Ageing characteristics and lifetime model of oil–paper insulation for oil-immersed paper condenser bushing

Sihang Gao1 | Lijun Yang2 | Tingjing Ke3

1Key Laboratory of Industrial Internet of Things and Networked Control, Ministry of Education, Chongqing University of Posts and Telecommunications, Chongqing, China
2State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing, China
3State Grid Chongqing Electric Power Company, Chongqing, China

Correspondence
Lijun Yang, State Key Laboratory of Power Transmission Equipment and System Security and New Technology, Chongqing University, Chongqing 400044, China.
Email: ylj@cjpu.edu.cn

Associate Editor: Dachun Huang

Abstract
This study extensively investigated the ageing characteristics and lifetime model of oil–paper insulation for oil-immersed paper condenser bushing. The accelerated thermal and electrothermal ageing experiments of oil-immersed paper condenser bushing were conducted respectively. The properties of oil–paper insulation during the ageing process were investigated. Results showed that descending speed of degree of polymerization of the innermost and the outermost layer paper was higher than that of middle layer paper, the difference in water content on different paper layers caused varying deterioration speeds. The aluminium foil contributed to a surge in aluminium dissolution in oil, further accelerating the ageing of insulation. Based on the obtained degree of polymerization data under thermal ageing at 90°C, 100°C and 130°C, the lifetime model of oil–paper insulation for condenser bushing model was established. In addition, the surface breakdown of the scale model of bushing occurred after 133 days ageing, the properties of bushing decreased gradually during the ageing process and sharply after the breakdown. Degree of polymerization deviation of different paper layers in bushing between calculated value according to the above lifetime model and actual value of bushing after the breakdown was less than 6%, further verifying the validity of lifetime model.

1 | INTRODUCTION

As a type of power equipment with insulation and support, oil-immersed paper (OIP) condenser bushing is a widely accepted electric equipment that can connect the outer and inner insulation systems to ensure the safe operation of power transformer [1]. With the increase in electrical energy demand, the voltage level of power transmission and transformation systems rise gradually, and the ultra-high voltage OIP condenser bushings are widely used in numerous countries. However, many bushings that passed the factory acceptance test still experience serious faults, such as the discharge explosion of capacitor core in practical application. Bushing failure causes severe power transmission loss and power failure and also affects power grid safety and stability [2, 3].

The oil–paper insulation of OIP condenser bushing, which is affected by the combined action of electric field, thermal, and moisture, gradually deteriorates in operation, thereby declining the insulation performance and severely threatening the safe operation of bushing [4]. The discharge explosion of the bushing capacitor core is mainly induced by the accumulation of insulation deterioration during long-term operation. The structure design and the online monitoring of OIP condenser bushing have been currently investigated [4–8], and the ageing characteristics and lifetime model of oil–paper insulation for OIP condenser bushing must be investigated further. At present, the ageing characteristics of oil–paper insulation in oil-immersed transformer have been studied extensively [9–16]. However, given the extreme difference in the structure and weight proportion of oil/paper between OIP condenser bushing (1.5:1) and oil-immersed transformer (10:20:1), whether the research results of the oil-immersed transformer are suitable for OIP condenser bushing remains unclear. In addition, the oil–paper insulation and the conductive foils located between the insulating
papers constitute the special structure of ‘oil-paper–foil’ in the OIP bushing. This feature can uniform the electric field effectively. The influence of conductive foil on the characteristic of oil-paper insulation remains unknown. Thus, the present study explores the ageing characteristic of OIP condenser bushing under the conditions that the operating parameters, such as temperature and voltage, are high, and guides the structural and technological progress of OIP condenser bushing.

