Abstract: Saturable reactor insulation is currently stressed by an exponential decay pulse voltage under normal operating conditions. The partial discharge (PD) characteristics of epoxy resin under an exponential decay pulse voltage were studied here and were compared at 25 and 110°C. In addition, this study compares these PD characteristics with those under a sinusoidal decay pulse voltage to better measure the insulation design margin of the saturable reactor under an exponential decay pulse voltage. Finally, this study explains the PD mechanism based on the three-capacitor circuit model and space charge accumulation. Compared with the sinusoidal voltage, a higher amplitude, a higher inception voltage and fewer PDs are obtained under the pulse voltage. The reason may be related to the accumulation of space charge. Due to the duality of the space charge effect, the promotion effect of space charge accumulation on the PD under the pulse voltage is dominant, and an increase in temperature will weaken the promotion effect. In contrast, the inhibitory effect of space charge accumulation on the PD under the sinusoidal voltage is dominant. The experimental results can provide a basis for the optimal design of saturable reactor insulation under an exponential decay pulse voltage.

1 Introduction

Saturable reactors are important pieces of equipment that protect the thyristors in ultrahigh-voltage direct current (UHVDC) converter valves. Insulation failure of a saturable reactor directly threatens the safe operation of a converter valve [1, 2]. Studies have revealed that under normal operating conditions, the electric field of saturable reactor insulation is complex [3]. The electrical degradation rate can be very high when partial discharges (PDs) are initiated, which can occur when the insulation is stressed by a bipolar exponential decay pulse voltage with large amplitude. Moreover, the air gap defects caused by the manufacturing process will lead to local electric field distortion, which may harm the saturable reactor insulation. In fact, the saturated reactor epoxy resin is subjected to a microsecond bipolar exponential decay pulse voltage [3], but the current insulation design of the converter valve saturable reactor only refers to the PD standard under a sinusoidal voltage. Thus, studying the PD characteristics of saturable reactor insulation under an exponential decay pulse voltage is important.

In past research, the PD studies of internal air gap defects in solid insulation have been mostly concerned with sinusoidal voltages. The influence of the frequency, voltage amplitude and temperature on the PD characteristics of insulation materials has been studied by many scholars, and many achievements have been made [4–7]. In contrast, PD studies of insulating materials under exponential decay waveforms are relatively lacking.

However, some research has been performed on PD in other insulation materials under a pulse voltage. Hayakawa and Okubo [8] investigated the PD inception characteristics of a simplified inverter-fed motor-coil sample. The PD inception voltage (PDIV) under surge voltages was 1.6–1.8 and 2.3–2.7 times higher than those under AC voltages. The PD characteristics of the sine waveform, square waveform, triangular waveform and other waveform voltages and their effects on the lifetime characteristics of twisted pair specimens were compared and analysed in [9].

Moreover, the PD characteristics of the winding insulation of low-voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10]. Compared with sinusoidal waveforms, higher amplitude and fewer PDs are obtained under square-shaped voltages. Furthermore, the effect of the duty cycle on PD features and the effect of the rise time on PD voltage induction motors were also compared under square-shaped voltages and sinusoidal waveforms in [10].
2 Experimental setup

2.1 PD defect model

A cylindrical air gap defect is fabricated in accordance with the recommended methods of CIGRE Method II [16] and ASTM D149-09 [17]. The sample is fabricated using epoxy resin (bisphenol A, Huakai-Resin, E-51) and a hardener (methyl tetrahydrophthalic anhydride, Huakai-Resin, HKR-0719). First, the epoxy resin and hardener are mixed well, and their curing is completed in a high temperature and vacuum environment to ensure that the epoxy resin sheet has no bubbles. Two epoxy resin sheets are separately produced. One epoxy resin sheet has a thickness of 0.5 mm with a cylindrical cavity of Ф 5 mm × d 0.25 mm in the middle. The other epoxy resin sheet has a thickness of 0.25 mm without a cavity. Then, the two epoxy resin sheets are bonded together using a mixed liquid, which is well mixed from the epoxy resin and the hardener, and a schematic diagram of the air gap defect is shown in Fig. 1a. The obtained epoxy resin sample is shown in Fig. 1b.

2.2 Experimental PD system

In this paper, the PD signal is detected using the pulse current method. A current sensor (2877, Pearson Electronics) with a bandwidth of 300 Hz–200 MHz is used to detect the PD signal. The PD measurement system used in this paper corresponds to the ultra-wideband system described in the standard IEC60270-2015 and cannot be calibrated [18]. Therefore, the subsequent experiment uses the voltage amplitude detected by the sensor as the equivalent PD value [19].

