Dielectric Breakdown Testing of Insulation Materials Under High-Frequency Bipolar Square Wave Voltage by Repetitive Pulses

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ABSTRACT- **As the essential component of a power electric transformer (PET), the high-voltage, high-frequency transformer has significance for power transmission and electrical isolation. Although high-frequency transformer efficiency increases with frequency, the high-frequency electro-thermal interaction phenomenon causes major insulation issues. Bipolar high-frequency square waves of various frequencies were used to conduct breakdown tests on two distinct types of inter-turn insulation materials. The two-parameter Weibull distribution was used to calculate the insulation breakdown voltage at various frequencies. The inverse power function model was used to derive the voltage life characteristic. In this paper, two kinds of thermostable insulation materials were tested under a high-frequency square wave power supply. Moreover, it discusses the new breakdown phenomena of insulation materials through the frequency dependence of breakdown strength experiments. The results show that the typical breakdown voltage lowers with increasing frequency and approaches a maximum at 1~5 kHz. The voltage life characteristic curves alter as frequency increases, and thermal breakdown is the most common cause of failure.**

Keywords: **Dielectric breakdown, high-frequency wave voltage, insulation materials**

I. INTRODUCTION

Despite the traditional stresses on insulating systems, repetitive voltage pulses are becoming increasingly common in modern power systems. Due to the rising insulation failure caused by high-frequency non-sinusoidal loads and high temperatures, the insulation system constantly faces new challenges [1]. High dV/dt, high harmonic voltages, and overvoltage in the insulation can be brought on by high-frequency square wave voltages induced by the power electronic device's high-speed switching [2-3]. One of the most frequent voltage types in electrical and electronic equipment, such as solid-state transformers, is repeating frequency bipolar square wave voltage frequencies ranging from 1 kHz to 100 kHz. Insulation may inevitably be subjected to complicated, multi-frequency pressures, which can cause early breakdown and deterioration of the insulation [6]. The insulation's dielectric strength is a crucial performance factor for the dependability of high-voltage power electronic equipment. Therefore, it is essential to research how high-frequency square voltage affects insulator breakdown strength.

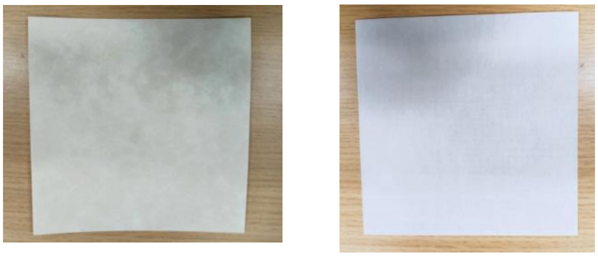
Previous research has used the AC and DC breakdown criterion to calculate the breakdown strength of insulating materials. However, a few publications used appropriate methodologies to focus on the high-frequency breakdown. P. Wang, J. Wang & H. Xu et al. studied PD characteristics for inverter-fed motor insulation under both sinusoidal land repetitive square wave voltage conditions by setting up the partial discharge (PD) test system. The result showed that the PD magnitude, phase, energy distribution, and endurance lifetime under sinusoidal voltages are different from that of repetitive square wave voltages even the corona resistance performance of the insulation system of inverter-fed motors will conflict if the sinusoidal voltage is used [4]. Phloymuk analyzed the DC breakdown characteristics of a non-uniform electric field affected by inserting a solid dielectric barrier in the air. The result showed that the breakdown voltage increased when air pressure was increased. Moreover, the thicker the solid barrier, the lower the field stress compared to the thinner barrier. The negative DC breakdown voltage exhibits a lower value compared to the positive case at a pressure lower than 1.5 bars and higher at a pressure higher than 1.5 bars [5]. W. yin and D. Schweickart found that dielectric breakdown strength will decrease with increasing temperature after investigating dielectric breakdown behaviors on polymeric insulation films under AC, DC, and pulsed voltage. Furthermore, the breakdown voltage under high-frequency unipolar pulses is significantly lower than DC or AC breakdown voltage at power frequency [9]. Recently, there has been a need for more comprehensive research into the complex dielectric breakdown phenomena under high-frequency non-sinusoidal stresses. The research presented above is frequently based on various application conditions, and the type and thickness of the insulation materials employed in the trials cannot be applied to the inter-turn insulation of high-frequency transformers. As a result, it is vital to investigate the breakdown characteristics under high-frequency square wave conditions to select inter-turn materials and resolve high-frequency transformer insulation challenges.

