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UNEDITED ROUGH DRAFT TRANSLATION

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English Pages: 15

Source: Izvestiya Akademii Nauk SSSR, OTN,
Energetika i Avtomatika, No. 2,
1962, pp. 47-54.

SC-1578
SOV/24-62-0-2-1/12

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A METHOD FOR PROBE STUDIES OF A D-C CORONA FIELD USING AN OSCILLOGRAPH

(Moscow)

The probe method of studying a field of d-c corona discharge [1] necessitates the making of a great number of measurements and therefore a great expenditure of effort and time for the measurements themselves, as well as in processing their results. This gives rise to the problem of automation of the measurements, which can substantially widen the possibilities of the practical use of the method for detailed study of not only relatively simple, but also more complicated fields for systems of conductor-conductor type electrodes, split conductor in a cylinder or against a surface, etc.

A possible course for automation is the use of an oscillograph for recording the probe characteristics. A procedure for probe measurements using an oscillograph is examined in the present work.

A result of probe measurements at a given point of an electrical field of d-c corona is the volt-ampere characteristic of the probe (Fig. 1), which makes it possible to determine the potential of the field U_0 (by the point of intersection of the extension of the linear part of the characteristic with the voltage axis) and the product of the ionic mobility and the space-charge density $k\rho$ (by the slope of the linear part of the characteristic and the capacitance of the probe).

The capacitance of the probe is determined only approximately [1]. Therefore, it is desirable to seek a method of measurement in which it is not necessary to know the capacitance of the probe to determine $k\rho$. The use of an oscillograph for measurements, as will be seen, allows this problem to be solved, and also the capacitance of the probe to be determined experimentally.

In order to record the probe characteristics with an oscillograph, it is necessary to assign to the probe a time-variable voltage which satisfies certain requirements.

To avoid affecting the discharge to be studied, the probe potential in measurements must not substantially deviate from the field potential U_0 at the point to be studied. This requirement can be satisfied if the probe voltage consists of a constant component which is close in magnitude to U_0 and an alternating component whose amplitude is limited by the indicated requirement.

The alternating component of the probe voltage, besides having an amplitude limitation, must also satisfy certain frequency requirements.

When an alternating component is present in the probe voltage, the probe current will contain two components: an ion current $i_{p\ ion}$ and a displacement current $i_{p\ d}$.

The amplitude of the displacement current is proportional to frequency; the amplitude of the ion current is not a function of frequency. Therefore, by proper choice of the frequency of the alternating component of the voltage, it is possible to obtain any required ratio between the current components, i.e., the displacement current can be made considerably lower than the ion current, commensurate with it, or even considerably higher.

To determine the ratio between the ion and capacitive currents of the probe, let us assume that the alternating component of the voltage is sinusoidal and that its amplitude is $m\Delta U_0$, and the magnitude of the constant component is equal to U_0 (see Fig. 1), i.e.,

$$U(t) = U_0 + m\Delta U_0 \sin \omega t. \tag{1}$$

Let us also assume that when the alternating component of the probe voltage is sinusoidal, the displacement current is also sinusoidal, i.e., let us assume that the capacitance of the probe is constant. In this case the displacement current is determined by the expression

$$i_{p\,d} = \omega m q_{o\,p} \cos \omega t \tag{2}$$

where $q_{op} = 4\pi\varepsilon_0 r_p E_{po}$ is the surplus charge of the probe; E_{po} the strength of the electrical corona field where the probe is placed; and r_p the radius of the probe.

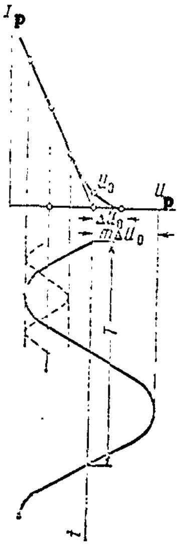

Fig. 1. Volt-ampere characteristic of probe.

