Evaluation of Paper Insulation Condition of Distribution Transformers Based on the Concentration of 2-FAL and Methanol

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Abstract

Monitoring and evaluation of transformers are essential to prevent their insulation failure. In this paper, the use of 2-furan-carboxaldehyde (2-FAL) and methanol (MeOH) concentrations as the main products of paper insulation degradation, and insulation condition markers, has been studied. In order to study the degradation process and production of degradation products, the thermal aging process of the transformer insulation system was implemented in laboratory conditions. The results of laboratory studies show that in the early stages of degradation the amount of MeOH is significant compared to 2-FAL. Also, the estimation of the degree of polymerization (DP) in the early stages of degradation (DP>800) through MeOH concentration and with decreasing DP (DP <800) through 2-FAL concentration is closer to the real value. The results of studies performed on 35 distribution transformers confirm the production of significant amounts of MeOH in the early stages of degradation. Also, the estimated DP values for the studied transformers were obtained through 2-FAL and MeOH concentration. The results show that estimating the amount of DP through MeOH concentration is associated with a probability of error of about 9% compared to estimating DP through 2-FAL concentration.

Keywords

Condition Assessment, Distribution transformer, Furans, Methanol.

1. Introduction

Distribution transformers are one of the main and vital equipments in power distribution networks. The correct and fault-free operation and remnant life of transformers largely depend on the condition of their insulation system. The degradation of the insulation system, which is an irreversible process, is the main cause of the transformer collapse [1-3]. Paper and oil insulation are the essential part of the insulation system of transformers. The combination of oil-impregnated paper creates a higher insulation level than their separate use. Insulating oil also prevents acceleration of paper degradation by facilitating cooling and heat transfer of the coils. However, due to technical issues and operating conditions of the transformers, both the insulation paper and oil have deteriorated and the insulation strength of the system is reduced [4-7].

As a result of the process of deterioration of the insulation system, the oil of transformers undergoes chemical changes. Also, some of the oil's physical characteristics such as color, density, viscosity, and flashpoint change in the aging process. Due to physical and chemical changes in the oil, its insulating properties also change, and it loses its insulating quality. However, by physical and chemical purification of the oil or even by changing it, the insulation failure can be prevented to some extent and the efficiency and remnant life of the transformer can be increased [4, 5]. But aging and degradation of paper insulation are incurable and its failure can lead to transformer failure. Therefore, monitoring and evaluating the condition of paper insulation is very important.

So far, several diagnostic methods have been proposed to evaluate the condition of paper insulation in transformers [4, 8]. In a general category, these methods can be divided into direct and estimated categories. The processes performed on a paper insulation sample to measure its quality and degree of degradation are called direct methods, such as measurement of degree of polymerization (DP) by viscosity method or by measuring the tensile strength of paper. On the other hand, estimation methods, are processes that estimate the paper insulation condition assessment based on cellulose degradation products dissolved in transformer oil (such as furan derivatives and methanol) [3,8-10].

Direct methods of measuring DP are seldom used despite high accuracy and reliability in sampling quality. Because of the impossibility of sampling of in-service transformers, the need to disassemble the transformer for sampling, the imbalance of the transformer insulation structure after sampling, and the high cost of DP measurement per transformer, has caused the estimation methods to be considered by industry users[11].

Among the estimation methods, furan analysis is a common and well-established method in estimating the DP value of paper insulation. In [12] provides complete studies on furan compounds, their history, and how they were produced due to the degradation of paper insulation. In the reference [13], the mathematical equations presented to express the relationship between the concentration of furan compounds and DP paper insulation have been collected and studied. Equations (1) to (3) are the most valid of these mathematical equations.

$$DP = \frac{2.6 - \log_{10}([f])}{0.0049} \quad (1)$$

$$DP = \frac{1850}{[f] + 2.3} \quad (2)$$

$$DP = \frac{8.88 \times DP_0}{8.88 + [f]} \quad (3)$$

Where, *DP* and DP_0 are the degree of polymerization of aged and new insulation paper, and $[f]$ is the concentration of 2-FAL in ppm.

Methanol, as well as furan compounds, is produced only from the paper insulation degradation and dissolves in oil [14]. There is a significant relationship between methanol concentration and degradation of 1,4-β-glycosidic bonds of paper insulation cellulose [15,16]. In [17-19], the correlation between methanol concentration and insulation paper aging and DP has been proven. In [20], by studying 6 transformers, the possibility of evaluating the insulation status using methanol and Furan has been investigated. To estimate the amount of DP from the methanol concentration, equation (4) is proposed [19]:

$$DP_t = \frac{DP_0}{1.5542\left(1-e^{-0.0054[MeOH]}\right)+0.00101[MeOH]+1} \quad (4)$$

where $[CH_3OH]$ is the methanol concentration in ppb and *DP* and DP_0 are the degree of polymerization of aged and new insulation paper.

