Charge migration of multilayer oil paper on the process of partial discharge under AC voltage

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Abstract
As one of the main reasons for the deterioration of Nomex paper and charge migration, partial discharge (PD) plays a critical role during PD degradation. In this study, the PD characteristics of multilayer oil paper are focused on. In order to explore the characteristics of charge migration, the experiments of the relative permittivity, conductivity, isothermal surface potential decay, scanning electron microscopy and Fourier infrared spectroscopy have been carried out. The results show that the discharge branches of the second layer are two and three times longer than those in the first layer. In addition, the trap level of the first layer for PD degradation samples increases with the degree of PD degradation. The charges captured by deep traps provide seed charges for PD on the surface of the first layer. The charge transportation will accelerate the formation of shallow traps. The charge distribution and shallow traps contribute to the expansion of discharge branches.

1 | INTRODUCTION
The on-board traction transformer plays an important role in power conversion and transmission of electric locomotives [1]. Oil paper insulation is one of the important insulations of on-board traction transformer. Nomex papers with good heating ability and excellent electrical properties are used as inter-turn insulation material for windings of on-board transformer [2]. During the operation process of on-board traction transformer, some defects are produced because of the electrical, thermal and mechanical stresses. The defects, that is, the fracture, metal tip and cavity tend to lead to the unevenness of electrical field, the accumulation of free charges, and even the occurrence of partial discharge (PD). The deterioration of insulation and the chain scission of Nomex paper caused by PD may correlate with the variation of trap parameters and charge migrating characteristics [3–5]. Therefore, it is very important to take PD characteristics and the charge transportation characteristics in PD degradation progress into consideration.

At present, most existing achievements have focused on the characteristics of PD of oil paper insulation [6–8]. For example, Kunicki and Cichoń [9] described the PD characteristics of oil paper insulation under long-term AC voltage. Li et al. [10] investigated PD characteristics of oil paper insulation under superposed inter-harmonic and pure AC voltages. It was found that the higher $\frac{dv}{dt}$ caused by inter-harmonic component was the main reason for the difference of PD characteristics between superposed inter-harmonic and pure AC voltages. Cui et al. [6] investigated the division of PD progress and reported that the development of PD is depended on the depolarisation of cellulose in pressboard.

Recent research works indicated that PD characteristics are related to the charge transportation and the trap distribution of oil paper insulation [11]. Muhammad et al. [12, 13] reported that the shallow traps produced by the aluminum oxide (Al$_2$O$_3$) nanoparticles in oil paper insulation contribute to the enhancement of creeping flashover voltage. Wei et al. [14, 15] described the variation of trap energy for oil-impregnated paper aged under electrical and thermal stresses. It showed that the trap energy decreases under electrical stress but increases under thermal stress. The variation of trap parameters causes the change of charge transportation characteristics [16]. Moreover, it leads to the variation of PD activities and has been reported in [17–20]. However, the literature on charge activities during discharge progress is rare. Meanwhile, it is found that charge distribution and trap level are relevant to the intensity of PD.
via a series of experimental tests. Consequently, it is essential to investigate the charge migration characteristics of multilayer oil paper insulation on the process of PD under AC voltage.

In order to investigate the characteristics of charge migration, PD experiments of multilayer oil paper are designed. The samples at different PD stages are selected according to the discharge characteristics. The tests of relative permittivity, conductivity, isothermal surface potential decay (ISPD), scanning electron microscopy (SEM) and Fourier infrared spectroscopy (FTIR) are carried out and the corresponding properties are analysed. The mechanism of charge migration on the PD process is also discussed.

2 | EXPERIMENTAL SETUP

2.1 | The experimental set up of PD

The experimental setup of PD measurement under AC voltage is shown in Figure 1, including the AC power source, PD measurement system and test cells. The AC power source was generated by PD-free transformer rated at 100 kV and 10 kVA, which was measured by the divider with a ratio of 1000:1. PD was detected by MPD600 system consisted of the CPL542 and the MPD600.

The inter-turn insulation defects of on-board traction transformer are prone to appear under multi-stresses in the operation process. In this experiment, a needle-plane defect model was designed according to the operation condition as shown in Figure 2. In this model, Nomex papers produced by DuPont with three layers were selected, and the thickness of each layer was about 0.18 mm.

