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, switchgears, 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 a high value for the injection voltage, 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 is applied the space charge cloud for various 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].

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), where 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 rate of increase of space charge is proportional to (E – Ethac). In the case of AC voltages, the rate of increase of space charge is proportional to (E – Ethac). In the case of AC voltages, the rate of increase of space charge is proportional to (E – Ethac). In the case of AC voltages, the rate of increase of space charge is proportional to (E – Ethac).

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 strength for charge injection is Emax=1.2x10^6 V/m, a value much higher than the one reported in [28] (3.3x10^6 V/m), but lower than that reported in [29] (10^7 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 3x10^6 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 it was assumed that model 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 charge can 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
electromechanical energy 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 enhanced 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,
elier 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], 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.

REFERENCES

[1] H. J. Wiesmann and H. R. Zeller, “A fractal model of dielectric breakdown and prebreakdown in solid dielectrics,” Journal of Applied Physics, vol. 60, no. 5, pp. 1770–1773, 1986.
[2] M. G. Danikas and G. E. Vardakis, “A review on electrical treeing in solid dielectrics,” The Journal of CPRI, vol. 5, no. 1, pp. 75–88, 2009.
[3] G. Mazzanti, G. C. Montanari, and L. Dissado, “A space charge life model for the ac electrical ageing of polymers,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 6, pp. 864–875, 1999.
[4] M. G. Danikas, “A study of the behavior of a uniaxially oriented polyethylene tape/oil insulating system subjected to electrical and thermal stresses,” Ph. D. Thesis, University of London, Queen Mary College, Department of Electrical and Electronic Engineering, 1985.
[5] T. Takada, “Acoustic and optical methods for measuring electric charge distributions in dielectrics,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 6, no. 5, pp. 519–547, 1999.
[6] T. Tanaka and A. Greenwood, Advanced Power Cable Technology – Volume I. Boca Raton, Florida: CRC Press, Inc, 1983.
[7] T. Okamoto and T. Tanaka, “Auto-correlation function of PD pulses under electrical treeing degradation,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 2, no. 5, pp. 857–865, 1995.
[8] R. Cooper, “Breakdown in solids”, in: Electrical Insulation. London, UK, 1983.
[9] J. H. Mason, “Breakdown of solid dielectrics in divergent fields,” in Proceedings of the IEEE, 1955, vol. 102, Pt. C, pp. 254–263.
[10] G. E. Vardakis, “Breakdown phenomena in solid insulating materials: A study of electrical tree propagation,” Ph. D. Thesis, Democritus University of Thrace, Department of Electrical and Computer Engineering, Xanthi, Greece, 2006.
[11] K. S. Suh, H. J. Lee, D. S. Lee, and C. G. Khang, “Charge distributions in PC/SAN/PCL polymer blends,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 2, no. 3, pp. 460–466, 1995.
[12] C. Laurent, T. G. Teysseide, S. L. Roy, and F. Baudot, “Charge dynamics and its Energetic features in polymeric materials,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 2, pp. 357–381, 2013.
[13] C. Mayoux, “Contribution al’étude de l’action sur du polyéthylène de differentes formes d’énergie présents dans les dechargespartielles,” Ph. D. Thesis, Universite Paul Sabatier, Toulouse, France, 1972.
[14] C. Zhang, T. Mizutani, K. Kaneko, and M. Ishioka, “Decay of space charge in LDPE and its blend polymer,” Journal of Physics D: Applied Physics, vol. 35, pp. 1875–1879, 2002.
[15] P. H. F. Morshuis, “Degradation of solid dielectrics due to internal partial discharge: Some thoughts on progress made and where to go now,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 12, no. 5, pp. 905–913, 2005.
[16] L. Yu, F. B. Madsen, and A. L. Skov, “Degradation patterns of silicone-based elastomers in electrical fields,” International Journal of Smart and Nano Materials, vol. 9, no. 4, pp. 217–232, 2018.
[17] Z. Lv, X. Wang, K. Wu, X. Chen, Y. Cheng, and L. Dissado, “Dependence of charge accumulation on sample thickness in nano-SiO2 doped LDPE,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 20, no. 1, pp. 337–345, 2013.
[18] T. Unemura, K. Akiyama, and T. Kashiwazaki, “Dielectric behavior of solid/liquid insulation system,” IEEE Transactions on electrical insulation, vol. 17, no. 3, pp. 276–280, 1982.
[19] D. B. Watson, “Dielectric breakdown in Perspex,” IEEE Transactions on Electrical Insulation, vol. 8, no. 3, pp. 73–75, 1973.
[20] M. Ieda, “Dielectric breakdown process of polymers,” IEEE Transactions on Electrical Insulation, vol. 15, no. 3, pp. 206–224, 1980.
[21] K. C. Kao, Dielectric Phenomena in Solids. San Diego, California, USA: Elsevier Academic Press, 2004.
[22] L. Li, “Dielectric properties of aged polymers and nanocomposites,” Ph. D. Thesis, Iowa State University, Department of Materials Science and Engineering, 2011.
[23] T. Hibma and H. R. Zeller, “Direct measurement of space charge injection from a needle electrode into dielectrics,” Journal of Applied Physics, vol. 59, no. 5, pp. 1614–1620, 1986.
[24] Y. Inuiishi, “Effect of space charge and structure on breakdown of liquids and solids,” in Annual Report on Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), 17-21 October 1982, Ann Arbor, MA, USA, pp. 328–338.
[25] T. Tanaka and A. Greenwood, “Effects of charge injection and extraction on tree initiation in polyethylene,” IEEE Transactions on Power, Apparatus and Systems, vol. 97, no. 5, pp. 1749–1759, 1978.
[26] A. Hippel, “Electric breakdown of solid and liquid insulators,” Journal of Applied Physics, vol. 8, pp. 815–832, 1937.
[27] K. H. Stark and C. G. Barton, “Electric strength of irradiated polythene,” Nature, vol. 176, pp. 1225–1226, 1955.
[28] G. Bahlde, C. Katz, and W. Vahlstrom, “Electrical and electrochemical treeing effect in polyethylene and crosslinked polyethylene cables,” IEEE Transactions on Power, Apparatus and Systems, vol. 93, no. 3, pp. 977–990, 1974.
[29] D. Pitas, G. E. Vardakis, and M. G. Danikas, “Electrical tree growth simulation in nanocomposite polymers: The role of nanoparticles and homocharges,” in Proceedings of the 2010 IEEE International Conference on Solid Dielectrics (ICSD), Potsdam, Germany, Jul. 2010, pp. 726–728.

