Space Charges as Pre-breakdown Phenomena in Solid Dielectrics: A Concise Approach and Some Critical Comments

Michael G. Danikas
Democritus University of Thrace
Department of Electrical and Computer Engineering
Power Systems Laboratory
Xanthi, Greece

George E. Vardakis
Democritus University of Thrace
Department of Electrical and Computer Engineering
Power Systems Laboratory
Xanthi, Greece

Ramanujam Sarathi
Indian Institute of Technology Madras
Department of Electrical Engineering
Chennai, India

Abstract-**This short review deals with some aspects of space charges in solid dielectrics, and, in particular, in polymeric materials. The relationship between space charges and pre-breakdown events is discussed and the importance of space charges for the breakdown of solid dielectrics is emphasized.**

Keywords-space charges; breakdown strength; polymers; interfaces; pre-breakdown phenomena

I. INTRODUCTION

Polymers have excellent electrical properties, which render them appropriate for applications in high voltage engineering with applications such as in underground cables, outdoor insulation, switchgrears, capacitors, electrical machines etc. A great deal of research has been performed regarding the breakdown of solid dielectrics and particularly polymers. Breakdown by ionization, thermal breakdown, electromechanical breakdown, breakdown caused by partial discharges (PD), are some of the proposed mechanisms [1-3].Efforts have been made in the past to relate space charges and breakdown [4]. It is the aim of the present paper to supply a short review on space charges and their relation to the pre-breakdown phenomena.

Space charges are charges that are trapped inside a solid dielectric, loosing thus their energy without loosing their charge [5]. Charges can be injected inside the solid dielectric from electrodes. Such charges are called homocharges because they have the same polarity as the injecting electrodes. Charges that come about from ionization and the migration of impurities under the influence of an electric field are called heterocharges because they have the opposite polarity from the neighboring electrode [6-8]. Space charges depend on the physical and chemical structure of the polymer, possible additives, foreign chemical species, interface conditions, the nature of the applied voltage (AC, DC or impulse) and temperature [9]. Space charges may be trapped in various chemical species, in interfaces between amorphous and crystalline regions, in the free volume between the molecular chains of polymers, in oxidation byproducts, in the interfaces between polymers and the electrodes and in asperities [10]. Traps may be shallow or deep. In case of presence of low molecular weight chemicals, acting as space charge traps [8], the probability of space charges accumulation increases. Trapping of space charges depends on the very structure of the polymer, i.e. on whether it amorphous, semi-crystalline or primarily crystalline. It has been observed that with amorphous polymers, space charge accumulation may be quite large [11].

As reported in [12], space charges become crucial in the case of DC cable insulation. With the application of DC voltage, the formation of space charges begins. Space charge distribution reaches a steady state after a certain period of time. If such a space charge cannot move – in response to a sudden change of voltage – there is a danger of insulation breakdown. Such situations may be caused by a reversal of polarity, by the malfunction of a converter or even by lightning overvoltages. The importance of ionic carriers for the dielectric behavior of an insulating system consisted of polypropylene and oil was noticed quite early [13]. At very low voltage levels, ionic carriers are accumulated near the interface without being trapped but as the voltage increases they are trapped near the interface causing a decrease in ionic concentration in the thin oil layer and consequently a decrease in dielectric loss. The importance of impurities (and consequently of space charges) was noted in [14, 15], where polyethylene insulation was investigated.

In yet some other publications and considering needle-plane electrode arrangements, space charge distribution was taken into account in polymer breakdown [16-18]. More specifically in [16], the notion of Field Limiting Space Charge (FLSC) is discussed and the radius of the space charge cloud for various geometries of the tip of the needle is calculated. Publications [16-18] were significant in that they tried to relate injection of charges, treeing phenomena, insulation damage and breakdown. These publications proposed that, studying the injected charge w.r.t. time, two types of materials exist, i.e. materials of Type I having a low value for the injection voltage (and leading to a great amount of injected charge) and materials of Type II having the onset of charge injection at higher voltages, causing thus the charge decrease with decreasing voltage. A point of criticism leveled against the aforementioned publications is that recombination effects were not taken into account, although such effects contribute to the increase of the rate of loss of carriers in an existing treeing structure [19, 20].