The experimental PD system is shown in Fig. 2. The complete experimental system is composed of two voltage sources, an experimental chamber and a PD signal detection loop. The voltage sources include a power frequency sinusoidal voltage source (PYDJ-1000/10KV, Shanghai PangLang Electromechanical Equipment Manufacturing Co., Ltd) and a premade exponential decay pulse voltage source. The temperature control range of the ageing chamber (DHTH-100-40-P-SDM, DOAHO) used in the experimental system is −40 to 180°C, and the precision is 0.1°C. A high-voltage probe (P6015A, Tektronix, USA) is used as a divider and is connected to the trigger channel of the oscilloscope. A 6 GHz bandwidth and 20 Gs/s digital sampling oscilloscope (Wavepro 760Zi-A, Lecroy) is used to show the output signal of the sensor and the applied voltage. The pulse data are transferred to a personal computer cycle by cycle by utilising a general-purpose interface bus card [12].

2.3 Experimental PD scheme

2.3.1 Test voltages: The parameters of the exponential decay pulse voltage and sinusoidal voltage used in this paper are shown in Table 1. The exponential decay pulse voltage waveform shown in Fig. 3 is basically the same as the actual voltage waveform of the saturable reactor in reference [3]. This waveform consists of positive and negative pulses with an interval of 8 ms. The periods of the exponential decay pulse voltage and the sinusoidal voltage are both 20 ms. The PDIV under the exponential decay pulse voltage is higher than that under the sinusoidal voltage. Therefore,
the PD experiment under the exponential decay pulse voltage is performed at 1.5-fold of the PDIV peak, and the PD experiment under the sinusoidal voltage is performed at the same peak value as for the exponential decay pulse voltage.

2.3.2 Experimental procedures: The PD experimental procedures under the exponential decay pulse voltage refer to the experimental PD method under a power frequency sinusoidal voltage [18]. The specific steps are as follows: the epoxy resin samples are first fixed in a square glass container made of quartz, and then, the samples are immersed in silicon oil to avoid flashover along the surface of the samples. After placing a treated sample in the experimental system, the temperature, humidity and start time of each test are recorded. Then, the ageing chamber is heated to the set temperature and the voltage is applied to the sample after 20 min. After each test voltage reaches the set value for 30 min; that is, when the PD reaches a steady state, the PD information is recorded. Next, PDIV experiments under the exponential decay pulse and the sinusoidal voltage are carried out, and the PDIV peaks are recorded. Moreover, the tests at 110°C were always performed after the 25°C test with a time interval of 1 h to ensure that the temperature has reached the set temperature value. All measurements are repeated on five similar samples with reproducible results, and 200 PD pulses of each sample are acquired to obtain the statistical properties. Additionally, statistical analysis is performed on the data using MATLAB, and the values are expressed as the means ± standard deviations.

2.4 PD detection and extraction
Owing to the fact that exponential decay pulse voltage source has a very steep rising edge, the PD signal contains a large number of interference signals. Pulse-type interference with a stable amplitude and phase is generated at the beginning of the rising edge of the positive polarity pulse, and its waveform is partially amplified to distinguish the PD signal from the interference signal of the pulse power supply, as shown in Fig. 4a. To accurately extract the PD characteristics under the exponential decay pulse voltage, six layers of decomposition were performed based on the db1 wavelet to eliminate power interference and high-frequency noise. A typical single PD waveform is obtained, as shown in Fig. 4b.

3 Experimental results
3.1 PDIV peak
For the exponential decay pulse voltage, the minimum peak pulse voltage at which >5 PD pulses occur on ten applied pulses of the same polarity is regarded as the PDIV peak [20]. For the sinusoidal voltage, the applied voltage at which >10 PD pulses are first observed during the consequent ten power frequency cycles is regarded as the PDIV peak. The PDIV peaks of epoxy resin samples under the sinusoidal voltage and exponential decay pulse voltage are shown in Fig. 5. For the exponential decay pulse voltage, the PDIV peak is ∼7.0 kV at 25°C and ∼6.70 kV at 110°C. For the sinusoidal voltage, the PDIV peak of the epoxy resin sample is 3.0 kV at 25°C and ∼2.50 kV at 110°C. In addition, the peak to peak values of the PDIV are also compared. At 25°C, the PDIV values of the exponential decay pulse voltage and the sinusoidal voltage are ∼8.4 and 6.0 kV, respectively. At 110°C, the PDIV of the exponential decay pulse voltage and the sinusoidal voltage are ∼8.0 and 5.0 kV, respectively.

