacity of the two condensers in series was $C = 1500$ mmf., the capacity of the cable was $C_c = 2167$ mmf. The calculated value of $f_{AB}/f_A = 1.19$, was within 2 per cent of agreement with numerous measurements made at different frequencies. Evidently the use of an oscillation circuit at each end of the cable increases the frequency as compared with that obtained by the use of only one circuit.

Measurements were made of oscillations produced by ionization at different settings of the inductance $L$ of the cable circuits so that the greater part of the frequency spectrum from 106 to 900 kc. was explored. With the receiver tuned into resonance with the cable circuit curves similar in character could be obtained for the ionization oscillations within this frequency range. In Section 13 it was mentioned...
that oscillations were produced by ionization within the broadcasting range of \( f = 550 \) to 1500 kc. In connection with experiments on localization of the source of ionization in a cable still higher frequencies were obtained within a range of 3000 to 15 000 kc. Altogether a range of \( f = 106 \) to 15 000 kc. was thus explored, which embraced a spectrum of about 150 octaves without marked indication of approaching an upper or lower limit.

17. Influence of Outside Interference.—With such an enormous scale of frequencies at our disposal it is comparatively easy to get rid of interferences which effect the receiver by radiation. The sparking in transformers and corona discharges on conductors leading to the cable must be eliminated before any measurements are made. As an example of how a single outside discharge influences the measurements, Fig. 12 may serve. The abscissas represent the voltages applied to the cable while the ordinates show the indications of the thermionic voltmeter connected to the third stage of radio amplification. The readings were in radio-frequency volts at \( f = 212.6 \) kc. A sudden increase of the ionization oscillations occurred when the applied voltage reached 23.25 kv. This marked increase of intensity of oscillation from 0.4 to 1.1 volts could be repeated at exactly the same applied
FIG. 13. RESULTS OF MEASUREMENTS ON 22-kV. 500 000-cir. mils LEAD-COVERED SINGLE-CONDUCTOR CABLE
voltage. It was found that this steep break in the curve at the point $D$ was due to a tiny bluish discharge about 0.3 mm. long concentrated in one spot between the hemispheres of the aluminum shield ($Q_a$ in Fig. 10). The hemispheres were held together by three silk strings threaded through three holes bored at the circumference of each hemisphere. The protruding ends of the strings entered the space between the hemispheres and thus formed a gap. By removing the strings and by pressing the hemispheres together by means of rubber bands the discharge, and with it the break in the curve, disappeared, and a smooth continuous curve was then obtained. This experiment served also to illustrate an important property of the surges due to ionization, namely, that their amplitude changes abruptly with the change of the character of the discharge.

18. Measurements of Ionization Oscillations by Means of Radio-Frequency Amplification Combined with Group-Frequency Amplification.—Considering that the cable sample had never been overloaded, it was interesting to start the measurements with the greatest practically available sensitivity of the receiver, in order to determine the lowest limit of the applied voltage at which discharges could be detected.

In Fig. 13a three curves are shown taken with the thermionic voltmeter connected to the last stage of audio amplification. The original amplitude of oscillation underwent altogether three stages of radio amplification, then rectification in the detector, and finally two stages of group-frequency amplification. The results are shown in Fig. 13a. Each of the three curves was taken at a different degree of coupling of the receiver with the cable circuit. Curve $A$ corresponds to a tighter coupling than Curve $B$. Curve $C$ was taken with a still smaller coupling than $B$. All three curves converge towards a point $S$ on the abscissa axis which corresponds to 700 volts. This zero point of oscillation has been determined by carefully observing the pointer of the indicating instrument at the highest sensitiveness of the receiver.

This is the lowest starting voltage for discharges observed on cables during the course of this investigation. It raises the question whether the idea of a characteristic starting voltage is at all justified and whether the starting voltage will not be shifted even closer towards zero by the use of more sensitive methods. What is usually called the “starting” voltage of discharges in cables therefore may be defined more rationally as the voltage at which ionization becomes so copious that its rate of change with voltage increases markedly. Such a low starting voltage could not be established after the cable was loaded
during a week's experimental work with voltages about 10 to 30 kv., and for a short time with 50 kv. The curves in Fig. 13b support the possibility that the cable, from an initial state of copious ionization, improved after a short period of loading. The earlier curve $D$ resembles the curve $E$, which was taken seven days later, with the exception that the latter is shifted toward the higher voltages by an amount corresponding to an average of 7 kv. Curve $E$ has been obtained by using high sensitivities of the receiver at small magnitudes of applied voltages and low sensitivities at large voltages. The ordinates were then reduced to a scale of equal sensitivity corresponding to that used for taking curve $D$.

19. Measurements of Ionization Oscillations by Means of Radio-Frequency Amplification Exclusively.—By excluding the detector and group-frequency amplification stages, radio-frequency amplification alone was used to measure the oscillations produced by ionization.

