Technical Report

Gas discharge in a cavity – First part of a PD measurement process in power cable systems

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Introduction

This paper focuses on the initial stage of measuring partial discharge (PD) in a cable, which involves a gas discharge that occurs within a suitable cavity. It investigates how physical parameters associated with the cavity and cable construction affect the gas discharge within the cavity and the resulting charge magnitude due to PD activity. By analyzing these factors, the work aims to establish a framework for gaining a better understanding of the phenomenon detected by the PD measurement system and the severity of any defects present in the cable.

Partial discharge (PD) is a phenomenon that occurs in the insulation of power cables and can lead to the deterioration and failure of the cable system. A variety of factors, including manufacturing defects, aging, mechanical stress and environmental conditions can result in cavities in different types of extruded insulation as well as liquid-impregnated dielectrics, which can cause PD activities. Therefore, detecting PD and interpreting the PD results are critical aspects of cable system maintenance and reliability.

Along with physical/dimensional tests and high-voltage time (proof) tests, a PD test has become a standard part of the toolbox used to identify such defects and to assure the reliability of power cable systems at the factory. PD tests are increasingly part of the suite of tests applied to new MV and HV/EHV systems in the field (commissioning test) and to assess the health of components in the field. International standardization activities have resulted in test protocols (test times and voltages) that guide in the process of determining the presence of discharges, usually in terms of the magnitude of the discharge (either in MV or a charge). In general, these guidelines are based on what is commonly practicable in the factory or the field for a wide range of accessories and components. Usually, the factory PD detection sensitivity of 5 pC or better is referenced in multiple power cable standards for the laboratory. Conversely, the field PD testing sensitivity is not defined and is determined based on the agreement between the cable manufacturer and the end user.

In practice, the effectiveness of PD detection relies on several critical factors. These include the characteristics of the discharge, the propagation of the signal from the discharge location to the detector, the detection system itself and the approach to interpreting the detected PD. Researchers have extensively discussed these factors in published literature, such as CIGRE Technical Brochure TB728. In this paper, a significant emphasis is placed on interpreting the magnitude of a discharge in the void. Understanding the magnitude of PD is crucial in evaluating the severity of the discharge in the void and determining appropriate measures to mitigate potential damage or failure of the surrounding insulation.

Figure 1(a) presents the electric field distribution in a 15 kV cable with a conductor radius of 4.9 mm, insulation thickness of 4.5 mm. To show the impact of location on the stress distribution two cavities with a radius of 0.5 mm have been inserted next to a) the conductor, and b) the outer radius of insulation, respectively. In this, and all cases in this paper, the cavities are assumed to be filled with air.

Figure 1(b) is the field distribution along the dotted line running through the cavities. This shows the significant local electric field enhancement in the cavity area, which may result in gas discharge in the cavity.

This paper focuses on understanding the cavity type defect in the cable insulation and correlating the physical attributes of the cavity defects and the magnitude of the discharge that occurs within it. The study will illustrate the measured apparent charge magnitude as a function of defect size, position in the cable insulation, gas characteristics, and the shape and orientation of the cavity compared with the radial electric field. It will also consider the factors outside of the defect such as the testing voltage and cable dimensions (conductor size, insulation thickness, etc.), together with the initiation dynamics.