Thus the amplitude of the displacement current

$$I_{p\,d} = \omega m 4\pi\varepsilon_0 r_p E_{o\,p} \tag{3}$$

The amplitude of the ion current (see Fig. 1) is

$$I_{p\,ion} = m\Delta I_0 = m\pi 4 r_p k_0 E_{p0} \tag{4}$$

By using expressions (3) and (4), we find the ratio of the amplitude of the ion current to the amplitude of the displacement current

$$n = \frac{I_{p.ion}}{I_{p.d}} = \frac{\text{[illegible]}}{\text{[illegible]}} = 18\cdot 10^{11}\frac{k\rho}{f} \qquad (5)$$

where f is the frequency of the alternating component of the voltage.

The form of the volt-ampere characteristic of the probe on the oscillograph screen is determined by the value of n, which is a function of the space-charge density at the point being studied and of the frequency of the alternating component of the probe voltage. By changing the frequency, n can be made greater than, equal to or less than one. Let us examine these three cases.

When $n \gg 1$, the ion current of the probe is considerably greater than the displacement current. In this case the volt-ampere characteristic on the oscillograph screen will have the form of that shown in Fig. 1. Thus the volt-ampere characteristic of the probe can be obtained on a single oscillogram, which with the usual method of measurement is constructed by points obtained as a result of a great number of individual measurements.

For the outer zone of d-c corona, $k\rho = 10^{-12}$ to 10^{-13}. In accordance with this, in order to fulfill the condition $n \gg 1$, the frequency of the alternating component of the probe voltage must be considerably less than 1 cps. Therefore, a special source of low-frequency voltage is required for making oscillograms of the probe characteristics.

In the case of $n \simeq 1$, the shape of the volt-ampere characteristic will depend upon in what range the probe voltage varies. The most simple shape (ellipse) of the characteristic will occur if the range of variation of the voltage is within the limits of the linear part of the volt-ampere characteristic of the probe (see Fig. 1). This condition is fulfilled when

$$U(t) \leqslant U_0 - m\Delta U_0 + (m-1)\Delta U_0 \sin \omega t \tag{6}$$

In this case the expression for the total probe current will have the form

$$i_{\mathrm{p}}(t) = I_{\mathrm{p}} - I_{\mathrm{p\,ion}} \sin \omega t + I_{\mathrm{p\,d}} \cos \omega t = I_{\mathrm{p}} - I_{\mathrm{p\,d}} \sin (\omega t - \varphi) \tag{7}$$

where I_p is the constant component of the ion current of the probe; $I_{p\ \mathrm{ion}}$; $I_{p\ d}$; $I_{p\ m}$ are the amplitudes of the alternating component of the ion current, displacement current and total alternating component of the probe current; φ is the phase angle of the alternating component of the probe current relative to the alternating component of the probe voltage.

Taking into account that

$$n = \frac{I_{\mathrm{p\,ion}}}{I_{\mathrm{p\,d}}} = \frac{k\rho}{\varepsilon_0 \omega} = \frac{1}{\sin \varphi} \tag{8}$$

we find

$$k\rho = \frac{\varepsilon_0 \omega}{\sin \varphi} \tag{9}$$

Thus, determining the angle φ by using the oscillograph, we can find $k\rho$. Here it is not necessary to know the capacitance of the probe. What is more, this method allows us to determine experimentally the capacitance of the probe in a d-c corona field. The latter can be found by dividing the slope of the linear part of the volt-ampere characteristic (see Fig. 1) by the value of $k\rho$ determined by the above method.

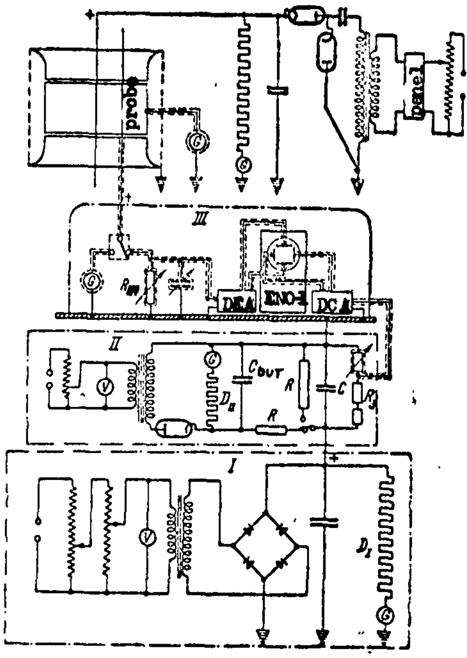

Fig. 2. Schematic diagram of experimental apparatus.

