

Understanding DC Partial Discharge: Recent Progress, Challenges, and Outlooks

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Abstract—As a non-destructive local gas breakdown phenomenon within a surface or bulk cavity surrounded by insulation, partial discharge (PD) contains important information which can be used to evaluate and diagnose electrical insulation systems. In this paper, distinctive characteristics of PD for DC versus AC are reviewed. A summary of experimental studies on DC PD in different insulation coordinations is presented, including PD in gaseous insulating media, PD in solid insulating media and PD in liquid insulating media. Conclusions and some thoughts based on existing studies are provided, and challenges and suggestions for future studies are given. This paper can serve as a guide reference for readers to learn the background and state-of-the-art of DC PD studies. More importantly, it is hopeful that this study can inspire novel ideas for further advancing fundamental research of DC PD mechanisms and PD mitigation methods.

Index Terms—Charge injection, DC power systems, partial discharges, surface charging.

I. INTRODUCTION

Partial discharge (PD) occurring inside or on the surface of outdoor insulators in high voltage power grids and wall bushings in converter stations, on the surface of spacers inside gas insulated High Voltage Direct Current (HVDC) equipment, such as HVDC GIS/GIL, as well as inside the insulation of cables for HVDC power transmission systems, within the windings of rotating machines and transformers, not only highlights a local degradation region of the insulation, where the local electric field is large enough to support a continuous PD activity, but also accelerates insulation degradation due to ion bombardment [1]–[3]. For instance, the occurrence of PDs at weak points within an oil impregnated pressboard inside the valve side winding of converter transformers enhances the possibility of insulation degradation and even breakdown of liquid dielectrics [4], [5]. Meanwhile, for industrial equipment powered by DC voltage ranging from several hundred volts to kilo-volts, such as X-ray equipment, image intensifiers, traveling wave tube broadcasting equipment in satellites, and

DC power systems in hybrid electric propulsions in aircraft as well as in submarines, PD is always a difficult and inevitable problem that affects the communication system and causes energy losses. However, according to the Interim Report of the CIGRE Working Group D1.63, international standards for PD measurements on DC equipment are still quite rare [6]–[10].

In this paper, we present first a survey of the physical models of gas discharge, and the differences between AC PD and DC PD is briefly reviewed. A summary of experimental studies on DC PD in different electrical insulation coordinations is then presented, including PD in gaseous insulating media, PD in solid insulating media and PD in liquid insulating media. Furthermore, we provide conclusions and additional thoughts based on existing studies, and challenges and suggestions for future studies on DC PD, including factors affecting DC PD, which include surface charge and space charge behaviors, temperature and gas pressure variations, relative humidity change, as well as ways of applying voltage, etc., which are discussed as well. It is hopeful that this paper can serve as a guide reference and inspire novel ideas for readers focusing on further advancing fundamental research of DC PD mechanisms and PD mitigation methods.

II. DISTINCTIVE CHARACTERISTICS OF PD FOR DC VERSUS AC

Although PD is characterized by its stochastic behavior and availability of free electrons and ions to trigger the physical processes, such as ionization and excitation, non-variable electric field, rising from voltage sources which abates the electrical stresses and tension among the gas particles in DC voltage applications. In this case, interaction of charges and atoms with gases and solids would play a paramount role in development of a streamer or avalanche in the process of discharge. Continuation of the PD process depends on electric field intensity recovery after each PD incident which would need a longer time lag between pulses. The primary previous research which has discussed the time lag recovery concept belongs to Morshuis [3] and Fromm [11]. Unlike AC voltage where the PD repetition rate with a direct relationship with the external voltage can be rapidly increased arising from the voltage polarity reversal, the PD repetition rate in DC inception voltage is zero and PD occurrence with the rate of one pulse per minute is considered the initiation of consistent PDs. Also, the capacitively graded field during

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voltage ramp transient converts to the resistively graded field in stable DC voltage where operating conditions of the insulation system should be involved in the PD behavior. Increases of the temperature and its gradient have direct influence on the insulation conductivity and in turn the repetition rate of the PDs [3]. The magnitude of the PD pulses in DC voltage is considerably lower than AC voltage. It is necessary to consider both the low repetition rate and the magnitude of PDs possibly as low as the noise level complicate the separation of real pulses and unavoidable noises.

As mentioned, due to the lack of voltage stress, the availability of ions and electrons depends on other factors, such as conductivity, temperature, pressure, or alteration of lattice structure or free radical formation due to defects and degradation. These parameters can have significant influence on many small-scale processes of particles, such as charge injection/extraction, trapping and de-trapping, hopping and transport [6], [12], and affect the abovementioned time lag and probability of available dominant charges for the discharge process. Positive and negative ions and electrons have different roles in propagation of discharge due to their different mobility and mass and depending on the polarity of the voltage, one group of atoms could have a dominant impact on the discharge activity. For example, propagation of positive and negative streamers in the air and on the surface of dielectric material has been discussed in [13], [14]. Based on the experimental results on streamers developed in the positive and negative DC voltage applied to the needle, it is observed that the negative streamers develop at higher voltages starting with a glowing cloud unlike the positive streamer initiating with a lower voltage level with a branching pattern. Delayed negative streamers can reach to 25% of the positive streamer velocity at high voltages. The diameter of the streamer tips revealing the dominant charge carriers' mobility, spatial concentration and diffusion is two to three times higher for the negative streamers compared to the positive streamers [14]. Quantitative comparison between the positive and negative discharges should be discussed for the specific electrode configuration, gas combination, and testing condition.

Although the researchers have tried to conduct studies on PD behavior and characteristics at DC voltage, there is not much published resources discussing the principle of the DC voltage induced discharges in detail as addressed above [15].

III. PD INSIDE SOLID INSULATION

When the solid insulation has internal voids or gaps due to the defects from the manufacturing process or aging, PD would occur in these voids and gaps due to a lower PD inception electric field in the gas. For cases where electrical trees are initiated inside the solid insulation, the PD can be triggered inside these tree channels. In this section, the studies of DC PD in solid insulation are reviewed in two parts which include part A: PD due to electrical treeing activities, and part B: PD due to internal voids and gaps.

A. PD due to Electrical Treeing Activities

An electrical tree may start to grow at a location where there is a field enhancement. The initial stage of trees results in

micro voids and channels in which PD may occur. Compared with treeing behaviors in AC voltage, the growth of electric trees in DC voltage is slower, which is due to the mitigation of homo-polar space charges near the defects. As a result, the branches induced in DC voltage are much less than that in AC voltage, and the correlated PD inside tree channels in DC voltage has a smaller discharge amplitude and would gradually be diminished, even in a much higher electric field [16]–[18]. Liu *et al.* found in their study that the PD in DC can be found during voltage ramping, however, almost no PD can be observed when the voltage was constant [19]. The amplitude of PD remains with a small amplitude even when there was a fast re-growth process of electrical trees under the positive DC bias voltage [20].

B. PD due to Internal Voids and Gaps

The completion of the first HVDC project using extruded polymeric insulated cables was in the Swedish island of Gotland, 1999 [21]. The LCC-HVDC HVDC cable is primarily used for grid-interconnections with a voltage rate of 500 kV [22]. However, for a very long time, PD measurement focusing on HVDC cables, has not been recommended in the CIGRE Technical Brochure, due to a lack of understanding of the DC PD mechanism and the fact that at present, PD detection for cables is very complicated under DC voltage [23].

