Power Transformer Condition Assessment Based on Standard Diagnosis

Cattareeya Suwanasri

Abstract— *The diagnostic techniques of electrical and insulating oil testing are proposed to assess the internal condition of power transformer, bushing and on-load tap changer. Then, the specified limit of normal and abnormal condition of each technique is used to evaluate the condition of transformer component. The condition assessment of 4 transformers in case of winding deformation and degradation of insulating oil in on-load tap changer compartment is presented. The investigation experience together with evaluation of measurement result shows that single phase leakage impedance is a powerful test to detect winding deformation. The gas ratio method of DGA is also an effective method to detect the degradation of insulating oil. The ability to evaluate every test method together with weighting according to important and powerful of each test method would provide the reliable result in the future.*

***Keywords*—Condition assessment, diagnostic test, dissolved gas analysis, failure statistic, insulating oil, power transformer.**

1. INTRODUCTION

Power transformer, an expensive and one of important equipment in power system, plays a significant role in the transmission and distribution networks. Its function is to transform the voltage level to suit the connected equipments. However, transformer failures are unavoidable and could occur in any major parts of the transformer [1]. In general, power transformer is subject to degradation regarding to normal aging and stresses in operation, which could lead to transformer failure. Because of the high percentage of failure probability, winding, magnetic core, bushing and on-load tap changer (OLTC) should be carefully focused. Generally, the internal condition can not be determined from visual inspection or human sensing method. Nowadays, the well-accepted electrical testing including frequency response analysis (FRA) method has been proposed to determine the condition of magnetic core and winding. However, the FRA method is sensitive and needs the comparison with reference signature, which is sometimes unavailable. The appropriate standard diagnostic techniques [2] - [4] and the evaluation to assess the condition of power transformer [5] should be considered.

In this paper, the diagnostic techniques proposed are separated into two methods, which are electrical and insulating oil tests. The electrical testing consists of exciting current, ratio, DC resistance, winding insulation resistance, single phase and three phase leakage impedances, capacitance and power factor tests. The oil insulation testing consists of color, dielectric breakdown test, acidity, interfacial tension, power factor and dissolved gas analysis (DGA).

The advantage of these diagnostic techniques is the ability to evaluate the internal condition of magnetic core and windings without uncovering main tank of power transformer as well as bushing and OLTC conditions. The joint analysis of both electrical and oil insulation tests significantly improves the accuracy of transformer condition evaluation by comparing the testing result of each diagnostic technique with the limitations given in [2] - [4], which are widely used for condition assessment by different research institutes and power utilities in different countries [4], [6], [9]. Consequently, each power transformer can be properly scheduled its service time with cost saving resulting in better reliable power in service.

2. FAILURE STATISTIC AND PROBLEM OF POWER TRANSFORMER

Failure Statistics According to Cigré

According to the international survey by Cigré [6], the group of power transformer components is divided into, on/off-load tap-changer, leakage concerning tank and insulating fluid, bushing, winding, core, and others such as temperature problem. The failure of power transformer as reported in [6] is presented in Figure 1.

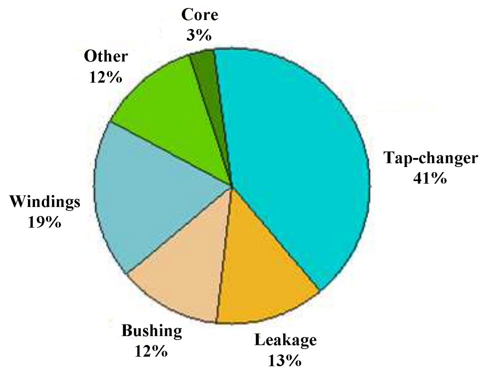

Fig.1. Failure statistics of power transformer components reported by Cigré.

