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RESEARCH ARTICLE

The Method for Improving the Effect of Oil-Replacement on Aging Assessment of Power Transformers Insulation Based on Methanol

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ABSTRACT Methanol was considered as a new chemical marker for estimating the aging state of transformer insulation paper, whereas oil-replacement could influent greatly the accuracy of the assessment results. In this paper, the 130 °C thermal aging experiment was carried out, and the oil-paper samples were divided into four groups for investigating the effect of the oil-replacement on assessment deviation of aging states of insulation paper. The results indicated that the present aging assessment model was not suitable for oil-replacement based on methanol in oil and the aging assessment errors of degree of polymerization (DP) had a decreasing tendency with increasing the aging time after oil-replacement. Furthermore, the oil-replacement correction factor was proposed as power-series expansion based on the experiment results, and a modified model was proposed by integrating the basic Methanol-DP model and the correction factor. Eventually, the verification experiment was prepared to test the accuracy of modified model and the results indicated that the relative assessment error of DP was within 4.8%. The accuracy of aging assessment are improved by oil-replacement correction factor.

INDEX TERMS Power transformers, aging assessment, methanol, oil-replacement, correction factor.

I. INTRODUCTION

The large power transformers play an important role in the power system, and its internal insulation is composited of oil-paper insulation system which mainly withstands the high electric field intensity [1], [2], [3]. The oil-paper insulation system is aged by temperature, oxygen, moisture, acid, et al., which could reduce the insulation property of oil-paper system [4], [5].

The insulation oil could recover its insulation property by replacing the oil, while the insulation paper is inconvenience to be replaced for power transformers [6], [7], [8]. Therefore, the operation conditions of transformers are determined by the aging state of insulation papers, and adopting the effective measurement methods for evaluating the aging state of insulation paper is important [9], [10], [11], [12].

The on-line assessment methods for insulation papers could be concluded into CO/CO_2 analysis, 2-furfural (2-FAL) analysis, and methanol analysis, et al., which are chemical diagnostic methods [13], [14], [15], [16], [17], [18]. These methods, have the competitive advantages of non-destructive detection, convenient operation and immunizing to electromagnetic interference, is widely applied in oil-paper insulation assessment technology [19], [20]. However, the on-line assessment methods were easily affected by operation condition, such as temperature, moisture content, and oil-replacement, et al.. [21], [22], [23].

Oil-replacement could effectively increase the service life of the transformers through filtering out the acid, water, and other chemical aging product in aged oil [24]. However, the oil-replacement will lead to the loss of chemical

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characteristics (2-FAL methanol, et al.) dissolved in aged oil, which may result in the larger evaluation errors [25]. Several literatures have investigated the influence of oil-replacement on aging assessment of insulation papers and improved the accuracy of the assessment results based on 2-FAL [26], [27]. As a new marker, methanol has been firstly proposed by Jalbert group [28], [29]. However, the scholars mainly focus on the detection technology, the generation mechanism, and influence factors, et al.. of the methanol in insulation oil in the recent years, the effect of oil-replacement on evaluating the insulation aging state of insulation paper based on methanol content in oil is seldom investigation [30], [31], [32], [33]. On the condition of oil-replacement, the relationship between degree of polymerization (DP) and methanol content in oil is not established.

The effect of oil-replacement on the methanol content in oil and the oil-replacement correction model for assessing DP of insulation paper were investigated. The 130 °C accelerated thermal aging experiment was conducted, and the variation tendency of DP value and methanol content in oil at different oil-replacement stage were performed. Based on the relationship between the DP of insulation paper and methanol content in oil, the oil-replacement correction factor was proposed and the oil-replacement assessment model was established. Finally, accuracy of the improved oil-replacement assessment model was verified by 120 °C thermal aging samples.

