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Explaining the impact of conductor surface type on wet weather HVDC corona characteristics

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ABSTRACT

Corona of HVDC overhead-lines is important in the planning of transmission corridors. Effects that need to be considered include corona losses (CL), audible-noise (AN), radio-interference (RI) and ground level ion currents. Water on conductor surfaces influences these quantities. It was previously shown that certain conductor surfaces lead to considerable reductions in wet weather CL. This publication studies the causes of these differences using optical methods. A key finding is that the size of water drops is decisive for differences in CL. Furthermore, different discharge mechanisms are shown to be the reason for differences in AN during and after rain showers.

1. Introduction

Rain strongly affects the corona behavior of HVAC and HVDC overhead lines. For both, CL increase significantly [1,2]. In HVDC systems, an increase in CL causes a proportional increase in ground level ion currents [3], which causes an increase in the ground level electric field and a reduction in human sensation thresholds [4]. In transmission corridors in which AC and DC systems are in close proximity, DC ion currents can also be collected by AC conductors [5,6] and could lead to transformer saturation [7].

With regard to corona AN, the behavior of HVAC and HVDC systems differs: during rain the noise level increases for AC but decreases for DC [8,9]. For AC, the increase in AN can be attributed to the increased number of field enhancements caused by water drops on the conductor surface, which lead to increased corona activity. An additional noise component in AC comes from the fundamental frequency oscillation of corona ions, which increases with CL [10]. The reason for the decrease in DC AN during rain is generally attributed to shielding effects from ionic space charges [11] but, to the best of the author's knowledge, more detailed explanations of the responsible mechanisms do not exist. Another particularity of HVDC corona is that only the positive pole contributes significantly to AN [8]. Wet weather CL, however, are very comparable for both polarities with only slightly higher values for the negative pole [12]. Therefore, this paper will focus on positive polarity corona.

The aim of this paper is to investigate the effect of the conductor surface on wet weather HVDC corona characteristics. The measured effects are CL and partial discharge (PD) amplitude. The latter can be used as an indicator for AN as well as RI [13]. The paper builds directly on a previous publication, in which optical investigation methods of water drops on energized conductors were presented [14]. That publication can be consulted for a more detailed literature survey. The following paragraphs will focus on a smaller selection of relevant literature.

Experiments have shown that rain leads to a large increase in HVDC CL [11,12,14]. In Ref. [14] it was shown that in the first few minutes after the start of a rain shower, PD amplitudes significantly overshoot the steady state value that is reached during continuous rain. At the beginning of the drying phase, immediately after the rain shower has ended, PD amplitudes again increase continuously until the conductor has dried enough for corona activity to cease completely. Initial evidence presented in Ref. [14] suggests that these differences are related to changes in the size and distribution of water drops on the conductor.

In Ref. [12] a number of different overhead conductor types were investigated with respect to their HVDC corona losses during rain. For conductors of the same nominal diameter, differences in CL in the order of 20–40% were observed. These discrepancies were attributed to differences in the wetting behavior of the different

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conductor surface types but the collected data did not allow derivation of the root causes.

Understanding the differences that were presented in Ref. [12] was the primary motivation for the development of the image acquisition and processing methods presented in Ref. [14]. The algorithms automatically detect the location and shape of water drops on the conductor surface, allowing characterization of its wetting behavior under a DC voltage stress. Demonstration of the method's capabilities was carried out for one conductor type in Ref. [14]. The goal of this paper is to now apply the developed methods to two different conductor types, in order to understand the reasons for the observed differences.

2. Experimental set-up and procedure

The experimental setup and procedure are described in detail in Ref. [14] and only a few key aspects will be repeated here.

2.1. Experimental setup

A DC voltage was applied to a 6.8 m long conductor suspended 1.095 m above ground (lowest point, sag = 5 cm) in an indoor laboratory. Prior to every experiment the conductor was cleaned with lint-free ethanol wipes. In parallel to the conductor were 2.15 m high grounded fences (at a distance of 1.45 m to one side and 1.3 m to the other side). Two conductor types with a nominal diameter of 22 mm were investigated. For the presented tests, a DC voltage of +137 kV was chosen, which leads to a maximum conductor surface field strength (field strength in the air just outside the conductor) of around 25 kV/cm, which is a typical recommended maximum for HVDC conductors [15]. This is based on the FEM calculations described in Section 3 assuming a cylindrical, smooth conductor and neglecting space charges. Electrical quantities that were measured are DC voltage, corona loss current and PD amplitude according to IEC 60270.

