Onset Voltage of Positive Corona on Dielectric-Coated Electrodes

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Abstract: This paper is concerned with theoretical and experimental investigations of the onset voltage of positive corona as influenced by coating the coronating electrodes. Dielectric-coated hemispherically-capped rod-plane gaps positioned in air are investigated. The onset voltage is determined when a developed primary avalanche triggers successor avalanches to sustain the discharge process. Laboratory measurements of the onset voltage on bare and coated electrodes were carried out. The effects of varying field nonuniformity, thickness and permittivity of coating material on the onset voltage values were investigated. The results show that coating the electrodes with a dielectric material is effective in increasing the onset voltage of corona. The calculated onset voltage values for coated and bare electrodes agreed satisfactorily with those measured experimentally within 10 %.

Introduction

Gas insulated substations (GIS) are successfully used for high-voltage ac power systems. With the tremendous increase of power transmitted over distances greater than 500 miles [1], dc transmission becomes competitive and many dc transmission lines are installed everywhere in the world. This has created a growing interest in the study of self-maintained corona discharge on dc transmission lines. The problems associated with the corona discharge are power loss, audible noise and radio and TV interference [2]. Direct current corona may be either steady or pulsating in nature. Only pulsating corona produces radio and TV interference. As is well known [3], the positive corona contributes more to the radio and TV interference because of the higher charge content per pulse in comparison with negative corona. This is why this paper is aimed at investigating the onset criterion for positive corona.

Gaseous insulation systems are typically designed to minimize the corona discharge. A dielectric coating material on a stressed electrode may lead to an acceptable solution for minimizing the corona discharge; i.e. it increases the onset voltage of corona on its surface [4,5]. Therefore, this voltage should be ensured to exceed the rated operating voltage of the equipment. Hence, knowledge of this voltage is of paramount importance in the gas-insulated systems. More research in this area is of great importance, since the improvements obtained in insulation ability are substantial and remarkable [4-7]. This will encourage the high voltage engineers to construct extra-high-voltage systems.

This paper aims to investigate the effect of surface coating on the onset voltage of disruptive corona on a hemispherically-capped rod stressed by a positive dc voltage relative to an opposite grounded plane. At the initiation of disruptive corona phenomenon, a hissing noise is heard and ozone gas is formed [8, 9]. The onset voltage is determined when a developed primary avalanche triggers successor avalanches to sustain the discharge process. To check the accuracy of the proposed theoretical model, laboratory measurements are carried out. The concept of critical avalanche size for the corona onset is discussed in the results.

Onset criterion of positive corona

The criterion of the onset voltage of positive corona is based on the physical streamer model [3, 5, 10,11] as follows:

If a free electron originates by any source of radiation at the intersection point of maximum field line with the ionization zone boundary (where α the ionization coefficient, exceeds η, the attachment coefficient) Figure 1, an electron avalanche will be created. This avalanche is called primary avalanche (first generation of avalanches). It grows by the ionization by electron-collision. As the primary avalanche builds up, an increasing number of electrons crowd at its progressing tip while positive ions form a growing cloud in its wake. These electrons accelerate under the resultant of both the applied field and the field produced by the positive space charge in the wake. This avalanche proceeds towards the HV electrode and ends at its surface. The growth of the avalanche size, Figure 1, is expressed mathematically as:

$$n\ (z) = \exp\left(\int_{z_i}^{H-t} (\alpha(z) - \eta(z))dz \right) \qquad (1)$$

When the primary avalanche reaches the HV electrode, the number of its positive ions is designated by N_{+1}.

While the primary avalanche builds up, photons will be emitted from the avalanche head in all directions. They will be absorbed at various distances from their origin depending on the absorption coefficient of air. The number of photons produced from its head is given by $I_0 = f\,n\,(z)$, where, f is the ratio of the number of exciting collisions to the number of ionizing collisions per cm of the electron path under the prevailing field strength.