[30] H. R. Zeller and W. R. Schneider, “Electrofracture mechanics of dielectric aging,” Journal of Applied Physics, vol. 56, no. 2, pp. 455–459, 1984.

[31] S. S. Barmi, “Electroluminescence – A technique to detect the initiation of degradation in polymeric insulation,” IEEE Electrical Insulation Magazine, vol. 15, no. 3, pp. 9–14, 1999.

[32] E. J. McMahon and J. R. Perkins, “Evaluation of polyolefin high-voltage insulating compounds: dendrite (tree) formation under highly divergent fields,” IEEE Transactions on Power, Apparatus and Systems, vol. 83, pp. 1253–1260, 1964.

[33] Y. Zhang, J. Lewiner, C. Alquie, and N. Hampton, “Evidence of strong correlation between space-charge buildup and breakdown in cable insulation,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 3, no. 6, pp. 778–783, 1996.

[34] M. G. Danikas and S. Morsalin, “Foreign incursions, enclosed cavities, partial discharge models, and discharge energy: A short review regarding solid dielectrics and composite insulating systems,” Engineering, Technology & Applied Science Research, vol. 9, no. 5, pp. 4659–4666, 2019.

[35] R. Arora and W. Mosch, High Voltage and Electrical Insulation Engineering. Hoboken New Jersey, USA: John Wiley & Sons, Inc, 2011.

[36] E. Kuffel, W. S. Zaengl, and J. Kuffel, High Voltage Engineering Fundamentals. Newnes, Oxford, UK, 2000.

[37] M. S. Naidu and V. Kamaraju, High Voltage Engineering, tenth ed. New Delhi, India: Tata McGraw-Hill Publishing Co. Ltd, 2000.

[38] D. Kind and H. Kaerner, High-Voltage Insulation Technology. Braunschweig, Germany, 1985.

