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Characteristics of partial discharge on high-density polyethylene insulation under AC and DC voltages

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ABSTRACT

The majority of insulation system failures in electrical grids are caused by partial discharge (PD) activity. Continuous PD activity gradually degrades the quality of insulation, potentially resulting in total breakdown. This study investigates PD activity in high-density polyethylene (HDPE) insulation, detected through the observation and measurement of PD charge using the CIGRE Method II electrode system. The objective is to analyze PD behavior in HDPE cable insulation containing cavity-type defects under alternating current (AC) and direct current (DC). The samples consist of three layers of HDPE sheets, each 1 mm thick, with an artificial circular cavity of 1 cm in diameter embedded in the middle layer. This configuration enables detailed analysis of insulation damage and degradation. The results show that HDPE performs better under DC voltage compared to AC. This is evidenced by the average PD inception voltage (V_{in}) under DC conditions reaching 15.5 kV, higher than the 11.8 kV observed under AC, as well as a significantly longer PD inception time (T_{in}) under DC conditions. Although the PD charge magnitude is nearly the same under both voltage types, the higher voltage required to trigger PD under DC indicates that HDPE exhibits superior insulation resistance to DC voltage.

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1. INTRODUCTION

The insulation system plays a critical role in ensuring the safe and reliable operation of high-voltage equipment and power electronic devices under high electric fields [1]–[3]. In general, polymeric materials are widely used for insulation in high-voltage equipment due to their high breakdown strength under electrical stress [3]–[5]. Polymers are commonly employed as insulating materials, particularly in cable applications within electrical power systems [4]–[6]. Among various types, polyethylene is the most widely used polymer for dielectric insulation in cables, including low-density polyethylene (LDPE), cross-linked polyethylene (XLPE), and high-density polyethylene (HDPE) [4], [6]–[8].

High-voltage power cables must possess strong resistance to high electric stress and overcurrent loads [9]. High-density polyethylene (HDPE) is a type of polyethylene with high density, synthesized from ethylene monomers [7]. HDPE is considered an excellent insulating material due to its dielectric characteristics that closely resemble those of cross-linked polyethylene (XLPE) [10]. As a result, HDPE is widely used in high-voltage insulation systems [6], [11]. However, prolonged use of high-voltage cables may lead to a decline in insulation quality, potentially causing failure in the insulation system. Such degradation is influenced by various factors, including thermal effects, electric field stress, mechanical pressure, environmental conditions, and chemical corrosion [3], [12], [13]. Damage to the insulation system can lead to insulation failure, which significantly affects the reliability of power network operations. Among the contributing factors, partial discharge (PD) activity is recognized as the most common cause of insulation system failure in power networks [14].

According to IEC 60270, partial discharge (PD) is defined as a localized electrical discharge that only partially bridges the insulation between conductors and may occur near the conductor [13], [15]–[18]. The causes of PD include defects or aging effects, such as voids, protrusions, and impurities in the insulation material [19], [20]. PD events do not immediately lead to insulation failure. However, continuous PD activity gradually degrades the insulation quality, which can eventually result in total breakdown [8], [20]–[22]. The consequence of total insulation failure in a power network is a sudden power outage [8], [20], [21]. Therefore, it is necessary to analyze PD activity in insulating materials.

Several studies on the behavior of PD during aging in cable insulation systems containing cavity defects have been reported in the literature [3], [20], [23], [24]. In addition, some researchers have focused on investigating PD characteristics under both AC and DC voltage sources. Morris and Siew [15] conducted a study analyzing the PD characteristics of LDPE insulation samples with artificial cavities under AC and DC voltages using a plane-plane electrode configuration. The results showed that the PD inception voltage (PDIV) under DC conditions was nearly three times higher than under AC conditions. Although the measured PD magnitude was comparable to that under AC, the number of discharges was significantly lower, while the applied voltage was considerably higher. Lee *et al.* [25] conducted research to compare PD characteristics in XLPE insulation samples under AC and DC conditions and to analyze the changes in PD behavior before breakdown in defect regions under DC voltage. Their findings indicated that the PDIV under DC voltage was significantly higher than under AC for most types of defects. Moreover, the dispersion of corona discharges under DC voltage was much lower than that caused by other types of defects. Additionally, under DC voltage, both the discharge magnitude and the PD waveform were observed to change before the breakdown occurred.