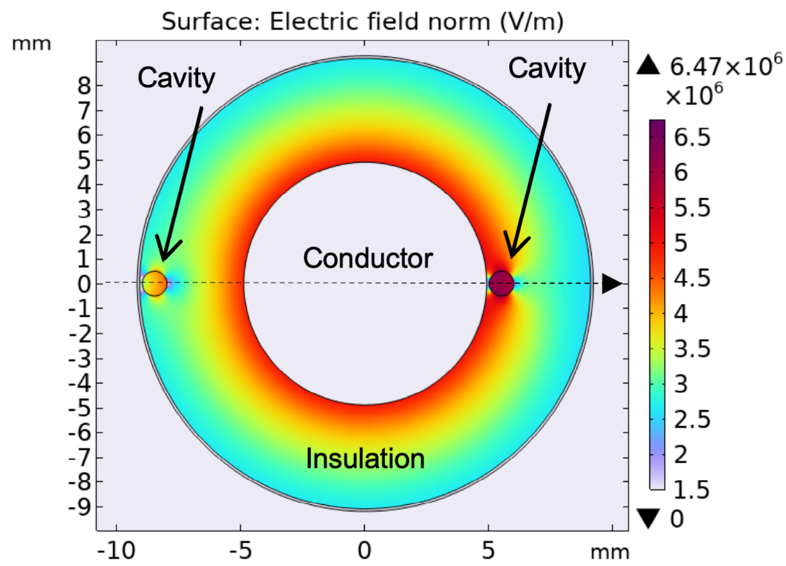

Figure 1(a)
Electric field distribution across the insulation of a 15 kV cable with two cavities with 0.5 mm radius

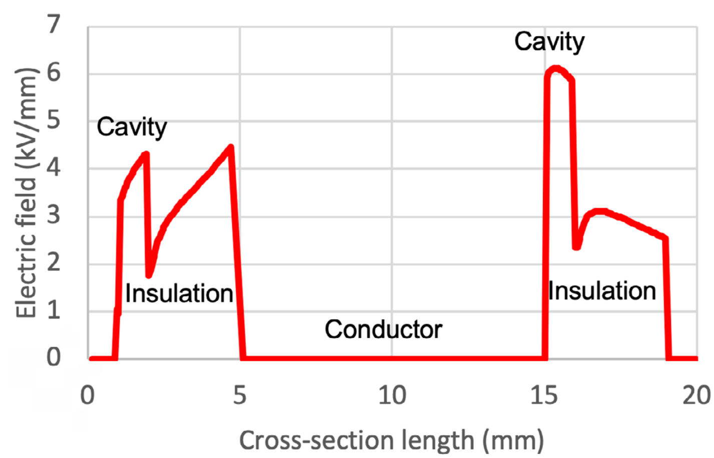

Figure 1(b)
Variation of electric field along the dotted cross-section line

Theory

A discharge inside of a cavity may occur if the electric field within it is enhanced beyond the minimum breakdown field. However, specific conditions must be met for this to happen [Figure 2], including the presence of an initiating free electron, a high electric field, and an adequate distance between the electron and the cavity wall to allow for electron multiplication before reaching the wall. In other words, the electron must gain enough energy from the electric field to create sufficient current (critical avalanche size) through collisions with molecules within the cavity to generate a well-defined breakdown channel known as a streamer. Two main factors affect the delay between voltage surpassing the minimum breakdown field and discharge initiation: the amount of voltage that exceeds the minimum breakdown field, which determines the size of the critical volume necessary to initiate the discharge, and the rate at which free electrons are generated per second.[1]