In a d-c corona field ($k\rho = 10^{-12}$ to 10^{-13}), in order to fulfill the condition $n \approx 1$ the frequency of the alternating component of the probe voltage must be from 1 to 0.1 cps, i.e., as in the first case ($n \gg 1$) it is necessary to have a special low-frequency voltage generator.

If the frequency of the alternating component of the probe voltage is such that $n \ll 1$, then, approximately, we can assume that the alternating component of the probe current is equal to the displacement current, i.e.,

$$I_{p\,m} = I_{p\,d} = \omega C U_m \tag{10}$$

where U_m is the amplitude of the alternating component of the probe voltage.

Hence

$$C = \frac{I_{\mathrm{pm}}}{\omega U_{\mathrm{M}}} \qquad (11)$$

Thus it is possible to determine the capacitance of the probe by measuring from oscillograms the amplitudes of the probe current and the alternating component of the probe voltage. In addition, the rate of change of the voltage must be known. In a d-c corona field, in order to fulfill the condition n << 1, the frequency must be euqal to several tens of cycles, i.e., voltage of industrial frequency can be used.

This method of oscillographic measurement was checked experimentally; the schematic of the experimental apparatus is shown in Fig. 2. A number of the circuit components (measuring capacitor with a diameter of 1.92 m, the probe and probe platform with measuring cabin) were described in detail in articles on the probe study of an a-c corona field [2, 3]. The other circuit components (in the voltage-supply part), naturally, differ from those described earlier [2, 3], since here d-c corona is being studied.

The d-c high voltage supply for the probe is from rectifier I (Fig. 2), the output voltage of which is measured by using high-voltage resistor D_I and a galvanometer. A low-frequency voltage generator II, mounted inside the measuring cabin, is connected to the probe circuit in series with the d-c source. All the measuring apparatus of the probe circuit III is also installed in the cabin. The generator and measuring apparatus operate at high potential, therefore they are supplied through an insulating transformer.

The output voltage of the low-frequency generator must be on the order of several (up to 10) kilovolts. It is rather difficult to build such a generator having a sine-wave voltage. It is much simpler to build a saw-toothed voltage generator (Fig. 3). The low-frequency voltage is created by charging capacitor C through resistor R_1 from d-c source $U_{0\,\text{gen}}$ and then discharging it through resistors R_2 and R_3. Transition from charge to discharge is accomplished by switch P, the moving contact of which is alternately connected to fixed contacts 1 and 2.

For periodic operation of the switch with equality of the time constants of charge and discharge ($\tau_{\text{ch}} = \tau_{\text{dch}} = \tau$) of capacitor C, the output voltage of the generator is described by the equations

for charge

$$U_{C\text{p}} = U_{\text{gen}}[1 - M\exp(-t/\tau)] \tag{12}$$

for discharge

$$U_{C\text{p}} = U_{\text{gen}} M \exp(-t/\tau)$$
$$M = \frac{1-\exp(-T/2\tau)}{1-\exp(-T/\tau)} \tag{13}$$

where T is the period of the operating cycle of the switch

$$U_{\text{gen}} = U_{0\,\text{gen}} \frac{R_3}{R_1 + R_3}$$

It is natural that in the case of a saw-toothed alternating component of the probe voltage, the expression for the ratio of the ion current of the probe to its displacement current will differ from the ratio for sine-wave voltage.