Before PD measurements, the samples need to be treated to avoid the influence of moisture and gaseous impurities. Initially, the samples were treated in the air condition of 105 °C for 48 h to remove the moisture. Then, the dry samples were treated in vacuum at 85 °C for 24 h under the pressure of 80 Pa to remove the gaseous impurities. Last, Nomex papers were impregnated in the Karamay 25# transformer oil under vacuum condition as 80 Pa at 85 °C for 48 h.

2.2 | Measurement of trap distribution

Figure 3 shows the measuring system of surface potential. The experiment was performed at room temperature with relative humidity of 40%. The needle electrode was set to 1 cm above the position where the high voltage electrode was placed in the PD experiment. Samples were charged in corona charging method. Before the experiment, the surface of the samples was wiped with ethyl alcohol. Then, they were treated in the air condition of 80 °C for 24 h to remove the moisture.

In order to obtain a uniformly distributed charge, the gate electrode was added between the ground and the needle electrodes, the gate electrode was set to 5 mm above the samples. The needle and the gate electrodes were connected with the DC voltage. Its voltage amplitudes were ±8 kV and ±3 kV, respectively. The voltage applied to the needle and the gate electrodes was held for 10 min. Then, the samples were rapidly shifted to the probe to ensure that the probe was in the same position as the needle. An electrostatic voltmeter (trek model 341-b) connected to a Kelvin probe (model: trek-3455-et) was used to measure the surface potential. The probe was positioned 3 mm above the samples [21]. The curves of surface potential with the increase of the time were recorded. We can use the curves to calculate the trap distribution of samples.

The trap density and energy can be expressed as [22, 23]

\[
N(E) = \frac{4\varepsilon_0\varepsilon_r}{qkT^2} \left| \frac{dV'}{dt} \right|
\]  

(1)
where \( t \) is the decay time, \( V \) represents the surface potential, \( \varepsilon_i \) is the relative permittivity of the sample, \( \varepsilon_0 \) is the permittivity of vacuum, \( q \) is the elementary charge, \( L \) is the thickness of the samples, \( T \) is the Kelvin temperature, \( k \) is the Boltzmann constant, \( N(E) \) is the trap density occupied by carriers at trap level \( E \), \( E_t \) is the trap energy, \( \nu \) is the attempt to escape frequency and is selected as \( 10^{12} \) s\(^{-1}\).

3 | RESULTS

3.1 | Electrical properties of samples

3.1.1 | PD characteristics

The applied voltage was raised in steps of 0.5 kV until the experiment model was broken down and each step was held for 5 min. The PD characteristics under AC voltage were obtained, and the process of PD as shown in Figure 4 was recorded.

As can be seen from Figure 4, ‘tree-like’ carbonised tracks on the first layer of oil paper that locates close to the needle tip could be observed when the applied voltage is below 15.5 kV. They are formed because of the erosion of PD branches on Nomex paper. It can be observed that the intensity of PD and the length of discharge branches increase as the applied voltage increases. During the stage of near breakdown, that is, applied voltage up to 15.5 kV, the first layer of oil paper is punctured and interlayer discharge occurs in the second layer of oil paper. The interlayer discharge branches are not obvious, and as a matter of the fact, they are observed through the first layer. Compared with the discharge below 15.5 kV, the interlayer discharges intensify and the much longer branches occur in the second layer of multilayer oil paper. Also, the sound of the discharge can be heard. A large number of bubbles existing at the tip and the bubble column are formed. The intensified discharges continuously bombard the oil paper sample and lead to the breakdown of oil paper sample quickly.

Figure 5 shows the PD patterns at different applied voltages. It indicates that PDs mainly concentrate on the rising edges and part of the falling edges of the applied voltage. With the increase of the applied voltage, the amplitude and number of PD pulses rise, resulting in the difference of PD patterns. PD pattern presents a ‘triangular’ distribution when the applied voltage is 12 kV but shows a ‘trapezoid’ distribution between 12 and 15 kV. At 15.5 kV, the PD pattern shows a ‘triangular’ distribution. These differences are related to the charge transportation.
3.1.2 Dielectric properties

