

# The Investigation on Thermal Aging Characteristics of Oil-Paper Insulation in Bushing

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**Abstract** – Bushing is the key link to connect outer and inner insulating systems and also the essential electric accessory in electric power system, especially in the high voltage engineering (AC 1000kV, DC 800kV). This paper presented the experimental research of thermal aging characteristic of oil-paper insulation used in bushing. A thermally accelerated aging experiment at 90°C was performed. The bushing models containing five layers of paper were sealed into the aging vessels and further aged for 250 days. Then several important parameters associated with the aging were observed and evaluated. The results showed that the degree of polymerization (DP) of papers gradually decreased. The DP values of outermost layer and middle layer fit well into the second-order kinematic model and first-order kinematic model, respectively. Less deterioration speed of the inter-layer paper than outer layer was confirmed by the variation of DP. Hydrolysis was considered as the main cause to this phenomenon. In addition, the logarithm of the furfural concentrations in insulation oil was found to have good linear relationship with DP of papers. Interestingly, when the aging time is about 250 days and DP is 419, the aging process reaches an inflection point at which the DP approaches the leveling off degree of polymerization (LODP) value. Both  $\tan \delta$  and acid number of oils increased, while surface and volume resistivity of papers decreased. The obtained results demonstrated that thermal aging and moisture absorbed in papers brought great influence to the degradation of insulating paper, leading to rapid decrease of DP and increase of the  $\tan \delta$ . Thus, the bushing should be avoided from damp and real-time monitoring to the variation of  $\tan \delta$  and DP values of paper is an effective way to evaluate the insulation status of bushing.

**Keywords:** Bushing, Aging characteristics, Oil-paper insulation, Thermal aging

## 1. Introduction

The bushing is one of the most critical electric power accessory components. It plays a vital role in electric power system acting as insulation and support [1-2]. With the increase of electrical energy demand, the voltage levels of power transmission systems increase rapidly and ultra-high voltage engineering (AC 1000kV, DC 800kV) have been established in a large number of countries. The voltage level of bushing must be improved correspondingly and efforts have been made to innovate or improve the reliability of bushing. However, the failure of bushing still happened frequently, and a common characteristic of each failure was the arcing marks found between the draw lead cable and the tube in the center of the bushings, although these bushings passed the corresponding standard routine test. The failures have become the main cause of transformer, leading to bring huge damage to economy. At the same time, the failures of high voltage bushings have

drawn lots of attentions as well [3-5].

Generally speaking, the bushing is a hollow insulator that allowing a kind of Copper conductor to pass along its center and connect at both ends to other equipment such as electric power transformer. The investigation carried out in this paper is based on the typical oil impregnated paper (OIP) condenser bushing as shown in Fig. 1.

Inside the OIP bushing [6], the Copper conductor is wrapped by paper insulation medium, which has been impregnated with insulating oil around copper conductor (Fig. 1a). Innermost layer is connected to high voltage copper conductor and the outermost layer is connected to the grounded flange. Some conductive sheets or foils are placed within paper winding. These foils are positioned to control the electric field distributions within the bushing (Fig. 1b).

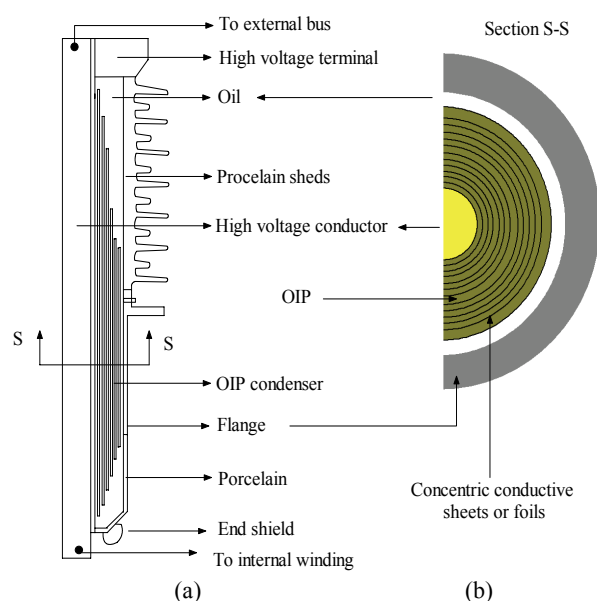
It is commonly accepted that most of bushing failures are caused by the following two factors: bushing structure design and insulation characteristic. Generally, the lifetime of insulation determines the lifetime of bushing to a great extent. Unfortunately, during the course of operation the oil-paper insulation will deteriorate under a combination of heat, water, electric field, oxygen and other environmental stress [7-9]. Among these factors, thermal stress is proved to be the leading one. And water, only second to