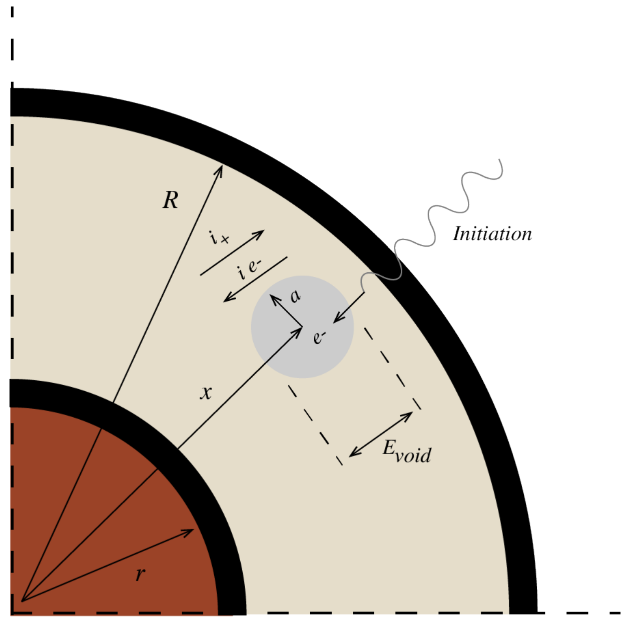

Figure 2.
Cross section of a cable with a spherical cavity at the position of x

Discharge initiation

As mentioned, the initial electron is crucial to start the first avalanche of the ionization process and trigger a partial discharge [Figure 2]. Discharge initiation plays a critical role in determining the statistical characteristics of the PD activity, such as frequency of initiation and the delay in inception. Volume generation and surface emission of electrons are two primary methods for generating the first electrons. Ionization of gas molecules by energetic photons and detachment of electrons from negative ions under electric field enhancement are two ways of volume electron generation.[1] In addition, the emission of electrons through field emission from cathodic conductors, de-trapping of electrons from traps on the surface of insulators, electron release by ion impact, and electron release by surface photo effect on both conductive and insulating surfaces are the mechanisms of the first electron generation from the surface.[1]

Charge magnitude

A detailed discussion on the theory and calculation of electric field within a cavity and the associated magnitude of PD resulting from cavity discharge is presented in References.[1,2] The complexity of the calculations and formulations for various cavity shapes and geometries were also explained in these papers. In the current work, we focus on applying the formulations to interpret and understand the measured charge magnitude due to PD activities in a cable system. Therefore, the principal formulations for a spherical cavity within cable insulation are explained. This will help clarify the variation of charge magnitude with different parameters of the cavity as well as the dimensions of the cable.

The minimum breakdown electric field for air captured inside of a spherical cavity can be calculated by Equation 1.[2,3]

[1] $E_i = (1 + 8.6/\sqrt{(2ap)}) \times 24.2p$

where p is the pressure in Pascals (Pa), a is the void radius in meters (m), and E_i is the minimum electric field (V/m). The electric field at the location of a cavity in an insulation system depends on the geometry of the system. In the case of a cylindrical cable structure, electric field distribution is calculated by Equation 2.

[2] $E = V/(xln\left(\frac{R}{r}\right))$

where V is the applied voltage (V), x is the radius of the position at which the electric field is calculated (x), and R and r are the outer radius and inner radius of the cable insulation (x), respectively. The cavity inside of cable insulation in most cases is significantly smaller compared with the geometry of the cable. Thus, we can assume that the electric field inside the small cavity is uniform. Therefore, the electric field in a spherical cavity can be approximated by Equation 3 .[2,3]

[3] $E_{void} = [3\varepsilon_r/(2\varepsilon_r + 1)]E_x$

where ε_r is the dielectric constant of the material containing the void and E is the electric field at the position of the void (V/m). Placing Equation 2 in Equation 3, the electric field inside of a spherical void is expressed in Equation 4.

[4] $E_{void} = [3\varepsilon_r/(2\varepsilon_r + 1)]V/(xln\left(\frac{R}{r}\right))$

Given a cavity filled with air, whenever the electric field inside the void is higher than the minimum breakdown electric field ($E_{void} > E_i$), breakdown will happen inside the gap and some charge will be transferred to the system electrodes. Figure 2 presents the schematic view of the cross section of a cable with a cavity inside the cable insulation. The transferred charge because of discharge inside an air-filled cavity can be calculated using Equation 5.[2,3]

[5] $q = 1.64 \times 10^{-8} \times a^{2.5}\varepsilon_r p^{0.5} \times [1/(xln\left(\frac{R}{r}\right))]$

Inception delay time

The period of time between the applied voltage and providing the first electron in a virgin void is known as the PD inception delay. The first electron generation within a void wholly within the insulation is generally controlled by the ionizing impact of cosmic and radioactive radiation in the absence of any induced radiation such as X-rays. Within spherical voids, where the ratio of surface area to volume is small, the dominant factor contributing to PD inception delay is volume ionization in the gas.[2,4]

The average inception delay time can be calculated using Equation 6.[2]

[6] $$t = [(\pi/6)C_{rad}\emptyset_{rad}(\rho/p)_0 pa^3(1 - v^{-\beta})]^{-1}$$

where v is the ratio of the applied voltage to the inception voltage (referred to as the overvoltage ratio), a is the cavity radius, C_{rad} is the interaction parameter between radiation and gas, $\emptyset_{rad}$ is the quantum flux density of radiation ($m^{-2}\cdot s^{-1}$), $(p/p)_0$ is the pressure-reduced density of gas ($kg \cdot m^{-3} .Pa^{-1}$), and β is the effective ionization coefficient.

