Effect of Temperature on PD Characteristics Under Nanosecond Pulses

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Abstract. Protecting inverter-fed motor insulation system from failure of inverter overvoltage is nowadays of paramount interest in the fields of electric vehicles (EVs), especially when the insulation structure undergoes partial discharge (PD) and electrical-thermal aging. In this work, the effect of temperature on the PD characteristics of insulating paper of inverter-fed motor slot is investigated with bipolar repetitive pulses. The PD spectra with different temperature are plotted. The distribution of surface charges will change with the growth of temperature. As a result, the distribution of electric field and generating probability of initial electrons are affected accordingly. Besides, to verify the experimental results, numerical simulations of PD characteristics are studied. The distribution of electric field and density of electrons are obtained. These results can provide valuable information for the study of PD characteristics of insulation systems in inverter-fed motor.

Keywords: partial discharge · space charge · temperature · modeling

1 Introduction

The booming development of EVs is one of the most effective paths to solve the global energy crisis and mitigate environmental degradation. However, safety remains to be overcome in EVs. For instance, the pulse width modulation (PWM) technology used in EVs leads to drive motors being subjected to overvoltage during the operation. Furthermore, the abrasion on the insulation structure of motor stator wingding during the operation leads to air gaps between the stator core and insulation layer. As a result, the probability of PD occurrence grows. The drive motor suffers from the PD erosion for several years [1], which will destroy the insulation performance and threaten the safety and stability of EVs [2]. The Nomex type 410 insulating paper has high dielectric strength, heatproof and mechanical properties, which is widely used in the slot insulation of motor stator windings [3]. Therefore, the investigation of its insulation durability is essential for assessing the safety level of the entire motor insulation system.

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Vast researches have already been conducted on PD erosion to investigate its degradation behavior on the insulation materials. The aging phenomenon and discharging mechanism of the rotating machines under nanosecond pulse were analyzed by Wang. The influence of voltage frequencies, duty cycles and rise times on the PD characteristics were discussed [4, 5]. Wu conducted accelerated thermal aging experiments on Nomex insulating paper, and investigated the characteristics of material surface charges accumulation and dissipation after charges injected into the insulating paper at different aging cycles [6]. Illisa established a physical model of PD activity of the void inside the cable [7]. The PD physical phenomenon of the inhomogeneous electric field inside the void was simulated with finite element method. The distribution of surface charges and electric field were obtained. Nevertheless, few studies have been conducted to report the statistical characteristics of PD of insulating materials and the distribution of electric field energy under temperature promotion.

In this paper, a PD test system under nanosecond pulse voltage is built, and the effect of temperature on PD characteristics of Nomex type 410 insulation paper is analyzed. The PD signals and activities are studied with experimental diagnosis. Besides, the process of PD of Nomex type 410 insulation paper is simulated with the Parallel Streamer Solver with Kinetics (PASSKEy) [8]. The distribution of electric field and density of electrons are obtained.

2 Experimental and Modeling Parameters

There are two sections. In the first section, a PD test system is built. PD experiments are conducted under different temperatures to extract and analyze the PD signals. In the second section, the simulation model and parameters of PD activities at different temperatures with the actual experimental conditions are introduced.

2.1 PD Test System

The PD test system is shown in Fig. 1, which mainly consists of the nanosecond impulse power supply, ultra-high frequency antenna, high voltage probe, oscilloscope, and the

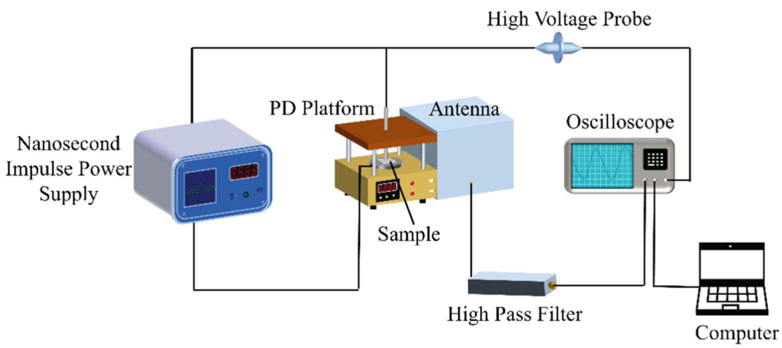

Fig. 1. Schematic of the PD test system.

