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Study on Development Characteristics of Partial Discharge in Oil-Pressboard Insulation under Constant DC Voltage

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Abstract: The converter transformer is the core equipment of HVDC transmission system, the valve-side winding of which needs to withstand DC voltage. Partial discharge is one of the main threats to the safe operation of converter transformer, yet the characteristics of partial discharge development of the oil-pressboard insulations under constant DC voltage are insufficiently understood. In order to better understand the partial discharge characteristics of the oil-pressboard insulation under DC voltage and provide deeper theoretical support for insulation diagnosis of converter transformers, development characteristics including the time-varying tendency of discharge magnitude and repetition rate of partial discharge in oil-pressboard insulation under constant positive and negative DC voltage were studied. The results indicate that the development of partial discharge in a needle-plane oil-pressboard insulation model under constant DC voltage has three stages: the intensive discharging stage, the silent-burst stage, and the breakdown stage. Throughout all stages, the partial discharge magnitude and repetition rate first decrease and increase afterwards. At the silent-burst stage, the partial discharge appears in the form of a "cluster" with very large magnitude and repetition rate. Each cluster exists for tens of seconds but with at a very long interval with each other. Further analysis shows that the repeated accumulation and dissipation of free charges on the surface of the pressboard cause the above phenomena. Negative charges are easy to accumulate and difficult to dissipate under the same voltage amplitude compared to positive charges, leading to a weaker actual electric field at the needle tip and thus partial discharges under negative DC voltage with a lower magnitude and longer interval.

Keywords: oil-pressboard insulation; partial discharge; DC voltage

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1. Introduction

The converter transformer is the core equipment of an HVDC transmission system. Different from the traditional power frequency transformer, the oil-pressboard insulation of the valve side winding within the converter transformer needs to withstand the DC voltage [1,2]. The actual operation experience shows that the partial discharge of the oil-pressboard insulation under DC voltage is one of the main causes that affect the safe operation of the converter transformer [3–5]. Therefore, it is of great significance to study the partial discharge characteristics of oil-pressboard insulation under DC voltage, both for optimizing the insulation structure design of valve side winding and ensuring the safe operation of converter transformer.

At present, research on partial discharge in oil-pressboard insulation under DC voltage has been carried out at home and abroad. For example, Yang studied the development process of DC partial discharge in needle-plane oil-pressboard insulation and divided the discharge development into four stages based on discharge magnitude and repetition rate (number of partial discharges in a certain time interval) [6]. Nie also studied the development of DC partial discharge in oil-pressboard insulation and divided the discharge development process into four periods: "initial period", "middle period", "end period", and "critical breakdown". In the initial period, the discharge develops slowly, mainly with a large magnitude and low repetition rate. In the middle and the end period, the magnitude of discharges is mainly low, and the discharge interval is evenly distributed. In the critical breakdown period, the discharge interval is concentrated, and it is easy to form intensive discharge clusters [7]. Morshuis studied the partial discharge development process of the oil-pressboard insulation of a DC cable and also divided the discharge development into stages according to the change law of discharge magnitude and the number of discharges [8]. Although the above scholars seem to have reached a consensus on the research conclusion, previous research on the development of DC partial discharge mostly used the step-up voltage method. With the change of experimental time, the applied voltage amplitude is different, which will lead to the discharge phenomenon of different voltage stages not being comparable.

Fromm studied the relationship between the DC partial discharge magnitude and the amplitude of the applied voltage in needle-plane oil-pressboard insulation and found that with the increase of the amplitude of the applied voltage, the discharge magnitude increased in power function [9]. Okabe produced a partial discharge in oil with different magnitudes by changing the amplitude of the applied voltage [10]. The above research results indicate that the applied voltage amplitude does affect the DC partial discharge magnitude and repetition rate. The higher the voltage amplitude, the more severe the DC partial discharge in the oil-pressboard insulation. The experimental results under different voltage amplitudes are not comparable. In contrast, the partial discharge experiment of the oil-pressboard insulation under constant DC voltage can better simulate the actual working conditions in the converter transformer [11]. Meanwhile, partial discharge of oil-pressboard insulation under constant DC voltage has the characteristics of "silent" and "burst"; namely, the discharge will stop for a period of time and then suddenly burst, which has not been deeply recognized and understood [12,13]. Therefore, it is of practical significance to study the development of partial discharge in oil-pressboard insulation under constant DC voltage for understanding the mechanism of insulation failure and exploring the mechanism of DC partial discharge.

In this paper, the development process of partial discharge in oil-pressboard insulation under constant positive and negative DC voltage is studied. The time-varying tendency of discharge magnitude and repetition rate was investigated from the beginning of the partial discharge to the breakdown of oil-pressboard insulation in the whole life cycle, as shown in Section 3.1 and 3.2. Moreover, the distribution of discharge magnitude was counted and analyzed. On this basis, the characteristics of "silent" and "burst" in the development of partial discharge are proposed, and the mechanism of such phenomenon is explained from the point of the surface charge distribution of the pressboard in Section 4.

2. Experimental Descriptions

In order to study the development characteristics of partial discharge in oil-pressboard insulation under DC voltage, the experimental platform shown in Figure 1 was adopted, which mainly includes the DC voltage source, the partial discharge measurement system, and the oil-pressboard experimental sample. The DC voltage was generated by the voltage doubling circuit with the maximum output of ±140 kV and a ripple factor less than 2%. The partial discharge measurement system includes a resistance voltage divider (10,080:1) and a high-frequency current transformer (HFCT, sensitivity 1 pC, output impedance 50 Ω, bandwidth 150 kHz~80 MHz). The high-frequency response time of the HFCT was about 4.4 ns, fully capable to measure partial discharge pulses in oil [6,14,15]. The apparent charge/magnitude ratio of the discharge pulse was 2.12 pC/mV. The minimum partial discharge pulse that the system can measure is 10 pC. Partial discharges collected by the HFCT were transmitted to Techimp PD Check via a coaxial cable for further statistical analysis. The oil-pressboard sample was a needle-plane model marked as 3 in Figure 1, with a radius of the needle tip of 0.5 mm, an oil gap between the needle tip and the pressboard of 5 mm, and a radius of the plane electrode of 40 mm.

