Study on the Influence of Oil Replacement on Furfural Content in Transformer Oil and Insulation Aging Assessment

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Abstract. The service life of a transformer was determined by the aging state of solid insulation. When the aging state of the transformer insulation reaches a certain level, oil replacement or oil filter was performed to improve the insulation ability of the insulating oil. A series of treatments of insulating oil inevitably result in the loss of furfural in the oil. In order to study the effect of oil replacement on the furfural content in oil, oil-paper insulation samples with different aging degrees were prepared under laboratory conditions. Besides, oil replacement was carried out in different aging stages, and the times of oil replacement was divided into once and multiple. Furthermore, the furfural content in oil was compared before and after oil replacement, and the effect of oil replacement on the furfural content in transformer oil was analyzed. The results showed that oil replacement had little effect on furfural content in the early aging stage, while it has a greater effect on furfural content in the late aging stage. In addition, the cumulatively of multiple oil replacement on the loss of furfural in oil can cause greater deviations in transformer aging evaluation. Therefore, the effect of oil replacement on the evaluation of insulation aging of transformer is not negligible.

1. Introduction

The power transformer is one of the core equipment of the power grid, and its stable and safe operation is of great significance to the power grid system [1]. The oil-paper insulation system of transformer has experienced irreversible deterioration during long-term operation and was affected by aging factors such as electricity, heat and vibration [2-4]. Therefore, the aging status of oil-paper insulation of transformers is effectively and reliably evaluated, which can effectively eliminate the potential risk of failure. Ensure reliable operation of the transformer [5].

Since the sample of transformer insulation paper was difficult to obtain, at present, indirect evaluation method is often used to evaluate the insulation deterioration of transformer through the aging characteristic substances dissolved in the transformer oil [6]. Typical methods include moisture in the insulating oil, acid value analysis and dissolved gas analysis in oil [7], alcohols and furfural analysis. Since the furfural content in the transformer oil was high and stable, the detection cost was low. Therefore, the detection of furfural content in oil as an ideal method is widely utilized for evaluating the aging state of transformer insulation paper.
Furfural is a furan substance produced by the breakage of cellulose molecular chains during the deterioration of insulating paper [8-9]. In 1984, British scholars first proposed the method of evaluating the aging of insulating paper by using furfural content in transformer oil and it has been widely recognized. Furfural produced from insulating paper is diffuse into the insulating oil until it is equilibrium distribution between the oil-paper insulation systems. Therefore, the furfural content in the oil is closely related to the degree of aging of the insulating paper.

When the deterioration of insulation oil has reached a certain level during the operation of the transformer, in order to improve the insulation performance of the transformer, the transformer oil was replaced. The maintenance cost of power Grid Company can be greatly reduced by oil replacement instead of transformer. Therefore, oil replacement is of great significance for improving the insulation state of the transformer. During the oil replacement process, Furfural is eliminated. Thus, the Furfural content in oil can't reflect the aging state of insulating paper correctly.

In this paper, accelerated thermal aging experiments were carried out on oil-paper insulation samples in the laboratory, and the oil replacement operation of samples at different aging stages. The number and time of oil replacement for oil-paper insulation samples are different. Then the content of furfural in oil was analyzed and compared before and after oil replacement. The results show that the oil replacement was carried out at the later stage of the sample aging, and the loss of furfural in the oil is large, which has great effect on the insulation aging assessment of the transformer. And multiple times oil replacements have a greater impact on insulation aging assessment.

2. Experiments
The experiment mainly includes Sample pretreatment and accelerated thermal aging, Furfural equilibrium and sampling, oil replacement.

2.1. Sample pretreatment and accelerated thermal aging
The oil-paper insulation samples used in the experiment were made of Karamay 25# mineral oil and 0.5 mm thick cellulose insulation paper (90% cellulose, 6-7 % hemicellulose and 3-4% lignin). The mass ratio of insulating oil to insulating paper is set to 20:1. The insulating paper was cut into pressboard disc with a radius of 9 cm and placed in an insulating paper holder. Firstly, the insulating paper holder containing the insulating paper and the stainless steel aging tank containing the transformer oil are respectively dried in a vacuum immersion tank, and the drying temperature is 95°C for 48 hours. The moisture content of paper and oil are controlled below 1% and 10 mg/kg, respectively. Secondly, the insulating paper was immersed in oil at 60°C for 48 hours under vacuum conditions. Thirdly, the oil-paper insulation sample placed in the aging tank was strictly sealed. Finally, the obtained oil-paper insulation sample was placed in an aging chamber at 130°C for accelerated heat aging experiments. The process of the experiment is shown in Figure 1.

![Figure 1. Experimental process.](image)

2.2. Furfural equilibrium and sampling
The oil-paper insulation samples were subjected to accelerated heat aging for 35 days. During the aging process, some of the samples were sampled every 7 days. In order to better simulate the working
environment of field transformer, the aging tank was transferred to the incubator for 5 days at 60°C before sampling, which can ensure that the furfural was equilibrium between oil and paper. After equilibrium, the aging tank was opened and 40 mL of the insulating oil sample was taken by a pipette into a brown glass bottle to prevent decomposition of the furfural. The furfural content in the oil was determined by high performance liquid chromatography (HPLC) according to the IEC 61198. A piece of paper sample was taken out from the insulating paper holder with tweezers. The degree of polymerization (DP) of the paper sample was measured by a viscosity method in accordance with the IEC 60450.