heating platform. The test sample is selected for the DuPont Nomex type 410 paper, and the dimension of the samples is 20 × 20 × 0.18 mm. Before the experiment, the samples are cleaned with anhydrous ethanol and dried with ionizing air blower. Finally, the samples are divided into four groups and subjected to two hours of discharge treatment at 50 °C, 100 °C, 150 °C and 200 °C, respectively. The applied voltage used in the experiment is the bipolar repetitive pulses with the peak-to-peak value of 2.6 kV.

2.2 Simulation Modeling

A PASSKEy code [9] is used for the PD simulation under nanosecond pulses, which can be designed to calculate the electric field and hydrodynamic space time evolution process in gas discharge plasma containing complex chemical reactions. The Poisson's equation is used to obtain the distribution of electric field. Besides, the chemical kinetic equation is solved to simulate the process of discharge. In our model, 38 reactions and 18 substances are involved. The particles considered in simulation are e, N_2, O_2, O^-, etc. The scheme of simulation model is shown in Fig. 2. The sample size is set to 20 × 20 × 0.18 mm, and the diameter of the driven electrode is 8 mm. The pulse voltage is applied on the driven electrode area, which equals to ± 1.3 kV. Simulation experiments are carried out at one atmospheric pressure, and the gas discharge temperatures are set to 50 °C, 100 °C, 150 °C and 200 °C, respectively.

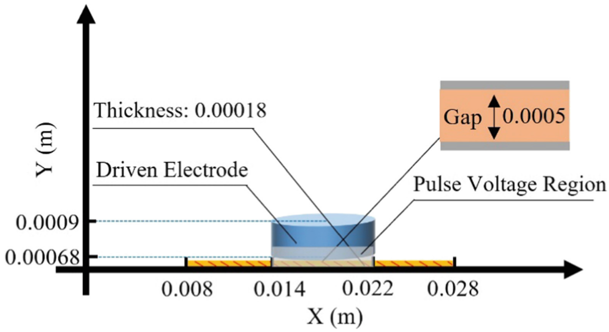

Fig. 2. The scheme of simulation model.

3 Results and Discussion

3.1 Effect of Temperature on PD Features Under Nanosecond Pulse Voltage

The Phase Resolved Partial Discharge (PRPD) patterns for 2 h at different temperatures are shown in Fig. 3. The red points in the Fig. 3 represent the maximum magnitude of PD at a moment. The PD signal is mainly concentrated at the rising edge of the nanosecond pulse voltage, the maximum magnitude increases with increase of temperature. Besides, the phase decreases with increase of temperature. There is no obvious variation in the PD amplitude at 150 °C and 200 °C.

The temperature affects the cumulative effect of the surface charges of the insulation materials [10], and the accumulation of more anisotropic charges is prone to form a strong distortion of electric field at the insulation air gap for PD [11]. According to the Richardson-Schottky law, the increase of temperature makes it more likely to excite the initial electrons generated by PD, resulting in the decrease of Partial Discharge Inception Voltage (PDIV). Thus, the PD is prone to occur, and the phase decreases.

