Partial Discharges in Solid Insulation Cavities: Basic Concepts, Definitions and Some Thoughts for Further Research

M. G. Danikas, R. Sarathi

Democritus University of Thrace, School of Engineering,
Department of Electrical and Computer Engineering,
Power Systems Laboratory, 67100 Xanthi, Greece [1]

Indian Institute of Technology Madras,
Department of Electrical Engineering,
High Voltage Laboratory, Chennai, 600-036 India [2]

Abstract

This paper refers to some basic definitions of partial discharges (PD), a most important phenomenon taking place in insulating materials under high voltages. There is a brief description of PD modeling as well as a description of the means of detecting and registering such phenomena. This paper concentrates mainly on the PD phenomena taking place in enclosed cavities in solid insulation. Some directions of future research are discussed.

Keywords

Solid insulation, partial discharges, dielectric breakdown, dielectric strength, electrical strength, breakdown strength

Introduction

Partial discharge (PD) is the name given to the electrical discharge, which involves only a portion of the dielectric between two electrodes and which does not bridge the electrodes [1]. PD may happen in a cavity (or void) in a solid insulation (and such PD are usually referred to as internal PD), on a surface or around a sharp point subjected to a high voltage. Internal PD are extremely harmful to solid insulating materials and start appearing when a cavity is subjected to an AC stress- greater than its breakdown value. They occur at each half-cycle of the applied sinusoidal voltage [2]. PD are intimately linked with the notion of PD energy, as was explained in [3], where the PD energy (w) of a single PD is given as

$$W = 0.7\, q\, V_i \qquad (1)$$

where, q is the apparent charge of the PD and V_i, the discharge inception voltage.

PD develop in inclusions is a solid dielectric. Such inclusions have a lower dielectric strength than that of the surrounding material. With rising applied voltage, the voltage at which PD start occurring in an inclusion is called inception voltage. When the voltage is decreasing somehow, PD stop occurring. That voltage is called extinction voltage [4]. It must be emphasized that the quantities "inception voltage" and "extinction voltage" depend on the sensitivity of the detecting apparatus available [5 - 8]. It must also be pointed out that, reference [4] written by a most distinguished scientist, restricts the definitions of "inception voltage" and extinction voltage" to AC conditions. Inclusions in a so-lid insulation can be gas-filled cavities found in extruded plastics, lapped impregnated paper and cast re-sins, cavities filled with oil (as in layers and in butt gaps of oil impregnated paper insulation) or may consist of various foreign particles (such as textile fibers or dirt). The problem of PD and their injurious effects on so-lid insulation has been studied for many years [7, 9, 10 - 12]. This paper will concentrate on the PD in enclosed cavities in solid insulation. Some aspects of PD will be reviewed. Some of the remaining problems in conjunction to PD in cavities will be discussed.

PD modeling

The most popular and widely used model for the description of the behavior of PD in enclosed cavities is the well known a-b-c model or capacitance model [13, 14]. The model represents the enclosed cavity as a capacitor (C_c), with another capacitor the adjacent insulation (C_b) and yet another capacitor the rest of the healthy insulation (C_a). In case of an applied AC voltage V_a to the insulation sample, another voltage V_c appears in the cavity, with these voltages related with the following equation

$$V_c = V_a\,[C_b\,/\,(C_b + C_c)] \qquad (2)$$

According to appropriate analysis [3], it follows that the apparent charge (q) of a discharge in a cavity can be expressed as

$$q = C_b \, \Delta V_c \qquad (3)$$

with ΔV_c the voltage drop in the cavity during the PD.

Another model – based on the electromagnetic theory – is the model proposed in [15], where the charge (q) induced on the measuring electrode by the PD in a cavity of geometric factor (k) and having a volume (Ω), with the inception electric field for streamer inception (E_i) and a limiting electric field for ionization (E_l), the relative permittivity of the surrounding insulation (ε_r) with (ε_0) the permittivity of the free space, and $\nabla\lambda_0$ the function giving the ratio of the electric field at the position of a cavity (in the absence of the cavity) to the voltage between the electrodes, is given in the following equation

$$q = k \, \Omega \, \varepsilon_r \, \varepsilon_0 \, (E_i - E_l) \, \nabla \lambda_0 \qquad (4)$$

This model was based on the streamer criterion and it was proved adequate for initial experimental conditions. The criticism which was leveled by Pedersen and colleagues against the a-b-c model was that an enclosed cavity cannot be represented as a capacitance since a capacitance by definition requires a metallic surface facing a metallic surface. In a paper [16], some criticism was leveled against Pedersen’s model, namely that whereas publication [15] takes into account the occurrence of sustained discharges, it does not take into account the eventuality of non-sustained discharges. Non-sustained discharges may well not only lead to a redistribution of charges inside a cavity, but they may also have an effect on the lifetime of the insulation. Later on, there was additional criticism of Pedersen’s model in a number of publications [17 – 19].

