

The Corona Voltmeter and the Electric Strength of Air

A Natural Secondary Standard of Voltage

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An improved form of the corona voltmeter is described. Precision measurements of crest values of high alternating voltage taken in the high-tension circuit are compared with the indications of the corona voltmeter.

The law of corona has been determined to a higher degree of accuracy, and a modification in the form of the law as heretofore accepted is revealed.

As based on the precision voltage measurements the corona voltmeter is proposed as a natural secondary standard of high voltages. Its advantages as a standard, and its practical operation are described.

I. INTRODUCTION

THE corona voltmeter is an instrument for measuring accurately the crest values of high alternating voltages. It makes use of the fact that corona forms on a clean round wire in air at a sharply marked definite value of voltage dependent in a simple relation on the density of the air. The range of the instrument using a single wire is extended to wide limits by enclosing the wire and varying the density of the air.

The essential elements of the instrument are a central rod or wire on which corona forms, an outer concentric cylinder forming the opposite terminal, an outer air-tight containing case in which the air pressure may be varied, and convenient means for determining accurately the first appearance of corona. The principle and method of operation, including the use of gaseous ionization and sound as corona indicators, and two earlier forms of the instrument have been described in an earlier paper.¹ An improved type of the instrument for voltages in the neighborhood of 150,000 volts is described below and shown in Figs. 9 and 10.

The principal object of this paper is to describe a series of experiments in which the values of corona forming crest voltages have been determined by precision measurements made in the high-voltage circuit. Also to show that the law followed is so definite, and the indications of the instrument so constant, that it constitutes not only an accurate measuring instrument, but also through the results of the present investigation, a natural secondary standard of high voltage possessing many advantages over others at present in use.

An important result of the work is the discovery of an interesting modification of the law of corona formation.

The various precautionary and check measurements

staken to ensure the accuracy of the final readings constitute in themselves prime evidence of the accuracy of the corona as a measure of voltage, and also of its constancy and reliability in operation in the corona voltmeter. In addition some further notes on the operation of the voltmeter are given towards the end of the paper.

II. THE CORONA AS A STANDARD OF VOLTAGE

Two striking properties of the high-voltage corona in air have led to the suggestion of its use for the measurement of voltage and to the development of the corona voltmeter. The first is the remarkable constancy of the value of voltage at which, under fixed conditions, the corona appears on a round wire or rod; and the second is the simplicity of the law connecting the critical or corona-forming voltage with the diameter of the rod and the condition of the surrounding gas.

The former of these properties has been noted by a number of observers and in particular by one of the present authors in the first of a series of papers on the electric strength of air,² and again especially in a paper on the corona voltmeter.¹ Using a clean round rod and the best type of portable voltmeter in the low-tension circuit, on repeated raising and lowering of the voltage corona appears sharply at exactly the same value throughout, that is, at a value constant to within say one-tenth or one-quarter per cent. Under more refined conditions the constancy is shown to be even closer.

The empirical law connecting the critical or corona-forming voltage gradient E in kilovolts per cm., at the surface of the wire, the radius of the wire r in centimeters, and the relative density of the gas δ , is usually stated in the form

$$E = A \delta \left(1 + \frac{B}{\sqrt{\delta} r} \right) \quad (1)$$

A more convenient form for our present purposes is

$$E/\delta = A + \frac{B'}{\sqrt{\delta} r} \quad (2)$$

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1. A bibliography of all references will be found at the end of the paper.

which gives a linear relation between E/δ and $\frac{1}{\sqrt{\delta r}}$; obviously $B' = A B$.

The value of δ is given by

$$\frac{3.92 p}{273 + t} \quad (3)$$

in which p is the pressure in centimeters of mercury and t is the temperature in degrees centigrade.

The above relatively simple relations have now been corroborated by a number of observers and with quite close agreement as to the values of A and B . The influence of the diameter of the wire on corona-forming voltage was first emphasized by H. J. Ryan,³ who was also the first to point out the possibilities of the corona as a voltage indicator. The exact nature of this influence and the presence of the two constants A and B were first shown by one of the present authors.⁴ The precise influence of the density of the air was first shown by F. W. Peek, Jr.,⁵ in one of the most important contributions yet made to the knowledge of the subject. Moisture in the air has no effect on the critical intensity.²

The form of the above law is the same for both continuous voltages and crest values of alternating voltages. With continuous voltage, however, there are appreciable differences in the values of the constants A and B , as between positive and negative corona-forming wire, the form of the law in each case remaining the same.⁶ One of the most important results of the present work is the fact that this difference between positive and negative corona is reflected in the alternating corona, and that the law as given by formulas (1) and (2) must be modified. Briefly stated, the modification consists in the use of different values of the constants A and B above and below a definite

value of $\frac{1}{\sqrt{\delta r}}$, the form of the law, however, remaining the same in each case, as will be seen below.