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**Fig. 1.** Oil-impregnated paper condenser bushing: (a) Main structure; (b) Cross sectional view (S-S)

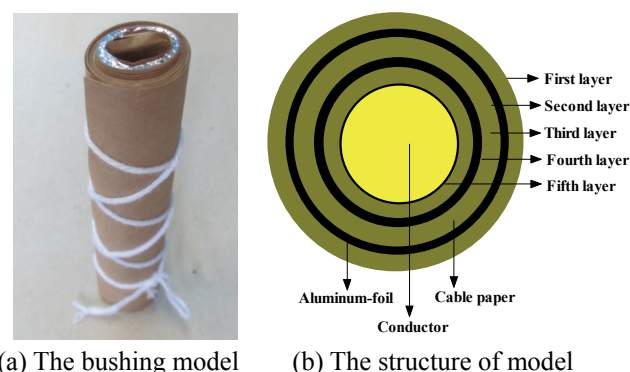
temperature, has been recognized as another culprit of oil-paper insulation. High temperature and moisture contents can not only accelerate the aging rate of the cellulose but also decrease the electric power device's life [10]. However, these conclusions were obtained all based on oil-impregnated power transformer, whether these conclusions are suitable for OIP bushing or not is not well understood. Because the weight proportion between oil and paper in bushing (3:2) is largely different from that in transformer (20:1). On the other hand, there are some conductive foils placed between insulation papers to uniform electric field. What influence will be brought to oil/paper insulation by foils is uncertain as well. And also researchers pay much attention to the structure design of bushing and on-line condition monitoring [11-13], but little to the thermal aging characteristic of oil/paper insulation inside the bushing.

Therefore, it is essential to investigate the thermal aging characteristic of oil/paper insulation used in high voltage bushing and add to the knowledge surrounding this subject. In this paper, the bushing models were aged at 90°C for 250 days to simulate the aging process of high voltage bushing. Several important parameters associated with thermal aging of oil-paper insulation were observed and analyzed, especially the DP, furfural concentration and variation of moisture content. The relationship of investigated parameters was further explored as well.

## 2. Experimental Arrangements

### 2.1 Sample preparation

The oil/paper insulation system in bushing consists of



**Fig. 2.** Hand-made bushing model and its structure

insulation oil and insulation paper. Cable paper (thickness: 0.125 mm) was used as paper insulation, provided by Chongqing ABB transformer Co. Ltd. The 25# mineral insulation oil was chosen as the insulation oil which satisfies the ASTM D3487-2000(II). In order to simulate the structure of real bushing, hand-made bushing model was made as shown in Fig. 2.

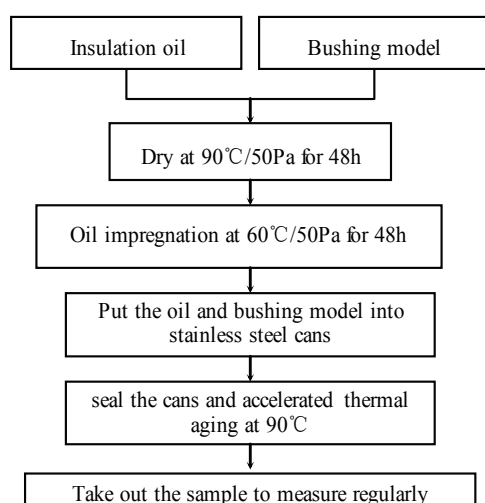
In this bushing model a kind of Copper conductor was wrapped with ten layers of cable papers, then a layer of aluminum-foil paper wrapped the cable papers and then wrapped ten layers of cable papers again, thirty layers of papers and two layers of aluminum-foil papers in all. The aluminum-foil papers are placed between insulating paper just in order to make the electric field more uniform. In other words, the conductive sheets or foils are positioned to control the electric field distribution within the bushing. The bushing model object and the structure of the model is given in Fig. 2(a) and Fig. 2(b), respectively. Five points were selected in this bushing model to conduct research as shown in Fig. 2(b).

Before the experiment, the oil / paper insulation was reprocessed to simulate the treating process of real bushing. The treatment of the samples was divided into three steps, as discussed in the succeeding paragraphs.

