Very Small Partial Discharges and Charging Phenomena Below Inception Voltage: An Effort for a Review and a Proposal for a Unified Theory

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]

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

Abstract

In this paper a review is presented regarding the very small partial discharges and their possible influence on insulation degradation is discussed. Moreover, very small discharges are discussed in relation to possible charging phenomena observed below the so-called inception voltage. Thus the question of whether there is a danger of potential damage to insulation from charging phenomena below inception voltage is posed and discussed. Furthermore, an attempt is being made in order to present a unified theory regarding the charging phenomena below the inception voltage, PD and electrical treeing.

Keywords

Partial discharges, charging phenomena, streamer discharge, Townsend discharge, glow discharge, polythene, polyethylene, epoxy resin, chemical byproducts, insulation voids, insulation cavities, electrical treeing (the terms "insulation voids" and "insulation cavities" are used in the context of the present paper interchangeably)

Introduction

Many years ago, Bruning and colleagues published some papers questioning the validity of the statement that "below the inception voltage the insulation life is practically infinite", in other words they questioned the "truth" that either very small partial discharges (PD) do not cause any appreciable insulation damage or that "below inception nothing of significance happens" [1 - 11]. It is true that, no matter how possibly interesting the research by Bruning and colleagues was, they just indicated that there may be charging phenomena below inception that may affect the insulation. They did not, however, prove anything since the number of their experiments was limited and they experimented only with certain insulating materials.

In this – not thorough as the title of this paper emphasizes – review, we will try to substantiate our view that there may be phenomena – called charging phenomena – worth studying below inception and/or that very small PD are not necessarily innocuous. We will search past literature and we will try to indicate that such ideas were not that foreign to researchers of previous generations. It was, however, Bruning and colleagues that insisted on this line of research.

Partial discharges – Some comments

Many decades ago, Mason reported that in many laboratory tests, the PD intensity decreased to a low magnitude after a few minutes at twice the inception voltage. During the next hour, the PD recovered its original magnitude and it was then stable until the discharge intensity increased and became unstable [12]. In polyethylene samples, deposits of brown opaque resin were found in addition to some transparent resin. In yet another paper, the same author claimed that the time to breakdown depends on the local stress concentration in relation to the intrinsic strength, the discharge energy, the discharge repetition rate and the specimen thickness. He observed that in thin specimens the average breakdown stress approaches the intrinsic strength, so that the field at the end of PD channels is much less divergent than it would be for thicker specimens [13]. This is because there is less necessity for reconcentration of electric stress after initial penetration. This explains why in industrial electric strength test, partial breakdown channels are often detected in thick specimens, where the average breakdown strength is less than one-tenth of the intrinsic value, but in thin specimens there is either no observable damage or complete breakdown. The above can be combined with later work, where it was noted that thicker specimens require a higher sensitivity of PD detector [14]. Questions as to how the above can relate to pitting PD parameters remain to be studied. It seems, however, that – with regard to pitting – PD energy is more important as a PD parameter. Conforming with the above, later work indicated that – working with polyethylene – "oxalic acid crystals are formed on the surface of the voids and these tend to concentrate the discharge energy into eroded pits" [15]. This suggests that the aforementioned formation is a prerequisite for pitting PD.

Further confirmation of the above came in a later paper, where the researchers working with polythene samples observed that the main chemical changes occurring in the insulation when exposed to PD were 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 [16]. Later work on artificial voids showed that PD generally decrease in magnitude and repetition rate with time and that such a decrease occurs because of a voltage decrease on the side wall due to the decline of the side wall resistance in the cylindrical void. The decrease with time is due to the discharging area which becomes narrow because of the development of low resistance in the inner void surfaces [17]. In their explanation and approach the authors of [17] were not that different from the researcher of [12, 13]. The chemical byproducts that are produced on the void walls because of the PD and their influence in turn on the further development of the PD was the subject of [17] as well as of other publications [18, 19]. The interplay between void pressure, weakly conducting layers on the inner void walls as well as void dimensions, was shown in [20, 21], where there was also mention of the role of the charges trapped on the surface of the inner void walls, affecting thus the extinction voltage.

The question of innocuous PD

Kelen [22] suggested that there is probably no safe threshold below which PD would be completely innocuous. Where insulation is subjected to heavy electrical stresses – as in cables and capacitors – the tendency is to avoid PD. In rotating machines and to some degree in transformer engineering there is a greater tendency to accept the presence of PD during service. It is evident that generalizations of the type "innocuous below x pC" etc. have no particular meaning and that each case should be treated separately. Kelen distinguishes Townsend, steamer or space charge enhanced single avalanche type PD for the case of gas discharges against dielectric surfaces. Streamer discharge consists of the formation of a plasma channel from the inflow of electrons from secondary avalanches initiated in the gas near the head of the primary avalanche. The same author [23] went a step further by pointing out that if electrons penetrate beneath the insulation surface, the next PD of opposite polarity at the same site leaves a positive charge owing to deposition of positive ions or extraction of electrons. A double layer of opposed charges is thus formed. If the resulting field intensity exceeds the local breakdown strength of the surface layer, local breakdowns may occur and produce microscopic channels in the surface layer. The whole idea – as proposed by Kelen leads us to suggest that there is a relation of the above mechanism to the mechanism of pitting discharges.