It has generally been accepted that within the commercial range frequency has no influence on the corona-forming voltage. Observations with the accurate methods use in the experiments show a slight influence of frequency within the range mentioned.

Since corona formation through the constancy of its appearance and the simplicity of its law offers a ready means for the measurement of high voltage, it is important that the constants A and B be determined accurately. When this is once done, such an instrument as the corona voltmeter has a calibration dependent only on its dimensions, and so constitutes a natural secondary standard of voltage.

Nearly all determinations of alternating corona voltages have been based on observations of voltage and crest factor taken in the low-tension circuit, and computed from transformer ratios. As is well known, this method is subject to serious errors on both accounts.

If therefore advantage is to be taken of the constancy of corona voltage as a standard and as a method of measurement, it is necessary that the constants A and B be determined by direct measurement in the high-voltage circuit of the crest values of corona voltage, and to a relatively high degree of accuracy in terms of accepted standards. These determinations once made over a sufficiently wide range of values of δ , corona formation, by reason of the simplicity of the relation of formula (1), and its freedom from outside influence, becomes a far more reliable standard than the sphere gap, the potential transformer, or any other standard at present proposed.

III. PRECISION MEASUREMENT OF CORONA CONSTANTS

For the determination of the values of A and B we must (1) measure accurately the crest value of alternating voltage at which corona appears, (2) be able to observe to as small a difference of voltage as possible the first appearance of corona, and (3) measure δ and provide a wide range of its values.

The crest value of voltage (1) may be determined from the average value of the charging current of an air condenser in the high-voltage circuit. This method first used by Chuob and Fortescue,⁷ was modified by Whitehead and Gorton,⁸ and is now further improved as described below.

For (2) the accurate observation of the first appearance of corona, two methods are used,—(a) the telephone for detecting the sound of the corona, and (b) the galvanometer for detecting the conductivity of the air caused by the corona. Both methods are used in the corona voltmeter and are described in detail in an earlier paper;¹ further observations are reported below. The visibility of corona is neither convenient nor accurate as a means of determining its first appearance.

The corona voltmeter with its air-tight outer casing provides the method (3) for the observation of δ , the relative air density, and its variation over a wide range. Pressure and temperature are read and the pressure may be adjusted to any chosen value, thus permitting setting for any value of δ .

III. 1. MEASUREMENT OF VOLTAGE

If an alternating voltage of maximum value E volts and frequency f be impressed on a condenser of capacity C , the average charging current is

$$i = 4 f C E; \quad (4)$$

if f and C are known and i is measured E the maximum for the maximum value of charging voltage is determined. When used for the high values of voltage pertaining to corona formation, one side of the condenser is grounded and the charging current measured in the ground connection. Since the condenser must withstand the full maximum voltage and have no dielectric or other loss, the most convenient form is that of concentric cylinders with wide radial separation, and

with air as dielectric. This, however, means small capacity per unit axial length, and small total capacity if the outside dimensions are to be kept within reasonable limits. Consequently the use of this method involves the use of a large air condenser of small capacity and a determination of the value of the capacity.

Chubb and Fortescue⁷ constructed a cylindrical condenser consisting of two wooden forms, each covered with sheet metal surfaces. The diameters of the two members were 60 cm. and 162.8 cm. respectively, and the outer member was provided with two flaring guard ring ends. The capacity between the inner member and the central section of the outer member was calculated as 2.65×10^{-11} farad, no attempt at measurement being made, doubtless owing to the difficulty of measuring so small a value. Chubb and Fortescue measured the charging current in the ground connection of the central section of the outer member of the condenser by means of a d'Arsonval galvanometer and a synchronous commutator connected as a shunt suppressor.

In the present experiments the same type of condenser is used, *i. e.*, the cylindrical guard ring type with voltage applied to the inside member and charging current measured in the ground connection of the central section of the outside member. The capacity, however, was measured, as described below. Further, the charging current was measured by the use of two rectifying kenotrons, thus obviating the irregularities and uncertainties of the synchronous commutator. The commutator was, however, frequently used for comparison and certain auxiliary tests.