This paper studied the effects of frequency on the dielectric breakdown performance of DMD and Nomex papers under bi-polar square wave voltages. The E_b data were calculated and analyzed statistically using the two-parameter Weibull distribution. The varied results were discussed based on experimental phenomena and electric-thermal breakdown processes. The establishment and calculation of the thermal breakdown equivalent model in this research give a way to understand the solid dielectric discharge process at high frequencies.

II. EXPERIMENT METHOD

A. *Insulation Sample Preparation*

In this research, Nomex paper with 0.25mm thickness and DMD paper with 0.2mm thickness sheets were cut in HV Lab into squares of dimension 150 x 150 mm to be considered as a research object Fig. 1. Inter-turn insulation material selection needs to adhere to the criteria for insulation strength and thermal stability [10,11]. For the breakdown tests described in this study, two distinct types of thermostable insulating materials were chosen to serve as the test materials. When constructing the inter-turn insulation, Nomex paper with a temperature tolerance grade of H is chosen for use by oil-insulated transformers because of its favorable electrochemical characteristics. In addition, the temperature tolerance grade of F is gradually being implemented for the modified DMD insulating paper used for the winding insulation structure. In the following Table 1, we can observe a description of the electrical properties often associated with these materials.



(a) Nomex paper (b) DMD paper

Fig. 1. Insulation papers for breakdown test

Table 1. Insulation material electrical characteristics

Material	Type	Resistivity (Ω m)	Relative permittivity	Dielectricloss factor
Nomex paper	T410	$\geq 2.0 \times 10^{14}$	1.6 ~ 3.7	$(4{\sim}7) \times 10^{-3}$
DMD paper	6641F	$\geq 1.0 \times 10^{14}$	≤ 3.0	$\leq 8.0 \times 10^{-3}$

B. *Breakdown Measurement System and Procedure*

A repetitive frequency bipolar square wave high voltage pulse power supply was used as the power source. Fig. 2 depicts the experimental setup for analyzing the breakdown characteristics at high frequencies. The first part is a high-frequency voltage source that can be adjusted to provide an output voltage between 0 and 20 kV and a frequency between 1 and 20 kHz. Protective resistance links this part to the electrode receiving the high voltage. The second is a 75 MHz-bandwidth non-sinusoidal voltage monitor, or voltage probe. The digital oscilloscope has a bandwidth that may go up to 300 MHz, and the electric current transducer comes in at number three on the list of pieces of equipment. Recording the impulse current produced by a breakdown by a breakdown discharge is the function of this component. The data collected from the oscilloscope is statistically and analytically analyzed using a computer.

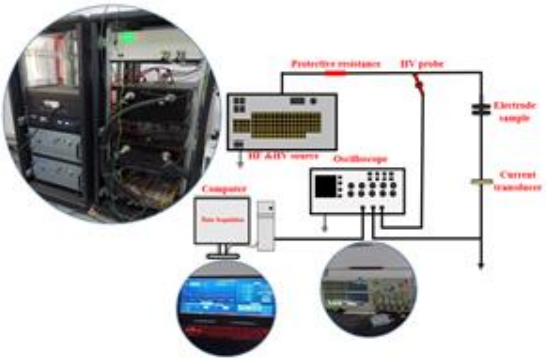


Fig. 2. Breakdown discharge testing infrastructure with high-frequency signals.

The practical operational conditions of the high-frequency machine were mimicked by setting up a high-frequency, high-voltage power supply. It can generate signals as a voltage and frequency-adjustable bipolar square waveform. Parameter definitions for the output waveform are shown in Fig. 3, and the waveform's settings are shown in Table 2.