In this paper, the aging process of paper insulation in the laboratory is first simulated. The degradation process and the production process of methanol and furan compounds, and DP changes have been studied. Then, oil samples were taken from 35 distribution transformers (20 kV/400V) to measure the concentration of furan compounds and methanol, to investigate the relationship between furan compounds, methanol, and DP changes in field transformers.

2. Accelerated Thermal Ageing Experiment in Laboratory

2.1. Materials

In order to simulate the conditions inside the transformer and to study the degradation process and production of methanol and furan compounds, an experiment was designed. The type and amount of consumables were selected according to the project objectives in accordance with a distribution transformer. Table I shows the materials used in laboratory samples (including samples of insulating paper, copper used in transformer windings, and new insulation oils), their mass, and specifications. According to [21], the presence copper piece creates similar conditions in terms of chemically active agents with the actual operating conditions in the transformer. Copper catalyzes the thermo-oxidative degradation and some of the possible chemical reactions within the oil [22,23], while the other items present in transformer tank (Iron, etc.) are inert and will not affect the aging process.

Table I. Materials used in laboratory samples, their mass, and specifications [24].

Materials	Mass and Specifications	
Insulating paper	Brand: DP_0: Mass:	T4 Weidmann paper 1150 2.2 g
Copper	Mass:	22.2 g
Insulating oil	Brand: Pour point: Flash point: Break down Voltage: Water content: Mass:	Niroo-T296 ≤ -45 ºC ≥ 135 ºC 76 kV 26 mg/kg 222.2 g

2.2. The Process of Preparation and Aging of Samples

In order to dry the insulation paper and copper piece, the sample container (with insulation paper and copper piece) was dried at 30 °C for 48 hr in vacuum to eliminate moisture [24]. These conditions were selected to ensure no negative effect of drying temperatre on the DP of the insulating paper. After that, the containers were filled with insulating oil and their NS-standard joint lids closed to prevent from air moisture. Five similar series of samples of copper, paper insulation, and mineral oil used in distribution transformers were prepared (according to the mass specified in Table I) and put inside of each container (Fig. 1).

Although ageing or deterioration of transformer insulation systems is a time function of temperature, moisture, oxygen and acid contents. Due to the significant effect of temperature, the experiment was designed based on thermal aging. For this purpose, the oven temperature for accelerated aging was selected according to the IEC 60076-7 standard. According to the IEC 60076-7 standard the relative aging rate (V) of kraft insulation papers, in the absence of oxygen and moisture was defined by the equation (5):

$$V = 2^{(\theta_h - 98)/6} \quad (5)$$

where V is relative ageing rate, θ_h is the hot-spot temperature in °C.

According to the equation(5), for temperatures higher than 98 °C, for every 6 °C increase in temperature, the aging rate doubles, relative to the rate in 98 °C. In other words, at 110 °C the aging rate is equal to 4. The aging rate of 4 means that at 110 °C the paper insulation ages 4 times faster than at 98 °C. Therefore, by increasing the aging temperature, the duration of the aging process can be reduced. On the other hand, as the temperature rises, the insulating oil begins to break down and produce some gaseous products. Cosidering the flash-point of the oil, which is in the range of 135 °C, inevitably, the temperature of the aging process must be lower than the flash point temperature of the oil. Due to the mentioned limitations and the characteristics of the used oil, the temperature of 110 °C was determined as the aging process temperature.

Then the oven temperature was set at 110 ± 5 °C and prepared five similar samples in containers were put in the oven to start the aging process. After aging time intervals of 24, 48, 144, 288 and 576 hour, respectively, one of the samples were taken out of the oven, cooled to the room temperature and the aging process and necessary tests were performed on each of them.

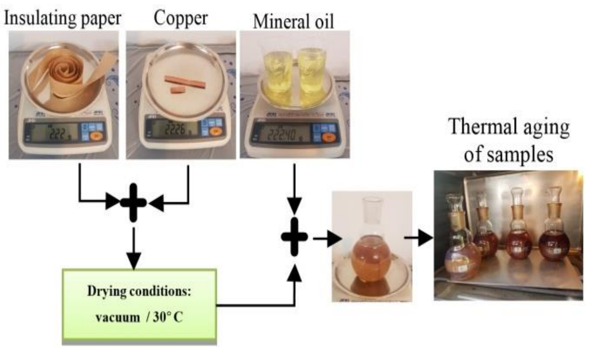

Fig. 1. Flowchart of Experimental Process in Laboratory Aging

2.3. Analysis Techniques

In order to evaluate and monitor the degradation process of insulation paper and measure the concentration of degraded products following tests were performed:

2.3.1 DP Measurement by the Viscometric Method

Measuring the degree of polymerization (DP) is one of the most reliable methods for evaluating the quality of paper insulation. IEC 60450 and ASTM D 4243 provide a method for measuring DP by the viscometric method. In this method, the paper insulation sample is dissolved in a Cuen, and by measuring the viscosity of resulting solution, the specific viscosity (vs) is obtained according to (6). Then, using the specific viscosity, the intrinsic viscosity (v) is calculated according to (7) [25]:

$$v_s = \frac{viscosity\ of\ paper\ solution - viscosity\ of\ solvent}{viscosity\ of\ solvent} \quad (6)$$

$$v_s = [v].c.10^{k.[v].c} \quad (7)$$

Where k is the Martin's constant and for kraft paper k = 0.14, and c is the concentration of chemical in solution, k can be calculated according to [21]. Finally, the mean value $\overline{DP_v}$ is obtained based on (8):

$$[v] = K.\ \overline{DP_v}^{\alpha} \quad (8)$$

where K and α are the Mark Houwink constants: α = 1 and K = 0.0075.

Here, DP of the samples were determined by viscometric method according to IEC 60450 standard.

2.3.2 Measurement of Furan Compositions Using HPLC

High-performance liquid chromatography is one of the powerful tools of analytical chemistry. HPLC can separate and measure any compound dissolved in a liquid to the nearest 0.01 mg. The standard method to measure the furan compounds in the insulating oil of transformers by HPLC is given in ASTM-D-5837. High accuracy and reliability in measuring are the most important advantages of using HPLC. In this study, the concentration of furan compounds was measured by a HPLC system manufactured by Knauer Smartline, Berlin, Germany.

2.3.3 Methanol Measurement

Methanol (CH_3OH) is the simplest alcohol that is liquid at room temperature. Different chromatographic methods have been used to detect alcohols and gases in insulating oils, such as Gas Chromatography - Mass Spectrometry (GC-MS), Flame Ionization Detectors (FID), High-Performance Liquid Chromatography (HPLC), and Solid-Phase Micro-Extraction (SPME) [26, 27]. In this work, the method presented in [26] was used to measure the methanol concentration in the oil. In this method, a system consisting of a 6890 N gas chromatograph equipped with a 5973 network mass spectrometer (both from Agilent Technologies, Santa Clara, CA, USA) in the absence of a costly headspace autosampler is used to measure alcohols.

3. Results and Discussion

Paper and oil insulation samples were removed from the oven after given aging time and cooled down to room temperature. Fig. 2 shows oil samples, aged insulating paper, and a microscopic image of the aged insulating paper. Fig. 2 clearly shows the discoloration, aging of the paper insulation, and the reduction of the tensile strength of the paper. In this process, the insulating oil has also aged, its color change and turbidity indicate the aging of the insulating oil.

Table II shows the results of DP measurements by the viscometric method (measured according to IEC 60450). The results of Table II show that with increasing the aging time at 110 °C, the aging process has been done and the DP of paper insulation has decreased. The T1-24H sample, which was exposed to 110 °C for 24 hours, has a good insulating condition, and its DP is measured near 1100. But the T5-576H sample, which was exposed to 110 °C for 576 hours, its insulation is completely destroyed and its DP value has reached 200, which indicates the end of its insulation life. The T5-576H is also very weak in terms of tensile strength and breaks with a slight external force.

Table II. Results of DP measurement by the viscometric method and evaluation of paper insulation condition.

Sample name	Aging time (h)	$\overline{DP_v}$	Paper insulation condition

T1-24H	24	1100	Healthy insulation
T2-48H	48	1000	Healthy insulation
T3-144H	144	820	Moderate aging (acceptable)
T4-288H	288	440	Critical aging
T5-576H	576	200	End of insulation life

stages of degradation (samples T1 to T3), Equation (4) performs better than Equations (1) to (3) (which estimate DP from 2-FAL). In other words, in the early stages of degradation, the estimated DP from methanol based on (4) is closer to the actual DP. However, with the increasing the severity of aging and degradation of paper insulation,