2.3. Oil replacement
Different time points and times of oil replacement were arranged during the experiment. The specific experimental scheme is shown in Figure 2. The aging tank was placed in an incubator at 60°C for 5 days before oil replacement. The fresh oil was dried under vacuum at 95°C for 48 hours. After the furfural in oil-paper insulation system was distribution equilibrium, the aged oil in the aging tank was replaced with the dried new oil, after the oil replacement process, the aging tank was kept vacuum sealed. The aging tank was placed in an incubator at 60°C after the oil replacement, which makes the furfural reached equilibrium at a constant temperature for 10 days. Furthermore, the furfural in oil was measured after oil sample was taken every 48 hours.

3. Results and Discussions
The thermal aging accelerated experiment was carried out for 35 days. According to the experimental scheme of Fig. 2, the samples of group A was measured furfural content in the insulating oil and the degree of polymerization of insulating paper every 7 days during the aging process. The furfural content and the degree of polymerization of the insulating paper can be obtained. The relationship between them is shown in Figure 3. As shown in Figure 3, that In the early stage of aging, the polymerization degree of insulating paper decreased rapidly while the furfural content in oil increased slowly. However, the polymerization degree of insulating paper decreased slowly and the furfural content of oil increased rapidly in the later stage of aging. The logarithm of the content of furfural in the oil exhibits a good linear relationship with the degree of polymerization of the insulating paper. The furfural-polymerization equation can be established by fitting, as shown in Equation 1.

$$DP = \frac{1.495 - \log_{10} F_{Al}}{0.00311}$$

In group B, C and D, oil replacement procedures were carried out in three different aging stages. Namely, group B: oil replacement on the 7th day, group C: oil replacement on the 14th day, group D:
oil replacement on the 21st day, respectively. It represents the oil replacement in the early, middle and late stages of aging. After oil replacement, the accelerated heat aging of the samples was continued and the content of furfural in the oil was measured. The analysis results are shown in Figure 4.

![Figure 3. Relationship between furfural content in oil and DP.](image1)

![Figure 4. Furfural content in oil after oil replacement.](image2)

As shown in Figure 4, furfural content in the oil decline due to the oil replacement, and the effect of oil replacement on different aging days has different effects on the furfural content of the oil. Using group D as an example, there was a significant difference in furfural content before and after oil replacement. By contrast, the differences in furfural content were relatively small in Group B. This phenomenon could be easily explained because furfural is produced by the cracking of cellulose chain. During the early aging stage, the aging degree of paper was low, so the furfural content in oil was low. But in the later stage of aging, a lot of furfural was produced and dissolved in oil. It can be concluded that the furfural content of oil is slightly loss after oil replacement at the early stage of aging, and significantly loss after oil replacement at the late stage of aging.
As can be seen from figure 5 and figure 6, Aging assessment based on the furfural content of oil produce great deviation due to oil replacement process. The influence of oil replacement in the early stage of aging on the aging evaluation of transformer is small. However, huge deviation in aging evaluation due to oil replacement in the later stage of aging. When the oil replacement process was just completed, the error between the evaluation of polymerization degree and the real value was the largest. With the aging process, the error decreases gradually. As shown in figure 6, the later the oil replacement time is, the better the improvement effect is on the insulation state of oil-paper insulation samples. This finding indicates that oil replacement of transformer can improve the insulation performance of transformer and enhance the service life of transformer.
Figure 7. Multiple oil replacements and single oil replacements.

Figure 7 shows the oil replacement for multiple times and once time. For Group E, the aged oil was replaced twice (i.e., during early and late aging stages). And single oil replacement (Group B, Group C). It can be seen that the loss of furfural in oil can be accumulated by replaced oil multiple times. It can be concluded that greater deviations in transformer aging evaluation due to multiple oil replacements.

4. Conclusion

In this paper, the oil-paper insulation samples are accelerated aging in the laboratory and oil replacement is carried out in different aging stages. The polymerization degree of insulating paper and the content of furfural in oil were analyzed under different oil replacement conditions. The conclusions are as follows.

(1) In the oil-paper insulation samples by accelerating thermal aging in the laboratory, the logarithm of the content of furfural in the oil showed a good linear relationship with the degree of polymerization of the insulating paper, and the linearity is excellent.

(2) Oil replacement is carried out in the early stage of aging, and the loss of furfural in the oil is small and has little effect on the insulation aging assessment of the transformer. Oil replacement is carried out in the later stage of aging, and the loss of furfural in the oil is large and has a great influence on the insulation aging assessment of the transformer.

(3) The insulation performance of oil-paper insulation system is slightly improved after oil replacement at the early stage of aging, and significantly improved after oil replacement at the late stage of aging.

(4) The accumulative loss of furfural in oil caused by multiple oil replacements will cause greater deviation to the insulation aging assessment of the transformer.

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