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J. Electrical Systems 12-3 (2016): 442-459

Regular paper

A Case Study on Fault Detection in Power Transformers Using Dissolved Gas Analysis and Electrical Test Methods

JES Journal of Electrical Systems

This paper presents methodologies for power transformer fault diagnosis using dissolved gas analysis and electrical test methods. These methods are widely used in determination of inception faults of power transformers. Dissolved gas analysis test provides fault diagnosis of power transformers. On the other hand the electrical test methods are used for detection of root causes and fault locations and they provide more specific information about the faults. The aim of this work is to study the faults that are measured and recorded in Turkish Electricity Transmission Company (TEIAS) power systems. For this purpose, four specific cases are considered and analyzed with dissolved gas analysis and electrical testing methods. Three of these cases are defective situations and one case is a non-defective situation. These real cases of measurements have been analyzed with both methods in detail. Assessment results showed that a single method cannot yield accurate enough results in some specific fault conditions. Therefore it was concluded that cooperation of both methods in the assessment of fault condition gives more trustworthy results.

Keywords: Power transformer, Fault detection, Dissolved gas analysis, Electrical test methods.

Article history: Received 1 February 2016, Accepted 6 August 2016

1. Introduction

Power transformers are one of the most essential and expensive equipment in power systems. Their faults cause significant losses and environmental risks such as power cuts, explosions, loss of life and property. Economically viable operation of electric power systems is closely related to reliability and availability of power transformers [1-2]. It is very important to diagnose incipient faults and quickly remedy the situation at the event of failures. Hence, the progression of the fault could be stopped, economic losses are reduced and repair time is shortened.

The preventive maintenance program is very important to increase lifetime of transformers and avoid abnormal conditions. For this purpose, Dissolved Gas Analysis (DGA) and electric test methods can be applied to power transformers periodically or when needed. The DGA is a widely used and worldwide-accepted diagnostic method for detection of potential transformer internal faults. In oil-immersed power transformers, incipient faults lead to breakdown of the insulating materials and as result of this fault some gases will be released. The composition of these gases depends on the type and severity of the fault [3-4]. If the amount of gases is known, it is possible to make correct interpretation about power transformer faults such as partial discharge, arcing and overheating. So, power transformer maintenance program could be modified by the knowledge of DGA. Another important technique that is applied to power transformers is called routine electrical test method. This method includes several techniques such as excitation current, power factor, DC insulation, turns ratio, DC winding resistance and oil dielectric strength test, etc. Electrical tests allow taking preventive actions before malfunction of power transformers. It also provides determination of the location of a possible fault for required maintenance.

An overview is presented in[5] covering condition monitoring and condition assessment, performing maintenance plans, aging, health, and end of life asset managements of transformers. Evaluation of effects of preventive maintenance and failure

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repair cost of power transformers are studied in [6]. Another relevant study is presented in [7] that reviews existing monitoring and diagnostic methods for power transformers in service. In this work, a case study on fault detection in power transformers with dissolved gas analysis and electrical test methods are presented in detail. It is aimed to demonstrate applications and performance evaluations of both methods on real case measurements and to make assessment for considered specific conditions.

The structure of the paper is organized as follows: the introduction is given in Section 1, the DGA is presented in Section 2 and Electrical Testing Methods are offered in Section 3. Analysis of test results and assessment with both DGA and electrical testing methods are given in Section 4. Discussions and comparison with physical fault are presented in Section 5. Finally, conclusion remarks are drawn in Section 6.

2. Dissolved gas analysis

DGA is applied by using the oil samples taken from an in-service power transformer for condition monitoring of the transformer. Early warning information could be received about existing or developing faults. Faults that are proceeding slowly and without noticeable signs, especially in the initial stages, can be prevented, and thus potential malfunction of transformer can be avoided.

In the evaluation of the DGA results, variety of determination methods have been developed in literature that include key gas, Duval triangle, Roger ratio, Doernenburg ratio, IEC ratio methods, logarithmic nomograph [8-12]. These methods classify faults using reference tables and charts which are prepared according to amount or particular ratios of gases. Sensitivity and accuracy of these methods are associated with the collected knowledge since the tables and graphs are gathered from results of long years of experiences [10]. Some gases are formed only as result of some particular faults. Depending on the type and severity of the fault, formed gases vary in type and amount. If the type and amount of gases are known, accurate comments can be made about the failure and preventive precautions can be taken. It is well known that several conventional methods can be used for evaluation of DGA results. From these techniques Duval triangle and key gas methods generally have higher classification accuracy and consistency [13-14]. Therefore, these methods are studied for interpretation of DGA results of the power transformers in this study.

2.1. Key gas method

In the key gas method, which is based on which gases are typical or dominant at various temperatures, characteristic "key gases" are used for the detection of certain faults.

Table 1: Fault interpretation based on key gases [4, 15]

Detected key gas	Interpretation
Hydrogen (H_2)	Electrical partial discharge (corona effect)
Ethylene (C_2H_4)	Thermal fault (electrical contacts)
Acetylene (C_2H_2)	Electric fault (arc, spark)
Oxygen (O_2)	Transformer seal fault
Ethane (C_2H_6)	Secondary indicator of thermal fault
Methane (CH_4)	Secondary indicator of an arc or serious overheating
Carbon Monoxide (CO)	Cellulose decomposition
Carbon Dioxide (CO_2)	Cellulose decomposition

Percentage values of combustible gases are calculated when making assessments according to this method. Probable fault consequence can be made based on excessive gas or gases [4, 15]. Detected key gases and their corresponding general failure causes are given in Table 1.