In this part, PD tests in solid insulating media, which refers to the PD test for real cables and for specimen, are reviewed and discussed, as presented in Figure 1. On the left side, Figure 1 shows PD studies in real cables or mini cables, while on the right side the PD occurring in the voids inside of solid dielectrics is presented. The features and major conclusions of the studies in Figure 1 are reviewed and discussed as follows.

In a study conducted in 2016, several model HVDC XLPE cables provided by Nexans, with a conductor cross section of 95 mm² and insulation thickness of 4.9 mm and length of 10 m, were manually damaged with defects [24]. A knife cut with a depth of 1 mm and length of 10 mm was performed under the grading system near the end of the outer semiconducting layer, and a misplacement of the grading system was made, as shown in Figure 1. PD was tested at both AC and DC voltages and the difference in the PD parameters for both AC and DC was discussed and compared. It was found that AC PDIV for the misplacement defect had relatively small dispersion compared with DC PDIV [24]. In addition, AC and DC PDIV for the knife-cut defect all displayed relatively large dispersion. It was presumed that the reason could be due to the charge accumulation at the PD source and a possible electric field distort in the insulation layer around the defect due to space charge accumulation [24]. In 2017, similar model cables with a misplaced grading system were produced and tested for AC and DC. It was further concluded that the measurement results of PDIV and PDEV showed large dispersion obtained under DC, which was due to the role of the memory effect since the residual charge from the previous discharge were still trapped on the dielectric surface [25].

Similar to defects of misplacement and knife cut voids conducted in 2016 and 2017, in 2018, Gu *et al.* built a test cable loop using a 320 kV HVDC XLPE cable with

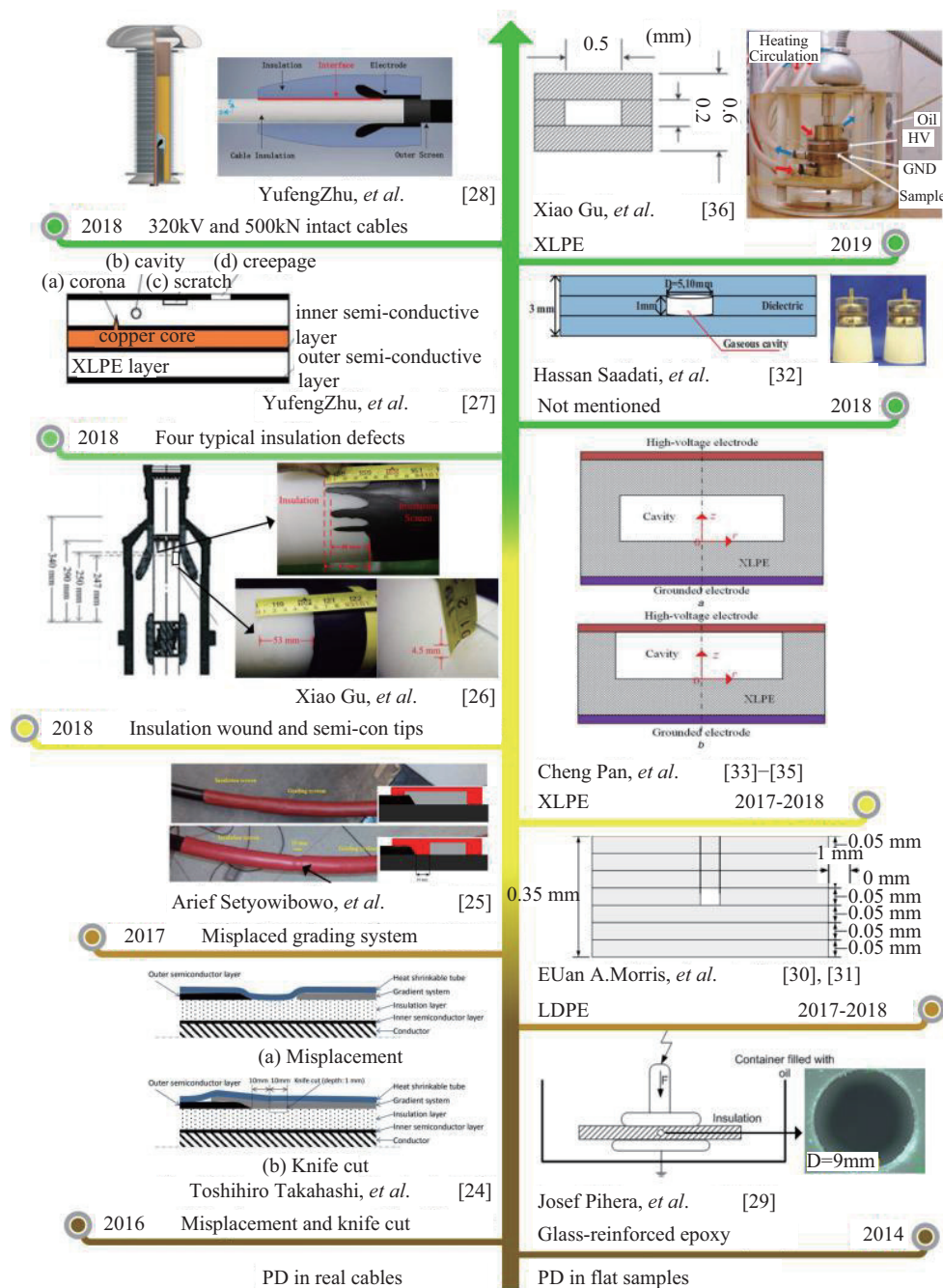


Fig. 1. The flow chart of reviews regarding fundamental researches in DC PD in solid insulating media.

artificial defects, i.e., insulation wound and semi-conductive layer tips, as shown in Fig. 1. In their test, defects were effectively detected under DC, with the PDIVs being -320 kV and -290 kV for defects of insulation wound and semi-conductive layer tips, respectively. Compared to the PD from the insulation wound, the defect of the semi-conductive layer tips triggered PD with higher amplitude and higher dispersion in surface discharges, even at lower voltage. Meanwhile, similar to the large dispersion in PD parameters for HVDC cables presented in [25], [26], intermittent PD up to several minutes was reported when measured beyond PDIV, followed by some PD with a very high repetition rate for cable with

semi-conductive layer tips. It was attributed to the space charge phenomenon and the accumulation of by-products generated by PD induced degradation [26]. For the above-mentioned studies, residual charges in the voids are believed to be responsible for PD behaviors at DC voltage. However, there still is no solid evidence to verify the charge distribution and transport and thereby verify the findings.

Insulation defects, including corona defect, cavity defect, scratch defect and creepage defect were introduced to HVDC cable in literature [27] and differences in parameter features of these four typical insulation defects were analyzed. The results showed that the corona defect had the most serious distortion

and the creepage defect had a more slight distortion in electric field distribution [27].

The PD test on commercialized DC Cable systems, including a 320 kV cable insulated by XLPE material enhanced by nano-filler and a 500 kV cable insulated by Super-clean™ XLPE material, was performed by Zhu *et al.* in 2018. Other than EPDM, they used the more commonly used silicone rubber as the insulation of accessories for DC cables. Interestingly, they found that DC PD can only be detected before the breakdown of accessories in the load cycle tests. They recommended to apply the PD test with AC voltage of peak value slightly higher than the DC rating before the load cycle test (as a part of development tests or type test) [28]. However, to the authors' knowledge, in AC voltage, some intrinsic charge transport properties in DC may not be stimulated and the measured PD pulses may be denser compared with that in DC voltage, depending on different electrode-insulation arrangements. One simple example is that for an asymmetry electrode arrangement, PD in DC voltage usually shows a polarity effect. However, in AC voltage such polarity effect does not exist.