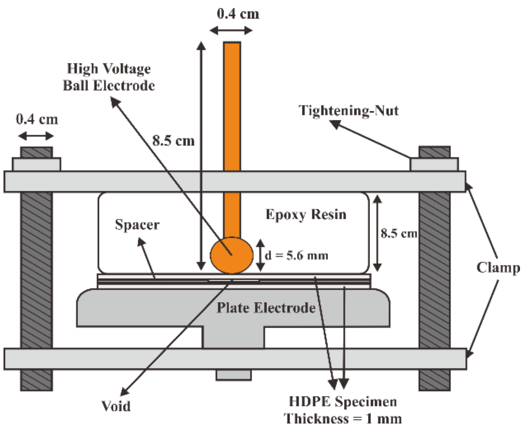
Unfortunately, detailed research on the activity of PD in HDPE cable insulation with void defects under AC and DC voltages is still limited. Moreover, there are differences in the material technology of the test samples used compared to previous studies, particularly regarding thickness, configuration, defect types, and void diameter. This indicates a gap that needs further investigation. This study will focus on PD activity in HDPE insulation, detected through the observation and measurement of PD charge pulses using the CIGRE method II electrode system. This electrode is used to estimate the PD resistance of HDPE insulation caused by voids within the insulation. This research aims to analyze PD activity in HDPE cable insulation with void defects under both AC and DC voltages. The samples consist of three layers of HDPE sheets, each 1 mm thick, with the middle layer containing an artificial round void with a diameter of 1 cm. This sample arrangement allows for the analysis of damage and degradation in the insulation layers. Based on the more stable characteristics of the DC electric field, it is highly likely that the PD inception voltage (V_{in}) under DC conditions will be higher compared to AC conditions, consistent with previous findings [15], [25].

2. METHOD

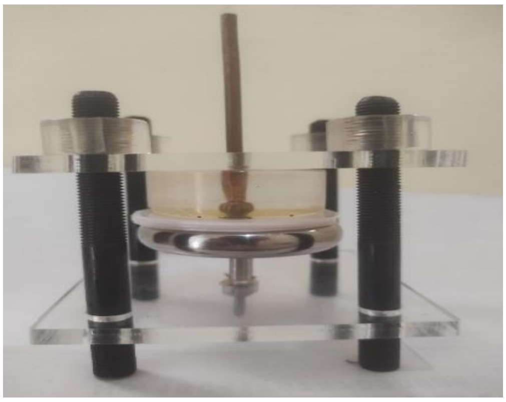
2.1. Electrodes and sample

In this experiment, the electrode system based on the CIGRE method II (Conference Internationale des Grands Réseaux Électriques) was employed for the observation and measurement of partial discharge (PD) pulses, as illustrated in Figure 1. The CIGRE method II electrode is an improved version of the original CIGRE method I. This electrode configuration is used to evaluate the insulation endurance against PD caused by internal voids in insulating materials and has been proven effective in testing various types of insulation [26]. HDPE sheets are used as test samples in this research. To create a high discharge concentration at specific points on the sample's surface, the sample is positioned beneath a high-voltage spherical electrode, resulting in a non-uniform electric field within the artificial cavity [5].

The spherical electrode, with a diameter of 5.6 mm, is placed above the HDPE sample, applying pressure on it. The sample is sandwiched between the spherical electrode on top and a flat plate electrode at the bottom. The test setup consists of three layers of HDPE samples, each with a thickness of 1 mm. An artificial cavity with a diameter of 1 cm is embedded in the middle layer. The flat plate electrode at the bottom is made of stainless steel. A clamp mechanism is used to hold the sample firmly in place, preventing any shifting or dislodging during testing and facilitating easy sample replacement. The top clamp is designed to be detachable, allowing it to be removed by loosening screws or fasteners. The framework of the testing apparatus is constructed using acrylic material for durability and ease of use. Figure 1(a) illustrates the electrode system design based on the CIGRE method II, while Figure 1(b) presents the physical realization of the electrode system.



