Condition Assessment of Oil-Impregnated Paper Insulation of Transformers by Using CFA Index and Degree of Polymerization

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Abstract

This paper presents a mathematical model of transformer condition assessment index. Using analyze transformer conditions in case of limited data. The CFA index (Carbon, Furfural, and Acetylene) use to assess the degree of polymerization level (DP), which is the value that shows dielectric strength of paper insulation. Both values were obtained by estimating the furan compound (2 furaldehyde, 2FAL) in relation to the technical test results and the transformer capacity. The correlation was determined by a linear regression method. The results shown that the DP value correlated with the CFA index, which obtained from the mathematical model. The coefficient of determination of the power transformer and distribution transformer is 75.63% and 79.66%, respectively. This study used sampling test data from transformer 27 units.

Keyword: Power Transformer, Furans compound, DGA, Degree of polymerization (DP), CFA index

1. Introduction

Power transformers are high value and important assets in electric power systems, as they are essential in maintaining a reliable supply and very high in cost and essential components in high-voltage systems. This makes evaluating the condition of transformers very important for asset management. Most transformers have a rigid insulating system, kraft paper and the liquid transformer oil are insulation. The dielectric condition of the paper is an important factor affecting the remaining life of the transformer. If the transformer oil insulation is deteriorated, the oil can be replaced throughout its service life [1], but the deterioration of the paper insulation is an irreversible process. Because of paper insulation cannot be restored or maintained to restore its electrical insulation and mechanical strength to a new working condition. Hence the end of the transformer life. Therefore, it is often considered from the end of use of the paper insulation [2]. In addition, it is quite difficult to determine the insulation condition of the paper by the degree of polymerization (DP). Therefore, DP is not commonly tested directly because it is a destructive insulation test. If the transformer is in service, it is necessary to disconnect the transformer for a while in order to take a sample of the insulating piece of paper in the area that is most heated for examination in order to get accurate values. But there is another method of verification that uses a non-destructive chemical indicator that is dissolved in oil. Which is furan compound analysis. Furans are a group of organic compounds produced by the degradation of paper insulation. When cellulose deteriorates, the glycoside bonds that hold the glucose molecules break free and become contaminated in the transformer oil. Glucose is an unstable molecule that is converted to furan compounds [3]. Furan compounds in oil were used to estimate the remaining life of paper insulation and assessed with the CFA index, which takes into account CO, CO_2, C_2H_2 and 2FAL parameters, to determine the deterioration status of the paper insulation. If the CFA index is between -2 and -5.3, paper insulation can be ensured that it will not suffer from severe degradation within the transformer [4].

Types of transformer and paper insulation have different effects on the formation of furan compounds. Free-breathing or conservator tank transformers, which are mostly power transformers, tend to accumulate more furan than others. Sealed or hermetically sealed fully oil filled transformers belong to distribution transformers. All of the transformers used in this case study had paper insulation as non-upgraded paper, and most often found 2FAL furan compounds, representing 96.8% of the total furan compounds[5], of which there were 5 types.

2. The degradation processes of cellulose paper

The transformer when used undergoes electrical stress and chemical reactions occur inside the transformer. There are four main factors contributing to deterioration: high cumulative temperature, oxygen, humidity and acidity. They are the factor that causes chemical reactions, heat, oxidation and hydrolysis. This produces products from chemical reaction processes such as gases, moisture, acids, dissolved in transformer oil [6], affecting the insulation condition of the paper and the dielectric properties of the transformer gradually decrease as the service life increases. As a result, the transformer has a chance of failure

3. Degree of Polymerization

The paper insulation used in transformers is approximately 90% cellulose by weight and has the molecular structural formula ($C_5H_{10}O_5$), where cellulose is a natural polymer with a number of glucose units of the monomer showing the degree of polymerization (DP) or organic compounds consisting of a straight chain of glucose. Typically, the average number per chain in each loop ranges from 1100 to 1500 after the vacuum heat pump dryer and after delivery of the new transformer to

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the customer it is reduced to approximately 1000 to 1200. When used through the service period of the transformer. The chain is broken as a result of chemical catalysts, resulting in a decrease in the dielectric strength of the paper insulation. The transformer's end life, the DP value is typically around 200. At this point, the paper loses its mechanical strength and its dielectric strength, eventually causing the transformer insulation system to fail [7].