II. EXPERIMENTS

A. SAMPLE PRETREATMENT

The experiment materials were insulation oil and insulation papers. The type of insulation oil which had been utilized in the experiments was Karamay 45# mineral oil. The type of insulation papers which had been utilized in the experiments were Kraft paper (Weidmann) of 0.12 mm thick.

The process of the samples pretreatment involved paper clipping, drying of samples, impregnation and sealing. Firstly, the insulation papers were cut into many strips of 7 cm × 1.8 cm as paper-samples. Secondly, the paper-samples and insulation oil were placed inside the vacuum oven at 100 °C for 20 h. The moisture contents of paper-samples and oil were below 10 mg/kg and 0.5 %, respectively. Thirdly, the dried oil and paper-samples were put into the glass bottles (high borosilicate glass, 100ml) as the mass ratio of 16:1 (The oil was 68.8g and the paper strips were 4.3g). After the glass bottles were put into a vacuum chamber to be impregnated in the insulation oil for 48 h, the bottles were filled with nitrogen in the upper headspace, and the bottle mouths were sealed with polypropylene caps and poly tetra fluoroethylene (PTFE) sealing gaskets. Lastly, the bottles with oil-paper samples were placed inside an air circulation oven (aging oven) at 130 °C for aging.

B. OIL-REPLACEMENT EXPERIMENT

The duration time of accelerated thermal aging experiment was 40 days. The oil-paper samples were divided into four groups: Group A (normal group without oil-replacement), Group B (oil-replacement at early aging stage, the 5th day), C (oil-replacement at medium-term aging stage, the 15th day), and Group D (oil-replacement at later aging stage, the 30th day). The Experiment scheme of oil-replacement was shown as Fig. 1.

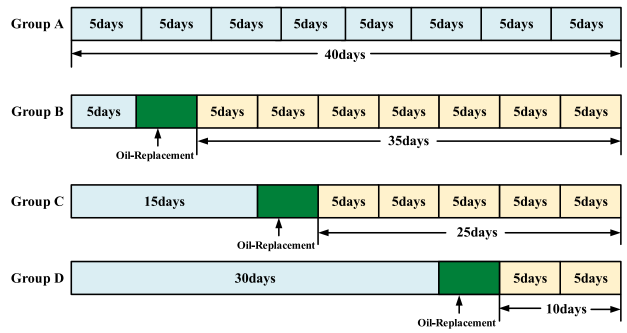


FIGURE 1. The experiment scheme of oil-replacement.

The Group A: The oil samples of Group A were not replaced in the whole aging duration time. During the thermal aging process, one bottle with oil-paper samples was taken out of the aging oven every 5 days, and was maintained the temperature at 20 °C for 72 h in calorstat. Then the methanol content in oil and the DP of insulation papers were detected respectively.

The Group B: After thermal aging for 5 days at 130 °C (the oil-paper samples were at early aging stage), the whole samples of Group B were taken out the aging oven, and maintained the temperature at 20 °C for 72 h in calorstat. Then opened the polypropylene caps and replaced the aging oil with new dry insulation oil. After the aging oil was replaced, the whole samples of Group B were put back in the air circulation oven for continued thermal aging experiment, and one bottle of Group B was taken out of the aging oven every 5 days to detect the methanol content in oil and DP of insulation papers.

The Group C: After thermal aging 15 days at 130 °C (the oil-paper samplers were at medium-term aging), the whole samples of Group C were taken out the aging oven, and the following processing steps were the same as Group B.

The Group D: After thermal aging 30 days at 130 °C (the oil-paper samples were at later aging stage), the whole samples of Group D were taken out the aging oven, and the following processing steps were the same as Group B.

C. APPARATUS AND METHODS

The samples with different aging stages were taken out of the aging oven, and were cooled to 20 °C for 72 h. Then methanol content in oil was detected by Headspace Samper-Gas Chromatography (HS-GC), in which the chromatographic column was DB-624 and the detector was flame ionization detector (FID). The relative apparatus parameters were shown in Table 1 [34]. According to the IEC 60450, the DP of

TABLE 1. HS-GC apparatus parameters for detecting methanol in oil.