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Failure Statistics of Power Transformers in Thailand

In Thailand, power transformer of two models was chosen. The first transformer of rated 115/22kV consists of 107 units, while the second of rated 230/115/22kV are 44 units. The failure statistics consists of 157 failure events for 115/22kV and 68 failure events for 230/115/22kV power transformer, respectively. By dividing the failure data of power transformer in the similar categories as above, the failure statistics of power transformer is presented in Figure 2 and Figure 3. The failure results show the similar contribution of component failure. The critical components of both power transformer types with the highest failures are bushing and tap changer respectively [7], [8].

The percentage of component failures and their associated causes are shown in Figure 2 for 115/22kV power transformer. The components with high percentage of failure are bushing 39.13% and OLTC 26.71%. The major causes of failure are leakage for bushing, and defect and leakage for tap changer. Figure 3 for 230/115/22kV power transformer, the components with high percentage of failure are bushing 29.58% and OLTC 19.72%. The major causes of failure are leakage for bushing, and defect for tap changer.

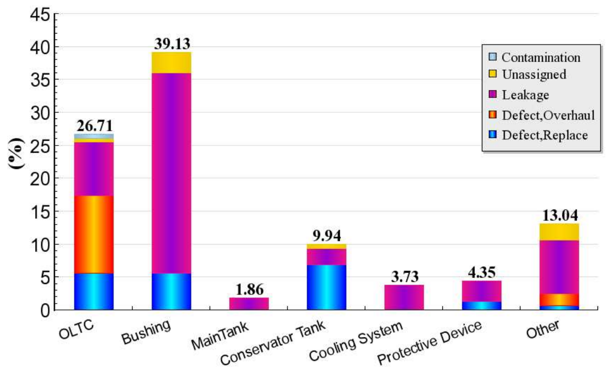

Fig. 2. Percentage of component failures and their associated causes for 115/22kV power transformer.

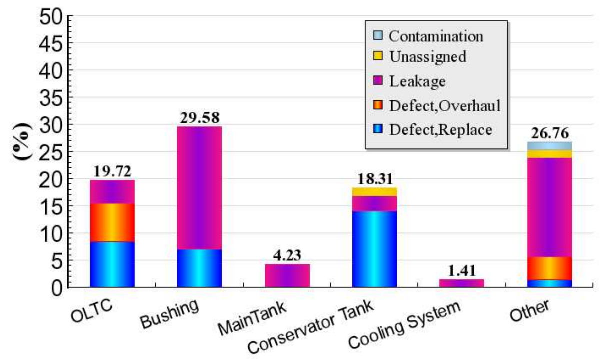

Fig. 3. Percentage of component failures and their associated causes for 230/115/22kV power transformer.

3. CONDITION ASSESSMENT OF TRANSFORMER COMPONENT

According to failure statistic, the condition of critical components, such as bushing and OLTC, must be able to determine. The internal condition of active parts, which are magnetic core and windings, is evaluated from electrical tests whereas the condition of insulating oil in main tank is defined by several diagnostic techniques.

Both electrical and oil testing techniques are basic and reliable diagnostic techniques, which are worldwide accepted for observing the health of power transformer without uncovering main tank [2]-[6]. For example in Thailand, the testing techniques are practically implemented as testing standard of power transformer [9].

Magnetic core and winding

To assess magnetic core and winding conditions, the following diagnostic techniques are applied:

1. Core ground insulation resistance to measure the insulation resistance between core and ground
2. Single phase low voltage exciting current to check for short turn and movement of core leg
3. Single phase leakage impedance measurement to check winding deformation. The measurement circuit is shown in Figure 4.
4. Winding turn ratio test to determine whether or not the winding is shorted turns or open circuit.
5. DC winding resistance to indicate the winding conductor and tap changer contact condition
6. Insulation resistance and insulation power factor to monitor the condition of transformer and bushing

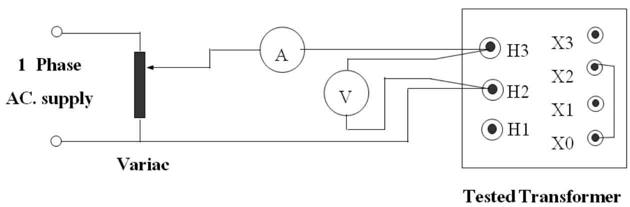

Fig. 4. Test circuit for single phase leakage impedance measurement

Their limit for normal and abnormal conditions is defined in Table 1.