Another model – which preceded Pedersen’s model – was proposed in [20]. Although the models of [15] and [20] present some similarities, they differ in that the latter is based on Townsend’s criterion. The equation expressing the apparent charge q of a PD taking place in a cavity is given in Eq. (5)

$$q = \varepsilon_r \, \varepsilon_0 \, E_z \, \gamma \, V / l_a \qquad (5)$$

where, ε_r, ε_0 as in Eq. (4) above, E_z the electric field given from Paschen’s curve, γ a parameter related to the electrode arrangement, V the cavity volume and l_a a geometrical factor depending on the cavity dimensions, i.e.

on the ration a/b if the cavity is ellipsoidal. The model proposed in [20] seems to be more appropriate for rather aging conditions whereas the model of reference [15] seems to be more suitable for initial experimental conditions.

More recently, a detailed account on PD modeling was reported in [21], where the authors analyzed – apart from the capacitance model and Pedersen’s model - the pros and cons - of other models, such as Niemeyer’s model, the plasma model and the Finite Element Method (FEM) model. It is a general truth that modeling cannot fully describe all the PD workings occurring in a cavity. Therefore, the above mentioned models have their own advantages and limitations. Niemeyer’s model, for example, correctly proposes cavity surface emission and volume ionization but it assumes that the cavity internal field remains constant and the discharge process takes place in the entire cavity. The plasma model gives details of the physics of the discharge but it cannot analyze multiple PD activities (e.g., in case there are multiple cavities in an insulation). The FEM model may well give accurate distributions of the electric fields but in case of complex physical activities may need extensive computing facilities [21].

PD in cavities

Mason [22] testing with plane discs from clean polyethylene with small cylindrical cavities and using uniform electrode arrangement, calculated that about 10^{-15} cm^3 of polyethylene is eroded by each PD having a 10 pC magnitude. The same researcher reported that deterioration of the dielectric increased with raising the applied voltage above the PD inception level. Among the main factors affecting the rate of deterioration of an insulating material are the ratio of the applied voltage to the PD inception voltage, the magnitude and energy of the PD, the waveform and frequency of the applied voltage, the resistance of the material both to PD erosion and to chemical attack by byproducts generated by the discharge and finally the electrical and chemical characteristics of the surrounding medium [23]. The energy of the discharges affects the local temperature rise at the point of impact of the PD and subsequently the value of the attained intrinsic strength. (it must be noted that the notion of "intrinsic strength", although still employed when referred to very localized phenomena, is not generally used [24]).

Earlier work [25], investigating the behavior of discharges in air gaps facing solid insulation, indicated that the increase of PD magnitude with increasing voltage was due to a continuous recombination and neutralization of deposited surface charges which reduce the shielding effect. Rogers [26] remarked that cavities adjacent to electrodes cause more damage than cavities inside the main body of the solid insulation, something that was also noted before [22]. Moreover, PD in cavities with a large diameter/depth ratio cannot extinguish as in cavities with a small diameter/depth ratio. The former type of cavities is likely to have the more injurious effect on the insulation. Such observations were also made by Nosseir and co-workers [27], whereas decades later, the observations by Rogers were also confirmed in [28].

Another researcher [29], many decades ago, tested two types of insulating specimens, namely one with artificial cavities and another with natural cavities and he found that the inception voltage of natural cavities was two to four times the calculated inception voltage, assuming the field was uniform in the cavity. Echoing such work, Kreuger [30] observed that PD magnitude increases with cavity area, with the number of PD per unit time increasing proportionally with frequency.

Quite early, particular attention was paid to the interconnection between insulation damage and chemical changes. Thus, it was reported in [31] that on non-uniform electrode system and polyethylene samples, the main chemical changes occurring – by the activity of PD – are crosslinking, increase in unsaturation and hydrogen evolution. The rate of chemical change depends on the total PD energy and the concentration of the end products. The total volume of hydrogen evolution V (in ml) in a system at a time t (in sec) was empirically given in Eq. (6)

$$V = \sqrt{2}\,kt \qquad (6)$$

with k the hydrogen evolution coefficient, which is directly proportional to the total PD energy per cycle. In the same publication it was pointed out that weakly conducting films play a significant role in retarding the ultimate failure of the solid insulation, agreeing in this respect with Kreuger [30, 32]. Somehow coupled with the previously mentioned work is a paper published in 1965, where it was shown that the PD rate rises almost linearly with the applied voltage irrespective of the gap setting and the vapor pressure in a spark gap [33].

