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Characterization of Corona and Internal Partial Discharge under Increasing Electrical Stress using Time Domain Analysis

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***Abstract*— Aging and abnormal stresses accelerate insulation degradation and reduce the lifetime of power equipment. Partial discharge (PD) measurement is an effective tool to study the condition of the insulation. Reliability of PD diagnosis depends on the accurate interpretation of the measured PD signals. PD itself is a complex phenomenon and the presence of different types of discharge sources makes interpretation of the PD data quite challenging. This paper investigates internal and corona PDs in order to distinguish them when both are active simultaneously. The presented work identifies the PD sources based on time domain analysis that provides a simplified solution as compared to identification techniques based on different statistical features leading to complex data processing. While superimposed phase-resolved partial discharge (PRPD) patterns provided incomplete information, time domain PD characteristics e.g. pulse repetition rate and pulse amplitude combined with PRPD mapping are analyzed to differentiate PD activity. Furthermore, the electrical stress (voltage level) is increased gradually in the experiments made and PD behavior is studied. The presented technique contributes to enhancing the accuracy of PD diagnosis that is necessary for appropriate decision making concerning the repair of affected components.**

Keywords—Electrical insulation, internal discharge, corona discharge, electrical stress, monitoring

I. INTRODUCTION

Electrical insulation is composed of a non-conductive material and performs a dual function: it provides mechanical support and forms a dielectric barrier between two electrodes of a power component. One of the major causes of insulation aging and deterioration are the electrical discharges that are triggered because of increased operational and environmental stresses [1]. Partial discharge (PD) is likely to occur in electrical installations and equipment operating at higher voltage levels where the electrical stress exceeds 3 kV/mm (the approximate breakdown strength of air in a uniform electric field). During progression of the PD activity, generation of compounds such as ozone (O_3) and nitric acid (HNO_3), growth of local hot spots, cracking associated with chemical breakdown and a gradual increase of the electrical conductivity accelerate the rate of insulation degradation [2]. Depending on the type of PD activity and the magnitude of the stresses, the affected component may eventually fail within months, weeks, or even hours, if not attended to in a timely manner [3].

Electrical insulation is present inside and around power equipment either as its design component and/or in the form of air surrounding the conductive parts of the equipment. PD emerges at the interfaces between the conductors and insulation under electrical stresses and can be divided into three distinct types; internal, corona, and surface. Internal PDs are produced when ionization occurs in the voids inside the solid or liquid insulation during an increase of electrical stress exceeding the partial discharge inception voltage (PDIV) [3]. A cavity inside the solid insulation of a cable or a gas bubble inside the transformer oil causes such PDs to be triggered. Small discharges or "spewing" of electrons from the sharp points on conductors to the air occurring due to high voltage stress are considered to be corona discharges [2]. The ends of a single cable strand, metallic edges, or scratches can be a probable source of corona discharges. Corona is not usually considered to be a dangerous type of discharge. However, it can appear as a disturbance during on-line PD monitoring [5].

PD can also occur along the surface of electrical insulation if the tangential electric field component at the surface is high enough [6]. Non-uniform contamination, moisture, or a high conductivity path from the conductor to the insulation surface under high voltage stress initiates surface discharges. Sometimes electrical treeing is presented as a 4th type of PD, which presents as a network of conducting channels growing inside the insulation (hence the name) [5]. However, due to its mechanism, it can be considered a progressive stage of internal PDs.

It has been observed that during medium or high voltage operation and testing, the PD measurements include one or more types of PD sources that are active simultaneously. Accurate interpretation of the observed PD activity is critical for reliable diagnostics of power components. A significant

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amount of research has been conducted for identification of the PDs using various sophisticated data processing techniques [7]-[8]. The given research accomplishes the identification tasks by performing the analysis using the probabilistic and statistical parameters or by using pattern recognition, referring to artificial intelligence based PD patterns such as presented in [9]-[11].

The available techniques are based on in-depth data processing which is performed at the data centers where the data are communicated from the field or on-site sensors and measurement units. Such techniques provide value; however, they are time-consuming and do not provide rapid on-site information due to remote processing. Furthermore, the identified PD diagnostic results gained by using the statistical techniques and pattern recognition based methods still need the validation from experts with knowledge about the actual PD mechanisms and their signatures.

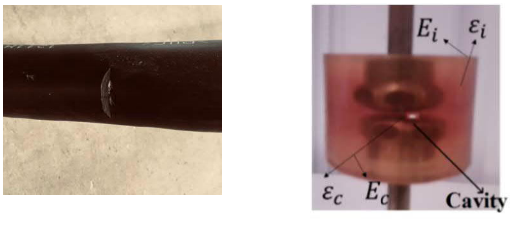
This paper presents an experimental study to identify the internal and corona PDs considering the characteristics associated with the PD mechanism. In this work, two types of measurement scenarios are presented, which include the individual and combined PD activity for internal and corona discharges. In addition to the PRPD based analysis, the pulse characteristics such as pulse amplitude, pulse repetition rate, and phase characteristics of the PD activity is used to study the types of discharges that are explained further in this paper.