Analysis and discussion

In this section, the effect of the physical parameters of the cavity and cable construction on the detected charge magnitude due to a gas discharge inside the cavity is discussed. It is useful to note that the requirements for the discharge magnitude used in manufacturing locations has evolved, and has not always been the 5 – 10 pC used today.[7]

Defect size in a spherical cavity

A typical 15 kV cable with an outer radius (R) of 14.6 mm and inner radius (r) of 10.4 mm for the cable insulation is considered. The center of the spherical cavity in the cable insulation is placed in the middle of the insulation. Therefore, the radius of the position of the cavity is 12.5 mm. The cavity is filled with air, and the pressure of air is 1 bar (105 Pascal). Figure 3 shows the variation of charge magnitude (q) with the radius of the cavity (a) for two major types of extruded dielectrics for cable insulations, namely WTR-XLPE and EPR with dielectric constants of 2.3 and 3.2, respectively.

Changing the radius of the cavity from 0.01 mm to 1 mm causes the charge magnitude to vary significantly from 0.0001 pC to about 10 pC for both dielectrics. The cavity radius that correlates a 5 pC charge magnitude with the mentioned assumptions is about 0.65 mm for EPR and 0.75 mm for WTR-XLPE. The cavity radius larger than these sizes leads to a charge magnitude higher than 5 pC.

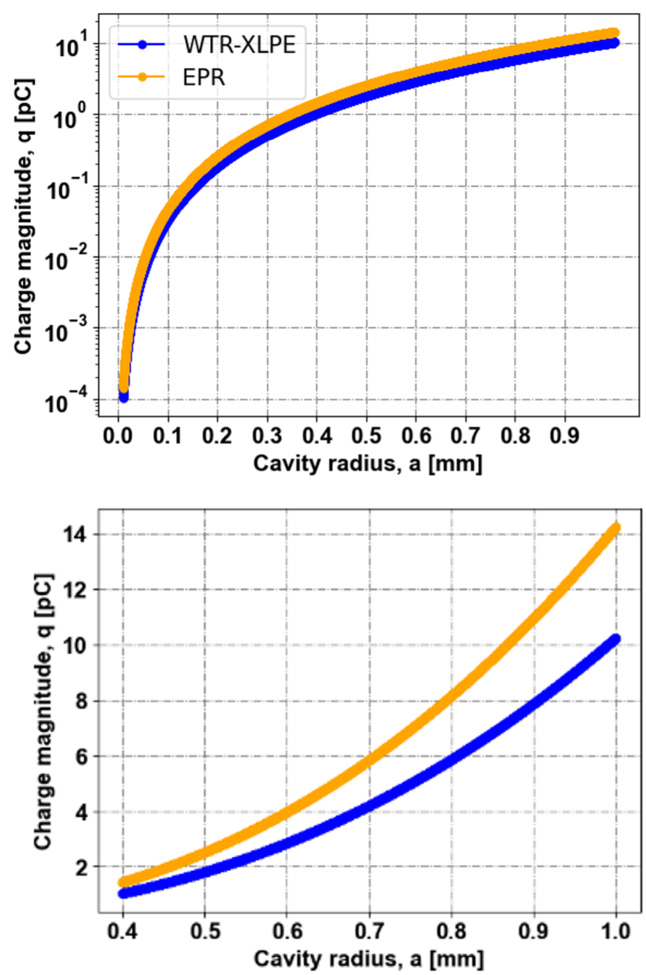

Figure 3.
Variation of charge magnitude with cavity radius from Equation 5 for a void centrally located in 15 kV cable

Position of cavity across the cable

Assuming a constant cavity radius of 1 mm, the position (x in Figure 2) of the cavity within the cable insulation is varied from a location adjacent to the conductor-insulation interface (at 10.4 mm) to a location at the outer radius of the cable insulation (at 14.6 mm). As shown in Figure 4, the resulting charge magnitude decreases from 12.4 pC to 8.7 pC as the cavity is moved further away from the conductor-insulation interface. This shows that the cavity close to the conductor-dielectric interface is more prone to aging and potential failure. The charge magnitude of the cavity remains above 5 pC for all positions considered across the cable insulation under the specified conditions.