This study designed the oil–paper insulation model of OIP condenser bushing and conducted a series of accelerated thermal ageing experiments under controlled laboratory conditions at 90°C, 100°C, and 130°C. The electrical and physical properties of oil–paper insulation were measured, and the thermal lifetime model of oil–paper insulation for OIP condenser bushing was obtained through the variation trend degree of polymerization (DP) data, the first-order kinematic equation, and Arrhenius thermodynamic equation. The scale model of the OIP condenser bushing further conducted the electrothermal ageing experiment at 100°C/62.8 kV. The dielectric properties were observed during the ageing process. The disintegration process was conducted on the bushing after its breakdown. The properties of oil–paper insulation in the bushing were also measured and analysed.

2 | EXPERIMENT

2.1 | Thermal ageing experiment of OIP condenser bushing

This study designed the condenser bushing model to investigate the ageing characteristics of OIP condenser bushing. The model consists of insulating paper (cable paper), copper conductor, and aluminium foil paper. The copper conductor was wrapped with 10 layers of insulating papers. Subsequently, a layer of aluminium foil paper was placed on the insulating paper, and 10 layers of papers were wrapped again. A total of 30 layers of papers and two layers of aluminium foil papers are all shown in Figure 1. The insulating paper at five sampling points from inside to outside in the condenser bushing model was selected to investigate its electrical and physical properties (Table 1).

With reference to the criterion for oil–paper thermal ageing from IEC 354-1991 [17], the reference temperature of oil-immersed transformer in normal operation is 80°C. When the operation temperature of oil-immersed transformer is between 90°C and 140°C, the insulation life of oil-paper decreases by about half for every 6°C increase in temperature. In order to obtain the lifetime model of oil-paper insulation based on the first-order kinematic equation and Arrhenius thermodynamic equation, a series of accelerated thermal experiments were conducted under controlled laboratory conditions at 90°C, 100°C, and 130°C. The oil-paper insulation samples of the OIP condenser bushing model with different degrees of thermal ageing were obtained. The experimental steps are presented as follows:

Step 1 Karamay #25 mineral oil with good properties and cable paper were selected as the insulating oil and insulating paper, respectively. The pretreatment of oil and paper was conducted before it was placed into operation for OIP condenser bushing [18, 19]. Oil and condenser bushing models were dried at 90°C/50 Pa for 24 h.

Step 2 Regarding the proportion of oil and paper in the OIP condenser bushing (1.5:1), the condenser bushing model was immersed in a certain amount of oil at 40°C/50 Pa for 24 h, and the oil-paper insulation samples of the OIP condenser bushing model was obtained. In addition, the bushing model without the aluminium foil papers was also immersed in the oil (1.5:1) at 40°C/50 Pa for 24 h, and the oil-paper insulation samples without the aluminium foil was obtained.

Step 3 The OIP condenser bushings were subsequently placed in a stainless-steel tank filled with nitrogen, which was placed in a thermal test chamber at 90°C, 100°C, and 130°C. The oil-paper insulation samples without the aluminium foil were also placed in the tanks, which were placed in a thermal test chamber at 130°C.

Step 4 During the thermal ageing experiment, the oils and papers were removed from the tank at intervals. The characteristic parameters of oil-paper insulation were measured and analysed (Table 2).

2.2 | Electrothermal ageing experiment of scale model of bushing

Figure 2 shows the scale model of OIP condenser bushing provided by Chongqing ABB transformer Co. Ltd according to the specification parameters of OIP condenser bushing. The parameters of the scaled model of bushing is shown in Table 3.

The electrothermal ageing experiment was conducted at 100°C and 62.8 kV (1.5 times of the phase voltage of bushing) to simulate the actual operation condition of OIP condenser bushing. Figure 3 shows the electrothermal ageing test platform of bushing, which is composed of silicone oil bath, alternating current (AC) test transformer, and OIP condenser bushing scale model. Silicone oil bath was used to control the experimental temperature. AC test transformer was used to provide electric stress to the bushing, the end shield of the
bushing was grounded. Given that oil–paper insulation cannot be removed from the bushing during the electrothermal ageing experiment, dielectric response analyser was used to measure and analyse the dielectric property of bushing during the experiment [8]. Bushing was disintegrated to obtain its oil–paper insulation when punctured by electric stress, and the electrical and physical/chemical parameters of oil–paper insulation of bushing were measured (Table 4).

