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Research Article

Some Thoughts on Charging Phenomena in High-Voltage Insulating Materials

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Abstract

This is a paper on a question that refers to possible deteriorating events below the so-called inception voltage in high voltage insulating materials and systems. Based on past technical literature but also on our experimental work, it seems that charging phenomena take place with possible consequences on electrical insulation. A brief background on this question is given as well as some thoughts on possible relations of events between air insulation and solid insulating materials.

Keywords: charging phenomena below inception voltage, inception voltage, polyethylene, solid insulation, sub-corona events

1. Introduction

A seminal paper published in 1991 suggested that chemical byproducts may be similar below and above the partial discharge inception voltage (PDIV) [1]. In subsequent publications [2-5], the claims of [1] were even more substantiated with both chemical diagnostic techniques as well as with partial discharge (PD) measurements. The latter indicated that charging events may occur at inception voltage and also below it [6]. The approaches, however, of [1-5] and [7-9] were somehow different in that, whereas the papers [1-5] dealt with voids in solid insulation, papers [7-9] experimented with increasing air gaps and constant applied voltage in order to observe even minute charging effects. In all cases, "something' was observed below the so-called PDIV and this gives us ground to believe that charging events take place. Even though, significant research has been done on the behaviour of PD at or above PDIV, only a lesser database has been established on what happens to the insulator below this voltage. In this review paper, a discussion will ensue as to the dangers arising from such charging phenomena as well as some related questions will be dealt with. In the context of the present paper, events taking place below inception voltage are termed as charging phenomena or sub-corona events.

2. Some comments on previous research on inception voltage

According to the definition given in a classical publication, inception voltage is the minimum voltage at which partial discharges are repeatedly recorded when an AC voltage is applied [10], as the applied voltage increases. PD may develop in inclusions, those being either gas-filled cavities (as found in extruded plastics, lapped impregnated paper and cast resins), 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). PD being able to break organic polymer bonds, can possibly result in insulation premature failure. It is also the result of aging mechanisms triggered by several operating stresses like mechanical stress and thermal cycling stress. Thus, PD measurement is an essential tool to ensure the reliability of the insulation systems [11-13]. Previous research on partial discharges indicated that very small PD at and/or near inception voltage were detected [14-16]. There was a lot of discussion on the mechanisms of the PD, i.e. whether they were of impulsive or non-impulsive nature [17, 18]. There was speculation as to the mechanisms of such small PD and also whether such PD could have an influence on the insulating material [19]. Furthermore, there was evidence that even at modest electrical stresses, significant PD could take place in a polyethylene/oil composite system [20-23].

Especially, if one considers PD in enclosed voids in solid dielectrics, the nature of the void in which very small PD take place is of vital importance as was indicated in [24]. It has also to be noted that for rectangular voids, edge effects may become significant, as they may affect the development of the PD and thus alter the sequence of the various PD mechanisms [15]. PD at inception voltage depend, among other factors, on void dimensions, location and void shape [25, 26]. Figures of merit regarding PD inception voltage are difficult to be drawn since different results may crop up from different laboratories for the same insulating samples. Furthermore, the tendency to move from "PD-resistant" to "PD-free' insulation in order to avoid electromagnetic interference in complex wiring systems does not seem without problems [27]. Regarding PD inception voltage measurements, another important factor mentioned in [28] is the selected threshold level. Also in [28] is discussed that the inception voltage depends on statistical time lag, residual voltage as well as on oxidation. Moreover, some researchers noted also a dependence of the inception voltage on void pressure, electrode design and material processing [29, 17].

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The physical phenomena which initiate PD in composite insulating materials are more complex than the PD phenomena in well defined voids [24]. It is due to the existence of micro-voids along the fibers of the composite insulating materials. Once the electric field of these micro-voids increases more than the critical field, the initiation of PD is governed by the initial electron availability. In case of unaged sample, the initial electrons are produced by micro-discharges or natural ionizing radiation which are caused by the charge separation due to micro-delaminations caused by mechanical stress [30]. It is well established that the mechanical stress has a significant effect on the PD induced aging phenomena in which the tensile stress accelerates tree growth and on the other hand the compressive stress will decelerate it [31, 32]. As indicated in [24], the temporal evolution of PD phenomena in composite insulating materials obeys the following sequence: generation of initial electrons, low mode PD, high mode PD, non-pulsating PD, chemical changes and finally leading to breakdown.

Previous experimental evidence with liquid/solid composite insulating systems indicated that very small PD at inception voltage may cause slight damage to the solid insulation [33], a conclusion in agreement with [34] but in disagreement with [35], where it was suggested that very small discharges may not influence the lifetime of the insulation. However, although that in [35] it was specified the level of harmless discharge magnitudes to the dielectric as 2 pC at 3 kV/mm, it is possible that even small PD are harmful since they may have a cumulative effect, which with time will possibly produce more carbonization, disruption of the polymer molecules and release of gaseous products leading thus to breakdown. It has to be noted that in this section, no exhaustive literature search regarding the inception voltage and related PD phenomena is being undertaken but only some hints are given as to the dependence of the inception on some factors.

3. Charging phenomena below inception

Long time ago, performing tests on polyethylene cavities, it was observed that extinction of PD may be caused by a low surface resistivity brought about by certain chemical substances (gel), which appear to be unstable intermediate products of oxidation process. A low surface resistivity may limit the charge accumulation and may tend to eliminate electric field non-uniformities. During the extinction period the slow physical changes which took place may have been caused by small PD. It was further noticed in those publications that there may have been PD but too small to be detected by the measuring equipment [36, 37]. The findings of [36] were confirmed in later research activities [38].