Apart from the DC PD experiment using real-sized cables, PDs in specimens with internal voids and electrode bounded voids were also studied [29]–[36]. In literature [29], a flat sample containing a void with a size of $d = 0.9$ mm was realized by attaching three sheets made of FR4 (a composite material composed of woven E-fiberglass cloth with an epoxy resin binder that is flame resistant) with dimensions of 80×80 mm and thickness of 1.8 mm (0.6 mm each). The magnitude of PD measured at DC voltage was lower than that in the case of AC test voltage, while the PDIV of DC PD at both voltage polarities is much higher than that of AC PD. They showed that differences in PD patterns at positive and negative voltage could be found using the Pulse sequence analysis (PSA) method [29]. Similar conclusions regarding variations in PDIV and PD amplitudes with respect to voltage can also be found in literature 30 and 31, where LDPE was used as the insulating sample and a void diameter of 1 mm was introduced. They found that the properties in pulse amplitudes and duration were not effectively useful in identifying defect types including single void, serial voids and parallel voids. However, they confirmed that the analysis in the frequency domain was the most effective method of PD analysis under HVDC conditions [31].

Tests regarding differences in PD behaviors between AC and DC have also been performed by Saadati *et al.*, using internal voids with a size of 1 mm in thickness and 5 mm in diameter [32]. It was verified in their experiment that the voltage over cavity had an exponential curve, and the maximum value of the voltage over the cavity was dominant by the resistive values of the RC-circuit model, which means, the conductivities of the dielectric and cavity were more important. They concluded that the value of the time constant decreased intensively with the increasing temperature. This is helpful in explaining why AC PD occurs sooner than DC PD and with a higher repetition rate.

The topics of most papers in recent years were focused on the feature parameter differences between DC PD and

AC PD. However, in Pan's work, the electric field strength on the surface of the insulation bounded void and electrode bounded void have been measured and the effect of charge decay both at the ambient environment and in the presence of air flow on PD behaviors was studied [33]–[35]. The results showed that when the applied voltage increased, the discharge frequency increased, and the decay time for positive charges was about 579 ms, while the time for negative ones was about 1211 ms [33]. Meanwhile, the introduction of airflow was identified as a factor for increasing the positive and negative surface charge decay rate and PD frequency by enhancing the neutralization process and homogenizing the charge carrier in the gap. He verified that the discharge frequency of the sample with one metallic surface was much larger under positive voltage than under negative voltage, while such voltage polarity dependent property was not found for samples with insulation bounded voids.

Based on previous results, in 2019, Gu *et al.* showed more details on PD behaviors regarding the effect of the electric field and temperature dependent conductivity of XLPE both by simulation and experiment [36]. They found that the cavity voltage after 10 hours of voltage application was 32.7 % higher considering the field and temperature dependence of the conductivity of the samples. In addition, their experimental results obtained at 23°C and 70°C under 30 kV showed an increase in the PD repetition rate of more than 1 order of magnitude, which can be found in Figure 2.

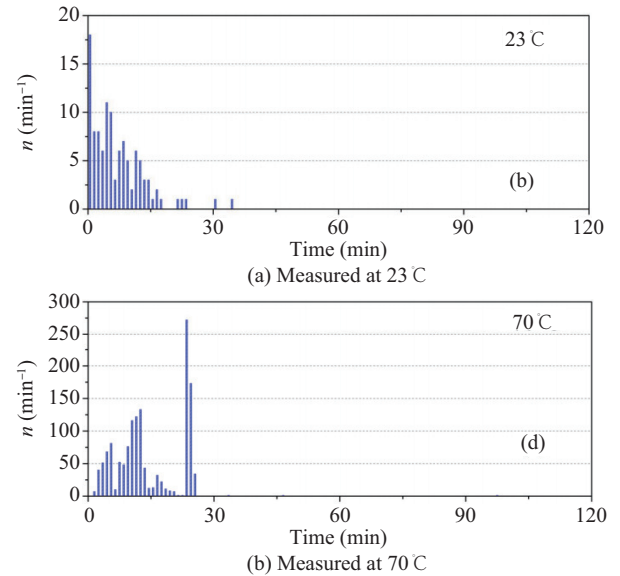


Fig. 2. PD repetition rate measurement results at different temperatures under 30 kV [36]. © [2019] IEEE 5200171059523.

IV. PD IN GASEOUS INSULATING MEDIA

The effect of charge decay in the gas phase on dielectric surfaces and barriers on PD behaviors is considered as it is especially pronounced in DC voltage. In this part, the PD in gaseous insulating media is reviewed and discussed. The studies are separated according to the gas type where PD occurs, i.e., in air, in SF₆, and their gas mixtures, which represent the insulation environment for out-door insulators,

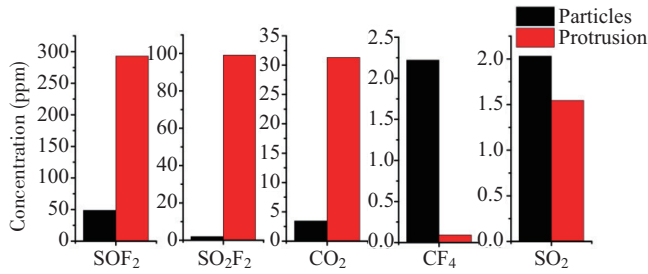


Fig. 4. 96 h SF₆ component decomposition concentration [45]. © [2018] IEEE 5200180865341.

higher (in ranges of hundreds of nanoseconds) than that of voids. PD behavior of protrusions can be irregular with some interruptions in the range of seconds when near the inception voltage, while for free metallic particles, the bouncing of particles preferred rounded particles while for sharp edged particles, the firefly effect was much easier to be detected.

As for PD occurring in air, Florkowski, *et al.* had PD properties investigated in 2016 with different pressures using various arrangements, including a point-to-plate setup as well as a setup modeling discharge along the post insulator surface. In this study, the PDIV and breakdown voltage for different arrangements as a function of pressure were concluded. Meanwhile, they found that in a point-to-plate configuration the evolution of PD patterns and discharge intensity as a function of voltage and pressure showed a transition from pulse to pulseless form of discharges, and the solid dielectric in the model point-to-plate arrangement had an influence on PDIV and led to further developments in the form of surface discharge [47]. However, the development of PD on the surface of a spacer depends not only on spacer material and moisture, but also the pressure. Flashover voltage at 0.1 MPa was ca. 70% higher than inception voltage, but at 0.4 MPa only 20% higher, because of pressure and surface processes.

A similar arrangement was also adopted by other researchers [48]–[51]. In literature 48, the corona PD and surface PD were investigated and the AC testing was proved to be a good sensitivity check before DC testing to ensure the PD from the specimen was consistent with what was expected under AC conditions. In literature 50, they found the AC inception voltage is much lower than DC positive inception voltage and higher than DC negative, while literature 49 and 51 focused on the pulse shape parameters of different types of PD as well as the influence of harmonic phenomena on DC PD.

In 2018, Takabayashi *et al.* performed experiments and quantitative analysis of DC PD and related flashover voltage (FOV) in air, with model electrode gaps containing a dielectric barrier and the experimental results showed that the final (DC steady-state) distribution of the accumulated charge is independent of the type of charge supply source, e.g., natural cosmic rays, electron emission from the cathode and partial discharge, but was uniquely determined by the electrode and solid insulator arrangement. In addition, they collected the PDIV and FOV characteristics in air at different voltage polarities for different gap lengths, as shown in Figure 5 [52].