### 3 | AGEING CHARACTERISTICS OF OIP CONDENSER BUSHING

#### 3.1 | Properties of oil–paper insulation

The DP is an important parameter for characterizing the mechanical strength and life expectancy of solid dielectric [23].
The change in the DP of the insulating paper at five sampling points from inside to outside in the OIP condenser bushing and oil–paper insulation without the aluminium foil is shown in Figure 4. The DP of different paper layers decreased with ageing time at different ageing temperatures. Figure 4a–c show that the decline rate of DP of the innermost and outermost paper layers were faster than those of the three other middle paper layers. The DP of the second middle paper layer was the highest. This finding indicated that the ageing degree of middle paper layer in the OIP condenser bushing was lower than the other paper layers. Figure 4c,d show that the decline rate of DP of paper in the oil–paper insulation without the aluminium foil was lower than that of paper in the OIP condenser bushing model. This finding preliminarily indicated that the aluminium foil accelerated the ageing degree of oil–paper insulation.

Resistivity reflects the deterioration degree of insulating paper during the thermal ageing process [18]. For example, the experimental data at 100°C provided the change in the resistivity of the insulating paper at five sampling points from inside to outside in the OIP condenser bushing and oil–paper insulation without the aluminium foil (Figure 5). The resistivity of different paper layers decreased with ageing time. Figure 5a shows that the decline rate of resistivity of the first and third middle paper layers was faster than those of the three other paper layers, and the resistivity of the second middle paper layer was the highest. Figure 5b shows that the decline rate of resistivity of paper in the oil–paper insulation without the aluminium foil was lower than that of the paper in the OIP condenser bushing, especially in the first and third paper layers. All of the above findings indicated that the aluminium foil with high electrical conductivity attached to the insulation paper easily decreased paper resistivity.

Water is the product of oil–paper insulation degradation. Water significantly influences the life expectancy of oil–paper insulation [24]. For example, the experimental data at 100°C presented the water content of insulating paper in the OIP condenser bushing, and the water content of different paper layers increased with some fluctuation (Figure 6). The increasing rate of the water content of the innermost and outermost paper layers were faster than those of the three other middle paper layers, and the water content of the second middle paper layer was the lowest. This finding preliminarily indicated that the water content of paper was negatively correlated with the paper DP. In Figure 6b, for example, the experimental data at 100°C in 110 days show that the relationship between the water content of different paper layers and DP indicated that the more water the paper contained, the lower the DP of the paper is. Water accumulates in the ageing process as a direct indicator of insulating system and significantly influences insulation life expectancy. The water with strong polarity generated by the degradation of oil–paper insulation has a low affinity for the insulating oil, which is easily transferred to the insulating paper fibre and promotes the hydrolysis action. This condition eventually causes a significant effect on DP variation. Hydrolysis action mainly caused the difference of deterioration speed at different paper layers.

Figure 7 shows the acidity and dielectric loss of oil in the OIP condenser bushing and oil–paper insulation without the aluminium foil, respectively. Acidity and dielectric loss increased with ageing time, the acidity and dielectric loss of oil at 130°C, 100°C, and 90°C was the highest, second highest, and lowest, respectively. The oil–paper insulation was gradually oxidized to generate a series of ageing products during the ageing process, in which the acidic substances dissolved in oil was deleterious. The ageing products with strong polarity also affected the dielectric properties of insulating oil, which lowered the dielectric loss of oil. In addition, the acidity and dielectric loss of oil in the oil–paper insulation without the aluminium foil were lower than that of oil in the OIP condenser bushing during the ageing process. This result further indicated that aluminium foil accelerated the deterioration of insulating oil.

