Diagnosis Techniques for Condition Assessment of Power Transformer Load Tap Changer

Juthathip Haema, Rattanakorn Phadungthin, and Thanapong Suwanasri

Abstract— *Power transformers in Thailand are failed mostly due to load tap changer failures. To evaluate the condition of the load tap changer, four categories of diagnostics consisting of contact condition analysis, oil contamination analysis, dielectric property analysis of the insulating oil and dissolved gas analysis are proposed in this work. Catastrophic consequences of the tap changer are caused by its aging mechanisms, which subsequently generate abnormal gases in the insulating oil. Hence, the historical test data of gases dissolved in the load tap changer oil of ten sample transformers rating 230/115 kV 200 MVA and 115/22 kV 50 MVA are selected and analyzed by key gas, ratio, and Duval triangle techniques. The worst case of each transformer group is investigated further by the oil contamination and dielectric property measurements over a period of time. Then the result of this work is useful for planning an appropriate maintenance strategy to keep the load tap changer in acceptable condition.*

Keywords— **Condition assessment, diagnosis techniques, failure statistics, load tap changer, power transformer.**

1. INTRODUCTION

Power transformer is one of significant equipment in power system. Its main function is to transform electrical power from one voltage level to another in order to meet various requirements in the network. As power transformer is very costly, adequate routine maintenance is required. Failure statistics in the last 10 years of the scattering 144 failure events of 71 power transformers rating 115/22 kV 50 MVA in Thailand are shown in Fig.1. The failures of power transformers are caused by aging effects of on load tap changer (OLTC). The main cause of failures from the recorded data is crack. The tap changer aims to modify the voltage ratio of a power transformer by means of adding or subtracting the tapping turns from the main windings. There are two types of OLTC for tap selection and arcing control method. The first part is a selector switch, at which the tap selector and diverter switches are combined together, as shown in Fig. 2(a). The other is so called a diverter switch type, at which both the selector and diverter switches are separately enclosed, as shown in Fig. 2(b). According to current limiting method, OLTC can be classified into two types: reactor and resistor. The first is frequently used for the voltage regulation at the low voltage side of the power transformer [1]. The latter is mainly used on the high voltage side. To eliminate the problem of oil contamination, vacuum interrupters have been introduced and used in both reactor and resistor types as well as for both of the selector and the diverter switch types.

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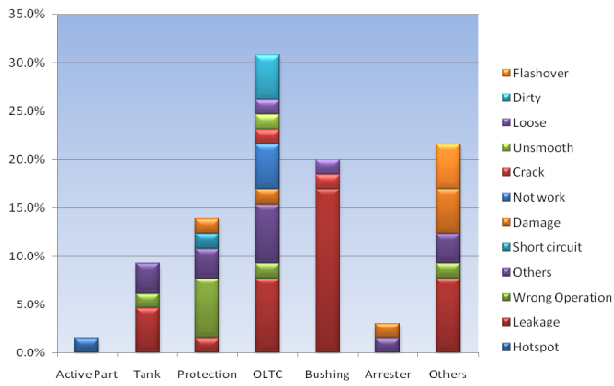
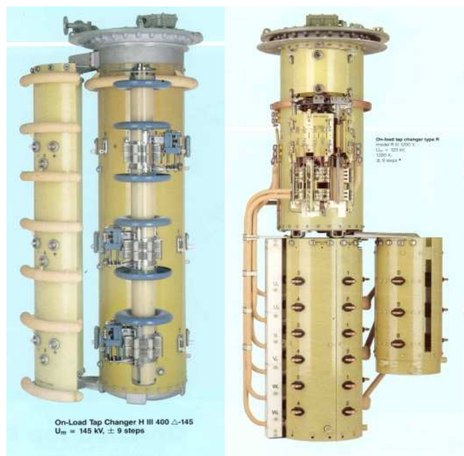


Fig.1. Defective Components and Their Failure Causes of Power Transformer, Rating 115/22 kV 50 MVA.