A total of four cameras were used to observe the conductors during the measurements. Two digital single lens reflex cameras (DSLRs) were placed so as to each cover 0.75 m to either side from the center of the conductor. Two digital compact cameras were positioned on top of each other to both observe the central 0.2 m section of the conductor. A corona scope (Forsyth Electro), which selectively amplifies light in the UV range and thereby makes corona discharges visible, was put in front of the lens of one of these cameras.

A rainfall simulation setup was used that allows rain to be switched completely "on"' and "'off"' within around 5 sec. A contrast agent (fluorescein, concentration 70 mg/L) was added to the tap water to enhance the visibility of drops. In Ref. [14] a comparison to deoinized water and to tap water without the contrast agent showed no measurable difference in the resulting corona current measurements. A rain intensity of 12 mm/h was used for this experiment, which corresponds to heavy rain.

2.2. Measurement procedure

The dry and clean conductors were subjected to the test voltage for 10 min, after which the rain was switched "on" (this instant is defined as t = 0 min). After 60 min of rainfall it was then switched off again. The experiment was continued until the corona current was reduced back to its pre-rain level (<2μ A/m). The DSLRs automatically took one image every second. The compact cameras recorded videos at 25 frames per second (fps).

3. Conductor types and field calculations

A schematic illustration of the two different conductors investigated in this paper is shown in Fig. 1. The two types are referred to as A and C in order to be consistent with the nomenclature presented in Ref. [12]. Table 1 compares the maximum and mean (averaged along a concentric circle with the nominal diameter) electric surface field strength of the two conductor types with that of an ideal conductor (geometry as described above, V = 137 kV). In this paper "ideal" is used to refer to an unstranded (cylindrical) and smooth conductor. All field strength values in this paper were calculated with the FEM software COMSOL Multiphysics. For type C, no detailed information of the strand shape was available, but own observations indicate that the fillet radius of the corners of each Z strand is approximately 400 μm.

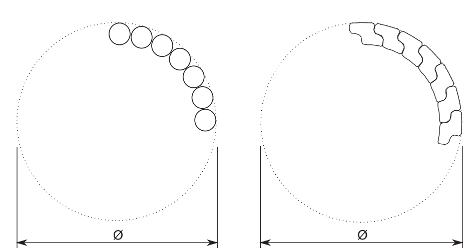
The surface field strength along a 10 mm section of the nominal circumference is shown for the ideal conductor and the two investigated conductor types in Fig. 2. Type A exhibits an approximately sinusoidal variation, with a maximum on each outward facing side of a strand and a minimum between two strands. Type C exhibits peaks on each side of one Z strand, a quasi-constant section along the outward facing side of each element, and a minimum between two strands. A 2D illustration of the surface field strength on the conductors is shown in Fig. 3. Dark red refers to the respective maximum values shown in Table 1.

Additionally, field calculations were carried out for conductive drops hanging on the lower side of the conductor. The size of the drops is described by the drop radius, r_0 (see Fig. 4). To account for the deformation of the drop due to gravity and electrostatic forces (prior to surface disruption), different length to width ratios, b/a as shown in Fig. 4, were considered. The position of the resulting ellipse is modeled such that its center coincides with the lowermost point on the conductors circumference. Because a change in the ratio was found to only lead to minor shifts in the resulting electric field distributions, the results and discussion in this paper are limited to a value of b/a of 1.5.

Fig. 5 depicts the field distribution along a vertical line downwards from the lower side of the conductor surface (shown by d in Fig. 4) for different drop sizes. The maximum electric field strength at the drop tip decreases with increasing drop size due to the higher radius of curvature. The rate at which the field decreases from the drop tip, however, decreases with r_0. This leads to an increase in the size of the region between the conductor and ground in which the electric field is above the critical value of air (from 1.6 mm for $r_0 = 1$ mm to around 1.9 mm for $r_0 = 6$ mm).

4. Optical evaluation methods

The processing of the image data collected with the four cameras was the main topic of [14]. Evaluation methods were presented that can automatically detect the location and shape of drops on the conductor. It was differentiated between two image regions. The first one is the projected area of the conductor itself (referred to as area "on"). The second one is the area just below the lower edge of the conductor (referred to as area "under"). For drops in the "under"



(a) round (Type A) (b) Z (Type C)

Fig. 1. Schematic illustration of the cross-section of the two investigated conductor types.