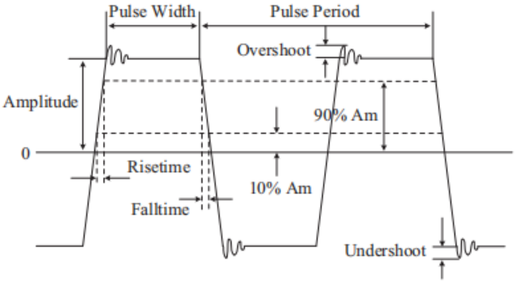


Fig.3. Present the output signal parameters of a high-frequency square wave power source.

The length of time it takes to go from 10% U_m to 90% U_m in a system where the significant value of U_m is 20 kV is one of these factors. When the HV-HF transformer is utilized, the characteristics listed in Table 2 get much closer than ever before to the winding voltage. Because of the complexity of the high-frequency power supply, it can be challenging to identify partial discharge characteristics while conducting insulation tests on the surfaces of insulation material. The audible sound and visual light emitted during high-frequency breakdown and surface discharge tests are the primary indicators that allow us to detect the initiation of a discharge.

Table 2. High-frequency power supply configuration parameters

Main Parameters	Settings
Peak-to-peak voltage	0~40 kV
Frequency	0~20 kHz
Maximum Current	100 mA
Overshoot/ undershoot	≤ ±5%
Minimum pulse width	25 µs
Rise/ fall time	5 µs
Dead zone or DC offset	None

C. *Experimental Electrodes and Samples*

The testing frequency is 2kHz, 4kHz, 6kHz, 8kHz, 10kHz, 12kHz, 14kHz, and 16kHz. The test sample thickness is 0.2mm of DMD and 0.25mm of Nomex papers. The breakdown phenomenon has certain randomness and dispersion, so more than two samples are required in this test to conduct a statistical analysis to obtain a certain probability of insulation materials' breakdown strength. This research considers insulation paper samples at each high-frequency condition and insulation position for the breakdown test with a constant voltage boost at 1 V/s. The thermostat is used for heating to guarantee the testing frequency. The breakdown electrode system comprises electrodes, incubators, and ground wires.

Fig. 4(a) depicts the construction of an electrode with a cylindrical shape and an equal-sized diameter. Both are intended to be suitable for insulating paper. The construction of this edifice took place. The height of the electrode measurement is 25 ± 1 millimeters, and its width is also the same. The round arc that makes up the electrode has a radius of 3.0 ± 0.2 millimeters and is composed of stainless steel. The sharp edges of the electrode have been rounded off to produce the circular arc. The electrode holder is utilized before beginning the breakdown test at high frequencies, as shown in Fig. 4(b), due to the correct alignment of the top and lower electrodes. The essential elements move to the composer's construction are a static conductive rod, a moving conductive rod, a scale, and an insulating cover in the shape of a pie. Adjusting the bolts brings the electrode plane near the material's surface and corrects the electrode holder's center deviation to within 1.0 mm. Both these adjustments can be made by bringing the electrode plane closer to the material's surface.

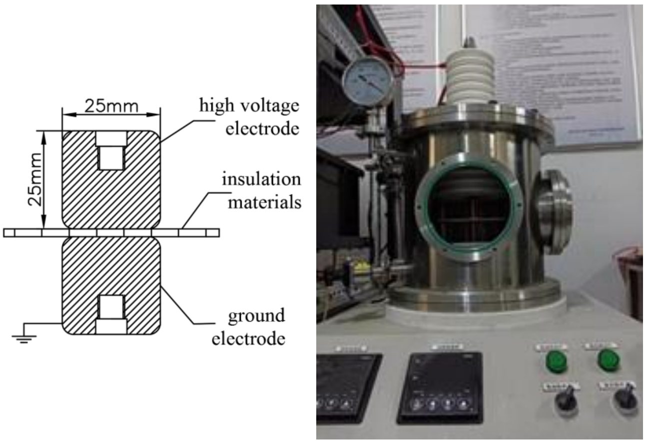


Fig.4. (a) Schematic diagram of equal-diameter cylindrical discharge electrode. (b) High-frequency discharge electrode holder.