4. Dissolved Gas Analysis, DGA

DGA is a widely accepted method for checking the condition of transformers. It can identify faults without interrupting the service. This approach is accompanied by the analysis of combustible and non-combustible gases dissolved in transformer oil. This causes the insulating properties of oil and paper to change. In addition, the catalytic effect of chemical reactions that occurs in paper insulation and transformer oil excites the reaction rate and produces various gases. Typical gases found in oil include hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_2H_4), acetylene (C_2H_2), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen (N_2) and oxygen (O_2).

The importance level of gas induced by each type of fault within transformer, as shown in Table 1. If it is a high-power electrical fault such as arcing, in addition to hydrogen, there is also a highly important C_2H_2 gas [8].

Table 1 Gas importance level by type of faults in transformer

Cause of gas generation			H_2	CH_4	C_2H_6	C_2H_4	C_2H_2	CO	CO_2
Electrical faults	Insulating oil	Corona PDs	◉	○					
		Arc + sparking PDs	◉			○	◉		
	Insulating paper								○
Thermal faults	Insulating oil	Low temperature	○	◉	◉				
		Mid- & high temperature	○	○		◉			
		700 ℃ or higher	○			◉	○		
	Insulating paper							◉	○
Aging	Insulating oil		○		◉				
	Insulating paper							○	◉

◉ : High importance, ○ : Medium importance

5. Relationship between DP and Furans compound

The evaluating method the paper insulation condition based on furan content is considered to be quite popular and has a certain degree of reliability. Therefore, a mathematical model of the relationship between the amount of furan compound 2FAL in oil and the DP value of the paper insulation is presented in Equation (1). However, using only the concentration of 2FAL in oil may give inaccurate results. Because of the concentration of 2FAL may be influenced by factors that are not the direct result of the cellulose degradation of the paper insulation but may also result from the pressboard made of overlaid wood pulp. Several layers of overlap can accommodate the pressure between the windings on the low voltage side [9] and the chemical reaction factor affects the change in 2FAL concentration. Therefore, a total of 6 parameters were used to evaluate the 2FAL concentration was shown in Equation (2),Which is a multiple linear regression method, where the 2FAL furan test result was obtained if the value was greater than 0.6 ppm. The rate of transformation of the furan compound was nonlinear depending on the age of the furan compound. Transformers serving 2FAL addition characteristics have a sigmoid function, but if less than 0.6 ppm the rate of change is linear [10], all transformers used in the case study have 2FAL values of less than 0.6 ppm.

$$\mathrm{DP} = \frac{1850}{\mathrm{Furfural} + 2.3} \qquad (1)$$

Where
Furfural = 2-furaldehyde (2FAL) (ppm)

$$\begin{aligned}\mathrm{Furfural} = {} & (0.03018\times T)+(0.03399\times A)+ \\ & (0.3883\times M)+(48\times10^{-6}\times G_{O2}) - \\ & (23\times10^{-6}\times G_{TOT}) - (7\times10^{-6}\times C) \\ & -(0.935)\end{aligned} \qquad (2)$$

Where
T = Top Oil Temperature (°C)
A = Age (Years)
M = Moisture content of the paper (%)
G_{O2} = Oxygen concentration (ppm)
G_{TOT} = Total Gas concentration (ppm)
C = Capacity of transformer (kVA)

6. CFA Index

Deterioration condition of paper insulation is determined by using the CO_2/CO concentration ratio as these gases are products of cellulose degradation. The concentration of gas can be used to determine the rate of deterioration of the paper insulation. If the ratio is between 3 and 10, indicating that the paper insulation is in good condition (Refer to the IEC 60599 standard). However, the use of CO_2/CO concentration ratio alone may lead to incorrect diagnosis of paper insulation deterioration. The CFA index was determined using four parameters: CO, CO_2, C_2H_2 and 2FAL, which are the result of high thermal decomposition in paper insulation. C_2H_2 is a relatively rare gas caused by high-power electrical faults within the transformer. The CFA index can indicate the deterioration of the paper insulation inside the transformer, if the value is between -2 and -5.3. It can be ensured that the paper insulation is in usable condition without severe degradation within the transformer [4].