The real part of the relative permittivity $\varepsilon'$ of PD degradation samples and untreated samples are tested, and the results obtained are shown in Figure 6. It can be observed that $\varepsilon'$ gradually decreases as the frequency increases. The results might contribute to explain that $\varepsilon'$ is related to the polarisation characteristics of oil-impregnated Nomex paper. The polarisation occurs in the interface between chopped fibre and pulp under the action of an electric field. At the same time, the interfacial polarisation is related to the binding capacity of charges. With the increase of frequency, the rate of polarisation cannot overtake the change rate of frequency, resulting in the decrease of $\varepsilon'$. It could be observed that $\varepsilon'$ shows a decreasing tendency when the applied voltage is below 14 kV but shows an increasing tendency when the PD degradation is 15 kV. This is due to the presence and enhancement of holes in oil-impregnated Nomex paper. Moreover, new groups are formed during the process of PD degradation. When the PD degradation is below 14 kV, the decrease of $\varepsilon'$ depends on the appearance of pores. But when the PD degradation is above 14 kV, a large number of new groups are produced, resulting in the enhancement of polarisation intensity on intermolecular of PD degradation samples and the increase of $\varepsilon'$.

It can be seen in Figure 6(b) that the value of $\varepsilon'$ for the first layer is the minimum, while the value of $\varepsilon'$ for the third layer is the maximum. This reveals that the number of pores inside the oil-impregnated paper increase as the degree of PD degradation increases, causing the decrease of $\varepsilon'$.

3.1.3 Conductivity properties

Volume and surface resistivity of different PD degradation samples are measured by using Model 8009 and Keithley 6517B. Then, the volume and surface conductivity can be calculated: 

$$\sigma_v = 1/\rho_v$$  \hspace{1cm} (3) 

$$\sigma_s = 1/\rho_s$$  \hspace{1cm} (4)
where $\sigma_v$ is the volume resistivity, $\sigma_s$ is the surface resistivity, $\rho_v$ is the volume conductivity and $\rho_s$ is the surface conductivity of Nomex paper.

The volume and surface conductivity of Nomex paper at different voltages are shown in Figure 7. It can be seen that the volume and surface conductivity of samples keep increasing with the PD degradation. The conductivity of untreated samples is much smaller than that of PD degradation samples. It is due to the appearance of tree-like carbonised tracks caused by PD. The carbonised tracks are intensified and expanded along the surface of oil-impregnated samples with the increase of PD degradation degree. Therefore, it comes out that carbonisation plays an important role in the growth of volume and surface conductivity.

Table 1 shows the volume and surface conductivity of different layers for PD degradation samples at 15 kV. It can be observed that the surface conductivity of the first layer is the largest, while the surface conductivity of the third layer is the smallest. It indicates that the macromolecular chains are broken and polar groups are formed in samples caused by a strong field. As a result, more conductive ions are produced that accelerate the increase of the conductivity.

### 3.2 Trap distribution

Figure 8 shows the trap distributions of the first layer for different PD degradation samples. It is observed that the hole and electron trap distributions show the same profile. Besides, the curves of each trap distribution have two peaks that present the level centre of the deep and shallow traps, respectively. One important observation is that for the untreated sample, the trap distribution depends on the deep trap. After the electrical ageing of untreated samples, the density of shallow trap increases. With the growth of applied voltage, the trap energy level increases and the deep trap density decreases. It means that the change of trap distribution is related to charge transportation characteristics on the process of PD. At the initial stage of PD (below 12 kV), the trapping, de-trapping, migration and the combination of charges causes the deterioration of samples. It will lead to the increase of shallow trap density and the decrease of deep trap density. At the development stage of PD (above 12 kV), PD activity is intensified and carbonised tracks are expanded along the surface of Nomex paper. The chemical bonds are broken and new groups are formed, resulting in the damage of fibre and the increase of trap level.

| PD degradation samples at 15 kV | The first layer | The second layer | The third layer |
|-------------------------------|----------------|----------------|---------------|
| Volume conductivity ($\times 10^{-17} \text{S/cm}$) | 7.76 | 6.74 | 5.18 |
| Surface conductivity ($\times 10^{-17} \text{S}$) | 3.54 | 2.31 | 1.32 |
The trap distributions of different layers for samples at 15 kV are shown in Figure 9. It can be seen that a large number of shallow traps have occurred in the second and third layers of oil-impregnated Nomex paper. As for the hole trap distribution of the second layer, the shallow trap density is the largest but the trap level is the lowest. It means that the second layer and third layer is gradually degraded because of the charge transportation characteristics, that is, the trapping, de-trapping, recombination and migration of positive and negative charges.