In conclusion, under the same voltage form, the PDIV peak of the epoxy resin sample at 110°C is slightly lower than that at 25°C. For the same temperature, the PDIV peak under the pulse voltage is significantly higher than that under the sinusoidal voltage.
the applied exponential decay pulse voltage, the positive pulse voltage peak is much larger than the negative pulse voltage peak, and the PDIV peaks mentioned below are obtained under the positive pulse.

3.2 PD repetition rate

The total PD numbers in the 200 power frequency cycles under the exponential decay pulse voltage and sinusoidal voltage are shown in Fig. 5. When the exponential decay pulse voltage is applied, the total PD numbers are ∼390 at 25°C and 300 at 110°C. When the sinusoidal voltage is applied, the total PD numbers are ∼1800 at 25°C and 5200 at 110°C, which is significantly larger than that at 25°C.

At the same temperature, the PD number under the sinusoidal voltage is significantly greater than that under the exponential decay pulse voltage. For the exponential decay pulse voltage, the total PD number of the epoxy resin sample at 110°C is less than that at 25°C. For the sinusoidal voltage, the PD number at 110°C is greater than that at 25°C.

3.3 PD pulse magnitude

The average PD pulse magnitudes under the exponential decay pulse voltage and sinusoidal voltage at 25°C and 110°C are shown in Fig. 5. For the sinusoidal voltage, the average PD pulse magnitude of the epoxy resin sample is ∼4 mV at 25°C and is greatly increased to ∼17 mV at 110°C. For the exponential decay pulse voltage, the average PD pulse magnitude is ∼137 mV at 25°C, which is ∼34-fold the PD pulse magnitude under the sinusoidal voltage. At 110°C, the average PD pulse magnitude is ∼61 mV, which is smaller than that at 25°C.

The PD magnitude under the exponential decay pulse voltage at 110°C is significantly smaller than that at 25°C. The PD magnitude under the sinusoidal voltage at 110°C is significantly larger than that at 25°C. For the same temperature, the PD magnitude of the epoxy resin under the pulse voltage is significantly larger, by dozens of times, than that under the sinusoidal voltage.

In our case, the positive pulse is much larger than the negative pulse, and we compare the PD characteristics under the exponential decay pulse voltage and sinusoidal voltage in a more conservative way. In other words, the results obtained utilising the peak value are more convincing that those obtained utilising the peak to peak value.

3.4 Statistical PD distribution

3.4.1 PD distribution under the exponential decay pulse voltage: The PDIV peak of the epoxy resin sample under the exponential decay pulse voltage is ∼7.0 kV. The PD experiment is carried out under a 1.5-fold PDIV peak. The PD scatter plot of 200 periods at 25°C is obtained, as shown in Fig. 6. The PD distribution at 25°C is similar to a triangular distribution. The PDs are concentrated at the rising edge of the applied voltage, and almost no PDs are distributed at the falling edge of the applied voltage. The PD magnitudes under the applied positive pulse voltage are mostly between 100 and 300 mV, and the PD magnitudes under the applied negative pulse voltage are mostly between 20 and 100 mV. The PD scatter plot at 110°C is shown in Fig. 7. The PDs under the applied positive pulse are mostly concentrated at the rising edge of the applied voltage and are more concentrated than those at 25°C,
with most PD magnitudes between 100 and 200 mV. The PDs under the applied negative pulse are more dispersed than those at 25°C, with most PD magnitudes between 0 and 60 mV, which are significantly reduced compared with those at 25°C.

3.4.2 PD distribution under the sinusoidal voltage: To compare the PD characteristics of the epoxy resin sample under the exponential decay pulse voltage with those under the sinusoidal voltage, the peak value of the sinusoidal voltage used in the PD experiment is the same as the peak value of the exponential decay pulse voltage. The PD information of 200 periods is obtained, and the scatter plot is shown in Fig. 8. At both 25°C and 110°C, the PDs are mostly concentrated at the rising and falling edges of the applied positive and negative half-waves. The PDs of the positive half-wave occur between −45° and 80°, and the PDs of the negative half-wave occur between 145° and 270°. Almost no PDs occur at the other phases. The PD number at 110°C is significantly greater than that at 25°C, and the number of PDs with a large magnitude is significantly increased.

4 Discussion
4.1 Effect of different voltage forms on PD

The above experimental results indicate that when applying exponential decay pulse voltages to the air gap epoxy resin sample, higher PDIV peaks, higher amplitudes and fewer PDs are observed compared to sinusoidal waveforms.