**Step 1.** The insulation oil and bushing models were all placed in a vacuum chamber dried at 90°C/50Pa for 48h. Then nitrogen was fed into the vacuum chamber and one of the bushings and oil sample were taken out to measure the moisture content which must be controlled within the ranges of 0~0.5 % for paper and 0~10 ppm for oil, respectively. If not, the samples should be dried for a longer time to ensure the moisture content is within the ranges.

**Step 2.** Put the bushing models into the insulation oil immediately under the circumstance of nitrogen. Both of them were placed in stainless vans and dried for another 48h at 60°C/50 Pa to accomplish the oil impregnation process.

**Step 3.** Took all samples out of the vacuum chamber and sealed the stainless vans. Then put them into the aging oven whose temperature was set to 90°C for accelerated



**Fig. 3.** Accelerated thermal aging experiment flowchart

thermal aging experiment. Finally, took out the samples one by one regularly, measured and analyzed the associated parameters subsequently. The flowchart of accelerated thermal aging experiment of oil-paper insulation samples is shown in Fig. 3.

## 2.2 Test items for thermal aging

Two objects including six associated parameters were measured to investigate the aging characteristic of oil/paper insulation. The detail information is listed in Table 1.

**Table 1.** Test objects, items and methods

Objects	Test items	Methods / Equipment
Oil	Tan $\delta$	DTL C
	Acid number	Potentiometric titration
	Furfural content	Liquid chromatograph
Paper	DP	Viscometer
	Moisture content	Moisture meter
	Resistivity	Keithley 6517B

The measurement of DP was carried out by using viscometer. The moisture content was analyzed by Karl Fischer Titration at 25°C. Surface and volume resistivity of paper were conducted by Keithley 6517B ohmmeter made in Germany. The dielectric loss tangent was determined according to the method of ASTM D924-08 using DTL C BUAR made in Austria. The acid number and furfural concentration were observed by potentiometric titration and liquid chromatograph, respectively.

## 3. Results and discussion

### 3.1 The DP of paper

It is commonly accepted that the insulating paper consists of cellulose and some residual lignin whose main

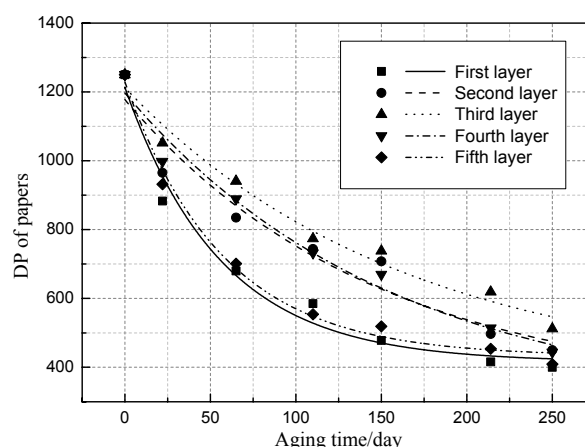
component is cellulose substance. Basically, the cellulose is formed by linear, polymeric chains of cyclic, anhydro- $\beta$ -D-glucopyranose units, the number of which per chain is defined as the degree of polymerization (DP). The mechanical strength of insulation depends on DP of paper, and the mechanical strength is one of the most important factors that limit the technical lift of bushing. IEEE recommended that the mean DP can be represented as a reliable characterization of insulating paper aging [14]. Unfortunately, the DP value of paper will decrease gradually due to environmental factors such as heat, moisture, electric field and other stresses, especially the first two stresses. The tensile strength of insulating paper drops to 20% of its original value when the DP of the paper falls to 200 [15]. At the same time, the lifetime of paper insulation has reached its end point. It was reported that first/second-order kinematic model can be adopted to describe the degradation process of the cellulose based on the DP information with aging or the hypothesis of random chain scission [16-17]. The two models are shown as follows:

$$\frac{1}{DP_t} - \frac{1}{DP_0} = kt \quad (1)$$

$$\frac{1}{DP_t} - \frac{1}{DP_0} = \frac{k_1}{k_2} (1 - e^{-k_2 t}) \quad (2)$$

Where  $t$  indicates the aging time,  $DP_t$  and  $DP_0$  are degree of polymerization of paper at  $t$  and the initial time respectively,  $k$ ,  $k_1$  and  $k_2$  are constant. Five points from five layers were selected to observe the DP values as shown in Fig. 2(b) to get a better understanding of the DP difference, Five curves which described the variation of DP value at different insulating paper layers associated with aging time was given in Fig. 4.