3.3 | Surface morphology and chemical composition

3.3.1 | Surface morphology and chemical composition

The Nomex paper, called Aramid paper, consists of the chopped fibre and pulp. The chopped fibre plays an important role in the skeleton. The pulp fibre is the filler and the adhesive. The surface morphology of Nomex paper is characterised by SEM.

Figure 10 shows the SEM of untreated and PD degradation samples. It is noticed that the surface of untreated Nomex paper is smooth, while the chopped fibres and the pulp are gathered tightly. With the increase of PD degradation at 12 kV, the holes and debris are formed on the surface of Nomex paper of the first layer. The bonds between the chopped fibres and pulp are loose slightly. At 14 kV, the chopped fibres begin to break. A large number of holes and debris are formed on the surface of Nomex paper of the first layer. The chopped fibre becomes slender due to electrical stress. When the applied voltage is up to 15 kV, the chopped fibres become loose and disordered, and the pulp is destroyed completely near the needle in the first layer.

Figure 11 shows the SEM of the second and third layers for the PD degradation sample. It is shown that the second and third layers of Nomex paper are destroyed slightly.

3.3.2 | Chemical composition of Nomex paper

Figure 12 indicates the chemical groups of different layers for PD degradation sample at 15 kV. It is clearly shown that the influence of electrical deterioration on the absorbance of wavelength mainly concentrated on 1642–1605, 2925 and 2853 cm$^{-1}$. Absorption peaks in 2925 cm$^{-1}$ ($–\text{CH}_2–$) and in 2853 cm$^{-1}$ ($–\text{CH}_3$) increase with the ageing degree of Nomex papers. Absorption peak in 1642–1605 cm$^{-1}$ (amide band) decreases with the deterioration of samples.

4 | DISCUSSION

4.1 | The effect of PD on trap distribution of Nomex paper

The trap distribution of Nomex paper is related to the physicochemical properties. According to the obtained SEM and FTIR results, the surface morphology and chemical composition of Nomex paper changed during the PD progress, resulting in the variation of trap parameters.

For untreated Nomex paper, its surface is smooth and the corresponding trap distribution is depended on the deep trap. During the PD progress, Nomex paper is gradually degraded for the charge activities when the applied voltage is below 12 kV. The broken molecular chains and surface morphology further result in the variation of trap distribution of samples, that is, the density of deep trap decreases and the density of shallow traps increases (Figures 8 and 9). With the increase of applied voltage, samples are degraded for the bombardment of charged particles and heat effects caused by PD. The increased amplitude and intensity of PD cause the destruction of the surface morphology of Nomex paper (Figures 10 and 11). The formation of holes and chain scission may contribute to the increase of trap level. Besides, the chemical erosion caused by PD intensifies, leading to the decrease of absorption peak in 1642–1605 cm$^{-1}$ for the amide band (Figure 12). It indicates that chemical chains are broken, while impurities with hydroxyl groups are formed. These impurities existing in the Nomex paper cause the faster injection and the slower de-trapping of charge. It will result in the trap energy level of the first layer for the sample increases as the PD degradation increase.
FIGURE 10  Surface morphology of Nomex paper during PD degradation (a) the first layer at 0 kV, (b) the first layer at 12 kV, (c) the first layer at 14 kV, and (d) the first layer at 15 kV.

FIGURE 11  Surface morphology of PD degradation samples at 15 kV (a) the second layer, (b) the third layer.
4.2 Charge transportation characteristics on PD progress

4.2.1 Charge transportation model

As described in Section 3.1, PDs mainly concentrate on the rising edges and part of the falling edges of the applied AC voltage. These are related to the charge distribution characteristics. The corresponding charge transportation models are shown in Figure 13. It can be seen that the charge distribution of the positive half cycle is different from the negative half cycle. In the phase from 0 to $\frac{\pi}{2}$, the positive charges are gradually accumulated on the surface of Nomex paper and migrate along its surface under the electrical field. The recombination of positive and negative charges will release energy, causing the appearance of PD. In the phase from $\frac{\pi}{2}$ to $\pi$, the majority of positive charges are accumulated on the surface of Nomex paper. Also, the number of accumulated positive charges increases with the increase of phase. The accumulated positive charges cause the distortion of the electrical field. The distorted field promotes the reappearance of PD (Figure 5). Besides, negative charges are always accumulated at the position far from the centre. The longer migration distance of the electron at the same condition is found. This is due to the mass of the electron being smaller than ion. In the phase from $\pi$ to $\frac{3\pi}{2}$, the negative charges are gradually accumulated on surface of Nomex paper and migrate along its surface under the electrical field. The recombination of negative and positive charges will release energy, causing the appearance of PD. In the phase from $\frac{3\pi}{2}$ to $2\pi$, negative charges are accumulated on the surface of Nomex paper. The accumulated negative charges cause the distortion of the electrical field. The distorted field promotes the reappearance of PD (Figure 5).