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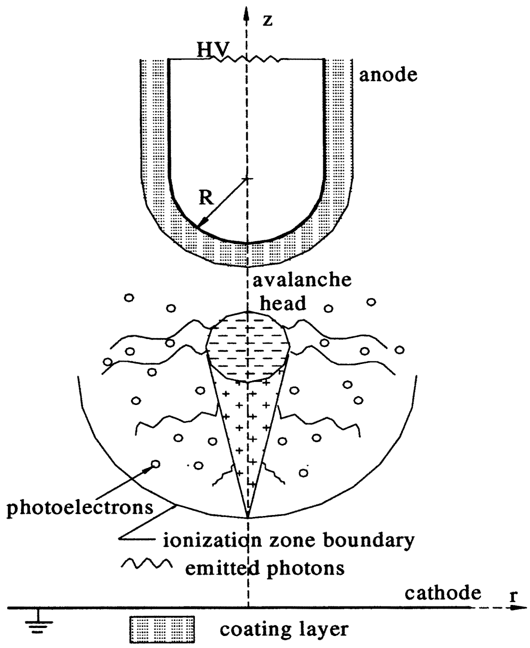

Figure 1: Growth of the primary avalanche and emission of photons in positive corona.

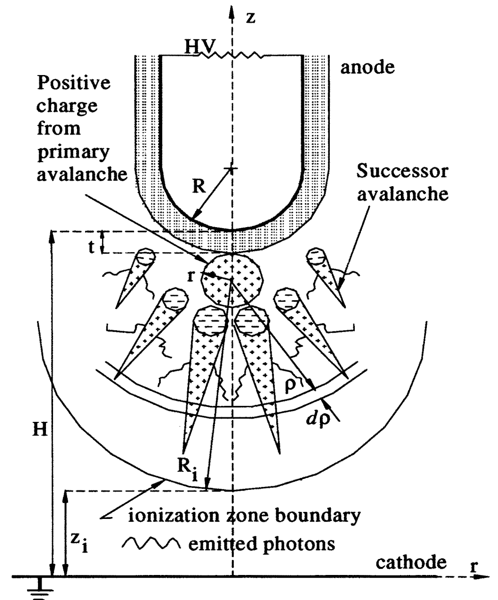

Figure 2: Growth of successor avalanches and emission of photons in positive corona.

Generated photons get absorbed by air molecules and some of them lead to photoionization. Due to absorption by air, the number of photons, I, reaching a distance ρ from the center of the avalanche head, as shown in Figure 2, will be $I = I_0 e^{-\mu\rho}$ where, μ is the absorption coefficient of air. As the photons travel through air, their initial intensity I_0 will be attenuated according to the general relation $dI = -\mu I_0 e^{-\mu\rho} d\rho$. The amount of radiation absorbed is proportional to the number of photoelectrons released by these absorption processes. The proportionality is given by factor p, which is a measure of the probability of the ionization for the given photo-absorption conditions. Therefore, the number of photoelectrons $n_{ph}(\rho)$, generated in a spherical shell of thickness $d\rho$ at a distance ρ from the avalanche-head center is simply $n_{ph}(\rho) = p\ dI$. Then, they may calculated by

$$n_{ph}(\rho) = g\,p\,f\,n\,(z)\mu e^{-\mu\rho} d\rho \tag{2}$$

where, g is a geometrical factor accounting for the fact that some of the photons get lost to the anode. One can assume that, immediately in front of the anode, approximately one-half of the photons get lost to the anode [12]. Therefore, g is considered to be one-half when the primary avalanche reaches the anode (i.e. during the last step of its growth).

The ionization zone has been divided into radial sectors originated from the intersection point of maximum field line and the anode tip as shown in Figure 3. As long as the primary avalanche grows, the emitted photons are assumed to be continually absorbed in all sectors producing photoelectrons. These photoelectrons are considered to be the initiators of successor avalanches (of the second generation). The size of each successor avalanche is integrated through its path, from the center of the sector to either the HV electrode or the positive ion cloud left by the primary avalanche.

Summing the size of the successor avalanches of all sectors, give the size of the positive space charge N_{+2}, left by the second generation of avalanches. Then, N_{+2} is compared with the positive space charge, N_{+1}, produced by the primary avalanche, as determined by (1). The criterion for onset voltage of corona is achieved when N_{+2} just exceeds N_{+1}.

