Modification of Duval Triangle for Diagnostic Transformer Fault through a Procedure of Dissolved Gases Analysis

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***Abstract*— Dissolved gas-in-oil analysis (DGA) is a sensitive and dependable technique for the detection of incipient fault condition within oil-immersed transformers. When the mineral oil is subjected to high thermal or/and electrical stresses, it decomposes and, as a result, gases are generated.**

This paper presents modification of Duval triangle DGA diagnostic graph to numerical method that is easy to use for diagnosing and a Matlab program. To study such as the following evaluation. This evaluation is carried out on DGA data obtained from three different groups of transformers each group are two identical transformers. A Matlab program was developed to automate the evaluation of Duval Triangle graph to numerical modification, Also the fault gases can be generated due to oil decomposing effected by transformer over excitation which increasing the transformer exciting current lead to rising the temperature inside transformer core beside the other causes.

***Index Terms*— Dissolved Gas Analysis (DGA), mineral oil, decomposition, degradation, and transformer condition.**

I. Introduction

Dissolved gas analysis (DGA) is a popular diagnostic technique that is used to detect incipient faults in oil-filled power transformers [1]. By using DGA data, transformer criticality can be identified with proposing the proper maintenance action [2].

Several methods were proposed to diagnose incipient faults based on DGA. These methods are key gas method, Rogers's ratio methods, Duval triangle method, Doernenburg Ratio method, Basic Gas Ratio, and artificial intelligence based methods.

The key gas method identifies the key gas for each type of fault and uses the percent of this gas to diagnose the fault as suggested by IEEE standard C57.104 [3]. The percent amount of gas is obtained in terms of the total combustible gases (TCG). The main disadvantage of this method is that the interpretation by the individual gases is difficult in practice since each incipient fault produces traces of other gases in addition to the key gas of such fault. The ratio methods for fault diagnosis use certain ratios of dissolved gas concentrations according to combinations of codes [4, 5]. An incipient fault is detected when a code combination matches with the code pattern of the fault. The most widely used ratio methods are the Doernenburg Ratio Method, Rogers Ratio Method, and IEC standard. Six gas ratios have been used by different methods. The major drawback of ratio methods is the "no decision" problem associated with some cases that lie out of the specified codes.

In recent years, many researchers have studied the application of artificial intelligence based techniques for transformer fault diagnosis. These techniques include expert systems, fuzzy logic, artificial neural networks or mixed techniques [6, 7]. However, these methods are too complicated to be implemented practically on a wide range.

This paper investigates the new aspects, accuracy and consistency of these methods in interpreting the transformer condition.

II. DGA TO DIAGNOSE TRANSFORMER FAULTS

When an incipient fault occurs, either thermal or/and electrical, a number of gases are generated and dissolved into the oil. These gases are mainly H_2, CH_4, C_2H_2, C_2H_4 and C_2H_6. In addition CO and CO_2 will exist if cellulose degradation is involved, based on the type and amount of generated gases [1, 8-9].

A. Duval Triangle (DGA) Diagnostic Graph Method

M. Duval. Proposed another diagnostic method to overcome this limitation, well known as Duval triangle. This method is based on a triangle graphical representation to visualize the different cases for oil-insulated high-voltage equipment (mainly transformers), Fig. (I) provides a graphical method of identifying a fault. It uses a three-axis coordinate

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system, where concentrations of CH_4, C_2H_4 and C_2H_2 are used as coordinates, and the likely fault falls within one of the fault regions of the triangle. The various regions within the Duval Triangle are given in Table (I) [10-13].

For example if $C_2H_2 = 0.07$, $CH_4 = 0.2$ and $C_2H_4 = 0.73$. The fault diagnostic is T3 (Thermal fault t > 700 °C), and if $C_2H_2 = 0.36$, $CH_4 = 0.32$ and $C_2H_4 = 0.32$, the fault diagnostic is D2 (High-energy electrical discharge), as shown in fig (I).