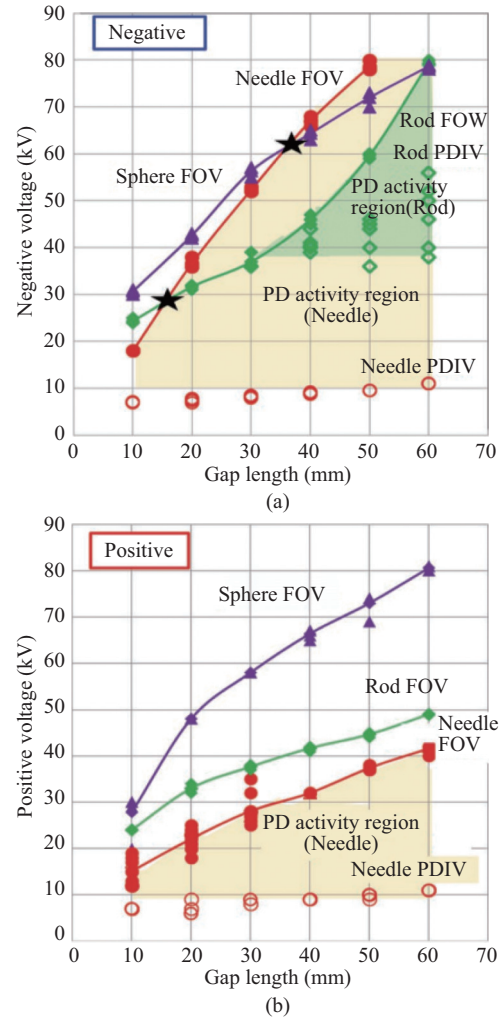


Fig. 5. Partial discharge inception voltage (PDIV) and flashover voltage (FOV) characteristics in air, under negative and positive DC voltage application, for needle, rod, and sphere electrodes (without solid insulators) [52]. © [2018] IEEE 5200181313840.

V. PD INSIDE LIQUID INSULATION

The PD which occurs in liquid insulating media refers to PD in the insulation system of the converter transformer where the oil impregnated pressboard and the insulating oil serve as the main insulating media. In this section, PD types inside oil are categorized according to whether there is an oil-impregnated pressboard or no such barrier in the oil. The experimental setup for this research can be found in Figure 6.

It can be shown that PD tests inside oil without dielectric barriers were conducted with ball-plate, needle-plate and parallel plates arrangements [53]–[56]. Sarathi *et al.* studied the PD behavior of a single conducting particle inside transformer oil under both DC and AC voltages [53], [55]. When the particle moved in a gap at just above the levitation voltage, the PD activity was regular (as the particle moved between the electrodes) [53]. The polarity effect of PD amplitude was also reported, representing a higher amplitude of PD at negative voltage than that at positive voltage at different voltage levels [55]. When compared with PD inception voltage under AC, the PD inception voltage for DC is much lower

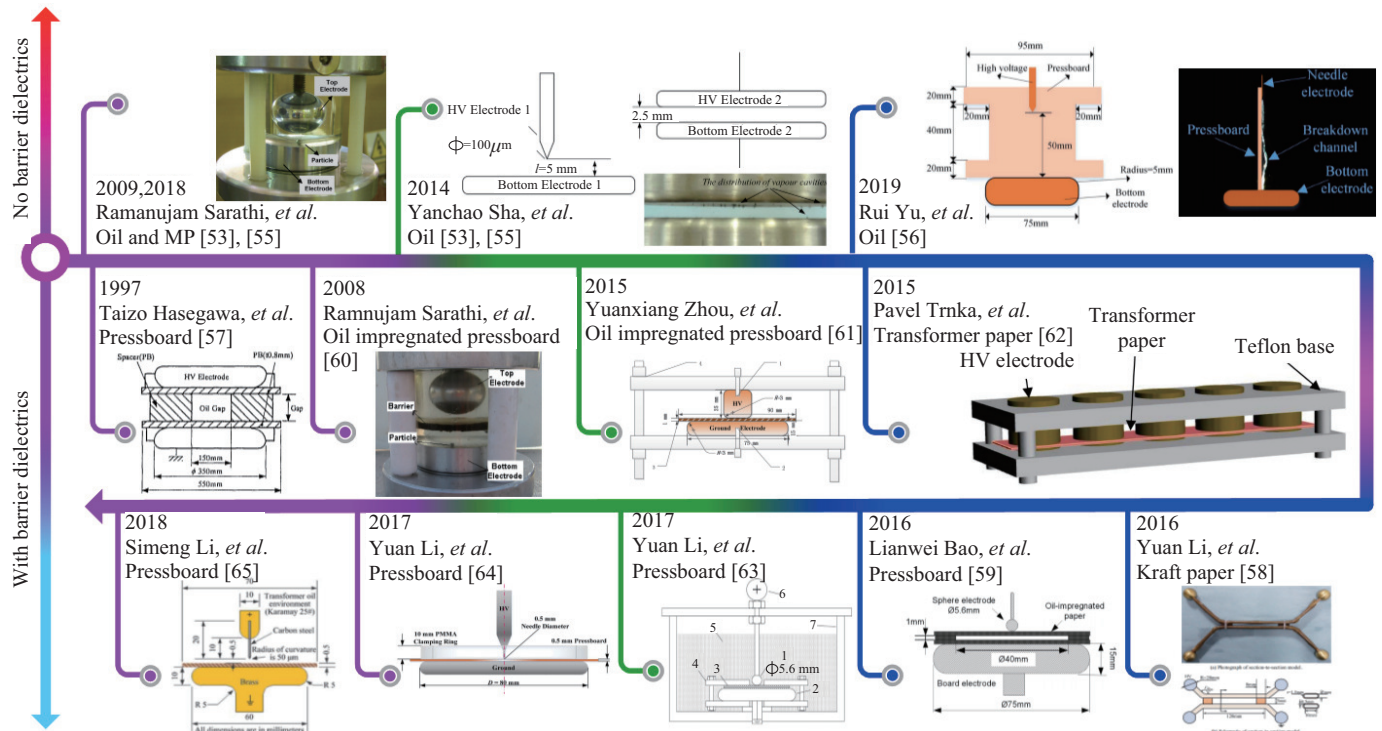


Fig. 6. The flow chart of reviews regarding fundamental research of DC PD in oil insulating media.

and the particle motion is much less confined than that under AC conditions, which implies that a much stronger destructive pulse can be obtained for DC.

Sha *et al.* studied DC PD using both needle-to-plate and plate-to-plate arrangements [54]. However, compared with those in literature [55], the results did not match well, especially in PD amplitudes. As shown in Figure 7, the PD amplitude under positive DC voltage is much higher compared with that at negative DC voltage for needle-to-plate arrangements. However, for PD at plate-to-plate arrangements, the differences between PD amplitudes are not significant. Interestingly, similar trends can be found under AC voltage, which is contrary to the results reported in literature [53] and [55], as shown in Figure 8 [54]. These contradictions may be due to the influence of metal particles as well as voltage applying methods. To the author's knowledge, however, we cannot give a very satisfied answer in response to the reason of these contradictions, since the DC PD behaviors are very complicated which involves many physical processes. Any changes in the setup or materials may result in different PD behaviors.

Apart from PD due to metal particles or being inside oil, PD from the oil and pressboard interface can be one of the PD types inside transformers. In 2019, Yu *et al.* studied the PD properties of such arrangements and found that the damage to the pressboard under the negative polarity is much severer than the positive voltage [56], which corresponds with the results mentioned in literature [53] and [55]. Based on the results, they suggested that the negative DC voltage should be avoided on the interphase pressboard surface [56].