Equation (2) gives the number of photoelectrons, $n_{ph}(\rho)$, generated in a spherical shell of thickness $d\rho$ at a distance ρ from the avalanche-head center. Therefore, it is implied that the level of ionization in the secondary avalanches is such that sufficient photons and hence photoelectrons will be generated to make the ionization self-sustained when

$$N_{+2} \geq N_{+1} \tag{3}$$

$$N_{+2} = \int_{rod\,tip}^{R_i} g.pf.N_{+1}.\mu. \times \exp\left[-\mu\rho + \int_{\rho}^{R^*} \left(\alpha(\rho) - \eta(\rho)\right) d\rho\right] \tag{4}$$

where, R^* defines the value of ρ at the rod surface, or at the surface of the space charge left by the primary avalanche depending on the direction of the avalanche growth. The critical value of the applied voltage satisfies (4) is the onset voltage of positive corona.

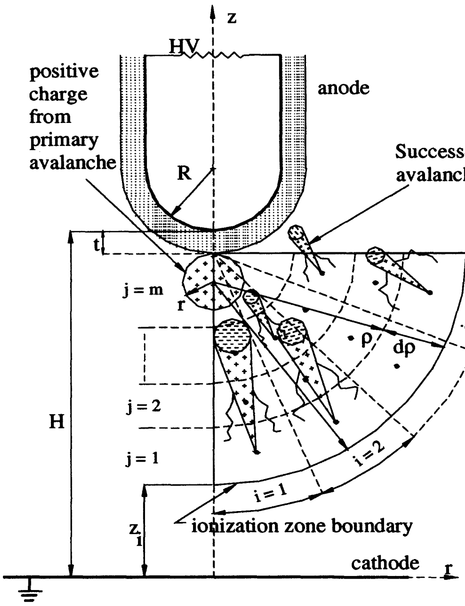

Figure 3: Growth of successor avalanches starting from the centers of sectors and ending at the sphere of positive charge or the rod tip.

A computer program has been built for calculating the positive onset voltage of corona. The program is based on the analysis presented in the above criterion. The static electric field distribution was calculated by the method of charge simulation method as described in [13] and [14] for bare and coated hemispherically-capped rod-plane gaps, respectively. The physical parameters α, η, and μ are given in [11,15] and *pf* is given function of ρ and μ [16]. The ionization zone was divided into *m* shells around the rod; each was segmented into *m* sectors for calculating the growth of the successor avalanches, Figure 3.

Experimental procedures

The experiments were carried out in atmospheric air with bare and dielectric-coated rod-plane electrode systems. Cylindrical hemispherically capped rods of radii 3 mm and 4 mm and length 0.25 m were tested. The rods were coated with an insulating varnish of thickness t equals to 0.5 mm and 0.375 mm. The used varnish is Dolphen BC-352 clear epoxy varnish. Its relative permittivity is ε_r = 3.29. The lower plane electrode was a plate of 0.15 m diameter with a rounded edge to avoid the occurrence of corona at this edge. The gap spacing, H, in the experiments was varied within a range of 0.04 m to 0.10 m for all rod-plane gaps. A high voltage dc source (Hipotronics, Model 800PL-10MA series) has been employed to energize the stressed electrode up to 80 kV. Overall accuracy of voltage measurement was considered to be within ± 2 %. The stressed electrode is connected to the HV source through a water resistance of 1 MΩ as a current-limiting resistor.

The onset voltage of audible corona discharge was measured for bare and dielectric-coated rod electrodes. The applied voltage was raised to about 90% of the expected value at a rate of 1 kV/sec and thereafter at a rate of about 0.1 kV/sec until human ears in the dark, quiet, could just hear the audible flutter sound closed laboratory [9]. Time interval between two successive applied voltages was a minimum 1-minute. At least 10 measurements were taken to estimate the mean of each measuring point. The relative standard deviation of the mean values was generally smaller than 1%. The tests have been conducted in dry air at room temperature (about 22-25° C) and atmospheric pressure.

Results and discussion

The ionization zone is divided into m shells, each is divided into m sectors, neglecting the upper part above the plane z = H-t, Figure 3. Thus, the total number of sectors is m^2. The order of the sectors is expressed by its shell j and its sector i. The contribution of sectors defined by j = 1,... m, and i = m Figure 3, reaches about 0.3 % from N_{+2} value. This justifies why the upper part of the ionization zone (above the plane z = H-t) was neglected, Figure 3.