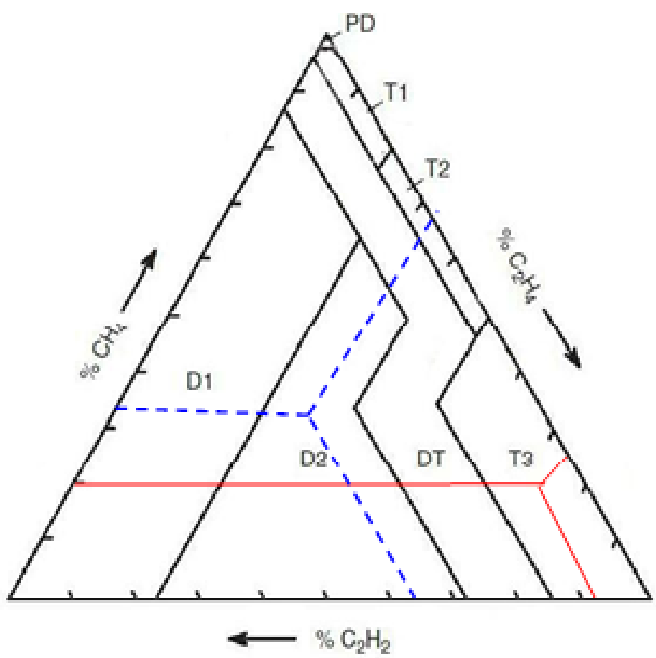

Fig. 1. Duval Triangle

TABLE I. FAULT CODE

PD	Partial discharge
T1	Low-range thermal fault (below 300 °C)
T2	Medium-range thermal fault (300-700 °C)
T3	High-range thermal fault (above 700 °C)
D1	Low-energy electrical discharge
D2	High-energy electrical discharge
DT	Indeterminate - thermal fault or electrical discharge.

A. Duval Triangle Graph to Numerical Method

In this paper, we developed A Matlab program to automate the evaluation of Duval Triangle graph to numerical modification. Table (II) shows the Modification of Duval triangle DGA diagnostic graph to numerical method.

For example if $C_2H_2 = 0.1$, $CH_4 = 0.3$ and $C_2H_4 = 0.6$. We can use table (II) easy to determine the fault Diagnostic (Thermal fault t > 700 °C), and if $C_2H_2 = 0.36$, $CH_4 = 0.32$ and $C_2H_4 = 0.32$, the fault diagnostic is (High-energy electrical discharge), the same results as in the previous example.

TABLE II. MODIFICATION OF DUVAL TRIANGLE (DGA) DIAGNOSTIC GRAPH TO NUMERICAL METHOD

C2H2%	CH4%	C2H4%	Fault
0.00 - 0.02	0.98 - 1.00	0.00 - 0.02	Partial discharge (electrical fault)
0.00 - 0.04	0.46 - 0.80	0.20 - 0.50	Thermal fault 300 < t < 700 °C
	0.76 - 0.98	0.02 - 0.20	thermal fault t < 300 °C
0.00 - 0.15	0.00 - 0.50	0.50 - 1.00	Thermal fault t > 700 °C
0.04 - 0.13	0.47 - 0.96	0.00 - 0.40	Mixtures of thermal and electrical faults
0.13 - 0.29	0.21 - 0.56	0.40 - 0.50	
0.15 - 0.29	0.00 - 0.35	0.50 - 0.85	
0.13 - 0.29	0.31 - 0.64	0.23 - 0.40	Discharge of high energy (electrical fault)
0.29 - 0.77	0.00 - 0.48	0.23 - 0.71	

III. CASE STUDY DISSOLVED GAS ANALYSIS

The case study carried out from three different groups of transformers each group are identical in Abu-Sultan steam power plant. Fig. (2) Shows the schematic diagram configuration for transformers under testing. The first group of transformers are three single phase 192 MVA, 15/220 KV, Off L.T.C. The Second group of transformers are three phase 16 MVA, 220/6.3KV, ON.L.T.C, and the third group of transformers are three phase 16 MVA, 15/6.3/6.3 KV, ON.L.T.C. The rating and (DGA) testing results for the above-mentioned Power Transformer are shown in tables (III, IV).

