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A Review of Partial Discharge Signals Occurrence in Polluted High Voltage Insulator

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Abstract
The application of sufficiently intense electric fields to insulators induces finite currents and then the insulators become conductive. This phenomenon is called dielectric breakdown and known as a fundamental non-equilibrium and nonlinear transport phenomenon in solids. Partial discharge (PD) is a small electrical avalanche caused by locally disrupted electric fields in dielectric materialsand is known to be one of the major factors which accelerates the degradation of electrical insulation. Pollution is the most important cause of external electrical failure of the insulator, fol-lowed by the operation of relays and the exit of transmission lines from the power grid. It is believed that the flashover and partial discharge phenomena are strongly related to environmental conditions such as temperature, humidity, pressure, pollution, and even space charges. In this review paper, we will identify the types of insulators associated with pollution sources and present laboratory results while defining partial discharge and its effects on equipment.

Keywords: Partial discharge, insulator, high voltage, contamination, flashover.

1. INTRODUCTION

Infected insulation behaviors were studied through researchers over the years. While the humidity reaches a massive level, the contaminants that deposit at the insulation floor shape a conductive layer on that floor.

With this formation that appears, the incidence of leakage moderns will observe. Leakage current increases the temperature, and as a result, dry bands shape on the floor of the insulation. All through the formation of dry bands, minor discharges and arcs arise, as a stop end result, viable insulating glide takes area [1-4].

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A good way to simulate the phenomena happening at the surface of insulators, numerous theoretical fashions have been proposed, among which, Rizak version [5] attempts to provide the simulation of the crucial arc length of infected insulation and additionally the impact of dynamic voltage drop. Inside the leakage modern-day waveform, the important flashover voltage grows to be additionally investigated. Vosloo and Holtzhausen [6] recently proposed a version of a circuit identical to an infected insulator based mostly on which everyday leakage present-day measurements were considered. In the unique case, the leakage contemporary waveform is saved wherein the almost everyday rate occurs. A theoretical version for predicting the flashover voltage is likewise provided [7], which includes the re-ignition homes of dry band arcs. Within the stated fashions, the same circuit, in particular, includes a conductive layer resistor at the floor of the tainted insulation, which seems to indicate the incidence of a mainly quick arc in circulating along the vicinity [5-7]. Not one of the above models encompasses the analytical mathematical evaluation of the corresponding equal circuit proposed.

Monitor partial discharge, as a symptom of insulation deterioration, can be used to improve the reliability of HV insulation. Usually, the techniques employed for PD detection are based on chemical [8], acoustic [9], optical [10], and electrical which all involved with ultra frequency measurements. The electrical measurement of PD in HVDC systems are widely used. Leakage current data flowing in a reactor's insulation post, to help to build a better understanding of the correlation between PD. When the visible discharge is caused by environmental impacts, we will have a better understanding of environmental impacts, and HVDC insulation systems will be considered for future design.

The definition of PD is almost huge, generally defined as a comprehensive discharge or surrounded by an insulating fabric [11]. Due to the excessive electrical resistance of insulating substances, PDs are typically low density within the tool. One of the drawbacks that have obtained a lot of research interest is air-filled cavities, generally spherical or cylindrical, surrounded with the aid of solid dielectric fabric. Those experiments especially use the "sandwich" method to make a cylindrical hollow which includes three plates with a circular hole drilled within the main ab plate. The compressed plates are then placed among the parallels plate electrodes. The outstanding dielectric material used to make cylindrical cavities is called LDPE [12]. Spherical cavities in epoxy resins [13,14] and silicone rubber are made by using injecting air and syringes earlier than the filtration machine [15].

The present paper part of a long-term study for a Partial discharge.

The main objectives of this article can be summarized as follows:

- Search for literature in the following areas
  - Definition of partial discharge
  - Types of partial discharges
- Study of insulation classifications
- Pollution types of infections
- Scientific study of the effect of pollution on increasing partial discharge

2. PARTIAL DISCHARGE (PD)

Based on the IEC60270 standard, partial discharge is defined as “localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor,”. The IEC60270 standard also states that:

“Partial discharge is generally thought to be the result of a concentration of local electrical stress on the insulation or insulation surface. In general, such discharges appear as pulses lasting much less than 1 us. Therefore, more persistent forms can occur, such as so-called pulse discharges in gas dielectrics. Partial discharges are often accompanied by the emission of sound, light, heat, and chemical reactions,” [16].

Since PD will compromise insulation materials in both physical and chemical ways, PD is important to be discussed. If PD issues keep happening, it might eventually cause high-voltage equipment failure. Thus, detecting and mitigating PD problems are critical topics in the field of high-voltage engineering. Based on different characteristics, PDs can be defined as internal discharge, surface discharge, and corona. By internal discharge, it is meant that discharges occur inside the solid insulation or at the edge of conductors in solid/liquid insulation. Surface discharge is a type of discharge that may occur on the surface of insulation material. Corona charge refers to partial discharge in gasses around conductors that are removed from solid or liquid insulation. Partial discharge is a complex physical process with stochastic properties [17].

• Partial Discharge Pulse (PD pulse): In IEC 60270 standard, partial discharge pulse is defined as “The current or voltage pulse can be caused by a partial discharge inside the object under test. The pulses will be measured using appropriate tracking circuits that haveentered into the test circuit for testing”.

• Discharge Inception Voltage (PDIV): “The starting voltage is the lowest operating voltage at which a PD pulse value is equal to or less than a specified value”.

• Discharge Extinction Voltage (PDEV): “The extinction voltage *U*e is the lowest applied voltage when the magnitude of the selected PD pulse is equal to or less than the specified value”.

• Apparent Charge (q): “The apparent charge q of a PD pulse is a charge that, if injected into a sample test circuit in a very short time between the test terminals, it does the same thing on the PD current pulse meter itself. Significant cost is usually described in pico-coulombs (PC). The apparent load is not equal to the local charge at the discharge point, so, it cannot be measured directly”.

• PD Pulse Repetition Rate (n): “The ratio between the total number of PD pulses stored in a time interval and the duration of that interval. In practice, only pulses above a certain value or within a certain range is considered”.

3. TYPES OF PARTIAL DISCHARGE

IEC 60270 (PD measurements) defines partial discharge as ‘a localised electrical discharge that only in part bridges the insulation between conductors and which may additionally or won't occur adjoining to a conductor’. If the insulation is completelybridged then the insulation breaks down. These discharges can occur internally or externally to the insulation.

In line with the nature, and area of partial discharge, they can be classified into the subsequent three categories [18]:

1- internal discharge - normally happens in cavities packed with a gas known as cavities of liquid, and solid insulation substances.

2- surface discharge - happens on the surface of an insulating fabric or in reference to various insulating substances.

3- Corona discharge - occurs at sharp edges or skinny conductors which can be connected to excessive capability or ground.

Figure 1, shows the different types of discharges along with their locations.

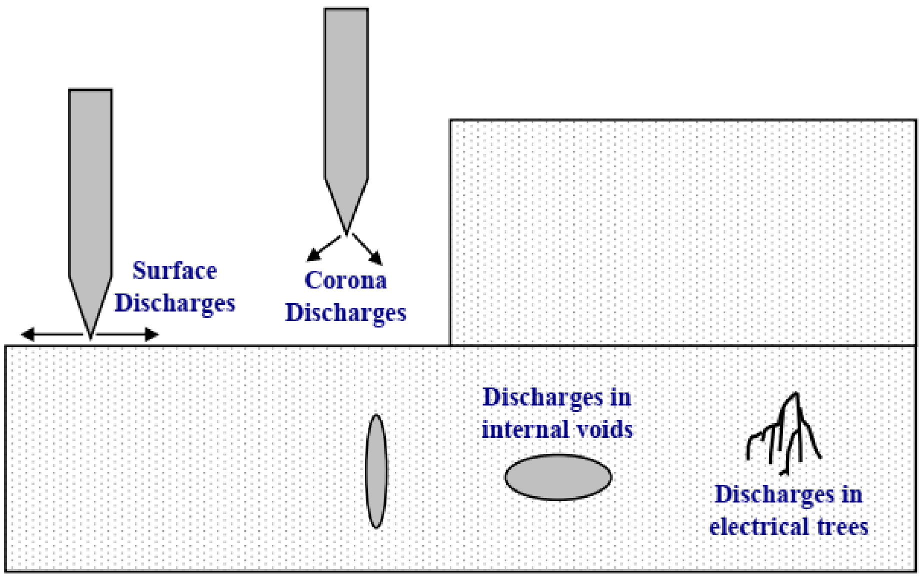


Fig. 1. Different Types of Discharges.

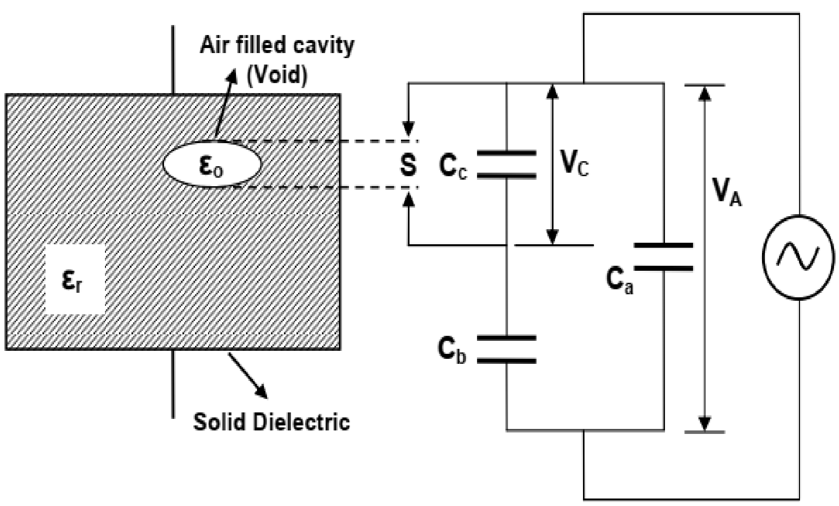


Fig. 2. Simple model of a cavity in dielectric.