In Fig. 13c the results of measurements repeated on three consecutive days and made with only three stages of radio amplification are shown. Curves $F$, $H$ and $G$ were taken under exactly the same conditions of sensitivity of the receiver. They are all of the same character, the differences from day to day may be ascribed partly to the variations of operating conditions of the amplifying tubes, and partly to changes going on in the cable.

In order to compare these curves with those obtained by additional group-frequency amplification curve $E$ was plotted. It is the same curve $E$ as shown in Fig. 13b, but with all ordinates reduced 20 per cent. The agreement with $F$, which was taken on the same day, is very close. However, it did not always happen that with the two methods identical curves were obtained. Background noises affected the two methods differently. Also, at different sensitivities the distortions inherent in every stage of amplification are not alike. Both methods of amplification were equally satisfactory. It is useful, however, to make use of one stage of audio-frequency amplification in addition to radio-frequency amplification for the purpose of operating a loud-speaker for adjustments of the receiver, preliminary to taking data. From the point of view of preserving fidelity of the original wave forms of oscillations produced in the cable by ionization, pure radio-frequency amplification is preferable. Additional group-frequency amplification requires the use of a detector stage, which is the chief source of distortion and should be avoided unless the available stages of radio-frequency amplification are not sufficient for the required magnitude of deflection of the indicating thermionic voltmeter.
In connection with pure radio-frequency amplification the question whether the voltage output or the current output of the radio-frequency transformers shall be used for measuring the ionization oscillations had to be investigated. For this purpose simultaneous measurements were made with the thermionic voltmeter connected parallel to the secondary coils of the third stage radio transformers and a thermocouple inserted in series. The entire available range of 0-62 kv. 60 cycles alternating current potentials was this time applied, first by about 10 per cent increments, then by similar decrements.

The results are shown in Fig. 14. Curves $J$ and $K$ represent the voltage output, while $L$ and $M$ represent the voltmeter deflections,
Fig. 15. Relation Between Amplitude of Oscillations Due to Ionization and Time of Continuous Application of 60-Cycle Voltage
which are proportional to the square of the output current due to the ionization oscillation. Arrows directed upwards or downwards indicate the branches due to increasing or decreasing applied potentials. The loop $J-K$ appears to be entirely different in character from the current loop $L-M$, because of the quadratic relation between current and deflections. When the values of the ordinates of the voltage curve $J-K$ are raised to the second power and divided by a factor depending on the scale of the $L-M$ curve, both pairs of curves become closely similar. The branch $M$ for increasing values of applied voltage supplemented by the branch $L$ for decreasing voltages form together a time-effect loop of the same character as those described in Section 12 (see Fig. 6). The latter, however, were obtained by radio- and group-frequency amplification, while for the curves in Fig. 14 pure radio-frequency amplification and a much larger range of applied voltages were used.

20. *Time Effect of Ionization as a Function of Applied Voltage.*—The radio-frequency method of measuring ionization in a cable may be applied for the study of the changes of ionization which take place with time. The effect of time on ionization has been discussed in Section 12, where the intensity of oscillations due to ionization was shown to depend on whether the applied voltage was gradually increased or whether it was changed by decrements. Characteristic loops were also described in the preceding section. The effect of time may be conveniently investigated at constant applied voltage by observing the deflections of the oscillation-measuring indicating instrument as functions of time.

The curves in Fig. 15 represent the result of such measurements, obtained with three stages of radio-frequency amplification and a thermionic voltmeter. An interval of one minute of rest was given to the cable after each series represented by curves $O$, $P$ and $Q$. The interval between $N$ and $O$ was five minutes. For the particular cable investigated the rate of change decreased with time. Small changes in ionization continue to take place even after half an hour of continuous application of potential. The curve $R$ demonstrates such changes. What the processes are in the cable which cause the time effect is not definitely known. A thorough study of the ionization oscillations, which are so markedly influenced by these processes, may contribute to the solution of this problem.

21. *Relative Advantages of Thermoelectric, Thermionic, and Rectifying Indicating Instruments.*—During the course of the investigation
three types of indicating instruments were used for measurements of output currents of receivers. The thermoelectric instruments were usually connected to the receiver by means of step-down transformers. Their advantage consists in their simplicity and the facility of changing the sensitivity by shunting the galvanometer. However, the disadvantage lay in the comparatively large currents required for their operation, in the danger of burning out the thermocouples, and in the resistance of the heating element, which is especially detrimental when inserted in radio-frequency circuits. In connection with vacuum thermocouples, the disadvantage of slow action due to the time required for heating the couple should be mentioned.

The thermionic voltmeter is more complicated in construction and operation, but has the great advantage of responding quickly, and requiring less energy than the thermoelectric instruments. The type which has two scales, 0-4 and 0-20 volts, was found especially convenient.

Thermionic voltmeters were used in this investigation for measuring both group frequency and radio frequency. In the latter case they were found more convenient for determining the starting point of ionization oscillations than thermoelectric instruments. Due to the deflections of galvanometers connected to thermocouples increasing with the square of the heating current, thermoelectric instruments brought out more clearly sudden changes of ionization. The curves in Fig. 14 may serve as an example. While the curves $J-K$, obtained with a thermionic voltmeter, are definitely directed towards a starting point $S_1$ on the axis, close to 11 kv., the curves $L-M$, obtained with a thermocouple, show at the point $S_2$, close to 30 kv., more distinctly the sudden change in the rate of increase of oscillation characteristic of copious ionization.