(a) (b)

Fig.2. Type of On Load Tap Changer [2].
(a) Selector Switch (b) Diverter Switch

However, only reactor type with the selector and the diverter switches is investigated in this paper with proposed diagnostics for the condition evaluation. As a tap changer faces various aging mechanisms, the insulating oil inside the tap changer housing becomes dirty. Moreover, the abnormal gases from arc and heat due to the switching of diverter switch are generated. Thus, the quality of the insulating oil is primarily concerned. Therefore, this paper focuses on condition assessment of OLTC insulating oil of ten transformers rating 230/115 kV 200 MVA and 115/22 kV 50 MVA as examples by applying dissolved gas analysis method with three techniques: key gas, ratio and Duval triangle. The integrity of the insulating oil is firstly checked by the key gas and ratio techniques. The Duval triangle is subsequently used to identify the fault type. Moreover, the investigation on the worst case of each transformer group is performed further by means of the oil contamination as well as dielectric property tests.

2. BASIC KNOWLEDGE

Due to the fact that the condition of tap changer is one of significant causes to an operating performance of power transformer, the condition of the tap changer and the integrity its insulating oil should be evaluated. The diagnosis tests comprise four main groups such as contact condition analysis, oil contamination analysis, dielectric property analysis of the insulating oil, and dissolved gas analysis (DGA). The first three groups of the diagnosis tests are utilized for accessing the condition of the tap changer and its insulating oil. The last, DGA analysis, is applied to identify the possible fault types from gases dissolved in the insulating oil.

2.1 Contact Condition Analysis

Condition of tap changer contact can be assessed by two measurements: transition resistance and contact wear. The limits of these tests are shown in Table 1.

1) Transition Resistance

The measured value of transition resistance is compared to the nameplate value. The maximum limit of deviation for transition resistance is 5% otherwise the contact condition is poor.

2) Contact Wear

The wear of the main switching contacts and the transition contacts is measured in terms of millimeter (mm) per 100,000 tap change operations to evaluate the contact wear condition. If it exceeds 1 mm/100,000 operations, the contact is in poor condition.

2.2 OLTC Oil Contamination Analysis

Condition evaluation of the oil contamination can be performed by two measurements such as color and water content. The limits of these tests are shown in Table 1.

1) Color

Color is represented by a number, which is compared with color standard to assess whether or not the oil is contaminated. Poor condition is represented by high color number. The maximum limit of the color number for the load tap changer is 5.5 for all high voltage transformer ratings.

2) Water Content

Some water content always occurs in the transformer when the oil is service-aged. This accelerates a degradation of transformer insulation and decreases transformer cooling efficiency [3]. The maximum water content in the insulating oil for all high voltage transformer ratings is 45 parts per million (ppm).

2.3 Dielectric Property Analysis of OLTC Insulating Oil

Two measurements consisting of dielectric strength and power factor are used to analyze dielectric property of OLTC insulating oil. The limit values are presented in Table 1.

1) Dielectric Strength

Dielectric strength or dielectric breakdown voltage measures the ability of the insulating oil to withstand the electrical stress. The low value of breakdown voltage implies that the oil has been contaminated by a large amount of particles. Referred to the standard ASTM D1816 with 2 millimeter gap, the acceptable minimum breakdown voltage is 30 kV for all power transformers.

2) Power Factor

Power factor indicates the dielectric loss in the insulating oil. A high power factor means deterioration and/or contamination of the oil. As the power factor value is dependent on temperature, the measured values should be converted to the reference temperature 20ºC by a correcting factor (CF). The value above or equal to 1.0 indicates poor condition of dielectric property [4].

