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NON-CONTACT MEASUREMENT METERS OF MICRO-SIZES ON CORONARY DISCHARGE

Abstract. The basis for non-contact cores micrometers on corona discharge is the results of studies of the high-frequency (HF) conductivity of the plasma of the corona discharge case, the method for determining the radius of curvature of the surface of the corona electrode, methods and devices for monitoring and measuring the diameter of micro wires. The investigations were carried out when a large constant voltage and a small HF alternating voltage are applied simultaneously to the discharge gap, which is carried out by supplying an additional high voltage between the electrodes with an amplitude lower than the value of the high-voltage DC voltage, while in the plasma of the corona discharge case the mode of the resonant oscillatory process is established.

Keywords: corona discharge, radius of curvature, HF conductivity, microelectrodes, crown cover, electronic component.

Introduction. The presence of a measuring probe in the ionization region of the corona discharge greatly violates the distribution of the field density and space charges. In this connection, a method for HF diagnostics of a corona discharge plasma was developed, when a low-amplitude HF alternating voltage is applied to the discharge gap. Probing with HF alternating voltage with a small amplitude makes it possible to determine the dependence of the HF conductivity on the parameters of the discharge gap and electrical characteristics of the discharge [1].

In the device, a fully formed corona discharge, i. developed corona, is subjected to an additional alternating voltage with a frequency in the range from 200 Hz to 1.5 MHz with an amplitude of 10 to 100 V. By supplying an alternating voltage with adjustable frequency and with a small amplitude to the corona-discharge gap and measuring the high-frequency (HF) conductivity of this gap, we, as it were, perform HF probing of the developed corona, similar to the method of microwave plasma diagnostics. In this case, the most sensitive to the effect of the HF-field is the corona layer (cover) of the discharge, where, in fact, all the basic ionization processes in the corona discharge occur. Therefore, it is natural to assume that the electron density (n_e) and their collision frequency with neutral conductors (v_m) in the corona cover can be determined from the values of the HF conductivity of the discharge gap by passing a small microwave field used as a probing signal.

The HF-conductivity of the corona-discharge gap is determined by the ratio of the value of the high-frequency current of the corona to the value of the applied alternating voltage. In view of the fact that the probing HF-field has a small amplitude (10÷100 V) in comparison with the main constant voltage (3÷4 kV) supporting the corona discharge, the measured conductivity is called the dynamic differential HF-conductivity (q_d) as opposed to the static, determined from the current-voltage characteristic of the corona. When measuring q_d of the developed corona in a wide range of frequencies (from 200 Hz to 1.5 MHz), a number of anomalies were found in the dependences of q_d on the probing voltage frequency, frequency location of which also depends on the magnitude of the corona current, on the atmospheric air pressure and on the dimensions of the corona and external electrodes. All measurements were carried out for a positive corona on a micro wire in a coaxial cylinder.

To exclude the effect of the geometric capacity of the discharge chamber, it is also necessary to measure the differential HF-conductivity of the chamber (q_e) in the absence of the corona discharge. To do this, we determine the bias current through a given gap at a value of the probe field voltage equal to q_d. Knowing the total current of the corona gap and the current of its geometrical capacity, it is possible to determine the current called the "compensated" current, which makes it possible to calculate the differential HF-conductivity of the corona itself (q_d-q_e).

From the experimental data it follows that the total q_d (f) in the frequency range up to 200 kHz has a plateau (minimum), the location of which depends mainly on the diameter of the outer cylinder. With increasing frequency, the q_d (f) curve slowly increases, reaching a maximum and at a certain frequency, depending on the diameter of the corona wire and the value of the corona discharge current, crosses the conductivity straight line of the geometric capacity of the discharge chamber ($q_d = q_e$), decreasing to a minimum, and then again increases [2].

Figure 1 shows the functional diagram of the device for diagnosing the plasma of a corona discharge case. The proposed device comprises two identical chambers 1 and 2 with identical in shape and size electrodes 3 and 4, a high-voltage power supply 5 and a high-frequency voltage generator 6. The signal outputs from the two current converters 7, which are the resistors, are connected to the inputs of the balance circuit of the difference voltages 8, while the output of the balanced circuit 8 is applied to one of the inputs of the microprocessor 9. The signals from the two arms (points "a" and "b") of the chambers 1 and 2 are fed to the other inputs of the microprocessor via the separation capacitors C_1. High voltage is supplied to the main corona discharge chamber 1 through the ballast resistance $R_б$, and high-frequency voltage is applied to both chambers 1 and 2 through the separation capacitors C_2. The second ballast resistance $R_б$, connected to the point "b" of the additional chamber 2, serves to create the symmetry of the two measuring arms of the device, which also leads to mutual compensation of high frequency pickups on them.