The rectifying output meters made up of cuprous oxide plates were found convenient as indicators in the audio-frequency stages, but could not be used in the radio-frequency stages, due to their large capacitance and inefficiency in rectifying radio-frequencies above 10 k.c.

IV. Application of Principle in Connection with Testing of Paper Samples

22. Description of Apparatus.—The dielectric of a high-voltage power cable consists generally of layers of paper impregnated with a semi-liquid compound. In search for a correlation between ionization
and the oscillations it produces in cables, the investigation led to the application of the methods described in the preceding chapter to testing of paper samples. Different kinds of paper are made of various raw materials, they undergo numerous manufacturing processes, and naturally would show different characteristics. The breakdown of paper has been repeatedly studied, but its ionization characteristics were entirely unknown.

In order to take into account the inhomogeneities which occur in paper, strips 80 cm. in length, Fig. 16, were pasted at the ends to form an endless belt which was pressed between two rotating rubber rollers. The upper roller $B$ was supported by the bakelite arm $C_1$ which was pivoted on the brass stand $T_1$. By means of a screw $D_1$ the arm $C_1$ and the rubber roller $B$ could be pressed down against another rubber roller, set with the driving pulley $A$ on a common spindle $S$, and supported in the stand $T_2$. Another bakelite arm $C_2$ carried a cylindrical nickel electrode $F_1$, ¼ in. in diameter, in the form of a roller, similarly adjustable by means of the screw $D_2$ and pressing against another nickel electrode $F_2$ set between point bearings $L$. A ball and socket joint $E$ was provided for each of the arms $C_1$ and $C_2$, for the purpose of insuring proper alignment of rollers at all times during
rotation. A subsidiary roller $G$ served to guide the paper sample and to remove any static charge collecting thereon. The voltage was applied to the upper nickel electrode $F_1$ through a copper bronze brush $H$, which was connected to the binding post $K_1$. The lower electrode $F_2$ was grounded through the brush $J$ and the binding post $K_2$, attached to the frame $T_3$. The pulley $A$ was driven by means of an electric motor through a speed-reducing gear. A scale was attached to the base of the apparatus, so that the picture may give an idea of the general dimensions and the dimensions of the parts.

The general arrangement of auxiliary apparatus including the amplifiers and measuring instruments is shown in Fig. 17.

The power was supplied to the paper sample $P$ by the transformer $T_2$ at a voltage adjustable between 0 to 2300 volts. Condenser pairs
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C1 grounded at midpoint, and an intermediate transformer T1 were used in order to free the testing circuits from line disturbances. Choke coils L1 prevented the propagation of high-frequency oscillations to the line.

The paper sample P represented a dielectric moving in a condenser C3 whose electrodes were rotating nickel rollers. In series with the latter were inserted fixed condensers C2, C4 and a variable air condenser C5. A variable inductance L2 completed the oscillating circuit B. This circuit was energized by the ionization at the surface and within the fibers of the moving paper sample P whenever a weak spot entered the space between the electrodes. At voltages of about 1200 volts ionization appeared in the form of a bluish film of corona discharge plainly visible in complete darkness. The high-frequency ionization oscillations were impressed at the points 1-2 on the primary of a radio-frequency coupler, whose secondary energized the grid of the first thermionic tube of a three-stage radio-frequency amplifier A1. By means of the switch S1 the output of this amplifier could be connected either to a thermionic voltmeter or to the detector D. Another switch S2 transferred the rectified pulses to a telephone receiver or to a group-frequency amplifier Aa. The output of the latter was indicated by a thermionic voltmeter. A three-transformer system T3 served to step up the output voltage at a ratio of 1:10.

23. Relation Between Applied Voltage and Amplitude of Corona Oscillations for Different Kinds of Paper.—Four samples of paper of equal thickness (0.011 cm.) and equal length (84 cm.) were chosen for the test.

(a) Manila Cable paper
(b) Wood Pulp Cable paper
(c) Eggshell Drawing paper
(d) Bristol Drawing paper

The samples were driven through the apparatus with a speed of 23.5 cm. per min. The period of repeated application of voltage to the same spots was \(\frac{84 \times 60}{23.5} = 214\) seconds. For each sample the investigation was made in three stages.