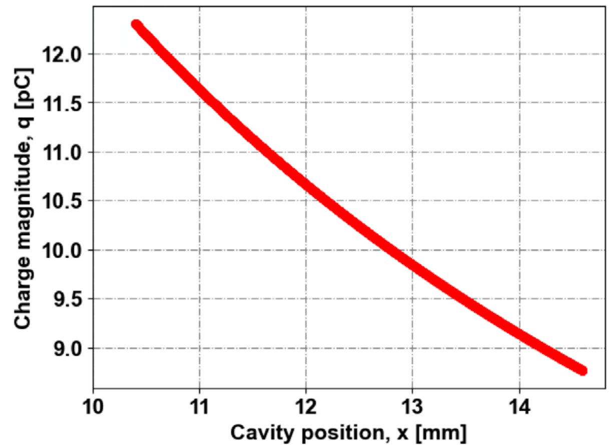

Figure 4.
Variation of charge magnitude with cavity position for a 1 mm radius cavity (Equation. 5) located in 15 kV cable

Cable size

To understand the effect of cable size, the variation of charge magnitude with conductor radius for three different cables including 15 kV, 35 kV, and 138 kV is presented. The cavity radius is 1 mm, and the insulation thickness is 4.2 mm, 8.4 mm, and 16 mm for 15 kV, 35 kV, and 138 kV, respectively. Figure 5 shows changes in charge magnitude with the variation of the conductor radius in the range of 4.6 mm to 15 mm where the cavity is next to the conductor-insulation interface.

In the case of the 15 kV cable, the charge magnitude reduces from 53 pC to about 6 pC when the conductor radius enhances from 4.6 mm to 15 mm. The general trend of the charge magnitude concerning the conductor radius is similar for the 35 kV and 138 kV cables as well. While for the 35 kV cable, the charge magnitude varies from 85 pC to 11 pC, while for the 138 kV cable, it ranges from 123 pC to 18 pC. It is worth noting that in all cases, the charge magnitude is larger than 5 pC when the cavity is adjacent to the conductor-insulation interface.

Two important trends emerge when considering cable size and scale, with the cavity located next to the conductor-insulation interface. First, increasing the conductor radius while keeping the insulation thickness constant significantly reduces the charge magnitude due to the PD activities inside the cavity. Second, increasing the cable voltage leads to an increase in the charge magnitude of a PD activity within a cavity with the same physical parameters and conductor radius and at the same position.

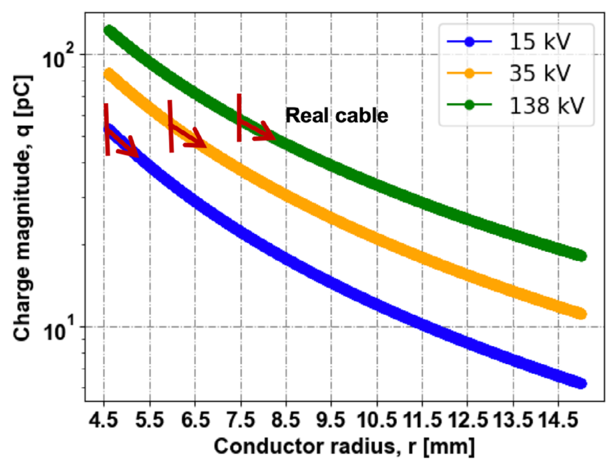

Figure 5.
Variation of charge magnitude with changing conductor radius, the cavity next to the conductor for 1 mm cavity radius

The charge magnitude variation is presented in Figure 6 for the condition where the cavity is located in the middle of the insulation thickness for the three cables. Considering the 15 kV cable, the charge magnitude decreases from about 35 pC to 5 pC as the conductor radius increases from 4.6 mm to 15 mm. This decreasing trend is observed for all three cables, and the charge magnitude reduces from about 44 pC to 9 pC as the conductor radius increases for the 35 kV cable. Similarly, for the 138 kV cable, the charge magnitude changes from about 45 pC to 12 pC as the conductor size increases from 4.6 mm to 15 mm. Thus, for all three cables, the charge magnitude is larger than 5 pC throughout the range of conductor radius change when the cavity with a radius of 1 mm is in the middle of the insulation.