The question of PD and their relation to energy as well as to insulation damage is one of the most crucial ones. Megahed and co-workers [34] thought preferable to measure continuously both PD magnitudes and repetition rates in order to correlate PD damage with PD activity rather than measure either the maximum PD magnitude or the total PD energy. Later [35], Megahed confirmed the above conclusions studying the PD repetition rates in cavities in epoxy resin, polyethylene and mica under AC conditions. At about the same period, other researchers working on internal PD behavior in polyethylene with artificial cavities, reported that PD generally decrease in magnitude and repetition rate with time and that absorbed water can greatly influence the pattern of discharges [36]. The decrease of repetition rate of PD with time occurs because of a voltage decrease on the side wall due to the decline of the side wall resistance in the cylindrical cavity. The apparent charge of maximum PD (q_a) in a cylindrical cavity is given by Eq. (7)

$$q_a = (\varepsilon_0\, \varepsilon\, V_{GO}\, s) / (D - d) \quad (7)$$

with ε_0 the dielectric constant of vacuum, ε the dielectric constant of the solid material, D the thickness of the specimen, d the cavity depth, s the area of the cavity and V_{GO} the inception voltage of the cavity. The diminution of q_a with time is due to the narrowing of the discharge area by the development of low resistance to inner top and bottom surfaces. Results published in [37] at about the same period showed that the impulse inception stress increases with decreasing cavity diameter at constant cavity depth as well as with decreasing depth at constant cavity diameter. Such data on the effect of cavity dimensions on the PD activity and on inception voltage were confirmed in more recent research [38 – 40].

Okamoto and co-workers [41] pointed out that the nature of internal PD is greatly affected by the assembly of the electrode system and the adhesion of films. This means that the preparation procedure plays a pivotal role on the experimental results one can get. Furthermore, they reported that internal discharges become unstable as time goes on and this in turn may result in very long lifetimes. Such conclusions were confirmed later in [42, 43].

Selvakumar and Nema [44] found that the PD inception voltage depends on both the pressure within the cavity and on the cavity diameter, with the PD inception voltage decreasing at low pressures. PD inception voltage also decreases approaching a minimal value as the diameter becomes larger. The extinction voltage, on the other hand, depends on the conditions of charges trapped on the surface of the insulation. They reported that, for consistent measurements of quantities such as inception voltage, of stress across the cavity and of extinction voltage, long periods of stressing are recommended and not overvoltages since the latter may damage the insulation. The effect of cavity pressure on PD behavior was confirmed the same year by other researchers [45]. Important work done in [27], indicated that a hysteresis effect exists between inception and extinction voltage, i.e. for the same applied voltage V, the PD magnitude recorded was less when the voltage was being decreased than when the applied voltage was being increased. The hysteresis effect was more pronounced for deeper cavities. The authors attributed this to the slower rate of discharge leakage in case of deeper cavities. The hysteresis effect – as noted in [27] – was studied and used many years later as an effective diagnostic tool for electrical machine insulation ageing and degradation [46 – 48].

A direct relationship between PD intensity and the rate at which deterioration takes place in an internal cavity was observed by Reynders [49], who worked with low density polyethylene (LDPE). His observations were confirmed in another paper published a few years later [50]. Reynders noted a phenomenon observed also by others before, namely that PD initially of large magnitude decrease with time. Such a behavior may be attributed to the diminishing of the cavity area associated with each PD with time and this can happen if the PD occur between sites where degradation products accumulate. As the degradation products spread over the cavity surface, smaller areas between them are available to PD [51]. Regarding the degradation of LDPE, two degradative processes were observed:

(a) crosslinking of polyethylene, which may be due to ultraviolet radiation and electrons and this is evident by hydrogen evolution, and

(b) erosion of polyethylene, which may be due to ion bombardment and the evolution of organic gases, such as carbon monoxide, methane and carbon dioxide [52].

With respect to process (a), publication [52] did not differ from the explanation of [31].

Researching the notion of inception voltage, Golinski and co-workers [53] studied PD activity in cylindrical cavities enclosed in epoxy resin specimens with various electrode geometries. They observed that the effect of polarity is distinct only in the region where $V = V_{vi}$ (V being the applied voltage and V_{vi} the inception voltage for the cavity). At V = (3 or 4) V_{vi} the effect of polarity almost disappeared. They speculated that at higher voltage the important secondary phenomena (photoionization, dissociation of the negative ions formed by the preceding PD) in gas breakdown originate from the gas and not from the metal electrodes.

Garcia and Fallou [54] proposed discharge energy as a reliable and useful tool in evaluating the relationship between loss of weight and dissipated power since the apparent charge reflects just the voltage pulse induced at the terminals of the test object providing thus little information concerning the deteriorating effect of the PD. The energy delivered to the test object is expressed according to these authors as

$$E_T = \Sigma U_i Q_i \qquad (8)$$

where, E_T is the energy supplied by the source over a period T during which N discharges have taken place, Q_i and U_i being respectively apparent charge of the PD and U_i the instantaneous value of applied voltage when the PD takes place. The conclusions of [54] were not different from those reported in [55, 56]. The notion of discharge energy was adopted by a variety of researchers later, especially with the advent of Pulse Height Analyzers (PHA) and Phase Resolved Partial Discharges Analysis (PRPDA) [57 - 65]. The latter two techniques also greatly contributed in observing various PD patterns as was reported and analyzed in [21, 66] as well as in analyzing in detail the cavity physics and chemistry when this is under PD activity. Furthermore, relatively recent studied successfully exploited PHA and PRPDA in order to relate energy patterns of delaminations, slot and cavities in high voltage rotating machines with tanδ measurements [67].