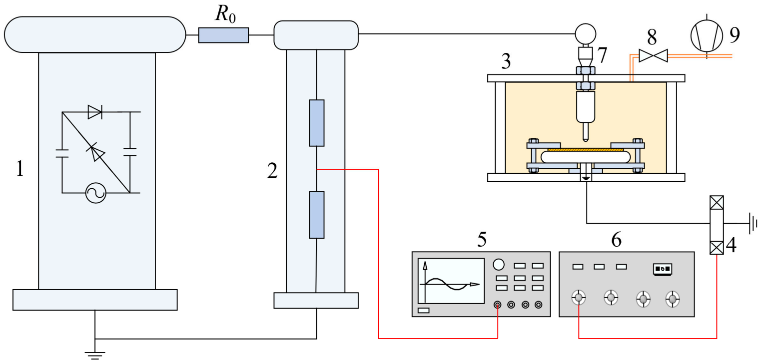


Figure 1. 1—DC voltage source 2—Resistance voltage divider 3—Experimental sample 4—High-frequency current transformer 5—Oscilloscope 6—Techimp PD Check 7—Micrometer 8—Valve 9—Vacuum pump. Oil-pressboard composite insulation DC partial discharge test platform.

Kunlun #25 transformer oil was adopted as the oil sample in the experiment. Prior to the experiment, the oil was vacuum-dried in the oven (24 h, 80 °C, 1000 Pa). After drying, we adopted Karl Fischer titration to make sure its water content was less than 20 ppm. The titration results are shown in Figure 2. Under this water content, the DC breakdown voltage of the oil was higher than 70 kV/2.5 mm, based on IEC 156: 1995. For the pressboard sample, Jinsong B3.1 pressboard was used. The thickness, density, and relative dielectric constant of the sample are 0.5 mm, 1.1 g/cm^3, and 4.2, respectively. Prior to the experiment, the sample was cut into a 100 mm × 100 mm square and dried in the oven (24 h, 60 °C, 1000 Pa). Afterwards, the sample was placed in the experimental chamber for oil impregnation at 200 Pa for 24 h.

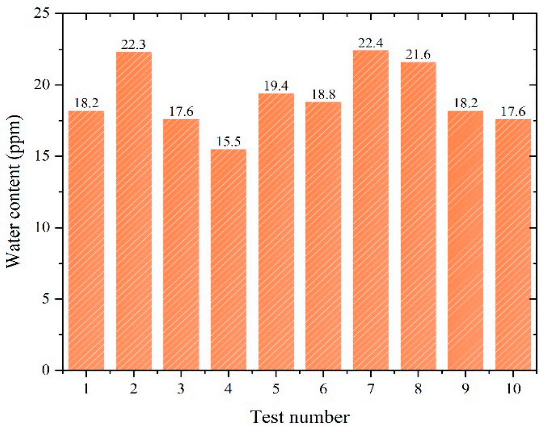


Figure 2. Water content results of 10 repetitions of Karl Fischer titration of the dried oil.

Constant DC voltage was applied to the samples to study the development of partial discharge. The pre-experimental results show that the inception voltage of positive and negative DC partial discharge of the sample was +19 kV and −27 kV, respectively. When the applied voltages were +76 kV and −88 kV, the pressboard would break down after fewer than 10 repetitions of partial discharges. Therefore, the voltage amplitudes adopted in the following experiment were chosen between the two values, namely ±35 kV, ±40 kV, ±45 kV, and ±50 kV, respectively. Under the above amplitudes, partial discharge in the sample can last for hundreds of minutes, which meets the measurement and analysis needs.

3. Experimental Results

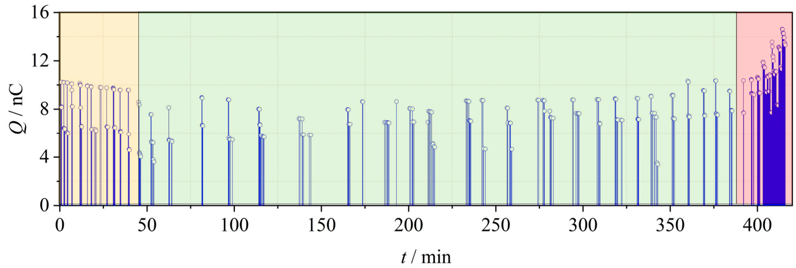
In this section, the time-varying tendency of discharge magnitude and repetition rate is investigated from the beginning of partial discharge to the breakdown of the oil-pressboard insulation in the whole life cycle. The distribution of discharge magnitude is counted and analyzed.

3.1. Partial Discharge Development Process under Positive DC Voltage

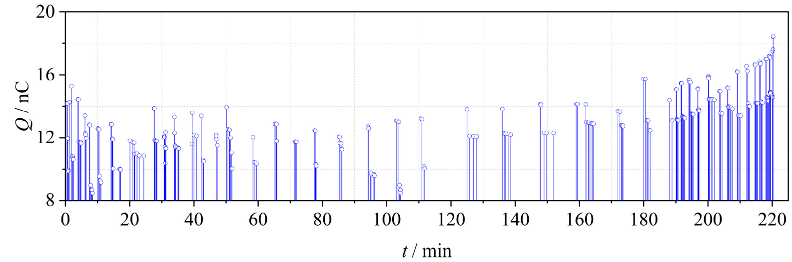
The development of partial discharge in oil-pressboard insulation under positive DC voltage was studied at +35 kV, +40 kV, +45 kV, and +50 kV, respectively. Under each amplitude, 10 experiments were carried out. The results indicated the development process of partial discharge under each amplitude exhibited similar tendencies; therefore, only one of the ten results is presented.

3.1.1. *Q-t* Spectrum

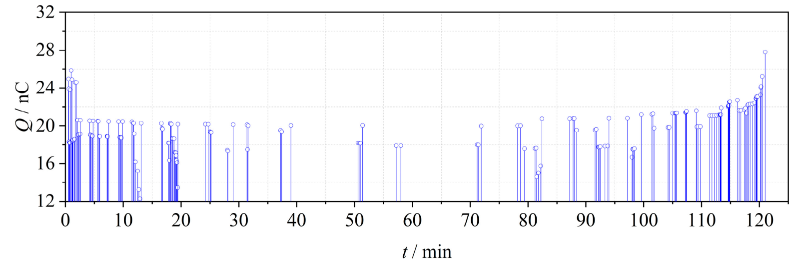
All the discharge pulses detected in a complete experiment were sorted by time, and the *Q-t* spectrum of the partial discharge development process was obtained, as shown in Figure 3. With the increase of the applied voltage, the total values of partial discharge and the time needed for insulation failure were significantly reduced. Under the same applied voltage, the discharge magnitude decreased first and increased afterwards. By comparing the experimental results under four voltages, it was found that the development of partial discharge can be divided into three stages. Taking the results under +35 kV as an example, the details of each stage are explained.