2.2. Duval triangle method

Duval triangle method is the graphical representational diagram. It uses only methane, acetylene and ethylene concentrations (in ppm). There is a triangular diagram which is divided into different areas as shown in Fig. 1. Definition of the point of intersection is carried out according to the percentage values of the related gases in the coordinate system. Percentage values of these gases are calculated according to equations given as:

$$\%CH_4 = \frac{100 \times x}{x + y + z} \tag{1}$$

$$\%C_2H_4 = \frac{100 \times y}{x + y + z} \tag{2}$$

$$\%C_2H_2 = \frac{100 \times z}{x + y + z} \tag{3}$$

Here, x = $[CH_4]$, y = $[C_2H_4]$, z = $[C_2H_2]$ represent the ppm values of dissolved gases in oil [6]. Fault types with this method are classified into six classes as partial discharge (PD), low-energy discharge (D1), high energy discharge (D2), low temperature thermal fault (T1), medium temperature thermal fault (T2) and high temperature thermal fault (T3) [8-10].

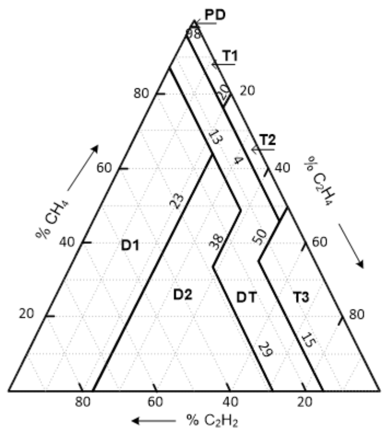

Fig. 1. Duval triangle diagram

3. Electrical testing methods

Longevity of the power transformers may be improved by continuously observing the system and fixing the faults in the early stages [7]. For this reason, power transformers must be tested periodically to get information about their general conditions. The electrical test results of the power transformers give information about the condition of the insulating material, status of winding connections, slippage of the windings , change of the distance between the windings to ground, occurrence of winding short circuits, the state of the tap changer and the status of transformer insulating oil, etc. Electrical tests allow taking preventive actions before malfunction of power transformers. They also provide the location of a possible fault for the required maintenance and repair. Thus the reason for the fault of the transformer and where it occurred can be detected quickly. This section is going to focus on the electrical testing aspect of maintenance and fault detection.

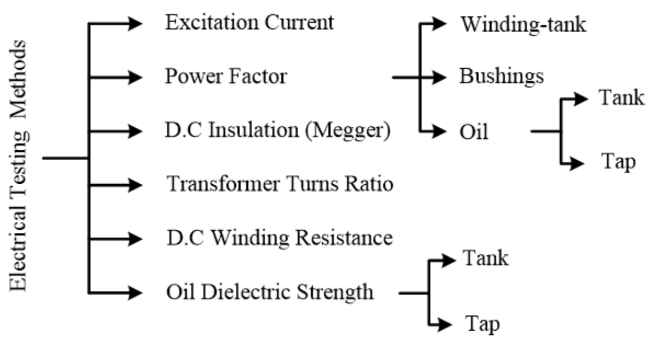

Fig. 2. Classification of electrical tests for power transformers

The classification of conventional field tests applied in power transformers is given in Fig. 2. These test methods are generally consist of excitation current, power factor, DC insulation, turns ratio, DC winding resistance and oil dielectric strength test. Fig. 3 illustrates a photo of a power transformer and the electrical test equipment, which used in carrying out power transformer tests.

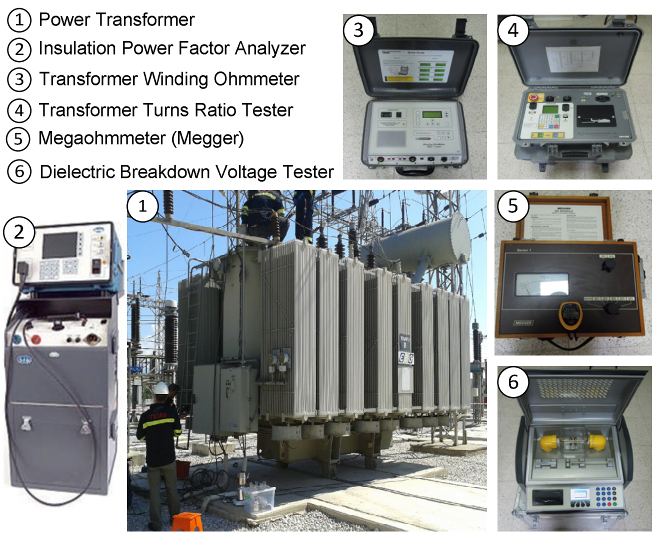

Fig. 3. A photo of a power transformer and the test measurement devices

3.1. Excitation current test

The excitation tests are usually performed during (commissioning) an acceptance test, after transformer repair/refurbishment, during preventive maintenance and after fault trips for detecting undesirable conditions in power transformers [16-17]. The aim of this test is to find poor electrical connections, inter-turn short circuits, abnormal core faults and winding problems. It gives information for electrical and mechanical assessment of transformer conditions. Principle of the excitation current test connection diagram is depicted in Fig. 4 for three-phase power transformers. The test is performed on each phase that the current flows in any winding to excite the transformer in conditions of all other winding are open circuited. It is generally expected to read similar currents for outer limbs of the power transformer when the magnetizing current of the center limb is slightly lower. This test has been an effective method for detecting the transformer faults, nevertheless, it should be noted that the excitation current is much more sensitive and fragile method in some cases. Hence, the test results should be confirmed with turn ratio and DC winding resistance tests.