It was found that the DP variation tendency of the first and fifth paper layers were similar with each other, and the second and fourth paper layers showed the same tendency, but lower deterioration speed than that of outermost (first



**Fig. 4.** DP of paper and its fitting

layer) and innermost (fifth layer) paper layers. However, the DP variation tendency of third layer indicated that its deterioration speed was the lowest. In addition, the measured DP values of first/fifth and third layers are fitted to first and second-order kinematic model, respectively.

According to the Fig. 4, the DP (third layer) is fitted to Eq. (1). The adjusted R-square (goodness of fitting) is 0.9751 and  $k$  is  $4.4 \times 10^{-6}$ . The DP (first/fifth layer) is fitted to Eq. (2). The adjusted R-square (goodness of fitting) is 0.98989,  $k_1$  is  $1.08 \times 10^{-5}$  and  $k_2$  is  $-4.1 \times 10^{-3}$ . The results shown in Fig. 4 indicate that the experimental data fits into these two models well. On the other hand, a hypothesis was proposed to explain this difference of deterioration speed at different paper layers. Hydrolysis action was considered as the main reason to this phenomenon. Further investigation was carried out in the following part.

### 3.2 The moisture content in paper

The moisture content in paper was measured at 25°C and the variation of moisture during the aging process is given in Fig. 5. It was obviously that the moisture content increased and decreased alternately, the values fluctuated in whole process.

It is known that water is one of the by-products produced by the degradation of oil/paper insulation. And in turn, water accelerates the depolymerization of paper insulation leading to the consumption of water, both of above reasons result in the fluctuation in the aging process. Reference [18] proved that there was a relationship between the distribution of water content in paper insulation and its DP and ambient temperature. Therefore, it is inferred that the action of water called hydrolysis action might have a significant effect on variation of DP in different layers of paper.

In order to investigate the phenomenon of part 3.1, two aging samples (aged for 150 days and 214 days) were chosen to measure the moisture contents, the DP of five different layers of paper as shown in Fig. 2b were obtained to explain the causes. The Fig. 6 shows the results.

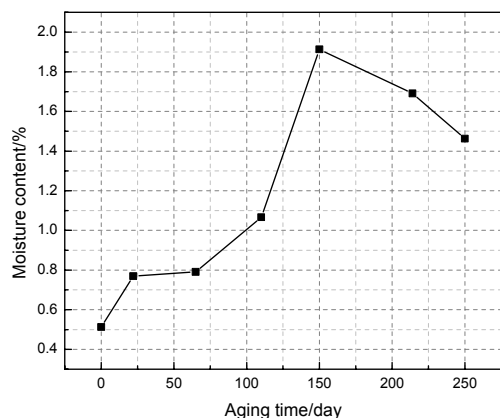
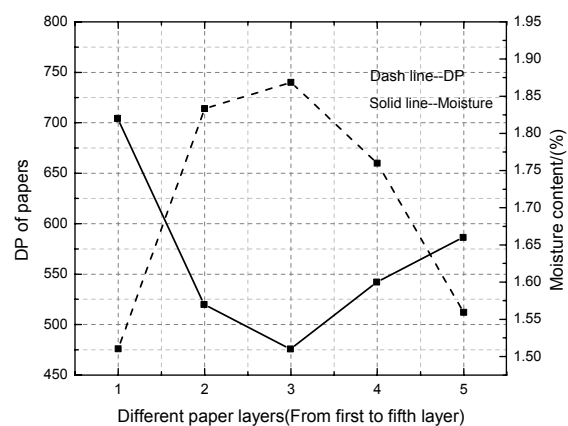
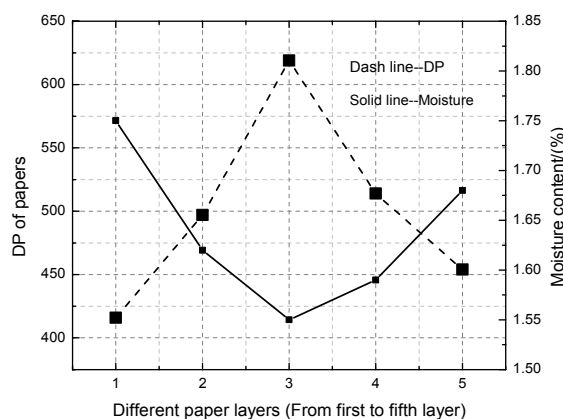