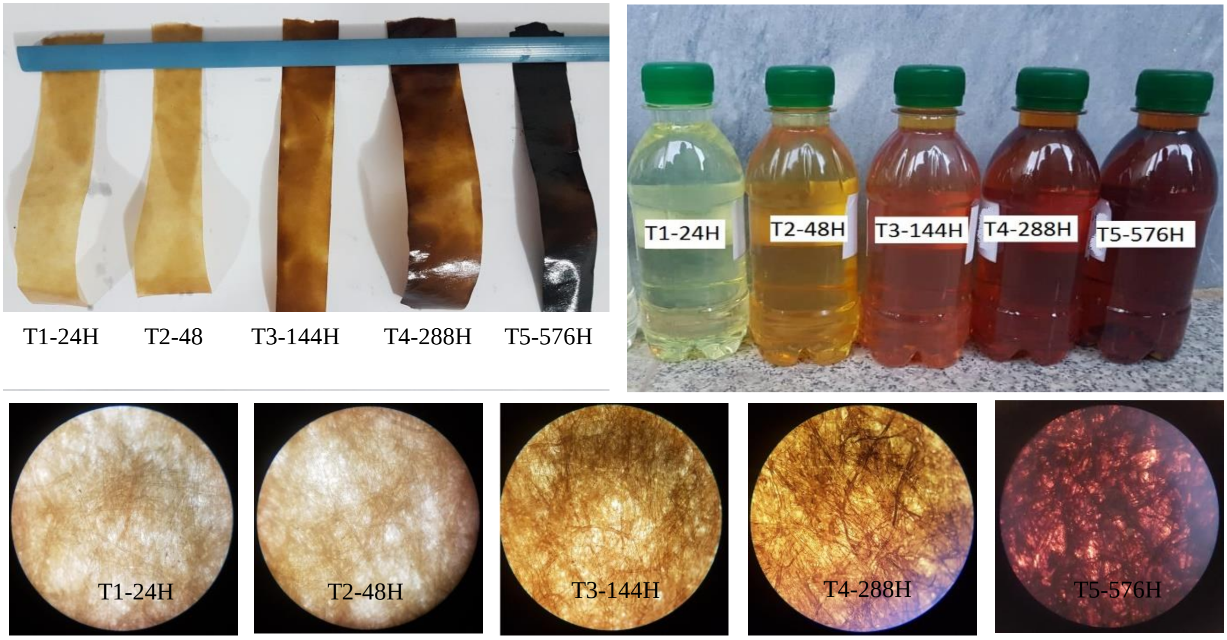

Fig. 2. Aged Insulating Oil and Paper Samples.

the results obtained from (1) to (3) are closer to the actual value of DP and have a better performance than equation (4).

The test results of the study samples are shown in Fig. 3. Fig. 3 shows the trend of changes in the concentration of 2-FAL, methanol, and DP in the aging process. According to the results obtained, during the degradation process of paper insulation and with decreasing the amount of DP, the concentration of methanol and 2-FAL increases. However, this increase is more severe for methanol in the early stages of degradation (DP <1100 <700) and for 2-FAL per DP <800. In other words, in the early stages of degradation (1100 <DP <700), the amount of methanol concentration in the oil was significant. While 2-FAL concentration did not change significantly with decreasing DP up to 800 units, but for DP <800, the intensity of 2-FAL concentration changes is noticeable.

Fig. 4 shows the DP values measured for the studied samples and the estimated DP values through equations (1) to (4). According to the chart in Fig. 4, in the early

4. Studies in Field Transformers

In order to further investigate the methanol indicator and its relationship with 2-FAL and DP concentrations of paper insulation, 35 transformers, which were included in the list of critical transformers, were selected for the study. In selecting the transformers, it was tried to take into account criteria such as environmental conditions of the transformer operation, age, type and condition of annual load, as well as the similarity of the transformer insulation system. In this regard, out of 381 critical transformers, 35 devices were selected for oil sampling. The studied distribution transformers with voltage levels of 20 kV/400 V and nominal power of 800 to 1600 kVA were installed and operated between 1975 and 2018. Unfortunately, no information was available on the history of transformer

