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Experimental and modelling study of the dependence of corona discharge on electrode geometry and ambient electric field

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ABSTRACT

The results of experimental observations and mathematical modeling of corona formation on the tips of grounded rods are presented as a function of their tip height, curvature radius, the magnitude and polarity of the applied electric field producing corona. The investigations demonstrate that corona current depends on the active volume of zone in which electric field strength exceeds the breakdown criteria for air. The mathematical model was verified with the experimental data, enabling dependence of corona current on rod tip height, tip radius and applied electric field strength to be quantified with the need for a plethora of experiments.

1. Introduction

The appearance of corona discharges on electrical system components leads to a number of negative consequences. The most significant of these consequences is the loss of electric power. Another consequence is appearance of high-frequency electromagnetic disturbances. High-frequency current, voltage and electromagnetic field components that appear because of corona discharges have a negative influence on the performance of sensitive digital and electronic equipment, including automation and control systems.

A common source of corona discharge is from the wires of overhead power lines, so this issue attracts much attention [1,2]. Various solutions have been proposed, to solve this problem e.g., [2]. In rod-plane gaps, corona processes from the sharp edges of the configuration have been studied in relation to ozone generators [3]. Experimental investigations of corona discharges have been carried out mainly in systems with point-to-plane geometry, with needle-electrode energization using DC of both polarities [4–6]. Sometimes, the electric field (EF) strength around electric power facilities is sufficient to produce corona discharges around the more geometrically sharp points and elements of components and equipment, e.g., insulators, fittings, switches, high-voltage bushings, etc. In summary, the corona produced around such points may be DC (positive or negative), for example, arising from thunderstorms, or may be due to the high voltage AC in the power system itself.

The theory behind corona processes is quite complex and has been described many times in the literature, e.g., see Refs. [7–9]. Put simply, a corona discharge may be considered to be comprised of two components: (i) a diffuse form of gas discharge often called "glow corona" (hereafter termed the "steady-state" component), and (ii) incomplete plasma channels often called "streamer corona" (hereafter termed the "impulse corona" component). Component (i) can be readily measured with a microammeter whilst component (ii) is measured with an oscilloscope and pulse counter.

Experimental investigations of the dependence of corona current on the applied EF and geometry of rod-type electrodes are described elsewhere, e.g., [10–12]. However, in these papers, the conditions for corona initiation were not considered. The latter aspect is a key focus of the present paper.

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Mathematical modeling of physical systems is an effective method for studying corona formation processes and their dependence on parameters such as the EF strength and the geometrical configuration of the elements of electric power systems. Given the plethora of geometrical features in and around electrical equipment, as well as the wide range of heights of such features, modelling and simulation methods facilitate the analysis task and they make it relatively easy to assess worst-case scenarios for the location and geometry of electrodes in an external EF.

A modelling approach can enable parameter dependence of corona current to be assessed, for example on the magnitude of the applied EF and ratio of height and radius of curvature of the "sharp" features of objects. Optimal ratios can be selected when constructing electric power equipment and improvements, such as protective rings, shields, protective fittings, etc. can be prescribed to reduce the amount of corona discharges on and around equipment.

Hence, the aim of the present work is to quantify the dependence of corona processes in air on object height and radius of curvature when subjected to DC or AC external EFs. The "object" to be studied will be represented by cylindrical grounded rods with different heights and tip radii of curvature. The intensity of corona discharges on their tips will be characterized by the measured corona current.

2. Experimental observations of corona discharges from rod electrodes

2.1. Corona current measurement

Corona current measurements on various grounded rod electrodes located in air were made using the experimental setup shown in Fig. 1. Experiments were made under conditions close to NTP ($T \approx 20–23\ ^\circ C$, $p = 1$ atm).

This setup comprises high-voltage and grounded planes having dimensions of 4×4 m, separated by a distance $d = 2.1$ m. The rod of height h and spherical tip radius R (a conical tip was also used, but is not shown here) was located and bonded electrically to the grounded plane. A high voltage U_0 was applied to the high-voltage plane to create an external or "ambient" electric field of magnitude $E_0 \approx U_0/d$ between the two planes. The instrumentation setup enabled wideband oscilloscope registration and counting of the corona current impulses to be carried out.