Table 1. Limit Value of Each Diagnostic Test

Analysis	Diagnostic Test	Limit Value	
OLTC Contact	Transition Resistance (%Deviation)	≤ 5	Good
		> 5	Poor
	Contact Wear (mm/100,000 operations)	≤ 1	Good
		> 1	Poor
OLTC Oil Contamination	Color	< 1.0	Good
		1 - 5.4	Suspect
		≥ 5.5	Poor
	Water Content [ppm]	< 20	Good
		20 - 44	Suspect
		≥ 45	Poor
OLTC Dielectric Property	Dielectric Strength [kV]	≥ 46	Good
		31 - 45	Suspect
		≤ 30	Poor
	% Power factor at 20 °C	≤ 0.05	Good
		0.06 -0.9	Suspect
		≥ 1.0	Poor

2.4 OLTC Dissolved Gas Analysis

Dissolved gas analysis, so called DGA, is a well-known technique for insulating oil analysis to identify incipient faults inside transformers before catastrophic damages occur [5]. Nowadays, it becomes one of routine measurements for all power transformers. The DGA of

OLTC, insulating oil used in the analysis, consists of three techniques as key gas, ratios and Duval triangle. The key gas method is primarily used to evaluate the condition of the insulating oil by applying scoring and weighting technique. The scoring is utilized for condition classification into three levels: good, suspect and poor. The weighting is determined according to the importance of each gas. The oil condition is eventually presented by color indicators: green indicating good condition for 0-40% DGA factor (DGAF), yellow indicating fair condition for 41%-60%, and red indicating poor condition for 61%-100%. Subsequently, the ratio method is used to evaluate the oil condition according to its specified good and poor limits. Finally, the Duval triangle technique is applied to identify the fault type.

1) Key Gas Method

The four key gases are CH_4 (Methane), C_2H_6 (Ethane), C_2H_4 (Ethylene) and C_2H_2 (Acetylene). The limit values of each key gas for OLTC are summarized in Table 2 [6]. Working procedure of the oil condition evaluation is shown in Fig. 3. The abbreviation "n" is 4 because of 4 types of key gases.

Table 2. Limit Value of Each Key Gas for OLTC Oil

Type	Gas	Si: 1 Good	Si: 2	Si: 3	Si: 4 Poor	Wi
Vacuum	CH_4	<30	30-50	50-100	≥100	3
	C_2H_6	<20	20-30	40-50	≥50	3
	C_2H_4	<50	50-100	100-200	≥200	4
	C_2H_2	<3	3-4	4-5	≥5	5
Resistive	CH_4	<100	100-200	200-300	≥300	3
	C_2H_6	<50	50-100	100-200	≥200	3
	C_2H_4	<200	200-400	400-600	≥600	5
	C_2H_2	<500	500-1000	1000-5000	≥500	3
Reactive (Diverter Comp.)	CH_4	<200	200-300	300-700	≥700	3
	C_2H_6	<100	100-150	150-500	≥500	3
	C_2H_4	<300	300-500	500-1400	≥1400	5
	C_2H_2	<1000	1000-3000	3000-7500	≥7500	3
Reactive (Selector Comp.)	CH_4	<50	50-150	150-250	≥250	3
	C_2H_6	<30	30-50	50-100	≥100	3
	C_2H_4	<100	100-200	200-500	≥500	5
	C_2H_2	<10	10-20	20-25	≥25	3

2) Ratio Method

The five combustible gases dissolved in the insulating oil and used for ratio calculation are H_2 (Hydrogen), CH_4 (Methane), C_2H_6 (Ethane), C_2H_4 (Ethylene), and C_2H_2 (Acetylene). The ratios and their limits are shown in Table 3.