For studies regarding PD occurring in oil with dielectric

barriers, three types of electrode-insulation arrangements are normally used, including 1) internal void/gap bounded with dielectrics [57]–[59]; 2) dielectric barrier floating between electrodes [60]; and 3) dielectric barrier touching grounded electrode [61]–[65]. The electrode setup for these arrangements can be found in Figure 6.

For studies regarding internal void/gap bounded with dielectrics inside oil, Hasegawa *et al.* studied the PD properties using epoxy resin molded electrodes in transformer oil [57]. The PDIV for both DC polarity reversal conditions and AC condition is much lower than the breakdown voltage (Figure 9), which is different compared with the conclusion that PD occurs at a voltage that is nearly at breakdown as mentioned in literature [56]. Meanwhile, they concluded that the stress imposed on pressboard by PD can nearly be halved by the remaining DC pre-stress on the pressboard.

In 2016, internal gaps with thicknesses of 5 mm and 1 mm using Kraft paper and oil-impregnated paper were introduced in literature [58] and [59] and PD properties at DC were studied. In literature [58], the aging of oil and the corresponding PD property in different stages of bridges inside oil were the main focus, and the conclusion showed that for the initial stage of oil bridges, PD was not a necessity, and PD was triggered during the growth of the oil bridge. The so-called “hazardous bridges” can trigger PD with extremely high amplitude, which ultimately lead to the breakdown. In literature [59], the content is focused on influences of temperature on PD behaviors under pulsating DC voltage. Their results showed that compared to PDIV at temperatures of 30°C and 70°C, PDIV dropped significantly at temperatures higher than 90°C. They believed that the volume resistivity of oil-impregnated paper and gas

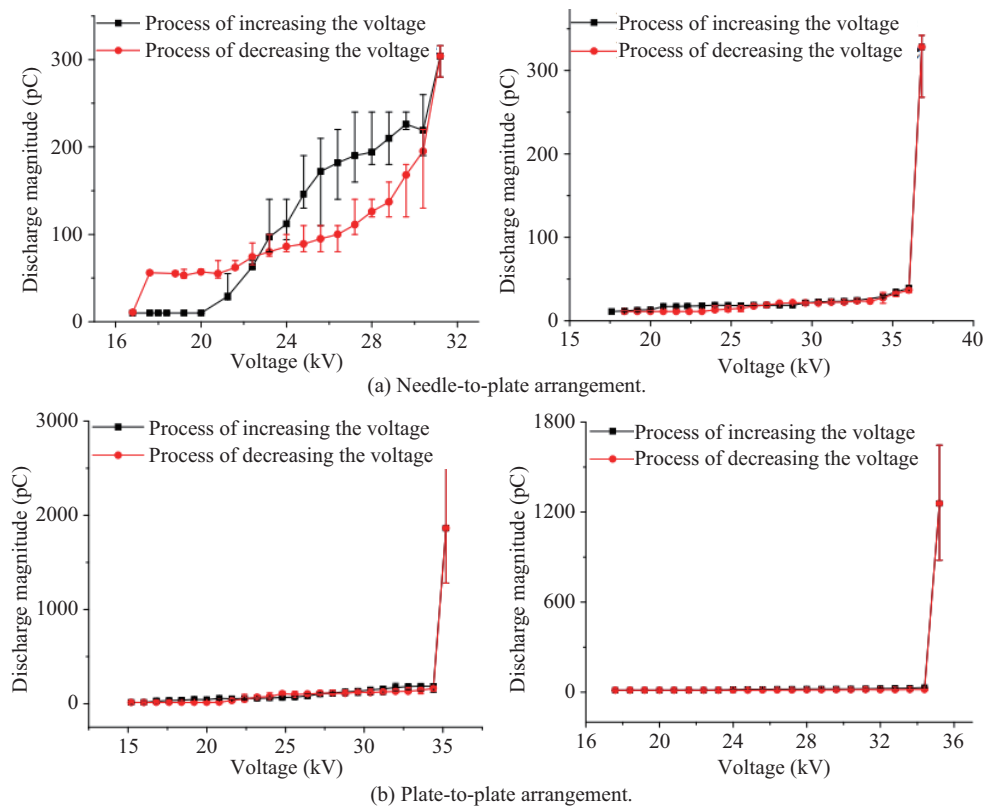


Fig. 7. PD amplitude for different electrode arrangements at different voltages. Left: at positive voltage, and right: at negative voltage [54]. © [2014] IEEE 5200190387455.

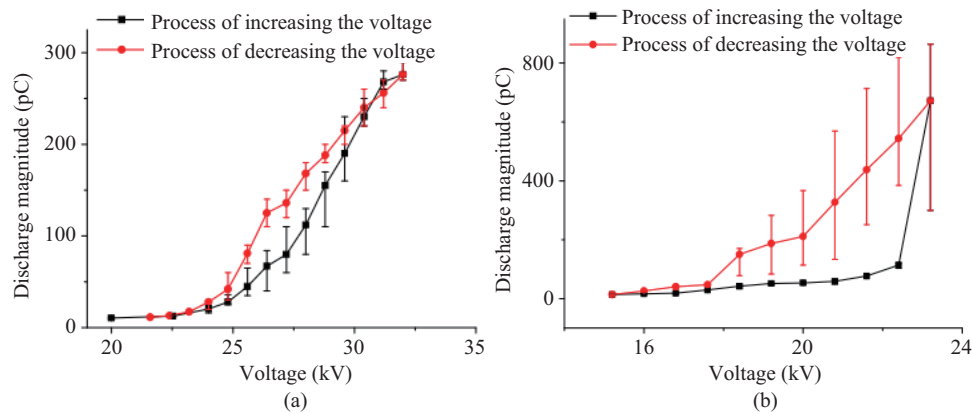


Fig. 8. PD amplitude for different electrode arrangements at AC voltages. Left: needle-to-plate arrangement, and right: plate-to-plate arrangement [54]. © [2014] IEEE 5200190387455.

pressure in the cavity were responsible for such variations, since these parameters affect the charge decay time constant inside the voids and further influence the electron generation rate. In addition, it is interesting to note that as has already been verified in literature [53] and [54], the levitation voltage of metal particles inside oil, here in literature [59], does not obviously change with respect to temperature variations ranging from 30°C to 90°C at both voltage polarities.

Sarathi *et al.* studied PD properties under AC and DC using a dielectric barrier plate floating between electrodes inside oil. Different from their results obtained without the dielectric barrier published in 2009, which showed a polarity

effect of PD amplitude, in this study, in case of the dielectric barrier, no particle movement or PD were observed when the particle was placed over the pressboard material, under AC and DC voltages [60]. Furthermore, they found that the levitation voltage of the particle in the oil gap (with and without barrier in the oil gap) was nearly the same irrespective of polarity of applied DC voltage.

Arrangements regarding dielectric barrier touches grounded electrode were studied using oil impregnated pressboard, transformer paper, and pressboard in literature [61]–[65]. In literature [61], the effects of DC prestressing on PD in oil-impregnated pressboard (OIP) insulation was studied. The

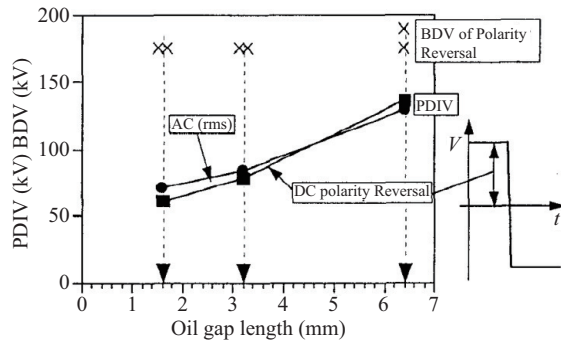


Fig. 9. Comparison of PD inception voltages between polarity reversal and AC stress [57]. © [1997] IEEE 5200190765627.