III. RESULT AND DISCUSSION

Statistics and the examination of insulation test results frequently use three distinct calculating models: the Weibull distribution, the Logarithmic normal distribution, and the Gumbel distribution. These models are utilized in a variety of contexts. Out of these three models, the Weibull distribution is the one that is most suited for assessing faults that take place at the location in solid dielectrics that is considered to be the weakest [12,13]. In addition to the Logarithmic Normal Distribution and the Gumbel Distribution, the Logarithmic Normal Distribution is also very common. Each point on the Weibull plot of 10 test points for one frequency represents an alpha value, and the chance of failure at that point is 63%. Our previous work has shown that the Weibull distribution may be exploited for the statistical analysis of high-frequency square waveforms, as shown by equations (1) and (2).

$$F(\alpha, \beta, u) = 1 - \exp[-(u/\alpha)\beta] \qquad (1)$$

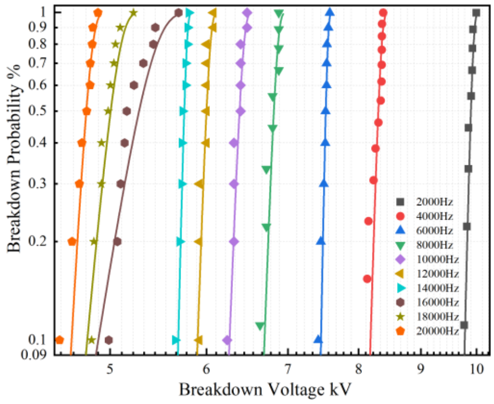
$$\ln\left(\ln \frac{1}{1-F(u)}\right) = \beta \ln u - \beta \ln \alpha \qquad (2)$$

Scale parameter α = breakdown voltages at 63.2 percent failure probability F = failure probability at test voltages below u. Both are the data variance and the shape parameter, which is modified negatively.

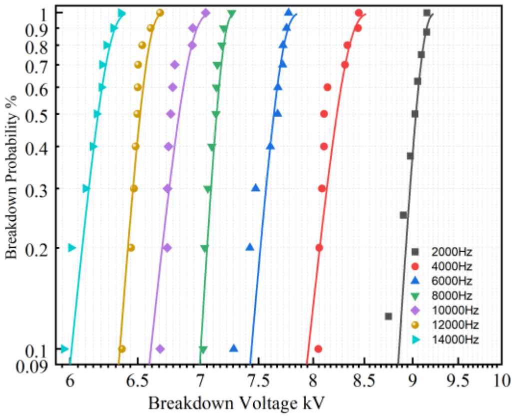
A. *Breakdown Characteristics*

On a double logarithmic coordinate system, we showed the results of computing and comparing the Weibull distributions of two different inter-turn insulating materials. The Weibull distribution is used in Fig. 5 to display the breakdown data of DMD and Nomex insulating materials at various frequencies. At high frequencies, bipolar square wave voltages still follow the two-parameter Weibull distribution, which describes the breakdown voltage of solid insulators.

In the graph shown in Fig. 5, the slope corresponds to the shape parameter, and the intercept may be used to determine the value of the scale parameter. The estimated values of the two-parameter of insulating materials show that the scale parameter at various frequencies and that scale parameter also referred to as the characteristic value of breakdown voltage, drop dramatically with the rise in frequency.



(a) DMD paper



(b) Nomex paper

Fig. 5. Breakdown voltages follow a Weibull distribution with two parameters.

These results are based on the calculations of the two-parameter. In the following, we shall conduct an in-depth analysis of the variation law of Fig. 6. Table 3 demonstrates β decreases with increasing frequency. The intensity of the thermal effect increases with frequency, slightly increasing data dispersion. At a frequency of 1–20 kHz, the large values of the shape parameter imply that the dispersion of the experimental data is within an acceptable range.