Fig. 5. The moisture content in paper



(a) Aged for 150 days

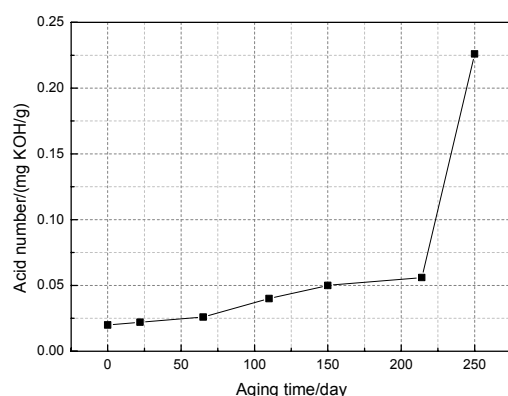


(b) Aged for 214 days

Fig. 6. The relationship between moisture content of different paper layers and DP

Although it is difficult to get good correlation between water content and aging time as shown in Fig. 5, good relationship can be found between DP of different paper layers and its water content. As seen in Fig. 6, the horizontal axis represents five layers of papers from outermost layer to innermost layer. The vertical axis represents DP of paper (dash line) and water content (solid line) in paper, respectively. It was obviously that DP of paper increased (from outermost layer to third layer) and then decreased (from third layer to innermost layer). However, the water content in papers manifested the opposite trend (decreased from outermost layer to third layer, increased from third layer to innermost layer). It is obviously that there is a negative correlation between DP and the position where papers locates. More water content the paper contains, lower DP it becomes.

A balance for distribution of water between paper and oil will be kept after the oil-paper sample is placed in a certain condition. This status of balance is called dynamic balancing, since the water transfers into oil-paper insulation back and forth. During the process of aging, the water generated by paper will transfer into bulk oil due to the concentration gradient. The outermost and innermost



**Fig. 7.** Variation of acid in oil with the aging time

layers of papers are close to the bulk oil. It is obviously that the interaction or transference of water between paper and oil seems like more frequent than that of middle layer of paper. On the other hand, acids including high and low molecular weight acids generated by aging of oil-paper affect the degradation of paper greatly [19-20] due to the ionization of  $H^+$ . Part of acids can dissolve into the bulk oils which are close to the first and fifth layers of paper. Both of above two reasons result in the accelerated hydrolysis of cellulose paper.

### 3.3 The acid number of oil

The variation of acid number is given in Fig. 7. As the aging goes on, it is obviously that the acid number of oil increases slowly, the value of acid number is less than 0.06 mg KOH/g, which still satisfies the demand of oil quality. However, in the middle or the later stage of aging, the acid number increases quickly.

It was commonly accepted that the acid was generated by the aging of oil/paper insulation, and in turn the acid exacerbates the aging of oil-paper, leading to an increasing amount of  $H^+$ . The  $H^+$  not only reduces the insulation performance of bushing by accelerating hydrolysis of paper, but also enhances the electrical conductivity of oil-paper insulation. On the other hand, more metal ions such as copper ions will be formed due to reaction between  $H^+$  and copper conductor, which results in the increase of  $\tan \delta$ .

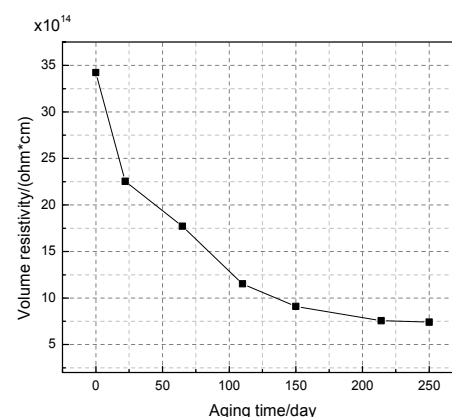
Although the acid has a great influence on the characteristic of oil-paper, especially the aging of cellulose paper, not all of acids do. The acids only absorbed or permeated into the paper contribute to the aging of cellulose, most of which are low molecular weight acids. As the low molecular weight acids favor water, and the water is mostly stored in paper. The measured acid numbers in oil are high molecular weight acids due to the fact that they dissolve easily in the oils. These acids contribute little to the aging of paper [21]. The reference [22] proved that the effect of acid, especially the water solution acid on the aging of paper will highlight when the paper is affected by damp. At the same time, the

combination effect of acid and water called “autocatalytic reaction” accelerate the degradation process. However, the coexistence problem of acid and moisture in oil-paper cannot be avoided. Oil filtration or oil change should be taken into account.