(a)



(b)

Figure 1. CIGRE Method II electrode (a) design and (b) realization of the design

2.2. Experimental circuit

The experimental setup is illustrated in Figure 2. Measurements were conducted using high-voltage AC and DC sources, with a frequency of 50 Hz applied to the electrodes based on the CIGRE method II configuration. When the HDPE sample is subjected to high AC or DC voltage, PD is generated and detected by an RC detector, which functions as a signal integrator. This RC detector is also equipped with a high-pass filter (HPF), allowing the detected PD pulses to be processed and filtered based on their frequency components. Subsequently, an arrester connects the RC detector to the oscilloscope via channel 1, while channel 2 is used to capture the fundamental waveform. The oscilloscope records the PD signals and transfers the data to a laptop or computer via a USB flash drive for further processing and analysis.

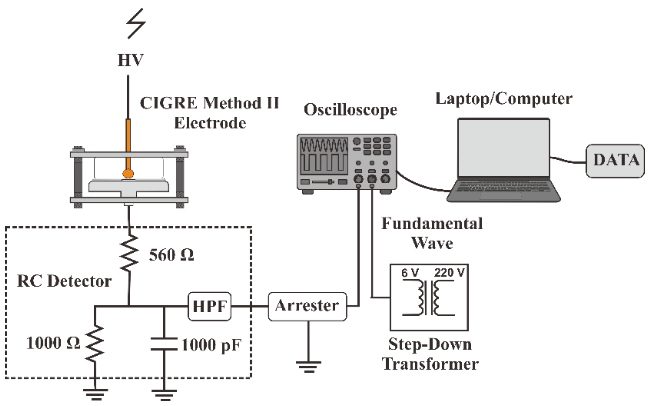


Figure 2. PD measurement circuit

The PD inception voltage (V_{in}) is determined by gradually increasing the applied voltage until the first occurrence of PD is observed. Once Vin is identified, the voltage is maintained at a constant level below this value to observe the time delay before the onset of PD, referred to as the PD inception time (T_{in}). Subsequently, the voltage is increased by 10% above V_{in}, kept constant, and PD data is then recorded for a 1-hour testing period [15], [18]. The equivalent circuit of PD activity in the HDPE sample during this measurement is shown in Figure 3.

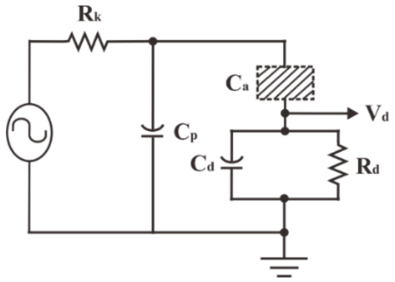


Figure 3. Equivalent circuit of PD activity in HDPE

Where R_k=Test circuit resistance, C_a=Sample capacitance, R_d=Detector resistance, C_p=Test circuit capacitance, C_d=Detector capacitance, V_d=Output voltage.

To determine the value of V_d, the following equation is used [27]:

$$V_d(t) = \frac{1}{C_d}\int_0^t i(t)\,dt \tag{1}$$

$$V_d(t) = K\exp(-t) \tag{2}$$

From Figure 3, the value of K can be determined using the following equation:

$$K = \frac{q}{C_d\frac{C_pC_a}{C_p+C_a}} x \frac{C_p}{C_p+C_a} \tag{3}$$

$$\frac{1}{\alpha} = \left(C_d + \frac{C_dC_a}{C_p+C_a}\right)R_d$$

However, since $C_p << C_a$ dan $C_d >> C_a$, then:

$$K \approx \frac{q}{C_d} \tag{4}$$

$$\frac{1}{\alpha} = C_dR_d$$

Thus, (3) becomes:

$$V_d(t) = \frac{q}{C_d}\exp(-t) \tag{5}$$

or

$$q \approx V_d \cdot C_d \tag{6}$$

3. RESULTS AND DISCUSSION

3.1. PD inception voltage (V_{in})

The PD inception voltage (V_{in}) is obtained by gradually increasing the voltage until the first occurrence of the PD phenomenon. This PD phenomenon can be observed using an oscilloscope. In this measurement, three trials are conducted to obtain the average Vin, with a new HDPE sample used for each trial. The measured V_{in} values for HDPE samples with artificial voids are shown in Table 1. This experiment specifically aims to compare the effects of AC and DC voltage on the V_{in} values in HDPE material with artificial void defects.

Table 1 presents the measurement results of the PD inception voltage (V_{in}) for two types of voltage sources, AC and DC. The test results show that the average V_{in} value is 11.8 kV under AC conditions and 15.5 kV under DC conditions. These findings indicate that the PD inception voltage is higher under DC conditions compared to AC, suggesting that the type of voltage source has a significant impact on the occurrence of PD. This result is consistent with several previous studies [15], [18], [28], [29], which states that the PD inception voltage under DC conditions tends to be higher than under AC conditions. This difference is attributed to the characteristics of the electric field produced by the two types of voltage sources. The electric field in DC conditions is stable and constant, requiring higher voltage for PD to occur. In contrast, the electric field in AC voltage is sinusoidal, allowing PD to occur at lower voltages [28]. Therefore, this experiment confirms the initial hypothesis that the PD inception voltage is higher under DC conditions. These results provide deeper insight into the influence of voltage type on partial discharge characteristics and can serve as a consideration in the design of insulation systems for high-voltage equipment.

Table 1. Comparison of PD inception voltage (V_{in}) measurements under AC and DC conditions

Experiment	PD inception voltage (kV)	
	AC	DC
1	12.2	15.1
2	11.5	15.6
3	11.6	15.7
Average PD inception voltage	11.8	15.5

3.2. PD inception time (T_{in})

After the PD inception voltage (V_{in}) is determined, a constant voltage is applied with a value below the initial voltage at which PD occurs, or before the PD phenomenon appears. This is done to prevent the immediate occurrence of PD, allowing the time delay until PD is observed. This time delay is referred to as the PD inception time (T_{in}). This experiment aims to observe the effect of voltage magnitude on PD inception time and to analyze the difference in PD response between AC and DC voltage sources with respect to the inception time. Measurements were conducted by applying three voltage variations to each voltage source type (AC and DC) with a 0.3 kV difference.

The measurement results shown in Table 2 indicate that as the applied voltage decreases, the PD inception time (T_{in}) increases. This is because the electric field formed at low voltage is not strong enough to immediately trigger PD activity. Additionally, the PD inception time under DC voltage is significantly longer than under AC, as more time is required for charge accumulation and electric field enhancement. This difference is important to understand, as in real-world applications, the type of voltage used (AC or DC) will influence the speed and mechanism of PD occurrence in insulating materials such as HDPE.

Table 2. Measurement results of PD inception time (T_{in})

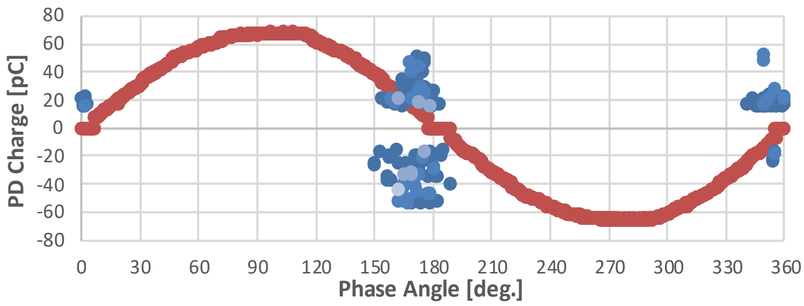
Voltage (kV)		PD inception time (minutes)	
AC	DC	AC	DC
11.5	15.2	1:00	1:46
11.2	14.9	5:21	7:00
10.9	14.6	13:41	20:00