TABLE 1. ***The relative permittivity and breakdown strength of HV insulating materials.***

Material	Relative permittivity	Breakdown strength kV/mm
Air (atmospheric pressure)	1.006	2
Transformer Oil	2.2	28
Polyethylene	2.3	24
Polyurethane	4.0	10
Paper	3.0	9
Mica	6.0	42
Epoxy	4.7	12

3.1. Internal Discharges

Inner discharges take location in inclusions or cavities (voids) within the insulation. It isn't always nearly feasible to completely dispose of the prevalence of small faults like voids in an insulating material. A practical insulation shape of a high voltage stator will invariably incorporate small voids or cavities, often due to inhomogeneities inside the insulating material used for the production. Herbal resin-based coils and artificial resin-based totally coils contain gaseous inclusions and are formed because of small quantities of air that grow to be trapped in the insulation during the curing and urgent levels.

These cavities, packed with air, commonly have a decrease permittivity and a decrease breakdown strength in comparison to the insulating fabric. This causes the sphere depth to be higher within the hollow space than within the dielectric material and can motive a breakdown, even beneath everyday operating stress, affecting the long time integrity of the insulating fabric.

3.1.1. Analogue Discharge Circuit

Inner partial discharge behavior below voltage stress a.c. can be without problems described by using representing the analog equivalent circuit, regularly known as the ' abc' circuit [18]. Figure 2 displays a simple chart of a hollow in a segment of strong insulation fabric with its equal circuit.

In figure 2, the capacitor C_c represents the capacitance of the cavity; C_b represents the Capacitance of the dielectric material in collection with the hollow space, and C_a represents the capacitance of the rest of the dielectric material. 'S' represents the spark gap which breaks down whilst the voltage across it reaches the void breakdown level.

Table 1 shows the relative permittivity and breakdown strengths of a few typical high voltage insulating materials.

The relative permittivity of air 'ε_o' is the same as harmony, whereas the permittivity of soliddielectric (e.g. Insulated epoxy mica) which is given via 'ε_r' which varies between 4 and 6. While the Given solid dielectric is subjected to high voltage (E_S), the electrical strain advanced, across the hollow space (E_C), given by using:

$$E_C = (\varepsilon_r/\varepsilon_o).E_S \qquad (1)$$

where ε_o equals to relative permittivity of air and ε_r equals to relative permittivity of solid dielectric

For that reason, it's miles clean from equation (1) and table 1 that the electrical stress across the hollow space is appreciably improved. The quantity of pressure awareness, within the hollow space, relies upon on numerous other factors such as the shape and length of the hollow space. Kang et al. [19] confirmed that discharge parameters consisting of significance, repetition fee, imply discharge strength and suggestion drift price was higher in samples with larger cavities. Due to this fact that breaking electricity of air at a atmospheric stress is about 3 kV/mm, it can be seen that discharges occur at medium to excessive voltage.

In keeping with figure 3, the high voltage across the dielectric is denoted by V_a and the voltage throughout the hollow space is denoted via V_c. A discharge happens when the V_C voltage exceeds the fantastic breakdown voltage U+ (initial voltage) of the cavity. The breakdown voltage U+ is decided with the aid of the Patches curve, which relates the breakdown voltage of the air to the fabricated from pressure and electrode distance [18]. While the discharge occurs, the voltage throughout the hollow space drops to voltage V+ (extinction voltage) and the release is switched off. This usually takes place at instances less than 0.1μS. The voltage does not attain zero since a residual voltage will continue to be for the duration of the hole.

After the extinction of discharges, the voltage throughout the hollow space increases again along side the applied voltage V_a. Some other discharge occurs while the voltage across the hollow space reaches U-. This sequence of discharges repeats numerous instances till the applied voltage V_a starts offevolved to lower and the discharges cease. For this reason, several discharges are produced in the course of the growing portion of the tremendous 1/2 cycle. A similar method takes region within the bad half of cycle in which the discharges arise while the

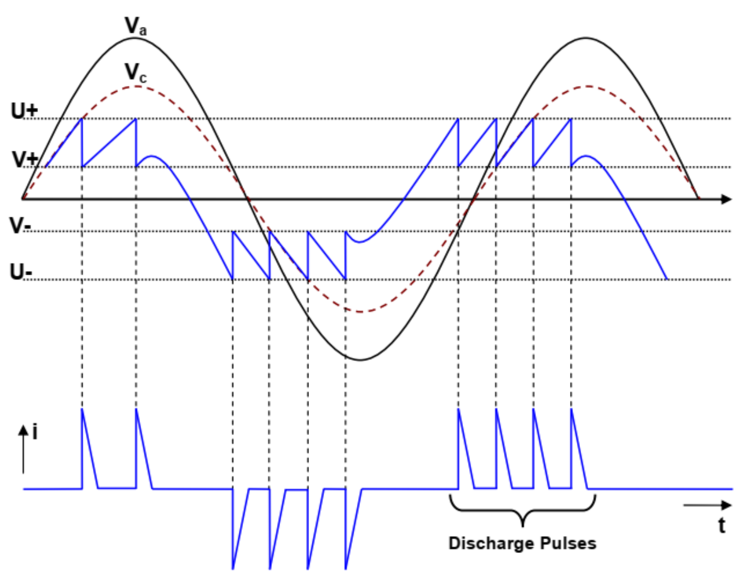


Fig.3. Sequence of internal discharges under a.c. voltage.

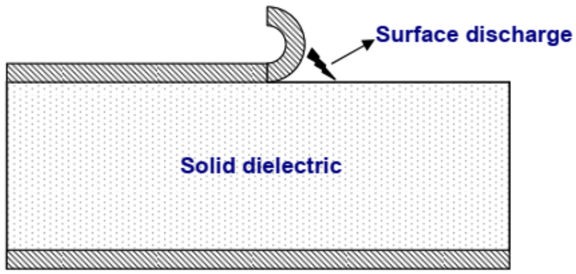


Fig. 4. Surface Discharges.

voltage throughout the hollow space exceeds U-. On this manner companies of regularly taking place superb and terrible Discharges will be produced. Each discharge will motive a present day pulse as shown in figure three, and those can be detected through electricalway [20,21].

3.2. Surface Discharges

Surface discharge can also arise while there may be a pressure element parallel to the dielectric surface, as proven in Figure 4. Strain causes depletion. They are normally located in trees, cable ends, and device winding coils. Floor discharge relies upon on numerous elements [22]:

- Physical residences of the surroundings wherein discharge takes region (gas, liquid).
- Physical houses of solid dielectrics (permittivity, floor resistance, conductivity).
- Distribution of electric subject within the site between electrodes.
- Type of voltage and time of operation.
- State of surface of strong dielectrics (pollut-ed, sodden).

Cracking is the end result of carbonation of insulation surface and carbon tracks which have a tendency to reduce electrical insulation making the very last damage system quicker [23].

3.3. Corona Discharges

Corona discharges are electrical discharges resulting from the ionisation of the medium, surrounding the conductor. They have a tendency to occur around sharp factors or edges at excessive voltage due to an excessive awareness of charge on a small floor vicinity. The inception voltage of corona discharges is difficult to the country as it's far dependent on various factors like surface smoothness and environmental conditions which have an effect on the distance fee near the conductor. They seem faster at negative than at fantastic voltage; with a.c. voltage, they often arise throughout the terrible 1/2 cycle best [18].

In rotating machines, the stop-windings are more susceptible to corona kind discharges as the electric stress is intensified in the overhang component because of its featureshape. The fuel adjoining to the insulation in the immediate place of the slot go out breaks down and might result in the improvement and propagation of discharges over end-windings [24,25]. Consequently, the software of strain grading structures alongside the end windings is taken into consideration critical for high voltage machines.

4. CATEGORIS OF HIGH VOLTAGE INSULATION

The demand for electrical energy has been increasing gradually. For transmitting a massive amount of electricity, high voltage transmission systems have been extensively used. In the transmission system, high voltage apparatus, such as insulators, play a significant role in attaining normal operation of the power supply [26].

Outdoor insulators are widely used in power transmissions and distribution networks. They help in providing mechanical support to the overhead line conductors, and they isolate them electrically from the tower. This section aims to provide an insight into three different insulating materials in use today: porcelain, glass, and polymers. Porcelain and glass are also known as ceramic insulators, and polymeric insulators are known as composites or non-ceramic insulators. Different profiles of insulators are selected based on the environmental conditions and the application for which they are used, for instance, suspension, tension, and post types. Insulators are also available with different dimensions and designs according to the voltage rating [27, 28].

4.1. Porcelain Insulators

Porcelain insulators have been well known in the power system industry for a long time and are still the most widely used. This inorganic material has demonstrated relatively higher thermal resistance and strength regarding the degradation of the surface. Porcelain is a highly glazed surface [27-29]; this gives the insulator better self-cleaning properties in heavy pollution areas and helps reduce the discharges activities at sharp edges. Moreover, the glaze is chemically inert due to the strong molecular bonds that form the porcelain material. Therefore, the insulator is mechanically solid and has a good resistance surface against corrosion [30, 31]. Figure 5 shows a typical standard profile of a cap-and-pin porcelain insulator, with the main components of a glazed porcelain shed and metal cap-and-pin, which are all embedded together with the mortar [32]. The insulators are joined in series to achieve a string. The number of units used in the string varies based on the system voltage.

4.2. Glass Insulators

Glass insulators have been used in service for up to 70 years, as is discussed in detail in [33]. These insulators offer great resistance due to the thermal handling they receive. With this handling, insulators have enhanced their mechanical properties compared with porcelain cap-and-pin insulators [27]. Toughened glass insulators (Figure 6) have the advantage of facilitating the inspection of the electrical lines even in the case of breakage. Though the glass disc smashes into small parts, the mechanical strength of the insulator remains the same as for the unbroken insulator.