The outcomes of the computations are presented in Table 3; looking at it, one can see that the normal values of the breakdown voltage decrease as the frequency increases from 6 kHz to 10 kHz. The breakdown voltage characteristic values drop to 56.5 % of their starting values when the frequency increases within 6 kHz~10 kHz. By doing that, it is possible to acquire the Weibull distribution density expressions of inter-turn insulation materials, which provides a foundation for estimating the probabilities of the breakdown of insulation materials in engineering applications.

Table 3. Estimating the Weibull Distribution Density

Material	f	α	β	$F(u)$
Nomex (T410)	6 kHz	7.5	209.01	$F(u)$=1-exp[1-$(u/7.5)^{209.01}$]
	10 kHz	6.41	99.980	$F(u)$=1-exp[1-$(u/6.41)^{99.98}$]
DMD (641F)	6 kHz	7.68	70.950	$F(u)$=1-exp[1-$(u/7.68)^{70.95}$]
	10 kHz	6.87	56.50	$F(u)$=1-exp[1-$(u/6.87)^{56.50}$]

Nomex paper and DMD paper are subjected to breakdown voltage calculations using the scale parameter within the frequency ranging from 1 kHz to 20 kHz. The findings that were obtained point to an intriguing pattern, which is as follows: when the frequency is raised, the breakdown voltage of both types of material considerably drops. When the voltage frequency is raised from 1 kHz to 20 kHz, the breakdown voltages of Nomex paper and DMD paper drop to approximately 40.54% ~ 53.76% of their original values.

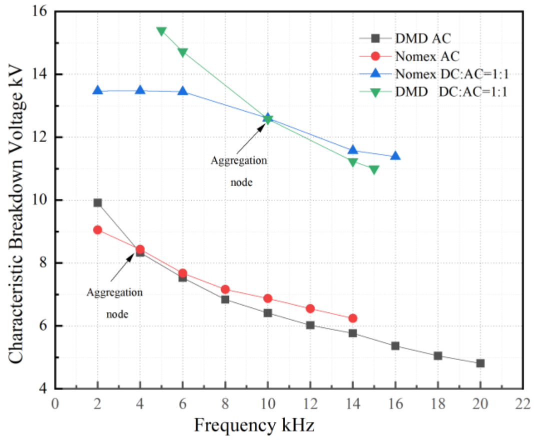


Fig.6. Breakdown voltage frequency fluctuation (1-20 kHz).

Furthermore, it is observed that the AC breakdown voltages of both Nomex paper and DMD paper become essentially the same when the voltage frequency exceeds 4 kHz, which can be observed in Fig.6. The development of this convergence suggests that the two materials display comparable breakdown properties under AC voltage stress at frequencies higher than 4 kHz. The structural similarities and similar dielectric characteristics of Nomex and DMD sheets may cause this convergence. The DMD breakdown strength at 10 kHz is 34.05 kV/mm, and according to Fig.6, extrapolation suggests that the electric strength at 2 kHz will be roughly 49.57 kV/mm.

Additionally, the combined DC and AC currents in Nomex paper and DMD paper exhibit similar behavior when the frequency voltage is set at 10 kHz. The similarity in current characteristics further highlights the comparable performance of Nomex and DMD papers under the given frequency conditions. Understanding the frequency dependence of breakdown voltage in the Nomex paper and DMD paper has significant implications for their practical applications in electrical insulation systems. Engineers and designers can employ this information to make informed decisions regarding selecting appropriate insulation materials based on specific frequency requirements. It enables them to design systems that can withstand voltage stress at different frequencies, ensuring the overall reliability and safety of the electrical infrastructure.