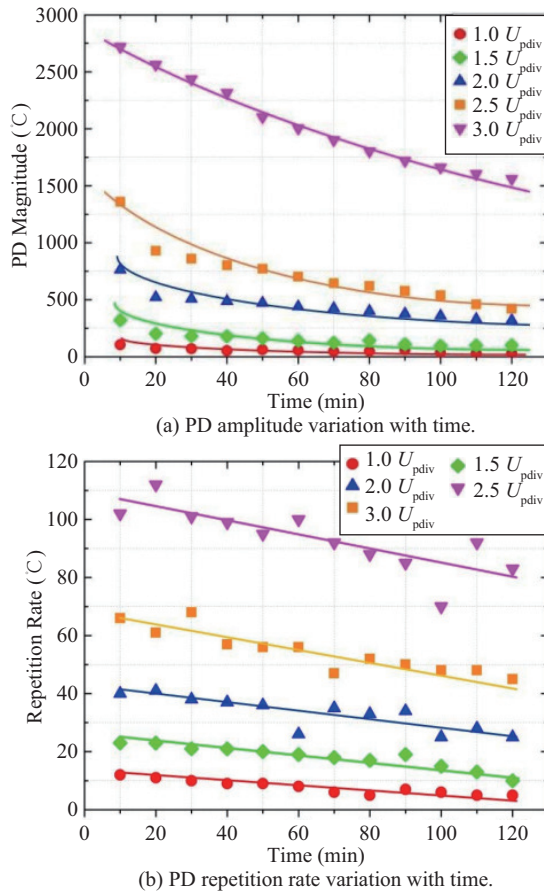


Fig. 10. Downward trend in PD amplitude and PD repetition rate [63]. © [2017] IEEE 5200191396851.

PDIV showed first that increasing then decreasing with increasing of prestressing time, and the PDEV of the OIP exhibited a gradually decreasing trend with longer prestressing time and higher DC prestressing voltage. Similar electrode and insulation arrangements have been used in literature [62], in which a significant increase of discharge activity a few moments before breakdown was detected.

In 2017, the PD properties and the degradation characteristics of oil-immersed pressboard were studied by Li *et al.* [63], [64]. They found the downward trend for the amplitude and repetition rate of DC PD above PDIV, as shown in Figure 10. In addition, they found that pre-treatment using PD with

amplitudes lower than 1000 pC merely changes the breakdown voltage while pre-treatment using PD with amplitude higher than 1000 pC decreases the breakdown voltage.

PD behaviors in oil-pressboard at positive DC voltage were also studied in literature [65]. A highly non-uniform electric field can be found near the needle under positive DC, resulting in a PD with different pulse waveforms and channel shapes even under identical conditions, as shown in Figure 11.

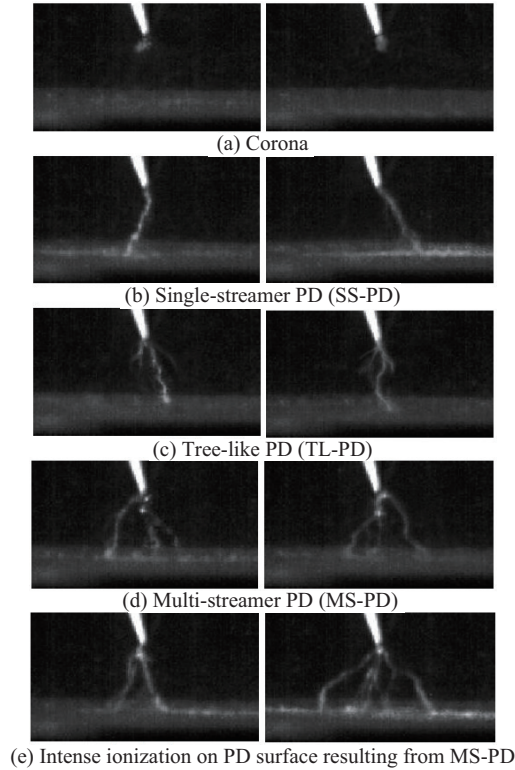


Fig. 11. Typical PD streamer profiles [65]. © [2019] IEEE 5200200389085.

VI. CONCLUSIONS AND SOME THOUGHTS BASED ON THE EXISTING STUDY

In this paper, we review and discuss the studies of DC PD for the gas-solid interface, inside insulation voids, and inside insulating oil along timeline. In this section, we attempt to conclude the knowledge we have obtained over previous studies and provide some of our own thoughts.

A. PD Intrinsic Property and Influencing Factors

Based on the review of the existing results in the above-mentioned sections, what we know at present is that the PD behavior at DC voltage has different characteristics, and this difference first depends on different scenarios in which PD occurs (solid internal voids, liquid-solid interface, and gas-solid interface, etc.). The PD in the gas environment tends to have a lower PDIV than the PD inside insulation voids. In addition, different material morphologies and electrical properties affect the characteristics of PD. For example, smoother and rougher insulation surfaces may both be unfavorable when considering PD suppression. A “normal” surface should be favorable for PD suppression, but what is “normal?” When PD

occurs using the rod-insulation-ground arrangement, it can be well suppressed if the conductivity of the insulation is within a certain range [66]. Additionally, different environmental conditions have a very large impact on the PD property, which is due to the influence of environmental factors, i.e., temperature, temperature gradient, air pressure, and humidity, on the ionization and electron collapse process.

Most of the existing studies focus on finding the relationship between these scenarios and PD properties. However, we still do not have a thorough understanding of the mechanism which is hidden behind. Some scholars have tried to tackle the mechanism of PD in the insulation voids by directly measuring the surface electric field of the internal void [33], however, there are still too much unknown in the mechanism of PD inception at different electrode-insulation arrangements and operating scenarios.

B. Insulation Degradation Inspection

Compared with AC PD, to date, it is very difficult to determine which type of PD under DC is the most destructive, nor do we understand which type of destructive defects of the insulation can be reflected by PD measurement results. It has been found that in many cases, PD only occurs before the insulation is about to breakdown, especially at higher pressure as mentioned in literature 47, and in case of PD occurring inside the oil as mentioned in literature 56. Additionally, from our recent study of PD measurement on print circuit boards (PCBs), for DC it is very difficult to detect a PD signal before surface breakdown, even for scenarios with short insulation distance with extremely uneven electric fields. AC PD measurement has to be implemented as a way for insulation surface property inspection.

Some other questions remain such as do the measurement results of DC PD really reflect the insulation performance? Is it possible to consider other methods, such as AC PD instead of DC PD in the estimation of potential defects of the insulation system of DC equipment? Such suggestions have already been mentioned in literature 6 and 7.

C. PD Measurement Standards and Issues

For AC electrical power equipment and components, PD measurement can effectively detect and locate local defects in the insulation system. There are already complete standards for PD measurement of AC electrical equipment (such as IEC 60270). In contrast, international standards for PD measurement of DC equipment are still not very sound [7]. Existing standards, which have been released, include IEC/IEEE 60076-57-129:2017 for use in converter transformers and IEC/IEEE 65700-19-03:2014 for use in DC bushings. However, in these cases, the PD limit is the number of individual PD pulses that exceed a given pulse amplitude threshold in a certain period of time. Some very important factors, i.e., voltage ramping rate, repetitive features, voltage duration, etc., during PD measurement, should influence the PD behaviors and are not considered in these standards.