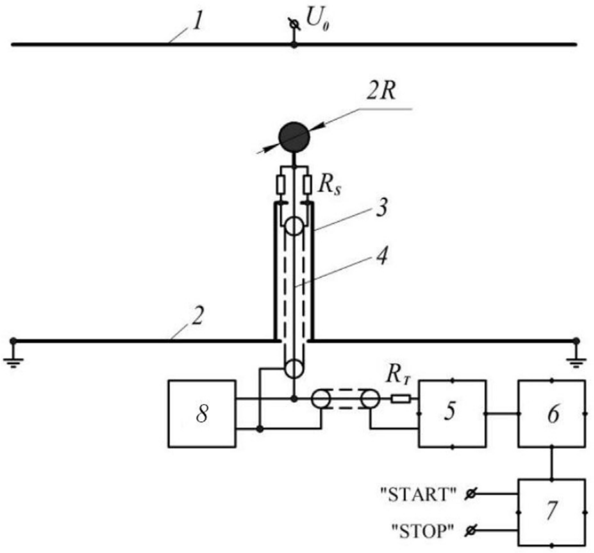

Fig. 1. Experimental setup schematic for recording the corona current. U_0 is the applied high voltage; 1, 2 are high-voltage and grounded planes; 3 is grounded rod electrode; R_S is a wideband shunt; R_T is a 25 Ω coaxial cable terminator; 4 is the measuring coaxial cable; 5 is a high-frequency amplifier У3-33 (input impedance is 50 Ω); 6 is the pulse generator (Г5-54); 7 is a cymometer (Ф5034) set to pulse counting mode; 8 is an oscilloscope.

Voltages proportional to the corona current flowing to ground were recorded via a wideband shunt with resistance $R_S = 75\ \Omega$. An impedance-matched coaxial cable was used to relay the voltage to a high-frequency amplifier and oscilloscope (model Rigol DS1204B). At the other end, a wideband coaxial resistor $R_T = 25\ \Omega$ was used to ensure there were no reflections of the impulses at the termination. The equivalent input resistance of the measuring system was therefore 37.5 Ω. The amplified signal triggered the pulse generator whose output was fed to a cymometer. As a result, a sequence of pulses corresponding to the corona current impulses was formed at the input of the cymometer. Trigger pulses to start and the stop the counting by the cymometer were applied for assigned time intervals.

To ensure wideband registration of impulses of the corona discharges, the base of the grounded electrode comprised a short length of metal pipe with a coaxial cable inside, as shown in Fig. 1. To provide a total resistance of 75 Ω, equal to the characteristic impedance of the cable, six low-inductance resistors were connected in parallel at the upper end of the cable. Average corona current impulses were numerically integrated and the resulting value was multiplied by the average pulse repetition frequency.

Measurement of the steady-state component of the corona current was made with a magnetoelectric microammeter (M266M) connected in series in the circuit between the rod electrode and grounded plane.

2.2. Corona current dependence on applied EF

The corona current measurements were carried out for three cases, namely:

I. HV DC (up to 170 kV) applied to the high-voltage plane electrode – *positive* polarity.
II. HV DC (up to 170 kV) applied to the high-voltage plane electrode – *negative* polarity.
III. HV AC voltage (50 Hz, up to 100 kV rms) applied to the high-voltage plane electrode.

Fig. 2 shows the typical corona current waveform recorded from a grounded rod electrode for Cases I, II and III. The height of the grounded rod electrode was fixed at $h = 1.2$ m. The rod used in these tests had a conical tip that was tapered over a length of 0.14 m, with a base diameter of 0.04 m, and radius of curvature at the extreme tip of the order of 0.1 mm.

In Case I (Fig. 2*a*), aperiodic impulses of the corona current appeared. The mean amplitude and duration at half-height of these impulses was 2.27 mA and 28 ns respectively. These magnitudes were found to be almost independent of the applied voltage. The average charge carried by an impulse was about 0.1 nC. The impulse repetition frequency increased with the applied voltage. At 50 kV, this frequency was 3.18 kHz. The average impulse corona current was of the order of 0.3 μA. The steady-state corona current measured by the microammeter was about 2.6 μA. Hence, the impulse corona was about 10% of the steady-state corona.

In Case II (Fig. 2*b*), corona current impulses were observed only within a narrow range of applied voltages, i.e., from 30 to 40 kV. However, the mean amplitude and duration at half-height of these impulses were significantly higher than in Case I, namely 5.72 mA and 85 ns respectively. On the other hand, the impulse repetition