It was realized some decades ago that chemical byproducts are qualitatively very similar above and below inception voltage [1, 39, 40]. It is indicated that the cavity surface is roughened due to chemical reactions that are induced due to PD. Further, the deposition of these discharge byproducts from chemical reactions, causes electric field enhancement and leads to local attack of the cavity surface, resulting in pits formation. This pits formation initiates the electrical tree growth [32]. Research performed with a special point-plane electrode arrangement, where a conducting path in a void enclosed in polyethylene was simulated, indicated that the magnitude of the peak value of current pulses were in the range of 1 to 10 mA [2, 5, 19], i.e. range far below to those pulses of ~ 1A registered with more conventional electrode arrangements [41]. Elsewhere, it was suggested that although some charging phenomena may manifest themselves as glow or pseudo-glow mechanisms and may evade detection, the fact that some pulsive charging phenomena may as well be present, means that at least some charging events may be detected even with conventional circuitry [42].

The pioneering work by Bruning and co-workers [1, 39, 40] demonstrated that sub-corona causes chemical changes similar to post-corona events but it did not demonstrate that sub-corona events cause failure of insulation. The “leap” from chemical changes to insulation failure is still something to be investigated, as was noted in [43]. Moreover, a possible relationship between the data reported by Bruning and co-workers and the extinction voltage was also suggested [43].

Supporting evidence for the results of [1, 39, 40] was published in [7-9], where instead of solid dielectrics, experiments were carried out with air gaps. In [7-9], it was reported that the charging event mechanism changes as the air gap increases with a constant applied voltage, i.e. the duration of the charging phenomena shows an increasing tendency and their pulse height decreases as the air gap increases. Such observations - on air gaps - may have implications for solid insulation materials. As was noted in [44], if the charging phenomenon mechanism changes with an increase in air gap distance, what does this mean for voids in cables or accessories? If experimental data on charging phenomena below inception are intermittent, what does this mean for cable systems? Do non-pulsive charging phenomena below inception voltage, as those reported in [7-9], occur also in cable systems? Such questions are in need of an answer.

As was noted in [1], a possible insulation degradation below inception may imply that the well-known formula $L = c(V - V_0)^{-k}$ (with L time to insulation failure, V the applied voltage, V_0 the voltage below which no deterioration takes place and k a constant) valid for the calculation of the remaining insulation lifetime has to be modified into $L = cV^{-k}$. It is good to remember that most equipment designers use this empirical relation without having settled the fundamental question as to whether $V_0 = 0$ or not, since empirical experiments in reasonable time periods cannot distinguish between the two aforementioned forms [1, 45]. It is well known that the corona currents lead to polymeric insulation failure in a relatively short period of time. By taking the above statement as a supportive evidence, Bruning and co-workers in [1] have indicated that the sub-corona ageing can possibly cause substantial damage, even when a PD detector shows the insulation system is operating below the corona inception voltage (CIV). As was noted, if the changes above and below inception are real according to [1], this should impact our thinking on the mechanism of aging and indeed about the significance of PD will have to be revised [46]. Also, it is mentioned in [1, 47], that there is a direct correlation between the chemical reactions on the cavity surface in polymers due to these sub-corona events and the ageing of the polymeric insulating material. Furthering the thoughts expressed in [15] on the influence of PD on insulation ageing, one may say that a question remains as to the way charging phenomena below inception contribute to the ageing of an insulation. A question in need of an answer is whether charging effects below inception voltage – which cause chemical changes similar to post-corona events – may also cause insulation failure [43, 46].

The question of charging phenomena and their possible influence on insulation degradation and aging is further complicated since earlier studies [1, 7-9, 39, 40] did not take into account the importance of antioxidant in cable insulation. As was reported, polyolefin degradation can be understood through the formation of free radicals, especially initiated by accelerated electrons with energies of more than 3.8 eV [48]. Although the initial degradation phase is controlled to a great extent by the presence and eventual decay of the primary antioxidant, the role of the residual antioxidant (possibly resulting into "clusters" acting as contaminants, or even of small discontinuities in polyethylene cables) which may affect insulation response to aging have never really been quantified [44, 49]. A further complication may be oxidation which may affect both treed and non-treed regions. Consequently, charging phenomena – if they are of importance – may be studied in relation also to the above factors besides to other factors, such mechanical stresses and foreign inclusions [50-54].

Furthermore, a possible link, between the research reported in [1, 39, 40], that reported in [55], where pre-discharge phenomena in both cross-linked polyethylene (XLPE) and polyethylene (PE) were discussed, and [56], where pre- and post- treeing PD signals were observed, must be investigated. After all, a possible link between charge injection and extraction at an interface [57], chemical changes [1, 39, 40] as well as minute charge injections [58] does not seem that improbable.

4. Conclusions

This short paper is just a series of comments on the possible appearance of charging phenomena below the so-called inception voltage. Although for the time being there is a lot of work to be performed regarding the eventual influence of such phenomena on insulation degradation, hints and indications are offered from the experimental work done on the possible implications of the charging phenomena on the lifetime of insulation. It has been well established that charging phenomena do occur below inception voltage, and also has the potential to become a serious threat to the life of the insulating system. However, there is still a missing link between such phenomena and the long-term damage they may cause. Much more can certainly be focused on relative to antioxidant and oxidation under real world aging conditions.

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