The equation to find percentage of maximum impedance deviation is expressed in Equation (1).

$$\text{Maximum percent deviation} = \frac{(Z_{max} - Z_{min})x100}{Z_{min}} \quad (1)$$

Bushing Condition

Bushing condition can be assessed by the measurement of % power factor test and capacitance test as follow:

- %Power Factor at 20^{o}C of C_1
- %Power Factor of C_2
- Capacitance of C_1
- Capacitance of C_2

The limitation of bushing condition, e.g. good, suspect or poor, are defined in Table 2.

Table 1. Electrical diagnostic limitation of core and winding

Diagnosis	Limit
Core Insulation Resistance	• A new transformer 1000 MΩ • A service-aged transformer 100 MΩ
Exciting Current	• Difference between two phase exciting current < 10% (rated exciting current <50mA) • Difference between two phase exciting current < 5% (rated exciting current >50mA)
Impedance (% deviation)	• 0.5-2% Normal • 2-3% Suspect • > 3% Abnormal
Ratio	• Change from nameplate < 0.5% • New transformer < 0.1%
DC Resistance	• Resistance change from factory value < 5%
Insulation Resistance	Polarization Index (PI) = $R_{at\ 10min}/R_{at\ 1\ min}$ • < 1 Dangerous • 1.0-1.1 Poor • 1.1-1.25 Suspect • 1.25-2.0 Satisfactory • > 2.0 Good Insulation Power factor • Power factor < 0.5% (at 20°C)

Table 2. Electrical diagnostic limitation of bushing

Diagnosis	Limit
%Power Factor at 20°C of C_1	• %PF ≤ 0.5 = Good • 0.5 ≤ %PF < 1 = Suspect • %PF > 1 = Poor
%Power Factor of C_2	• %PF ≤ 0.5 = Good • 0.5 ≤ %PF < 1 = Suspect • %PF > 1 = Poor
Capacitance of C_1	• % Capacitance ≤ 5 = Good • % Capacitance > 5 = Poor
Capacitance of C_2	• % Capacitance ≤ 1 = Good • % Capacitance > 1 = Poor

On-load Tap Changer Condition

The condition of OLTC is considered from the result of oil contamination, dissolved gas analysis and dielectric property of insulating oil in OLTC compartment as shown in Table 3. For DGA method, there are 3 gas ratios as follow:

- Gas ratio 1 is
  $CH_4+C_2H_6+C_2H_4)/(H_2+CH_4+C_2H_6+C_2H_4+C_2H_2)$
- Gas ratio 2 is
  $(CH_4+C_2H_6+C_2H_4)/(C_2H_2)$
- Gas ratio 3 is
  C_2H_4 / C_2H_2

Table 3. Diagnostic techniques and their limitation for OLTC condition

Diagnosis	Limit
OLTC Oil Contamination • Color • Water Content	• Color < 1 = Good, Color ≥ 5.5 = Poor • Water Content < 20 = Good, Water Content ≥ 45 = Poor
Dissolved Gas Analysis Technique • 3 gas ratio	• Gas Ratio1 < 0.5 = Good, Gas Ratio1 ≥ 0.5 = Poor • Gas Ratio2 < 2 = Good, Gas Ratio2 ≥ 2 = Poor • Gas Ratio3 < 1 = Good, Gas Ratio3 ≥ 1 = Poor
Dielectric Property of Insulating Oil • ASTM D1816 Gap 2mm • % Power Factor at 20°C	• $U_{breakdown}$ > 46 = Good, $U_{breakdown}$ < 30 = Poor • %PF ≤ 0.05 = Good, %PF ≥ 1 = Poor

Condition of Insulating Oil in Main Tank

The condition of insulating oil in main tank is considered from the result of oil contamination, e.g. dielectric strength ASTM D1816 Gap 1mm, interfacial tension, neutralization number, water content, color and % power factor at 20°C and at 100°C as shown in Table 4.