HS	Parameters	GC	Parameters
Specimen	1.0 ml	He carrier gas	5ml/min
Oven Temperature	90 °C	Injector	200°C, Splitless
Syringe Temperature	100 °C	Column	length 30 m, inner diameter 0.53 mm, film thickness 3.00μm
FID Temperature	220 °C		
H_2	40 ml/min	Oven Initial	40°C for 4min
Air	350 ml/min	Heating method	3 °C/min to 49 °C, 80 °C/min to 245 °C,10 min
N_2	25 ml/min		

insulation paper-samples were detected by Ubbelodhe viscometer [35].

III. RESULTS AND ANALYSIS

A. THE NORMAL RESULTS

The methanol content in oil of Group A to D with aging time was shown in Fig. 2.

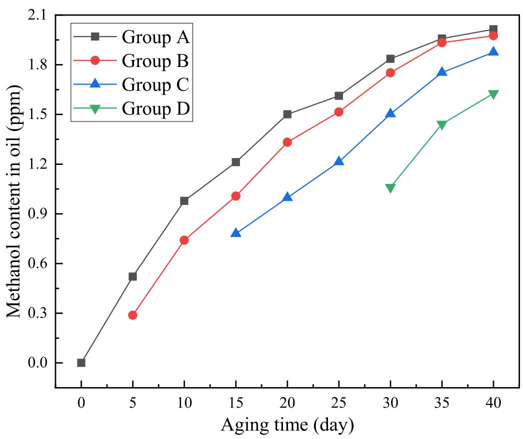


FIGURE 2. The methanol content in oil of the four groups after oil-replacement.

The Fig. 2 indicated that the methanol content in oil of Group A had a rising trend with increasing the aging time, and the rising rate of methanol in oil was initially fast and then slowed down. The methanol content of other groups were lower than Group A after oil-replacement, while the deviation between Group A and other groups had a decreasing trend with aging time.

The variation tendencies of the DP values with aging time were shown in Fig. 3.

The Fig. 3 indicated that the DP of insulation papers exhibited a decreasing trend with increasing the aging time, while the rising rate of methanol in oil was initially fast and then slowed down. The DP values of the other groups were higher than Group A after oil-replacement, whereas there was a tendency for convergence across different groups.

The assessment model for establishing the relationship between the methanol in oil and the DP of insulation papers

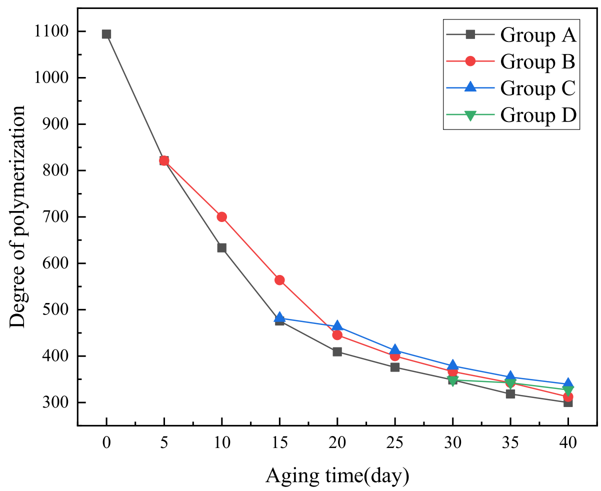


FIGURE 3. The DP of the four groups after oil-replacement.

was given in equation (1) [34]:

$$[\text{CH3OH}] = dJ_a(1 - e^{-p_a NS}) + dJpNS \tag{1}$$

$$NS = DP^0/DP - 1 \tag{2}$$

where [CH3OH] corresponds to the methanol in oil (ppm), d corresponds to the proportion of the methanol in oil to the generated methanol from insulation papers, J_a corresponds to the methanol production in the amorphous regions, J corresponds to all the constant parameters of the unknown mechanisms and kinetics in crystalline regions, p_a and p can be defined as "conversion rate" between cellulose degradation and methanol production in amorphous and crystalline regions, respectively, DP_0 and DP correspond to the degree of polymerization at an initial time ($t = 0$) and at a given time t.