B. *Dielectric strength*

In addition, the typical value of the breakdown strength, denoted by E_b, is utilized to evaluate the breakdown properties of insulating samples. How frequency affects material breakdown strength is seen in Fig. 7. The breakdown strength of DMD and Nomex sheets noticeably decreases at high frequencies with increasing frequency. The drop in E_b at frequencies greater than 10 kHz is particularly noticeable, where it takes on a more negligible value. Fig.7 illustrates how increasing frequency reduces breakdown field strength. When the frequency is raised from 1 kHz to 20 kHz, the breakdown field strength of the dielectric decreases to 36.5~54%. High-frequency signals can increase dielectric internal discharge activity. Heat generation exceeds heat dissipation in a short time due to dielectric loss, and its temperature rises. As a result, field-strength thermal breakdowns are more likely.

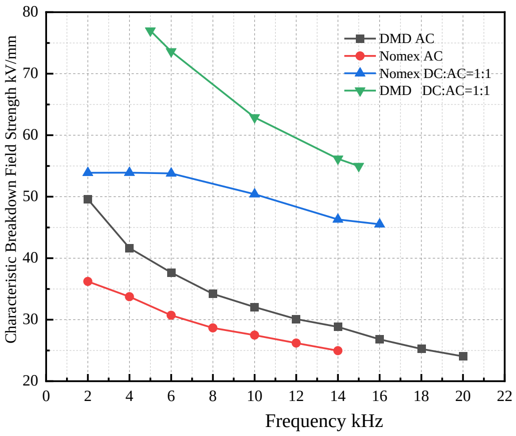


Fig.7. Relation between characteristic breakdown field strength and frequency

Fig.8. displays the results of an investigation into the form parameter of the DMD AC, the DMD DC: AC, the Nomex AC, and the Nomex DC: AC under various frequency settings. How packed or dispersed a distribution's data points are may be determined by a metric called its "shape.". It shows how the data points are distributed. It has been noticed that the form parameter for the DMD AC diminishes as the frequency is increased above 15 kHz and that it drops below 25 when the frequency reaches 16 kHz. This would imply that the data spread would stabilize as the frequency increased. To

put it another way, when the frequency increases, there is a tendency for the data points to cluster more tightly together, which indicates a narrower dispersion in the values.

Similarly, the DMD DC: AC exhibits a similar phenomenon to the DMD AC, where increasing frequency stabilizes data dispersion. As the frequency increases, the shape parameter decreases, indicating a more concentrated distribution of data points. In contrast, the behavior of Nomex AC and Nomex DC: AC differs. Here, the phenomenon shows an increase in the shape parameter with frequency. In other words, the data points exhibit a more comprehensive range of values and are more dispersed across the distribution.

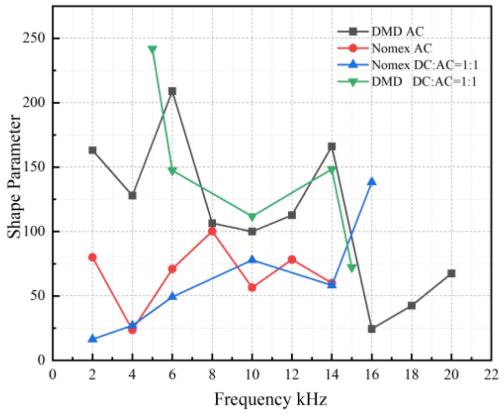


Fig.8. The correlation between shape parameters and frequency conditions.

The analysis suggests that the frequency and data dispersion relationship varies depending on the material and measurement type. The DMD AC and DMD DC: AC show a trend of decreasing dispersion with increasing frequency, indicating more stable data patterns. On the other hand, the Nomex AC and Nomex DC: AC exhibit an increasing dispersion with frequency, suggesting a more comprehensive range of values and less stability in the data patterns.