Some evidence has been obtained on the differences between PD at ramp voltage and stable DC voltage. Before a stable DC is reached, a ramp voltage should be applied

on the sample, in which, during this process, the PD is easier to be triggered. The voltage boosting rate of the ramp can be very important in DC PD tests since it potentially triggers first PD which brings a surface charge distribution that affects the following PD property during the whole test period. This is due to the dielectric response to the voltage step, which determines a transient electric field distribution ruled by permittivity, therefore PDIVAC has to be considered, PD could be triggered only during transient and/or also in steady state DC (different field distribution, different PD characteristics and phenomenology). However, most of the people testing PD in DC cables do not even realize that they mostly measure PD during electric filed energization transient, that may last hours. Figure 12 shows that the surface charge distribution left by PD and these patterns differ significantly, resulting in different local electric fields which for sure influence the following PD activity on the surface [12], [67].

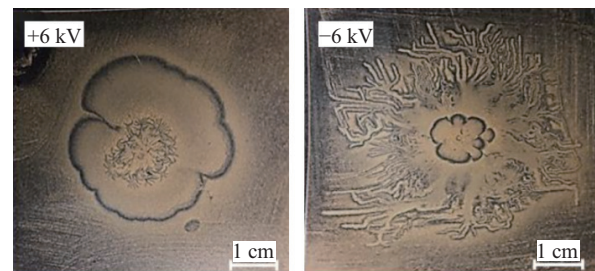


Fig. 12. Dust figures formed on the surface of ETFE after ± 6 kV was applied at 20 kPa.

However, it is not always the case. For example, for the needle-to-plate arrangement with the air as the insulation media in between, if the voltage exceeds the ionization inception voltage, there would be a gas ionization near the needle. The generated charges from the needle tips would migrate along the electric field lines and accumulated on the insulation surface, forming a homo-polar surface potential which is effective in decreasing the electric field near the needle tip and suppress the ionization. If the voltage is further increased, some streamers would occur near the needle tips followed with discharge activities, i.e., PD. However, such activity takes place near the needle tips in the gas phase, and the residual charges due to the previous PD disappear very soon, which would not influence the surface charge distributions and the next PD.

VII. CHALLENGES AND SUGGESTIONS FOR FUTURE STUDY

With the rapid development of electric power equipment as well as electronic devices operating in DC voltage over large application fields, such as power transmission, high-temperature turbine-generators, electric propulsion systems in air- and space-craft, marine, WBG power electronic encapsulations, satellite, and rail transportation, the problem of PD is getting more prominent and has become a hot research area for researchers all over the world.

Previous researchers have made great contributions on PD measurement [15], [68]–[71], identification [72]–[75], and

noise reduction [76], etc. in both AC voltage and DC voltages. However, these scopes are not the main focus of this review. What we want to say here is that the property of PD at DC voltage depends more on the surface charge behaviors, and more innovative studies may be needed as well on aspects including the study of the property of residual charges, mechanism of PD at different environmental conditions, and PD suppression techniques. Based on the above discussion over previous studies and the authors' experience, some challenges and suggestions for future studies are presented and discussed in this chapter.

A. Field-dependent Charge Property

The charge accumulation in DC provides a prerequisite for a discharge. Therefore, before we discuss the PD behaviors, we first need to deal with the surface charge problem.

The surface charges made from the free migrating charges in the gas and/or introduced by the leakage current are terminated at the interface. The charges can also be from the ionization of the gas and liquid induced by local electric field distortion. The charge properties, including charge dissipation, migration, and polarity, are all electric field-dependent, as has been discussed in previously published papers [77], [78]. To be more specific, we use the following two examples to explain the impact of field-dependent charge characteristics on PD.

Example 1. The convex surface of the spacer inside GIL has uniformly distributed homo-polar charges which inhibit the electric field stress at the triple junction near the high-voltage electrode, and which cause the PD to be suppressed. However, the gas near the ground enclosure surface with higher roughness can be ionized due to an increase of the local electric field, and hetero-polar charges introduced migrate to the convex surface of the spacer, which, on the contrary, greatly distort the electric field near the triple junction, resulting in a lower PDIV.

Example 2. When a needle-plate electrode arrangement is used to deposit surface charge on the insulation surface, the homo-polar charges generated by the ionization of the air near the HV needle accumulate on the insulation surface as a low electric field. However, when the voltage is increased, hetero-polar charges in the center of the plasma zone under the needle can be formed. As a result, hetero-polar charges in the central area of the insulation surface can be introduced. When you uncover the charged coatings from the ground electrode, the potential caused by these charges' triggers PD between the insulation surface and the grounded plate, generating charge patterns of different polarities which can be patterned by the dust figure method, as shown in Figure 13. The charge polarity reversal greatly increases electric field distortion on the insulating surface, which has a further impact on PD behaviors.

When applying a DC voltage to the dielectrics, complex physical phenomena on the surface and inside the volume of the dielectric, including homo-polar charge injection, polarization, homo-polar charge accumulation on the surface, and hetero-polar charge accumulation on the surface, all affect PD

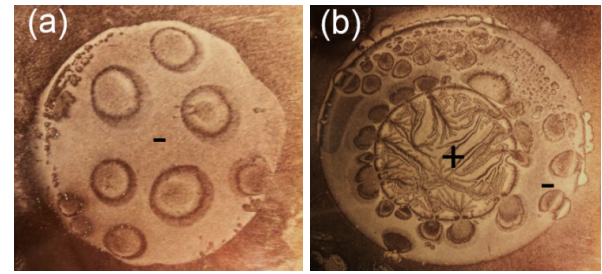


Fig. 13. Dust figures of PI film after being separated from the grounded plate after the corona discharge treatment at different voltages: (a) Cycled discharge patterns triggered by negative surface charge generated at 5 kV, and (b) tree-like discharge patterns triggered by positive surface charge in the middle and cycled discharge patterns triggered by negative surface charge on the periphery generated at 9 kV.

behaviors while these physical phenomena are all electric field-dependent. Therefore, we need to first clarify the relationship between surface charge behaviors and the electric field applied under certain insulation-electrode coordination, before we start to tackle problems of DC PD.

B. Special Application Scenarios

Due to the development of clean energy in power transmission, the application of electrical cables and power electronic components in DC voltage is increasing. The PD at the complex operating environment brings a severe test to the insulation design. Some scenarios and emerging problems caused by PD at DC voltage are as follows:

The DC cables to be used in an all-electric aircraft operate at high temperature and low pressure. The aging and conductivity changes of the insulation at high temperature and the decrease of ionization inception field stress at low pressure have a great impact on PD behaviors [67], [79], [80]. However, there are still very few studies in this area.

Printed circuit boards (PCBs) are used as one of the key parts in the DC power convertor in an all-electric aircraft, which are usually subjected to surface charge accumulation at low air pressure. The PCB layout is more complicated than the cable structure and once PD occurs, it is more likely to damage components and affect the communication system. The study of DC PD behavior on the PCB surface under low pressure is becoming a hot research area in recent years. Additionally, DC PD problems also exist in similar special applications, including WBG power electronic encapsulations, and PCBs and electric power cables in satellites.

The emerging offshore projects use DC GILs/GIS as an option for space-saving. The spacers inside of GIL operate in a DC field in a temperature gradient and SF₆ pressurized environment. The pressurized SF₆ aggravates the density of charges on the spacer surface, and the temperature gradients promote the redistribution of surface charges, which all influence local electric field distributions and further PD behaviors.