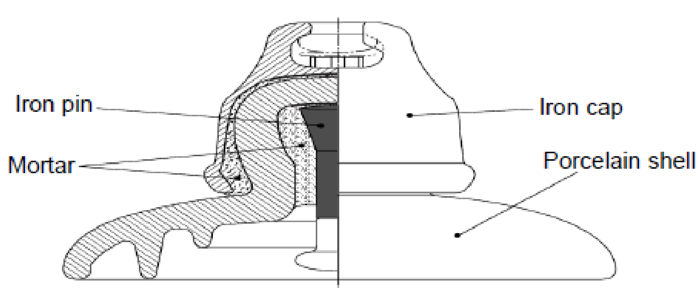


Fig. 5. Standard design cap-and-pin porcelain insulators.

Fig.6. Cap-and-Pin glass insulators.

Nonetheless, glass has a lower melting point than porcelain, making it more susceptible to surface erosion owing to the heat produced by surface discharges [27]. Thus, problems occur in contaminated environments where channelling of the glass surface, particularly the undersides, undermines the mechanical strength of the unit [33].

The flashover performance of ceramic (glass and porcelain) insulators under polluted conditions is substantially reduced, and a larger number of units is required resulting in a heavy insulator string. Therefore, to reduce the size of high voltage apparatus systems, the use of polymeric insulators have been introduced. These insulators are light in weight and have a water-repelling surface, which ensures excellent performance in polluted environments.

4.3. Polymeric Insulator

Due to the increased demands for electricity, it is becoming important to raise the capabilities of power transmission and distribution networks, which has led industrialists to develop and design lighter

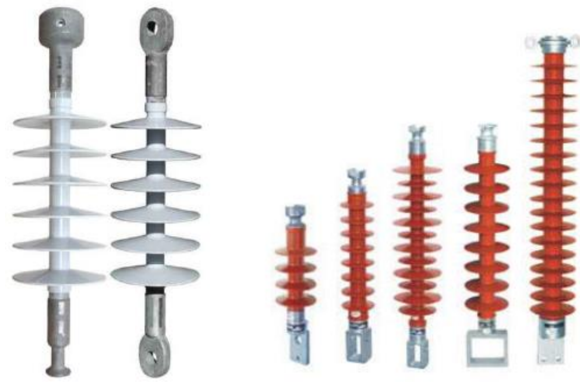


Fig. 7. Polymeric insulators.

insulators that have good mechanical and electrical properties compared with porcelain and glass insulators. In 1970, the first generation of commercial polymeric insulators was introduced [34, 35]. With this inception, developments of composite or non-ceramic insulators increased rapidly [36].

Currently, polymeric insulators are being used in various applications, which include housings, bushings, and simple insulators. This is due to the numerous advantages that they have over porcelain and glass insulators, namely, reduced weight, excellent electrical strength, easy handling and transportation, reduced breakage, and improved resistance to vandalism; recently, they also have improved contamination performance. Nonetheless, despite these advantages, they have a limitation in the form of aging [37-39], that is, degradation, which has a negative influence on their performance and makes them liable to damage.

5. TYPES OF POLLUTION

Contaminated materials can be divided into two groups:

- When solid contamination with insoluble particles settles on the surface of the insulators, this deposit becomes a conductor when wet. This contamination can be well determined through measurement methods such as (ESDD / NSDD). Often related to remote areas, deserts or areas with industrial pollution. This type of pollution also occurs in a series of coastal areas that form a salt layer on the insulator surface and is moistened by dew, moisture, fog or drizzle.

This type of pollution is classified into two groups:

Soluble contamination: The media layer is formed on the surface of the insulator. The soluble contamination itself is divided into highly soluble solutes, and low soluble solutes. Soluble contamination is measured by the ESDD salt deposition density method in mg / cm^2.

Insoluble contamination: In this type of contamination, the contaminants form a solid layer for the media layer. Examples of this type of pollution are dust, sand, soil, and oil. Insoluble contamination is measured regarding NSDD insoluble sediment density in mg / cm2. Insoluble contamination may include conductive contamination (such as metal particles).

- When the liquid electrolyte settles on the surface of the insulators with very fine particles or insoluble particles. These contaminants can be well determined through measurement methods such as conduction or output current. This type of pollution is mostly related to coastal areas where saline or conductive water settles on the surface of insulators. In some areas, both types of contamination may appear on the surface of insulators [40,41].

5.1. Material of Pollution

The type of pollution varies according to the conditions of different types of pollution sources, which are as follows:

Desert - These areas naturally contain solutes that dissolve in water. In these areas, due to irregular rainfall and the type of pollution, self-cleaning is not very effective. Sandstorms and winds, even during the rainy season, can contaminate the surface of insulators.

Beaches - Polluted bill in these areas contains solutes with a high solubility rate in water and very small amounts of insoluble matter. And over a longer period can occur through the deposition of salt particles caused by wind.

Industrial - The contaminated layer may contain conductive particles such as coal, metal particles and soluble particles such as SOX, NOX in gases from industrial installations or particles that are difficult to dissolve such as cement and gypsum.

Agriculture - Pollution layer in these areas includes various solutes with fast or slow dissolution such as chemicals used for chemical products, bird droppings or solutes in the soil [42,43].

6. RESULTS PD AND FLASHOVER EXPERIMENTS

To investigate the hypothesis discussed, a downscaled insulator testing unit inside a fog chamber was built at the University of Manitoba's McMath High Voltage lab. By adjusting the environmental parameters (temperature and humidity) and injecting free charges to the surface of the insulator, we tired to recreate an environment, similar to that at the substation, when we observed partial discharge [44]. Ultra-sonic and heated humidifiers were used to adjust the relative humidity levels and the temperature inside the fog chamber. A needle corona ring was

TABLE 2. ***Details of the insulators samples used for PD and ash-over experiments.***

Insulator Type	Outer material	Core Material	Total Diameter	Outer Material Thickness
FRP	Fiber glass reinforced epoxy resin	hollow/foam filled	3.2 cm	3.0 mm
SIR	Silicone rubber	Fiber glass Reinforced epoxy resin	3.0 cm	3.0 mm

used to apply the load to the surface of the test specimen [45]. Free of charge for simulating and modeling was the cost of the HVDC transmission line, which was captured and trapped at the insulation level. Copper strips and two sharp objects are introduced to create a triple points connection between air, insulation, and simulated electrodes for modeling the joint corona, created by the sharp edge of the anvil. The details of the experimental setup, methodology and procedure are demonstrated and discussed in the following sections [46].

6.1. Experimental Setup

Fiber glass reinforced epoxy resin (FRP), Silicone rubber (SIR) insulator samples were used in the experiments. The samples were all 13 cm long. The details of each sample are shown in Table 2.

The FRP sample is from a Chance universal hot stick tool. The silicone samples are from silicone covered FRP rods for use as a modular system of suspension type insulators. The relative permittivity of FRP and silicone rubber was assumed as 4.0 and 3.5. Below in Figure 8, a picture of the samples is shown.

The effective length of the sample is 11 cm, because 1 cm on each side is placed in the grooves of two smooth round metal electrodes on a stick. Figure 9 shows the laboratory equipment used to measure leakage current and the electric field around the test unit.

Figure 10 shows the circuit diagram of the laboratory setup used for investigating the partial discharge performance of different insulation samples under different conditions. Two 150kV, 12mA Glassman HVDC

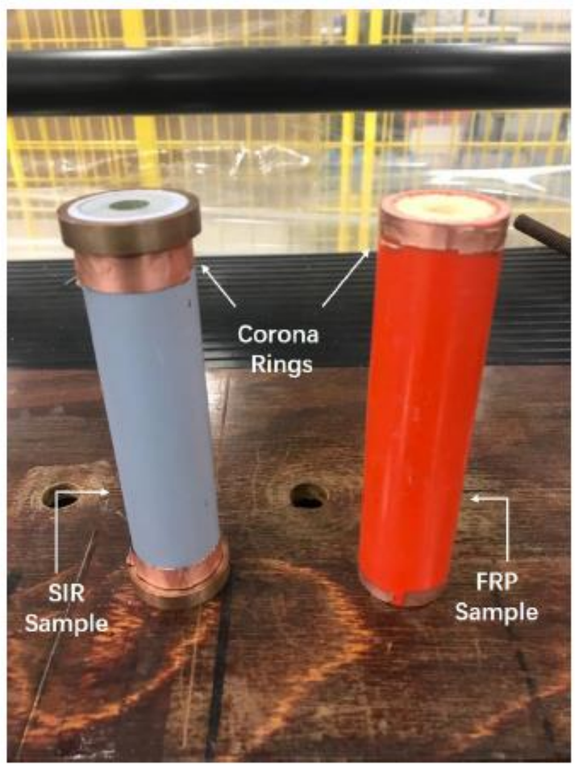


Fig. 8. Insulator samples used in PD and flashover experiments.

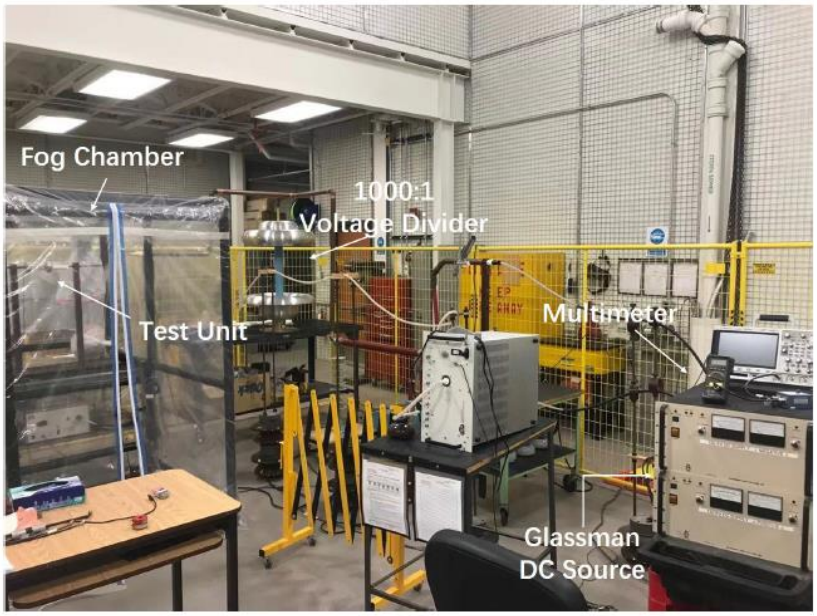


Fig. 9. PD and flashover experiments setups.