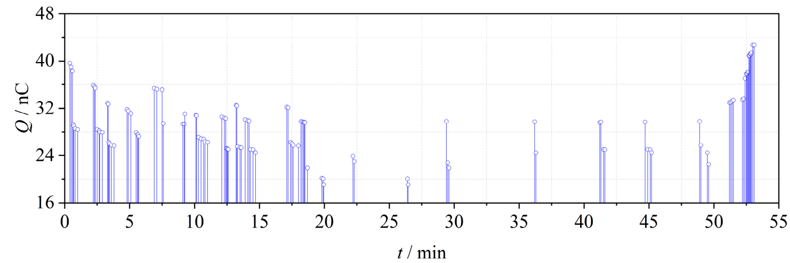
(**a**) +35 kV



(**b**) +40 kV



(**c**) +45 kV



(**d**) +50 kV

Figure 3. *Q-t* spectrum of partial discharges in oil-pressboard sample under +DC voltage.

(1) Intensive discharging stage

Corresponding to the orange region in Figure 3a, this stage occurred at the beginning of partial discharge development and had the following features: (1) The duration of this stage was short. In all four groups of experiments, the intensive discharging stages all ended within 30 min. The higher the applied voltage, the shorter the duration. (2) Partial discharges were more intensive and relatively concentrated in this stage compared with the stage that followed. However, the discharge repetition rate and the magnitude all decreased with time, exhibiting a "silent" trend, until the next silent-burst stage.

(2) Silent-burst stage

Corresponding to the green region in Figure 3a, this stage occurred after the intensive discharging with the following features: (1) The duration of this stage was the longest (hundreds of minutes) compared with the other two stages, which accounted for more than 70% of the total experimental time. Similarly, the higher the applied voltage, the shorter the duration of this stage. (2) Partial discharges in this stage occurred suddenly, with many pulses in a very short time, which appeared as a "cluster" on the *Q*-*t* spectrum. Between each cluster, no discharges were detected. This interval could reach tens of minutes. At the end of the silent-burst stage, the density of the cluster became higher, leading to the next breakdown stage.

(3) Breakdown stage

Corresponding to the red region in Figure 3a, this stage occurred after the silent-burst stage with the corresponding features: (1) The duration of this stage was the shortest, only lasting for 10 min to 30 min. (2) Partial discharges in this stage were very intensive. The discharge magnitude and the repetition rate all increased significantly with the experimental time. In this stage, the time interval of partial discharges was very short, and even more than 10 pulses occurred within 1 min. Total breakdown of the oil-impregnated pressboard signified the end of this stage.

3.1.2. ΔN-t Spectrum

On the basis of *Q*-*t* spectrum, the tendency of the discharge repetition rate ΔN was analyzed. The results are shown in Figure 4. The red curve in the figure is the approximate upper envelope of ΔN.

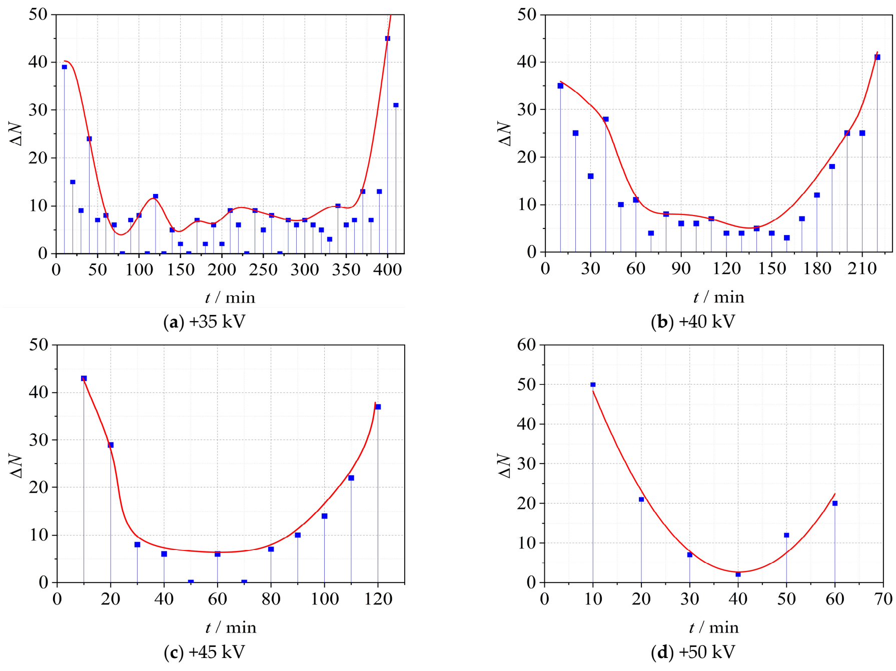


Figure 4. ΔN-t spectrum of partial discharges in oil-pressboard sample under +DC voltage.

Corresponding to the three stages of partial discharge development, Δ*N* also shows a three-stage variation. In the intensive discharging stage, Δ*N* decreased with time. The longer the DC voltage was applied, the fewer pulses were counted. In the silent-burst stage, the discharge repetition rate was very low but relatively stable. In the breakdown stage, Δ*N* increased rapidly. Partial discharges with large magnitude occurred intensively until the breakdown of the insulation. Meanwhile, a significant positive correlation between Δ*N* and applied voltage amplitude *U* was also noticed. Taking the discharge in the first 30 min as an example, when the applied voltage was +35 kV, the average discharge repetition rate in the first 30 min was 2.1 times/10 min. When the applied voltage was increased to +50 kV, the average repetition rate in the last 30 min increased to 2.7 times/10 min.

3.1.3. Probability Distribution of Partial Discharge Magnitude

Taking 1000 pC as the unit, the partial discharge magnitude under each applied voltage was counted to obtain its distribution diagram, as shown in Figure 5. It can be seen that the magnitude approximately obeyed the Gauss distribution.