A diagram of the principal connections is shown in Fig. 1. Voltage is applied from the transformer A to

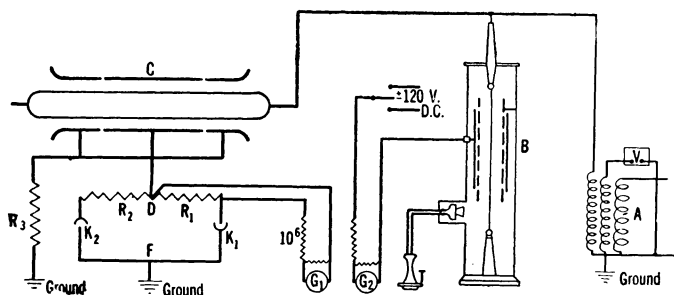


FIG. 1—PRINCIPAL CONNECTIONS

the corona voltmeter B and the air condenser C. The charging current of the central section of the latter passes to ground in alternate half waves through the resistances and kenotrons R_1 , K_1 , and R_2 , K_2 . The currents in R_1 and R_2 are therefore pulsating but unidirectional and so may be read by a continuous-current instrument in series or in shunt, as shown in Fig. 1, G_1 being a sensitive d'Arsonval galvanometer critically damped. A second galvanometer G_2 and a telephone T are used to detect the first appearance of corona on the central rod of the corona voltmeter as described below. A number of auxiliary circuits

have been omitted from Fig. 1 and will be referred to in connection with the various measurements.

We will now describe in turn the methods of measuring the charging current, the frequency, and the capacity of the condenser, together with the precautions taken, the limits of accuracy, and all leading to the determination of the value of voltage present on the first appearance of corona in the corona voltmeter B.

(a) *Charging Current.* Balance in kenotron circuit. In formula (4) i is the average value of the charging current. In Fig. 1 all positive half waves will pass through one kenotron and all negative half waves through the other. The d'Arsonval galvanometer in shunt to the resistance R_1 will therefore receive a

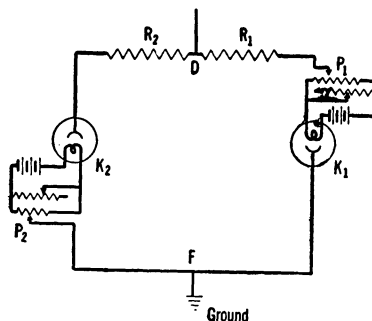


FIG. 2—KENOTRON CONTROL

tion the galvanometer will read one-half the average value of the charging current. In view of the foregoing it is of first importance that when no charging current is passing there be no continuous current flowing in the closed circuit $K_1 D K_2 F$. This condition was realized by the adjustment of the point of connection to the filament exciting circuits of the kenotrons as indicated at $P_1 P_2$ in Fig. 2. This in pulsating unidirectional current and show a deflection proportional to its average value. Obviously the combination may be calibrated directly in terms of continuous current in R_1 and in terms of such a calibration effect interposes a small adjustable e. m. f. counter to the normal direction of conductivity, at each kenotron. If this is not done the normal leak of electrons from the filament, particularly at its negative end, results in a small current in the circuit $K_1 D K_2 F$. In making these adjustments the galvanometer G_1 was connected first in series in the circuit $K_1 D K_2 F$ and then between the points D and F , repeating with adjustments at P_1 and P_2 until both readings are simultaneously zero. After balancing the kenotron circuit, as above, it was connected into the condenser ground circuit and with alternating voltage on was further balanced for equal resistance in the two branches by adjustment for zero current in the galvanometer connected across $D F$; on removal of the alternating voltage the circuit $K_1 D K_2 F$ is still balanced. Without these adjustments a small error is possible, the galvanometer G_1 in the connection of Fig. 1 showing at times a deflection of 0.5 mm.; after

the adjustments mentioned no deflection can be detected.

(b) *Influence of Wave Form.* The use of the kenotrons for rectifying the charging current introduces an error if the wave form of voltage is not smooth, i. e., if it has more than one maximum in each half wave. In this case there is a reversal of condenser current following every such maximum or elevation in the wave and since the kenotron passes current in only one direction, this reverse current passes through the opposite kenotron and so does not contribute to the galvanometer reading. Similarly in the next half cycle the reverse current is recorded in the galvanometer as positive. Thus due to both half waves the result is a galvanometer reading higher than that corresponding to the average charging current.