The aluminium dissolved in oil was detected in the OIP condenser bushing during the ageing process. In Figure 8, the aluminium content of oil at 130°C, 100°C, and 90°C was the highest, second highest, and lowest, respectively. This result indicated that high temperature accelerated the dissolution of aluminium in oil. The aluminium foil in the OIP condenser bushing contributed to a surge in aluminium dissolution in oil, which further accelerated the deterioration of oil–paper insulation.

In general, the properties of oil–paper insulation in the OIP condenser bushing decreased with ageing time and temperature. This finding was consistent with the ageing trend of oil–paper insulation in the oil-immersed transformer. However, given the special construction of insulation layer in the bushing, the innermost and outermost layers of the insulating paper of bushing were in contact with the copper conductor and the aged oil, respectively. This exposure aided the easy adsorption of copper ions and ageing products dissolved in oil, thereby eventually accelerating the accumulation of water and degradation of oil–paper insulation.

### 3.2 Lifetime model of OIP condenser bushing

In this study, the thermal model of condenser bushing mainly considers the effect of temperature and ageing time on the insulation life of oil–paper, the thermal model of oil–paper in
The mechanical strength of insulation depends on the paper’s DP, which is the most significant parameter that reflects the degradation of paper cellulose and the service life of oil–paper insulation in the OIP condenser bushing. The lifetime model of oil–paper insulation in the OIP condenser bushing can be established through the first-order kinematic equation and Arrhenius thermodynamic equation based on the DP data of different paper layers in the OIP condenser bushing that varies with temperature and ageing time [25].

\[
\frac{1}{DP_t} - \frac{1}{DP_0} = Kt
\]

where \( DP_t \) and \( DP_0 \) represent the DP of the insulating paper at the ageing moment of \( t \) and initial time, respectively. \( K \) represents the kinetic parameter. \( \Delta E \) represents the activation energy. \( R \) represents the molar gas constant. \( T \) represents the thermodynamic temperature. \( A \) represents the constant.

The measured DP values of different paper layers at various thermal ageing temperatures were fitted to the first-order kinematic model (Figure 9a–c). This procedure exhibited the linear relationships with high goodness of fit. Arrhenius thermodynamic equation was further processed by logarithmic transformation, the kinetic parameter \( K \) from the matched curves between \( 1/DP_t - 1/DP_0 \) and ageing time was fitted to the Arrhenius thermodynamic equation (Figure 9d). The result obtained the dynamic model parameters of each paper layer (Table 5). At present, no relevant regulation regarding the end of thermal life of DP of insulating paper in the OIP condenser bushing is available. Referring to the stipulation of IEEE about the initial DP (1250) and end of thermal life of DP (250) of insulating paper in the oil-

![Image of DP of insulating paper at five sampling points from inside to outside in the OIP condenser bushing and oil-paper insulation without the aluminium foil.](image-url)
immersed transformer [26], the thermal lifetime model of oil–paper insulation in the OIP condenser bushing was established as follows. It should be noted that the hot spot temperature and temperature gradient inside the bushing are not same to the test temperature of accelerated thermal ageing condition in this study, and the lifetime model of oil–paper in the OIP condenser bushing was obtained through the accelerated thermal ageing experiments.

\[ L = \frac{1}{\tau K} = \frac{1}{250} - \frac{1}{1250} A \exp \left( \frac{-\Delta E}{RT} \right) \]  

4 | AGEING CHARACTERISTICS OF OIL–PAPER INSULATION IN THE SCALE MODEL OF BUSHING

To observe the electrical performance of bushing during the ageing process, we measured and analysed the dielectric response of bushing. After 133 days ageing of scale model of bushing under the action of electrothermal at 100°C/62.8 kV, the pressurized circuit of bushing tripped due to overcurrent protection. In order to exclude tripping caused by the discharge of bushing against the oil bath wall, the voltage applied to the scale model of bushing raised to 60 kV, and the overcurrent protection worked again. It can be determined that
the insulation of bushing failed after repeatedly checking the appearance of bushing and oil bath. The disintegration of bushing was then conducted to further determine the occurrence of breakdown and investigate the electrical and physical/chemical parameters of oil-paper insulation.