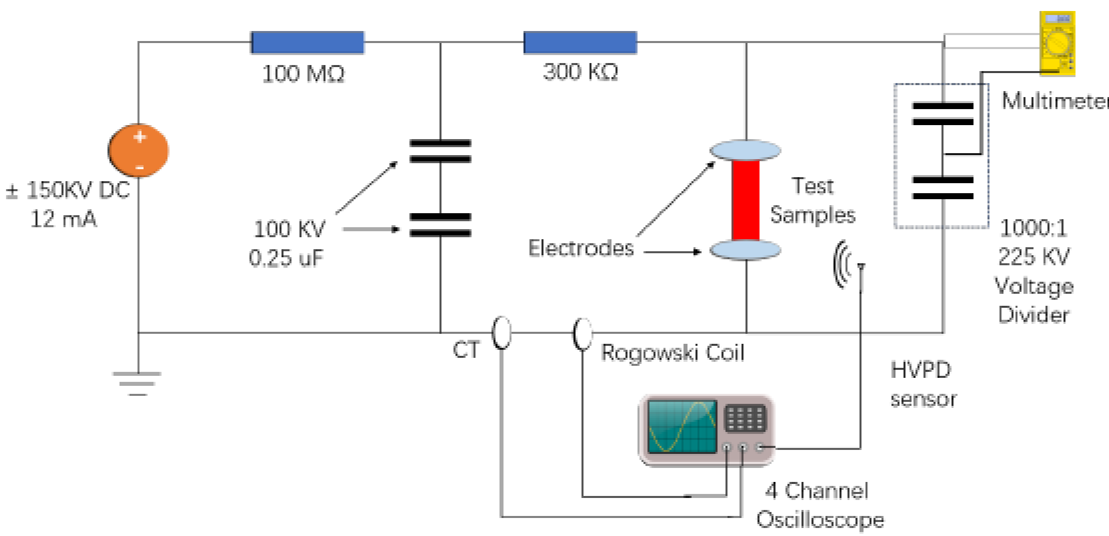


Fig. 10. PD and flashover test circuit diagram.

sources are used separately to generate positive and negative DC voltage. A 300 kΩ resistor is connected in series with the sample to limit the current of the capacitors during flashover. PDIV voltage is controlled by a multimeter by dividing the resistance-capacitive voltage of the mixture from a ratio of 1000: 1 and a maximum of 225 kV with a measurement accuracy of 0.1% DC. Two current transducers are installed separately on the system's ground wire to monitor leakage current [47,48]. One is a CT-C1-S wideband current transformer; the other is a customized Rogowski Coil. A TEV sensor from HVPD with 115mV/V sensitivity is installed on the ground to monitor the electric field distributions.

The oscilloscope was programmed in a controlled memory mode with a 10G sample per second acquisition rate to record the signals from the CT, Rogowski Coil, and the PD sensor. Each segment is 1μs long, including 400ns pre-triggered and 600ns post-triggered data. The oscilloscope trigger was programmed at the falling edge at -270 mV [47].

6.1.1. Methodology Testing for Under Humidity Conditions

A fog chamber made by a transparent plastic shield was introduced to simulate the humid environment in the HVDC substation. By changing the humidity inside the fog chamber, we were able to study PD and flashover characteristics under different humidity levels [49]. The PDIV and breakdown voltage was expected to have significant variation due to the influence of humidity on charge density and the electric field around the energized electrode. The temperature, humidity, and pressure inside the fog chamber were monitored by a BOSCHE BME280 sensor connected with an Arduino Utno microcontroller. Two humidifiers were controlled by the micro-controller to maintain the humidity level inside the chamber [50]. The fog chamber was activated 20 minutes before the PD and flashover experiments and the humidity level inside the chamber was set to 5% above the desired test value so that the humidi_er did not need to operate during the test. After the experiment was complete, the chamber was left open overnight to dissipate the ionized gas inside the chamber. The test was carried out and repeated on 3 different relative humidity levels: dry conditions (20%RH), normal room conditions (50% RH), and humid conditions (80% RH). Since the temperature inside the lab was different during the tests, the relative humidity levels were converted into absolute humidity and used to keep all test conditions the same [51-53].

6.1.2 Methodology Used for Surface Charging

Two different charging methods were investigated to investigate the load characteristics in insulated samples. The first method creates spatial loads in the surrounding air for the first time through a corona-free discharge source called a needle corona ring. This protected a 3D-published polyethylene frame on which 27 needles have been mounted. Lengthy needles 6.4 cm at the margin of the frame with a distance of 1 cm were distributed between both adjoining needle tip. The needles were distributed asymmetrically across the patterned floor and the separation distance among the needle tip and the sample surface became maintained throughout 5 mm inhibition. The two electrodes were held on the ground as shown in Figure 11,. The needle ring was tangled and could be easily opened for installation and removal. The needle ring in Figure 4.5 is shown closed and open on top of each other [54].

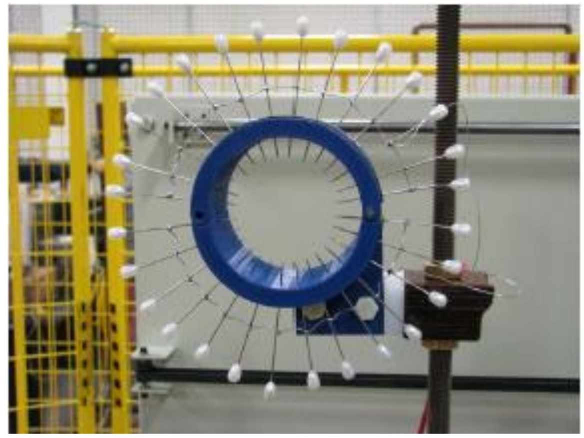
The second charging method become conducted to charge to the area alongside the sample surface through direct touch between the patterns and the DC voltage supply. This method results inside the electrodes with DC voltage by way of giving energy to one of the electrodes, in order that the alternative electrode is stored in base mode. Charging on the floor of insulation utilizing draining corona, from close to-strength gadgets or direct contact with electricity gadgets, enables load-precipitation to manage at the insulation surface [55,56].

Copper strips and two distorted nails were introduced to create a triple-point junction between air, the insulator and the electrodes. This setup is shown in Figure 13. Tests were carried out without copper strips, with copper strips at both ends, with copper only at the ground or energized side and with copper strips and nails at both ends [57].

6.2. Experiment Procedure

6.2.1. PD and Flashover Test Under Humid Condition

All samples had been cleaned before the test to make certain that the surface become easy, dry, and free of any strain. The simplest way to neutralize the weight is to soak a saturated fabric in distilled water, and wrap it across the pattern for two min. FRP and SIR samples are then washed with isopropyl alcohol to clean the surface to ensure that no contaminants or conductive residues stay on it [49].



(a) Corona Ring Closed

(b)Corona Ring Open

Fig. 12. Corona ring of needles used for applying non-contact space charge.

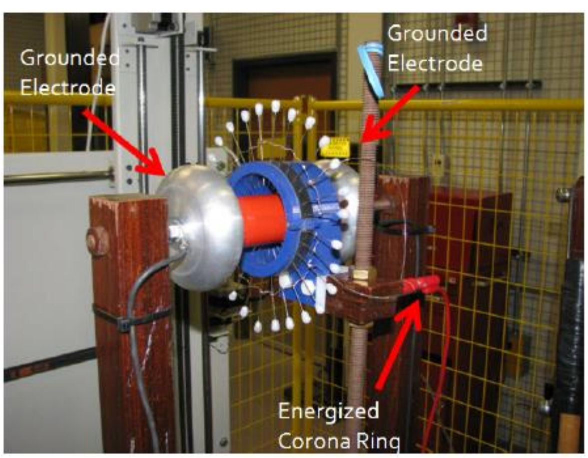


Fig. 11. Needles ring to introduce surface charges.

The samples to be tested were mounted on the wooden structure, as per Section 6.1. Two identical 0.5 cm wide copper strips with bent nails were attached to both ends of the sample. The test structure was sealed inside a transparent fog chamber with two ultra-sonic humidiers inside. The temperature, humidity, and pressure were monitor by a BOSCHE BME280 sensor. The humidity test was carried out and repeated at 3 different relative humidity levels: 20%,50%, and 80%.

After the relative humidity inside the chamber reached the desired level, the circuit was groundless and the voltage increased at an approximate speed of 500V/s until a partial discharge occurred. The PDIV was recorded with a multimeter while the leakage current from the sample to the ground and the associated electric field were continuously monitored on an oscilloscope. Next, we continued raising the voltage at the same rate until 15 to 20kV above the PDIV. When the PD appearance frequency was significantly higher than regular conditions, we began recording the leakage current from the sample to the ground and its associated electric field. The oscilloscope was programmed to use segment memory mode and triggered at negative 270 mv on the falling edge, with a 10G samples per second acquisition rate. Each segment was 1 µs long include with 400ns pre-triggered and 600ns post-triggered data. Typically, we recorded 128 to 256 segments before we moved to the flashover test [51].

After the PD test, we kept raising the voltage at the same rate until the flashover occurred.