Ideas as to the importance of PD energy in relation to insulation damage were expressed quite early. The complexities of PD energy vs. PD magnitude were very early noted by Mole [68], who suggested that the energy dissipation of an individual discharge in a cavity appeared to be more important than the PD magnitude. In the same paper it was pointed out the significance of the cumulative energy dissipation in a cavity (which was determined by the individual energy dissipation together with the PD repetition frequency in a particular cavity). Building on earlier ideas and concepts, Bartnikas [2] expressed the energy dissipated in each discharge as

$$\Delta W = C_V\,(\Delta V)^2 / 2 \qquad (9)$$

where, C_V the cavity capacitance and ΔV the voltage drop in the cavity during a discharge. The same author correctly pointed out the great significance of the PD energy because of its direct relationship to the degradation of an insulation subjected to PD. Starr [69] reported that the spatial concentration of the PD energy is very important, since in some cases, discharges alter the material on which they impinge rendering it partially conductive and consequently removing the electrical stress from the area where the discharges firstly occurred. This may well cause the discharge mechanism process to cease or start somewhere else. A consequence of the above is that a discharge energy / material damage relationship may be different from what is expected.

The question as to how we can relate insulation damage with PD parameters is one of the crucial problems. Insulation damage, depending on the material and the experimental and/or the service conditions, may manifest itself in various forms, e.g. discolored areas, chemical alterations, solid by-products, liquid by-products, gaseous by-products etc. It was reported that even very small PD may cause some insulation damage, and consequently affect the lifetime of an insulation [70]. This statement is at variance with earlier findings of [30], where it was reported that "...very small discharges may not influence the lifetime of the insulant". In [70] as well as in more recent publications [71 - 75], it was indicated that even very small PD may have a cumulative effect and be harmful since in the mid- and long- term may produce more carbonization, disruption of the polymer molecules and release of gaseous by-products.

The failure of earlier researchers [76] to obtain a more explicit quantitative relationship between insulation damage and PD parameters was remedied in more recent years with the advent of powerful tools of PD analysis, such as the PHA and the PRPDA mentioned above as well as the Pulse-Sequence Analysis (PSA) [77 - 80]. Needless to say that such techniques also help with the identification of the types of the defects in an insulation and also with the clarification of the kind of PD mechanisms involved [81 - 84].

Some further thoughts on partial discharges

In this paper, an effort was made to present a blend of older and more recent research regarding partial discharges in enclosed cavities. It is evident that scientific research has a continuity and it is always very interesting to see how recent techniques may tackle older problems. Although there was not a dramatic change in basic PD definitions - albeit sometimes of efforts in introducing neologisms [85, 86] -, the development of PD analyzers and related detecting techniques emphasized the need of defining in greater detail what is inception voltage and what is extinction voltage. With the passing of the years, the refinement of detecting apparatus and the advent of the fast digitizers, more attention – and rightly so - was paid to the fast measurements of PD [87, 88]. The latter may supply useful information as to the PD mechanism inside a cavity, whereas the techniques PHA and PRPDA, mentioned above [57 - 65], are an excellent tool for monitoring the PD cavity development and consequently the insulation behavior in the mid- and the long- term. Some criticism against the PHA and PRPDA techniques was leveled recently, by pointing out that the former two methods are sometimes susceptible to losing useful information when multiple PD sources are in action [89]. Possible future research may enlighten further the pros- and cons- of the various diagnostic techniques.

Regarding the modeling of PD in a cavity, discussions still go one regarding the preponderance of Pedersen’s model [15] w.r.t. the more classical capacitance model [13, 14]. The issue is not yet settled, as some recent publications indicate [17 - 19, 90, 91].

Conclusion

In the context of the present paper, some aspects of partial discharges in enclosed cavities have been partially reviewed. Important issues, such as inception and extinction voltages, PD energy and its relation to insulation damage, have been discussed. The interconnection between PD energy and what can be taken as "insulation damage" is still one of the vital subjects for further research.

References

[1] Timpe N. B., "Partial discharge measurements in distributed parameter systems: Cables", Engineering Dielectrics, Vol. I, Corona Measurements and Interpretations, ASTM Special Technical Publication 669, 1979, pp. 134 - 175

[2] Bartnikas R., "Corona discharge processes in voids", Engineering Dielectrics, Vol. I, Corona Measurements and Interpretations, ASTM Special Technical Publication 669, 1979, pp. 22 – 67

[3] Gallagher T. J., Pearmain A. J., "High Voltage – Measurement, Testing and Design", Eds. John Wiley & Sons, New York, USA, 1983, pp. 166 – 168

[4] Kelen A., "Studies on partial discharges on solid dielectrics: A contribution to the discharge resistance testing of insulating materials", Acta Polytechnica Scandinavica, No. EI 16, Monograph, 1967, total number of pages 138

[5] Tanaka T., Greenwood A., "Advanced power cable technology: Volume I – Basic concepts and testing", Eds. CRC Press, Boca Raton, Florida, USA, 1983, p. 87

[6] Mason J. H., "Dielectric breakdown of solid insulation", Progress in Dielectrics, Vol. 1, 1959, pp. 1 – 58