4.1 | Electrical properties of scale model of bushing during the ageing process

Figure 10a presents the variation trend of the frequency domain spectroscopy (FDS) of bushing during the electro-thermal ageing process. Before the breakdown of bushing, the FDS curve of bushing showed a trend of movement toward the high-frequency region with ageing time. After the breakdown of bushing at 133 ageing days, the amplitude of FDS increased dramatically in the high and middle frequency regions. The variation trend of power frequency dielectric loss of bushing with ageing time can be obtained on the basis of the FDS curve of bushing. In Figure 10b, the power frequency dielectric loss of bushing increased slowly during the ageing process, that is, it increased dramatically after the breakdown of bushing. Compared with the ageing time at 0 and 130 days of bushing, the power frequency dielectric loss of bushing after the breakdown increased by 850.7% and 465.7%, respectively.

Figure 11 presents the variation trend of the time domain dielectric characteristics of bushing during the electro-thermal ageing process. In Figure 11a,b, the polarization/depolarization current (PDC) of bushing showed an overall trend of shifting to the right with ageing time, indicating that the PDC increased and the insulation of bushing may suffer from damp [6, 8, 14]. After the breakdown of bushing, the PDC increased dramatically. Based on the PDC curve of bushing, the variation trend of insulation resistance of bushing with ageing time can be obtained (Figure 11c). When the dielectric is applied to the polarization voltage for 60 s, the ratio of polarization voltage \( U_0 \) (200 V) to the output current \( i_p \) seconds is obtained as the insulation resistance, which can be expressed as:

\[
R_{60} = \frac{U_0}{i_p(60)} \tag{4}
\]

In Figure 12, the \( R_{60} \) of bushing gradually decreased during early ageing, the rate of decline of \( R_{60} \) slowed down between 60 ageing days to 130 ageing days, thereby exhibiting a fluctuation between 4.5 and 5 GΩ. Compared with the ageing time at 0 and 130 days of bushing, the \( R_{60} \) of bushing after the breakdown decreased by 67.5% and 36.3%, respectively. All of the aforementioned findings indicated that the dielectric
properties of the scale model of bushing decreased gradually during the electrothermal ageing process and had a dramatical decline after the insulation breakdown.

### 4.2 Disintegration process of scale model of bushing

Figure 13a presents the internal components of bushing after disintegration. The insulation layer of bushing was composed of hundreds of layers of cable papers that wrapped the copper
conductor, and 13 layers of aluminium foil papers were equally located in the insulation layer of bushing. After the disintegration of the insulation layer, the discharge trace was found on the outermost paper layer, whereas no discharge trace appeared on the inner paper layer (Figure 13b,c), indicating that the occurrence of surface breakdown rather than bulk breakdown. The evident discharge trace was observed on the outermost layer insulating paper located between the copper conductor without the side of oil conservator and the end shield of bushing. However, no discharge trace was found on the outermost paper layer located between the copper conductor at the side of the oil conservator and end shield of bushing. Regarding the same creepage distance from the end shield of bushing to the two ends of copper conductor, the oil conservator plays a significant role in improving the distribution of electric field, thereby increasing the initial discharge voltage.

4.3 | Properties of oil–paper insulation in the scale model of bushing

The properties of insulating oil were investigated after the disintegration of the scale model of bushing. In Table 6, compared with the unaged oil before ageing experiment, the properties of oil had degraded severely after the bushing was punctured under the electrothermal action, especially the water content and dielectric loss were much higher than the threshold specified in the operation of bushing. The aluminium
content of oil increased from the initial 0 to 5.7 mg/L after bushing breakdown. Compared with the thermal ageing of OIP condenser bushing (Figure 8), the aluminium content of oil in the scale model of bushing under electrothermal ageing considerably increased because of the electrical stress. Metal dissolution was subjected to the thermal and electrical stresses, and electric field easily promoted the dissolution of metal in oil, thereby accelerating the ageing of oil [27]. Thus, aluminium foil can be used to control the electric field distributions within the bushing and also contributes to a surge in aluminium dissolution in the oil under the action of electrical stress. This effect further increases the content of metal ions in oil. The properties of oil are subjected to the metal ion, which results in hydrogen peroxide decomposition and free radical formation, thereby eventually promoting the deterioration process of insulating oil.