The flashover leakage current was recorded on the same oscilloscope, triggered at negative 500mv on the falling edge with segment windows of 100 µs (40 µs pre-triggered and 60us post-triggered data). The tests terminated after 10 flashovers occurred. Samples were replaced if there was any significant damage on the surface. Degradation of the FPR samples was experienced after 4 to 5 tests (40 - 50 flashovers) [49].

Fig. 13. SIR Sample with Pre-stressing setup.

6.2.2. PD and Flashover Test with Surface Charge

All samples were free of floor fees earlier than going for walks during the experiments. This is done by removing the pattern of a piece of moistened material (distilled water) for two minutes by eliminating any residual storage costs, and then wiping the surface with isopropyl alcohol. Extra care became given now not to rub the floor because the friction from wiping can cause significant floor price [55]. Alternatively, the surface was rinsed and dabbed gently. The ring of needles became established symmetrically around the pattern in the desired place, then the needles have been energized with a 20kV DC voltage of each polarity. The length of the implemented voltage to the needles was 10 minutes. Afterward, the voltage supply become became off, grounded, and the ring of needles changed into cautiously eliminated - without touching the insulator. After that, the voltage source became the base, and the needle loop was carefully removed without touching the insulation. After injecting a space charge using a needle loop, the flashover circuit was groundless and the voltage increased at an approximate speed of 500V/s until a partial discharge occurred. The PDIV, PD signal recording procedure followed the same steps as per Section 4.2.1 [56].

6.3. Simulating Partial Discharge Activity

In fashionable, two situations need to be frequented so that it will start the evacuation. First, there is an electric powered discipline high sufficient in a huge sufficient region. Second, an preliminary seed electron is to be had. The electric field of the electron hurries up the seed to such a volume that impact collision ionization can take region. Collision ionization is the method through which a high-power electron strikes a neutral molecule and ionizes it to supply one electron and every other high-quality ion. If the electrical discipline is excessive sufficient, this system maintains as a chain response with the increasing quantity of charge kinds referred to as electron avalanches. Townsend's evacuation is composed of a sequence of electronic Bahmans. So, one can be self-sustaining, secondary methods which include the release of the weight of the steel surfaces are irradiation. If the compression of the wide variety of loaded species is high sufficient, the nearby context produced by way of the rainfall species will begin to protect towards the internal avalanche, which could cause a brand-new discharge mechanism. This is due to the fact that even though the inner avalanche protects itself, it nonetheless reasons an increase outside that area. If this discipline is high sufficient, it could produce an ionizing wave, generally referred to as a contemporary conductor. The forward velocity of the nozzle exceeds the speed of the electron drift, causing discharges to occur within the nanosecond c program language period. Whilst PD turns into a dielectric barrier, it replaces the floor fee that is opposite to the discharge area, reduces the ionization price, and as a result, shuts off the discharge [58].

To simulate PD pastime, you need data about the availability of seed load and electric area in a disorder. Consequently, it's far necessary to provide an easy pattern of how discharge influences these processes. PD pastime models generally present the subsequent simplification assumptions:

1. Despite the fact that the onset and release of the release rely upon on the strength of the electrical area over a given region, it is also assumed that the electric area inside the cavities in PD structures is sort of uniform, or that the PD is controlled as lots as the electric area of an unmarried unit. If this quantity is greater than the primary components, it's far assumed that the electric area is enough for discharge.

2. PD is efficiently modeled as a section exchange in surface price density at an empty boundary [58] or in a vacuum conductor and works to lessen the intracranial electric powered field to a few residual iscipline [60].

3. Comparable assumptions are made about electron era methods, all of which might be managed by means of a single amount of electric area.

The governing equations for the beginning subject, the residual subject, and the electron generation are offered in Niemeyer's work. They have been largely unchanged in the use of other authors and taken into consideration pd interest basically when simulated. In the subsequent sections, an evaluation of the origin of those equations is completed, and using these cash statistics on their software in PD modeling is offered.

6.3.1. Initial Electric Field

PD pastime models use an inception field, usually denoted as E_{inc}, to determine whether or not the electrical subject is enough for a discharge to take region. The inception subject for an air gap that is typically used inside the PD activity literature is added in [61].

$$E_{inc} = A\rho\left(1 + \frac{B}{(\rho L)^{1/2}}\right) \tag{2}$$

where A and B are constants, L is the gap length and p is the air pressure. In spite of the tremendous utilization of (2) it does not continually seem that its origins, consisting of the theoretical and experimental evidence in the back of it, is well known. In this section, a derivation of (2) is provided, including a summary of the original experi-intellectual investigations used to decide It and a dialogue of its applicability to PD structures.

The empirical proof at the back of (2) is a sequence of experiments undertaken within the 1960s with the aid of researchers at the college of Strathclyde [62]. Those experiments consisted of measuring the 'Sparkover' (a time period synonymous with breakdown) voltage Of parallel plate electrodes in the air at atmospheric pressure and humidity. The experimental records may be outfitted by means of the Curve.

$$V_{spark} = CL + D\sqrt{L} \tag{3}$$

where C = 2.449 kV/mm and D = 2.09 kV/mm. As the breakdown voltage is a function of pL from Paschen's law, and using the fact that the experiment was performed at atmospheric pressure $p = p0$ = 101325 Pa, it follows that

$$V_{spark} = (C/P_O)PL + D/P_O^{1/2}\sqrt{PL} \tag{4}$$

Setting the inception field equal to the 'sparkover' field

$$E_{inc} = \frac{V_{spark}}{L} \tag{5}$$

it follows that the constants A and B in (2) can be written as

$$A = \frac{C}{P0} = 24.2 \text{ V Pa}^{-1} \text{ m}^{-1} \tag{6}$$

$$B = \frac{D}{P_O{}^{1/2}A} = 8.6 \text{ V Pa}^{1/2} \text{ m}^{1/2} \tag{7}$$

these values for A and B are provided in [63]. It is of interest to note that the values of A used in [64], used subsequently bya number of authors, is 25.2 V P_a-1 m^{-1}. This appears to be a typographical error; however, this is not of particular significance as the error it introduces is approximately 5%.

From (2) it is clear that regardless of gap length L the electric field must still exceed Ap in order for discharges to take place. In [65] Ap is referred to as a limiting field, more commonly it is defined as the critical field E_{cr}. Below the critical field, attachment processes dominate ionisation processes and charge multiplication cannot take place. In [61] A is rewritten as $(E/p)_{\text{cr}}$ to demonstrate that it is a constant of proportionality between the critical field and the air pressure. As an aside at atmospheric pressure $E_{\text{cr}} = (E/p)_{\text{cr}}\, p$ = 2.45 kV/mm which is a typical value for the breakdown strength of long air gaps.

It must be mentioned that the experiments in keeping with fashioned through Strathclyde, [62], have been conducted beneath a uniform field among metal electrodes for air gaps among 3. Five cm to 17 cm.

Furthermore, the authors took remarkable care to smooth the electrodes to hold them free from dust, and indeed discovered an unacceptable scatter whilst the electrodes have been positioned in an open ecosystem, ensuing in the measurements being executed in an enclosure. The 'Sparkover' voltage, acquired in these conditions, isn't necessarily going to be applicable to PD experiments. One simple motive is that the air gaps used within the experiment are certainly too big. In many PD experiments, voids are fabricated with air gaps less than five mm; consequently, while using (2), a researcher is performing a tremendous extrapolation out of the range of the statistics that its miles derived from.

Some other difficulty is that the Sparkover experiment has changed into finished among metal electrodes. In PD experiments, voids are generally bounded through the insulation material. This fabric may nicely have very exceptional secondary emission characteristics to metals, which can have an effect on the inception field.

Similarly, greater, the complexity of fabricating voids in dielectric fabric might also cause modifications in humidity and contaminate the void surface, and as previously discussed, (2) changed into decided from cautiously controlled experiments. Every other key factor is that during [63-67], (2) is believed to hold over many tiers of PD interest, with the stress altered as a loose parameter such that the model suits measured records. This isn't always specifically accurate, firstly because (2) is derived for gaps containing air. It's miles probably that discharge interest will unexpectedly get rid of the oxygen and form by products on the void floor resulting in a void containing usually nitrogen. It is argued in [68] that the gaseous products fashioned due to discharge interest can have pretty similar ionisation characteristics, even though this isn't completely convincing. Furthermore, (2) assumes that the electric field inside a void is uniform. By way of merchandise on the void surface, along with oxalic acid crystals in LDPE [69], should produce high discipline factors main to divergent fields.

As turned into noted previously, PD activity models interpret E_{inc} as the minimal electric powered subject required for a discharge to take area inside a disorder. This can seem to correspond with the PD inception voltage (PDIV), that's determined as the voltage at which PD activity starts offevolved [67,70]. But E_{inc} is used in models to simulate PD hobby, in other words it's far the electric area required for disprices to take location for the duration of a length after the primary discharge. The interpretation inside a PD activity model is consequently that E_{inc} is electric area that corresponds to the PD extinction voltage (PDEV), the minimal voltage required to sustain PD interest. Considering E_{inc} as the electric discipline corresponding to PDEV has been proven to be pretty rea-sonable for a few experimental records [70-72].

A possible purpose for why the PDIV exceeds PDEV is that, in voids surrounded by dielectric cloth, the mechanism through which seed price is available for the first PD may also require a higher electric discipline.

This may no longer be the case for voids bounded by way of metal electrodes, which have been used to determine (2) because of their differing secondary emission characteristics.

Discharges in PD experiments may additionally and regularly take location in environments which differ from the careful managed situations used to decide (2). These motives aren't sufficient to say that (2) can't be used when analyzing PD systems. But it must be realized that deviations from it are not unexpected, and they have to be interpreted as an approximation relevant to the initial stages of PD activity rather than a physical regulation [72].