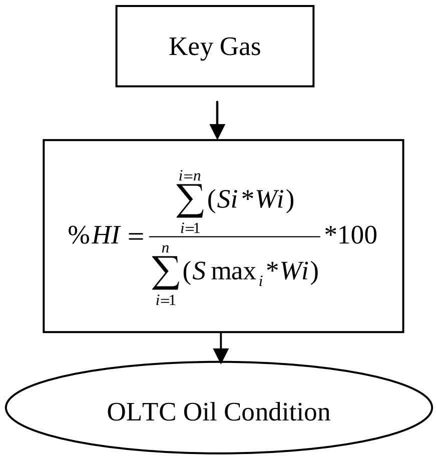
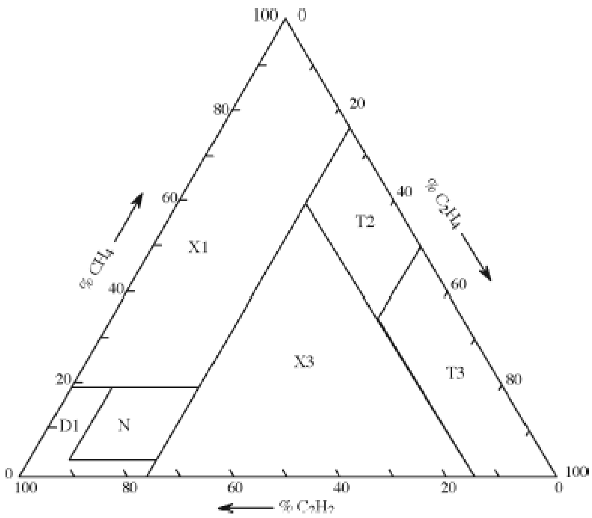


Fig. 3. Working Procedure of OLTC Oil Condition Evaluation by Key Gas Method.

Table 3. Limit Value of Each Ratio for OLTC Oil

Gas Ratio	Limit Value	
1. Ratio1: $(CH_4+C_2H_6+C_2H_4)$ / $(H_2+CH_4+C_2H_4+C_2H_2+C_2H_6)$	<0.5	Good
	≥0.5	Poor
2. Ratio 2 : $(CH_4+C_2H_6+C_2H_4)/(C_2H_2)$	<2.0	Good
	≥2.0	Poor
3. Ratio 3 : (C_2H_4/C_2H_2)	<1.0	Good
	≥1.0	Poor



Fault Codes:

N: Normal Operation

T2: Severe thermal fault (300-700ºC), coking

T3: Severe thermal fault (above 700ºC), heavy coking

X1: Abnormal arcing or thermal fault in progress

X3: Fault T3 or T2 in progress (mostly) with light coking or increased resistance of contacts. Or, severe arcing

D1: Abnormal Arcing

Fig. 4. Coordinate and Fault Zones of the Duval Triangle for Oil Type Load Tap Changer.

3) Duval Triangle Method

The Duval triangle method concerns only three hydrocarbon gases: CH_4, C_2H_4, and C_2H_2. Concentrations in ppm of the gases are expressed as percentages of the total of CH_4+C_2H_4+C_2H_2 and plotted as a coordinated point of %CH_4, %C_2H_4, and %C_2H_2 in a Duval triangle. Fig. 3 shows several fault types of the Duval triangle for load tap changers of oil type [7].

3. ANALYSIS AND TEST RESULTS

The available historical test data of OLTC insulating oil of ten sample transformers rating 230/115 kV 200 MVA and 115/22 kV 50 MVA are selected in the analysis. Firstly, the data in 2009 of the first group including five sample 200 MVA transformers is analyzed by the DGA method with three different techniques. It is followed by focusing on the worst case by means of oil contamination and dielectric property tests. After that the second group data in 2009 of five sample 50 MVA transformers is analyzed with a similar procedure.

3.1 The First Group of Transformers with 200 MVA

1) OLTC Insulating Oil Condition of Five Sample Transformers

According to the DGA test result of the 200 MVA transformers shown in Table 4, concentrations in ppm of gases dissolved in the oil of all five transformers are very high. To interpret the result, three techniques of the DGA method are applied.

Table 4. DGA Result of the First Transformer Group

Tx \ Gas	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6
Tx1	14349	7033	14939	40138	11437
Tx2	220	1141	2375	4539	644
Tx3	27977	6861	15303	20333	4022
Tx4	12688	5249	11417	21286	3661
Tx5	19749	6283	12146	20767	3690

- ***Key Gas Technique***

The %DGAF is obtained from the calculation of OLTC insulating oil condition. The obtained results are that the %DGAF of four transformers equals 100% while the other is 89%. This implies very poor condition of the insulating oil for all sample transformers represented by red color indicators.