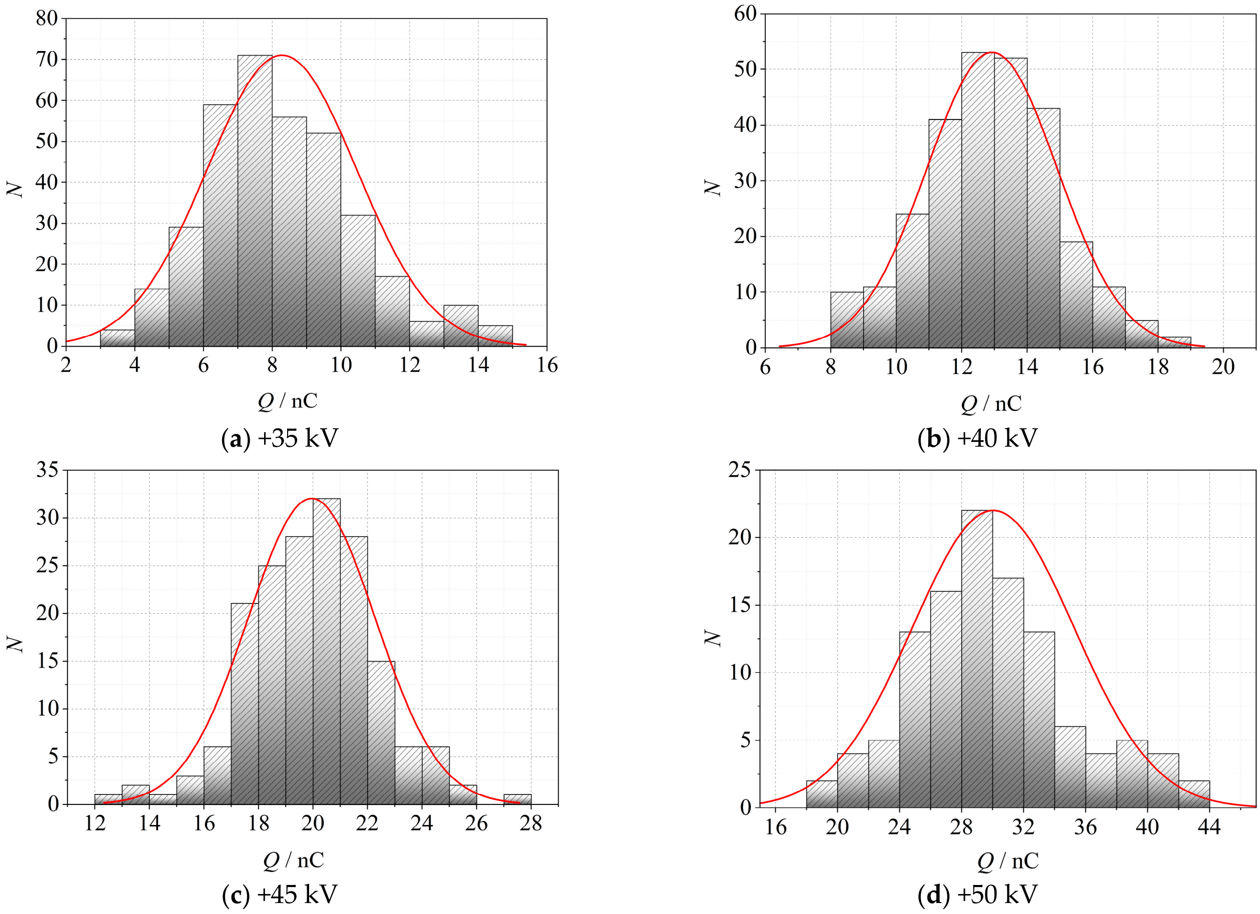


Figure 5. Distribution of partial discharge magnitude in oil-pressboard sample under +DC voltage.

Based on Figure 5, the distribution parameters in Table 1 can be obtained, which reflect the average and standard deviation of the discharge magnitude. It can be found that with the increase of the applied voltage, the average discharge magnitude increased significantly, while the standard deviation was maintained as constant. In order to obtain the quantitative relationship between the average discharge magnitude and the applied voltage amplitude, the data in Table 1 were plotted as Figure 6.

Table 1. Distribution parameters of partial discharges magnitude under +DC voltage.

Distribution Parameters	+U/kV			
	+35	**+40**	**+45**	**+50**
Q_{avg}/pC	7943.17	13,168.24	20,463.53	29,773.61
σQ/pC	2180.08	1992.05	2056.25	1978.14

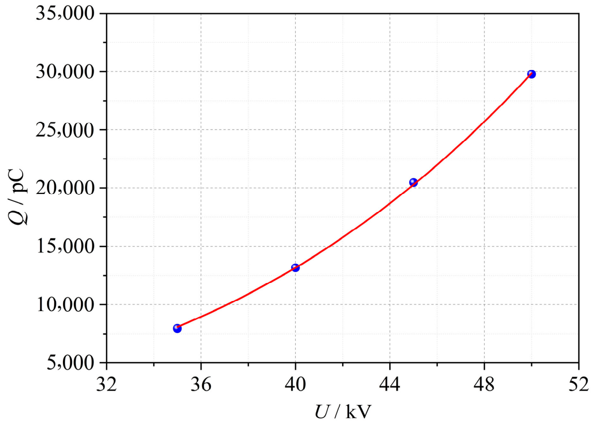


Figure 6. Average magnitude of partial discharges varied with the amplitude of +DC voltage.

According to the trend in Figure 6, the average magnitude of partial discharges and the amplitude of +DC voltage obey the power function relationship. Therefore, Equation (1) was adopted to fit the data:

$$Q_{avg} = 0.017U^{3.671} \quad (1)$$

In the above analysis, the partial discharge development of oil-pressboard insulation under positive DC voltage was studied from aspects of *Q-t* spectrum, Δ*N-t* spectrum, and probability distribution of partial discharge magnitude. It can be seen that there were three stages in the development of partial discharges under positive DC voltage. The discharge process showed obvious "silent" and "burst" characteristics.

3.2. Partial Discharge Development Process under Negative DC Voltage

The development of partial discharge in oil-pressboard insulation under negative DC voltage is studied in this section, the results of which are shown as follows.