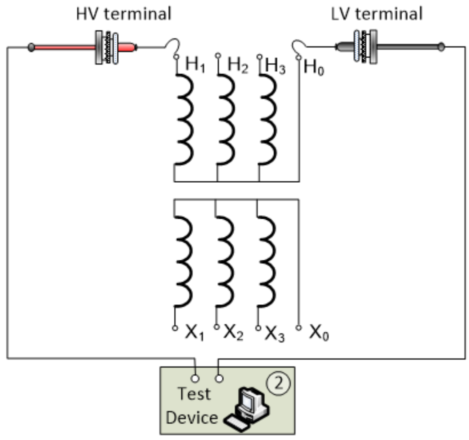

Fig. 4. Principle connection diagram of the excitation current test for three-phase power transformer

3.2. Power factor test

The measurement of power factor is one of the fundamental tests for assessing the condition of the transformer insulation. It is also known as "Tan Delta" or "Dissipation Factor" test. The purpose of this test is to determine the quality of the overall insulation of power transformer such as windings, bushings and oil insulation [17-20]. Equivalent circuit and vector diagrams are illustrated in Fig. 5 for power factor. The power factor (*PF*) is a ratio of the resistive current component (I_R) divided to total leakage current (I) under an applied AC voltage, which is defined as;

$$PF = \cos\theta = \frac{I_R}{I} \tag{4}$$

In other words, this equation can be stated as;

$$PF = \frac{Watts\ absorbed\ \ in\ insulation}{Applied\ Voltage \times Charging\ Current} \tag{5}$$

The other definition is called dissipations factor (*DF*), which is the ratio of the resistive current component divided to capacitive current (I_C) and defined as below;

$$DF = \tan\delta = \frac{I_R}{I_C} \tag{6}$$

The PF measurement demonstrates the dielectric loss on power transformer insulation since the leakage current is related to power loss. If there is a small PF, it means that the tested equipment has good insulation. If PF is high on the other hand, the transformer insulation tends to have deteriorations and/or contamination because the dielectric losses are largely caused by oxidation, carbonization, water, moisture, carbon, contamination in bushings, windings and liquid insulation etc.

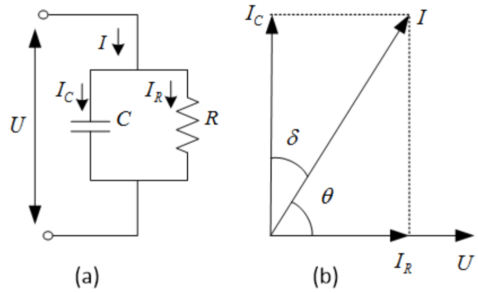

Fig. 5. Power factor (a) equivalent circuit (b) vector diagram

The measurement can be done between the windings and also between the windings and the tank. The PF test connection diagram is depicted in Fig. 6 for three-phase transformer. As seen from this figure, the high voltage winding to ground capacitance, the low voltage winding to ground capacitance, the high voltage to low voltage winding capacitance are labeled as CH, CL and CHL, respectively.

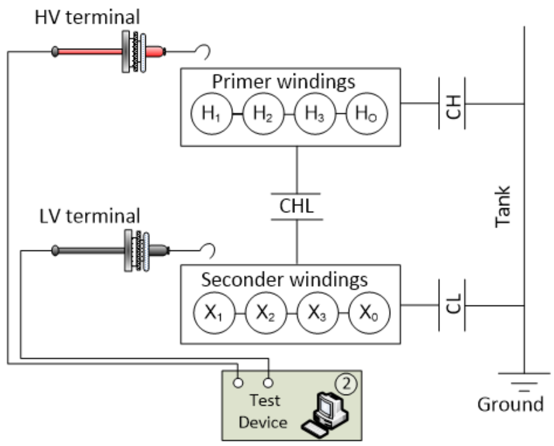

Fig. 6. Principle connection diagram of PF test for three-phase power transformer

The results of overall PF tests on power transformers indicate the insulation condition of the windings barriers, tap changers, bushings and oil. The limit values are determined by TEIAS according to relevant standards. The modern oil-filled power transformers should have power factors of 1 % or less, for CL, CH and CHL as well as bushings insulation. The power factor of the oil insulation system shall not exceed 0.5 % at 20°C.

3.3. DC insulation test

Direct Current (DC) insulation test is widely used for determination of the insulation conditions of the power transformer since it is an accurate and simple method. The principle connection diagram of this test is very similar to the power factor test connection diagram (see Fig. 6). However, the applied test voltage is DC and can be usually between 1 kV and 10 kV for power transformer. In this test, it is also generally used “Megger” test device which is labeled with number 5 as shown in Fig. 3. Applied DC voltage causes polarization of insulation system via polarized current. The test is applied to insulation resistance for a specified time period. The time resistance test should be recorded for a specific time such as 15th, 30th, 45th and 60th seconds and 10th minute after the voltage is applied. The polarization index ratio (PI) is the 60th second value divided by 15th second value or 10th minute value divided by 1st minute. The other determination ratio, dielectric absorption ratio (DAR), can be described as 60th second value divided by 30th second value. In general, the PI and the DAR are used in the assessment of this test result [17, 21-23]. The PI and DAR values give information about insulation conditions for power transformer and interpretations of their values are given in Table 2.

Table 2: Interpretations of DAR and PI values for power transformer.