C. Coupling Effect of Environmental Factors

In DC voltage, the mechanism for how PD is triggered still needs more investigation, especially for PD influenced by different environmental factors and/or coupling effect of these factors. It is far from enough to merely obtain the relationship

between variations of the influencing factors and the PD parameters. Let us take the PD behavior of PI film at different relative humidity (RH) as an example. Figure 14 shows the relationship between the cumulative value of PD amplitude measured using PI film with a rod-insulation-plate arrangement at constant humidity and humidity variation conditions. It can be seen that at constant humidity, i.e., RH = 23 %, intensive PD occurs at ramp voltage, and the PD amplitude grows slower at stable DC voltage. In the case of humidity variations, the PD activity is suppressed at the ramp voltage, which is manifested in the reduction of the PD cumulative. However, when the RH increases to 99 %, the PD activity increases sharply after 120 s. This conclusion is inconsistent with the existing research conclusions that high humidity has an inhibitory effect on PD behavior [81], [82].

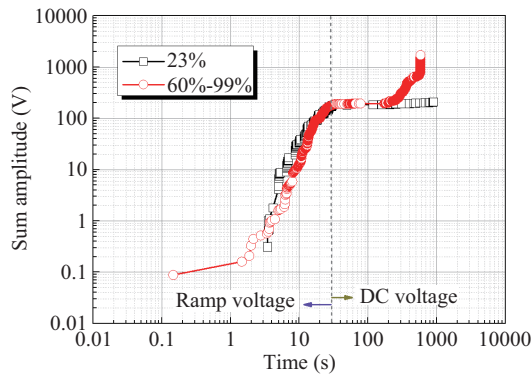


Fig. 14. The cumulative PD amplitude vs. time measured using PI film with rod-insulation-plate arrangement at constant humidity and humidity variation conditions at 6 kV. The time takes for humidity to reach 99% is 120 s.

What we would like to emphasize here is that there are complicated coupling physics phenomena behind this seemingly simple problem which you might not be aware of. As shown in Figure 15, higher humidity enhances gas ionization, which has already been verified [83]. The ionization increases the gas side charge density, resulting in an increase of the surface charge density. However, the polarity of these surface charges depends on the direction of electric field lines which are determined by the insulation-dielectric arrangement in certain scenarios, as has been discussed in the previous section. Under the premise that the polarity of the charge is not clear, it is difficult to be sure whether the newly introduced charge further inhibits or promotes PDIV. Additionally, once the PD occurs, it neutralizes the surface charge and reduces the surface charge density. Still, it would be difficult for us to judge whether the decrease of the charge density alleviates or aggravates the local electric field distortion, and it is impossible therefore to judge

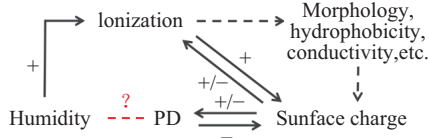


Fig. 15. Coupling physical factors before PD was triggered at higher humidity.

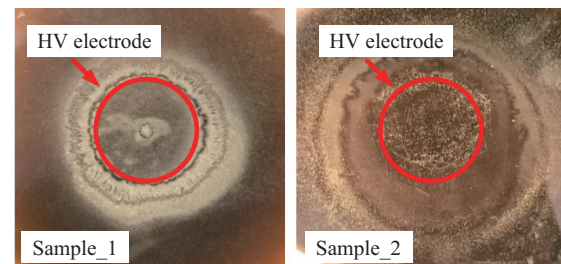
the further development characteristics of PD.

Additionally, since different materials may have different surface morphology (which affects the development of electron avalanches along the surface), hydrophobicity, and electrical conductivity, the coupling of these characteristics affects the distribution of surface charges. For example, an insulating material with strong hydrophilicity is easy to form a water film on the surface at higher RH. Once the continuous water film is formed, it would, to some extent, decrease PDIV due to less insulation distance.

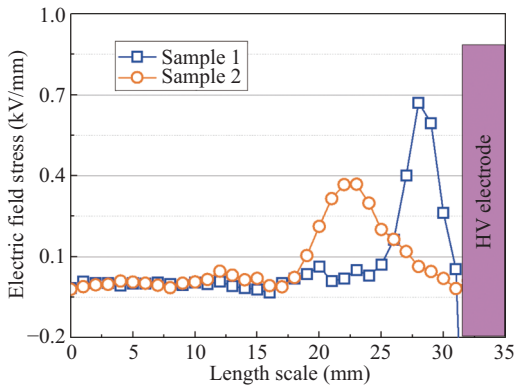
Therefore, the coupling effect of multiple physical phenomena and material and environmental factors before PD occurs, to be more specific, from the process of the initial ionization to the first PD and to the subsequent PDs, should be further explored. This helps us to understand the physics of PD under different scenarios. In addition, we can consider suppressing or promoting any one or several links in the coupling effect to inhibit PD activity. For example, to optimize electrodes and control humidity to reduce the onset voltage of ionization, or to avoid hetero-polar charge accumulation and adjust the position of homo-polar charge as ways to modify local electric field distribution.

D. PD Suppression Methods

The study in PD intrinsic characteristics and mechanism provides a basis for further controlling PD. At DC voltage, we can never overemphasize the importance of the influence of insulation surface charge on PD behaviors. The initiative controlling of surface charge behaviors to mitigate surface electric field can be a useful solution for PD suppression. Our recent study confirms that for a bar-insulation-plate arrangement, if we increase the surface conductivity to reach a certain range, the homo-polar surface charge packet can be regulated and the electric field can be modified near the triple junction, which is useful for PD suppression. Figure 16(a) shows the surface PD position reflected by dust figures on two PI samples with different surface conductivities using a bar-insulation-plate arrangement. The diameter of the surface PD area for sample_2 which has a higher surface conductivity is larger than that of sample_1. The amplitude of the tangential component of the electric field calculated by surface potential measured along the radius direction drops significantly for the sample with higher surface conductivity as shown in Fig. 16(b). More details can refer to our recent study [66].



(a) Dust figures of PI films with different surface conductivity after applying 6 kV for 1 min (Surface resistivities for sample_1 and sample_2 are $4.6 \times 10^{17} \Omega$ and $4.1 \times 10^{13} \Omega$).



(b) Calculated tangential component of electric field based on surface potential measurement results along the radius direction.

Fig. 16. Dust figures and tangential component of electric field of PI films with different surface conductivities after 6 kV was applied for 1 min using a bar-insulation-plate arrangement.

VIII. CONCLUSION

In this paper, an overview considering PD characteristics under DC voltage in the gas-solid interface, inside insulation voids, and inside oil media is given and the study on PD measurement results and analysis of PD properties, in particular the study that was performed in the past 10 years, is discussed.

Some discussions over the links and relationships between results obtained by previous researchers are somewhat missing in this paper. To be frank, when we were preparing this paper, we found that at present, it is difficult for us to have too many discussions over the relationship between existing studies, partially due to the reason that the study of DC PD is still in its early stages, and there are not enough documents that can provide sufficient knowledge for us to have a thorough understanding of the mechanism to explain accurately the PD phenomena in different scenarios. Additionally, it is more difficult for us to compare the results obtained by different research groups with different experimental parameters, such as setups, voltage ramping rate, RH, voltage level, etc. In the last section, we shared our knowledge based on our understanding of the DC PD phenomena, and this is what we can best provide at the moment. We hope that more mechanism-based studies can be performed to fill the gaps in this field in the near future.

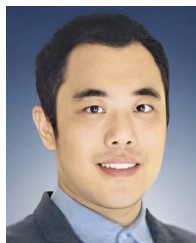
The pattern recognition and measurement techniques are not the focus of this paper.

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