Laurent and co-workers [24] noted that there is a period when PD activity is low or even very low. PD are related to micro-channels developing from a cavity. This is a crucial observation since it has also been noticed by Mason [12], Kreuger [18] and Omal el Gendy [25]. It has also been noticed in a more recent publication [26] and also by Ashcraft and co-workers [27]. The authors of [24] distinguish several phases in the PD characteristics of electrical trees: a) the number of detected PD increases during the initial ageing, b) a decrease in PD number related to the appearance of a different kind of filament and c) a sudden increase of PD magnitude and number as soon as the filament reaches the ground electrode. In another more recent paper, the same authors [28] noted that current pulses during transition to electrical treeing had magnitudes with typical values between 0.04 pC and 0.1 pC with the PD magnitude increasing with the increasing tree length. Such small magnitudes may also go undetected.

A similar behavior is observed in artificial voids, as the decrease of PD number occurs simultaneously with the concentration of the PD near the void walls [29]. In yet another paper [30], it was noted that typical PD pulse shapes for streamer, Townsend and pitting discharges are given. These mechanisms are related to three distinct ageing stages. Morshuis and Gulski pointed out that the consecutive stages in the PD patterns are not random but the result of physical changes induced by the ageing process. According to data presented, pitting discharges seem to be pulsive discharges [29, 31]. If we remember the disagreement between some researchers, as to the nature of the very small discharges (pulsive or pulseless) one realizes how important the fast time-resolved measurements are [32 - 34].

In yet another paper, Morshuis [35] noted that after several hours of PD activity, discharges with high repetition rate were observed. At that point in time, the increased conductivity of the void surface, combined with a field intensification at clusters of acid crystals result in a new discharge stage. Due to the spreading of the charge over the conductive surface, the voltage across the void very rapidly recovers after a discharge has occurred. This – in combination with the field intensification – leads to a high discharge repetition rate concentrated at specific locations of the void. The result is the start of severe degradation recognizable in the growth of pits. The PD level is very low because of the small area participating in the process. Such observations are in agreement with experimental data presented earlier, where work on polyethylene samples with well defined voids showed that there are occasions where failure of insulation may occur after many hundreds of hours of relative PD inactivity [36].

Low or very low PD activity has been noted by Tanaka [37], even smaller than 1 pC. Swarming micro-partial discharges (SWMPD) assume the consumption of oxygen in the cavity. They will generate pits rather than erode uniformly and will lead to the formation of electrical trees. There is a similarity between the observations of [35] and [37], the difference being in terminology. SWMPD (or Swarming Pulsive Micro-Discharges – SPMD) are apt to be missed from detection by conventional PD detectors and probably were misunderstood to be as self-extinction [38]. In fact, as was noted in [38], oxalic acid, nitric acid and related substances make the dielectric wall conductive. Such products can be dissociated by PD itself or active species formed by PD. Kahle [39] indicated also that the appearance of very small PD (in the order of 10^{-12} C or even smaller) is possible. Such PD are very difficult to be measured. They can, however, be responsible for some ageing effects according to [39].

There is always a question – posed in [24] – whether the PD localization is caused by the material structure or whether it is the localization phenomenon which creates a weak point in the structure. The approach of [24] goes in parallel with previously published work by Shibuya and co-workers [40], where it was noted that a tree may start from a tiny void, where the phenomenon takes place during the induction period, i.e. the interval between voltage application and the inception of the tree. Neither physical changes nor discharge pulses have been observed so far during this period. The logical following from the above is that if microscopic voids or cracks are present, they can grow due to the deterioration of the insulation produced by high energy electrons accelerated in the cavities, even without ionizing discharges. The question here is whether there is a relation between the high energy accelerated electrons and the pitting discharges. Related to this question is the statement by Okamoto and co-workers, namely that degraded cavities may not differ from new ones and also Bartnikas' approach as to whether it is quite conceivable that in some cavities, the PD may disappear after a certain time and the ensuing breakdown would have little relation to the PD intensity initially observed at the beginning of the test [41 - 43]. Such views – albeit somehow differently – were also expressed in [29, 30]. Related to the above are also views published in [44], where the author claimed that an electric field produced at a stress concentration is sufficiently large in order to initiate PD in micrometer or sub-micrometer sized cavities located near the tip. The magnitude of the PD would be too small to be measured. Needless to say that the breakdown in a cavity requires initiating electrons for the PD. Such PD may well be related to pitting. Relations as to PD and the smallest cavity size and to Paschen's curve and the streamer criterion were investigated many years ago. It has been shown that a high electric field can break down cavities smaller than 0.01 mm according to Paschen's law