7. PRACTICAL STUDY OF THE EFFECT OF CONTAMINATION ON THE INCREASE OF PARTIAL DISCHARGE ON THE INSULATOR SURFACE

The type of contamination used in this experiment was as follows: a mixture of 40 g of annul and 20 g of salt dissolved in one liter of distilled water. This solution was equivalent to light contamination on the surface of the insulator.

To clarify the angles of the effect of contamination on the increase in partial discharge, a completely healthy and clean insulator was first injected with voltage. In the next step, the contamination was sprayed with the above-mentioned compound on the surface of the insulator and re-injection of voltage was performed [73,74].

For a healthy insulator in two cases mentioned, the results of the numbers recorded on the oscilloscope are as shown in Tables 3 and 4.

In addition, the creep current waveform recorded on the oscilloscope for these two states was equal to Figures 14 and 15.

Although the amplitude of the current in these two modes are not very different, with precision in the revealed current shapes, it is easy to confirm the ohmmeter property of the observed voltage source on the insulator surface in the contaminated state. While the current waveform on the surface A is healthy, clean insulator is approximately 90 degrees pre-phase, but the amount of pre-phase in the creep current observed on the surface of a contaminated healthy insulator is about 30 degrees. The same behavior in both insulators is the waveform which deviates from the

TABLE 3. ***Results of AC voltage injection in healthy and clean ceramic insulator mode.***

p_{loss}(w)	Creep distance (cm)	Creep flow (uA)	Applied voltage (ac kv)	Equipment status		Equipment name
3	48	80	20	Dry and clean	Healthy	Two-piece insulator

TABLE 4. ***Results of AC voltage injection in a healthy and contaminated ceramic insulator.***

p_{loss}(w)	Creep distance (cm)	Creep flow (uA)	Applied voltage (ac kv)	Equipment status	Equipment name	
20	48	390	20	Wet and pollution	Healthy	Two-iece insulator

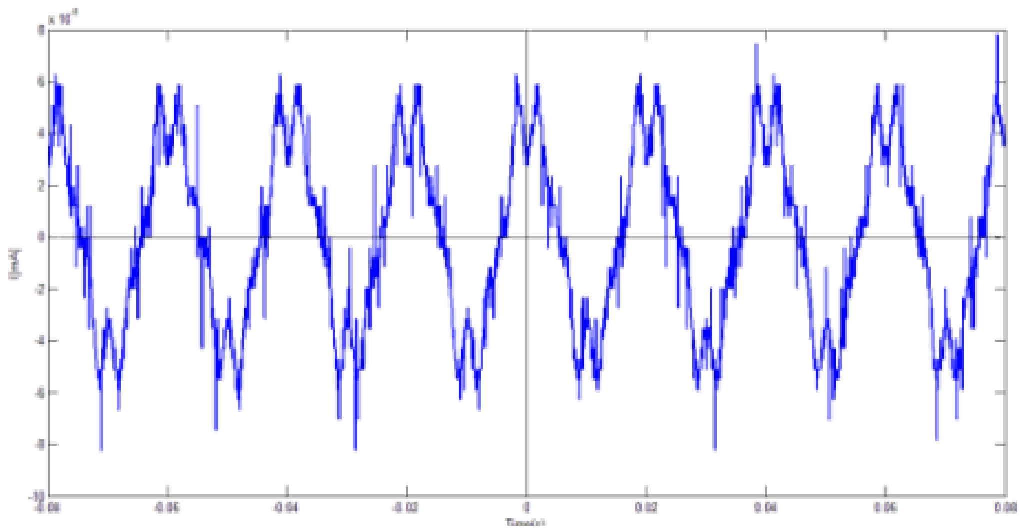


Fig. 14. Leakage flow in dry and clean state on the surface of a healthy ceramic insulator.

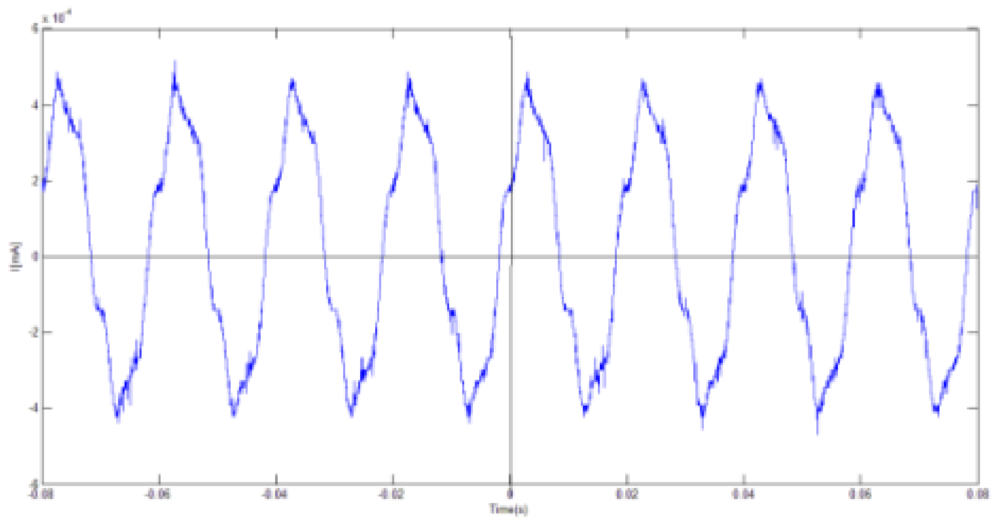


Fig. 15. Wet and contaminated leakage current on the surface of a healthy ceramic insulator.

TABLE 5. ***Results of AC voltage injection in the case of ceramic insulators with partial fracture of the umbrella and contaminated.***

p_{loss}(w)	Creep distance (cm)	Creep flow (uA)	Applied voltage (ac kv)	Equipment status		Equipment name
22.4	30.5	1120	20	Wet and pollution	Minor fracture	Two-piece insulator

sinusoidal state when dry. There are much sharper distortions on it. The cause of this event can be considered the shorter life and more frequent partial discharge sparks in that state [75,76].

Next, an insulator with a partial fracture of the umbrella was examined. For this case, the contamination was first sprayed on the surface of the insulator and then voltage was injected. The results obtained from the oscilloscope are shown in Table 5.

As can be seen, the creep current in this case has increased sharply and almost tripled. However, the creep interval has decreased by only 34%. The current waveform is completely deviated from the sinusoidal state and in 1/8, 8/3, 5/8 and of each cycle, large distortions are observed due to the proximity of the partial discharge to the complete discharge.

The impedance waveform can be felt on the set in this case according to Figure 16. The average of the diagram is out of position, and a small width from the origin is observed in the whole diagram which indicates ohmic losses and ohmic resistance during discharge on the insulator surface with the above conditions.

In the next case, a ceramic insulator with a major fracture in the umbrella, which has increased the creep distance to 27.5 cm, was injected with voltage and the results were recorded in Table 6.

A simulated image of a creep flow waveform on the surface of a two-piece insulator with a low-fringed umbrella and part of the lower edge of the insulator where the insulator needle is broken is shown in Figure 17.

factor in determining the components of the creep current waveform is the creep distance, which in this case is minimized from the insulator tested. However, the pollution conditions, which are fully consistent with the environmental conditions of the insulators installed on the power distribution network, can greatly help

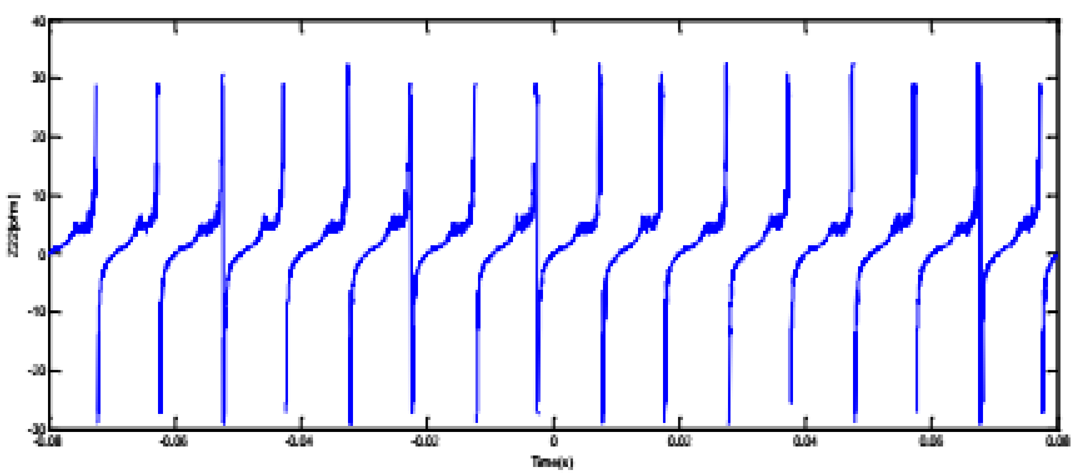


Fig. 16. Impedance waveform on the surface of a ceramic insulator with a contaminated partial fracture.