The first stage consisted in detecting and eliminating tiny holes which gave rise to spark discharges. In order to protect the indicating instrument from excessive voltages, a telephone receiver connected to the output of the detector D, Fig. 17, was used for this part of the investigation. The voltage was increased in steps of 100 volts after
every two or three runs of the sample. During each run the time was marked at which a breakdown click was heard. This helped to locate tiny holes by inspection with light transmitted through the sample. Wherever a tiny hole was found it was patched with a narrow strip of the same paper. Often no visible holes were found in the places marked. Nevertheless in a repeated run a sharp click characteristic of breakdown was heard in exactly the same place. With this method holes of much smaller size than could be perceived by inspection could be detected. As the applied voltage was increased the number of such breakdowns increased, but the intensity of the clicks diminished, due probably to diminishing cross-section of the discharge channels. As soon as a condition was reached when none of the individual clicks gave a deflection on the indicating meter amounting to more than half of the available scale, no more patching was carried out. This part of the tests revealed the existence of breakdowns in individual places of the samples before ionization started throughout the sample.

The second stage of the investigation consisted in measuring the deflections due to ionization for each individual cross-section of the paper samples at constant voltage. Curves were plotted showing the distribution of the ionization oscillations along the entire length of the samples. Due to the intrusion of local breakdowns and to the usual nonuniformity of the structure of paper these curves showed rather rugged outlines. The breakdowns could be discerned by the steep peaks they caused. For each sample a number of such constant voltage curves were obtained. Each curve was taken for a higher voltage than the preceding within the range of 500-1400 volts.

All these curves show that in general the "weak" places—those giving largest deflections—repeat at each voltage used. It was also observed that when a run was repeated at the same voltage the character of the curve was also repeated.

The third part of the investigation consisted in averaging the curves by means of a planimeter. Large peaks due to breakdowns were excluded so that an average deflection due chiefly to ionization was obtained for every sample for a number of magnitudes of applied voltage. On the basis of these average values curves shown in Fig. 17 were plotted.

24. Characteristics Revealed by Tests.—The curves in Fig. 17 reveal the following characteristics of the paper samples. For the Eggshell drawing paper, which has the roughest surface of all the papers, corona starts at the lowest voltage, about 600 volts. Next follows the
Manila cable paper, with the loosest texture, at about 700 volts, then the Wood pulp cable paper at about 800 volts, and, lastly, the Bristol paper, with the densest structure and smoothest surface, shows corona discharge at the highest voltage (about 850 volts).

Up to 900 volts all the paper samples show at every voltage the same order of quality; the Bristol producing the least, the Eggshell drawing paper the most ionization oscillations. At higher voltages this order remains the same, except for the Eggshell drawing paper, which above 1000 volts show less ionization than both of the cable papers.

Besides the determination of ionization characteristics, the method allows the paper samples to be graded in accordance with the frequency of occurrence and size of weak spots. The latter produce detectable breakdowns or ionization at a smaller applied voltage than the average ionization characteristic for the particular paper.

V. BRIDGE METHODS

25. Principle of Discharge-Detection Bridge.—In the case of insulated power cables, as well as in many other insulated electric power devices, it is impossible to detect the existence of ionization discharges in the gaseous voids in the insulation by means of oscillograms obtained with the standard type low-frequency magnetic oscillograph. This is due to the fact that the ionization discharges are usually less than $\frac{1}{1000}$ part of the magnitude of the 60 cycle charging current and its harmonic residue. The magnetic oscillograph will indicate the presence of discharges in certain extreme cases, such as in the case of the charging current of a corona tube when visible corona exists within the tube and on the surface of the inner wire. It is also possible to make the discharges appear superimposed upon the oscillograph record of cable charging current when a short piece of lead-covered paper-insulated cable is intensely heated with a flame so as to drive out most of the excess oil or viscous saturant from the paper insulation, thus making the ionization discharges in the spaces between the dry paper layers very intense so that they will show as disturbances of the 60-cycle charging current. Oscillogram Number 144 of Fig. 19 shows such an oscillographic record with a definite indication of the intense ionization discharges. For the ordinary type of paper-insulated cable provided with the normal amount of saturant there is no possibility of obtaining any indication of ionization discharges by means of the ordinary charging current oscillogram, even though sur-
face-listening tests, power-factor measurements or discharge-detection bridge measurements indicate a badly deteriorated condition within the cable insulation.

In order to utilize the full sensitivity of the oscillograph for the purpose of recording disturbances due to ionization, it was necessary to eliminate the charging current from the oscillographic element. Accordingly, a simple resistance-capacitance type of bridge was assembled with which to balance out wholly or partially the normal cable-charging current and its harmonic residue. Figure 18 shows schematically this particular device with some of its associated equipment. The bridge, diagram a, is made up of two resistance-ratio arms, the cable or other insulating device under test, and an ionization-free high-potential air condenser. This air condenser provides the balancing component of charging current which is free from any ionization disturbances. If a high-resistance telephone receiver is connected across the diagonal $DD'$ and the value of the resistance-ratio arms adjusted for approximate amplitude balance while sufficient testing voltage is applied to the cable conductor and sheath, the characteristic ionization discharge sound will be noted in the telephone receiver, but only imperfectly, due to the comparatively intense masking effect of
the unbalanced fundamental and harmonic residue. Instead of the usual telephone receiver a suitably designed bridge output transformer is provided for exciting an amplifier system through a suitable arrangement of filters.