[45]. Moreover, according to [46], electrical trees have been found to be proportional to the cavity diameter of 1 to 30 µm. Others reported that the estimated distance within which injected electrons can interact with material to produce trees near a tip of a needle is < 20 µm [47]. Furthermore, if one bears in mind that the mean free path in air for ambient pressure and temperature is ~ 0.1 µm, which implies that cavity size below this dimension would be unable to initiate a PD, one has to conclude that the general criterion for the cavity diameter below which Townsend PD can be considered innocuous should be based on the 0.1 µm limit [39, 48].

B. Florkowska experimenting with epoxy/mica insulation, noted that the dielectric conductivity γ_s increases after a PD action in the air up to about 10^{-9} S. The said insulation was subjected to both electrical and thermal stresses simultaneously. After stressing of more than 200 hours, it was observed an increase of the repetition rate of PD and a decrease of their magnitude. The value of extinction voltage in the void is then only slightly lower than that of the inception voltage whereas in the initial stage, it was much lower than the inception voltage [49]. Such observations are valuable and can be related to previous publications [42]. The nature of the void plays presumably a vital role in determining the sequence of PD mechanisms. This is evident in the work by Kutil and Froehlich [50], where the order of the appearance of the PD phenomena is not the same as in other papers. The authors used a slit instead of a spherical void. Low magnitude PD were firstly observed because the electric field inside the slit can only be compensated to a small extent according to the number of involved electrons and ions. Then there is a transition from Townsend to high magnitude (streamer) PD. A consequence of the continuous PD activity will be a high number of charge carriers to be accumulated in the slit walls. The wall conductivity becomes so high so that only surface current remains without pulsating PD. This may explain the observed breakdown after several minutes, if a significant ageing of the material also by the surface current is assumed. The "reverse" order of PD phenomena noted in [50], is due to the wall conductivity causing a superposition of pulsating PD and a surface current on the void walls. There are perhaps non-pulsating PD but this is due to the void geometry.

Wall conductivity, void wall roughness are intimately related as was pointed out in [51], where it was shown that void roughness promotes the change of normal PD into SPMD, probably due to the increased supply of the initial electrons with the enhanced local field at the surface protrusions. SPMD were also noticed in an older publication [52], where it was reported that such small PD may go unnoticed by conventional PD detectors even though the material degradation continues. Such research is also related to the work of other researchers, who characterized the degradation of the polymer by broken chains – tending to gather in thin bubbles called "nodules" – by the growing of such "nodules" and also by morphological modifications of the large "nodules". The nodules tend to crystallize forming thus "clusters", which in turn enhance the electrical field. Bulk degradation similar to electrical trees start from such clusters [53]. The approach in [53] strongly reminds a similar earlier proposal based on the following cumulative model [54]: since defects exist in all insulating materials, at the initial stages of field stressing charge carriers of low energies can extend pre-existing defects and increase their density, so that clusters of interacting defects will take place. Such charge carriers can acquire higher energies from the applied field within these clusters because of longer "free paths". The clusters will grow into macroscopic defects in the direction of the applied field. As the process goes on, the density of charge carriers and their "free paths" will increase (and also the energies available to them) until the macroscopic defects form a single channel of high probability of continuous conduction between the electrodes. A high current density will follow from this channel leading to thermal destruction of the insulation. Related to [54] is also an earlier view, according to which tree initiation begins at a surface where field enhancement occurs due to macroscopic irregularities in the dielectric, pointed electrodes and surface charge concentrations [55].

Reference to PD which may cease completely for fairly long periods and to PD impulses that may occur in the form of "discharge packets" was made in [56], where it was pointed out that the structural strength of casting in the case of epoxy resin is of paramount importance as well as the boundary layer between the filler and the resin matrix. Such views are not far off from some aspects of the work mentioned above [35]. The question as to whether PD in the order of 0.1 pC can be damaging for an insulation – consisted of polyethylene sheets having an artificial cavity – was raised more recently, where the resistivity of the inner cavity walls was at first infinite and at the end of the experiments was measured to be 600 - 900 x 10^6 Ω [57].