Using Eqs. (12) and (13) and letting

$$U_{\text{gen}} = 2m\Delta U_a \tag{14}$$

we obtain for the amplitude of the displacement current

$$I_{\text{p d}} = \frac{2}{\tau}\pi m 4 r_{\text{p}} \varepsilon_0 E_{\text{p}0} M \tag{15}$$

The amplitude of the ion current

$$I_{\text{p ion}} = 4\pi m r_{\text{p}} k \rho E_{\text{p}0} M \tag{16}$$

Therefore, the ratio of the amplitude of the ion current to the amplitude of the displacement current

$$n = k\rho / \left(\varepsilon_0 \frac{2}{\tau}\right) = 18 \cdot 10^{11}\, k\rho / \left(\frac{1}{\pi\tau}\right) \tag{17}$$

This equation is similar to Eq. (5) for sine-wave voltage, and differs from it only in that here we have in the denominator $1/\pi\tau$ instead of $\underline{f}$. Expression (17) allows us to select a value of τ, and, therefore, values of R and C for the generator, which will ensure the required value of $\underline{n}$ for measurements.

The period of the operating cycle of the switch T must conform to τ. This is necessary in order that the amplitude of the output voltage of the generator be close to the magnitude of the d-c supply of the generator $U_{0\,\mathrm{gen}}$, i.e., for sufficiently complete use of $U_{0\,\mathrm{gen}}$. This requirement, for all practical purposes, is satisfied by the relation

$$T \geqslant 6\tau \tag{18}$$

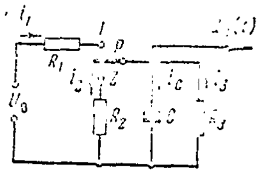

Fig. 3. Circuit of low-frequency saw-toothed voltage generator. $U_{0\,\mathrm{gen}}$ is the supply voltage to the generator; P is a switch.

The switch, which is one of the basic parts of the generator, must satisfy still another series of requirements. First of all, its contacts when open must withstand a relatively high voltage (on the order of 10 kv). In addition, it must have a switching time which is sufficiently small in comparison with the period of the switching cycle. And, finally, the switch must permit regulation of its operating period within sufficiently wide limits.

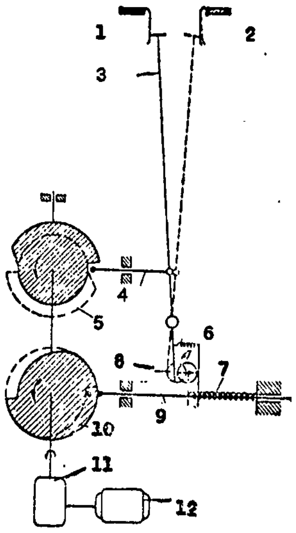

Fig. 4. Schematic of switch. KEY: 1) contact 1; 2) contact 2; 3) switch P; 4) guide lever 1; 5) cam 1; 6) spring 1; 7) spring 2; 8) free-running wheel; 9) guide lever 2; 10) cam 2; 11) pinion drive; 12) electric motor.

The schematic of a switch satisfying these requirements is given in Fig. 4.

The switch operates as follows. A Warren-type electric motor, with which the speed of the driven shaft can be varied, turns cams 1 and 2, along whose surfaces slide guide levers 1 and 2, which are connected to the moving contact.

In the position shown in Fig. 4, spring 1 pushes the moving contact to fixed contact 1. The moving contact will be in that position until guide lever 2, by the action of cam 2, eases the tension of spring 1. This occurs one half-turn (t = 1/2T) after the position shown in Fig. 4. At this moment, spring 2 pulls guide lever 2 and the lever with wheel A toward the small arm of the moving contact, which practically instantaneously switches to position 2 and then is held there by cam 1 and guide lever 1. A certain time after switching, guide lever 2 and spring 2, by the action of cam 2, are returned to the starting position.

At the end of another half-turn, guide lever 1, by the action of cam 1, frees the moving contact, which is returned to starting position 1 by spring 1. The switching process is repeated periodically.

When making measurements, the probe is connected to a voltage source U_p through measuring resistor R_{meas} (see Fig. 2), which shunts a small capacitor C_{meas}. The latter was necessary to eliminate from the measurement circuit the high-frequency components of the corona current.

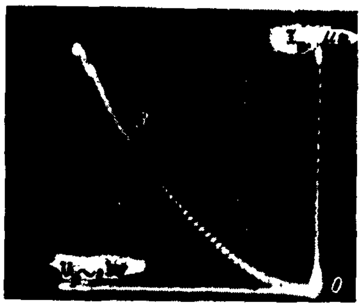

Fig. 5. Oscillogram of volt-ampere characteristic of probe at n << 1 for r = 8 cm, $U/U_0 = 2$.