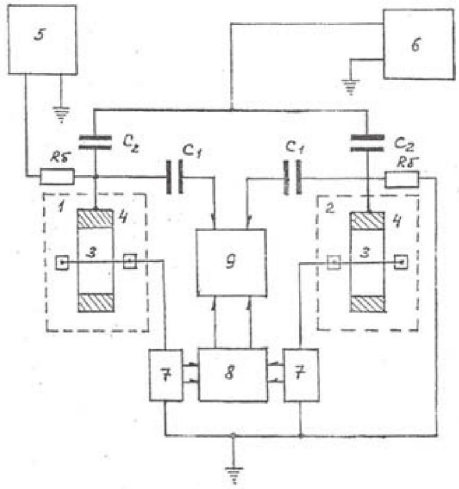

Figure 1 – Functional diagram of the device for diagnosing the plasma of the corona discharge case

When a sufficiently high voltage of negative polarity is applied to the outer cylinder of the main chamber, a corona discharge occurs between it and the corona electrode in the form of a micro wire, a stable shape of the positive unipolar corona shell is formed. When high-frequency voltage is applied to both chambers, the corona cover in the main chamber is probed, while in the additional chamber a capacitive current flows. High-frequency current components, passing through the chambers, are registered by current converters, then they enter the inputs of the balance circuit, where their differences are determined. These differences, only in the cases of q_{max}, q_0($q_d = q_e$), q_{min}, are measured by a microprocessor and simultaneously the corresponding resonant frequencies f_{max}, f_0, f_{min} are determined. When the experimental values of the characteristic points q_d and f on the q_d (f) curve are known, the microprocessor calculates the values n_e and v_m according to the given program, corresponding to the corona discharge case plasma.

Method for determining the thickness of the corona discharge case [3]. In this case, HF-diagnostics of corona plasma is also used, only with the difference that resonant oscillatory processes are created in the plasma of the corona discharge case by adjusting the frequency of the high-frequency voltage and then calculating the thickness of the corona discharge case by the calculation method.

When constructing the frequency dependence of the HF-conductivity of the corona, it was established from the arithmetic difference between the total current and the displacement current (capacitive) that the values of q_d may be greater or less than or equal to the value of the HF-conductivity of the discharge gap in the absence of a constant corona current (q_e).

For us, of greatest interest is the region when $q_d = q_e$, which is primarily the electronic component of the current in the corona discharge case. In this situation, as it were, a plasma resonance occurs in the corona case, i. e. the resistance of the corona case to the alternating voltage becomes minimal (voltage resonance) and the value of q_d is compared with q_e. It is established that the frequency f_0, at which $q_d - q_e = 0$, is very sensitive to changes in the thickness of the corona electrode and the corona discharge current. This means that f_0 will primarily depend on the velocity of the electron mean free path in the corona layer of the discharge gap.

Based on the obtained experimental data and theoretical calculations for the positive corona in the cylindrical system of electrodes, the calculated formula for the thickness of the corona layer (case) was derived:

$$L_e = \sqrt{\frac{0{,}7K_eU_0}{f_0 \ln\frac{R}{r_0}}}, \qquad (1)$$

where r_0 and R – radii of the corona and outer electrodes, cm; K_e electron mobility in the corona case, $cm^2/(B \cdot c)$; f_0 – resonance frequency at $q_d = q_e$, Hz; U_0 – alternating current voltage, V.

Thus, if the value of the corona discharge current is constant and for known values of R, r_0, U_0, K_e and f_0, the derived calculation formula makes it possible to determine the thickness of the corona case for a given electrode configuration. In other sizes and shapes of the electrode system, a calculation formula is also derived for determining L_e, starting from the distribution of the electric field and the drift zone of electrons in the corona layer, taking into account the location of the corona case in the area with a field density of 31 kV/cm (minimum breakdown voltage between the electrodes at a distance 1 cm).