[7] Mason J. H., "Discharges", IEEE Transactions on Electrical Insulation, Vol. 13, No. 4, 1978, pp. 211 – 238

[8] Danikas M. G., Sarathi R., "Very small partial discharges and charging phenomena below inception voltage: An effort for a review and a proposal for a unified theory", FunkTechnikPlus # Journal, Issue 33, Year 11, 2024, pp. 7 - 27 "www.ftpj.otoiser.org/issues/html/ftpj-issue-33-lo7532-export-ia1.htm" (33-1)

[9] Morshuis P., "Assessment of dielectric degrada-tion by ultrawide-band PD detection", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 5, 1995, pp. 744 – 760

[10] Kelen A., Danikas M. G., "Evidence and presumption in PD diagnostics", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 2, No. 5, 1995, pp. 780 – 795

[11] Koenig D., "Das Phaenomen der elektrischen Teilentladung", in the book "Teilentladungen in Betriebsmitteln der Energietechnik", Eds. VDE-Verlag, Berlin und Offenbach, Germany, 1993, pp. 15 – 39

[12] Moeller K., Meurer D., "Auswirkungen von Teilentladungen auf elektrische Isolierstoffe", in the book "Teilentladungen in Betriebsmitteln der Energietechnik", Eds. VDE-Verlag, Berlin und Offenbach, Germany, 1993, pp. 85–104

[13] Gemant A., "Die Verlustkurve lufthaeltiger Isolierstoffe", Zeitschrift der Technischen Physik, Vol. 13, 1932, pp. 184 – 189

[14] Gemant A., Philippoff W. V., "Die Funkenstrecke mit Vorkondensator", Zeitschrift der Technischen Physik, Vol. 13, 1932, pp. 425 – 430

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

[16] Danikas M. G., Vardakis G. E., "The case of Pedersen’s theory to model partial Discharges in cavities enclosed in solid insulation: A criticism of some of its aspects from an electrical engineers’ and from a physicists’ point of view", Journal of Electrical Engineering, Vol. 52, No. 5-6, 2001, pp. 166 – 170

[17] Achillides Z., Georghiou G. E., Kyriakides E., "Partial discharges and associated transients: The induced charge concept versus capacitive modeling", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, No. 6, 2008, pp. 1507 – 1516

[18] Achillides Z, Danikas M. G., Kyriakides E., "Partial discharge modeling and induced charge concept: Comments and criticism of Pedersen’s model and associated measured transients", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 24, No. 2, 2017, pp. 1118 – 1122

[19] Achillides Z., Kyriakides E., Danikas M. G., "Partial discharge modeling: An advanced capacitive model of void", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 26, No. 6, 2019, pp. 1805 – 1813

[20] Repp H., Nissen K. W., Roehl P., "Partial discharges in voids: Inception Conditions and detection limits", Siemens Forschung und Entwicklung Bericht, Vol. 12, 1983, pp. 101 – 106

[21] Afrouzi H.-N., Hassan A., Ye Chee D. T., Mehranzamir K., Malek Z. A., Mashak S. V., Ahmed J., "In-depth explorations of partial discharge modelling Methods within insulations", Cleaner Engineering and Technology, Vol. 6, 2022, total number of pages 13
"https://doi.org/10.1016/j.clet.2021.100390"

[22] Mason J. H., "The deterioration and breakdown of dielectrics resulting from internal discharges", Proceedings of IEE, Vol. 98, Part I, 1951, pp. 44 – 59

[23] Mason J. H., "Breakdown of insulation by discharges", Proceedings of the IEE, Vol. 100, Part IIA, 1953, pp. 149 – 158

[24] Cooper R., "Breakdown in solids", in the book "Electrical Insulation" edited by A. Bradwell, eds. Peter Peregrinus, London, UK, 1983, pp. 33 – 51

[25] Frielander E., Reed J. R., "Electrical discharges in air-gaps facing solid insulation in high-voltage equipment", Proceedings of the IEE, Vol. 100, Part IIA, 1953, pp. 121 – 131

[26] Rogers E. C., "The self-extinction of gaseous discharges in cavities in dielectrics", Proceedings of the IEE, Vol. 105A, 1958, pp. 621 – 630

[27] Nosseir A., Salama M. M. A., Soliman A., Rizk R., "Discharge detection and measurement in voids in solid dielectrics", Conference Record of 1984 IEEE International Symposium on Electrical Insulation, Montreal, Canada, June 11-13, 1984, pp. 336 – 338

[28] Hossam-Eldin A. A., Dessouky S. S., El-Mekkawy S. M., "Internal discharge in solid dielectric materials", Journal of Electrical Engineering, Vol. 9, No. 4, 2009, total number of pages 5
"www.jee.ro"

[29] Reynolds S. I., "On the behavior of natural and artificial voids in insulation under internal discharges",

AIEE Transactions on Power, Apparatus and Systems, Vol. PAS-77, Part III, 1959, pp. 1604 – 1608

[30] Kreuger F. H., "Discharge detection in high voltage equipment", Eds. Heywood London, UK, 1964, pp. 105 - 125