The current through the measuring resistor is on the order of 1μa or 10μa. Therefore, an oscillograph recording of the voltage drop through R_{meas}, which is proportional to the probe current, is impossible directly. Because of this, a d-c amplifier (DCA) was used. A similar amplifier was used in the voltage circuit, in order to ensure symmetry of the measuring circuit.

An ENO-1 oscillograph was used for recording. Its tube had high persistence, which made measurements easier, since it allowed visual observation of the curves on the screen. This is especially important when adjusting the measuring apparatus.

Experiments with this measuring apparatus were made in a cylinder with a diameter of 1.92 m on smooth polished conductors with diameters of 3.09 mm and 1.47 mm for positive and negative corona and for various values of overvoltage (from 1.1 to 2).

The results of measurements using the oscillograph were compared with data from measurements by the usual method (by points), and also with the results of calculations for a corona field by known accurate formulas [4].

A typical oscillogram of the volt-ampere characteristic of the probe for a corona conductor with a diameter of 3.09 mm at an overvoltage of 2 when the probe was 8 cm from the conductor is shown in

Fig. 5. Since the voltage of the generator ($U_{o\,gen} \sim 10$ kv) is limited, only a part of the volt-ampere characteristic of the probe appears on the oscillogram. In order to widen the range of recording of the volt-ampere characteristic, it is possible, by varying the magnitude of the constant component of the probe voltage, to take various sections of the characteristic. These sections (whose ends overlap one another) are reproduced in the graph in Fig. 6, where experimental points obtained by the ordinary method of measurement are also given. As follows from this graph, the volt-ampere characteristic from the oscillograph coincides, for all practical purposes, with the curve of the series of characteristics found by the usual method. It should also be noted that the parameters of the individual sections of the characteristic obtained at a different value of the constant component of the voltage—the slope of the linear part of the point of intersection of its extension with the voltage axis—remain, for all practical purposes, unchanged.

The results of measurements by both methods (the ordinary method and the oscillographic method) for the conductor with a diameter of 1.47 mm at two distances from the probe (35 cm and 60 cm) for two overvoltages (1.1 and 2.0) are shown in Fig. 7. As in the previous case, an entirely satisfactory agreement of results is obtained.

A graph of the potential distribution of the electrical field, constructed with data from measurements by both methods, is shown in Fig. 8. There the calculated curve was plotted with a continuous line. The oscillograph measurements give practically the same results as measurements by the usual method, but with considerable economy of time.

Comparison of the experimental data with that calculated (by accurate formulas) shows that the agreement of the results at values of the potential of the electrical field is completely acceptable. The deviation of the experimental data from that calculated does not exceed 6%. This proves the correctness of the use of this method for determining the potential distribution in corona gaps for d-c corona.

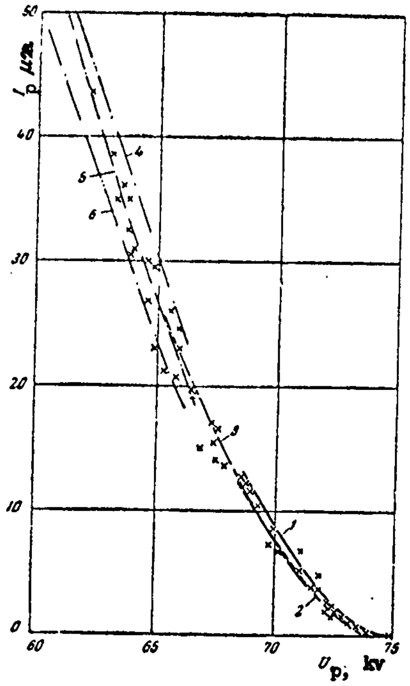

Fig. 6. Volt-ampere characteristic of probe in field of corona-producing conductor with 3.09-mm diameter. U_k = = 104 kv; r = 8 cm; 3-mm probe diameter.