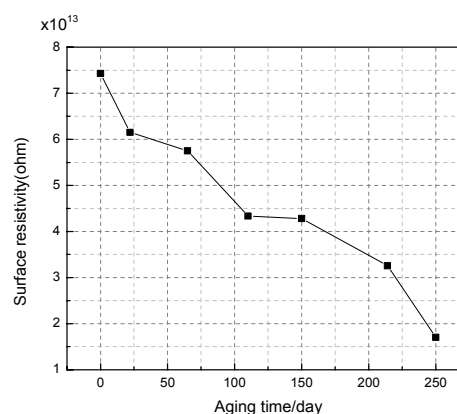
### 3.4 The resistivity of paper

The variation of volume and resistivity of papers are demonstrated in Fig. 8. With the increase of aging time, the volume resistivity of papers presented a decreasing trend and a turning point of descending rate at 200 days after which it kept stable. Interestingly, the surface resistivity of paper presented a single downward trend.

The volume and surface of resistivity are calculated based on the physical dimensions of the electrodes of the Model 8009 combined with 6517B electrometer. Generally speaking, volume resistivity is defined as the electrical resistance through a one-centimeter cube of insulating material (paper) and is expressed in ohm-centimeters the volume resistivity is measured by applying a voltage potential across opposite sides of the insulator sample, measuring the resultant current through the sample. The surface resistivity is defined as the electrical resistance of the surface of an insulator material. It is measured from



**(a)** Volume resistivity



**(b)** Surface resistivity

**Fig. 8.** Variation of resistivity with the aging time

electrode to electrode along the surface of the insulating material and by applying a voltage potential across the surface of the sample, measuring the resultant current. So, the volume resistivity largely depends on the thickness of paper or the degradation degree of inside of paper. However, the surface resistivity is obviously affected by the conditions of paper surface only.

The resistivity of paper is largely influenced by polar substances such as water, acid, metal ions and others. Especially the surface resistivity, the polar components deposited on the surface of paper will transfer when the paper is suffered from the DC applied voltage. More complicated the paper surface, the lower resistivity it is. However, the volume resistivity depends on not only the polar components but also the DP of paper. The strength of paper inside or the polar components inside of paper play a role in the variation of volume resistivity as well. With the aging time goes and the increase of polar substance, the volume resistivity decreased and then kept stable. It seems that the reason is attributed to the stability of the DP of paper. Thus, the variation of volume resistivity of paper could be considered as one of main parameters to evaluate the insulation status of paper to some extent.

### 3.5 The $\tan \delta$ of oil

The variation of  $\tan \delta$  is shown in Fig. 9. It increases slowly during the first 70 days, and then grows faster. And 200 days later, it grows remarkably. It is considered that  $\tan \delta$  is determined by the charge carriers within the oil and easily affected by polar compounds or conductive ions such as acids, water, furfural, copper ions and others. All above the substances are originated from the aging of oil-paper insulation. It is sensitive to the aging degree of oil and the insulating ability,  $\tan \delta$  is related with the oil aging directly [23]. Thus,  $\tan \delta$  can effectively be employed to gain insight into the status of oil-paper insulation and the dielectric loss behavior of oils, especially for bushings.

As we all know that the mineral oil is a kind of non-polar substance, the molecules of which are basically

symmetric. The dielectric loss is a function of ion concentration, the oil type, and mobility of the charge carriers. During oil aging, and mostly in case of overheating, the concentration of polar compounds and radicals increase, correspondingly the  $\tan \delta$  increases. So the variation of  $\tan \delta$  might be attributed to the polar compounds and radicals such as high molecular weight acid number, furfural concentrations, metal ions and so on.

### 3.6 The Furfural concentration

The furans can be used as an effective parameter to value the insulation status or deterioration degree of paper, as furans are part of the degradation by-products of paper in bushings [24-25]. And they can be easily measured because they dissolve in oils absolutely. Five main furan compounds including 2-furaldehyde (2FAL), 5-methyl-2-furaldehyde (5M2F), 2-acetyl furan (2ACF), 5-hydroxymethyl-2-furaldehyde (5H2F) and 2-furfural (2FOL) are formed due to the degradation of paper. Among these compounds, 2-furaldehyde (2-furfural) is considered measurement due to its relatively higher generation [26]. The change of furfural concentrations with the aging time is given in Fig. 11 which shows a rising trend with the development of aging.