Table 4. Diagnostic techniques and their limitation for oil in main tank

Diagnosis	Limit
OLTC Oil Contamination • ASTM D1816 Gap 1mm • Interfacial Tension • Acidity (NN) • Water Content • Color • % PF at 20°C • % PF at 100°C	• $U_{breakdown}$ > 30 = Good, $U_{breakdown}$ < 19 = Poor • Interfacial tension ≥ 38 = Good, Interfacial tension ≤ 24 = Poor • Acidity ≤ 0.015 = Good, Acidity ≥ 0.5 = Poor • Water Content ≤ 10 = Good, Water Content ≥ 31 = Poor • Color ≤ 1.0 = Good, Color ≥ 4.1 = Poor • %PF ≤ 0.1 = Good, %PF ≥ 1.1 = Poor • %PF ≤ 1.0 = Good, %PF ≥ 7.1 = Poor

4. ANALYSIS OF TEST RESULT

The proposed diagnostic tests and their limitation of both electrical and oil testing are used to evaluate the condition of power transformer.

The procedure of oil testing analysis is addressed as follows. Firstly, the historical test result of insulating oil in a sampled transformer is obtained. Secondly, the color, dielectric breakdown test, acidity, interfacial tension, power factor and dissolved gas analysis (DGA) of the sampled oil will be analyzed and compared each standard regarding its test. Finally, the oil conditions and the causes of failures can be determined.

Similarly, the procedure of electrical testing analysis is given as follows. The electrical testing criteria's should be firstly classified as exciting current, ratio, DC resistance, winding insulation resistance, single phase and three phase leakage impedances, capacitance and power factor tests. Next, the testing results will be analyzed and compared with the limits mentioned in Table I. Finally, core and winding conditions are observed. The historical test results of four transformers are presented in the following sections.

The First Transformer

The first transformer of rated 115/22kV, 50MVA is presented below as an example of the degradation of insulating oil in OLTC compartment. The oil testing results are analyzed with their associated limit to classify normal and abnormal conditions. The DGA test result of OLTC insulating oil is shown in Table 5. After gas ratio analysis, OLTC insulating oil is degraded because ratio 1 and ratio 2 exceed their limit since 20 October 2008 as seen in Figure 5. The result shows that the measured and gas ratio value increase with the age of power transformer.

Table 5. DGA test result of OLTC insulating oil of the first transformer

Date	CH_4 (ppm)	C_2H_6 (ppm)	C_2H_4 (ppm)	C_2H_2 (ppm)	H_2 (ppm)
03/04/2004	18	9	0	90	13
15/11/2007	308	33	633	6390	1231
30/03/2008	255	30	600	5000	923
20/10/2008	288	30	0	167	13
05/04/2009	158	42	0	89	15

The condition of insulating oil in main tank is further evaluated. The result of several diagnostic tests, which are breakdown voltage, interfacial tension, acidity, water content, % power factor at 20°C and % power factor at 100°C, are within limit of normal condition as shown in Figure 6 for interfacial tension. However, the color of insulating oil slightly exceeds the normal limit, but still below the abnormal limit. After maintenance on 20 October 2008, the color value fall down within limit as shown in Figure 7.