[31] Meats R. J., Stannett A. W., "Degradation of insulation materials by electrical discharges", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-83, 1964, pp. 49 – 54

[32] Kreuger F. H., "Industrial High Voltage: Fields, Dielectrics, Constructions", Eds. Delft University Press, Delft, The Netherlands, 1991, pp. 123 – 131

[33] Bartnikas R., d’Ombrain G. L., "A study of corona discharge rate and energy loss in spark gaps", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-84, No. 9, 1965, pp. 770 – 778

[34] Megahed I. Y., Mansfield B. C., Wootton R. E., "Detection and measurement of discharges in cavities in solid dielectrics", Proceedings of the IEE, Vol. 114, No. 11, 1967, pp. 1822 – 1824

[35] Megahed I. Y., "The discharge-repetition rate in cavities in epoxy resin, polyethylene, and mica under alternating voltage conditions", IEEE Transactions on Electrical Insulation, Vol. EI-10, No. 2, 1975, pp. 69 – 74

[36] Tanaka T., Ikeda Y., "Internal discharges in polyethylene with an artificial cavity", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-90, No. 4-6, 1971, pp. 2692 – 2702

[37] Densley R. J., Salvage B., "Partial discharges in gaseous cavities in solid dielectrics under impulse voltage conditions", IEEE Transactions on Electrical Insulation, Vol. EI-6, No. 2, 1971, pp. 54 – 62

[38] Ramachandra B., Nema R. S., "Characterization of partial discharge pulses in artificial voids in polyethylene films used in capacitors", Conference Record of the 1996 IEEE International Symposium on Electrical Insulation, Montreal, Quebec, Canada, June 16-19, 1996, pp. 517 – 520

[39] Kolcunova I., Sipos M., "Measurement of partial discharge in disc-shaped voids", Proceedings of the 8th International Scientific Symposium ELEKTROENERGETIKA 2015, Stara Lesna, Slovak Republic, August 16-18, 2015, pp. 334 – 337

[40] Srinivasa D. M., Harish B. N., Harisha K. S., "Analysis study on partial discharge magnitudes to the parallel and perpendicular axis of a cylindrical cavity", International Journal of Engineering Trends and technology (IJETT), Vol. 45, No. 7, 2017, pp. 334 – 337

[41] Okamoto H., Kanazashi M., Tanaka T., "Deterioration of insulating materials by internal discharge", IEEE Transactions on Power, Apparatus and Systems, Vol. PAS-96, No. 1, 1977, pp. 166 – 177

[42] Kim Y. J., Nelson J. K., "Assessment of deterioration in epoxy/mica insulation", IEEE Transactions on Electrical Insulation, Vol. 27, No. 5, 1992, pp. 1026 – 1039

[43] Gjaerde A.-C., Sletbak J., "Influence of partial discharges on void gas pressure", Proceedings of International Conference on Partial Discharge, Canterbury, UK, September 28-30, 1993, pp.119 – 120

[44] Selvakumar S., Nema R. S., "Low pressure discharges in narrow cylindrical voids", Proceedings of the 3rd International Conference on Dielectrics, Materials, Measurements and Applications, Birmingham, UK, September 10-13, 1979, pp. 113 – 115

[45] Stenerhag B., Danemar A., "Partial discharge characteristics of some liquid impregnated systems", Proceedings of the 3rd International Conference on Dielectrics, Materials, Measurements and Applications, Birmingham, UK, September 10-13, 1979, pp. 26 – 29

[46] Danikas M. G., "A novel diagnostic technique to study the ageing of rotating machine insulation: The "Hysteresis Phenomenon" based on partial discharge measurements", Acta Polytechnica (Journal of Advanced Engineering Design), Vol. 40, No. 5-6, 2000, pp. 91 – 97

[47] Danikas M. G., Karlis A. D., "Diagnostic techniques in rotating machine insulation: A diagnostic technique for model stator bars based on the maximum partial discharge magnitude", Electric Power Components and Systems, Vol. 34, No. 8, 2006, pp. 905 – 916

[48] Danikas M. G., Karlis A. D., "The hysteresis curve of the maximum partial discharge magnitude as a diagnostic technique for model stator bars", Proceedings of the 2006 International Conference on Electrical Machine Systems (ICEMS), Nagasaki, Japan, November 20-23, 2006, Session DS1F4, Paper no. 05

[49] Reynders J. P., "Electrical detection of degradation caused by partial discharges in polythene", Proceedings of International Conference on Dielectric Materials, Measurements and Applications, Cambridge, UK, July 21-25, 1975, pp. 19 – 22

[50] Reynders J. P., "Measurement of the effects of partial discharge activity on low density polyethylene", Proceedings of the 3rd International Conference on Dielectric Materials, Measurements and Applications, September 10-13, 1979, pp. 97 – 100

[51] Opoku R. R., Robles E. G., Mason J. H., "Degradation and breakdown polypropylene film by internal discharges", Proceedings of the IEE International Conference on Dielectric Materials, Measurements and Applications, Cambridge, UK, July 21-25, 1975, pp. 323 – 326