The oil-impregnated paper degradation mechanism depends on the DP of paper to some extent. However, it is impractical to get paper samples in field bushing because it will lead to de-energization of bushing and even bring intrusive impact to bushing. Fortunately, Lots of researchers found that furfural concentration in oil carried DP information which can reflect the degradation degree of paper [27-28]. As the furans is generated only by paper and it is convenient to obtain oil sample without the need to have a bushing outage.

Chendong and other researchers [29] considered that there was a liner relationship between the DP of paper and the logarithm value of furfural. DP information of paper can be gotten through this relationship as seen the Eq. (3) as follows called model a. The parameters are specified

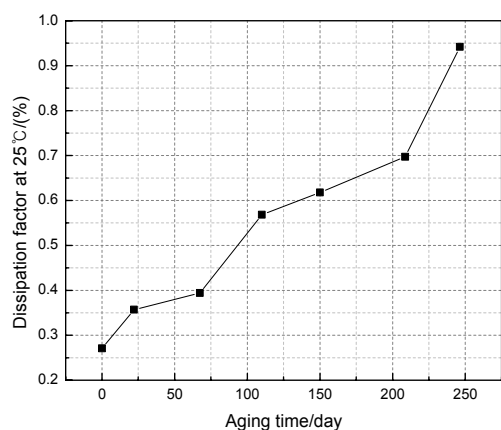


Fig. 9. Variation of dissipation factor with the aging time

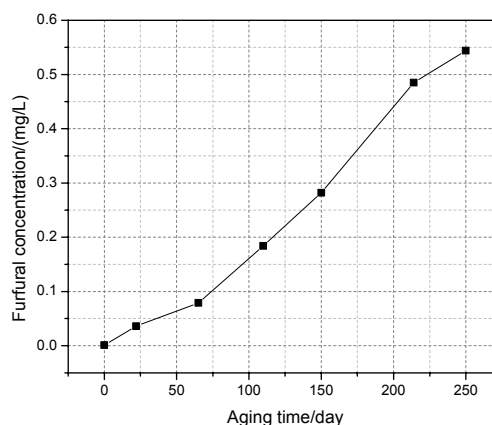


Fig. 10. Variation of furfural content with the aging time

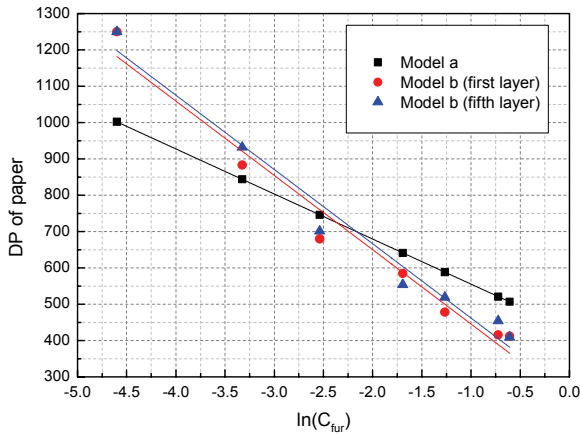


in this model. On the other hand, Pradhan et al. [30] proposed another model as seen the Eq. (4) named model b in which the parameters A/B must be gotten by fitting the experimental data.

$$DP = \frac{1.51 - \log_{10}(C_{fur})}{0.0035} \quad (3)$$

$$DP = A \times \ln(C_{fur}) + B \quad (4)$$

It is found in Fig. 4 that the degradation speed of the first and fifth layer papers were similar with each other and the speed of which were faster than other layers. At the same time, the first layer paper was close to the bulk oil area in which lots of substances will exert stress to the paper. While the fifth layer paper is nest to copper conductor and easily affected by the metal ions and other components in oil simultaneously.