Insulation Conditions	DAR $60_{sec}/30_{sec}$	PI $10_{min}/1_{min}$
Hazardous	-	<1
Bad	1 - 1.1	1 - 1.23
Doubtful	1.1 - 1.25	1.25 - 1.5
Adequate	1.25 - 1.4	1.5 - 2.5
Good	1.4 - 1.6	2.5 - 4.0
Excellent	>1.6	>4

3.4. Transformer turns ratio test

The transformer turns ratio (TTR) test is performed on all tap positions of every phases at no-load condition. The aim of the test is to obtain information on whether any connection problem and/or short circuit in the transformer windings exist [17-18, 21, 24]. The measurement principle of the test is based on applying alternating current (AC) low voltage to one of the primary windings and measuring the induced voltage of the related secondary winding later. Thereby, the ratios are calculated as the applied voltage value divided by the induced voltage reading and also the measurements are repeated in all phases and at all tap positions, sequentially. The TTR devices might be used to conduct this test and can be seen in Fig. 3 labeled with number 4. It should be noted that the principle of TTR test connection diagram depends on vector configuration and right polarity of the correspond windings, as an example, the TTR test connection diagram for three-phase power transformer with YNyn0 configuration is shown in Fig. 7.

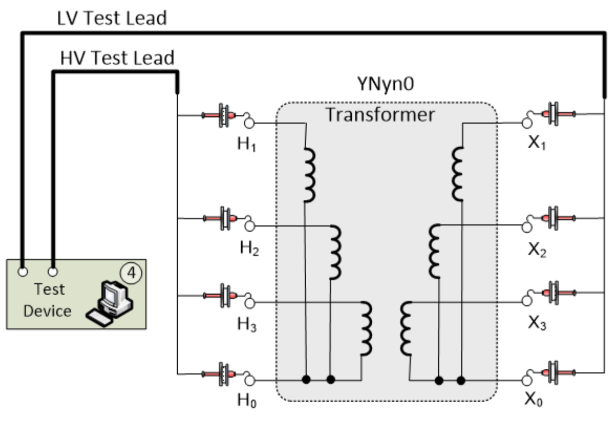

Fig. 7. Principle connection diagram of TTR test for three-phase power transformer with YNyn0 configuration.

In ideal three-phase transformers, turns ratios must be identical for all phases, however, the measured value may show a deviation from the ideal turn ratio of the transformer due to construction error, measurement error, device sensitivity etc. The percentage of the deviation can be calculated as;

$$E\,\% = \frac{measured \max ratio - measured \min ratio}{measured \min ratio} \times 100 \tag{7}$$

In the assessment of power transformers windings, a limit value has been defined according to *E %*. The percentage error rate shall not exceed 0.5 %.

3.5. DC winding resistance test

The DC winding resistance measurement test is performed on all phases and windings in order to interpret conditions of power transformer windings. The purpose of this test is to check transformer winding and terminal connections, such as short circuits and/or open circuits between windings or between turns, contact problems and also tap changer contact conditions [17, 25-26]. This result gives valuable information whether the winding is balanced or not. The measured winding resistance (aluminum or cupper) is very much influenced by temperature. Therefore, the resistances are converted to reference temperature with respect to the following equation;

$$R = \left(R_0 \times \frac{T_r + T_k}{T_0 + T_k} \right) \tag{8}$$

where, R is converted resistance at the reference temperature (T_r), R_0 is measured resistance at ambient temperature (T_0), and T_k is a constant depending on the conductive material. The T_k are selected 234.5 ^{o}C for copper and 225 ^{o}C for aluminum. The principle connection diagram of this test is very similar to excitation current test connection diagram (see Fig. 4). However, resistance meter is used in this test and called transformer ohmmeter. A commercial device photo is labeled with number 3 and shown in Fig. 3. The limit value is determined by TEIAS according to relevant standards. The maximum permissible ratio error of DC winding resistance must be lower than 2 % for every possible pair of windings.

3.6. Oil dielectric strength test

Dielectric strength level for each material is known or it can be easily determined experimentally in laboratory conditions. The dielectric strength test is an important method to evaluate oil insulation conditions of the transformers in service. The dielectric strength shows a degradation trend due to thermal or electrical faults as well as contamination of the oil such as including moisture, water oxidation, particles, cellulose fibers etc. This is a standard test method to measure the insulating ability of a liquid to withstand electrical stress. The oil sample, which is taken from transformer oil tank, filled into the test measurement devicewhich consists of two electrodes with a specified gap. In this test, controlled rate DC voltage is applied to the electrodes until it reaches the breakdown voltage. The breakdown voltage level gives information about condition of the transformer oil. Limit values have been defined by the standards in the evaluation of the test results. The voltage must be higher than a present limit or considered to have failed. The limit values of dielectric breakdown voltage (V_b) of insulating oils should not be lower than 45 kV and 40 kV for tank and tap changer, respectively [27-29]. But, these values are relative that the actual evaluation is related to the status of the transformer in operation. For the reason, it will be more appropriate to evaluate these results with together the appearance of the oil, chemical and gas analysis.

4. Analysis of Test Results

In this section, the results of both DGA and electrical testing methods are given for four specific power transformers that are selected from operating transformers inTEIAS. These power transformers are labeled as TR-1, TR-2, TR-3 and TR-4. Some characteristic information of these transformers is given Table 3. Three of the considered power transformers are defective, and one of them is non-defective.