II. INTERNAL AND CORONA PARTIAL DISCHARGES

Internal PDs pose a significant threat to electrical insulation. On the other hand, rather than a threat, corona is considered a source of disturbances during internal PD measurements. Therefore, it is essential to identify the origin of the measured PDs in order to make an accurate assessment of the ongoing discharge activity.

A. Internal PD

Considering solid insulation, cavities or voids may develop inside the insulation due to gas bubbles (Fig. 1(a)) forming during manufacturing or because of local hot spots appearing during elevated thermal stresses. Similarly, the cracks may appear because of bending beyond the permissible limits or mechanical stresses. Accidental cuts that cause damage of the outer sheath and the shielding in cables can also be a likely cause as shown in Fig. 1(b).



(a). A cut on the MV cable. (b). A cavity inside the insulation.

Fig. 1. Internal PD defects inside the solid dielectric insulation.

Considering the air cavity depicted in Fig. 1(a), the relative permittivity of the air is $\varepsilon_c = 1$ while the relative permittivity of the polyethylene insulation is $\varepsilon_i = 2.2$. The electric field strength E_c across the air cavity becomes greater than that of the healthy insulation E_i and can be estimated by [12]:

$$E_c = \frac{2\varepsilon_i}{\varepsilon_c + 2\varepsilon_i} E_i = 1.22\, E_i. \qquad (1)$$

This increase in the electrical field strength causes the cavity to breakdown earlier than healthy insulation. However, the surrounding healthy insulation is intact; the breakdown does not bridge the whole insulation.

B. Corona PD

Corona is likely to occur on high voltage equipment, especially at a sharp protrusion on a bare conductor energized to a high enough voltage. Because of the sharp edge, the local electrical field is significantly enhanced around the point. Considering corona in air at atmospheric pressure, when the electrical stress surpasses approximately 3 kV/mm, PD occurs. The inception voltage initiating corona discharges depends on the curvature of the point or edge of the conductor and its distance from the grounded electrode, which can be estimated based on [2]:

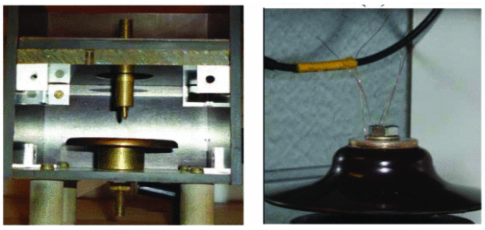
$$E_{max} = \frac{2V}{R \ln(\frac{4H}{R})}, \qquad (2)$$

where E_{max} is the electric field at the point, V is the voltage applied across the electrodes, R is the radius of curvature at the point and H is the distance between electrodes. The electric field required for the inception of corona at standard temperature and pressure (STP) can be expressed as [13]:

$$E_i = E_o(1 + 4.10^{-3}h)\left[1 + \frac{0.166}{R_e^{0.45}}\right], \qquad (3)$$

where E_o= 3 kV/mm (the breakdown strength of the air), h is the absolute humidity, and R_e is determined as:

$$R_e = 0.5 \ln(1 + 2\, H/R). \qquad (4)$$



(a) Corona at needle. (b) Corona around bare conductors.

Fig. 2. Test objects for creating the corona PDs.

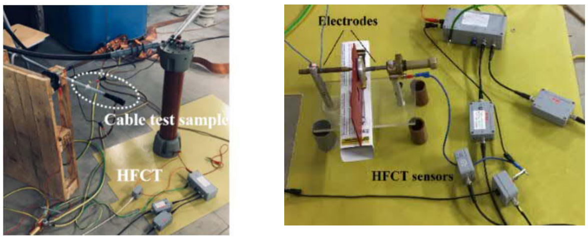
C. Characterstics of PD signals

The characteristics of the PD signals depend on the type of PD source, the physical dimensions of the cavities or cracks, the shape of electrodes, insulation type, magnitude of the applied voltage, and environmental conditions [14]-[15]. The general PD mechanism is based on the ABC capacitive model while behavior of the PD activity is dependent on PD type (internal, corona or surface) [5].