- ***Ratio Technique***

The results of three ratios calculated by using the concentration in ppm of three gases generated in the oil are shown in Fig. 5. It can be seen that three transformers which are Tx1, Tx2 and Tx4 encounter critical OLTC oil problem as their three ratio values exceed the limits.

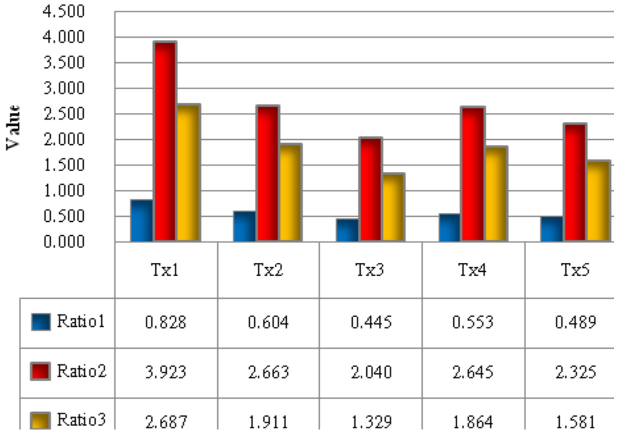


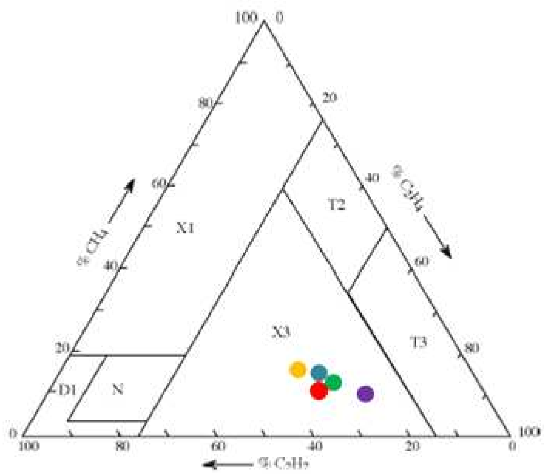
Fig.5. Ratio Values of Dissolved Gases of the First Transformer Group.

Table 5. Percentage of Duval Gases of the First Transformer Group

Key Gas \ Tx	Tx1	Tx2	Tx3	Tx4	Tx5
%C_2H_2	24.052	29.485	36.010	30.083	32.877
%C_2H_4	64.624	56.350	47.846	56.087	51.971
%CH_4	11.323	14.165	16.145	13.831	15.152

- ***Duval Triangle Technique***

The percentages of three gases in the Duval triangle technique are represented in Table 5. By plotting these percentages of five sample transformers in the Duval triangle, all coordination points are in X3 zone as shown in Fig. 6. It means that the OLTC should be inspected for light coking sign or resistance of contacts or severe arcing.



Purple = Tx1, Green = Tx2, Orange = Tx3, Red = Tx4, and Blue = Tx5

Fig.6. Duval Triangle of the First Transformer Group.

All oil conditions of the first transformer group, which are assessed by three distinguish techniques of the DGA methods, are summarized in Table 6.

Table 6. OLTC Oil Condition by the DGA Method of the First Transformer Group

Test	Rated	200MVA				
		Tx1	Tx2	Tx3	Tx4	Tx 5
Key Gas Method		R	R	R	R	R
Ratio Method	Ratio1	R	R	G	R	G
	Ratio2	R	R	G	R	R
	Ratio3	R	R	R	R	R
Duval Triangle Method		X3	X3	X3	X3	X3

R=Red or poor condition and G=Green or good condition

2) OLTC Insulating Oil Condition of the Worst Case of the 200 MVA Sample Transformers (Tx1)

- ***Oil Contamination Test***

The test results of color and water content during 2006-2009 of Tx1 are shown in Table 7. It is seen that the values of water content have been in suspect condition since 2006, but poor condition occurs in July 2009. The values of color have been zero, which were within the limit. However, the water content results imply that the insulating oil of this transformer is contaminated with water and other particles.