3.3. PD characteristics

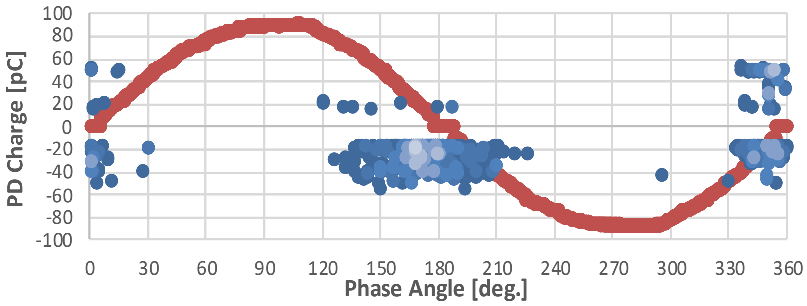
After determining the PD inception voltage (V_{in}), the voltage is increased by 10% above this value and maintained constantly. Measurements are conducted using both AC and DC high voltages. PD activity is then measured over a 1-hour testing period to assess the characteristics and magnitude of the PD charge in HDPE.

3.3.1. AC results

The measurement of the PD inception voltage (V_{in}) under AC voltage resulted in a value of 11.8 kV. Therefore, the applied voltage increased to 13 kV and 15 kV. PD was detected using an RC detector, and the results are presented in Figure 4, which illustrates the PD magnitude patterns over a one-hour aging process on HDPE material under 13 kV and 15 kV AC stress. As shown in Figures 4(a) and 4(b), PD events are predominantly concentrated on both sides of the sinusoidal cycle (positive and negative), frequently appearing during the initial phase of the voltage waveform near the zero-crossing point. This pattern aligns with previous research [30], which indicates that PD in solid insulation tends to occur more frequently around the zero-crossing point than at the voltage peak. This suggests that the rapid change in the electric field at the zero-crossing is more likely to trigger discharge activity than the relatively stable field at peak voltage. Accordingly, in Figure 4(a), under 13 kV, PD tends to concentrate at phase angles of 0°, 150°–190°, and 340°–360°, with a maximum discharge magnitude of ±53.2 pC. Meanwhile, in Figure 4(b), as the voltage increases to 15 kV, the PD pattern becomes more dispersed and occurs more frequently, covering a wider range of phase angles, including 0°–30°, 120°–225°, and 295°–360°. Along with this broader distribution, the maximum discharge also increases, reaching ±54 pC.



(a)



(b)

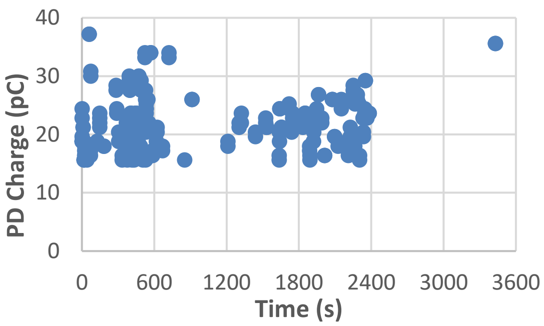
Figure 4. PD measurement results at (a) 13 kV AC and (b) 15 kV AC

This condition indicates that a higher applied voltage results in a stronger electric field around the sample, thereby increasing the likelihood of ionization within the material's cavities. Consequently, the discharge activity becomes more intense, accompanied by an increase in PD magnitude. These findings are consistent with previous studies [5], [13], [31]–[33], which reported that an increase in applied voltage significantly affects both the intensity and magnitude of partial discharge. Such insights can serve as a valuable reference for predicting insulation degradation patterns in AC-based electrical systems and for designing systems that are more resistant to PD phenomena.