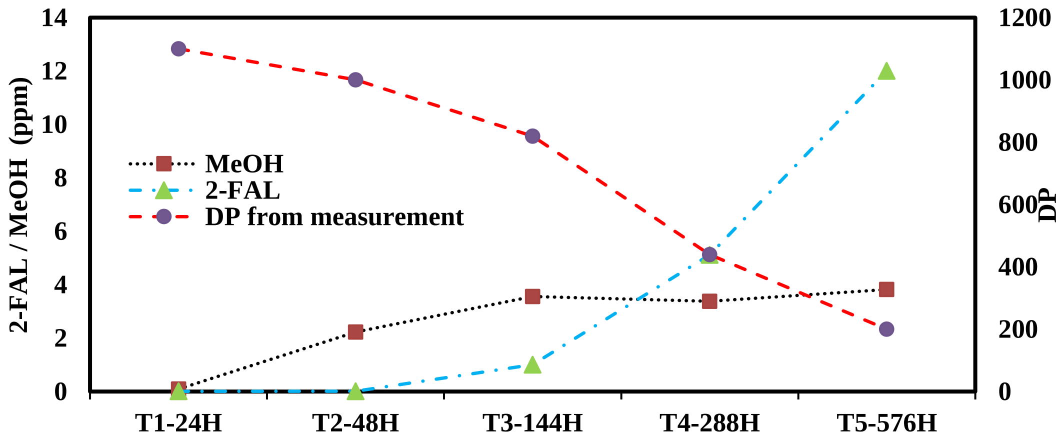

Fig. 3. The trend of changes in the concentration of 2-FAL, methanol, and DP in the aging process.

insulation oil change or refining. Due to the fact that the transformers were in service, it was not possible to obtain a paper insulation sample to measure DPv, so only oil samples were taken online from the transformers. The oil temperature at the time of sampling was between 40-50 °C.

Oil samples were immediately transferred to the laboratory for relevant tests. Methanol and 2-FAL concentrations in oil were measured according to reference [26] and ASTM-D-5837 standard, respectively. In Table III the specifications of the studied transformers and the results of measurement of methanol and 2-FAL concentrations in their oil samples were summarized.

The transformers in the operating time range of 2 to 45 years, which according to Table III, MeOH and 2-FAL produced in it increase with increasing operating time. But this increase is very small. As the main reason for the production of these compounds is the destruction and thermal aging of the transformer insulation system, which is mostly affected by operating conditions such as operating temperature and the overload time of the transformer.

Based on the results, methanol is present in all samples and a significant amount of methanol in the studied samples indicates the production of this compound during the aging of the transformer in real conditions. The presence of 2-FAL values also confirms the aging and degradation of the paper insulation system of transformers. Significant amounts of methanol and low levels of 2-FAL in the majority of the samples studied, based on the results of laboratory studies, probably indicate that these samples are in the early stages of degradation. To confirm this possibility, it is necessary to measure the amount of DPv, which, unfortunately, as mentioned earlier, is not possible to measure DPv due to the service of transformers. For this reason, in this paper, furan analysis based on (1) to (3) has been used to estimate the DP value. Table IV detailed the estimated values of DP based on 2-FAL concentration and according to (1) to (3). As was clear from the concentration of methanol and 2-FAL in the samples, the DP values indicate that the paper insulation of these transformers is in the early stages of degradation and their DP values are between 700 and 1000. In other words, the aging process of paper insulation of most transformers has been balanced. With the exception of Trans-09 and Trans-10, whose average DP is estimated to be less than 700 and in moderate deterioration conditions, the rest of the transformers are in healthy condition in terms of solid insulation. Table IV also shows the DP value based on methanol concentration (estimated using (4)).

Table III. Specifications of the studied transformers and the results of MeOH and 2-FAL concentration measurements in their oil samples.

Trans_ID	kVA rating	Age (year)	2-FAL (ppm)	MeOH (ppm)
Trans- 01	1250	9	0.0245	3.87
Trans- 04	800	19	0.0017	2.527
Trans- 05	1000	2	0.024	0.954
Trans- 07	800	36	0.3113	0.811
Trans- 09	1000	24	1.4153	3.44
Trans- 10	1000	45	0.9055	3.819
Trans- 11	1000	21	0.0776	2.836
Trans- 12	1000	18	0.1576	3.37
Trans- 13	1000	17	0.0171	2.4
Trans- 14	1000	15	0.0444	2.679
Trans- 15	1000	11	0.0355	2.59
Trans- 16	1000	4	0.2355	6.443
Trans- 19	1250	19	0.0469	0.911
Trans- 20	1250	17	0.2405	1.008
Trans- 23	1250	8	0.0082	3.165
Trans- 25	1250	20	0.0119	3.84
Trans- 26	800	16	0.0243	2.07
Trans- 27	1250	13	0.0267	1.97
Trans- 28	1250	24	0.001	1.98
Trans- 30	800	18	0.0209	2.14
Trans- 31	800	17	0.0324	2.89
Trans- 32	800	22	0.3647	3.32
Trans- 33	1000	22	0.0153	3.23
Trans- 34	1000	15	0.1778	4.78
Trans- 36	800	12	0.0029	1.404
Trans- 37	800	11	0.0013	0.873
Trans- 38	1000	13	0.0038	1.11
Trans- 39	1250	8	0.0034	0.785
Trans- 40	1600	13	0.0248	0.937
Trans- 42	1600	23	0.0014	2.562
Trans- 43	800	17	0.0547	1.303
Trans- 44	800	8	0.0029	1.718
Trans- 45	1000	14	0.0219	1.368
Trans- 46	1250	15	0.0083	1.34
Trans- 47	1250	8	0.0093	1.247

To evaluate the performance of the method for estimating the amount of DP by methanol marker (based on (4)), the average DP obtained from (1) to (3) was calculated. In order to evaluate the difference between methanol analysis and furan analysis, the Root-Mean-Square Error (RMSE) was used according to (9):

$$\mathrm{RMSE} = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)}{n}} \tag{9}$$

Where y_i is the mean DP obtained from the furan analysis and $\hat{y}_i$ is the estimated value based on the methanol analysis.