II. THE IMPORTANCE OF SPACE CHARGES IN THE PRE-BREAKDOWN PROCESSES – EARLIER RESEARCH

Quite early, experiments with polyethylene and needle-plane electrode arrangement pointed out that the variation of breakdown strength with polarity and radius of curvature of the needle electrode indicated that the stress-enhanced conductivity and space charge accumulation reduce the stress near the sharp points to values much lower than those calculated geometrically [21]. According to other researchers, space charge exists ahead of the breakdown channel persisting for some time even after the removal of the voltage pulse. They reported that if another pulse not larger than the previous one and of the same polarity is applied, it does no damage to the insulation because the insulation ahead of the channel is shielded by the first space charge [22].

A physical model developed for electrical aging and breakdown of extruded polymeric (polyethylene, cross-linked polyethylene, ethylene propylene rubber) insulated power cables assumed the entering of space charge into gas channels, with the increase of the voltage stress above the PD threshold level. The space charge entering the channels decreases the insulation breakdown voltage in proportion to (E – Ethac), with E being the applied voltage stress and Ethac the threshold voltage stress. Consequently, the depth to which the space charge penetrates into the channels of the insulation is also proportional to (E – Ethac). In the case of AC voltages, the flow of charges forward and backward along the channels causes the scission of molecular chains of the insulation adjacent to the channels and in this way, the diameter of the channels increases. The largest amount of charge will flow in the stem of the tree-like pattern. As the diameter of the stem increases, it will transform into a crater. As the latter achieves a critical depth, the voltage stress at its end will become sufficiently high for the development of local PD, which subsequently will lead to an electrical tree causing the complete breakdown of the insulation. The crater depth will be proportional to the charge flowing forward and backward through the channel in the insulation adjacent to a void [23]. The weakness of this model is that it depends on the knowledge of distribution, shapes and sizes of microvoids, which in turn depend on a variety of complex factors [24].The gist, however, of the approach of [23] conforms with earlier observations, where it was noted that the observed tree length can be taken as a measure of the spatial distribution of the space charge [25]. Publication [23] draws some ideas regarding the forward and backward flow of charges from an earlier paper [26].

According to [27], there is a possible link between the concentration of space charges in the crystalline-amorphous interfacial regions and the subsequent formation and propagation of tree channels. In [27], it was indicated that the electric field value for charge injection is Emax=$1.2\text{x}10^8$ V/m, a value much higher than the one reported in [28] ($3.3\text{x}10^6$ V/m), but lower than that reported in [29] (10^9 V/m). The value mentioned in [27] for charge injection is not very different from the one reported in [30], where for a void-free insulation the maximum field to cause insulation deterioration was found to be $3\text{x}10^8$ V/m. The above publications conform with the proposed mechanism of breakdown in [31], where it was remarked that space charges deform the electric field and the rate of collision ionizations increases near the cathode [32].