To determine the thickness of the corona case, discharge chambers in the form of a cylinder with a diameter of 2 to 36 mm were used, and a microcircuit from tungsten with a diameter of 5 to 50 microns (μm) served as the central corona electrode. From the ГС-100И type of generator, an alternating sinusoidal voltage is applied to the chamber with an adjustable frequency from 200 Hz to 1.6 MHz. High voltage to the chamber is supplied from a high-voltage source of the BC-23 type. Parameters of the output AC voltage are measured at a load of 1 kOhm using the ДЭСО-2 oscilloscope, the B3-2A tube voltmeter and the frequency meter 43-22. The current of the corona was set beforehand on the microampere No. 1244 of class 0.2, which was then switched off in order to eliminate the influence of parasitic capacitances and pickups on the accuracy of measuring the main signal. The amplitude of the variable high-frequency voltage was chosen in the range from 2 to 100 V, depending on the steepness of the characteristics of the positive corona and the geometric dimensions of the discharge gap.

The value of f_0 ($q_d=q_e$) for a given configuration of the electrodes and with the constancy of the corona discharge characteristics (constancy of the discharge current and atmospheric conditions) is as follows: firstly, the dependence of the HF-conductivity of the discharge gap (q_e - capacitive) on the frequency of the alternating voltage in the absence of corona discharge is determined. Then the dependences of the HF-conductivity are constructed in the presence of the corona discharge (q_d) and by coincidence $q_d=q_e$ the value of f_0 is found, which is the calculated value for determining the thickness of the corona discharge case.

The calculated values of the thickness of the corona case are given in Table 1.

The experimental values of f_0 were determined for the corona discharge in the cylindrical electrode system when R=0.2 cm, U_0=10 V, I=20 μA, and for K_e=540 $cm^2/(V \cdot s)$ its mean value in the corona case under normal conditions of atmospheric air in Almaty (p=690 mm Hg, T=20 °C). The table shows the values of f_0 obtained for different r_0 and the calculated values for the thickness of the corona case L_e, and for comparison, the values of L_e calculated from the empirical formula $1.56\ r_0^{0.56}$ are presented.

Table 1 – Calculated values of the thickness of the corona discharge

r_0, cm	5·10-4	15·10-4	30·10-4	50·10-4
f_0, Hz	1450·103	1250·103	810·103	300·103
L_e, cm	20.63·10-3	24.15·10-3	30.1·10-3	56.13·10-3
$1.56\ r_0^{0.56}$, cm	11.1·10-3	22.82·10-3	28.02·10-3	52.4·10-3

The data of the table show that the resonance of the corona case plasma occurs at different frequencies, depending on the value of r_0, which determines primarily the thickness of the corona layer (case) of the corona discharge. As was to be expected, the L_e values obtained by the proposed method slightly exceed the known L_e data for the same series of radii r_0.

Thus, there is a solution for the task to develop a method for determining the thickness of the corona discharge case, which provides high measurement accuracy due to fixation of the resonant frequency, when the influence of the high-frequency alternating voltage on the measurement results is excluded.

Method for determining the radius of curvature of the surface of the corona electrode [4]. The development of the method for determining the radius of curvature of the surface of the corona electrode is also based on the results of studies of the high-frequency (HF) conductivity of the plasma of the corona discharge case, when a large constant voltage and a small HF alternating voltage are applied simultaneously to the discharge gap.

Before proceeding to the consideration of the method for determining the radius of curvature of a corona surface of arbitrary shape, to establish the correctness of its application for solving this problem, it is necessary to check it for electrodes with a simple geometric shape, for example, coaxial cylinders.

For comparing the measured values of the thickness (L_e) of the corona case according to this method, the value of the thickness of the corona layer, determined by the Peak formula, can serve as the first approximation. In normal atmospheric conditions (δ=1), it shows that when the corona discharge is ignited, the electric field strength at the distance $\Delta=0{,}308\sqrt{r_0}$ (cm) from the corona electrode remains constant for any r0 and is equal to 31 kV/cm. Neglecting the influence of the space charge in the corona layer (E_0r_0=Er), we really get

$$\Delta=\frac{E_0r_0}{E}-r_0=\frac{E\left(1+\frac{0.308}{\sqrt{r_0}}\right)r_0}{E}-r_0=0.3\sqrt{r_0}, \quad (2)$$

which indicates that the thickness of the layer is independent of the discharge current. Apparently, the formula (2) is valid only in the case when E_0r_0=Er.