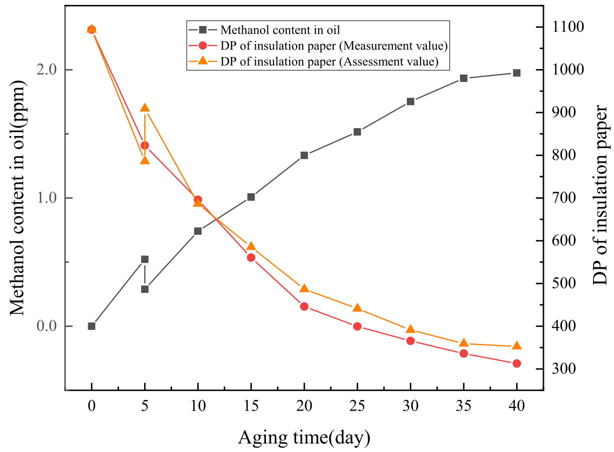
According to the experiment results of Group A, the parameters in equation (1) were obtained (dJ_a =1.944, p_a =0.581, dJp=0.287 and DP_0 =1094) and the equation (1) was equivalent to equation (3):

$$[\text{CH3OH}] = 1.944(1 - e^{-\frac{636.809}{DP}+0.581}) + \frac{314.291}{DP} - 0.287 \tag{3}$$

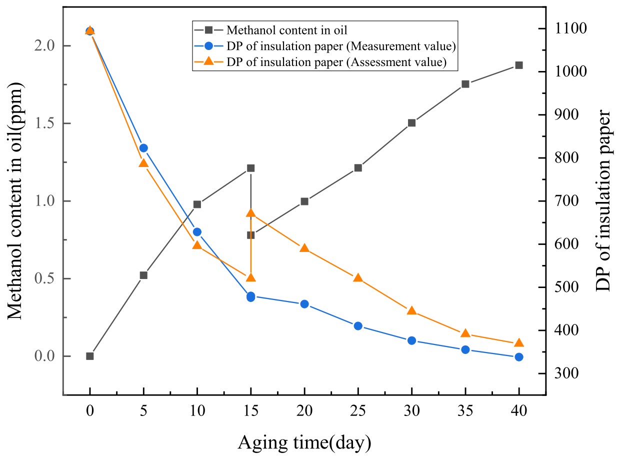
The equation (3) indicated the relationship between the methanol content in oil and the DP of insulation papers, and the R-squared value of equation (3) is 0.9942. According the equation (3), the DP of insulation papers which could be estimated based on the methanol content in oil were shown as Fig. 3.

B. THE RESULTS OF OIL-REPLACEMENT

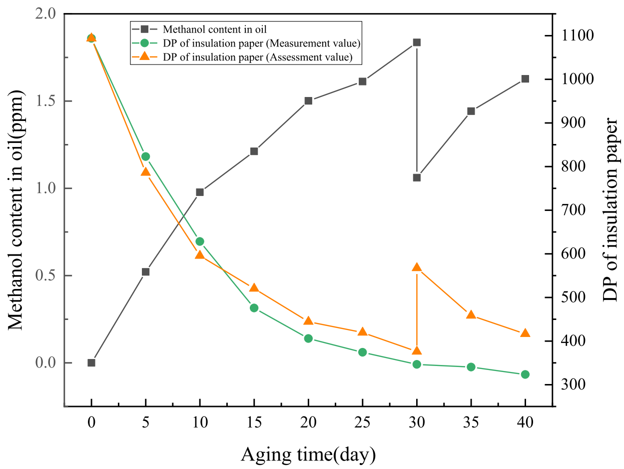
The methanol content in oil and the DP of insulation papers of Group B, C and D with aging time were shown in Fig. 4. According to the equation (3) and the methanol content in oil, the DP evaluation values on the condition of oil-replacement were shown in Fig. 4.