The ratio arms, $R_1$ and $R_2$, are adjusted until an amplitude balance is obtained for the 60-cycle charging current through the bridge. A phase balance may also be obtained by means of a variable condenser in shunt with $R_2$, as in the standard Schering bridge. It is not advisable to use this condenser, as its presence reduces the response of the bridge to the ionization discharges. This can be seen as follows: The ionization discharge has been found by oscillographic studies and filter design measurements to contain a conglomerate group-frequency of from 4000 to 10,000 cycles. These disturbances originating in the cable dielectric pass through the cable, the air condenser, $C_8$, and the resistance-ratio arms, $R_1$ and $R_2$, which together form a closed circuit. In addition, there is a shunt formed across the air condenser and the resistance arm $R_2$ by the secondary of the high-voltage transformer (and its self-capacitance) and the ground return to the point between $R_1$ and $R_2$. A current produced by the ionization disturbances thus flows through the arms $R_1$ and $R_2$ in series, and sets up a voltage at the diagonals $DD'$ which is applied to the output transformer. Since the resistance $R_2$ constitutes the larger part of the circuit resistance, any shunt, such as the condenser of the standard Schering bridge, tends to reduce the response of the bridge. This briefly outlines the fundamental action of the discharge-detection bridge.

The unbalanced charging current residue must be suppressed by a suitable filter system, many forms of which have been experimented with. To effectively suppress frequencies below 2000 cycles, and at the same time pass a band of frequencies from 4000 to 8000 cycles, a coupled filter system has been found to be most effective. The coupled inductance units of this filter are astatically arranged in order to prevent magnetic induction from stray fields and regeneration. The air-core inductances of the filter are preferably of rather generous proportions so as to obtain low resistance, in order to make the cut-off and pass band characteristics more pronounced. It is advisable to raise the energy level of the discharge component potentials across the bridge diagonals by providing a preliminary amplifier between the bridge output transformer and the filter. The general arrangement of the entire bridge, filter, and amplifier system is shown in diagram b of Fig. 18. The filter is in turn connected to the input of a three-stage high-gain amplifier, incorporating a power tube in its last stage,
together with a compensated rectifier-output meter circuit. The entire arrangement provides a sensitivity of approximately $10^{-5}$ volts per scale division deflection of the output microammeter. The entire device furnishes a fairly sensitive detector of ionization discharges, the sensitivity increasing with the resistance of the ratio arms of the bridge. A bridge having inductance-ratio arms can be made still more sensitive, and is feasible, and even more desirable, for cable testing under certain conditions. Using the detection equipment described, with the output rectifier circuit replaced by a suitable impedance-matching transformer, an oscillographic record of the discharges in an experimental 20-foot sample of 22-kv. lead-covered power cable was obtained and is shown as oscillogram Number 11 of Fig. 20. It should be noted that the charging current of about 0.075 amperes is completely suppressed, while the maximum ionization discharge amplitude is of the order of 20 microamperes. As can be easily concluded from the characteristic sound in cable discharges, the characteristic is that of random damping and conglomerate frequencies, producing a crackling or frying sound, which is unlike the regular form of disturbances shown in the oscillogram. The filter system is responsible for this, the regular forms with regular rates of damping are due to natural oscillations in the filter circuits, occasioned by impulse excitations from the steep wave front random discharging disturbances. Using aperiodic filters, oscillograph studies of the random character of the discharges have been made, but such filters have not been found to be completely effective; so for high-sensitivity comparative-intensity measurements the tuned filter has been found to be more satisfactory.

26. Measurement of Charging Current Harmonic Residue.—The members of the Cable Subcommittee of the Utilities Research Commission suggested that the well-known resonance bridge as used by G. Belfils* to measure the total harmonic residue of any wave may be used to test high-voltage cables, believing that possibly the harmonic content of the charging current may materially change when the cable exhibits altered power-factor due to ionization characteristics. Accordingly, this type of bridge was used in connection with some of the tests conducted at the high-voltage laboratory of the Commonwealth Edison Company, and readings were taken at various times of the total harmonic charging current residue. In Fig. 21 is shown a schematic diagram of this type of bridge. Quite a number of tests were made, and some interesting facts concerning the behavior of this

---

Fig. 19. Oscillogram of discharges in a cable superimposed on charging current

Fig. 20. Oscillogram of discharges in a cable, charging current eliminated
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harmonic residue were noted. In the limited time given to this particular work no apparent direct coordination between ionization conditions and harmonic residue was noted.

There were some noteworthy changes in this amount of harmonic residue, particularly when the cable insulation temperature changed. In the case of every cable tested the total harmonic residue current decreased materially when the cable was heated to its elevated operating temperature. Figure 21 shows a plot of some typical cables upon which measurements were made. It will be noted in particular that for certain of the cables the decrease was considerably more than for other cables. In nearly every case very smooth curves were obtained. The possibility of developing this test still farther remains quite large.
VI. Locating Sources of Ionization in Cables

27. Problem of Locating Sources of Ionization.—From the point of view of manufacturing and operating cables it is often desirable to determine the particular places along the cable where ionization starts first, how with increasing voltage it spreads to other places, and how the distribution of ionization along the cable changes with time. This vast problem has been attacked in different directions. Each of the methods devised has a very limited range of application as yet, and does not solve the problem in its entirety. The principles, however, which were applied in this investigation may become important as such and therefore will be briefly described.