PD occurs when the following two conditions are met [21]: (i) the electric field intensity in the defect area reaches the PD inception field and (2) the initial electrons trigger an electronic avalanche.

The experimental PD results of the epoxy resin samples under the exponential decay pulse voltage and the sinusoidal voltage can be explained by the three-capacitance circuit model [22], and schematic diagrams of the PDs under the exponential decay pulse voltage and sinusoidal voltage are shown in Figs. 9a and b, respectively. For the convenience of analysis, the residual voltage is assumed to be zero. $U$ is the voltage of the air gap when no PD occurs, $U_{cin}$ is the reverse voltage established by the space charge, and $U_s$ and $U_p$ are the composite voltages of $U$ and $U_{cin}$, respectively. $V_{inc}$ is the static breakdown voltage of the air gap. $t_s$ and $t_p$ are the effective discharge times of the voltage exceeding $V_{inc}$ in the first 1/4 cycle. $\Delta V_s$ and $\Delta V_p$ are the statistical time delays and the air gap voltage increases. In other words, the air gap voltage is higher than the static breakdown voltage when a PD occurs.

First, the PD mechanism under the positive polarity pulse voltage is analysed. Since the voltage rise time is short, only one PD occurs in the rise phase. Since a space charge is generated by the last PD event and a reverse voltage is established, the composite voltage of the air gap reaching the breakdown voltage again within the fall time is difficult. Therefore, the generation of a second PD during the fall time is difficult, which explains the PD phase distribution shown in Figs. 6a and 7a.

The PD process of the applied negative pulse voltage is similar to that of the positive pulse voltage. Although the negative pulse voltage amplitude is small, the rising edge is long. PD occurs as long as the volt-second characteristic of the air gap breakdown is achieved. Therefore, even if the amplitude of the negative pulse voltage is small, PD can occur within the applied negative pulse, which can explain the PD phase distributions of Figs. 6b and 7b.

The composite voltage of the air gap is not zero at the start of the applied voltage. The reason may be that the space charge generated by the previous PD does not decay to zero and the residual space charge establishes a voltage. The space charge generated by the PD under the applied positive pulse affects the PD...
and vice versa. Therefore, at the beginning of the applied positive pulse voltage, the space charge generated by the PD under the previous negative pulse voltage will ‘lift’ the composite voltage of the air gap to a certain extent, and the development of PD will be promoted, which is another factor that leads to the higher PDIV peak under the exponential decay pulse voltage. The above two reasons lead to a larger amplitude of the overvoltage under the exponential decay pulse voltage, \( \Delta V_p \gg \Delta V_s \). The PD amplitudes under the exponential decay pulse voltage and the sinusoidal voltage are positively correlated with \( \Delta V_p \) and \( \Delta V_s \) respectively. Therefore, the PD amplitude under the exponential decay pulse voltage is larger, which is consistent with the experimental results of Fig. 5b.

To further clarify the effect of the space charge on the PD under the exponential decay pulse voltage, the pulse voltage source was experimentally adjusted, and the negative pulse voltage was removed. When only positive pulses are applied to the epoxy resin sample, the PD scatter plot is as shown in Fig. 11. In contrast with Fig. 6a, the PDs are concentrated at the peak of the applied pulse voltage, and the PD phase is increased. The number of PDs, the average PD amplitude and the average PD phase comparison results are shown in Table 2. When only the positive pulse voltage is applied, the PD number and the average PD amplitude are significantly reduced, whereas the average PD phase is increased. Therefore, for the exponential decay pulse voltage, the space charge generated by the PD under the negative pulse voltage promotes the PD under the positive pulse voltage, resulting in significant increases in the PD number and PD amplitude.

### 4.2 Effect of the temperature on PD

In the epoxy resin air gap defect, a higher temperature results in lower PD amplitudes, fewer PDs and a slightly lower PDIV peak under the exponential decay pulse voltage. For the sinusoidal voltage, a higher temperature results in higher PD amplitudes, more PDs and a slight decrease in the PDIV peak, which can be explained as described below.