(a) Group B



(b) Group C



(c) Group D

FIGURE 4. The effects of oil-replacement on methanol in oil and the DP of insulation paper. (a) group B; (b) group C; (c) Group D.

The Fig. 4 indicated that the evaluation errors were largest at the moment of oil-replacement during the aging period, and then the assessment errors had a decreasing trend with aging time. Because the methanol in oil lost totally after oil-replacement and then the residual methanol in paper diffused to the new oil until the methanol content between oil/paper reached a new equilibrium, which result for the assessment values of the DP were bigger than measurement value. As the aging process continues, the methanol was generated more from insulation papers and recovered methanol in oil, which decreased the assessment errors of the DP values of insulation papers.

In addition, comparing the results of Group B, C and D, the assessment error of Group D was largest and the assessment error of Group B was least. Since the methanol content in oil increased with aging process, the later the oil replacing the more the methanol in oil lost, and result in more the assessment errors.

The results indicated that the assessment values didn't satisfied the measurement values well after oil-replacement, which meant the equation (3) could not be suitable for evaluating the DP of insulation papers after oil-replacement.

TABLE 2. The fitting parameter values of CF $_{OR}$.

Parameter	q_1	u_1	v_1	w_1	R^2
Group B	0.3379	0.0539	-0.0016	1.669×10^{-5}	0.9807
Group C	1.0242	-0.0592	0.0027	-3.297×10^{-5}	0.9921
Group D	-2.2048	0.1451	-0.0017	0	1

IV. ANALYSIS AND DISCUSSION

A. THE ASSESSMENT MODEL FOR OIL-REPLACEMENT

According to the oil-replacement experiments, the oil-replacement correction factor [CF_{OR}, (4)] was defined as regressing the methanol in oil after oil-replacement to the methanol in oil without oil-replacement.

$$CF_{OR} = \frac{[CH3OH]_R}{[CH3OH]} \tag{4}$$

where $[CH_3OH]_R$ was the methanol content in oil after oil-replacement (ppm), [CH3OH] was the methanol content in oil without oil-replacement (ppm).

According to the equation (4) and Fig. 4, the CF_{OR} of methanol content in oil at difference aging stages were shown in Fig. 5.

The Fig. 5 showed that the CF_{OR} of Group A was "1", the CF_{OR} varied from 0.55 to 0.98 with aging time on the condition of oil-replacement at early aging stage, the CF_{OR} varied from 0.64 to 0.93 with aging time on the condition of oil-replacement at medium-term aging stage, and the CF_{OR} varied from 0.58 to 0.80 with aging time on the condition of oil-replacement at later aging stage.

By applying a fitting function $CF_{OR} = q_1 + u_1 t + v_1 t^2 + w_1 t^3$ to fit the points in Fig. 5, where q_1, u_1, v_1 and w_1 were the fitting parameters, and t was the aging time (day).

The fitting results of q_1, u_1, v_1 and w_1 are shown in Table 2.

According to the equation (4) and Table 2, the oil-replacement modified model for assessing the DP of insulation papers based on the methanol content in oil could

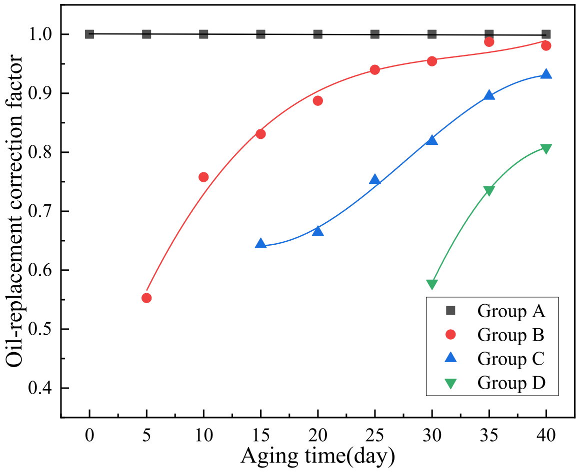


FIGURE 5. The oil-replacement correction factor of different groups.