The importance of space charges and their role in pre-breakdown processes was emphasized earlier on in [33], where –besides the proposed models for solid dielectric breakdown- it was pointed out that cumulative ionization creates positive space charges, which distort the electric field weakening thus the dielectric. Breakdown will occur when the electric field applied is so high that electrons travelling through the dielectric have a sufficient chance to traverse the maximum of the integral excitation function of the atoms. Space charges are also implicitly mentioned in [34], where it was reported that in mixed or amorphous solid dielectrics, a large number of electrons trapped in energy levels due to lattice imperfections can transfer energy to the lattice vibrations. In [35], special attention was given to the space charges. It was considered that the presence of space charges modifies the local value of the electric field according to Poisson's law. Collision ionization was assumed as the basic mechanism of space charge formation. The significance of space charges for breakdown was also stressed in [36], where discussing the breakdown of Perspex cubes with sphere-sphere electrodes, emphasis was put on the electron emission into the dielectric from the cathode. As the field near the cathode reaches a critical value, electron multiplication by impact ionization may initiate a type of multiple avalanche breakdown mechanism. The importance of interfaces, and in particular of the crystalline-amorphous boundaries, was discussed in [37], where it was reported that injected electrons from the cathode are trapped at the crystalline-amorphous boundaries, forming thus homotype space charge suppressing avalanche formation in the crystalline part especially in the case of DC application. Later publications [10, 27] agreed with the conclusions of [37] on the importance of the crystalline-amorphous boundaries. An implicit importance to the space charges –although in their model the sort of charge carriers is not specified– was also given in [38], where in the initial stage 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 clusters will grow into macroscopic defects and subsequently the density of charge carriers and their 'free paths" will increase until the macroscopic defects form a single channel of high probability of continuous conduction between the electrodes.

III. THE IMPORTANCE OF SPACE CHARGES IN THE PRE-BREAKDOWN PROCESSES – LATER RESEARCH

In [39], a variety of samples of cross-linked polyethylene samples (XLPE) was studied with DC as well as with AC electric stresses. No significant chargecan be observed in the sample subjected to 10 Hz AC electric stress, while accumulation of negative charges was observed at frequencies of 1 and 50 Hz. One possible explanation is the contribution of space charge on AC ageing is speculated to be mainly due to the fatigue mechanism associated with the electromechanicalenergy stored or released in trapping and detrapping as well as to the electromechanical forces exerted by the injected charge in each half cycle [40, 41]. With DC electric stress, the situation was more straightforward, in that the amount of homocharges increased with aging duration.

The role of space charges as pre-breakdown events was discussed in [42], where it was noted that the injection depth of space charges is inversely proportional to the initial applied electric field. This may be somehow surprising but the authors of [42] explain it by considering space charge kinetics and the process of trapping/detrapping. The role of interfacial zones is also considered in [42]. Trapping/detrapping of space charges as well as recombination process were studied in [43], where it was remarked that the latter is more energetic than the former mechanism. The findings of [43] justify the criticism of [19, 20] regarding [16-18]. It has to be noted that hints of the ideas of [43] were already present in an older doctoral thesis [44]. In [45], the authors tackled the space charge influence from another point of view, namely that of the influence of the thickness of the insulating sample. They found that, generally the accumulation of space charges increases with the increase of application time of the applied voltage, which results in a lower breakdown strength. Consequently, the accumulation of space charges in a thicker sample is greater since the time required for the internal electric field to reach the breakdown threshold value becomes longer under the same ramp voltage. The accumulation of space charges in a thicker sample is more severe making the electrical breakdown of a thicker sample lower than that of a thinner sample. Such observations were also noticed in [46]. The effect of sample thickness and of a slower ramp voltage in relation to space charges was noted as well in [47].

In [48], emphasis was given on the threshold voltage above which space charges appear, although as the authors remark there may be a second threshold voltage where the space charge behavior becomes even more complex, like the emergence of traveling space charge packets in the form of solitary waves. Disappearance of hetero-charges with increasing thickness may be interpreted by enhance electron-hole recombination in pure LDPE as well as with LDPE filled with SiO_2 nanoparticles. Such a mechanism depends on the trap density [48, 49]. Space charges play a role also in determining the breakdown strength of silicone-based elastomers, although it is not yet clear whether the observed breakdown failures were due to exclusively to charge delocation or a combination of both charge delocation and softness of the material due to excessive heating [50]. In fact, such an interplay between space charges and local heating was also noted in [51], where it was postulated that local current density due to space charges may cause heat flow conditions such that they may in turn lead to thermal instabilities. In [51], it was also noted that space charge currents may lead to filaments in the dielectric, which in turn will lead to treeing. This is in accordance with previously published seminal work [16-18, 52].