28. Listening Stick Telephone.—It is well known that at least fairly intense ionization discharges between the paper layers, and fairly near to the sheath of a cable, produce actual mechanical vibration which is transmitted to the surface of the lead sheath, and may be detected by direct contact with the ear, conveniently through a stick or rod. It is certain that these mechanical vibrations are associated with disturbances in the electric fields or voltage gradients, and hence produce disturbances in the cable charging current, or testing potentials, or both.

A convenient type of contact listening device was developed which is particularly suitable for the frequency range of the sheath vibrations. Figure 22 shows the principle of the construction of this device. The ordinary telephone receiver diaphragm is attached rigidly to the end of a well-seasoned mahogany stick, and the diaphragm is supported around its edge in the ordinary telephone receiver case. This device is placed so that the opening of the case is against the ear and the free end of the stick, in which a blunt steel pin is driven, is held against the cable sheath. Extraneous low-pitched random sounds are well excluded, while the high-frequency cable discharge sounds seem
to be magnified to partial resonance in the wooden stick and receiver case. Very sensitive detection is obtained with this simple device. Experiments were conducted with an electrical stethoscope loaned by the Western Electric Company without success. The stethoscope employed a contact microphone and high-gain amplifier with a system of filters, but the entire device was designed to be responsive to the low-frequency fundamental beats and the characteristic murmurs of the human heart, and was therefore unresponsive to frequencies above about 2000 cycles.

29. Harmonic Standing Wave Method.—In Section 6 the conditions under which standing waves are produced in a cable were discussed. The basis for the application of harmonic standing waves for the location of faults consists in subjecting particular points along the cable to a periodically-varying potential of maximum strength, while all the other points are subjected to smaller potentials. By repeated application to the cable of standing waves of higher and higher harmonics the entire cable length is successively subjected, zone by zone, to the maximum potential.

Exactly the same cable and arrangement of apparatus was used for these investigations as described in Section 9 and shown in Fig. 2. The cable was subjected to a 60-cycle high-voltage potential. At the same time radio-frequency oscillations were superimposed in harmonic sequence on one end of the cable and received at the other end. The fundamental frequency \( f = 2540 \text{ kc.} \), \( \lambda = 118 \text{ m.} \) was chosen, so that a standing wave of a half wavelength was established along the cable. The eighth harmonic \( f = 20970 \text{ kc.} \), \( \lambda = 14.3 \text{ m.} \) was the highest used in these experiments. The presence of copious ionization in a particular point of the cable influences differently each of the superimposed harmonics. Figure 23 serves to represent diagrammatically the operation of this method. First the case is shown when the fundamental frequency excites in the cable a standing quarter wave with a voltage distribution according to curve \( a \). Then the corresponding distribution for the 3rd, 5th, 7th, 9th, 11th, 13th, and 15th harmonics are shown by the curves, \( b, c, d, e, f, g, \) and \( h \), respectively. If a nodal point like \( A, E, C \), etc. coincides with a point where ionization occurs, the latter will not influence the amplitude or frequency of the particular wave. By applying, one after another in regular sequence, higher and higher harmonics, and noting those which remain unaffected, it is possible to determine the position of the source of ionization.
If, for instance, the fundamental, the 5th, and the 9th harmonics are affected, but the third harmonic shows a minimum effect, it follows with certainty that the source is close to the point $A$, which is located at a distance of one-third the cable length, counting from the end which has a potential antinode impressed upon it. Actually, the tests with the fundamental and the third harmonic would be sufficient to enable this conclusion to be reached.

By reversing the connections so that the other end of the cable becomes antinodal, another point $B$ may be located by the same two
tests which referred to the former cable end. It is located at two-thirds of the total cable length. In the same way, but using the fifth harmonic ionization in points C or D may be located at distances of one-fifth and four-fifths the cable length, respectively, from the cable end. The dotted line represents the voltage distribution when the connections are reversed. Further, in order to determine the points E and F, the additional test with the 15th harmonic exerting no effect would be required. Following up this method of applying harmonics any number of points along the cable may be tested for ionization. Considering, however, that ionization usually occurs in spots occupying larger areas, it should be sufficient to extend the test to about 12 points, which provide an inspection of spots located at the following fractions of the cable length: 0.09, 0.11, 0.14, 0.2, 0.33, 0.4, 0.6, 0.66, 0.8, 0.85, 0.88, 0.9.

With reference to Fig. 23, Table 1 gives the index $N$ of the harmonic in addition to the fundamental which should be applied for testing the particular points.