Charging phenomena in insulating materials even below the inception voltage

The previous cited publications substantiate the thought that it is difficult to envisage the existence of innocuous discharges. In fact, very small magnitude PD seem to play a role in the degradation of insulating systems as was indicated in [58]. Moreover, as was reported several years ago, extremely small signals corresponding to currents as small as 66 nA and charges as minute as 1.2 fC were measured [59, 60]. As was rightly noted, the detection of signals in the fC range demonstrated that "something" happens even in the absence of true partial discharges [61]. Publications [59, 60] showed that signals could be measured without PD whereas publications [1, 2] indicated that chemical changes could result without PD activity. In a certain sense [1, 2] and [59, 60] were complementary parts of research. Tanaka also discussed the phenomena of pre-discharging, emphasizing the role of space charges, electric field enhancement and finally electrical tree initiation [62], as well as the "non-destructive current pulses" that may initiate tree formation [63]. Pre-PD signals were recorded in [61], many minutes prior to the visual appearance of an electrical tree. Such views were reinforced by later work from the same researchers, where it was reported that signals detected may precede partial discharges [64].

Several years ago, the notion of charge packets, i.e. of discrete pulse or charge generation in contradistinction to continuous charge generation, was reviewed [65]. According to [65], a deeper understanding of electrode-polymer interface is needed. The author speculated as to the possibility of aging effects as the charge packets move. On the other hand, gas conductivity inside a cavity is also vital as was shown in [1, 2, 5]. That was confirmed in [66], where it was reported that in minute cavities, PD may have very long statistical time lag and the number of initial electrons may indeed be very small. In low voltages, ionization processes of low energy may occur, which means that charges appearing in the cavity may result in clusters of space charges on the cavity walls. These space charges result in an additional electric field to the insulation together with the applied electric field [67]. In [66], it was also remarked that the number of initial electrons prior to the first discharge in a cavity may depend on its dimensions and, therefore, may be very small if the cavity is in the order of micrometers. This is in accordance with [39, 48, 68], where it was indicated that the general criterion for a cavity diameter below which Townsend discharges can be taken as harmless should be based on the 0.1 μm limit. The latter limit is far more restrictive than the one based on the streamer criterion, where a cavity diameter larger than 0.4 mm is needed for a streamer discharge [68, 69].

Considering another point of view, it can be remarked that having an enclosed cavity in polyethylene, a conducting path may ensue with currents in the range of 1-10 mA [3], a range that is significantly lower than current pulses of about 1 A measured with other more conventional experimental arrangements [70]. Consequently, there are approaches that suggest the possibility of very small currents (or small charge displacements) inside a dielectric that cause events that may go undetected and still be able to cause damage. As was mentioned before, "the discussion of the pulsive or non-pulsive nature of partial discharge phenomena at and/or above inception voltage is shifted to a more fundamental question whether charge movement inside the dielectric causes deterioration, even below the inception voltage" [11, 71].

From the above approaches, a general picture may emerge as to the charging phenomena below the inception voltage, PD and electrical treeing. A picture that may take into account Bruning’s and co-workers’ research [1 - 10], Tanaka’s theory of charge injection and extraction on tree initiation [47, 72, 73], Dissado’s and co-workers’ work on charge packets [65, 74], Bernstein’s and co-workers’ experimental work on TR-XLPE insulation [61, 64] as well as Zeller’s and co-workers’ research on pre-treeing events

[75, 76]. Needless to emphasize that all the above mentioned research – which refers to phenomena below inception voltage – requires the full use of all available diagnostics, both electrical and non-electrical [77, 78]. It also goes without say that PD detection and related equipment sensitivity regarding PD registration above inception as well as charging phenomena below inception is of vital importance for the correct recording [18, 32, 77, 79 - 84]. Such a general picture may as well include older research, according to which there is a transition of pulse-type discharges to pulseless discharges, which in turn do not minimize the danger for the insulation [85, 86]. It may also include more recent work which indicated that in enclosed cavities in epoxy resin samples, a fast reduction of the pressure inside the cavity relates well with a short expected lifetime of the sample, whereas a slow reduction of the pressure means a longer lifetime [87]. Moreover, with further experimental work, it was remarked that the speed of ageing of an insulation is determined by the total sum of the various types of PD. It was observed, that the current that is due to PD decreases with time, whereas, the light emission from the PD remains constant. It is probable that part of the PD changes to PD of extremely small magnitudes or to glow-PD and, consequently, their detection is very difficult or even impossible with conventional detecting systems [87 - 89].

Conclusion

In the present paper, past work has been reviewed regarding the very small PD as well as charging phenomena below the so-called inception voltage. There are indications that even very small PD may start damaging the insulation. Charging phenomena below inception seem to be not that harmless. An attempt is being made as to combine theories and experimental results into a unified approach. Needless to say that the sensitivity of PD detecting equipment is of paramount importance in studying phenomena above and below inception voltage.

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