4.2.2 Charge migration along surface

The surface current density of free charge produced by the field component along the surface of Nomex paper can be written as

$$j_s(t) = E_s(t) \sigma_s$$

(5)

where $\sigma_s$ is the surface conductivity of Nomex paper, $E_s(t)$ is the field component along the surface of Nomex paper.
It can be seen from Equation (5) that \( j_v(t) \) is related to \( E_v(t) \). In the phase from \( \pi/2 \) to \( \pi \) and from \( 3\pi/2 \) to \( 2\pi \), a large number of charges are accumulated on the surface of Nomex paper. The accumulated charges cause the intensification of electrical field \( E_v(t) \), which further results in the increase of surface current density. With the increase of applied voltage, it is easier for charges to migrate along the surface of Nomex paper. Moreover, the increase of surface conductivity of the Nomex paper also facilitates the charge migration along the surface (Figure 7). In addition, the migration distance of charge is positively correlated with the amplitude of applied voltage [27]. The increase of applied voltage causes the expansion of the charge distribution along the surface of Nomex paper.

When the applied voltage is below 15 kV, the surface current density intensified and the charge distribution expanded with the increase of applied voltage, resulting in more serious damage on the surface of Nomex paper and the extending of PD branches (Figure 4). In addition, the result of trap measurement indicated that the trap level of the first layer increased with applied voltage (Figure 8). It indicated that the process of charges de-trapping is difficult, and trapped charges will provide seeds for PD.

4.2.3 Charge migration along volume

Assuming an infinitesimal volume element of Nomex paper with the height \( h \) and potential difference, the current density of free charges through the volume can be given [25, 26] as

\[
j_v(t) = \frac{\varphi(t)}{b} \sigma_v + \frac{\varepsilon}{b} \frac{d\varphi(t)}{dt}
\]

where \( \varepsilon \) is the permittivity of Nomex paper with the height \( b \), and \( \sigma_v \) is the volume conductivity.

As discussed in Sections 3.1.2 and 3.1.3, \( \varepsilon' \) of the first, second and third layers for Nomex paper gradually increase but \( \sigma_v \) decrease (Figures 6 and 7). The value of \( \sigma_v \) is much smaller than \( \varepsilon' \). Consequently, \( j_v(t) \) is mainly determined by \( \varepsilon' \). According to Equation (6), it is known that less free charges could migrate along the volume of the degraded sample. During the PD progress, free charges gradually migrate from the first layer to the second and third layers under the electric field. The charges transportation along the bulk of Nomex paper will destroy the surface morphology and break the chemical bonds of the Nomex paper. Meanwhile, the degradation of samples further brings about the difficulty in charge migration along volume, resulting in the formation of space charges and the distortion of the electric field. It accelerates the formation of shallow traps in the second layer of the samples. Free charges seized by shallow traps may free quickly from them [28]. As a consequence, the charges trapped in shallow traps are easy to participate in the development of PD. A large number of shallow traps in the second layer may contribute to the long branches of the interlayer discharge when the applied voltage is 15.5 kV (Figure 9).

5 CONCLUSION

In this study, PD and charge migration characteristics of multi-layer oil paper are investigated on the discharge progress. The main conclusions are presented as follows:

1. PD is mainly concentrated on the rising stage and part of the falling stage under the AC voltage. The discharge branches of the second layer are much longer than that of the first layer for PD degradation samples.
2. The trap level of the first layer for PD degradation samples increases as the applied voltage rises, and a large number of shallow traps are formed on the second layer of PD degradation samples.
3. The charges captured by deep traps in the first layer tend to provide seed charges for PD along the surface. The expansion of charge distribution range and the increase of charge accumulation are the main reasons for the increased length and quantity of discharge branches.
4. The shallow traps caused by charge transportation in the second and third layers make more trapped charges participate in PD.

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