The RMSE value for the above data was 90.27, which indicates the difference between methanol analysis and furan analysis. Therefore, it can be said that estimating the amount of DP through methanol analysis (based on (4)) is associated with an error of about 9%. Considering the advantages of methanol measurement in assessing the condition of paper insulation, it can be said that measuring methanol along with the furan analysis of transformer oil samples can be very useful in estimating the condition of paper insulation.

5. Conclusion

The results of laboratory studies and simulation of the thermal aging process of transformer insulation systems in a laboratory indicate that the concentration of methanol and 2-FAL in oil increases due to the destruction of paper insulation and reduction of DP. Thus, in the early stages of degradation of paper insulation, the concentration of methanol increases more rapidly and its production rate gradually decreases. Also, the concentration of 2-FAL in the early stages of degradation is very small and with decreasing DP value, its value increases exponentially.

Therefore, the presence of detectable amounts and abundance of methanol in the early stages of degradation

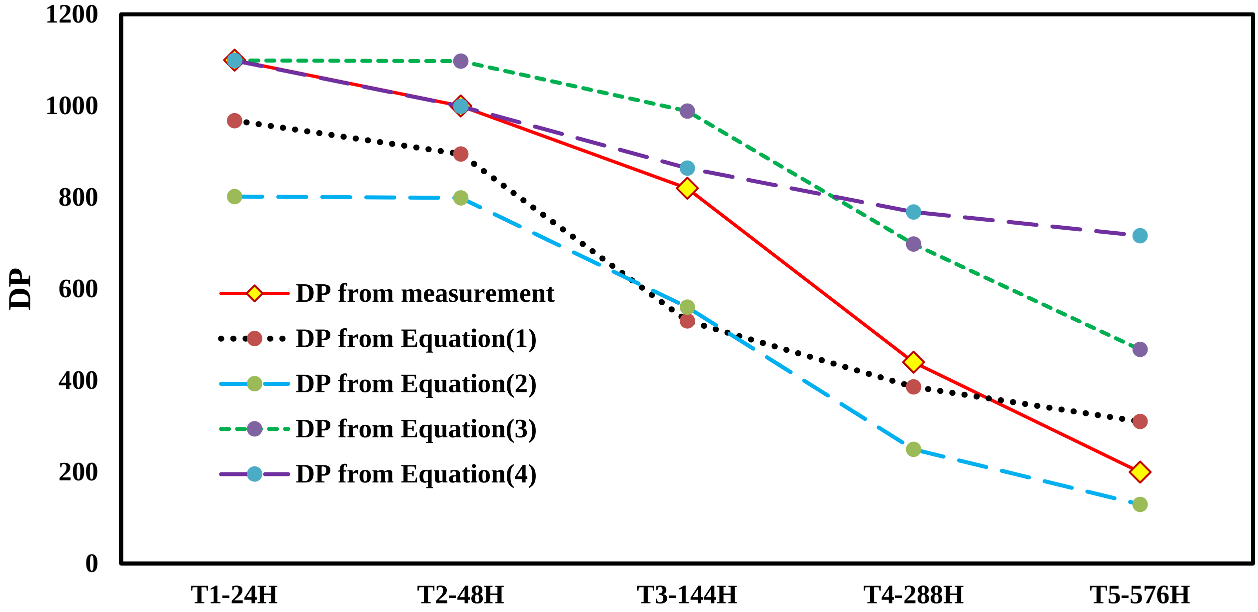

Fig. 4. Measured and estimated DP values for the studied samples.

compared to 2-FAL can be one of the advantages of methanol markers in assessing the paper insulation status of transformers.

The results of field transformer studies confirm the production of significant amounts of methanol in the early stages of degradation. Estimation of DP by methanol concentration with an RMSE = 90.27 also indicates that methanol can be used as a functional marker in the early stages of degradation. The significant amount of methanol versus the very low concentration of 2-FAL in distribution transformers makes the use of methanol in assessing the insulation condition of distribution transformers more attractive. However, the use of furan analysis along with methanol analysis is recommended to increase the accuracy of evaluation for low DP in estimating and evaluating the paper insulation condition of distribution.