The variation of charge magnitude with enhancing the conductor size in the case of the cavity next to the outer radius of insulation is presented in Figure 7. The charge magnitude decreases from about 28 pC to 5 pC with increased conductor size for the 15 kV cable. The charge magnitude reduces from 30.1 pC to 7.1 pC and from about 27 pC to 8 pC for the 35 kV and 138 kV cables, respectively. Interestingly, in the case that the cavity is next to the outer radius of the cable insulation and when the conductor radius is less than 6.5 mm, the charge magnitude due to PD activity inside the cavity for the 35 kV cable is larger than that for the 138 kV cable with a radius less than 7 mm.

Figure 6 illustrates the variation of charge magnitude with increasing conductor size when the cavity is located at the outer radius of the insulation. In the case of the 15 kV cable, the charge magnitude decreases from approximately 28 pC to 5 pC as the conductor size increases. Similarly, for the 35 kV and 138 kV cables, the charge magnitude decreases from 30 pC to 7 pC and from 27 pC to 8 pC, respectively. When the cavity is located next to the outer radius of the cable insulation and the conductor radius is less than 6.5 mm, the charge magnitude of the 35 kV cable is larger than that of the 138 kV cable.

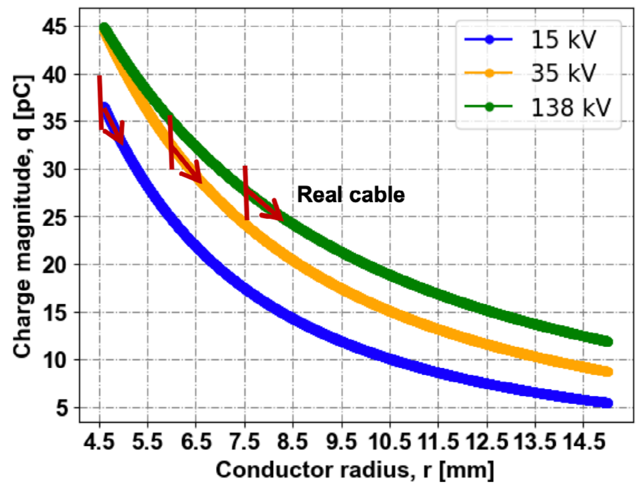

Figure 6.
Variation of charge magnitude with changing the conductor radius, the cavity in the middle of insulation for 1 mm cavity radius

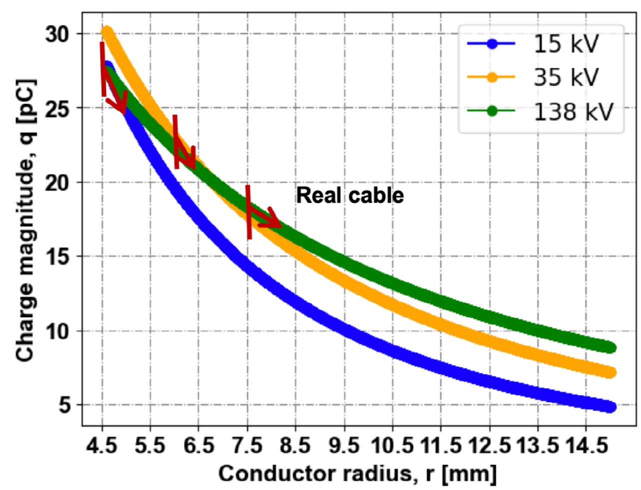

Figure 7.
Variation of charge magnitude with the change of the conductor radius, the cavity next to the outer radius for 1 mm cavity radius

Gas pressure inside of the cavity

Considering the same 15 kV cable with an outer radius (*R*) of 14.6 mm and an inner radius (*r*) of 10.4 mm for the cable insulation, a cavity size of 1 mm, and a cavity position in the middle of the insulation thickness, the effect of gas pressure inside the cavity on the charge magnitude due to PD is shown in Figure 8. The charge magnitude varies between 1 pC to about 32 pC, and pressures higher than 0.25 bar result in a charge magnitude larger than 5 pC.