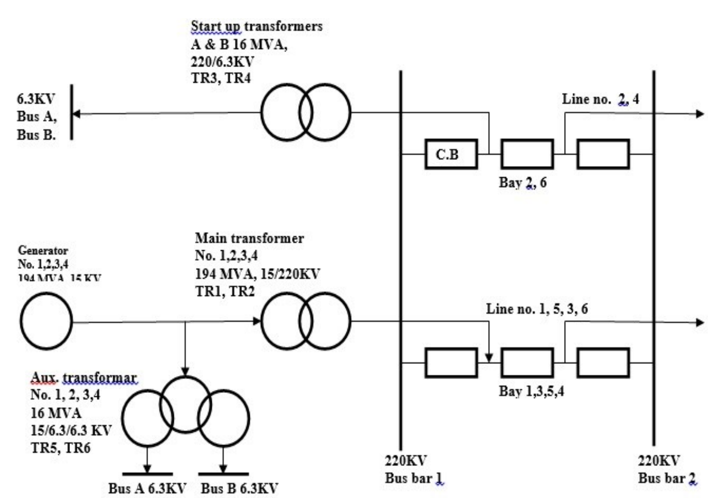

Fig. 2. Schematic Diagram for Transformers under Evaluation

TABLE III.
RATING OF POWER TRANSFORMER UNDER TESTING

Transformer Name	Operating Date	Rated Power MVA	Rated Voltage KV	Number Of Phases	Oil Type
Main transformer Unit no. 1 (TR_1)	19/3/1983	192	15/220	3 single Phase	Mineral Oil Naphthenic
Main transformer Unit no. 2 (TR_2)	15/8/1983				
Start Up transformer A (TR_3)	19/3/1983	16	220/6.3	3- Phases	
Start Up transformer B (TR_4)	15/10/1984				
Aux. transformer unit no. 1 (TR_5)	19/3/1983	16	15/6.3/6.3	3- Phases	
Aux. transformer Unit no. 2 (TR_6)	15/8/1983				

IV. DIAGNOSTIC METHOD USED BY MODIFICATION SYSTEM.

The diagnostic methods for DGA are used by a numerical method, The Matlab program diagnoses output for the under testing transformers. Table (V) shows application of the faults diagnosed by various methods, which indicate that all transformers are thermal faults.

V. RESULTS AND DISCUSSION

Comparison of various methods as shown in the table (V), a thermal fault in oil within all transformers is diagnosed for all five methods. Where winding temperature do not exceed 95°C and oil temperature do not exceed 85°C for all transformers during normal operation. Moreover, the possible collapse of cooling system during operation in this case is too small and there is no increase in the viscosity of the oil, as it is clear in the results of chemical analysis of samples oil and no wax materials. However, there is an important factor is the increased over excitation due to reduction of generator speed when some of the generating units from the network goes out during normal operation or the frequency disturbances that occur when large loads are connected to the electrical network system.

Over-excitation or/and under frequency protection may be or may be not operate depends on the response of power system control. The under frequency relay operate at 47.5 Hz with time lag 0.5 sec and over excitation relay operate at V/Hz = 1.1pu for 45 sec time lag or V/Hz =1.18 pu for 2 sec time lag at generators.

TABLE IV.
(DGA) TESTING RESULTS

Transformer & Samples date			Main transformer unit no. 1 ph (B) from 08/05//2013 to 27/11/2013	Main transformer unit no. 2 ph (B) from 08/05/2013 to 05/11/2014	Start Up transformer A from 08/05/2013 to 06/05/2014	Start Up transformer B from 07/04/2013 to 27/11/2013	Aux. transformer unit no. 1 from 08/05/2013 to 29/03/2015	Aux. transformer unit no. 2 From 07/04/2013 to 02/04/2014
Total combustible gases (T.C.G) without C3H6 & C3H8			274 477	164 592	98 249	219 426	246 429	193 400
Hydrogen	Combustible gases	H_2	9 7	3 16	1 19	5 6	14 28	7 35
Hydrocarbons		CH_4	25 48	15 37	2 4	19 61	48 49	9 12
		C_2H_2	0 0	0 0	0 0	0 0	0 0	0 0
		C_2H_4	5 2	1 12	2 8	5 6	3 10	2 3
		C_2H_6	12 29	10 50	1 3	57 142	28 45	2 3
		C_3H_6 & C_3H_8	14 26	5 -	2 3	30 81	14 -	2 3
Carbon Oxides		CO	223 392	135 477	91 215	132 212	154 297	173 348
	Non-Combustible gases	CO_2	2877 6052	775 4854	482 1324	848 1772	1632 3787	439 2581
Non-fault or atmospheric gases		O_2	2042 2664	1633 3758	3432 5766	991 1911	1420 13615	1118 3300
		N_2	31551 38801	45633 90526	39302 56161	74493 88856	82762 137375	\ 30606 119152