The insulating paper at five sampling points from inside to outside in the scale model of bushing was selected to investigate its electrical and physical properties (Table 7). As depicted in Figure 14a a fluctuated trend of resistivity of paper, which varied greatly in different paper layers. The resistivity of the outermost paper layer was lowest, and the resistivity of the middle paper layer increased from the outer to inner in the bushing; however, the resistivity of the innermost paper layer suddenly declined. The reasons were analysed as follows. The oil–paper insulation of bushing had degraded severely under the action of electrothermal, leading to the formation of ageing products due to the deterioration of oil–paper. The outermost paper of bushing directly contacted with the degraded oil, which caused the ageing products that dissolved in oil mainly deposited on the surface of the outermost paper and the decline of electric strength of paper. This condition accelerated the development of surface discharge on the outermost paper and eventually lead to the insulation failure of bushing. Given the tight spacing among the insulating papers in the insulation layer of bushing, the difference in permeability of polar substances and moisture gradually increased the resistivity of paper from the outermost layer to the innermost layer in the bushing. However, the innermost paper layer of bushing directly contacted with the copper conductor, which easily adsorbed the copper ions dissolved from the copper conductor and further lead to the decline of electric strength of paper.

As depicted in Figure 14b, the DP and water content of different paper layers showed a fluctuated trend, varying oppositely from the outer to the inner in the bushing. This finding was negatively correlated and approximately consistent with the results of OIP condenser bushing in Section 3.2. The ageing degree of bushing under electrothermal ageing was more severe than that of OIP condenser bushing under single-thermal ageing; however, ageing trends were consistent. Thus, the thermal lifetime model of OIP condenser bushing (Table 5 and Equation 3) was used to calculate and estimate the DP of different paper layers in the bushing at 133 days ageing time. Table 8 shows that the difference between the estimated results and the measured results was rather small by using the thermal lifetime model of OIP condenser bushing, the relative error was less than 6%, which preliminarily verified the validity of lifetime model.

5 | ANALYSIS OF THE EFFECT OF OIL–PAPER STRUCTURE ON THE AGEING CHARACTERISTICS OF CONDENSER BUSHING

According to the above results, the unique structure of condenser bushing determines that the ageing characteristics of condenser bushing was different from those of oil-immersed transformer. Combined with the ageing characteristics of oil–paper insulation in condenser bushing, the effect of oil–paper structure on the ageing characteristics of condenser bushing can be illustrated into two parts.

On one hand, compared with the structure of condenser bushing, as the main insulation of transformer, oil-immersed paperboard is widely used for supporting and insulation in high and low voltage winding. As the turn-to-turn insulation of transformer, insulation winding comprises copper strip wrapped with fewer layers of insulating paper and is widely used for insulation for current and voltage transmissions. However, the insulation layer of condenser bushing is composed of hundreds of layers of cable papers that wrapped the copper conductor (copper pillar). The differences in oil–paper proportions and structure cause varying deterioration speeds of oil–paper under ageing process. The weight proportion of oil/paper in condenser bushing (1.5:1) is much less than that in oil-immersed transformer (10:1), and the number of insulation layers of condenser bushing is much more than that of insulation winding. All above the conditions eventually lead to the difference of variation trend between condenser bushing and oil-immersed transformer in the accumulation of water and degradation of oil–paper insulation.