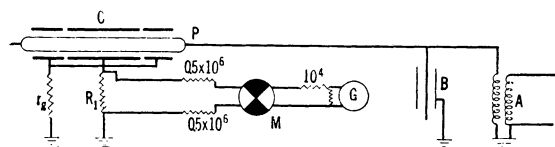


FIG. 3—MEASUREMENT OF CONDENSER CHARGING CURRENT WITH SYNCHRONOUS COMMUTATOR

The generator used in the experiments has a surface wound armature and shows a smooth wave on an oscillogram. The inserts of Figs. 4 and 5 show the voltage waves as taken from a low-tension tertiary coil on the transformer *T*, Fig. 1, for series and parallel connections respectively of the two primary coils. In order, however, to answer this question definitely, the wave form of the voltage at the high-tension terminals was taken by the method indicated in Fig. 3, in which

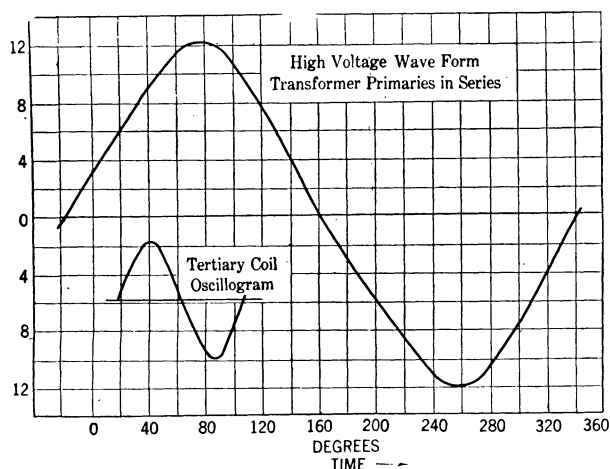


FIG. 4—HIGH-VOLTAGE WAVE FORM

M is the synchronous comutator connected as full rectifier or as half-wave suppressor. In this method first pointed out by Bedell,⁹ for any position of the brushes the galvanometer reading is proportional to the average value of the charging current for any particular half-wave interval between the brushes, and this in turn is proportional to the instantaneous value

of the voltage on the condenser. Figs. 4 and 5 show the wave forms so taken for series and for parallel connections respectively of the transformer primary coils, which together with Table I, giving a section from the complete sheet of readings, indicate the conditions of accuracy. The mean values of right and left readings of the galvanometer are taken in all cases in order to eliminate a slight right and left dissymmetry probably due to electrostatic disturbance, generally noticeable in the very sensitive galvanometer, in spite of most careful screening. For obvious

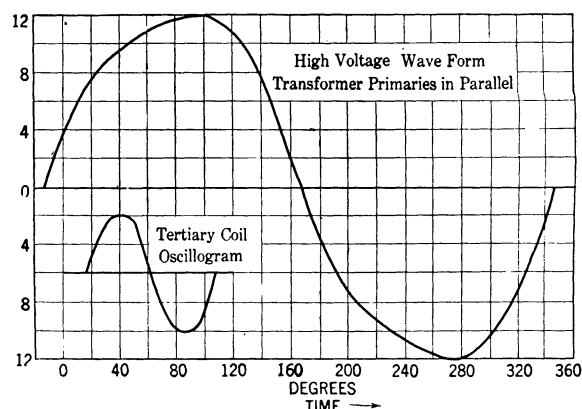


FIG. 5—HIGH-VOLTAGE WAVE FORM

reasons this disturbance is more pronounced in the half-wave measurements in which the galvanometer is used as a half-wave suppressor.

The curves of Figs. 4 and 5 were each taken at the critical or corona-forming voltage using the same corona rod and equal values of air density. Although there are noticeable differences in wave form and in

TABLE I.
WAVE FORM OF HIGH VOLTAGE

Brushes degrees	Galvanometer deflection cm.					
	Full wave			Half wave		
	Left	Right	Mean	Left	Right	2 X Mean
22.5	7.80	7.76	7.78	3.72	4.10	7.82
30	8.41	8.47	8.44	4.09	4.39	8.48
37.5	9.14	9.10	9.12	4.42	4.70	9.12
90	11.91	11.87	11.89	5.87	6.03	11.90
120	10.68	10.60	10.64	5.32	5.30	10.62

the values of effective voltage at the terminals of the tertiary coil (38 volts and 34.5 volts respectively) it is seen that the maxima of the two waves have very closely the same values. Further evidence that no error was present due to irregularities of wave form is found below in the comparison of corona readings taken with kenotrons and with commutator.

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