Table IV. Estimated DP of in-service transformers based on methanol and 2-FAL concentrations.

Trans_ID	DP from (1)	DP from (2)	DP from (3)	DP from (4)
Trans- 01	859	795	997	750
Trans- 04	1095	803	999	817
Trans- 05	861	796	997	919
Trans- 07	634	708	966	930
Trans- 09	499	497	862	770
Trans- 10	539	577	907	752
Trans- 11	757	778	991	800
Trans- 12	694	752	982	773
Trans- 13	891	798	998	824
Trans- 14	806	789	995	808
Trans- 15	826	792	996	813
Trans- 16	658	729	974	657
Trans- 19	801	788	994	922
Trans- 20	656	728	973	915
Trans- 23	956	801	999	783
Trans- 25	923	800	998	751
Trans- 26	860	795	997	843
Trans- 27	851	795	997	849
Trans- 28	1142	803	999	849
Trans- 30	873	797	997	839
Trans- 31	834	793	996	797
Trans- 32	620	694	960	776
Trans- 33	901	799	998	780
Trans- 34	683	746	980	713
Trans- 36	1048	803	999	886
Trans- 37	1119	803	999	925
Trans- 38	1024	803	999	907
Trans- 39	1034	803	999	932
Trans- 40	858	795	997	920
Trans- 42	1113	803	999	815
Trans- 43	788	785	993	893
Trans- 44	1048	803	999	865
Trans- 45	869	796	997	889
Trans- 46	955	801	999	891
Trans- 47	945	801	998	897

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7. References

[1] S. S. Ghoneim, “The Degree of Polymerization in a Prediction Model of Insulating Paper and the Remaining Life of Power Transformers.” *Energies*, Vol. 14, no. 3, pp. 1-14, 2021.

[2] V. Behjat, R. Emadifar, M. Pourhossein, U. Mohan Rao, I. Fofana, and R. Najjar. “Improved Monitoring and Diagnosis of Transformer Solid Insulation Using Pertinent Chemical Indicators.” *Energies*, Vol. 14, no. 13, pp. 1-13, 2021.

[3] R. Emadifar, N. Taghizadegan Kalantari, V. Behjat, and R. Najjar, “A new method for using the UV-visible