On the other hand, compared with the structure of oil-immersed paperboard and insulation winding in oil-immersed transformer, some layers of aluminium foil papers are equally
located in the insulation layer of bushing so as to control the electric field distribution within the bushing. Based on the experimental results of this study, the deterioration rate of insulating paper in condenser bushing was faster than that of paper in the oil–paper insulation without the aluminium foil. The aluminium foil in condenser bushing contributed to a surge in aluminium dissolution in oil under the action of thermal and electric stresses. The increase of metal ions in oil directly affected the properties of oil–paper insulation through hydrogen peroxide decomposition and free radical formation, further accelerating the deterioration of oil–paper insulation.
TABLE 8  Estimation results of the DP of different paper layers in the scale model of bushing by using thermal lifetime model of OIP condenser bushing

| Different layers of paper in bushing | Measured DP | Estimated DP | Relative error (%) |
|-------------------------------------|-------------|--------------|-------------------|
| Innermost paper layer               | 431         | 423          | 1.85              |
| First middle paper layer            | 468         | 488          | 4.27              |
| Second middle paper layer           | 461         | 487          | 5.64              |
| Third middle paper layer            | 454         | 472          | 3.96              |
| Outermost paper layer               | 384         | 406          | 5.73              |

Abbreviations: DP, degree of polymerization; OIP, oil-immersed paper.

6 | CONCLUSION

Based on the experimental data under the action of thermal and electrothermal conditions, this study investigated the ageing characteristics and lifetime assessment of oil–paper insulation for OIP condenser bushing. The conclusions are presented as follows:

i. The oil–paper insulation of OIP condenser bushing model had degraded severely under thermal condition. The descending speed of DP of the innermost and the outermost layer paper was higher than that of middle layer paper. Given the special structure of insulation layer in the condenser bushing, the difference in water content on the different paper layers caused varying deterioration speeds in the paper. The innermost and outermost insulating paper layers of bushing were in contact with copper conductor and aged oil, which easily adsorbs the copper ions and ageing products dissolved in oil, respectively. The unique structure of bushing accelerated to accumulation of water and promoted the hydrolysis action, eventually causing the degradation of oil–paper insulation.

ii. Aluminium foil in the condenser bushing contributed to a surge in aluminium dissolution in oil under the action of thermal and electric stresses. The increase of metal ions in oil directly accelerated the deterioration of oil–paper insulation through hydrogen peroxide decomposition and free radical formation.

iii. Based on the DP data of different paper layers in the condenser bushing model that varied with temperature and ageing time, the lifetime model of oil–paper insulation for condenser bushing model was established through the first-order kinematic equation and Arrhenius thermodynamic equation.

iv. The surface breakdown of the scale model of bushing occurred after 133 days ageing, the dielectric properties of scale model of bushing had degraded gradually during the ageing process, and the properties of oil–paper insulation decreased severely after the breakdown of bushing.

v. The DP deviation of different paper layers in bushing between calculated value according to the established lifetime model of oil–paper insulation and actual value after the breakdown of the scale model of bushing was less than 6%, thereby preliminarily verifying the effectiveness of life model of oil–paper insulation in bushing.

In terms of getting operation state information in field real bushing, FDS or PDC could be a good choice to assess bushing insulation condition in the further work. Moreover, in order to improve the lifetime model of oil–paper in the condenser bushing to obtain the more accurate prediction results, the effect of moisture content of paper on ageing properties of oil–paper should be further investigated, and a time-temperature-moisture superposition method may be helpful for making more rational estimation of insulation lifetime during long time ageing.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the fund projects of the National Natural Science Foundation of China (Grant No. 51907014) and Natural Science Foundation of Chongqing Province of China (Grant No. cstc2019jcyj-msxmX0070).

ORCID

Sihang Gao  https://orcid.org/0000-0003-1754-0364

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How to cite this article: Gao S, Yang L, Ke T. Ageing characteristics and lifetime model of oil-paper insulation for oil-immersed paper condenser bushing. **High Voltage.** 2021;6:278–290. [https://doi.org/10.1049/hve2.12015](https://doi.org/10.1049/hve2.12015)