Table 3: Characteristic information of the tested transformers

Cases	Rated power (MVA)	Voltage (kV)	Connection configuration	Number of taps
TR-1	25	154/31.5	YNyn0	17
TR-2	25	154/31.5	YNyn0	17
TR-3	100	154 /33.6	YNyn0	25
TR-4	25	154/31.5	YNyn0	17

4.1. Assessments of DGA results

Investigation of a power transformer fault condition starts with looking at whether DGA results are above limits or not. If the amount of any is above the limits or close to limits, then there is a possibility of a failure. Then further evaluations are done with fault diagnostic methods to determine the type of possible failures. Key gas and Duval triangle methods are selected for diagnosis of these faults among the commonly used methods and assessments are made. The DGA content values for all considered transformers are given in Table 4.

Table 4: Original gas data of the tested transformers

Gases	Limit Values (ppm)	TR-1	TR-2	TR-3 (Dome-A)	TR-4
Hydrogen (H_2)	<50-150	857*	5	111	5
Methane (CH_4)	<30-130	204*	3	23	2
Ethane (C_2H_6)	<20-90	20	1	13	1
Ethylene(C_2H_4)	<60-280	278	28	93	8
Acetylene (C_2H_2)	<2-20	625*	7	228*	1
Carbon monoxide (CO)	<400-600	588	192	66	158
Total Combustible Gases (ppm)		2572	236	534	175

* indicates that the value is above the limits according to the IEC 60599 standard.

4.1.1. Case TR-1

The assessment is made by using the Key Gas method: The percentage of each combustible gas is calculated and interpretation is done by the gas that has the dominant percentage value. In this case, amount of total combustible gas is found to be 2572 ppm. From this information, the percentages of other combustible gases are calculated and are shown in Fig. 8.

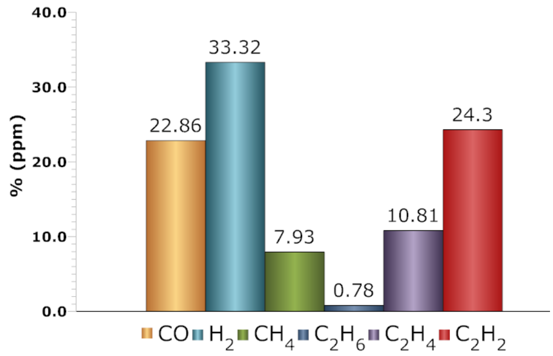

Fig. 8. Key gases and their percentage values for TR-1

It is obviously determined from the calculated percentage values of key gases that great amount of hydrogen and acetylene, small amount of methane and ethylene gases are formed. In analysis results, higher acetylene content indicates that arcing occurred in transformer. Also, rise in ethylene content shows that the oil is carbonized and broken down at high temperatures. This verifies the fact that fault is facilitated high energy discharge. In this type of fault, partial discharges occur because of roads or bridges that are formed on the surface of insulation materials. As a result of partial discharge there would be an increase in the amount of hydrogen gas. By looking at the assessment results, the principal gas is acetylene and its percentage value is 24.3. All these assessments show that the condition corresponds to a high energy discharge (arc, spark) fault. It is also observed that hydrogen increases since in the formation of acetylene the hydrogen gas is released.

In addition, the assessment is made by considering Duval Triangle method. First, percentage values of the related gases are calculated for TR-1. Here, ppm values of these gases are $x = [CH_4] = 204$, $y = [C_2H_4] = 278$ and $z = [C_2H_2] = 625$, respectively. The percentage values of gases are found by using the equation 1-3 that will be used in Duval triangle method are $CH_4\% = 18.43$, $C_2H_4\% = 25.11$ and $C_2H_2\% = 56.46$. When these percentage values are located at coordinate system in the Duval triangle diagram in Fig. 1, this fault corresponds to D2 field. In other words it points out that the fault is high energy discharge.

4.1.2. Case TR-2

All of the DGA contents for TR-2 are found to be under the limit values. Hence, according to DGA results, it can be concluded that there are no faults in the transformer for this case.

4.1.3. Case TR-3

The assessment made by considering the Key Gas method, DGA test was conducted by taking the oil sample from the main tank and high voltage cable box (Domes) of the TR-3. The DGA test results of the sample that was taken from the main tank of transformer are found to be in normal range. However, the samples that were taken from the high voltage cable connection boxes contain considerable amount of ethylene and, especially acetylene gases. Gas content of Dome-A is given in Table 4 as an example. In the assessment, it can be concluded that the principle gas is acetylene. Its percentage value is 42.69%. Key gases and their percentage values for TR-3 are illustrated in Fig. 9. Also, a large amount of methane as a secondary indication of overheating and arc is observed. All these considerations show that the fault corresponds to arc and/or high energy discharge.

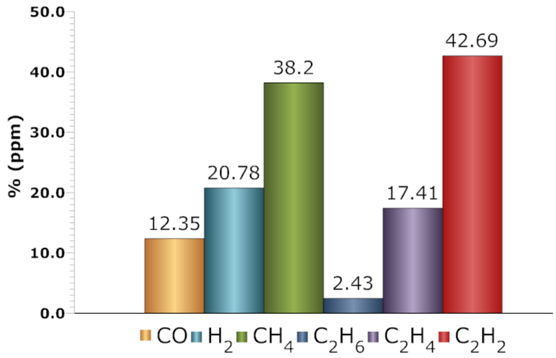

Fig. 9. Key gases and their percentage values for TR-3

Then the assessment is made by considering Duval Triangle method. First, percentages of related gases are calculated for TR-3. The results are CH_4 % = 7, C_2H_4 % = 27 and C_2H_2 % = 66. When these percentages are located at coordinate system in the Duval triangle diagram in Fig. 1, this fault corresponds to D2 field. In other words, it points out that the fault is high energy discharge.