[39] R. J. Brunt, E. W. Cernyar, and P. Glian, “Importance of unrolling memory propagation effects in interpreting data on partial discharge statistics,” IEEE Transactions on Electrical Insulation, vol. 28, no. 6, pp. 905–915, 1993.

[40] D. Pitas, M. G. Danikas, G. E. Vardakis, and T. Tanaka, “Influence of homocharges and nanoparticles in electrical tree propagation under DC voltage application,” Archiv fuer Elektrotechnik (Electrical Engineering), vol. 94, pp. 81–88, 2012.

[41] M. Mammeri, C. Laurent, and I. Salon, “Influence of space charge buildup on the transition to electrical treeing in PE under AC voltage,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 2, no. 1, pp. 27–35, 1995.

[42] K. Fukunaga, “Innovative PEA space charge measurement systems for industrial applications,” IEEE Electrical Insulation Magazine, vol. 20, no. 2, pp. 18–26, 2004.

[43] L. L. Alston and P. G. Dawson, “Life of polythene at very high stresses,” Proceedings of the IEE, vol. 112, no. 4, pp. 814–817, 1965.

[44] P. Robert, Materiaux de l’Electrotechnique. Lausanne, Switzerland, 1979.

[45] K. Wu and L. Dissado, “Model for electrical tree initiation in epoxy resin,” IEEE Transactions on Dielectrics and Electrical Insulation, vol. 12, no. 4, pp. 655–668, 2005.

[46] S. Goettisch, “Modellierung des Raudlungsaufbaus in der Umgebung von Einschlüssen in VPE-Kabelisolierungen,” Ph.D. Thesis, Rheinisch-Westfälische Technische Hochschule Aachen (RWTH), Fakultät Elektrotechnik, 1994.

[47] A. K. Jonscher and R. Lacoste, “On a cumulative model of dielectric breakdown in solids,” IEEE Transactions on Electrical Insulation, vol. 19, no. 6, pp. 567–577, 1984.

[48] G. Chen, J. Zhao, S. Li, and L. Zhong, “Origin of thickness dependent dc electrical breakdown in dielectrics,” Applied Physics Letters, vol. 100, pp. 222904–1–222904–4, 2012.
Electrical Insulation and Dielectric Phenomena, National Academy of
Sciences, Washington, D. C., USA, 1974, pp. 270–278,
[69] H. R. Zeller, T. Baumann, E. Cartier, H. Dersch, P. Pfluger, and F.
Stucki, “The physics of electrical breakdown and pre-breakdown in solid
dielectrics,” Festkoerperprobleme, vol. 27, pp. 223–240, 1987.
[70] G. E. Vardakis and M. G. Danikas, “The pioneering work by Zeller on
reeing in insulating materials: Some comments,” Journal of Electrical
Engineering, vol. 51, no. 11–12, pp. 341–344, 2000.
[71] J. T. Holboll, “The resistance of composite materials against electrical
discharges,” Ph. D. Thesis, Technical University of Denmark,
Department of Electric Power Engineering, 1992.
[72] J. J. O’Dwyer, The Theory of Electrical Conduction and Breakdown in
Solid Dielectrics. Clarendon Press, Oxford, UK, 1973.
[73] H. Froehlich, “Theory of electrical breakdown in ionic crystals,”
Proceedings of the Royal Society A, vol. 160, pp. 230–241, 1937.
[74] O. Dorlane, S. Sapiela, M. R. Wertheimer, and A. Yelon, “Thermally
stimulated discharge of polyethylene following a.c. stressing,” IEEE
Transactions on Electrical Insulation, vol. 17, no. 3, pp. 199–202, 1982.
[75] D. Min et al., “Thickness-dependent DC electrical breakdown of
polyimide modulated by charge transport and molecular displacement,”
Polymers, vol. 10, no. 9, p. 18, 2018.
[76] M. A. Charoy and R. F. Jocteur, “Very high tension cables with extruded
polyethylene insulation,” IEEE Transactions on Power, Apparatus and
Systems, vol. 90, no. 2, pp. 777–782, 1971.
[77] Y. Shibuya, S. Zoledziowski, and J. H. Calderwood, “Void formation
and electrical breakdown in epoxy resin,” IEEE Transactions on Power,
Apparatus and Systems, vol. 96, no. 1, pp. 198–207, 1977.