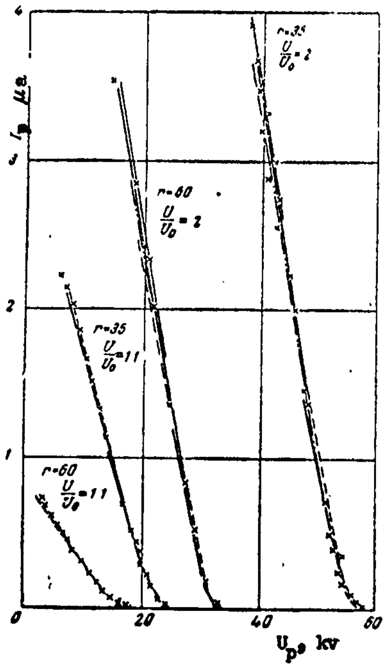

Fig. 7. Volt-ampere characteristic of probe in field of corona-producing conductor with 1.47-mm diameter.

Besides measurements of the potential distribution of the corona gap, measurements of the capacitance of the probe were also made. For this the source of low-frequency voltage II (Fig. 2) was replaced by a transformer, with which an alternating component of industrial frequency was supplied to the probe. Inasmuch as in this case $n \ll 1$, the probe current is, for all practical purposes, purely capacitive.

In order to determine the probe capacitance, the amplitude of the alternating component of the probe charge was measured with the oscillograph; wherein the resistor R_{meas} in Fig. 2 was replaced by a measuring capacitor. The ratio of the thus-measured amplitude of the charge to the amplitude of the alternating component of the probe voltage gives the probe capacitance.

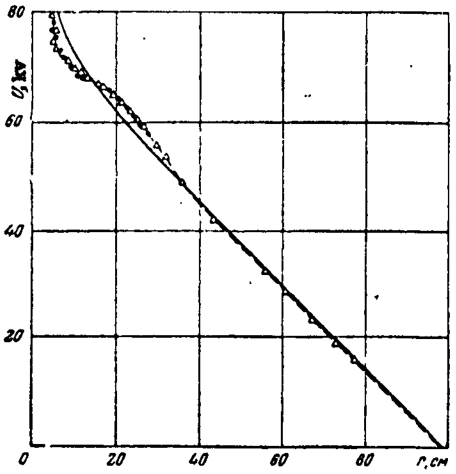

Fig. 8. Potential distribution in outer zone of corona for corona-producing conductor with 3.09-mm diameter.

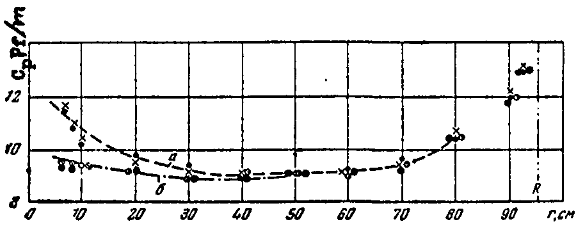

Fig. 9. Results of measurement of probe capacitance: a) relative to grounded main electrodes ($V_g = 0$; $U_{p\sim} = 2$ kv); b) in the presence of corona ($U_g = 2U_k$; $U_{p\sim} = 2$ kv)

Measurements of capacitance were made in two cases. In the first case there was no corona and the conductor was grounded. This circuit corresponds to the usually employed method for calculating probe capacitance with grounded main electrodes. In the second case the probe capacitance was measured in the presence of corona on the conductor. The voltage of the conductor in this case was equal to double the initial voltage of the corona.

The results of the measurements of capacitance at various points in the gap for these cases are shown in Fig. 9. As follows from the graph, the probe capacitance in a corona for distances of the probe from the conductor of up to 30 cm is lower than the probe capacitance relative to grounded main electrodes. An especially great difference is observed near the conductor. For example, at a distance of 6 cm from the probe to the conductor, the difference between the capacitance reaches 25%. Hence it follows that, at least for the zone of relatively small distances from the corona electrode, calculation of the probe capacitance leads to considerable error. In order to eliminate such error, the probe capacitance should be determined experimentally, using the method described here.

Submitted June 14, 1961

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