4.1.4. Case TR-4

All of the DGA contents for TR-4 are founded to be under limit values. Hence, according to DGA results, it can be concluded that there are no faults in the transformer for this case.

4.2. Assessments of electrical test results

4.2.1. Case TR-1

Excitation current test was applied to the aforementioned TR-1. The ambient air temperature was 14 °C, top oil temperature was 29 ° C and relative humidity was 58 % during to the test process. The measurements were made for all phases at the tap positions 12 since the transformer was operating at that position in the service. The excitation current test results are depicted in Table 5 for TR-1. It can be seen from the table that the exciting current is not determined both for primary H_3-H_0 winding and for secondary X_3-X_0 winding. Moreover, while the exciting current level for second phase is expected to be slightly lower than the other phases, it was observed that the exciting currents of these winding are approximately equal to the others. As a result, it is concluded that there is a fault in the primary H_3 or secondary X_3 phase.

Table 5: Excitation current test results for TR-1

	Tap position	Tested windings	Test voltage (kV)	Measured excitation current (mA)
Primary	12	H_1-H_0	10	35.8
	12	H_2-H_0	10	35.5
	12	H_3-H_0	10	None
Secondary	-	X_1-X_0	2	921
	-	X_2-X_0	2	921
	-	X_3-X_0	2	None

Power factor test was applied to windings, bushings and oils of TR-1. The PF test measurement results are given in Table 6. It can be seen from the table that none of the CH, CL, and CHL values can be measured for winding-tank insulation conditions. The results show that the insulations of primary and secondary windings against tank are damaged. In addition the test was applied for bushings and tank-tap oil separately where the PF percentages are found within the recommended limit values. Insulation values of bushings show that the fault do not spread to bushings.

Table 6: The measurement of power factor insulation test results for TR-1

	Measured insulation	Test voltage (kV)	Current (mA)	Power (watt)	Temperature (^{0}C)	PF %
Winding-tank	CH	10	None	None	29	Not available
	CHL	10	None	None	29	Not available
	CH+CHL	10	None	None	29	Not available
	CL	10	8.6	None	29	Not available
Bushings	H_1-C_1*	10	0.894	0.0362	29	0.40
	H_2-C_1	10	0.890	0.0352	29	0.40
	H_3-C_1	10	0.888	0.0343	29	0.39
Oil	Tank	10	0.756	0.0096	16	0.13
	Tap	10	0.754	0.0128	16	0.17

C1* denotes main core insulation of center conductor to tap

The DC insulation test was applied to the TR-1 and the results are given in Table 7. The ambient air temperature was 14 °C, top oil temperature was 29 ° C, relative humidity was 58 %, applied test voltage was 5 kV and the test duration was 2 minutes. The aim of this test was to observe whether insulation was normal or not between primary/tank, secondary/tank and primary/secondary. This assessment is made based on the DAR value that the limits are given in Table 2. As seen from Table 7, the DAR values are 2.11 for primary/tank and 1.82 for secondary/tank. However, DAR value of primary/secondary insulation could not be identified. Insulation value was decreased to kilo ohms level where it should be in mega ohms level. It is concluded that there is a problem in the insulation between primary and secondary windings.

Table 7: DC Insulation Test Results for TR-1

	Measured Insulation Resistance (MΩ)		
	Primary/Tank	Secondary/Tank	Primary/Secondary
15^{th} second	400000	453000	<0.1
30^{th} second	1800000	1700000	<0.1
45^{th} second	2700000	2200000	<0.1
60^{th} second	3800000	3100000	<0.1
10^{th} minute	>10000000	-	-
DAR	2.11	1.82	-

Table 8: Turns ratio test results for TR-1

Tap positions	H_1-H_0/X_1-X_0	H_2-H_0/X_2-X_0	H_3-H_0/X_3-X_0	E%
1	4.404	4.403	4.241	3.84
9	4.880	4.890	4.762	2.69
17	5.377	5.377	5.284	1.76

Table 9: The DC winding resistance test results for TR-1

Tap positions	H_1-H_0 (Ω)	H_2-H_0 (Ω)	H_3-H_0 (Ω)	E %
1	1.0180	1.0220	1.0210	0.39
9	0.8872	0.8893	0.8912	0.45
17	1.0220	1.0330	1.0250	1.06
Tap positions	X_1-X_0 (Ω)	X_2-X_0 (Ω)	X_3-X_0 (Ω)	E %
-	0.03637	0.03655	0.03695	1.57

The TTR test was performed on all tap positions of every phase at no-load condition. As an example, the TTR test results are given in Table 8 at 1st, 9th and 17th tap positions. As a result of applied tests, error rate in all positions were found to be exceeding standard limit rate, which is 0.5%. In addition, it is identified that there is a reduction in turns ratio of H_3-H_0/X_3-X_0 for all taps positions. So, it can be concluded that the fault is occurred in the third phase.

The DC winding resistance measurement test was performed on all phases and windings. Winding temperature is recorded to be 41 ºC in the test process. As an example, the DC winding resistance results are given in Table 9 at 1st, 9th and 17th tap positions. As a result of applied tests, error rate in all taps was found to be under the standard limit for all considered circumstances that the maximum permissible ratio error of DC winding resistance must be lower than 2%. As a result, it is observed from the test that there is no discontinuity problem of the all windings.