TABLE 6. ***Results of AC voltage injection in the case of ceramic insulator with sensitive fracture of the umbrella and contaminated.***

p_{loss}(w)	Creep distance (cm)	Creep flow (uA)	Applied voltage(ac kv)	Equipment status		Equipment name
50	27.5	2500	20	Wet and pollution	Perceived fracture	Two-piece insulator

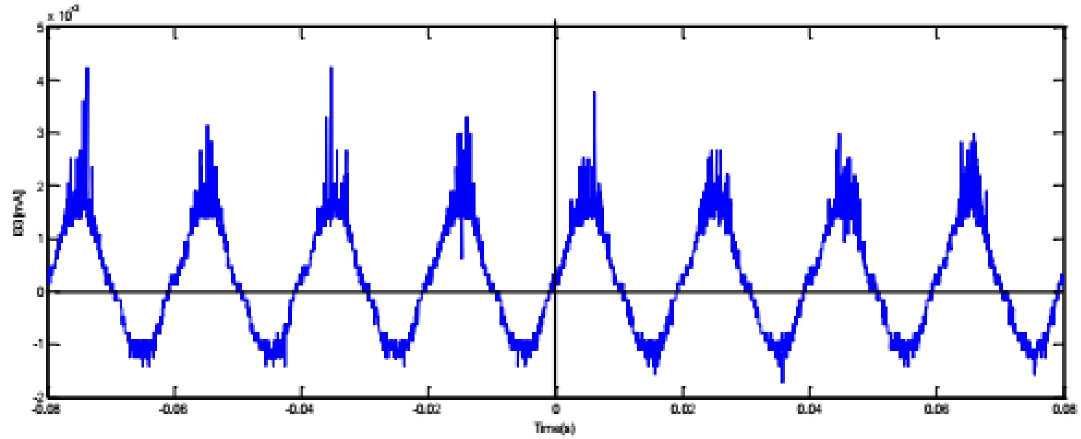


Fig. 17. Wet and contaminated leakage current on the surface of a ceramic insulator with a noticeable fracture.

increase the growth of partial discharges in severely defective insulators [75].

In this case, when the creep distance has reached 55% of the standard value, in the presence of wet contamination on the surface of the insulator, the current with a high approximation show the ohmic property for the impedance observed on the insulator surface. As the broken umbrella grows, the impedance waveform moves toward the waveform of an ohmic resistor with a larger true ohmic magnitude [76,77].

In the case of contamination on the surface of these damaged insulators, even the current waveform deviates from the symmetric state, and in the positive cycle, it travels more period and amplitude, which does not correspond to the performance of a linear resistor, and the positive peak is approximately 1.5 times the negative peak. Is. In this case, the current and voltage waveform are almost in phase [78].

Although it was mentioned that the impedance waveform on the insulator surface, especially when the insulator surface is clean and dry, is almost pure capacitor, but in the case of contamination and humidity, the creep distance can be significantly increased. It can be clearly proved that if the surface of the insulator is covered with wet contamination, if we skip many distortions that are observed, we have reached a very linear resistance with a very good approximation [79-82].

8. CONCLUTION

Currently, the application of a type of insulation is widely considered that has good insulating properties, anti-fungal change performance and resistance. It is heat resistant but has an effective coefficient creep distance, a simple production process, and a low cost. Although the transmission line is more and more used by glass insulators and composite insulators, Chinese insulators in the short term cannot be replaced completely. As it was observed, the main factor in increasing the creep current on the insulator surface is its creep distance, but the occurrence of contamination on the insulator surface has a significant effect on the growth of this increase. It also causes the observed impedance behavior to change from absolute capacitance to much closer to resistance. In the case of insulators with the major fractures of the umbrellas, the observed impedance is reasonably ohmic and resembles a capacitor only in transient pulses. The introduced PD and flashover laboratory experiments setups and the methodology of the test when introduced humidity or free surface charge. By following the described experiments procedures, performed PD and flashover test with humidity or free surface charge influences successfully. From the test result, we are able to identify the relationship between partial discharge and humidity and free surface charge influences. The best solutions for reducing discharge phenomena at the substation are as follows. First, install a corona ring between the insulator’s flange. A corona ring distributes the electric field gradient and lowers its maximum values below the corona threshold.

Second, apply a dielectric coating on the insulator’s flange. An insulating layer on top of the metal can prevent partial discharge from happening on the flange’s sharp edge.

REFERENCES

[1] J.S.T. Looms, Insulators for high voltage,IEE Power Engineering Series 7, London, 1990.

[2] R.S. Gorur, E.A. Cherney, J.T. Burnham, Outdoor Insulators, Ravi S. Gorur Inc., Arizona, 1999.

[3] B.F. Hampton, Flashover mechanism of polluted insulation, Proc. IEE (III) ,pp. 985–998,1964.

[4] J. Forrest, P. Lambeth, D. Oakeshott, The performance of high voltage insulators in polluted atmospheres, Proc. IEE. Vol.107,PP.172-187,1960.

[5] F.A.M. Rizk, D.H. Nguyen, Ac source interaction in HV pollution tests, IEEE Trans. Power Apparatus Syst. Vol.103,NO.4,PP.723-732,1984.

[6] W.L. Vosloo, J.P. Holtzhausen, A model for electrical discharge and leakage current development on high voltage insulators, in: Proc. 2nd IASTED International Conference: Power and Energy Systems,Crete, Greece, pp. 640–643,2002.

[7] J.P. Holtzhausen, Application of a reignition pollution flashover to Cap and Pin insulator strings, in:Proc. 6th IASTED International Conference: Power and Energy Systems, Rhodes Greece, pp.411–415,2001.

[8] Y. Li, Q. Zhang, M. Gao, H. Ni, Y. Zhao, G. Liu and K. Wang,Influence of fiber impurities on dc partial discharge process in oil-pressboard insulation, in *IEEE 19th International Conference on Dielectric Liquids (ICDL)*, pp. 1-5, June 2017.

[9] J. S. Pearson, O. Farish, B. F. Hampton, M. D. Judd, D. Templeton, B. W. Pryor and I. M.Welch,Partial discharge diagnostics for gas insulated substations, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 2, No. 5, pp. 893-905, Oct 1995.

[10] M. Amer, J. Laninga, W. McDermid, D. R. Swatek and B. Kordi,Surface charging and its effects on DC flashover strength of insulating materials, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 25, No. 6, pp. 2452-2460, Dec 2018.

[11] R.J. Van Brunt,Physics and chemistry of partial discharge and corona. recent advances and future challenges,IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 1, No. 5, pp. 761-784, 1994.
[12] P.H.F. Morshuis, Partial discharge mechanisms. PhD thesis, Delft University of Technology, 1993.
[13] F. Gutfleisch and L. Niemeyer,Measurement and simulation of PD in epoxy voids, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 5, pp. 729-743, 1995.
[14] H.A. Illias, G. Chen, and P.L. Lewin, The influence of spherical cavity surface charge distribution on the sequence of partial discharge events, Journal of Physics D: Applied Physics, Vol. 44, No. 24, p.245202, 2011.
[15] T. Tanmaneeprasert, P.L. Lewin, and G. Callender,Analysis of degradation mechanisms of silicone insulation containing a spherical cavity using partial discharge detection, in *Electrical Insulation Conference,IEEE*, June 2015.
[16] IEC 60270, High-voltage test techniques - Partial discharge measurements, *Tech. Rep.*, 2001.
[17] X. Wang and C. You ,Effect of Humidity on Negative Corona Discharge of Electrostatic precipitators, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 20, pp. 1720-1726, May 2013.
[18] F.H.Kreuger,Partial discharge detection in high-voltage equipment,Butterworth, pp 7,1989.
[19] S.H.Kang, Y.G. Park,C. Lee,J.N. Park and K.J. Lim,Voltage-time characteristics of PD patterns in void discharges, Proceedings of International symposium Electrical Insulting Materials, pp.25-28, 19th -22nd Nov,2001.
[20] J.H.Mason, The deterioration and breakdown of dielectric resulting from partial discharges, IEEE proceedings, 98, Pt 1, pp 44-59,1951.
[21] D.Ryder,The interpretation of partial electrical discharge measurements with insulation damage and ageing, Conference on Electrical Insulation and Dielectric Phenomena; pp 642-647, 17-20 October 1993.
[22] J.Kurimsky ,I. Kolcunova ,R.Cimbala,Partial discharge analysis for insulation systems of electric rotating machines with various voltage stress, Acta Electrotechnica et Informatica, Vol. 8, No. 4, pp 64-67,2008.
[23] N.Davies,Yuan Tian,J.C.Y. Tang and P. Shiel,Non-intrusive partial discharge measurements of MV switchgears, International conference on Condition Monitoring and Diagnosis, Beijing, pp 385-388, 21-24 April 2008.
[24] B.S.Nindra,V. Kogan,F. Dawson ,Surface corona suppression in high voltage stator winding end-turns, Proceedings of Electrical Insulation Conference and Electrical manufacturing expo, pp 411-415,1995.
[25] S.M. Cargill, D.G. Edwards, Corona screen effectiveness in large rotating machines under high voltage, high frequency transient conditions, IEE

proceedings on Electric power applications, Vol. 145, pp 469-474,1998.

[26] R. S. Gorur, E. A. Cherney and J. T. Burnham, *Outdoor insulators*, USA: Ravi S. Gorur, 1999.

[27] J. S. T. Looms, *Insulators for High Voltages*,London, United kingdom: Peter Peregrinus Ltd, pp. 2-12, 1988.

[28] C. Bayliss and B. Hardy, *Transmission and Distribution Electrical Engineering*, Oxford, UK: Elsevier Ltd, pp. 163-168, 2007.

[29] F. Kiessling, P. Nefzger, J. F. Nolasco, and U. Kaintzyk, *Overhead Power Lines*. Berlin, Heidelberg: Springer Berlin Heidelberg, pp. 257-270, 2003.

[30] T. Fujimura,The evolution of porcelain insulator technology in Japan, *IEEE Electr. Insul. Mag*., vol. 11, no. 3, pp. 26–36, May 1995.

[31] E. A. Cherney,Cement Growth Failure of Porcelain Suspension Insulators, IEEE Trans. Power Appar. Syst., vol. PAS-102, no. 8, pp. 2765–2774, Aug. 1983.

[32] D. A. Swift,Insulators for outdoor applications, in *Advances in High Voltage Engineering,* 1st ed., vol. 40. A. Haddad and D. Warne, Ed. London, United Kingdom: The Institution of Engineering and Technology, pp. 257-307, 2004.

[33] P. J. Lambeth,Effect of pollution on high-voltage outdoor insulators, Proc. Inst. Electr. Eng., vol. 118, no. 9R, p. 1107, 1971.

[34] H. M. Schneider, J. F. Hall, G. Karady and J. Renowden,Nonceramic insulators for transmission lines, IEEE Trans. Power Deliv., vol. 4, no. 4, pp. 2214–2221, 1989.