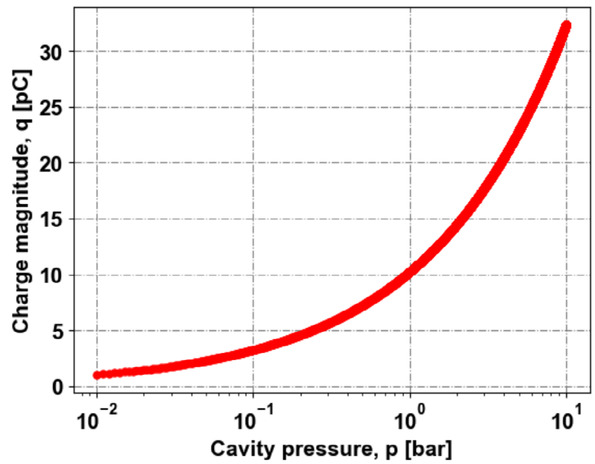

Figure 8.
Variation of charge magnitude with the gas pressure inside the cavity

Shape and orientation of the cavity

The amount of charge transferred during a discharge in a cavity is dependent on the shape and orientation of the cavity relative to the radial electric field in the cable. This relationship can be calculated using Equation 7.[1,5]

[7] $$q = \pi \varepsilon_0 b^2 (1 + \varepsilon_r \left(K\left(\frac{a}{b}\right) - 1\right)) \Delta E$$

where a is the axis parallel to the radial electric field (m), b is the axis perpendicular to the electric field (m), ΔE is the electric field change due to the voltage breakdown inside the void (V/m), ε_r is the dielectric constant of the dielectric of the cable, and $K(a/b)$ is a dimensionless function of the ratio of the axis. To estimate charge in this paper, $K(a/b)$ can be estimated using Equation 8.[6]

[8] $$K\left(\frac{a}{b}\right) \begin{cases} \sim 1 & a/b \ll 1 \\ = 3 & a/b = 1 \\ \sim 4a/b & 1 < a/b < 10 \end{cases}$$

To examine the impact of cavity shape and orientation on the charge magnitude, three cavities located in the middle of a 15 kV cable are analyzed. The cavities are characterized by the following parameters:

a/b≪1, a=0.001 mm

a=b

1<a/b<10, a=1 mm

In all conditions, the axis perpendicular to the radial electric field changes from 0.05 mm to 0.99 mm, and the variation of charge magnitude is plotted in Figure 9. Figure 10 illustrates various shapes and orientations of the cavities studied in this paper.

The charge magnitude varies from 0.02 pC to 11 pC when the ellipsoidal cavity orientation is perpendicular to the radial electric field. In the case of the spherical cavity, the charge magnitude changes from 0.15 pC to about 62 pC as the cavity radius varies from 0.05 mm to 0.99 mm. In the third case, where a is 1 mm, the charge magnitude increases from 5 pC to 88 pC.

The charge magnitude is larger when 1<a/b<10 and it changes more significantly compared to the other two conditions. Two things should be noted about this condition. First, the cavity is notably larger in this case compared to the other two conditions due to the constant value of a at 1 mm. Second, in this condition, the cavity is oriented in the direction of the radial electric field.

Inception delay

As discussed, the inception delay for the gas discharge refers to the time elapsed between the application of voltage and the first electron being provided in a cavity. To understand the effect of cavity size on the average inception time delay using Equation 6, v is considered 2, $C_{rad}\emptyset_{rad}$ =2×10^6 [kg^{-1}.s^{-1}] is adopted from Reference[2] for natural irradiation, $(\rho/p)_0$=10^{-5} (kg·m-3.Pa-1) and β=1/2 are also adopted from Reference[2] for one bar pressure. Figure 11 depicts the relationship between the average time delay and the cavity radius for three different overvoltage ratios (2, 10, and 100). The results demonstrate that the time delay decreases significantly from approximately 10^6 seconds to approximately 100 seconds as the cavity radius increases from 0.05 mm to 1 mm. Additionally, the effect of the overvoltage ratio on the time delay is relatively minor compared to the impact of cavity size.