The dielectric strength test was applied to oil of main tank and tap changer for TR-1. This test is carried out according to VDE-0370 standard. Breakdown voltages of oil samples taken from main and tap changer reserve tanks were measured to be 60 kV and 52 kV, respectively. Insulation oil dielectric strength test results are greater than the minimum specified limit value for both cases. It should be remembered that dielectric breakdown voltage of insulating oils should not be lower than 45 kV and 40 kV for tank and tap changer, respectively. When the insulation value of the oil is considered, it was still concluded that the oil fulfills the insulation task.

4.2.2. Case TR-2

All the relevant electrical tests specified in Fig. 2 are applied to TR-2. Excluding the DC winding resistance test, all other test results were found to be within the recommended values. The DC winding resistance measurement test was performed on all windings and tap positions. The primary windings measurement results are found to be within the recommended limits for all the positions. As an example the DC winding resistance results are given in Table 10 at 11th and 17th tap positions. However, an excessive error rate was calculated from measurement as 33% for the secondary windings. The resistance of X1-X_0 winding is measured higher than the other secondary windings. The reason for this is thought to result from looseness in the connection terminal.

Table 10: The DC winding resistance test results for TR-2

Tap positions	H_1-H_0 (Ω)	H_2-H_0 (Ω)	H_3-H_0 (Ω)	E %
11	1.501	1.500	1.502	0.13
17	1.654	1.653	1.655	0.12
Tap positions	X_1-X_0 (Ω)	X_2-X_0 (Ω)	X_3-X_0 (Ω)	E %
-	0.056	0.042	0.042	33.33

4.2.3. Case TR-3

All the relevant electrical tests specified in Fig. 2 are applied to TR-3. All test results were found to be within the recommended values except oil dielectric strength test. Insulation oil dielectric strength test was carried out by breaking down the oil sample taken from main tank at 70 kV instead of 45 kV, which is the limit value for main tank. Thus, insulation of the oil in the main tank is sufficient. On the other hand, in the test that was carried out for the tap oil, it was seen that the oil was broken down at 37 kV. This measurement indicates a fault in the insulation of tap oil because the test result was found to be lower than minimum permissible limit value of 40 kV. So, insulation of it is not sufficient to fulfill the insulation task.

4.2.4. Case TR-4

Similarly, all the relevant electrical tests specified in Fig. 2 are applied to TR-4. All test results were found to be within the recommended values. It is concluded that there are no problems with the transformer.

5. Discussions and comparison with physical fault

In this section, the fault assessment results are compared with actual physical fault conditions and validity of the methods are tested. General assessments of electrical tests for the reviewed power transformers are summarized briefly in Table 11.

Table 11: Electrical test results of the tested transformers

Type of Test			Recommended limits	TR-1	TR-2	TR-3	TR-4
Excitation Current			Typically two similar current readings and one lower from other phases	X*	√	√	√
Power Factor	Winding-tank		PF% < 1	X	√	√	√
	Bushings		PF% < 1	√**	√	√	√
	Oil	Tank	PF %< 0.5	√	√	√	√
		Tap-changer	PF% < 0.5	√	√	√	√
DC Insulation			DAR > 1.6 (excellent)	X	√	√	√
Transformer Turns Ratio Test			E% < 0.5	X	√	√	√
DC Winding Resistance			E% < 2	√	X	√	√
Oil Dielectric Strength		Tank	V_b>45 kV	√	√	√	√
		Tap-changer	V_b>40 kV	√	√	X	√

X*: abnormal, √**: normal

An analysis of the DGA test results in accordance with Key gas and Duval triangle methods for TR-1, it is deduced that the failure is high energy discharge. Furthermore, excitation current, PF, DC insulation and the TTR tests indicate an abnormal condition for TR-1. The excitation current from primary H_3-H_0 winding and for secondary X_3-X_0 winding cannot be measured. Likewise in the applied PF test, insulation could not be determined between winding-winding and winding-tank. The DAR value of primary/secondary insulation could not be identified in the DC insulation test. In addition, it was found in the

TTR test that there was a reduction in turns ratio of H_3-H_0/X_3-X_0 for TR-1. In conclusion, when all the tests are evaluated together; the fault has been observed in the primary and secondary windings of third phase. These results give rise to the thinking that there is a short circuit in the third phase. So, when the transformer was opened in the repair center, fault was detected where it was expected. Fig. 10 illustrates a photo taken from the top in the repair service for TR-1. Primary (outer ring) and secondary (inner ring) coils and their paper insulation on one leg of the core (innermost silica sheets) are seen in the figure. In the physical testing of third phase of the transformer, the insulation between the primary, secondary and core was found to be deteriorated. In addition, the windings were in contact with the core. Therefore, the transformer was taken to the maintenance service for required repair and maintenance tasks.

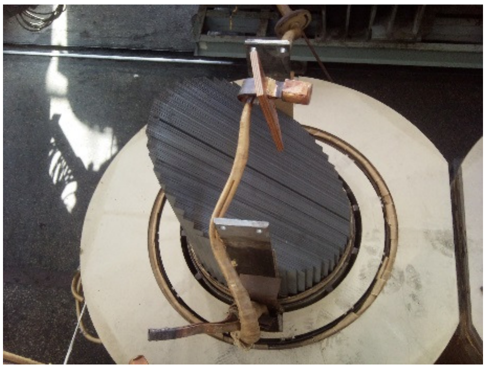

Fig. 10. A photo of faulty part of the TR-1 in the repair service

All of the DGA contents were found to be within the recommended limit values for TR-2. So, it can be concluded that there is no fault in the transformer for this case according to the DGA contents. Excluding the DC winding resistance test all other test results were found to be within the recommended values. In the applied DC winding resistance test, an excessive error rate (33% for the secondary windings) was obtained by calculations and measurements. The resistance of X1-X_0 winding is measured to be higher than the other secondary windings. This suggests that there is looseness in windings or in connection terminal of the X1-X_0 windings. In fact, as a result of physical inspections, looseness was detected in the connection terminal of the secondary X_1-X_0 winding. Fig. 11 shows a photo of the loose connection failure for this transformer. After the required maintenance, the values were measured in the desired range.