3.2.1. *Q-t* Spectrum

The *Q-t* spectrum of partial discharge development under negative DC voltage is shown in Figure 7. Similar to the results under positive DC voltage, the partial discharge magnitude also changed regularly with the amplitude of the applied voltage. The development process also included three stages:

(1) Intensive discharging stage

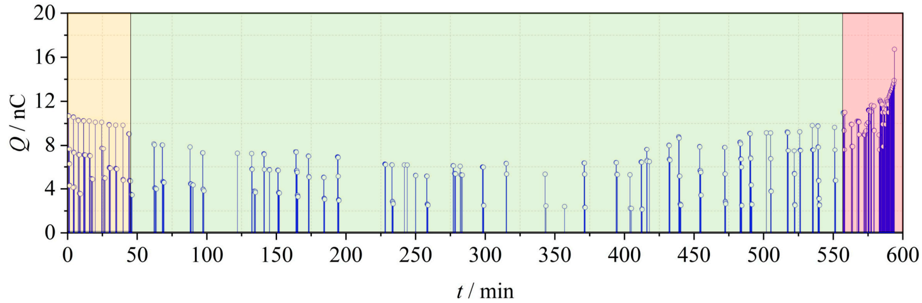
Corresponding to the orange region in Figure 7a, similar to the results in Section 3.1, the duration of this stage is short, with intensive discharges and a decreasing discharge magnitude. However, the number of partial discharges in this stage under negative DC voltage was generally smaller compared with that under positive voltage.

(2) Silent-burst stage

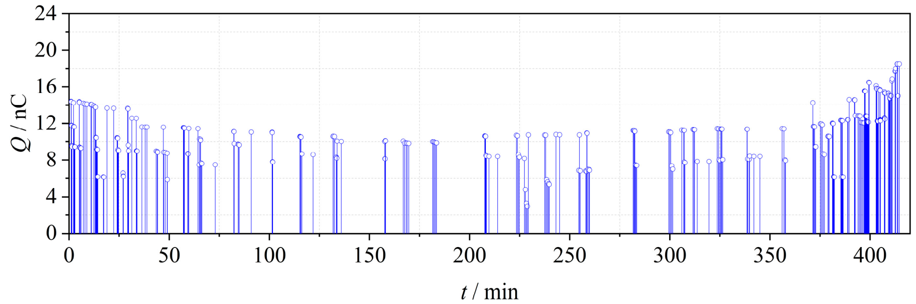
Corresponding to the green region in Figure 7a, this stage occurred at the middle period of the experiment. Compared with the intensive discharging stage, the silent-burst stage has a longer discharge interval and a lower discharge magnitude. Compared with the results under positive DC voltage, the partial discharge magnitude was lower. Similarly, the duration of this stage accounted for the vast majority of the total experimental time.

(3) Breakdown stage

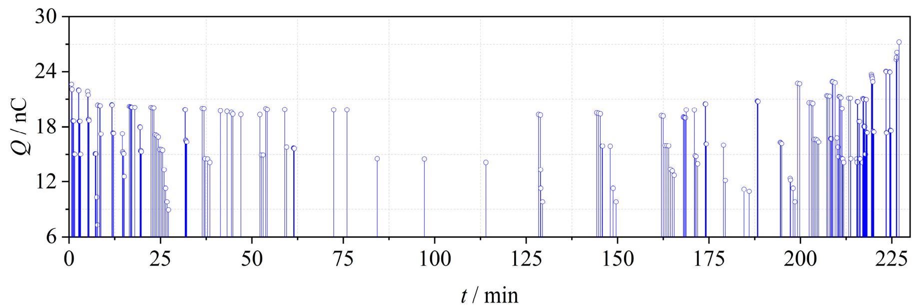
Corresponding to the red region in Figure 7a, the breakdown stage had the shortest duration time but the largest discharge magnitude and the most intensive discharge repetition rate. The number of low-magnitude discharges is significantly fewer than that of large magnitude ones. After tens of minutes of this stage, the pressboard broke down, representing the end point of the insulation.



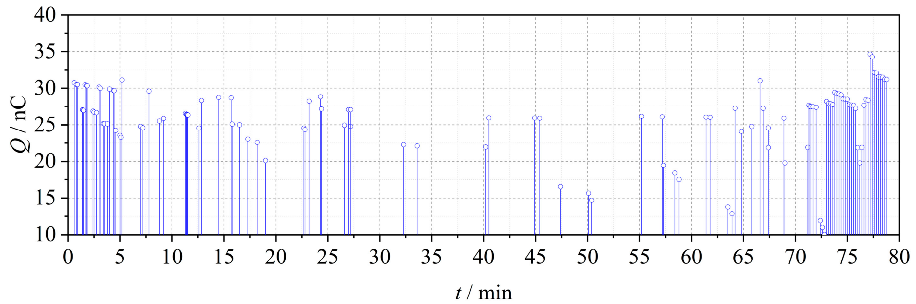
(**a**) −35 kV



(**b**) −40 kV



(**c**) −45 kV



(**d**) −50 kV

Figure 7. *Q*-*t* spectrum of partial discharges in oil-pressboard sample under −DC voltage.

Similarly, the development of partial discharges under negative DC voltage also exhibited three-stage characteristics, but compared with the results under positive voltage, the discharge magnitude under negative DC voltage was lower. The time required for insulation failure was longer, accompanied by more instances of partial discharges.

3.2.2. ΔN-*t* Spectrum

Figure 8 shows the relationship between the discharge repetition rate ΔN of the negative DC voltage with the voltage application time.