[35] J. F. Hall,History and bibliography of polymeric insulators for outdoor applications, IEEE Trans. Power Deliv., vol. 8, no. 1, pp. 376–385, 1993.

[36] R. S. Gorur, E. A. Cherney, R. Hackam and T. Orbeck,The electrical performance of polymeric insulating materials under accelerated aging in a fog chamber, IEEE Trans. Power Deliv., vol. 3, no. 3, pp. 1157–1164, Jul. 1988.

[37] R. Hackam,Outdoor HV composite polymeric insulators, IEEE Trans. Dielectr. Electr. Insul., vol. 6, no. 5, pp. 557–585, 1999.

[38] V. M. Moreno and R. S. Gorur,AC and DC performance of polymeric housing materials for HV outdoor insulators, IEEE Trans. Dielectr. Electr. Insul., vol. 6, no. 3, pp. 342–350, Jun. 1999.

[39] S.Vynatheya, N.Vasudev and R.T.Senthilkumar,Comparative Performance of Silicone Rubber Insulators with IEC Stipulated Test Methods, 10th IEEE International Conference on the Properties and Applications of Dielectric Material, pp. 1–4, Bangalore, India, 2012.

[40] M.H. Amrollahi,The effect of environmental pollution on insulators and appropriate methods to improve the performance of transmission network insulation against pollution, Fourth Conference on Power Distribution Networks, 1994.

[41] M. Zemorrodi,Types of Insulators and the Impact of Pollution on Them, Master Thesis in Electrical

Engineering, Faculty of Electrical and Computer Engineering, Babol University of Technology, 2012.

[42] S.D. Kabri, M. Myrazay and M. Hassani, Knowledgeable Types of Alodji Der Based, Rushhai Arziabe Anha and Arya Rahkarhai Bray Excellence Nmoydin Based, Domain Hamish Area a disstordhai noen der engineers of Lightning and Kampiwater, Danshaghe Azad One Joybar, 2014.

[43] B. Sheikh Douragh,Investigation and simulation of the effect of pollution on the voltage distribution of high pressure polymer insulators with corona rings by finite element method, Master Thesis in Electrical Engineering, Faculty of Electrical and Computer Engineering, Tarbiat Dabir Shahid Rajaei University, 2012.

[44] T. Chen, J. Cao, G. Zhou, Y. Wang, and X. Wen,Electric Field Research of ± 800kV Drytype Smoothing Reactor, International Conference on Electrical Machines and Systems, pp.1484-1487, 2014.

[45] T. Byrne,Humidity effects in substations,*11th Petroleum and Chemical Industry Conference Europe Electrical and Instrumentation Applications, PCIC*, pp. 1-10, 2014.

[46] X. Zhang, X. Bian, X. Cui, T. Lu, H. Li, Q. Li, Y. Zhu and A. E. Platform,Experimental Investigation on Humidity Effects on the Variations of Positive DC Corona Discharge,*IEEE International Power Modulator and High Voltage Conference(IPMHVC)*,pp.598-602,2016.

[47] J. J. Smit,Partial Discharges at dc Voltage : Their Mechanism, Detection and Analysis,*IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 12, pp. 328-340, April 2005.

[48] D. Wienold, U. L¨uhring and F. Jenau,Detection and distinction of partial discharges in air at DC voltage by using a non-conventional approach in the high-frequency range,*IEEE Industrial and Commercial Power Systems Europe*, No. 03, 2017.

[49] L. Hui, S. Qinghe, Y. Jun and M. Hailei,Detection and processing for ±660 composite insulator abnormal discharge, *International Conference on Power SystemTechnology*,pp. 1404-1409, Oct 2014.

[50] F. Meng, X. Zhang, X. Wu and B. Xu,Experimental studies on air humidity affecting partial discharge in switchgear, pp. 1237-1241, Oct 2013.

[51] X. Wang and C. You,Effect of Humidity on Negative Corona Discharge of Electrostatic Precipitators, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.20,pp.1720-1726, May 2013.

[52] E. Lemke, P. Schmiegel and W. Mosch,PD Phenomena on Dielectric Surfaces under dc Stresses Influenced by Air Humidity, *IEEE Transactions on Electrical Insulation*, Vol.26,No. 3, pp. 453-457, Jun 1991.

[53] R. Soltani, E. David and L. Lamarre,Study on the effect of humidity on dielectric response and partial discharges activity of machine

insulation materials, *IEEE Electrical Insulation Conference, EIC*, pp. 343-347, June 2009.

[54] M. Amer, J. Laninga, W. McDermid, D. R. Swatek and B. Kordi,Surface charging and its effects on DC flashover strength of insulating materials, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 25, No. 6, pp. 2452-2460, Dec 2018.

[55] R. Kubota, T. Kawashima, Y. Murakami and M. Nagao,Partial Discharge Inception Voltage under Surge Voltage Application Influenced by Surface Charge on Insulating Sheet, *IEEE Conference on Electrical Insulation and Dielectric Phenomena(CEIDP)*,pp.171-174,2016.

[56] K. Takabayashi, R. Nakane, H. Okubo and K. Kato,High Voltage DC Partial Discharge and Flashover Characteristics with Surface Charging on Solid Insulators in Air, *IEEE Electrical Insulation Magazine*, Vol. 34, pp. 18-26, 2018.

[57] B. X. Du and M. Xiao,Influence of surface charge on dc flashover characteristics of epoxy/bn nanocomposites, *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.21, No.2,pp. 529-536, April 2014.

[58] G.E. Georghiou, A.P. Papadakis, R. Morrow and A.C. Metaxas, Numerical modelling of atmospheric pressure gas discharges leading to plasma production, Journal of Physics D: Applied Physics,Vol. 38, No. 20, p. 303, 2005.

[59] H.A. Illias, G. Chen and P.L. Lewin, The influence of spherical cavity surface charge distribution on the sequence of partial discharge events, Journal of Physics D: Applied Physics, Vol. 44, No. 24, p. 245202, 2011.

[60] C. Forssen and H. Edin, Partial discharges in a cavity at variable applied frequency part 2: measurements and modeling, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15,No. 6, pp. 1610-1616, 2008.

[61] L. Niemeyer,A generalized approach to partial discharge modeling, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 4, pp. 510-528, 1995.

[62] H.A. Boyd, F.M. Bruce and D.J. Tedford,Sparkover in long uniform-field gaps, Nature,Vol. 210, pp. 719-720,1966.

[63] G.C. Crichton, P.W. Karlsson, and A. Pedersen,Partial discharges in ellipsoidal and spheroidal voids, IEEE Transactions on Electrical Insulation, Vol. 24, No. 2, pp. 335-342, 1989.

[64] F. Gutfleisch and L. Niemeyer, Measurement and simulation of PD in epoxy voids, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 5, pp. 729-743, 1995.

[65] I.W. McAllister and A. Pedersen,Corona-onset field-strength calculations and the equivalent radius concept,Archiv für Elektrotechnik, Vol. 64, No. 1, pp. 43-48, 1981.

[66] P.H.F. Morshuis, Partial discharge mechanisms. PhD thesis, Delft University of Technology,1993.

[67] IEC 60270, *Partial discharge measurements*, 1998.

[68] G. Callender, T. Tanmaneeprasert, and P.L. Lewin,Simulating partial discharge activity in a cylindrical void using a model of plasma dynamics, *Journal of Physics D: Applied Physics*, Vol. 52, No. 5, p. 055206, 2019.

[69] I. Gallimberti,The mechanism of the long spark formation, Journal de Physique Colloques, Vol. 40, No. 7, pp. 193-250, 1979.

[70] L. Niemeyer, B. Fruth and F. Gutfleisch,Simulation of partial discharges in insulation systems, in High Voltage Engineering, 7th International Symposium on, pp. 25-28, August 1991.

[71] C. T. Phelps,Field-enhanced propagation of corona streamers, Journal of Geophysical Research, Vol. 76, No. 24,pp. 5799-5806, 1971.

[72] G. Callender, I.O. Golosnoy, P. Rapisarda and P.L. Lewin,Critical analysis of partial discharge dynamics in air filled spherical voids, Journal of Physics D: Applied Physics, Vol. 51, No. 12, p. 125601, 2018.

[73] G. M.Hashemi, Partial discharge detection forcondition monitoring of coverd-conductor overhead distribution networks using rogowski coil,Helsinki university of technologyAugust 2008 .

[74] H. Mohseni,Fundamentals of High Electrical Pressure Engineering, Dah Tehran, third edition, 2007.

[75] S.Sarmadi and M.Nazari,Use of corona ring in electric field control and uniform potential distribution on composite insulators used in high pressure lines,.

[76] M.Anvar, partial discharge in electronic equipment ,Dissertation thesis,Brno University,2009.

[77] D. Bagheri,Design, simulation and construction of partial electrical discharge measuring device (PDT),.

[78] H. Khalouzadeh, S. Sadrbazzaz, Z. Adel Barkhordar and A. Rahmani, Study of methods for detecting punched insulators by corona cameras, 9th Conference on Power Distribution Networks, Daheh Zanjan, May 2004.

[79] M. Faramarzi Planger, M. Mirzaei, M. Faramarzi Planger and M. Gatabi,Improvement of the electric arc model of a high pressure insulator covered with uniform pollution,.

[80] F. Obenaus, fremdschichtÜberschlag und kriechweglänge,Deutsche electrotechnik, Vol. 4, pp135-136, 1958.

[81] H. Dostibarhagh, A. Honarmand ,J. Talebi ,Study and practical experiences of the reasons for punching porcelain needle insulators in Guilan Power Distribution Company, Fourth Conference on Power Distribution Networks, Kerman 2009.

[82] T. Shahsavarian and S.M. Shahrtash, Comparison of partial discharge models for insulation of high voltage cables, Fifth Specialized Conference on partial discharge, Sharif University of Technology, 2013.