spectrum of oil for evaluating the paper insulation quality of used transformers”. *Iranian Electric Industry Journal of Quality and Productivity*, Vol. 11, no. 1. pp. 1-9, 2022.
[4] T. K. Saha, “Review of modern diagnostic techniques for assessing insulation condition in aged transformers.” *IEEE transactions on dielectrics and electrical insulation*, Vol. 10, no. 5, pp. 903-917, 2003.
[5] R. R. Meena, S. Chaki, A. J. Khimani, and M. P. Deshpande, “Transformer oil degradation study by chromatography, spectroscopy and dissolved gas analysis.” *Petroleum and Coal*, Vol. 60, no. 5, pp. 872-878, 2018.
[6] O. H. Arroyo, I. Fofana, J. Jalbert, and M. Ryadi, “Relationships between methanol marker and mechanical performance of electrical insulation papers for power transformers under accelerated thermal aging,” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol.22, no.6, pp. 3625-3632, 2015.
[۷] امید قادری، محمدرضا فیضی، «روش جدید برای تخمین عمر باقیمانده ترانسفورماتورهای قدرت با استفاده از آنالیز گازهای محلول در روغن»، *مجله مهندسی برق دانشگاه تبریز*، جلد ۳۹، شماره ۱، صفحه ۵۷-۶۶، ۱۳۸۸.
[۸] محمدرضا آرین نیک، علی اصغر رضی کاظمی، «تخمین طول عمر ترانسفورماتورهای روغنی بر مبنای درجه پلیمریزاسیون»، *مجله مهندسی برق دانشگاه تبریز*، جلد ۴۹، شماره ۳، صفحه ۹۹۵-۱۰۰۶، ۱۳۹۸.
[9] S. Tang, G. Peng, and Z. Zhong, “Quantitative spectral analysis of dissolved gas in transformer oil based on the method of optimal directions,” In 2016 35th Chinese Control Conference (CCC) Jul 27, 2016, pp. 4425-4429.
[10] J. N’cho, I. Fofana, Y. Hadjadj, and A. Beroual, “Review of physicochemical-based diagnostic techniques for assessing insulation condition in aged transformers”. *Energies*, Vol. 9, no. 5, pp. 367-377, 2016.
[11] T. Leibfried, M. Jaya, N. Majer, M. Schafer, M. Stach, and S. Voss, “Postmortem investigation of power transformers—Profile of degree of polymerization and correlation with furan concentration in the oil.” *IEEE Transactions on Power Delivery*, Vol. 28, no. 2, pp. 886-893. 2013.
[12] L. Cheim, D. Platts, T. Prevost, and S. Xu. “Furan analysis for liquid power transformers.” *IEEE Electrical Insulation Magazine*, Vol. 28, no. 2, pp. 8-21, 2012.
[13] F. Ortiz, C. Fernández, A. Santisteban, F. Delgado, and A. Ortiz. “Estimating the age of power transformers using the concentration of furans in dielectric oil.” *Renewable Energy and Power Quality Journal*, Vol. 1, no. 14, pp. 1011-1015, 2016.
[14] C. Chen, S. Li. “An improved method of detection and concentration of methanol in oil-paper insulation.” *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 27, no. 5, pp. 1724-1727, 2020.
[15] J. Jalbert, R. Gilbert, P. Tétreault, B. Morin, and D. Lessard-Déziel, “Identification of a chemical indicator of the rupture of 1,4-B-glycosidic bonds of cellulose in an oil-impregnated insulating paper system,” *Cellulose*, Vol. 14, no. 4, pp. 295–309, 2007.
[16] L. Peng, Q. Fu, L. Li, and M. Lin, “Indirect detection of DP for insulating paper based on methanol content in transformer oil by spectroscopic approach,” *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 26, no. 1, pp. 90–94, 2019.
[17] A. Schaut, S. Autru, and S. Eeckhoudt, “Applicability of methanol as new marker for paper degradation in power transformers,” *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 18, no. 2, pp. 533–540, 2011.
[18] J. Jalbert, R.Gilbert, Y. Denos, and P. Gervais, “Methanol: a novel approach to power transformer asset management,” *IEEE Transactions on Power Delivery*, Vol. 27, no. 2, pp. 514–520, 2012.
[19] J. Jalbert, C. Rajotte, M. C. Lessard, and M. Rodriguez-Celis. “Methanol in oil interpretation model based on transformer post-mortem paper analysis.” *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 25, no. 2, pp. 568-573, 2018.
[۲۰] هدی مولوی، عباس یوسف پور، نعیم حسنی، اکبر میرمصطفی، سپیده حامدی، « ارزیابی وضعیت کاغذ عایقی ترانسفورماتورهای پایلوت از طریق نشانگر شیمیایی متانول »، سی و دومین کنفرانس بین المللی برق(PSC2017)، آبان ۹۶، تهران، ایران، ص ۱-۵.
[21] O. H. Arroyo, I. Fofana, J. Jalbert, and M. Ryadi, “Relationships between methanol marker and mechanical performance of electrical insulation papers for power transformers under accelerated thermal aging.” *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol. 22, no. 6, pp. 3625-3632, 2015.
[22]T. Amimoto, E. Nagao, J. Tanimura, S. Toyama, Y. Fujita, H. Kawarai, and N. Yamada. “Identification of affecting factors of copper sulfide deposition on insulating paper in oil.” *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.16, no. 1, pp. 265-272, 2009.
[23] I. Lingvay, O .Gabriela, L. C. Ungureanu, A. Pica, and V. Stănoi. “Thermal ageing of some insulating fluids in contact with insulation paper and copper.” *Rev. Chim.(Bucharest)*, Vol.68, no.12, pp. 2881-2885, 2017.
[24] E. Zhang, H. Zheng, C. Zhang, J. Wang, K. Shi, J. Guo, H.Schwarz and C. Zhang. “Aging state assessment of transformer cellulosic paper insulation using multivariate chemical indicators.” *Cellulose*, Vol. 28, no. 4, pp.2445-2460, 2021.
[25] Measurement of the Average Viscometric Degree of Polymerization of New and Aged Cellulosic Electrically Insulating Materials, IEC 60450, 2004. https://webstore.iec.ch/publication/2162.
[26] H. Molavi, A. Yousefpour, A. Mirmostafa, A. Sabzi, S. Hamedi, M. Narimani, and N. Abdi. “Static headspace GC/MS method for determination of methanol and ethanol contents, as the degradation markers of solid insulation systems of power transformers.” *Chromatographia*, Vol. 80, no. 7 , pp. 1129-1135, 2017.
[27] M. C. Bruzzoniti, R. Maina, R. M. De Carlo, C. Sarzanini, and V. Tumiatti. “GC methods for the determination of methanol and ethanol in insulating mineral oils as markers of cellulose degradation in power transformers.” *Chromatographia*, Vol.77, no. 15-16, pp. 1081-1089, 2014.