[52] Wolter K. D., Tanaka J., Johnson J. F., "A study of gaseous degradation products of corona-exposed polyethylene", IEEE Transactions on Electrical Insulation, Vol. 17, No. 3, 1982, pp. 248 – 252

[53] Golinski J., Calderwood J. H., Zoledziowski S., Sierota A., "Partial discharges in a cylindrical void with a metal rod electrode", IEEE Transactions on Electrical Insulation, Vol. 17, No. 6, 1982, pp. 560 – 569

[54] Garcia G., Fallou B., "Equipment for the energy measurement of partial discharges", Proceedings of the 1st International Conference on Conduction and Breakdown in Solid Dielectrics, July 4-8, 1983, Toulouse, France, pp. 275 – 281

[55] Viale F., Poitevin J., Fallou B., Morel J. F., Buccianti R., Yakov S., Cesari S., Serena E., "Study of a correlation between energy of partial discharges and degradation of paper-oil insulation", CIGRE, Report 15-12, 1982, pp. 1 – 9

[56] Lehmann K., "Teilentladungs- Monitoring an Grossgeneratoren", Ph.D. Thesis, ETH Zuerinch, Hochspannungstechnik Laboratorium, 1994

[57] Koyanagi E., "Partial discharge measurement with pulse analysis", Proceedings of 1980 IEEE International Symposium on Electrical Insulation, Boston 80 CH1496-9-EI, 1980, pp. 171 – 174

[58] Hikita M., Yamada K., Nakamura A., Mitsutani T., Oohasi A., Ieda M., "Measurements of partial discharges by

computer and analysis of partial discharge distribution by the Monte Carlo method", IEEE Transactions on Electrical Insulation, Vol. 25, No.3, 1990, pp. 453 – 468

[59] Gulski E., Kreuger F. H., vComputer-aided recognition of discharges sources", IEEE Transactions on Electrical Insulation, Vol. 27, No. 1, 1992, pp. 82 - 92

[60] Danikas M. G., "Study of samples of a composite insulating system under electrical and thermal stresses", IEEE Electrical Insulation Magazine, Vol. 6, No. 1, 1990, pp. 18 – 23

[61] Krivda A., Gulski E., Satish L., Zaengl W. S., "The use of fractal features for recognition of 3-D discharge patterns", IEEE Transactions on Dielectrics and electrical Insulation, Vol. 2, No. 5, 1995, pp. 889 – 892

[62] Fruth B., Fuhr J., "Partial discharge pattern recognition - A tool for diagnosis and monitoring of Aging", CIGRE Main Session 1990, Paris, Paper 15/33-12

[63] Das S., Purkait P., "φ-q-n pattern analysis for understanding partial discharge Phenomena in narrow voids", Proceedings of the 2008 IEEE Power and Energy Society General Meeting – Conversion and Delivery of Electrical Energy in the 21st Century, Pittsburgh, PA, USA, July 20-24, 2008, total number of pages 7

[64] Vogelsang R., Fruth B., Froehlich K., "Detection of electrical tree propagation in generator bar insulations by partial discharge measurements", Proceedings of the 7th International Conference on properties and Applications of Dielectric Materials, June 1-5, 2003, Nagoya, Japan, pp. 281 – 285

[65] Kai R., Yamanoue T., Tanaka H., Kawano H., Kozako M., Hikita M., "A study of PRPD statistics to improve the performance of PD detection and defect type identification", Proceedings of the 9th International Conference on Condition, Monitoring and Diagnosis 2022 (CMD 2022), November 13-18, 2022, Paper P3-24, total number of pages 6

[66] Rodriguez-Serna J. M., Albarracin-Sanchez R., Dong M., Ren M., "Computer simulation of partial discharges in voids inside epoxy resins using three-capacitance and analytical models", Polymers, Vol. 12, No. 77, total number of pages 26
"http://www.mdpi.com/journal/polymers"

"http://dx.doi.org/10.3390/polym12010077"

[67] Deshpande A. S., Mangalvedekar H. A., Cheeran A. N., "Partial discharge analysis using energy patterns", Electrical Power and Energy Systems, Vol. 53, 2013, pp. 184 – 195

[68] Mole G., "Improved methods of test for the insulation of electrical equipment", Proceedings of IEE, Vol. 100, part IIA, 1953, pp. 276 – 283

[69] Starr W. T., "Detection of corona discharges in lamped circuit specimens",Engineering Dielectrics, Vol. I, Corona Measurements and Interpretations, ASTM Special Technical Publication 669, 1979, pp. 101 – 133

[70] Pearmain A. J. Danikas M. G., "A study of the behavior of a uniaxially oriented polyethylene tape/oil insulating system subjected to electrical and thermal stresses", IEEE Transactions on Electrical Insulation, Vol. 22, No. 4, 1987, pp. 373 – 382

[71] Bruning A. M., Danikas M. G., "Observations on discharges above and below CIV in polymer insulation", Annual Report on Conference of Electrical Insulation and Dielectric Phenomena (CEIDP), 20-23 October, 1991, Knoxville, Tennessee, USA, pp. 638 – 647