Space charges contribute significantly to the initiation and propagation of trees in solid dielectrics. Space charges, injected from asperities, may cause ElectroLuminescence (EL), which in turn may be related to a degraded region of the polymer. EL occurs often prior to electrical treeing. EL may determine the effect of space charge during charge injection under AC, DC and impulse voltages [53]. Recombination processes may also be considered since they can eventually break the chemical bonds of a polymer [43, 54]. Other researchers pointed out the intimate relationship between space charges, PD and treeing [55]. A factor also contributing to the treeing phenomenon is the surface resistivity of the inner void walls. The interplay between surface resistivity, space charges and treeing was discussed in [56], where it was reported that as the material deteriorates, the surface resistivity of the inner walls of a void is reduced and the electric field increases at the boundary between the void and the healthy material. Such action, however, will further contribute to the extension of the damaged material. The latter thoughts bring us to another challenging problem, namely that of the relation between space charges and the ensuing PD activity inside the voids that may exist in a solid insulation. Charges trapped in shallow traps at the boundary between solid dielectric and void may serve as initiatory electrons and may have been deposited from previous PD events but, as mentioned in [57], they can also be the result of charge transport from the electrodes to the void. However, earlier remarkable publications [58-60], did not shed light to the relation between space charges and PD, although efforts which were undertaken indicated that electrical trees may be caused from recombination effects and by an increase of trap density to the point where shallow traps can connect together in the form of a percolation cluster under the application of an electric field. Impact excitation and impact ionization can ensue leading inevitably to filamentary damage and tree initiation [61, 62].

A study of space charges with both AC and DC voltages was reported in [63], where it was remarked that the comparatively lower AC breakdown strength (compared with DC breakdown strength) and the decreasing trend with increase in applied frequency are due to space charge induced electric field distortion in the vicinity of the electrodes. Consequently, breakdown with AC voltages starts mainly in the vicinity of the dielectric/electrode interface. On the contrary, when a DC voltage is applied, breakdown initializes in the bulk of the solid dielectric. The results of [63] are somehow at variance with those of [64], where it was reported that with DC voltages, both electrodes may play a role. The authors of [64] stressed the importance of the thermal nature of breakdown on the condition of the presence of space charges.

As a general comment, one may say that space charges have an influence on the applied electric field. The amount of charge formed in the sample of LDPE increases with the applied field and its duration. The maximum electric field shows time dependent and its position varies as well. The electric field enhancement can reach up to 60% at high applied fields [65]. This implies that space charge dynamics is a very complicated matter being dependent on the electrode material, the applied electric field and its duration. Such data conforms with earlier experimental results on cable insulation [66]. In fact, [66] also showed the relation between space charge buildup, electrical treeing and breakdown. In [67] it was remarked that polarity reversal processes tend to show the effect of pre-existing fields on space charge reversal. Space charges formed in the middle of cable insulation lead to currents which tend to move charges from the bulk of the insulation towards the electrodes, which in turn may be the source of damage [67].

IV. Some Additional Remarks

Although it seems that space charges are related to electrical trees [66], and that electrical trees are a pre-breakdown phenomenon [68-70], no effort is made under the context of the present work to refer to this relation. Also, no detailed mention is being made of the various techniques used in order to measure space charges [6, 54, 71, 72] in the present paper. Furthermore, space charge measurements have been proposed for industrial applications [73, 74] but such a subject needs a lengthy treatment which is beyond the scope of the present paper. The simulation of electrical trees in the presence of space charges (e.g. [5, 75-77]) is also not considered. All the aforementioned subjects can be treated in separate publications since the amount of theoretical and experimental data is too large.

V. Conclusions

This short review indicates that space charges are an important phenomenon related to the breakdown of solid insulation. Homocharges and heterocharges can significantly modify the electric field in a solid dielectric and thus shorten its lifetime. Space charges is a very complex phenomenon depending on a variety of factors, such as, among others, the nature of the applied electric field, existing interfaces inside the solid dielectric as well as between the dielectric and the electrodes, the kind and the nature of impurities.

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