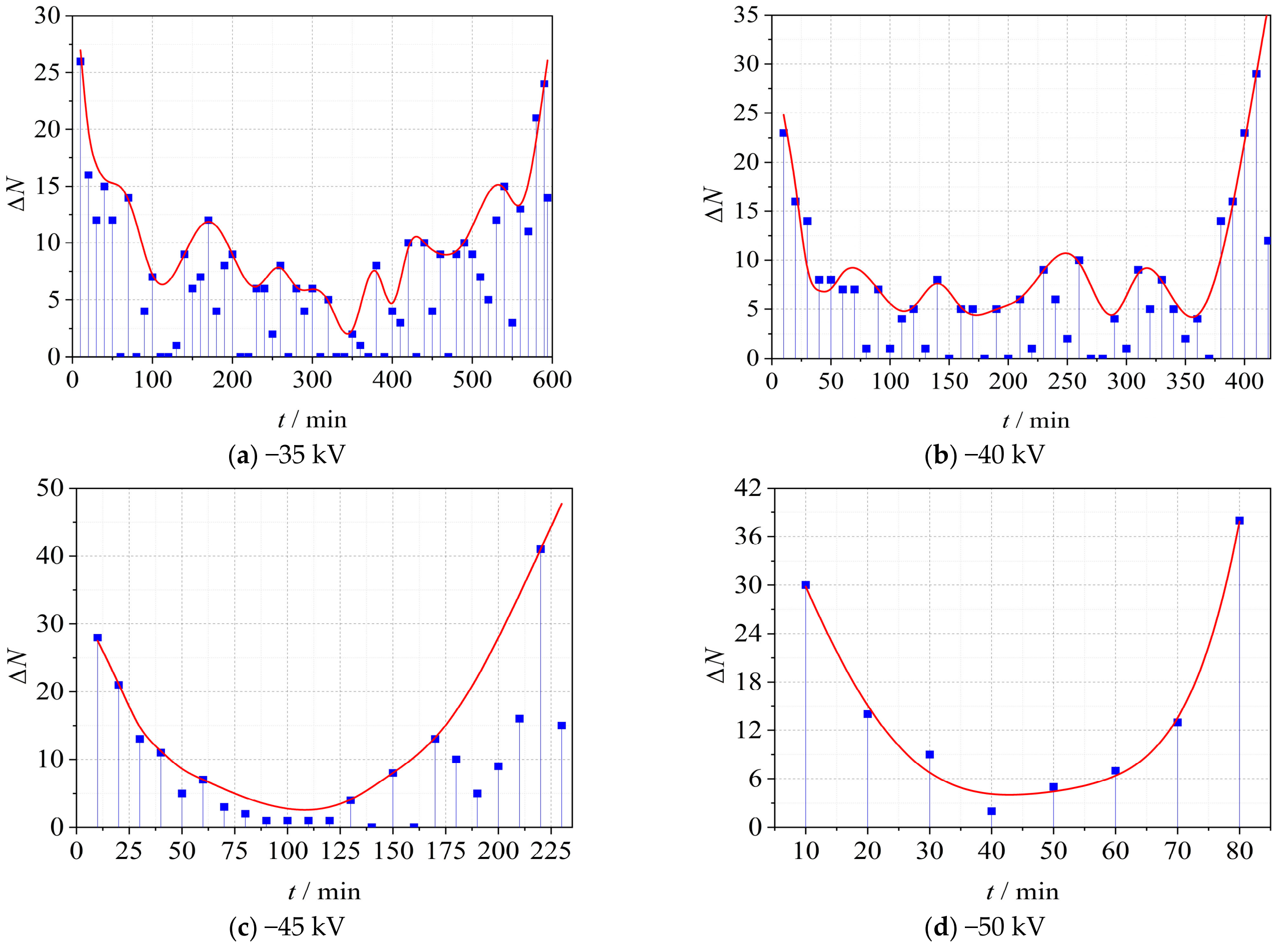


Figure 8. ΔN-*t* spectrum of partial discharges in oil-pressboard sample under −DC voltage.

The ΔN under negative DC voltage also showed a three-stage "U-shaped" variation, which proved that there was a similar mechanism for the development of partial discharge under the two polarities. However, it is worth noting that the ΔN under negative polarity is generally smaller compared with the results under the positive condition at the same discharge stage.

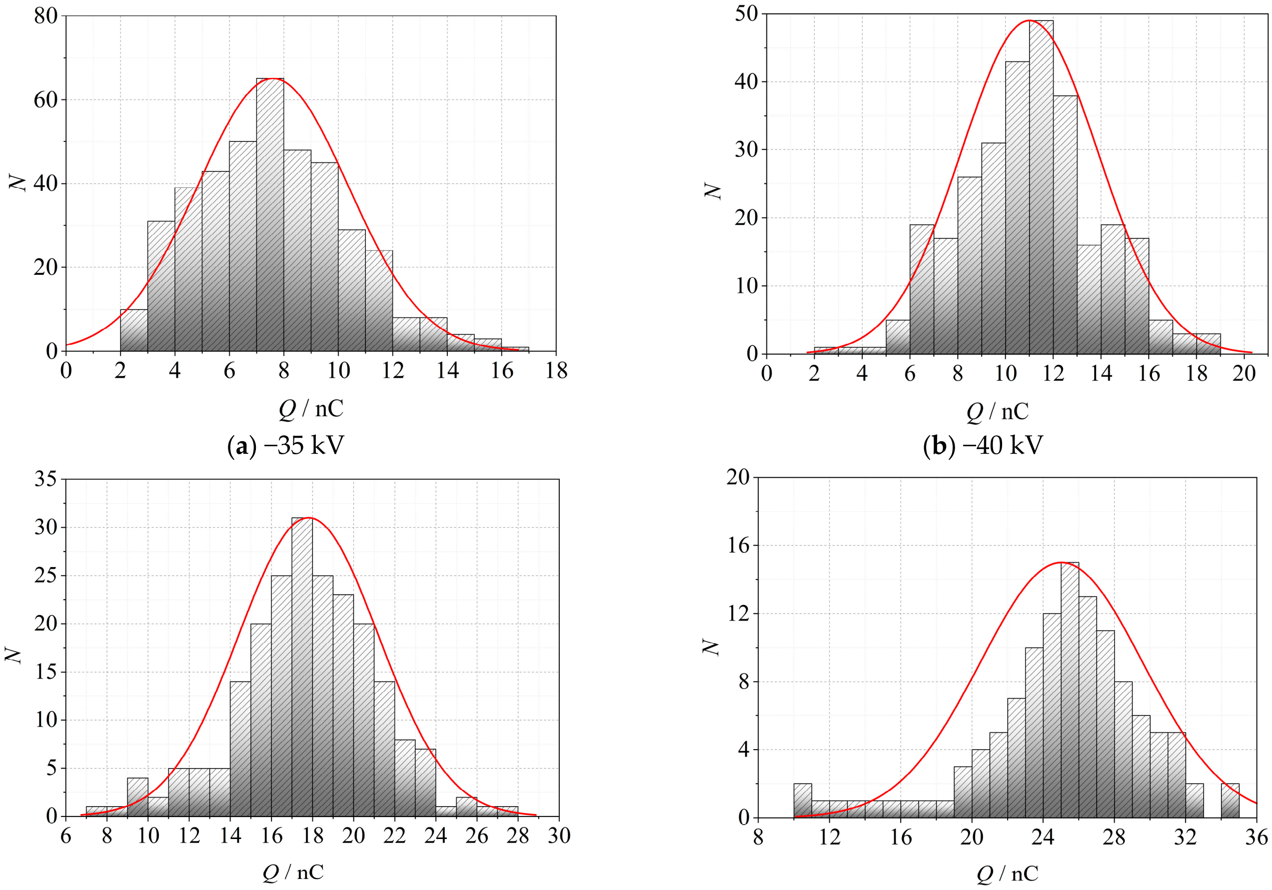
3.2.3. Probability Distribution of Partial Discharge