Fig. 11. A photo of loose connection failure for the TR-2 in the repair service

In interpretation of the DGA test results in accordance with Key gas and Duval triangle methods, it is deduced that the failure is high energy discharge for high voltage cable boxes

(Domes) of the TR-3. The high level of combustible gas amount indicates the presence of an arc for the oil in the cable boxes. After this conclusion, HV cable box was opened, the oil was poured and the examinations were made. As seen from the photo in the Fig.12 (a) no trace of arc was observed and oil was not carbonized in the dome. Although high amount of combustible gases were observed in the cable box, it is concluded they were not formed in there and an explanation is needed for this situation. However, it was observed that tap changer reserve oil was carbonized and broke down at a low voltage level as 37 kV in the oil dielectric strength tests. The carbonized oil in tap changer reserve is shown in Fig. 12 (b). Therefore it is almost certain that acetylene was produced because of tap oil had been exposed to arc gained. These combustible gases seen in the HV cable box are thought to be leaked from the tap-changer reserves. It is judged that there is a transition between the tank and the tap changer reserves which should be separated normally. As shown in Fig. 12 (c) an improper design was observed during physical examinations, which has a transition between the main tank and tap changer reserves. It is observed that combustible gas occurs during the tap changing and these gases are transferred to the cable box via diffusion from common reserve tank. As a result, gas formation in the high voltage cable box was attributed to manufacturing error, specifically to the transformer design. The issue has been resolved by closing the transition area between the common reserves and making the necessary modifications. After these operations, the transformer was inserted into service and it is observed that the transformer have been operated without any abnormal situation.

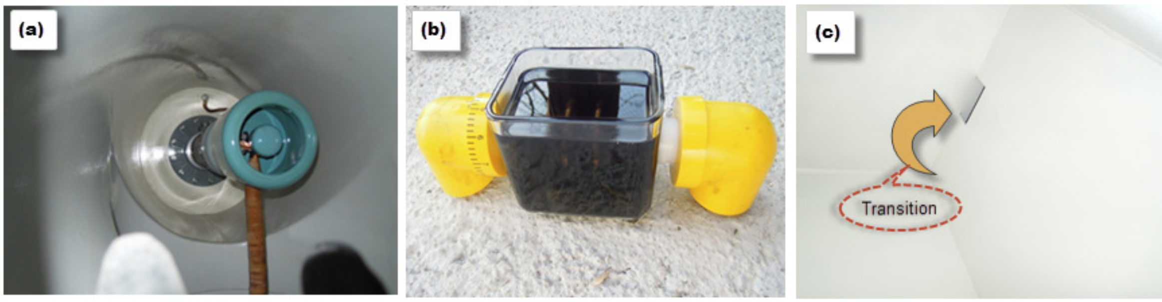

Fig. 12. a) High voltage cable box, b) Carbonized tap changer oil
c) Transition area between the reserves

For TR-4 both DGA and electrical test were performed. No evidence of any faults in analyzes and applied tests is observed in either method.

Table 12: Assessments of tested transformers with different test methods

Cases	DGA	Electrical Test	Physical Fault
TR-1	X	X	Phase to ground short circuit occurring in the third phase
TR-2	√	X	Looseness in the connection terminal of the secondary X_1-X_0 winding
TR-3	X	X	Design error. Transition between the main and tap changer reserves
TR-4	√	√	No-fault

DGA, electrical testing results and physical faults of the tested power transformers are given in Table 12 comparatively. Cooperation of electrical test methods and DGA methods has crucial importance in the detection of transformer faults. DGA mostly give a preliminary idea about the faults, whereas the electrical tests give more specific information about where and why exactly the fault occurs. In addition, both methods allow transformers to operate smoothly and increase their lifetime since necessary precautions and possible maintenance actions may be taken before faults occur.

7. Conclusion

It is very well known that power transformers are one of the most expensive and indispensable components of energy systems. Lifetime of the transformers can be increased and faults can be avoided by applying required maintenance and tests completely and accurately. In this work, DGA and electrical test methods have been studied in detail, which are widely used in the fault detection and maintenance processes of power transformers. Results showed that a single method cannot yield accurate enough results in some specific fault conditions. Therefore, collective use of both methods in the assessment of fault condition gives more reliable results.

DGA test method gives a preliminary idea about the possible cause of the failure. Main advantage of the test is that it is easily applicable and suitable for online monitoring systems. In contrast, the electrical test methods give more specific information about the fault, and allow the detection of fault location with high accuracy. However, they are mostly inappropriate for online monitoring systems because these tests could not be applied under-load. When comparing the test results with the actual fault, test results showed that the fault condition detected with great accuracy. Also these test methods are periodically applied in power transformers. Thus, both methods allow smooth operation and increase the lifetime of transformers by providing to take the necessary precautions and possible maintenance actions before faults occur.

Acknowledgment

This work was supported by the Turkish Electricity Transmission Company. I would like to express my utmost gratitude to all the people who have directly or indirectly contributed towards the successful completion of this technical paper.

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