IV. CONCLUSION

The DMD and Nomex papers were chosen as the samples to study breakdown in this paper. Characteristics under a uniform electric field of repetitive frequency bipolar square wave voltage. The results can be summarized as follows;

1) The high-frequency thermal effect is the main reason for the drop in breakdown voltage and solid insulation materials' shortening lifetime.
2) When the frequency is raised from 1 to 20 kHz, the characteristic values of the breakdown voltage of the two insulation materials drop to 40.54 ~ 53.76% of the original values. By analyzing the equivalent physical model of solid dielectric thermal breakdown, it is found that the thermal breakdown voltage is mainly affected by the frequency of the electric field, the dielectric constant, the dielectric loss factor, and the difference between the internal and ambient temperature of the dielectric.
3) The high-frequency thermal effect is the leading cause of the breakdown voltage decline and long-term insulation life reduction. Under the high-frequency square waveforms, the long-term accumulation of heat and the increase of the electric field unevenness together cause the breakdown voltage to exhibit a non-linear variation with the thickness.
4) The low-field/high-frequency or high-field/low-frequency zones should be considered while designing insulation. Future studies should focus on more detailed breakdown characteristics within wide ranges of frequencies and temperatures. For assistance in the design of high-power, high-frequency transformers, it is also required to investigate the breakdown mechanism and insulating structure.
5) The reduction of "hot electrons" is attributed to the increase of E_b below the Tg, which should be investigated further in future research.

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REFERENCE

[1] W. Wang, X. Wang, J. He, Y. Liu, S. Li and Y. Nie, "Electric stress and dielectric breakdown characteristics under high-frequency voltages with multi-harmonics in a solid-state transformer," International Journal of Electrical Power & Energy Systems, vol. 129, July 2021.
[2] J.W. Kolar and G. Ortiz, "Solid-state-transformers: Key components of future traction and smart grid systems," Proceedings of the International Power Electronics Conference - ECCE Asia (IPEC 2014), pp. 1–14, May 2014.
[3] J. E. Huber and J. W. Kolar, "Optimum Number of Cascaded Cells for High-Power Medium-Voltage AC–DC Converters," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 5, no. 1, pp. 213-232, March 2017.
[4] P. Wang, J. Wang, H. Xu, K. Zhou, Y. Lei, and Q. Zhou, “Comparative Study of PD Characteristics for Inverter-fed Motor Insulation under Sinusoidal and Repetitive Square,” 2022 IEEE 4th International Conference on Dielectrics (ICD), 2022. 8
[5] N. Phloymuk, A. Pruksanubal and N. Tanthanuch, “DC Breakdown Voltage of Solid Dielectric Barrier under Non-Uniform Electric Field,” 2013 IEEE Annual Report Conference on Electrical Insulation and Dielectric Phenomena, 2013, pp. 834-837
[6] W. Wang and S. Li, "Research status and development of insulation breakdown in engineering solid dielectrics," Chinese Science Bulletin, vol.65, no. 31, pp. 3461-3474, Feb.
[7] C. Chauvet and C. Laurent, “Weibull statistics in short-term dielectric breakdown of thin polyethylene films,” IEEE Trans. Dielectr. Electr. Insul, vol. 28, no. 1, pp. 18–29, Feb. 1993.
[8] Guide for the statistical analysis of electrical insulation breakdown data, IEC 60539: 2007.
[9] W. yin and D. Schweickart, “Dielectric Breakdown of Polymeric Insulation Films Under AC, DC and Pulsed Voltages,” 2009 IEEE Electrical Insulation Conference, Montreal, QC, Canada, 31 May - 3 June 2009, pp. 292-296.
[10] W. Pfeiffer, “High-frequency voltage stress of insulation. Method of testing,” IEEE Trans. Dielectr. Electr. Insul., vol. 26, no. 2, pp. 239–246, April. 1991.
[11] Tapan Kumar Saha and Prithwiraj Purkait, Transformer Insulation Materials and Ageing, Wiley-IEEE Press, 2017.
[12] C. Chauvet and C. Laurent, “Weibull statistics in short-term dielectric breakdown of thin polyethylene films,” IEEE Trans. Dielectr. Electr. Insul, vol. 28, no. 1, pp. 18–29, Feb. 1993.
[13] Guide for the statistical analysis of electrical insulation breakdown data, IEC 60539: 2007.