At high temperatures, a large number of free electrons inside the metal will overcome the surface barrier and move from the metal to the insulating medium according to the Richardson–Schottky law [23–25]

\[
\lambda = N_d(t)\nu_0 \exp \left( -\frac{\psi_{\text{e}} - E(t)/4\varepsilon_0}{kT} \right)
\]

where \( N_d(t) \) is the number of emitting electrons or ionizable ions on the dielectric surface where PD occurs, which are mainly caused by the surface charge generated by the previous PD, \( \nu_0 \) is the photoionisation constant, \( \psi_{\text{e}} \) is an effective work function, \( E(t) \) is the electric field at the emitting surface, \( K \) is the Boltzmann constant, \( T \) is the temperature, \( e \) is the elementary charge and \( \varepsilon_0 \) is the permittivity of the vacuum. The probability of initial electron generation is proportional to the surface charge produced by the previous PD. The greater the space charge \( N_d(t) \) is, the larger the initial electron generation probability and the smaller the discharge delay; thus, the discharge delay can be approximated as being inversely proportional to the space charge number \( N_d(t) \).

Since the exponential decay pulse voltage waveform is non-symmetrical, the space charge build-up will be different from a symmetrical waveform such as a sinusoidal waveform. Thus, an almost symmetrical PD pattern can be obtained under a symmetrical waveform, while a non-symmetrical waveform tends to produce a non-symmetrical PD pattern.

According to the literature [26], the effect of the space charge on PD has duality. For the sinusoidal voltage, on the one hand, the space charge hinders the subsequent PD of the positive half-cycle or the negative half-cycle. On the other hand, the space charge has a promotion effect on the PD at the time of polarity inversion. The voltage polarity inversion moment accounts for a small proportion of the total discharge phase in the positive and negative half-cycles. Therefore, the effect of the space charge under the sinusoidal voltage is mainly the suppression of PD during most of the
discharge phase. For the exponential decay pulse voltage, regardless of whether it is a positive polarity pulse or a negative polarity pulse voltage, the average number of PDs per half-cycle is ~1. Therefore, under the exponential decay pulse voltage, the effect of the space charge generated by the PD under different polarities is mainly the promotion of PD.

As the temperature increases, the electrical conductivity of the epoxy resin sample increases [27]. An increase in conductivity leads to an increase in the mobility of internal charges and difficulty in space charge accumulation. Therefore, for the sinusoidal voltage, the space charge accumulation is less at 110°C than at 25°C. The suppression of the PD by the space charge is reduced, and the PD number and PD amplitude are increased at 110°C.

However, for the exponential decay pulse voltage, the promotion of the PD by the space charge is reduced, and the PD number and PD amplitude are reduced at 110°C. The PD number and the PD amplitude under the positive and negative pulse voltages are shown in Table 3 and change synchronously with temperature. At 25°C, the PD numbers and PD amplitudes under positive and negative polarizations are greater than those at 110°C. The PDs of the positive and negative pulse voltages mutually promote each other. At 110°C, space charge dissipation is severe, and the promotion effect is weakened. As a result, the PD amplitudes and PD numbers under the positive and negative pulse voltages at 110°C are reduced.

5 Conclusion

This paper reveals the PD characteristics of epoxy resin under an exponential decay pulse voltage. An analysis of the differences in the PD distributions under an exponential decay pulse voltage and a sinusoidal voltage at various temperatures is performed in this paper for the first time. Compared with the PD characteristics under the sinusoidal voltage, the experimental results obtained under the exponential decay pulse voltage are similar to those under a square-shaped voltage in references [8, 11]. A higher amplitude, higher inception voltage and fewer PDs are observed compared to those produced from sinusoidal waveforms. The results of this work can be summarised as follows: for the two voltage forms, the exponential decay pulse and sinusoidal voltage, a larger PD magnitude and a higher PDIV peak are obtained under the exponential decay pulse voltage than under the sinusoidal voltage because of its larger dV/dt. However, due to the short effective discharge time under the pulse voltage, the PDs per cycle are fewer than those under the sinusoidal voltage. A higher temperature results in lower PD amplitudes, fewer PDs, and a slightly lower PDIV peak under the exponential decay pulse voltage. For the sinusoidal voltage, a higher temperature results in higher PD amplitudes, more PDs, and a slight decrease in the PDIV peak. The reason for these differences may be related to the accumulation of space charge. Temperature significantly affects the PD characteristics by affecting the accumulation of space charge.

Due to the duality of the space charge effect, space charge promotes PD under the pulse voltage but suppresses PD under the sinusoidal voltage. Therefore, compared with the PD characteristics at 25°C, fewer PDs and smaller PDs are obtained under the pulse voltage at 110°C, whereas more PDs and larger PDs are obtained under the sinusoidal voltage at 110°C.

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Table 3 Comparison of PD characteristics under positive and negative pulse voltages

| PD number (positive/negative) | Average PD amplitude (positive/negative), mV |
|-----------------------------|---------------------------------------------|
| 25°C                        | 200/197                                     |
| 110°C                       | 164/118                                     |

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