<table>
<thead>
<tr>
<th>Point</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>I</th>
<th>J</th>
<th>K</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5-9</td>
<td>5-9</td>
<td>7</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>$X$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{5}$</td>
<td>$\frac{2}{5}$</td>
<td>$\frac{3}{5}$</td>
<td>$\frac{4}{5}$</td>
<td>$\frac{1}{7}$</td>
<td>$\frac{6}{7}$</td>
<td>$\frac{1}{9}$</td>
<td>$\frac{8}{9}$</td>
<td>$\frac{1}{11}$</td>
<td>$\frac{10}{11}$</td>
</tr>
</tbody>
</table>

30. Fundamental Standing Wave Method.—The investigation of the locating of sources of ionization by means of standing waves has been extended to the case in which an exterior oscillator for the superposition of standing waves has been entirely omitted. Instead, the process of ionization was utilized for the production of standing waves. This method has been further simplified by omitting harmonics. The use of only the fundamental natural frequency of the cable was sufficient to locate a source of ionization.

The arrangement of the apparatus in connection with a cable is illustrated by Fig. 24a.

The operation of this method consists in building up along the cable a standing wave due to oscillations produced by ionization in a particular point of the cable, the position of which has to be determined. For this purpose the condenser, 6, and the inductances, 7, 8, are so chosen that when connected to any one of the ends of the cable
FIG. 24. ILLUSTRATING METHOD OF DETECTING AND LOCATING A SOURCE OF A SURGE IN A CABLE BY MEANS OF A FUNDAMENTAL STANDING WAVE

conductor, 2' and 2'', a disturbance once started by ionization builds up by reflections a standing wave of quarter wavelength with a voltage node at one end and an antinode at the other.

It depends on the position of the switch, 11, at which of the two ends will be the node and at which the antinode. When the tuning system 6–7–8, grounded at 12, is connected by the switch, 11, to the conductor end 2', the nodal point will form at the latter, while the antinode will build up at the open end, 2''. The reverse will take place when the switch connects the tuning system to the conductor end, 2''. The relative distribution of voltage along the standing wave follows a sine law, changing from point to point along the cable, and is independent of the position of the source of ionization along the cable. But the absolute effective value of voltage amplitudes which produce currents in 8 depends very much upon the location of the ionization source. It will be smallest when the source is nearest to the voltage node, and largest when it is nearest to the voltage antinode. It also
follows a sine law. This is true as well for the effective values of the currents which are induced at the coupling coil, 8, picked up by the amplifier, 9, and measured by the indicating instrument, 10. The latter will therefore indicate different intensities in the two cases where \(2'\) or \(2''\) is made the antinode. Changing the switch from \(2'\) to \(2''\) changes the distribution curve from a sine relation to a cosine relation with respect to the same reference point, say \(2'\). The ratio \(m\) of the two measurements is given by the relation

\[
m = \frac{A \sin X}{A \cos X} = \tan X
\]

where

\[
X = \frac{\pi d}{2L}
\]

\(L\) is the total length of the cable, \(d\) is the distance of the source from that end of the cable for which \(\sin X = 0\) if \(d = 0\), and \(A\) is the effective value of amplitudes when \(d = L\).

The verification of this method was carried out on a 22 kv., one-conductor, 500 000 cir. mils cable, which was connected to a 60-cycle 2300-volt transformer, 3" in Fig. 24a. The length of the cable was 7.48 m. Its natural fundamental frequency at a quarter-wave-length mode of oscillation was found to be \(f = 5390\) kc. (\(\lambda = 55.65\) m.) This was, therefore, the frequency which was chosen in this case for locating the sources of ionization.

For this purpose the cable had sixteen equidistant holes bored through the sheath and through the paper dielectric. Spark-over from conductor to sheath was prevented by bakelite bushings. An artificial source of ionization, made of a disc of lithographic stone pressed between two nickel electrodes, one of which was in the form of a sharp edged ring, the other in that of a disc with a plug attached in the center, could be inserted in any one of the holes. The disc electrode made contact with the cable conductor and the ring electrode with the sheath. At a voltage of about 1500 volts applied to the cable a visible corona set in between the ring electrode and the lithographic stone. This discharge gave rise to oscillations in the cable system. The effective currents measured by the indicator, 10, depended on the location of the hole in which the artificial source of ionization was inserted.

Curve \(E_{1}\) in Fig. 24b shows the theoretical readings which should be obtained with the thermionic voltmeter, 10, when the receiver, 9, is connected to the left-hand end of the cable, that is with the knife
switch, 11, connected to point 2'. Curve $E_2$ represents the theoretical readings when the receiver is connected to the right-hand end of the same cable, to the point 2".

If the left-hand end of the cable is chosen as origin, $E_1$ has the character of a sine wave, and $E_2$ that of a cosine wave. The curves intersect in a point $F$ corresponding to half the length of the cable, indicating that at this point the deflections of the meter would be alike. To the left of this point $F$ the relation $m = E_1/E_2 < 1$ holds, while to the right of the point $F$ the reciprocal values $m > 1$ apply.

In Fig 24c the results of the actual measurement of $m$ as a function of the position of a source of ionization are represented by a curve, and the corresponding calculated values are plotted for comparison.