be obtained as equation (5).

$$[CH3OH] = \frac{[CH3OH]_R}{CF_{OR}} = \frac{[CH3OH]_R}{q_1 + u_1 t + v_1 t^2 + w_1 t^3} \quad (5)$$

Combining the equation (1) and (5), the modified assessment model for oil-replacement was obtained as shown in equation (6).

$$\frac{[CH3OH]_R}{q_1 + u_1 t + v_1 t^2 + w_1 t^3} = dJ_a(1 - e^{-p_a NS}) + dJpNS \quad (6)$$

B. THE DP ASSESSMENT EFFECT WITH OIL-REPLACEMENT CORRECTION FACTOR

According to the equation (6), the DP assessment results of the insulation papers after oil-replacement with CF_{OR} were shown in Fig. 6.

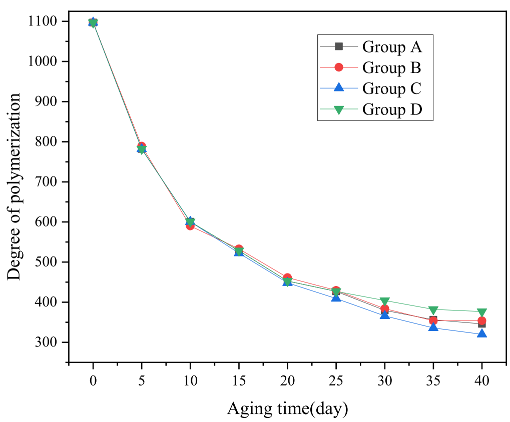


FIGURE 6. The DP assessment value of insulation paper with oil-replacement correction factor.

Comparing Fig. 6 with Fig. 4, the assessment results of the DP value with correction factor were close to the measurement results and the assessment errors of the DP after oil-replacement were decreased. The results indicated that the oil-replacement correction factor improved the accuracy of the DP assessment value after oil-replacement.

C. VERIFICATION

The sample pretreatment process was the same as Section II. The oil-paper samples, were placed inside the aging oven at 120 °C for 63 days, and were divided into two groups: Group E (normal group) and Group F (oil-replacement at early aging stage, the 28th days).

During the thermal aging process, one bottle with oil-paper samples was taken out of the aging oven every 7 days, and maintained the temperature at 20 °C for 72 h in calorstat. Then the methanol content in oil and the DP of insulation papers were detected respectively. The process of oil-replacement was the same as Group B to D.

It should be noticed that it needs different aging time to reach the same DP value of insulation papers on the condition of different thermal aging temperature. Therefore, the methanol content in oil on different aging temperature should be transformed into the same temperature. The transformational equation is deducted from Arrhenius equation and shown as follows [36]:

$$t_{T_1} e^{-\frac{E}{R(T_1+273)}} = t_{T_2} e^{-\frac{E}{R(T_2+273)}} \quad (7)$$

where T_1 and T_2 are the aging temperature, E is the activation energy (E = 111000±6000 J/mol), t_{T1} is thermal aging time at the aging temperature T_1, t_{T2} is aging time at the aging temperature T_2, R is the ideal gas constant ($R = 8.314$ J/mol·K)

The equation (6) is established at 130 °C while the verification experiment temperature T_2 is 120 °C, so the verification experiment results (T_2 =120 °C) need to be transformed to T_1 =130 °C by equation (7). Furtherly, the equation (7) could be substituted into equation (8).