Table 7. Oil Contamination Test Result of 200 MVA Tx1

Diagnostic Test Result for Oil Contamination		
Date	Color	Water Content [ppm]
19/04/2006	0	37
19/09/2007	0	32
26/11/2007	0	38
24/06/2008	0	42
04/06/2009	0	33
13/07/2009	0	45

Table 8. Dielectric Property Test Result of 200 MVA Tx1

Diagnostic Test for Oil Contamination		
Date	Break Down Voltage	%PF
04/05/2003	37.30	0.01
21/12/2004	28.46	0.01
04/06/2006	45.42	0.03
11/03/2007	41.98	0.04

- ***Dielectric Property Test***

The results of dielectric strength and power factor tested during 2003-2007 are presented in Table 8. The values of dielectric strength have mostly been in suspect condition, but in 2004 the condition was poor. In addition, the values of power factor corrected at 20ºC seemed to increase over time even in good condition. These results indicate that the insulating oil of the transformer faces the problem of withstanding the electrical stress due to oil contamination with particles.

3.2 The Second Group of Transformers with 50 MVA

1) OLTC Insulating Oil Condition of Five Sample Transformers

The DGA test result of the 50 MVA transformers is shown in Table 9. The number of gas concentration in ppm dissolved in the insulating oil of these five sample transformers is very high when compared to their limits. Three techniques of the DGA method are applied for result interpretation.

Table 9. DGA Result of the Second Transformer Group

Tx \ Gas	H_2	CH_4	C_2H_2	C_2H_4	C_2H_6
Tx1	7227	1713	15239	3243	307
Tx2	11032	2636	2208	2440	220
Tx3	33971	26250	19924	31197	6189
Tx4	3899	542	4877	1024	172
Tx5	8888	2269	207	887	299

- ***Key Gas Technique***

As the very high concentration of combustible gases, the calculated %DGAF is 100% as very poor condition for all five sample transformers. This indicates that these transformers must be immediately inspected to avoid severe problem.

- ***Ratio Technique***

The calculated results of three ratios are shown in Fig. 7. The result shows that the most critical tap changer condition is TX3 with all out-of-limit ratios. It is clearly seen that Tx5 may face a problem of its OLTC insulating oil because the value of second ratio is very high.

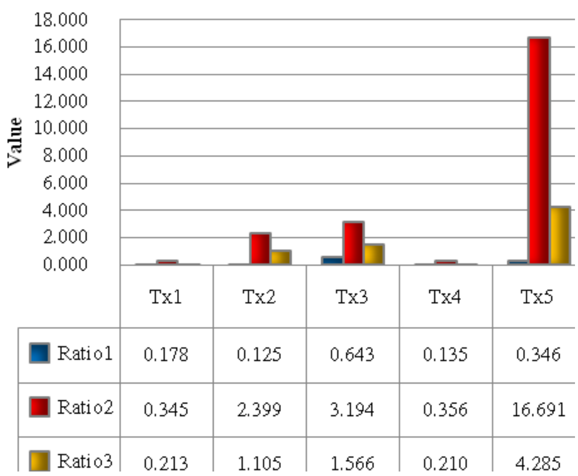


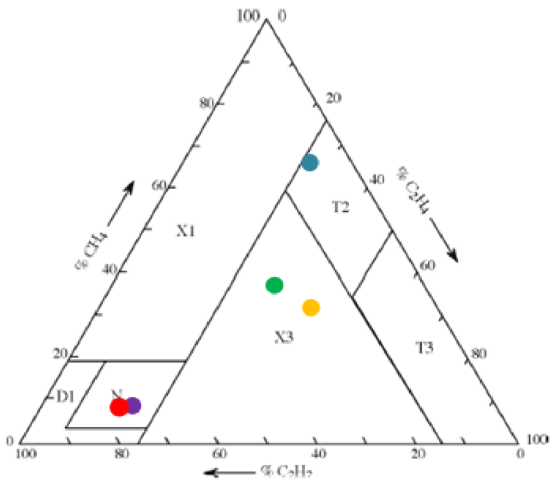
Fig.7. Ratio Values of Dissolved Gases of the Second Transformer Group.

