Space Charge Modulated Electrical Breakdown

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Electrical breakdown is one of the most important physical phenomena in electrical and electronic engineering. Since the early 20th century, many theories and models of electrical breakdown have been proposed, but the origin of one key issue, that the explanation for dc breakdown strength being twice or higher than ac breakdown strength in insulating materials, remains unclear. Here, by employing a bipolar charge transport model, we investigate the space charge dynamics in both dc and ac breakdown processes. We demonstrate the differences in charge accumulations under both dc and ac stresses and estimate the breakdown strength, which is modulated by the electric field distortion induced by space charge. It is concluded that dc breakdown initializes in the bulk whereas ac breakdown initializes in the vicinity of the sample-electrode interface. Compared with dc breakdown, the lower breakdown strength under ac stress and the decreasing breakdown strength with an increase in applied frequency, are both attributed to the electric field distortion induced by space charges located in the vicinity of the electrodes.

Electrical breakdown is an important physical phenomenon, which may occur in electrical equipment and electronic devices. Since the application of alternating current (ac) in power transmission began in the late 19th century, it has been realized that the dc breakdown strength is about twice or higher than the ac breakdown strength in insulating materials. Throughout the 20th century, many investigations on this phenomenon were conducted and it was discovered that this phenomenon commonly exists in many insulating materials, from thin films to thick boards. From the early 20th century on, classical theories such as electrical breakdown (introduced by Hipple in 1937 and Fröhlich in 1939) and thermal breakdown (introduced by Wagner in 1922) have been proposed. However, it is still the lack of a widely recognized understanding, which can fully explain the origin of this phenomenon. Given overall rapid developments in electrical and electronic engineering, the incomplete understanding of the mechanism of dc and ac breakdown has restricted the development of some electrical equipment and electronic devices.

In 1914, scholars first recognized the presence of charges injected from electrodes under electrical stress, i.e., space charges. After the establishment of pulsed electro-acoustic (PEA) method in 1990s, space charge distribution in solid insulating materials came to be intuitively demonstrated. During the same period, numerical simulations of space charge profiles were initially performed and some of the simulated results could perfectly match the PEA results in recent years. As a result of the development in understanding space charges, the electric field concentration and distortion induced by space charges were valued and considered as an important factor that modifies the dielectric behaviour of insulating materials. Based on present understanding, the origin of thickness-dependent dc breakdown was initially investigated through numerical simulations. However, there is still a lack of experimental support. Moreover, the origin of ac breakdown in connection with the presence of space charge has not been revealed.

In this work, after considering the characteristics of charge injection, migration and diffusion, we demonstrate the charge transport behaviours during dc and ac (50–1000 Hz) breakdown of one typical material employed in electrical engineering, i.e., the oil impregnated paper in power transformers. We discuss the differences in charge accumulation and electric field distortion between dc and ac electrical stresses, and reveal the breakdown mechanism modulated by space charges.

Our experiment employed Karamay transformer oil impregnated Kraft insulating paper (thickness of 0.07 mm) as the oil impregnated paper sample. A brass spherical electrode (φ = 25 mm) was used in conducting the breakdown tests. (Further details are provided in the Supplementary Information).

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observed that both positive and negative charges are accumulated in the vicinity of the electrodes. Compared 50–1000 Hz ac stress at 135 kV/mm (the experimental 50 Hz breakdown strength, peak-to-peak value). It can be no breakdown occurs in the following numerical simulation. Figure 2b shows the space charge distribution under sample.

The ac breakdown strength decreases with increasing applied voltage frequency. Under 50 Hz ac stress, the breakdown occurs at 135 kV/mm, which is 57.7% of the dc breakdown strength (233 kV/mm) of the same sample. Ac stress may induce homo-charge accumulation, which leads to a more obvious decrease of electric strength near the sample-electrode interface, while they increase in the bulk of the sample. It implies a higher maximum built-in electric strength in the bulk, which decreases the breakdown strength. As a result, the dc breakdown strength decreases with increasing sample thickness. For thickness-dependent dc breakdown of oil impregnated paper, the simulated breakdown strengths are in accordance with the experimental results, as shown in Fig. 1a.