During operation when the applied voltage approaches the inception voltage, the cavity collapses rapidly and produces a partial discharge event. The voltage across the cavity between the electrodes reduces to a small voltage (extinction voltage) and the discharge extinguishes at this stage. Voltage across the cavity again starts to increase until it reaches the inception voltage to create the next discharge. This causes continuous and repetitive discharge events during the power cycle. The PD activity emerges during different phase angles of the voltage during positive and negative half cycles. PD events cause very fast movement of charges and give rise to a high frequency transient current pulse (PD pulse) with pulse duration in the nanosecond to microsecond range [15]. The polarity of these PD pulses depends on the polarity of the applied voltage.

III. EXPERIMENTAL SETUP

Two types of test samples are used in this experimental investigation. For internal PDs, a test object was developed using a 40 cm meter long section of MV cable as shown in Fig. 3(a). The outer sheath, shielding, and the semiconductor layers are removed from the cable piece such that the insulation (cross-linked polyethylene- XLPE) is left over the cable conductor. The thickness of the insulation was 5.5 mm. A metallic pin was pressed inside the cable insulation up to approximately 3 mm and then retracted approximately 1 mm, creating a cavity. During the tests, the needle was energized while the conductor and screen were grounded.



(a). MV cable based sample. (b). Pin-plane based sample.

Fig. 3. Experimental setup for (a) internal and (b) corona PDs.

Fig. 3(b) presents a conventional test setup for creating the corona discharges where the pin-plane configuration is used. In order to avoid a disruptive discharge and short-circuit at increased voltages, a plastic insulating plate was placed adjacent to the flat electrode. A high frequency current transformer (HFCT) with a bandwidth of 0.5 – 80 MHz (at -3 dB) with a transfer ratio of 1:10 is used in both types of tests in order to measure the PD current from the test samples. The output of the HFCT was connected to a digital storage oscilloscope (DSO) with a sampling frequency of 2 GS/s. The tests were conducted at Tallinn University of Technology.

IV. MEASUREMENTS AND RESULTS

Fig. 4 presents the PD measurements for internal PDs during a full cycle of applied voltage. PDIV for the test sample has been recorded at 4.2 kV while the presented measurements (Fig. 4) are taken at 5 kV, 6 kV, and 7 kV. Similarly, during the corona test, PDIV is recorded at 6.3 kV

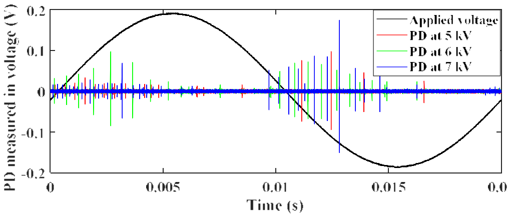


Fig. 4. Measured PD signals of internal discharges.

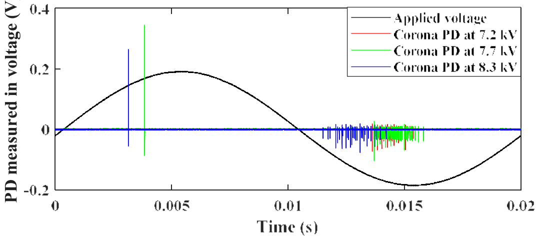


Fig. 5. Measured PD signals of corona discharges.

and the PD data was captured for further elevated voltages: 7.2 kV, 7.7 kV and 8.3 kV as shown in Fig. 5. A comparative analysis of both types of PDs is presented in this section.

A. Behaviour of PD Activity During a Voltage Cycle

Considering the occurrence of the PD activity, the internal discharges are primarily present after the zero crossings and span up to the peaks of the half cycles of applied voltage. This behavior is consistent during both positive and negative half cycles. It has been further observed that at a certain applied voltage level, the amplitude of the PD pulses during the negative half cycle is larger than the amplitudes of the PD pulses during the positive half cycle. This behavior is consistent for all the applied levels of the voltage.

Initially (above the PDIV), corona activity was concentrated around the peak value (270°) of the negative half cycle and continued spanning towards the zero crossing at 180°. During the positive half cycle, however, there was no sustained PD activity except for a single PD pulse with a significantly higher amplitude. Therefore, it can be clearly observed that internal and corona PDs have a distinctly different behavior during positive and negative half cycles.

B. PD Pulses per Voltage Cycle

By increasing the applied voltage above the PDIV, the PD activity during internal and corona discharges progressed according to certain trends. It can be seen in Fig. 6 (presenting a part of the negative half cycle) that during internal discharge activity, the phase span of the PD pulses remains approximately the same. However, the number of pulses increases with the increase in applied voltage. At 5 kV, mainly three pulses (in red) are observed while the number of PD pulses increases after increasing the applied voltage to 6 kV (green) and 7 kV (blue). Due to the very nature of the PD mechanism [4], the PD pulses appear and disappear rapidly. Therefore, it needs further exploration whether the increase in the number of pulses has a certain proportion in relation to the increase in applied voltage.