A statistical diagram of the partial discharge magnitude under negative DC voltage is shown in Figure 9, where an obvious Gauss distribution also exists. Table 2 calculates the distribution parameters, based on which similar equations between magnitude Q and the applied voltage amplitude U are derived, shown as Equation (2).

$$Q_{avg} = 0.010U^{3.791} \tag{2}$$

Table 2. Distribution parameters of partial discharges magnitude under −DC voltage.

Distribution Parameter	**−*U*/kV**			
	−35	**−40**	**−45**	**−50**
Q_{avg}/pC	7348.44	11,247.32	18,729.93	27,343.14
σQ/pC	3163.24	2941.34	3327.81	3012.33



(**a**) −35 kV (**b**) −40 kV (**c**) −45 kV (**d**) −50 kV

Figure 9. Distribution of partial discharge magnitude in oil-pressboard sample under −DC voltage.

Similarly, there is a power function relationship between the average discharge magnitude and the amplitude of the applied voltage. However, by comparing the experimental results under positive and negative polarity, it can be found that when the applied voltage amplitude is the same, the average discharge magnitude under negative DC voltage is lower and with larger dispersion.

4. Mechanism Analysis and Discussion

By comparing the experimental results in Section 3.1, it can be found that the partial discharge process under DC voltage is actually the alternate appearance of the "silent" and "burst" characteristics of discharges. The so-called "silent" factor refers to the period that the discharge magnitude and repetition rate decrease gradually, until no discharges occur in a long time. The so-called "burst" factor refers to the period that the partial discharge appears again in the form of "cluster" after a long time of silence, and its magnitude and repetition rate reach a very large value in a very short time. Because the duration of the "silent period" is different, and the "burst period" appears randomly, the overall partial discharge process under DC voltage appears disordered.

It is generally considered that the disorder of DC partial discharge is caused by the generation and extinction of space charges and surface charges [16,17]. At the intensive discharging stage, the discharge starts immediately as long as the applied electric field reaches sufficient strength. Although the discharge at this time is not strictly periodic, the interval time between two discharges is relatively short with low dispersion. However, as discharges continue, free charges begin to accumulate at the surface of the pressboard, which will change the discharging mode significantly.

Figure 10 illustrates the electric field distribution in the oil-pressboard sample adopted in this experiment, with consideration of surface charges. When the needle electrode is applied with positive/negative DC voltage, the positive/negative charges will accumulate on the surface of the pressboard and generate an induced electric field within the insulation. Assuming the direction of the applied electric field is positive, the induced electric field in the oil-pressboard insulation meets the following relationship:

$$\begin{cases} E_Q^o d_o + E_Q^p d_p = 0 \\ E_Q^p \varepsilon_p - E_Q^o \varepsilon_o = \sigma \end{cases} \tag{3}$$

where E_Q^o and E_Q^p are the induced electric fields generated by the surface charges within the oil and the pressboard, respectively; ε_o and ε_p are the dielectric constants of the oil and the pressboard; σ is the surface charge density. Based on Equation (3), the induced electric field within oil is as follows:

$$E_Q^o = \frac{-\sigma d_p}{d_o \varepsilon_p + d_p \varepsilon_o} \tag{4}$$

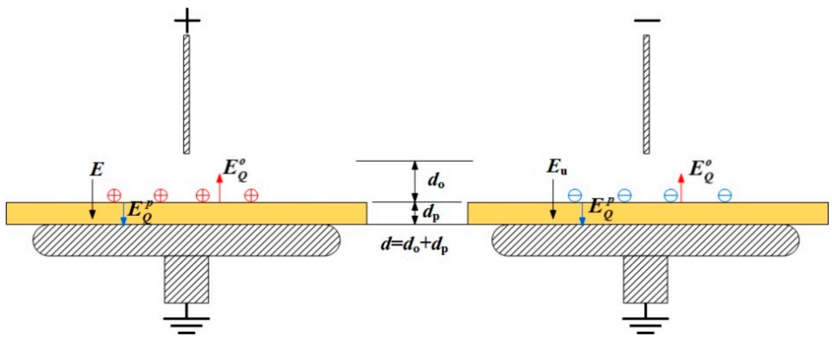


Figure 10. Electric field distribution of oil-pressboard with consideration of surface charges.

According to Equation (4), the direction of the induced electric field within the oil is opposite to that of the applied electric field. The actual electric field of transformer oil is the results of the subtraction of two electric fields. In the intensive discharging stage of the experiment, the first discharge in oil will produce a large number of electrons and positive ions in the oil gap. The electrons quickly enter the needle electrode, while the positive ions accumulate on the surface of the pressboard, which will generate the induced electric field in the oil, thus decreasing the electric field strength around the needle tip. The decreased electric field strength will hamper the following partial discharge, leading to lower magnitude and repetition rate. As the partial discharge continues, more charges accumulate on the surface of the pressboard to enhance the induced electric field. Once it increases to a certain extent, the actual electric field at the needle tip is not strong enough to trigger the next discharge, leading to the "silence" of discharges. Once the discharge is extinguished, the existing surface charges will gradually migrate to the plane electrode through the high-conductivity channel in the pressboard. According to previous studies, the dissipation of surface charge satisfies the following law [18]:

$$\begin{cases} \sigma = \sigma_0 e^{-\frac{t}{\tau}} \\ \tau = \varepsilon_p \rho_p = \frac{\varepsilon_p}{\gamma_p} \end{cases} \tag{5}$$

where τ is the surface charge dissipation time constant. For the pressboard adopted in this experiment, the parameters in Equation (5) are ε_p = 3.807 $\times$ 10^{-11} F/m, and γ_p = 4.6 $\times$ 10^{-14} S/m at room temperature (γ_p is the conductivity of the pressboard sample), based on which we obtain $\tau \approx 827$ s, which is in good agreement with the interval time between each discharge "cluster" in the experiment. As the discharge cluster repeats, the pressboard is repeatedly damaged, making the conductivity of the pressboard larger. Based on Equation (5), the interval between each cluster is therefore shorter, also corresponding to the experimental results.