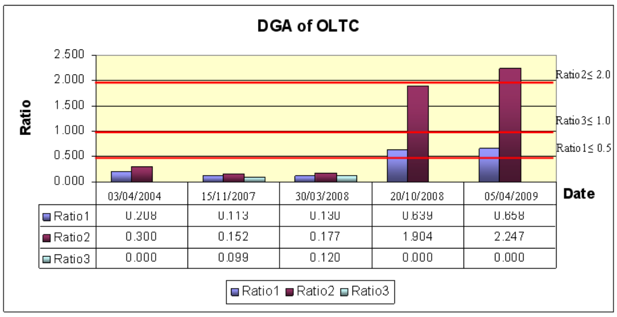

Fig.5. The result of DGA analysis in three ratios of the first transformer 115/22kV, 50MVA

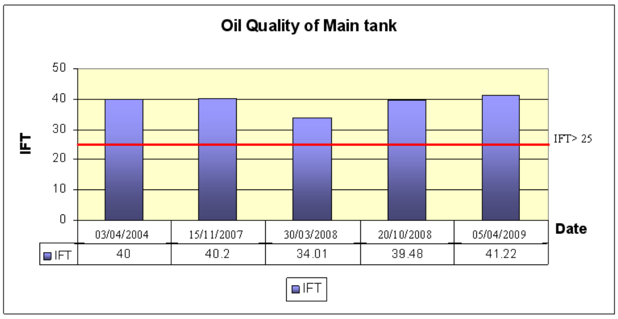

Fig.6. The interfacial tension of oil in main tank of the first transformer 115/22kV, 50MVA

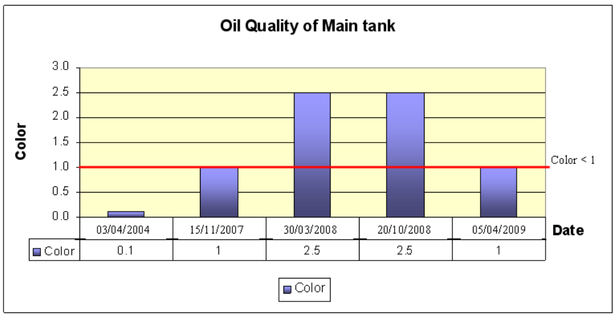

Fig.7. The color of oil in main tank of the first transformer 115/22kV, 50MVA

Table 6. DGA test result of OLTC insulating oil of the first transformer

Date	CH_4 (ppm)	C_2H_6 (ppm)	C_2H_4 (ppm)	C_2H_2 (ppm)	H_2 (ppm)
18/04/2004	18	9	0	90	13
30/03/2006	308	33	633	6390	1231
18/04/2007	196	30	510	5090	823
12/03/2008	144	30	0	80	13
31/03/2009	158	42	0	78	15

The Second Transformer

The second transformer of rated 230/115kV, 200MVA is presented below as an example of the degradation of insulating oil in OLTC compartment. The oil testing results are analyzed with their associated limit. The DGA test result of OLTC insulating oil is shown in Table 6. After gas ratio analysis, OLTC insulating oil is degraded because ratio 1 and ratio 2 exceed their limit since 12 March 2008 as seen in Figure 8. The result shows that the measured and gas ratio value also increase with the age of power transformer.

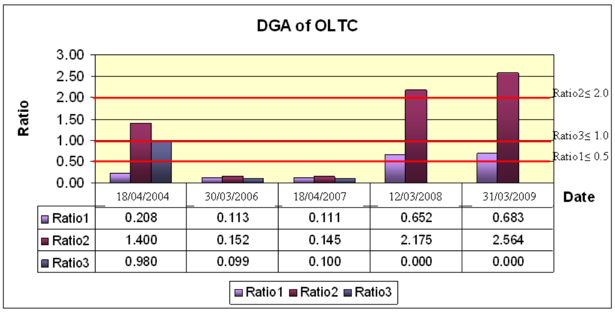

Fig.8. The result of DGA analysis in three ratios of the second transformer 230/115kV, 200MVA

The condition of insulating oil in OLTC compartment evaluated from the result of other diagnostic tests, which are color, breakdown voltage, water content, % power factor at 20°C, are within limit of normal condition as shown in Figure 9 for water content and Figure 10 for breakdown voltage, respectively.