In order to demonstrate the electric field distortion with the variation of applied frequency, it is assumed that no breakdown occurs in the following numerical simulation. Figure 2b shows the space charge distribution under 50–1000 Hz ac stress at 135 kV/mm (the experimental 50 Hz breakdown strength, peak-to-peak value). It can be observed that both positive and negative charges are accumulated in the vicinity of the electrodes. Compared
with space charge distribution under dc stress, the charge accumulation depth is tremendously narrowed, which is within 0–2 μm in the vicinity of the electrodes. Moreover, the position of positive charges is more shallow (compared to that of negative charges), owing to a lower mobility that controls the migration of charges. Although the total amount of space charges under ac stress is relatively small, the charge densities in the vicinity of the electrodes are extremely large. The maximum density reaches the order of 10^4 C/m^3 at the electrodes, while no space charge is observed inside the middle of the bulk. The densities of both positive and negative charges increase with increasing applied frequency, which is considered to determine the breakdown strengths with the variation of applied frequencies.

In Fig. 2b, it is observed that space charge accumulation is more dramatic in the vicinity of the left electrode, which forms a more distorted electric field. The amplitude of ac stress varies in one cycle. Electrical breakdown occurs at the maximum electric field, which is built at the phase angle of 90°, as demonstrated in Fig. 2c. It is observed that a tremendously distorted field is built near the sample-electrode interface and is strengthened with the increasing applied frequency. The maximum distortion appears at the junction of positive and negative charges, which can be explained by Poisson's equation. For 50 Hz ac stress, when the applied electric field is 135 kV/mm, the maximum electric strength reaches 233 kV/mm in the vicinity of the left electrode. As 233 kV/mm is the assigned value of intrinsic breakdown (that is, the experimental dc breakdown strength), this leads to the breakdown of the oil impregnated paper sample under 50 Hz ac stress. For 200–1000 Hz ac stress, the maximum distorted electric strengths at 135 kV/mm are far larger than 233 kV/mm and they increase with the increasing applied frequency. Therefore, the breakdown strengths decrease with the rising applied frequencies.

The simulated breakdown strengths under 200–1000 Hz ac stress are shown in Fig. 2a, which are in accordance with the experimental results. Ac breakdown is determined by space charges in the vicinity of the sample-electrode interface. The comparatively lower 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.

We have thus demonstrated the dc and ac (50–1000 Hz) breakdown characteristics of insulating materials, both in experiments and numerical simulations. Notably, the electrical breakdown of insulating materials is modulated by space charges. Generally, homo-charges are formed in a dc breakdown process, which reduce the electric strength in the vicinity of the sample-electrode interface and enhance electric strength in the middle of the bulk. In contrast, both positive and negative charges are accumulated within 0–2 μm in the vicinity of the electrodes under ac stress. These accumulated charges induce a significant electric field distortion that greatly enhances inner electric strength in the vicinity of the electrodes, which lead to the comparatively low breakdown strengths. This distortion is strengthened with applied frequency, which is responsible for the decreasing breakdown strength with applied frequency. In conclusion, dc breakdown initializes in the middle bulk of the material whilst ac breakdown initializes in the vicinity of the sample-electrode interface.

As the mechanisms of dc and ac breakdown are now revealed, it provides a new possible method in analyzing and explaining breakdown phenomenon. Moreover, possible quantitative methods in modifying space charge distribution, like oxidation and fluoridation, should be further developed and emphasized as important approaches to control and improve the breakdown performance of insulating materials.

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Figure 2. Space charge dynamics and breakdown strengths under ac stress. (a) Experimental and simulated breakdown strengths of one-layer oil impregnated paper under 50–1000 Hz ac stress, (b) space charge distribution as a function of position at applied electric strength of 135 kV/mm in 50–1000 Hz ac breakdown processes of one-layer oil impregnated paper, (c) electric field distribution as a function of position at applied electric strength of 135 kV/mm (at phase angle of 90°) in 50–1000 Hz ac breakdown processes of one-layer oil impregnated paper.
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Author Contributions
S.L. and Y.Z. planned the project, designed the experiment and wrote the paper. Y.Z. did sample preparation and performed the breakdown experiments. D.M. developed the program for numerical simulations. S.L. and G.C. provided analytical theory for electrical breakdown. All of the authors participated in the analysis of the results.

Additional Information
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