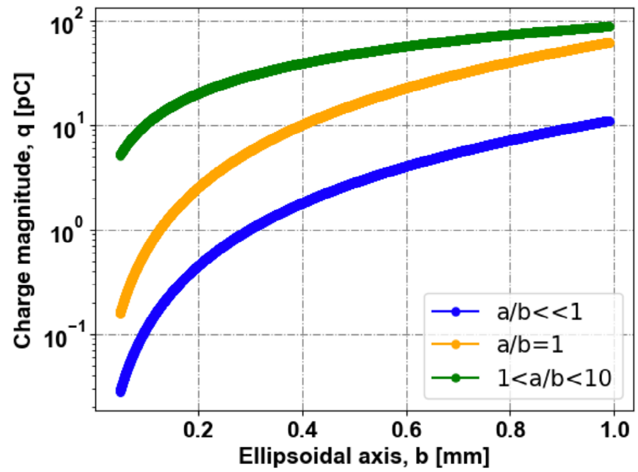

Figure 9.
Variation of charge magnitude with ellipsoidal axis, b, perpendicular on the radial electric field of the cavity located in the middle of insulation for the 15 kV cable

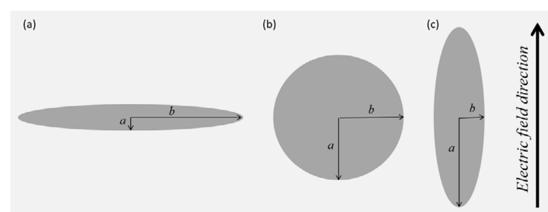

Figure 10.
Different shapes and orientations of cavity across the cable insulation: (a) ellipsoidal cavity a/b<<1; (b) spherical cavity a/b=1; and (c) ellipsoidal cavity 1<a/b<10

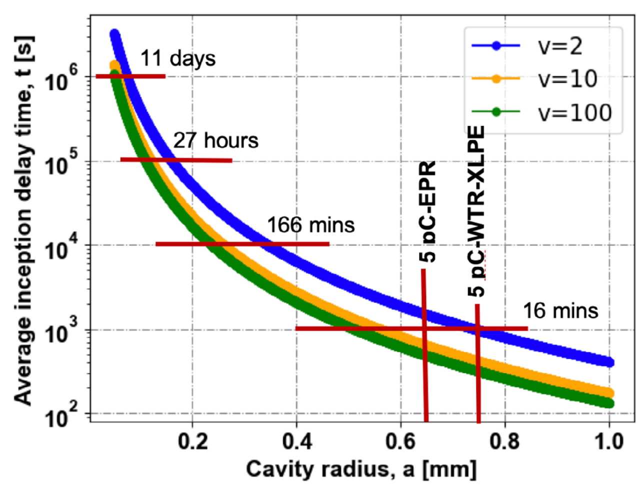

Figure 11.
Variation of average inception time delay with cavity radius for a spherical void in a 15 kV cable for the three overvoltage ratios (v)

Conclusion

This paper presents a practical analysis of the different parameters that affect void discharge in cable insulation. It aims to enhance end users' understanding by explaining the major physical attributes of cavities and their relationship with cable construction. Specifically, it attempts to address the question "What does 5 pC mean?" by providing a detailed account of the factors that contribute to the discharge in the cavity.

The key points of this study are as follows:

- The presence of a cavity in the insulation changes the local electric field distribution across the insulation.
- The impact of the dimensions/shape of the cavity and cable dimensions/material on the charge magnitude is nonlinear.
- The size of the cavity in the middle of insulation of a 15 kV cable made of either WTR-XLPE or EPR, corresponding to give a gas discharge of 5 pC, is quite large (approximately 0.6 to 0.8 mm radius).
- The size of the cavity for a particular magnitude of the charge is dependent on cable size. The size of the resulting cavity, for a given charge magnitude, increases as the cable size increases.
- The charge associated with a certain cavity size depends on its location within the cable insulation. The largest charge occurs when the cavity is in the region of the highest field — closest to the conductor.
- The orientation of the cavity relative to the radial electric field has a significant effect on the charge magnitude.
- The cavity radius has a large impact on the inception delay time. The inception times can be quite long for small to medium voids.

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