$$\mathrm{CFA} = \log_{10}\left(\frac{\frac{1}{(\mathrm{CO}+\mathrm{CO_2})}}{(100\times\mathrm{Furfural}) + \mathrm{C_2H_2}}\right) \qquad (3)$$

Where
CO = Carbon monoxide concentration (ppm).
CO_2 = Carbon dioxide concentration (ppm).
C_2H_2 = Acetylene concentration (ppm).
Furfural = 2-furaldehyde (2FAL) (ppm).

7. Implementation

Analysis of the relationship between DP(model) and CFA(model) and CFA(value) of both types of transformers by considering the correlation coefficient (r), which has a positive relationship or a direct variable relationship. The significant P-value indicates that it is important to the linear regression system, and the R-Square is the indicator of the parameter's influence. CFA can describe variations in DP parameters.

Table 2 Correlation coefficient and Coefficient of determination between DP (model) and CFA index

Type	CFA index	r	P-value	R^2
Power Transformer	CFA(model)	0.83580	0.0014	0.7563
	CFA (value)	0.33590	0.3125	0.0639
Distribution Transformer	CFA(model)	0.78611	0.0003	0.7966
	CFA (value)	0.76102	0.0006	0.7129

Table 2 shows the relationship between the two parameters and the entire linear regression process. It can be seen that the power transformer CFA(value) is insignificant to the DP(model) value. The mathematical model of the CFA index for DP evaluation is shown in Equations (4), (5) and (6). The relationship between DP and CFA obtained from mathematical model of the power transformer and the distribution transformer is shown in Fig. 1 and 2 respectively.

$$Y = (-320.0995) \cdot (V^2 + 9.7395 \cdot V + 21.4929) \quad (4)$$

$$Y = (-303.4182) \cdot (W^2 + 10.3953 \cdot W + 24.9947) \quad (5)$$

$$Y = (11.5210) \cdot (X^3 + 7.6198 \cdot X^2 + 18.4074 \cdot X + 65.9184) \quad (6)$$

Where
V = CFA(model) of Power Transformer
W = CFA(model) of Distribution Transformer
X = CFA(value) of Distribution Transformer
Y = DP(model)

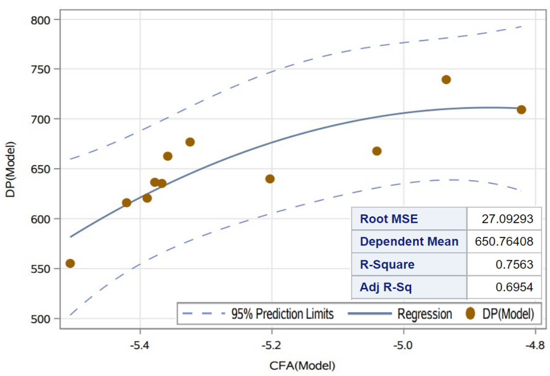
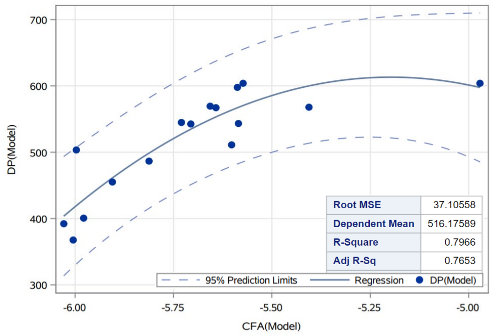
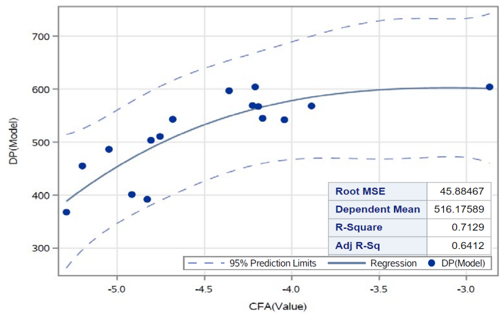


Fig. 1 Mathematical modeling of power transformers.