At comparable times of the electrons range and the half-period of the probing voltage, the decrease of q_d to negative values is already observed. To calculate the time range in the first approximation, a distance can be achieved as $0{,}3\sqrt{r_0}$, but when applied externally. Therefore, it is more correct to determine the shift of the apparent boundary, starting from the values of the half-periods of the alternating voltage E~.

The distribution of the field density of an alternating voltage in a cylindrical system is described by the formula

$$E_{\sim}=\frac{U_{\approx}}{(r_0+L_e)\ln\frac{R}{r_0}}, \quad (3)$$

where L_e– thickness of the corona layer.

For the range time of the electrons of the distance L_e it is valid

$$t=\frac{L_e(r_0+L_e)\ln\frac{R}{r_0}}{k_eU_{\approx}}, \quad (4)$$

taking t=T/2 and indexing the frequency f_0 *at* $q_d=q_e$ we determine the dependence of L_e from f_0 with the help of the formulas (3) and (4)

$$\frac{1}{2f_0} = \frac{L_e(r_0 + L_e)\ln\frac{R}{r_0}}{k_e U_0 \sqrt{2}}, \tag{5}$$

where U_0– the active value of the alternating voltage, which is equal to ~10, ~30V.

The solution of the equation is in the form of

$$L_e = -\frac{r_0}{2} \pm \sqrt{\left(\frac{r_0}{2}\right)^2 + \frac{k_e U_0 \sqrt{2}}{2f_0 \ln\frac{R}{r}}}, \tag{6}$$

Substituting the value K_e=540cm2/V·s and negleting $\left(\frac{r_0}{2}\right)^2$, we get the final formula

$$L_e = -\frac{r_0}{2} \pm 19{,}7\sqrt{\frac{U_0}{f_0 \ln\frac{R}{r_0}}}, \tag{7}$$

where L_e, R, r_0 – in cm; U – in V; f_0– in Hz.

Thus, if the value of the corona discharge current is constant and for known values of R, r_0, U_0, K_e, and f_0, the derived calculated formula allows to determine the thickness of the corona case for a given electrode configuration. With other dimensions and shapes of the electrode system, the calculation formula is also derived for determining Le, starting from the distribution of the electric field and the drift zone of electrons in the area with a field density of 31 kV/cm (minimum breakdown voltage between the electrodes at the distance of 1 cm).

The experimental values of f0 were determined for the corona discharge in the cylindrical electrode system when *R=0.2 cm*, U_0*=10 V*, *I=20 μA*, and for K_e*=540 cm2/(V·s)* its mean value in the corona case under normal conditions of atmospheric air in Almaty (ρ=690 mm Hg, T=20^{0}C).

The expression (7) allows to make qualitative estimates of the value L_e with the distance $0{,}3\sqrt{r_0}$. the calculations show, that the value L_e is closed to $0.3\sqrt{r_0}$, at frequencies f_0, though it is $L_e > 0.3\sqrt{r_0}$, with a decrease in the diameter of the corona wire. For example, L_e=0.029 cm for the values R=0.2 cm, r_0=0.005 cm, f_0=1070 kHz, U_0=10 V, and the distance $0.3\sqrt{r_0}$ is equal to 0.021 cm with decreasing radius r_0=0.001 cm, L_e=0.022 cm, and $0.3\sqrt{r_0}$ =0.0095 cm.

Table 2 shows the values of f_0 obtained for various r_0 and the calculated thickness values of the corona case L_e by the formulas (7) and $0.3\sqrt{r_0}$.

Table 2 – Calculated values L_e for various r_0

r_0, cm	5·10-4	15·10-4	30·10-4	50·10-4
f_0, Hz	1450·10-3	1250·10-3	810·10-3	300·10-3
L_e, cm	20.63·10-3	24.15·10-3	30.1·10-3	56.13·10-3
$0{,}3\sqrt{r_0}$, cm	6.71·10-3	11.62·10-3	16.43·10-3	21.21·10-3

The data obtained for L_e show that the resonance of the corona case plasma occurs at different frequencies, depending on the values of r_0, which determine, first of all, the thickness of the corona layer (case) of the corona discharge. As expected, the L_e value obtained by the developed method far exceeds the calculated data for the same range of radii r0 by the formula $0.3\sqrt{r_0}$. As mentioned above, this is due to the appearance of the buildup of electrons by a high-frequency field, which leads to an intensification of the ionization processes in the corona case.