The curve for measured values of $m$ shows a shift by a length corresponding to $1/16$ of the length of the cable. The general character of the curves is closely alike and confirms the correctness of the principle. The discrepancy can be ascribed to failure in adjusting the circuit constants with sufficient exactness so as to impress the node precisely at the end of the cable.

Tests have been made at high potentials on a cable, which also verify the underlying theory. So far, however, the location of the source can be determined only roughly. The difficulty is caused mainly by the fact that often more than one source of ionization is active in a cable subjected to high potentials.

31. Summary of Results.—The results of this investigation may be summarized as follows:

(1) The assumption of the existence of surges and oscillations due to ionization in dielectrics has been experimentally verified.

(2) These oscillations were studied and utilized in the development of apparatus for detecting and measuring the relative intensity of ionization.

(3) Characteristic curves were obtained which correlate the applied voltage and the effective values of oscillations due to ionization. These curves make possible the study of the effect of applied voltage on certain properties of dielectrics and especially of cables.

(4) The existence of a time effect in connection with the intensity of oscillations due to ionization and the applied voltage has been ascertained.

(5) It was found that the time effect is characteristic of the quality of a cable in regard to impregnation and to a property which tends to shift the voltage at which copious ionization sets in.
Ionization in a cable can be detected by radio-engineering methods, utilizing the electric impulses which ionization produces.

A large range of frequencies was used in designing the apparatus. Frequency ranges as high as 30,000 kc. and as low as 100 kc. were tried and all gave similar results. Also audio-frequencies of about 2 to 5 kc. have been utilized in a great number of investigations on cables.

The radio-frequency oscillations produced by ionization were utilized in three different ways. The first method was to amplify the magnitude of modulated radio-frequency currents and measure their effective values with thermoelectric and thermionic instruments. The second method was to apply intermediate detector action, and to measure amplified group frequency. The third method was to suppress the radio frequencies by rectification, and to select definite group frequencies for measurement.

The utilization of lower group frequencies necessitated the use of special bridge arrangements for balancing the charging current. On the other hand the application of higher frequencies required special provision for guarding against interference from outside electromagnetic fields.

The curves obtained with both types of apparatus are similar in character. They give the relation between the voltage applied to the cable and the intensity of the sum of the oscillations produced in a cable when ionization takes places.

Both types of surge-measuring apparatus indicate the existence of bubbles and airpockets in a cable, if provision is made to prevent discharges taking place in transformers, condensers, and other parts of the circuits connected with the cable. They may thus be used as impregnation-testing apparatus.

An application was made of the radio-frequency method to the testing of samples of paper moving between rotating nickel electrodes in air. Characteristic curves were obtained showing that the voltage at which corona discharge sets in, and the relative effective values of oscillations produced, are indicative of the character of the surface and texture of the paper.

Methods have been devised for locating sources of ionization in cables. The underlying principles were verified by a number of experiments. Their applicability for testing of cables, however, was found to be limited to special cases.

32. Conclusions.—The following conclusions may be drawn from these results:
(1) In the oscillations associated with ionization in the form of discharges in dielectrics, especially in cables subjected to high alternating potentials, a clue has been discovered which makes possible the detection of early stages of deterioration.

(2) The various methods developed for measuring these oscillations have laid the foundation for the study of composite dielectrics from a new point of view, namely, that of correlating the processes which take place in dielectrics with the frequencies, amplitudes, and wave form of these oscillations.

(3) With the embodiment of these methods into apparatus new tools have been added to the equipment of research and testing laboratories. These apparatus may serve to control the processes of manufacturing condensers and cables, to safeguard their operation, and to assist in systematic work towards improvements.
When high alternating voltage is applied to insulation it is believed that the temporary alteration in the structure of the material will increase its conductivity more in one direction than in the other, particularly if the voltage gradient is not uniform through the thickness of the insulating medium. This is recognized as the phenomena of rectification in the case of cold cathode discharges in gases. Accordingly, arrangements were made to superimpose a direct current potential of 2000 volts upon the high alternating testing potential applied to cable insulation, and to use a sensitive D'Arsonval galvanometer, protected by a suitable arrangement of choke coils, condensers, and spark gaps, to measure the direct current flowing in the alternating current test circuit. It was found that, as the testing voltage was raised, some cables showed an appreciable leakage direct-current flow, this current increasing with the test voltage. However, no positive coordination of this leakage direct current with the deterioration of the cable itself could be obtained. In testing single layers of samples of cable paper this test did show interesting results. Quite an appreciable leakage direct current was obtained, and most significant of all was the fact that as a piece of cable paper was allowed to absorb moisture
from the air the direct leakage current obtained with a fixed alternating test voltage increased. Figure 25 shows the results of a typical test. The curve marked June 28 shows conductivity before the sample absorbed any moisture from the air. When the sample absorbed moisture for 20 hrs. the test gave results shown by the curve marked June 29. Further exposure resulted in the curve marked June 30. The temperature and humidity was nearly constant during the three days of test.


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