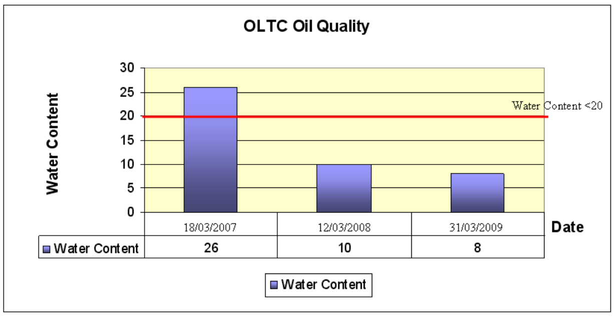

Fig.9. The water content of oil in OLTC compartment of the second transformer 230/115kV, 200MVA

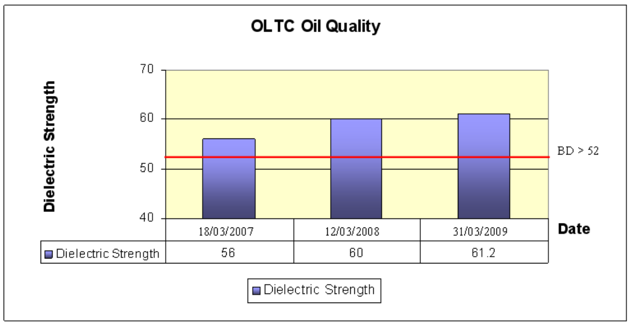

Fig. 10. The breakdown voltage of oil in OLTC compartment of the second transformer 230/115kV, 200MVA

The Third and the Fourth Transformer

The third and fourth transformer of rated 115/22kV, 50MVA are presented below as an example of winding deformation detected by single phase leakage impedance measurement. The measurement result is shown in Table 7 and Table 8. The % deviation of impedance, calculated from Equation 1, is -4.6% and -3.4%. Compared with its associated limit, it exceeds 3%. After opening the tank, the deformation of winding was found as shown in Figure 11 and Figure 12 for the third and the fourth transformer, respectively.

Table 7. Test result of single leakage impedance of the third transformer

Tap	Energize/ Short	7/4/2003	17/10/2008	Deviation
		Impedance	Impedance	Between Tests (%)
7L	H1-H2/X0-X2	129.40	123.71	-4.600
	H2-H3/X0-X3	125.00	123.21	-1.432
	H3-H1/X0-X1	125.00	123.15	-1.480

Fig. 11. Buckling of coil with leakage reactance -4.6%.

Table 8. Test Result of single leakage impedance of the fourth transformer

Tap	Energize/ Short	12/8/2002	9/12/2007	Deviation
		Impedance	Impedance	Between Tests (%)
7L	H1-H2/X0-X2	126.67	122.51	-3.400
	H2-H3/X0-X3	124.30	122.21	-1.710
	H3-H1/X0-X1	124.20	122.35	-1.512

Fig. 12. Buckling of coil with leakage reactance -3.4%.

5. CONCLUSION

The proposed diagnostic of electrical and insulating oil testing as well as their defined limit are used to assess and to evaluate the internal condition of power transformer, bushing and OLTC. The condition assessment of 4 transformers in case of winding deformation and degradation of insulating oil in OLTC compartment is presented. The historical test results of three transformers of rated 115/22kV, 50MVA and one transformer of rated 230/115kV, 200MVA are presented as an example. The electrical and oil testing results are analyzed with their associated limit to classify normal and abnormal conditions. The investigation experience and evaluation of measurement result shows that single phase leakage impedance is a powerful test to detect winding deformation. The gas ratio method of DGA is also an effective method to detect the degradation of insulating oil in OLTC compartment. Finally, the ability to evaluate every test with its associated weighting according to important of the test would provide the reliable result.

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