$$t_{130} = t_{120} e^{-\frac{E}{R}\left(\frac{1}{393} - \frac{1}{403}\right)} \approx 0.43 t_{120} \quad (8)$$

The equation (8) is substituted into equation (5), oil-replacement correction factor CF_{OR} can be deducted as equation (9).

$$CF_{OR} \approx q_1 + 0.43 u_1 t_{120} + 0.185 v_1 t_{120}^2 + 0.08 t_{120}^3 \quad (9)$$

The measurement results of Group E was shown in Fig. 7. According to the experiment results of Group E, the parameters in equation (1) were obtained (dJ_a =1.017, p_a =1.959, dJp=0.431 and DP_0 =1105). Then, combining the equation (9) with (6), the verification results of DP assessment values were shown in Fig. 8.

The Fig. 8 shown that the DP assessment value with CF_{OR} was closer to the measurement value than the DP assessment value without CF_{OR}. The assessment error was decreased from 18.20% to 4.84% based on CF_{OR} and had a decreasing trend with increasing aging time after oil-replacement regardless of assessment model with or without CF_{OR}. The above verification results indicated that the CF_{OR} could improve the

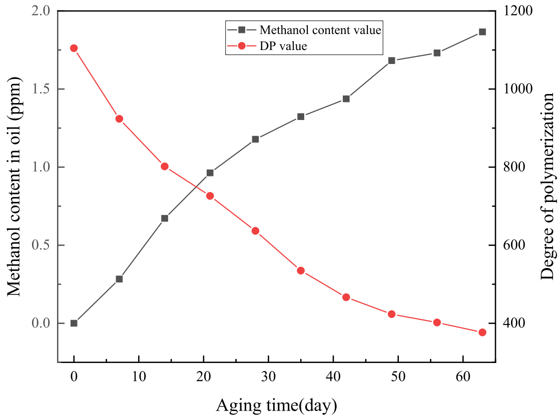


FIGURE 7. The verification experiment results of group E.

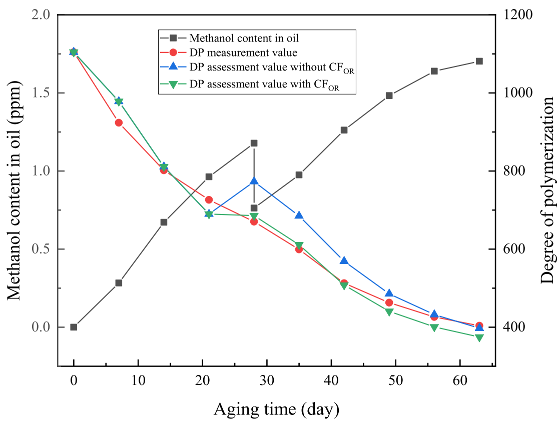


FIGURE 8. The verification experiment results of group F.

accuracy of DP assessment results after oil-replacement and the modified model had the well applicability.

V. CONCLUSION

This paper investigated the influence of oil-replacement on assessing the DP of insulation papers, and the correction factors for modifying the assessment errors was proposed. The main conclusions during the research were as follows.

(a) The present Methanol-DP assessment model is not suitable for assessing the DP of insulation papers after oil-replacement. The assessment errors are the biggest after oil-replacement and gradually decrease with aging time. The later the oil-replacement time is, the bigger the assessment errors are. Because the methanol in oil lost totally after oil-replacement, which leads the DP assessment value is higher than the measurement value.

(b) The methanol correction factor (CF_{OR}) is proposed for correcting the assessment errors after oil-replacement. The experiment results indicated that the CF_{OR} is in accordance with the power-series expansion regulation with aging time.

(c) The verification experiment results indicated that CF_{OR} could improve the accuracy of the assessment results and effectively corrected the methanol loss after oil-replacement.

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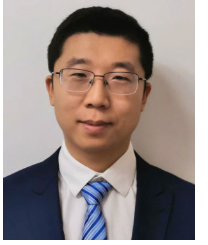

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