For positive onset voltage, the contribution of primary avalanche mostly significant during the last step of its growth [10]. This is why the reported results are obtained after paying attention to the last step of the avalanche growth. Figure 4 shows the variation of N_{+1}, and N_{+2} values for different gap lengths at a certain rod radius, R = 3mm and coating thickness t = 1.5 mm. The onset voltage is determined as shown when $\ln N_{+2} = \ln N_{+1}$ = 9.3-9.5 approximately. This corresponds to a value of $N_{+2} = N_{+1} = 1.1\times10^4$-$1.3\times10^4$ for the gaps under investigation against 3×10^4 and 10^8 for Townsend and streamer breakdown mechanisms [17] respectively. The critical avalanche size at onset voltage of corona was reported 10^4 for rods having radii of 1-5 mm[17]. It is satisfactory that the critical avalanche size calculated in this work agreed with the values reported before [17].

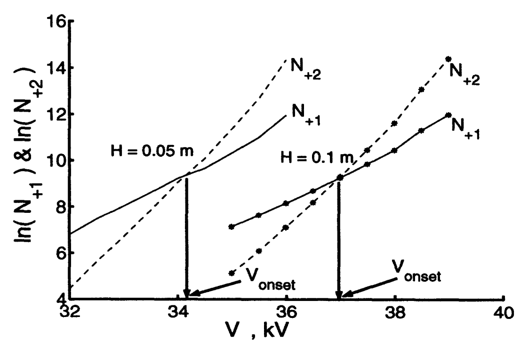

Figure 4: Variation of $\ln N_{+1}$ and $\ln N_{+2}$ versus the applied voltage, V, at different gap heights, H; R= 3 mm, t = 1.5 mm, and ε_r =3.

Figures 5 and 6 show the increase of the calculated and measured onset voltage values with increasing gap spacing, H, for bare and coated electrodes. The onset voltage values for thick bare and coated rods are higher than those for the thin ones. This is simply explained by considering the low electric field values near the thicker rods for the same applied voltage. The calculated onset voltage values agreed with those measured experimentally within 10 %.

Figure 7 shows the increase of the calculated onset voltage values with varying the thickness of the coating layer, t, at different values of relative permittivity. The onset voltage values at smaller value of relative permittivity are higher than those for the larger one. The extension of the curves intersects the ordinate axis at the calculated value for bare electrode, i.e. at zero thickness of coating layer.

Figure 8 shows the dependency of onset voltage on the relative permittivity ε_r of the coating layer. For the same value of coating thickness, t, the onset voltage shows a slight decrease with the increase of ε_r from 1.5 to 10. This confirms with the fact that a partial replacement of a given gaseous dielectric (air film around the electrode) by a solid dielectric of higher permittivity decreases the effective gap distance [5]. The effective gap distance decreases with the increase of ε_r of the coating layer. This reflects itself in an increase of the field in the air film surrounding the coating rod with a subsequent decrease of the onset voltage.

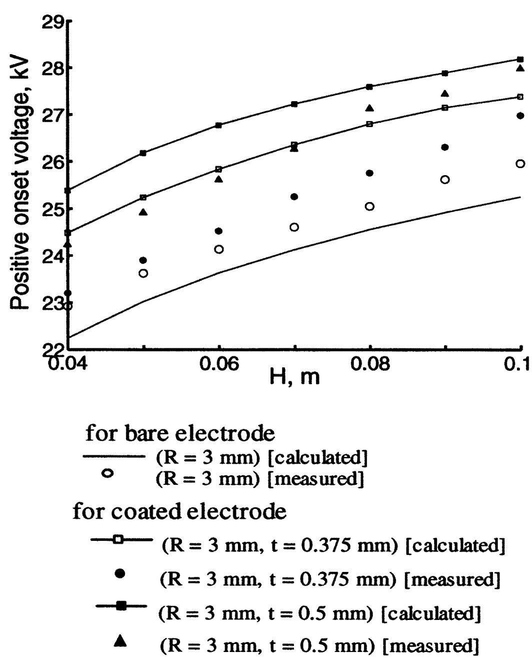

Figure 5: Measured and calculated positive onset voltage versus the gap spacing, H, for bare and coated electrodes at the same rod radius, R and at different coating thickness, t.