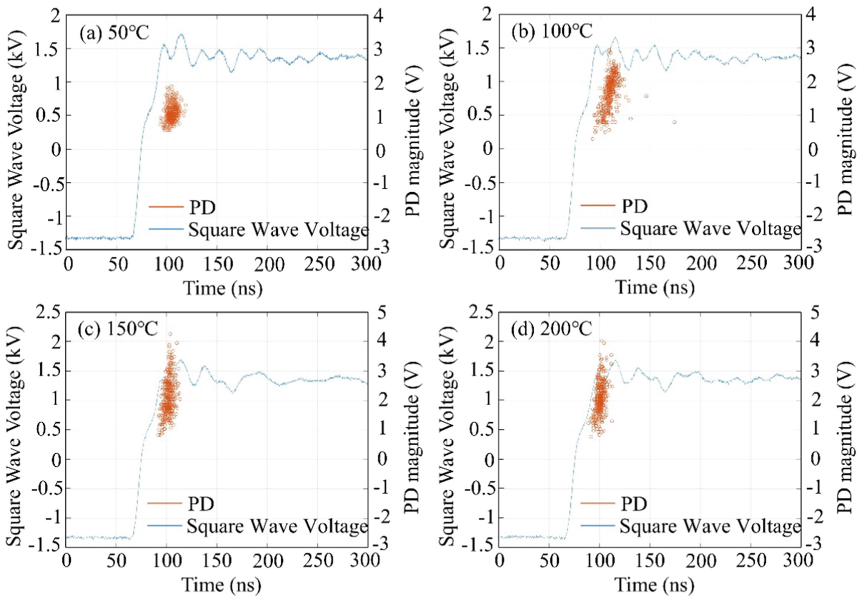

Fig. 3. PRPD patterns under different temperatures.

Moreover, it is clear that increasing temperature means more active PD activity, as shown in Fig. 4. The superposition of multiple PD magnitudes leads to increasing magnitudes of PD. However, the excessive temperature will increase the conductivity of the material surface, which makes the accumulated charges diffusion and inhibits the occurrence of PD. Therefore, the PD magnitude does not increase further at 200 °C.

3.2 Effect of Temperature on Simulated Electric Field Activity

The distribution of electric field at the same moment for different temperatures is calculated by the simulation, as shown in Fig. 5. And the discharge area is shown in Fig. 2. The bipolar repetitive pulses are applied to the drive electrode, and the discharge process occurs in the gap between the drive electrode and the Nomex type 410 insulating paper.

The region with high strength of electric field at low temperature is concentrated near the left and right tips of the electrodes, as illustrated in Fig. 5. However, with the growth of temperature, the region with high strength of electric field is uniformly distributed on the material surface. The density of electrons is shown in Fig. 6. The density of electrons

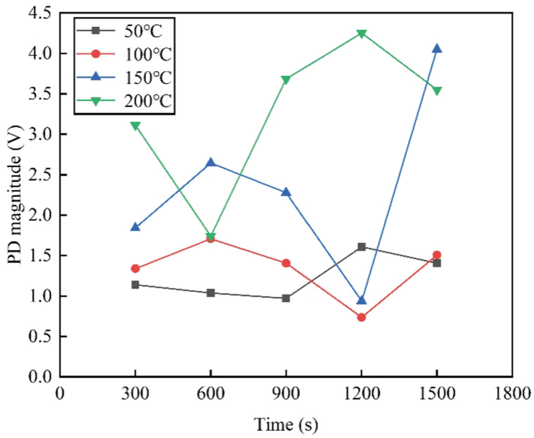

Fig. 4. Changes in the maximum magnitude of PD with aging time.

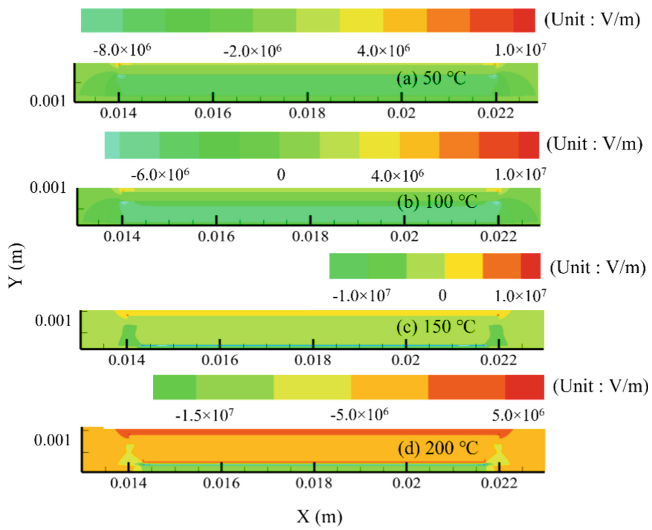

Fig. 5. Distribution of electric field at different temperatures.

multiplies for a shorter time at high temperatures and accumulates around the surface of the sample. When the temperature is 50 °C, the density of electrons accumulates almost near the electrode. Thus, higher temperatures imply more active electrons activities on the material surface [12], and the corresponding Fig. 7 reflects the same trend from the energy of electrons perspective. The high energy region means the region with high density of electrons. The high collision frequency of electrons reduces the PDIV and shortens the PD statistical delay. Eventually, PD at higher temperature is more prone to occur and is repeated with the increase of collision frequency.