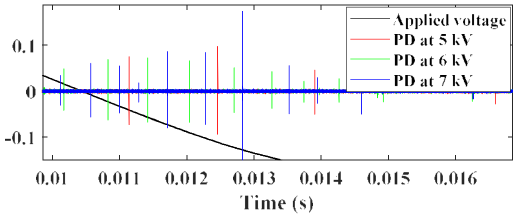


Fig. 6. Internal PDs during first quarter of negative half cycle.

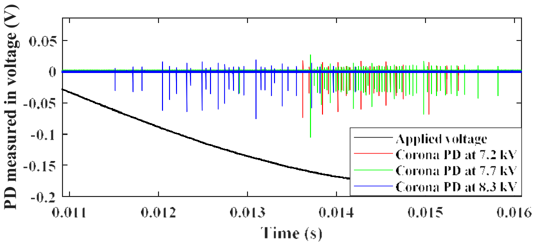


Fig. 7. Corona PDs during first quarter of negative half cycle.

Considering corona discharges, the PD activity has a consistent behavior at increased voltages. Fig. 7 shows that as the applied voltage is increased from 7.2 kV to 7.7 kV and 8.3 kV, the number of PD pulses increases in a certain proportion. It should be noted that the rate of increase of the number of pulses during corona discharges is significantly higher when compared with the increase in the number of pulses for internal discharges. Another consistent behavior can be observed in the phase span of the PDs during corona discharges. By increasing the applied voltage, the phase span of the PDs increases from the peak region (270°) of the half cycle toward the zero crossing at 180°. Considering the amplitude of the PD pulses, the average amplitude remains constant across different voltage levels.

C. Study of Superimposed Discharges

Observing the above presented characteristics, it can be stated that internal and corona discharges exhibit distinct PD activity that enables to assess their presence if they exist simultaneously in PD data. Fig. 8 shows the measured PD activity at two different voltages in which the corona PDs are superimposed on the internal PDs. Due to a greater number of pulses per unit time and an approximately equal amplitude, the corona discharges clearly develop a distinctive group or cluster of pulses that can be identified and separated from the internal PDs. It is also notable how this behavior occurs only during the negative half cycle.

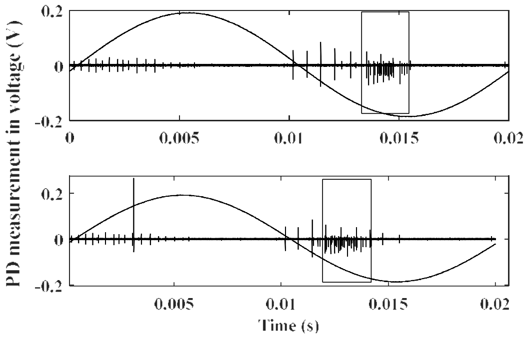


Fig. 8. Corona PDs superimposed on internal PDs.

During on-site measurements, generally, the applied voltage is not available with correct phase information due to power factor that may cause ambiguity while making a PRPD based assessment of the occurring PD activity. In this case, the captured data at certain voltage level may not present a distinguishable PD pattern. In order to carry out a reliable diagnosis, it is proposed to do an offline testing of the affected component by increasing the voltage up to a safe limit. A dense PD pulse cluster will appear if the corona is emerging in the measured PD data.

PD quantification is the concluding task during diagnosis that is usually carried out based on the apparent charge displaced. When using current pulses as PD data (as presented in this work), the amount of the charge is calculated by the area under the curve of the current pulses. Therefore, in case of internal PDs, it is important to select the correct pulses for charge quantification. In order to avoid ambiguity, the PD pulses with amplitude greater than the average amplitude of the corona PD activity should be selected for this purpose. The purpose is to ensure that the chosen pulse belongs to internal PDs.

V. CONCLUSIONS

The smart grid implementation roadmap demands for transformation of the conventional power grid into a resilient and more reliable grid. Therefore, advancements in PD monitoring and diagnostics are gaining popularity for the purposes of fault prediction and mitigation.

The aim of the presented work is to demonstrate how to identify the internal PDs when there is an indication of corona sources superimposed on the internal PDs, which are considered the most harmful type of PD for power equipment. The presented study enhances the understanding of the measured PD activity based on the measurement of PD current pulses using HFCT sensors.

The study proposes that when PD activity is detected during on-site investigation, the PD data should be captured by increasing the voltage stress up to suitably higher levels beyond the PDIV. The behavior of the number of PD pulses per power cycle, amplitude variation, and phase of PD activity during positive and negative half cycles provide valuable information in order to interpret the ongoing PD activity. The paper demonstrates a simple approach in the time domain for immediate analysis of the monitored PDs during onsite diagnostics.

VI. ACKNOWLEDGEMENT

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