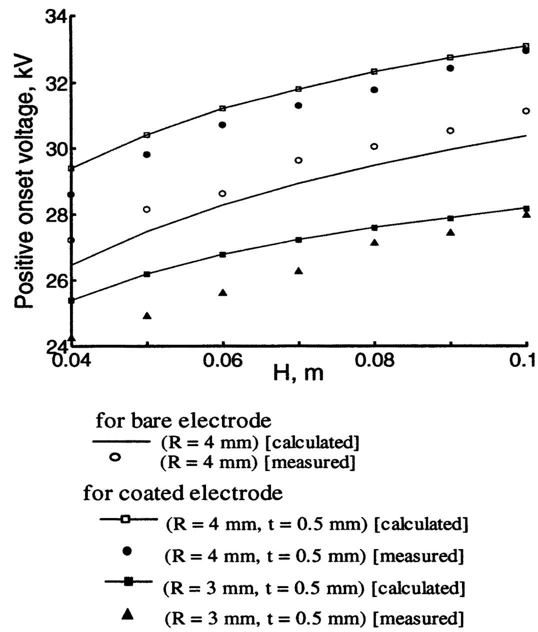

Figure 6: Measured and calculated positive onset voltage versus the gap spacing, H, for bare and coated electrodes at different rod radii, R, and at the same coating thickness, t.

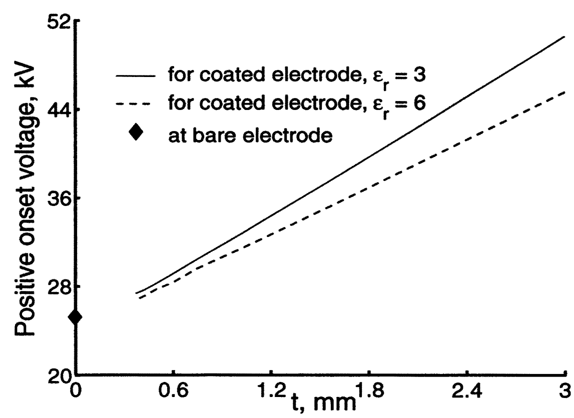

Figure 7: Effect of coating layer thickness, t, on the onset voltage at different values of ε_r of the coating layer; R = 3mm and H = 0.1m.

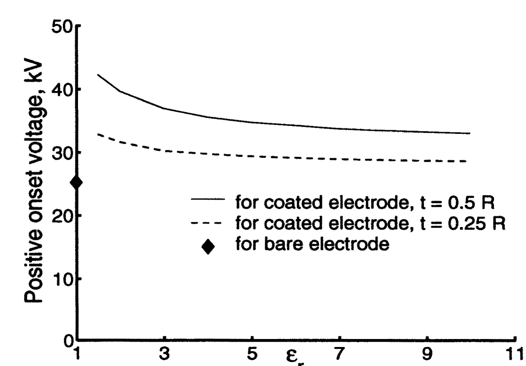

Figure 8: Effect of relative permittivity, ε_r, of coating material , on the onset voltage at different values of t; R = 3mm and H = 0.1 m.

Figure 9 shows the effect of electrode radius, R, on the onset voltage at different coating thicknesses. By increasing the rod radius, the electric field intensity decreases in the rod vicinity with a subsequent increase of the onset voltage. Figures 5, 6 and 9 show the effect of rod radius is more remarkable on onset voltage than that of the gap length.

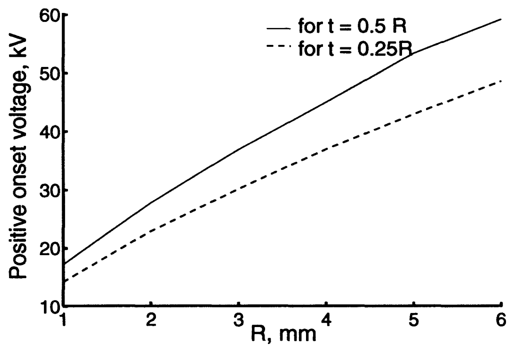

Figure 9: Effect of electrode radius, R, on positive onset voltage at different coating thicknesses; $\varepsilon_r = 3$ and H = 0.1m

Conclusions

1- The onset voltage values for thick bare and coated rods are higher than those for the thin ones.
2- Increasing either of the rod radius or gap length at any thickness of the coating layer results in an increase of the onset voltage. The effect of rod radius is more remarkable than that of the gap length.
3- Coating-layer permittivity does not have a significant effect on onset voltage when compared with the effect of coating layer thickness, rod radius and gap spacing.
4- The calculated onset voltages agreed satisfactorily with those measured experimentally within 10 %.

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