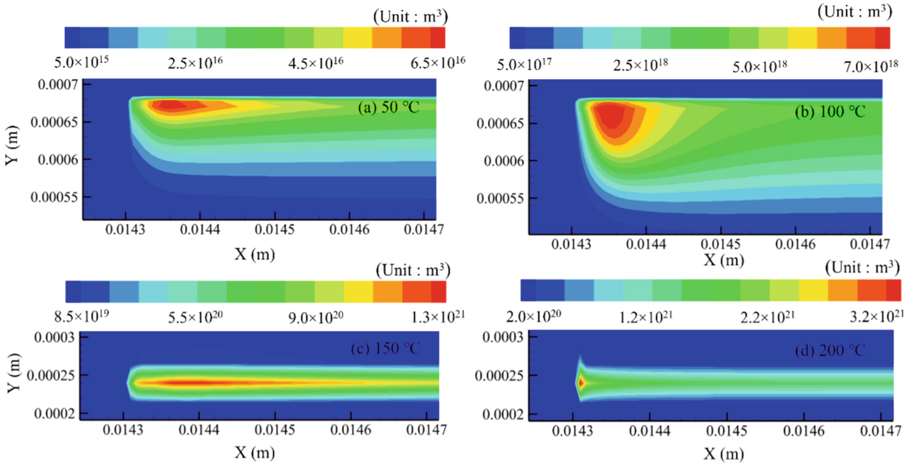

Fig. 6. Distribution of density of electrons at different temperatures.

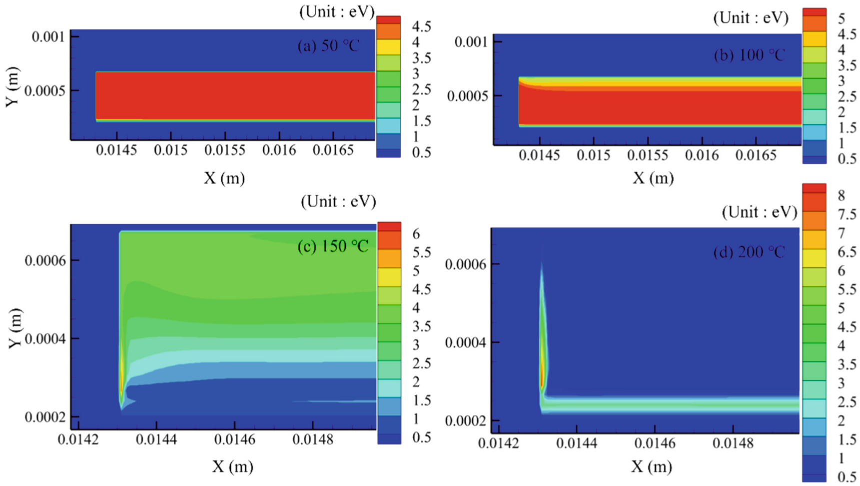

Fig. 7. Distribution of energy of electrons at different temperatures.

4 Conclusion

The effect of temperature on PD characteristics is investigated by Nomex insulating paper for drive motor. With the increase of temperature, the amplitude of PD increases and the phase of PD decreases. The PD behavior is more active at higher temperature. The experimental results are in good agreements with the simulation results. The higher temperature is more conducive to the formation of stable electric field with high strength and the multiplication of higher density of electrons. At the same time, the ratio of electrons with high energy increases, which has a facilitating effect on PD activity. Furthermore, the experimental and simulation results proposed in this paper can be expected to be applied in the artificial intelligence based on big data analysis, environmental protection, exhaust gas disposal technology, which have social impact and humanity influence.

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