[72] Bruning A. M., Danikas M. G., "Report on continuing work on parallel and non-parallel electric field chemical aging of polymer cavities", Proceedings of the 4th International Conference on Conduction and Breakdown in Solid Dielectrics, 22-25 June, Sestri Levante, Italy, 1992, pp. 241 – 245

[73] Danikas M. G., "On the damage of insulating materials below inception voltage", Journal of Electrical Engineering, Vol. 52, No. 11-12, 2001, pp. 367 – 371

[74] Harlin A., Danikas M. G., Hyvonen P., "Polyolefin insulation degradation in electrical field below critical inception voltages", Journal of Electrical Engineering, Vol. 56, No. 5-6, 2005, pp. 135 – 140

[75] Danikas M. G., Zhao X., Cheng Y., "Experimental data on epoxy resin samples: Small partial discharges at inception voltage and some thoughts on the existence of charging phenomena below inception voltage", Journal of Electrical Engineering, Vol. 62, No. 5, 2011, pp. 292 – 296

[76] Moraru D., Popesco C., Stoica M., Tanasesco F., "Detection of degradation produced by partial discharges in paper-oil insulation", CIGRE report, paper 15-05, 1970, pp. 1 – 8

[77] Suwarno S., Mizutani M., "Pulse-sequence analysis of discharges in air, liquid and solid insulating materials", Journal of Electrical Engineering and Technology, Vol. 1, No. 4, 2006, pp. 528 – 533

[78] Joyo T., Okuda, T., Kadota N., Miyatake R., Okada S., Mio K., "Phase resolved partial discharge patterns for various damage of winding insulation Detected with different measuring devices", Proceedings of the 2017 Electrical Insulation Conference (EIC), June 11-14, 2017, pp. 344 – 347

[79] Ilias H., Soon Yan T., Abu Bakar A. H., Mokhlis H., Chen G., Lewin P. L., "Partial discharge patterns in high voltage insulation", Proceedings of the 2012 IEEE International Conference on Power and Energy (PECon), December 2-5, 2012, Kota Kinabalu Sabah, Malaysia, pp. 750 – 755

[80] Endharta A. J., Kim J., Kim Y., "Online partial discharge measurement for condition-based maintenance of HV power cables in railway infrastructure", Journal of Engineering and Management in Industrial System, Vol. II, No. 1, 2023, pp. 54 – 59

[81] Liao R., Yan J., Yang L., Zhu M., Liu B., "Study of the relationship between damage of oil-impregnated insulation paper and evolution of phase-resolved partial dis-charge patterns", European Transactions on Electrical Power, Vol. 21, 2011, pp. 2112 – 2124

[82] Nair R. P., Vishwanath S. B., "Analysis of partial discharge sources in stator insulation system using variable excitation frequency", IET Science, Measurement and Technology, Vol. 13, No. 6, 2019, pp. 922 – 930

[83] Negara M. Y., Fahmi D., Asfani D. A., Hernanda G. N. S., Soebagio J. C., Siahaan V. Y., "Characteristics of partial discharge inception voltage patterns using antenna in air insulation", Proceedings of the 2020 12th International Conference on Information Technology and Electrical Engineering (ICITEE), October 6-8, 2020, Yogyakarta, Indonesia, pp. 263 – 268

[84] Lee C.-Y., Purba N., Zhuo G.-L., "Defects classification of hydro generators in Indonesia by phase-resolved partial discharge", Mathematics, Vol. 10, 2022, total number of pages 27
"https://doi.org/10.3390/math10193659"

[85] Danikas M. G., "The definitions used for partial discharge phenomena", IEEE Transactions on Electrical Insulation, Vol. 28, No. 6, 1993, pp. 1075 – 1081

[86] Danikas M. G., "Small partial discharges and their role in insulation deterioration", IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 4, No. 6, 1997, pp. 863 – 867

[87] Verhaart H. F. A., van der Laan P. C. T., "Fast current measurements for avalanche studies", Journal of Applied Physics, Vol. 53, No. 3, 1982, pp. 1430 – 1436

[88] Danikas M. G., van der Laan P. C. T., "Fast measurements of partial discharge currents in solid dielectric samples containing voids", Conference Record of the 1988 IEEE International Symposium on Electrical Insulation, June 5-8, Boston, MA, USA, 1988, pp. 250 – 252

[89] Shafiq M., Kiitam I., Kauhaniemi K., Taklaja P., Kutt L., Palu I., "Performance comparison of PD data acquisition techniques for condition monitoring of medium voltage cables", Energies, Vol. 13, 2020, total number of pages 14
"https://doi.org/10.3390/en13164272"

[90] Lemke E., "A critical review of partial discharge models", IEEE Electrical Insulation Magazine, Vol. 28, No. 6, 2012, pp. 11 - 16

[91] Kartalovic N., Kovacevic D., Milosavljevic S., "An advanced model of partial discharge in electrical insulation", Facta Universitatis, Ser: Electronics and Energetics, Vol. 24, No. 1, 2011, pp. 41 – 55