Finally, in the breakdown stage, the conductivity of the pressboard is greatly increased because of the accumulated damage. This will in turn increase the electric field strength in oil and the migration rate of surface charges. Both results in the increase of the actual field strength at the needle tip. The discharge is thereby strengthened until the final breakdown of the insulation.

In addition, according to the experimental results in Section 3.1, the discharge magnitude is lower, and the discharge interval is longer under negative DC voltage. This can be attributed to the difference of the dissipation rate of the positive and negative surface charges according to Equation (5).

Insulating pressboard is mainly composed of cellulose and hemicellulose [19,20]. Cellulose is a linear semi-crystalline polysaccharide, and its basic structure is glucose monomers, which are connected by glycosidic bonds. Based on this fact, stable intermolecular hydrogen bonds can be formed within cellulose, where a large number of unsaturated hydroxyl groups (-oh) are attached.

The oxygen atom in the hydroxyl group has a significant electronegativity, which makes the surface of the pressboard prone to absorbing negative charges, as illustrated in Figure 11 [21]. Negative charges are easy to accumulate and difficult to dissipate under the same voltage amplitude compared to positive charges, therefore leading to a weaker actual electric field at the needle tip and thus partial discharges with a lower magnitude and longer interval [22]. Moreover, under the non-uniform electric field, the breakdown strength of transformer oil under negative DC voltage is slightly higher than that under positive voltage. Under the same applied voltage amplitude, the discharge magnitude is thus smaller, and the discharge interval is thus longer under the negative condition.

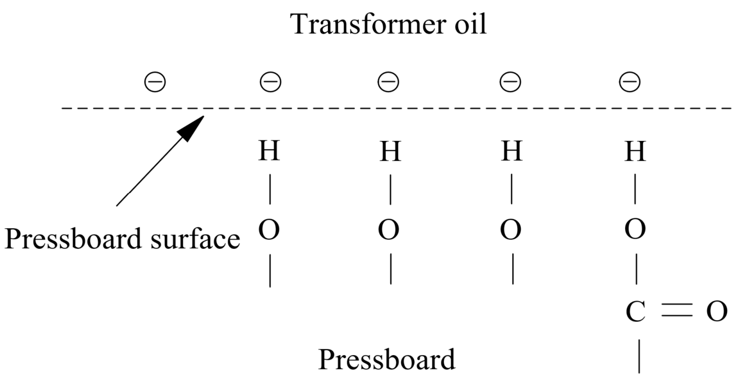


Figure 11. Schematic of negative charges adsorbed by the hydroxyl group on the pressboard surface.

Thus far, we systematically investigated the partial discharge law of oil-pressboard insulation under constant DC voltage, explained the principle of the burst and the silent features of discharges, and analyzed the differences of partial discharges under different voltage polarities. The results indicate that with the increase of voltage application time, both the magnitude and repetition rate of partial discharges will decrease first and increase afterwards. This brings problems to the factory and routine maintenance tests of converter transformers.

According to the current standard IEC 60270-2000, the DC-withstanding voltage test of converter transformers should be accompanied by a partial discharge measurement during the last 30 min of the test, and only when partial discharges that exceed 2000 pC occur fewer than 30 times can the converter transformer be regarded as qualified.

However, if the last 30 min of the 2-hour test happen to be in the silent stage, partial discharge may not be detected. Consequently, the equipment may be mistaken as normal. Therefore, based on the experimental results in this paper, suggestions can be given for the DC-withstanding voltage test with partial discharge measurement of converter transformers that, in addition to detecting partial discharge in the last 30 min, partial discharge in the first 30 min should also be detected. If the discharge exceeds 2000 pC for more than 30 times, the converter transformer should also be considered to have defects.

On the other hand, from the perspective of the experimental subjects, we used a single sheet of 0.5 mm thick insulating pressboard combined with transformer oil for the experiment. In actual converter transformers, solid insulation materials in addition to insulating pressboard also include insulating paper, with a thickness generally not exceeding 0.2 mm. This type of oil-paper insulation discharge law was not included in this study. In addition, the pressboard in converter transformers is not only a single layer. When there are multiple layers of pressboard, whether the partial discharge phenomenon will be different from that of a single layer will be one of the future research directions.

Another direction of future research is the insulation diagnosis of DC electrical equipment based on partial discharge detection. From the experimental results, the partial discharge signal is nonperiodic under DC voltage. The method of judging the type of insulating defects using the discharge phase information under AC voltage is therefore no longer feasible under DC voltage. The realization of insulation diagnosis of electrical equipment with limited information of DC partial discharge is also a great challenge.

5. Conclusions

In this paper, the development characteristics of partial discharge in oil-pressboard insulation under constant DC voltage were studied. It was found that the development of partial discharge in a needle-plane oil-pressboard insulation model under constant DC voltage has three stages: the intensive discharging stage, the silent-burst stage, and the breakdown stage. In the developing process of discharges, partial discharge magnitude and repetition rate obey the "U shape law" by first decreasing and then increasing. The overall discharges exhibit "silent" and "burst" features. Further analysis shows that the repeated accumulation and dissipation of free charges on the pressboard's surface lead to the above phenomena. Negative charges are easy to accumulate and difficult to dissipate under the same voltage amplitude compared to positive charges, therefore leading to a weaker actual electric field at the needle tip and thus partial discharges under negative DC voltage with a lower magnitude and longer interval.

In future research, we will investigate the partial discharge phenomenon within multi-layer oil-pressboard as well as oil-paper insulation models to simulate the real valve side winding as much as possible. The realization of the insulation diagnosis of electrical equipment with limited information of DC partial discharge is also one of our research targets in the future.

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