**Fig. 11.** Semi-logarithm liner relationship between DP and furfural concentration

So the DP information of two layers and experimental data of furfural concentration fitting to the model b are given in Fig. 10 above. Another model whose parameters are specified is drawn as well. The relationship between DP of two layer paper and furfural concentration based on the model b are shown in the following Eq. (5) and Eq. (6), respectively.

$$DP_1 = -204.6 \times \ln(C_{fur}) + 240.7 \quad (5)$$

$$DP_1 = -204.5 \times \ln(C_{fur}) + 257.6 \quad (6)$$

Generally speaking, the performance of models are compared through mean prediction error (MPE) and mean square error (MSE), both of whose values can be obtained Eq. (7) and Eq. (8) as follows:

$$MPE = \frac{1}{N} \sum_{i=1}^N \frac{y_i - \bar{y}_i}{y_i} \quad (7)$$

**Table 2.** Test objects, items and methods

	MPE	MSE
model a	0.10969	3622.95
model b (first layer)	0.02915	1553.14
model b (fifth layer)	0.00281	1970.14

$$MSE = \frac{1}{N} \sum_{i=1}^N (y_i - \bar{y}_i)^2 \quad (8)$$

Where  $y_i$  is the actual value of DP and  $\bar{y}_i$  is the predicted value of DP through the model, N is the sample number. The table 2 shows the calculated results. We can find that both of MPE and MSE in model b are smaller than that of model a, indicating model b has more advantage more model a, and can predict DP value more accurately. To model b, it is more available to predict the DP value of fifth layer other than that of first layer.

Thus, the DP value of paper can be obtained if given the furfural concentration in oil, and the furfural information can be used as aging indicator for the evaluation and residual life assessment of oil-impregnated bushing with paper as its solid insulation material.

## 4. Conclusion

A thermal aging experiment with bushing model and insulating oil is built to simulate the real operating condition of oil-impregnated paper bushing. Accelerated aging test is carried out at 90°C for 250 days and associated parameters are investigated. A surprising phenomenon could be observed that with process of aging, the DP of paper at different layers shows the different degradation speed, although the DP of all five layers of paper decrease compared with the initial ones. The DP of papers is almost inversely proportional to the moisture contents. The acid concentration and  $\tan \delta$  of oil increase with a faster rate in the later stage of aging. Both of the surface and volume resistivity decrease. The following conclusions could be drawn:

- (1) The DP variation of different layers of paper differ from each other, while the change of first and fifth layers of paper are similar to each other. The second and fourth layers of paper show the similar phenomenon as well. However, the degradation speed of third layer of paper suggests the slowest, the second and fourth layers come to the second, and DP degradation speed of paper whose places locates at outermost and fifth layer show the fastest. Hydrolysis action is considered as the main reason to this difference. In addition, the measured DP values of first/fifth and third layers are fitted to first and second-order kinematic model, respectively. The DP of first and fifth layers of paper has approached the leveling off degree of polymerization indicating the deceleration of the degradation process

of paper.

- (2) The moisture contents in paper fluctuates in the whole aging process, it is not easy to find the relationship between the change of moisture contents and the DP of paper. However, good correlation could be obtained between the moisture contents in paper and its layer. There is a negative correlation between DP and the position where papers locates. More moisture content the paper contains, the lower DP it becomes.
- (3) Acid concentration in oil plays a vital role in the increase of the  $\tan \delta$ . While acid permeated into the paper contributes to the degradation of paper, especially when the paper is suffered from the damp. It is considered that the Hydrolysis action on the outermost layer of paper leads to more degradation speed than that of middle layer paper, especially when the paper is suffered from the combination effect of water and acid. The degradation process is catalyzed and accelerated by the acids accumulated or dissolved in the bulk oil.
- (4) The surface resistivity shows a signal downtrend, while the variation of volume resistivity reaches an inflection point where the change of value becomes slowly. As the surface resistivity is largely affected by the polar substances on the surface of paper, however, the volume resistivity depends on the polar components and degradation degree of inside of paper simultaneously.
- (5) Furfural concentration in the oil is generated by insulating paper only. There is a liner relationship between the DP of paper and the logarithm value of furfural. This relationship can be used to obtain the DP information of paper when the furfural concentration is given.

The experiment was based on the bushing model and the associated parameters were obtained through measuring the oil and paper. However, in field real bushing it is not convenient to get above information. On-line status monitoring using non-intrusive detection methods such as frequency domain spectroscopy (FDS) technique to assess bushing insulation condition could be a good choice. And the future work lies in adapting FDS diagnostic technique to get insulation information of bushing, especially the variation of  $\tan \delta$  and capacitance.

### Acknowledgements

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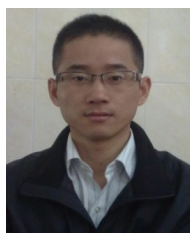
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