- ***Duval Triangle Technique***

Referred to the percentages of Duval gases in Table 10, the coordinated points of Tx2 and Tx3 are in X3 zone, indicating arcing problem. The coordination of Tx1 and Tx4 are in N-zone indicating normal operation, while Tx5 is in T2 indicating severe thermal fault.

Table 10. Percentage of Duval Gases of the Second Transformer Group

Key Gas \ Tx	Tx1	Tx2	Tx3	Tx4	Tx5
$\%C_2H_2$	75.459	30.313	25.751	75.695	6.155
$\%C_2H_4$	16.058	33.498	40.321	15.893	26.375
$\%CH_4$	8.482	36.189	33.927	8.412	67.470



Purple = Tx1, Green = Tx2, Orange = Tx3, Red = Tx4, Blue = Tx5

Fig.8. Duval Gases of the Second Transformer Group.

The oil conditions of the second transformer group by three different techniques of the DGA methods are accessed and summarized in Table 11.

Table 11. OLTC Oil Condition by the DGA Method of the Second Transformer Group

Test \ Rated		50MVA Tx1	Tx2	Tx3	Tx4	Tx5
Key Gas Method		R	R	R	R	R
Ratio Method	Ratio1	G	G	R	G	G
	Ratio2	G	R	R	G	R
	Ratio3	G	R	R	G	R
Duval Triangle Method		N	X3	X3	N	T2

2) OLTC Insulating Oil Condition of the Worst Case of the 50 MVA Sample Transformers (Tx3)

- ***Oil Contamination Test***

As seen from Table 12, the values of water content have been in good condition since 2008. These results show that the transformer did not face the problem of oil contamination.

Table 12. Oil Contamination Test Result of 50 MVA Tx3

Diagnostic Test for Oil Contamination		
Date	Color	Water Content
19/03/2008	0	9
08/04/2008	0	8
11/03/2009	0	10

- ***Dielectric Property Test***

The available results of dielectric strength and power factor were recorded during 2004-2008 and summarized in Table 13. The value of the dielectric strength was in good condition in 2007. After that it decreases to suspect condition in 2008. For power factor values corrected at 20ºC, the data is not available for the analysis. These results referring to the dielectric strength imply that the insulating oil of the transformer should be taken care.

Table 13. Dielectric Property Test Result of 50 MVA TX3

Diagnostic Test for Oil Contamination		
Date	BD	%PF
10/02/2004	42.32	N/A
27/02/2006	44.82	N/A
21/02/2007	46.32	N/A
06/02/2008	42.46	N/A

4. CONCLUSION

Condition evaluation of power transformer load tap changer can be accessed by four diagnostic techniques: OLTC contact, oil contamination, dielectric property and DGA. Due to available historical OLTC test results, the data of reactor type with the selector and the diverter switches is used in the analysis by applying the proposed diagnostics. First of all, the insulating oil conditions of ten transformers rating 230/115 kV 200 MVA and 115/22 kV 50 MVA are assessed by the DGA method with key gas and ratio techniques. The Duval triangle is subsequently applied to identify the fault type. It is clearly seen that only one technique is not recommended to detect faults inside the transformer. After that the investigation on the worst two cases is additionally performed by using the oil contamination and dielectric property tests. Therefore, according to the known condition and specific problem of power transformers OLTC, it is recommended that maintenance strategy and time interval should be planned to diminish catastrophic damage occurrence to the power transformer and its network. As the OLTC condition evaluation is still further researched in the utility in Thailand for getting higher reliability, all proposed techniques except Duval triangle are used in practice now. The triangle is optional because it is one of popular techniques in the world. Among the proposed techniques, the DGA with key gas technique is more popular in practice although it is much more expensive tool than the others. Furthermore, after some transformers in the network are untanked and the inspection is done, it seems that the ratio method might be unreliable technique whereas other techniques should be combined together to increase the reliability of the analysis.

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