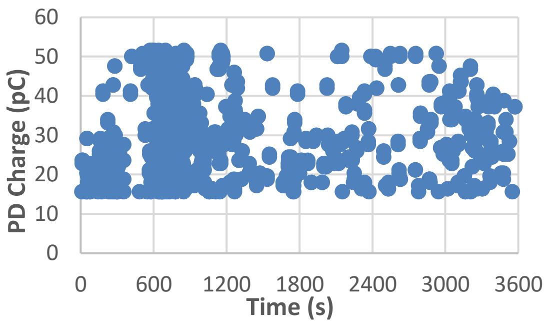
3.3.2. DC results

The measurement of the PD inception voltage (V_{in}) under DC voltage yielded a value of 15.5 kV. Therefore, the applied voltage increased to 17 kV and 19 kV. The measurement results presented in Figure 5 illustrate the PD charge activity during a one-hour aging process under DC voltages of 17 kV and 19 kV. Figure 5(a) shows the PD activity at 17 kV DC, where the discharges appear limited, with few occurrences concentrated within the 15 to 30 pC range, and no significant spikes exceeding 40 pC. Interestingly, toward the end of the test, PD activity was almost undetectable, with only a single event recorded. This indicates localized stabilization within the test sample, likely due to the applied voltage no longer being sufficient to sustain the local electric field necessary to trigger PD. As a result, PD activity temporarily disappeared. This condition suggests that although PD occurred, the material did not undergo significant degradation during the test period. In contrast, Figure 5(b) displays PD activity at 19 kV DC, which is more widespread and uniformly distributed compared to 17 kV DC, with more discharge events across a broader charge range. This observation aligns with the findings in [33], which state that both the magnitude and frequency of PD under DC conditions increase with the applied voltage. This pattern indicates that the insulating material is subjected to greater dielectric stress. A continuously applied high voltage can trigger PD with higher charge and frequency due to space charge accumulation, increased local electric fields, and cavity surface degradation resulting from repeated PD activity [34].

Based on the PD test results under two types of voltage sources, the magnitude of PD charge under DC voltage exhibited values comparable to those under AC conditions. However, a higher voltage was required in the DC case, as the inception voltage needed to trigger PD was also greater. This finding highlights the importance of understanding the different responses of insulation systems to PD under AC and DC voltages, particularly in the context of insulation design and reliability assessment in modern electrical applications. The variation in material responses to different voltage sources suggests that insulation performance evaluation cannot rely on testing under a single condition alone. PD testing under both AC and DC voltages is crucial to provide a comprehensive understanding of the insulation material's reliability under actual operating conditions. Nevertheless, PD test results can also be affected by various other factors such as electrode configuration, defect type, cavity size, material type, material thickness, and environmental conditions during testing. Therefore, further comprehensive studies are needed to confirm and expand the understanding of this phenomenon.



(a)



(b)

Figure 5. PD measurement results at (a) 17 kV DC and (b) 19 kV DC

4. CONCLUSION

Measuring and analysis of PD characteristics in HDPE samples using the CIGRE method II electrode system have been carried out, and the results indicate that HDPE performs better under DC voltage compared to AC voltage. This is evidenced by the higher average PD inception voltage (V_{in}) under DC conditions, which reached 15.5 kV, compared to only 11.8 kV under AC. Additionally, the PD inception time (T_{in}) was significantly longer under DC conditions. A correlation between the applied voltage magnitude and PD inception time was observed, with Tin tending to increase as the applied voltage decreased. Moreover, the magnitude of the applied voltage also influenced the PD charge values and activity intensity. Under AC voltage, PD patterns were concentrated on both sides of the sinusoidal cycle (positive and negative), particularly in the early phase near the zero-crossing point. In contrast, PD activity under DC voltage was not influenced by voltage cycles, resulting in a more stable distribution. Although the PD charge magnitudes under both AC and DC conditions were nearly the same, the voltage required to initiate PD under DC was significantly higher, indicating that HDPE exhibits better insulation resistance under DC voltage.

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