(a) Relationship between parameter DP(model) and CFA(model)



(b) Relationship between parameter DP(model) and CFA(value)

Fig. 2 Mathematical modeling of Distribution Transformer.

8. Discussion

From the research [11], the test results of distribution transformer oil with limited test data are shown in Table 3 by using Equation (6) to assess the DP value, which can be seen that tends to follow the health index examination results. The overall transformer of transformer insulation condition (Health Index, HI%) with the composition parameters DGAF (H_2, CH_4, C_2H_6, C_2H_4, C_2H_2, CO and CO_2), OQF (IFT, Water, Acidity, BDV, DDF and Color), and Furan (2FAL) in the assessment.

Table 3 subset of transformer oil samples

Test Data	TR1	TR2	TR3
CO	1019.6	132.5	237.6
CO_2	2619.3	1770.7	3654.1
C_2H_2	0	0	34.8
2FAL	0.01	0.28	0.54
HI (%)	100	66.67	44.05
CFA(value)	-3.56	-4.73	-5.54
DP	597.23	501.74	320.42

Table 4 shows the results of the oil test. Capacity and service life of both types of transformers, which TR01 – TR06 is a type of power transformer. In addition, it is a distribution transformer type. The transformer studied did not contain test data for the concentration of C_2H_2 dissolved in oil. It shows that the CFA(model) index

Table 4 Difference in DP(model) and CFA(model) for the used data set

TR	Capacity (kVA)	Age (Year)	Moisture in paper (%)	Top Oil Temp. (°C)	O_2 (ppm)	$CO+CO_2$ (ppm)	Total gas (ppm)	2FAL (model) (ppm)	DP (model)	CFA (model)
TR01	9000	28	0.6	48	2660	2150	63236	0.3086	709.1948	-4.8218
TR02	9000	15	1.3	54	22778	3601	89546	0.6801	620.775	-5.389
TR03	9000	28	1.2	50	22622	3109	86200	1.0319	555.2328	-5.5063
TR04	6200	16	0.7	54	24113	2329	93594	0.4717	667.4527	-5.0409
TR05	10000	28	0.8	46	18403	3741	79333	0.7043	615.7789	-5.4208
TR06	30000	28	0.9	44	27609	2699	96456	0.5909	639.9493	-5.2027
TR07	2000	28	2.2	44	22625	3480	94190	1.1045	543.3937	-5.5848
TR08	2000	28	5.5	48	18944	3696	76727	2.7316	367.6762	-6.0041
TR09	1800	28	3.5	44	7902	4563	91713	0.961	567.3129	-5.642
TR10	1800	28	2.6	58	16078	4556	77083	1.763	455.3314	-5.9048

correlated with the DP(model), if CFA(model) is between -2 and -5.3. It can indicate that the dielectric condition of the paper is still not severely degraded inside the transformer. From observing the DP value of the Power transformer is quite within the acceptable range. Although there is a slight deterioration due to aging and chemical change inside the transformer, Distribution transformers are quite risky, especially TR08 has a relatively low DP which requires regular inspection and maintenance.

9. Conclusion

From the data in Table 4 shown that the results of routine transformers oil quality tests can be analyzed the 2FAL to assess the dielectric strength of paper by DP with the CFA index method. Distribution transformer oils can collect local data or have a limited set of data to assess the quality of the paper insulation inside the transformer. In order to save time and cost in testing other additional topics, the CFA method (model) must have test results for both types of transformer oil quality, which can use the results of many tests to check the dielectric strength of paper. more efficiently Thus, a preventive transformer maintenance plan is established. To use it more efficiently and have a longer service life.

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