TABLE V.
APPLICATION OF THE FAULT DIAGNOSED BY VARIOUS METHODS

Transformer no.	Duval's triangle numerical modified P(96/4)	Basic gas ratio P(77/8)	Doernenburg ratio P(71/3)	Rogers Ratio P(62/5)	Kay gas P(42/58)
TR1	thermal fault t < 300°C	thermal fault t < 300°C	thermal decomposition	slight overheating t <150 °C	pyrolysis in cellulose
TR2	Thermal fault 300 < t < 700 °C	thermal fault t < 300°C	thermal decomposition	slight overheating 150-200 °C	pyrolysis in cellulose
TR3	Thermal fault t > 700 °C	thermal fault of low temperature t <150°C	Cannot be applicable	general conductor overheating	pyrolysis in cellulose
TR4	thermal fault t < 300 °C	thermal fault t < 300°C	thermal decomposition	slight overheating 150-200 °C	pyrolysis in cellulose
TR5	Thermal fault t > 700 °C	thermal fault t < 300°C	thermal decomposition	Cannot be applicable	pyrolysis in cellulose
TR6	Thermal fault 300 < t < 700 °C	Cannot be applicable	Cannot be applicable	general conductor overheating	pyrolysis in cellulose

If frequency decreases and the voltage is constant, the transformer core is heated. Fig. (3) Shown voltage, current and frequency of generating unit transformer number one at Abu-sultan steam power plant from 17/5/2015 to18/5/2015, which indicate that frequency, reduced to 49.2 Hz at voltage 14.85. KV.

The rated generator voltage and frequency is 15 KV and 50Hz respectively. So generator is over excitation =1.0061 Pu. At unit, start up the voltage may be built to 15KV at generator frequency 48 Hz then 1.042 Pu over-excitations. Disturbance in frequency is repeated from 18/5/2015 to 20/5/2015 in power system as shown in Fig. (4) and affect all network transformers in this moment and there is an instantaneous decrease in power system frequency to 45.36 Hz without operate under frequency or/and over-excitation relays because disturbance duration less than 0.5 sec as shown in Fig. (5).

Transformers require an internal magnetic field to operate. The core of a transformer is designed to provide the magnetic flux Necessary for rated load.

An over-excitation condition occurs when this equipment is operated such that flux levels exceed design values. The voltage output of a transformer is a function of the rate of change of the flux and the number of turns in the output winding. $e = N\, d\varphi/dt$ during normal power system operation.

The voltage is sinusoidal and the rate of change is determined by the frequency, which is in turn determined by generator speed [14].

The equation shows core flux to be directly proportional to voltage and inversely proportional to frequency $\varphi \propto V/f$. The actual magnitude of flux in transformer core is can be quantified in terms of per unit volts / Hertz.

A generator or transformer operating at no load with rated voltage and frequency would have one per unit excitation. The same equipment operating at rated voltage and 95% frequency would have 1.0/0.95 = 1.05 Pu flux or 1.05 Pu excitation.

Over-excitation will result from high voltage at rated frequency and from rated voltage with low frequency.

Because over excitation is a function of voltage and frequency, it can occur without notice. Transformers and generators can be subject to repeated over excitation by inappropriate operating.

The practices or operator error without a disruption to operations. The resulting thermal faults lead to oil decomposing to generate fault gases H_2, CH_4 at temperature 120°C, C_2H_6 at temperature 150°C, C_2H_4 at temperature 300°C, and C_2H_2 at temperature 700°C.

In addition, degradation of insulating material is cumulative. A transformer or generator that survives a serious over excitation event or many small events may fail because of a moderate event during normal service as all transformers under study.

In addition, if voltage increased, at rated frequency, the exciting current increases, as shown in Fig. (6). So Tr_1 through Tr_6 are effected by over excitation due to network normal operation but Tr_1, Tr_2,Tr_5, Tr_6 are effected by Over excitation damage usually occurs during periods of off-frequency operation such as start up or shut down for unit transformer as shown in Fig.(2) and table (VI).

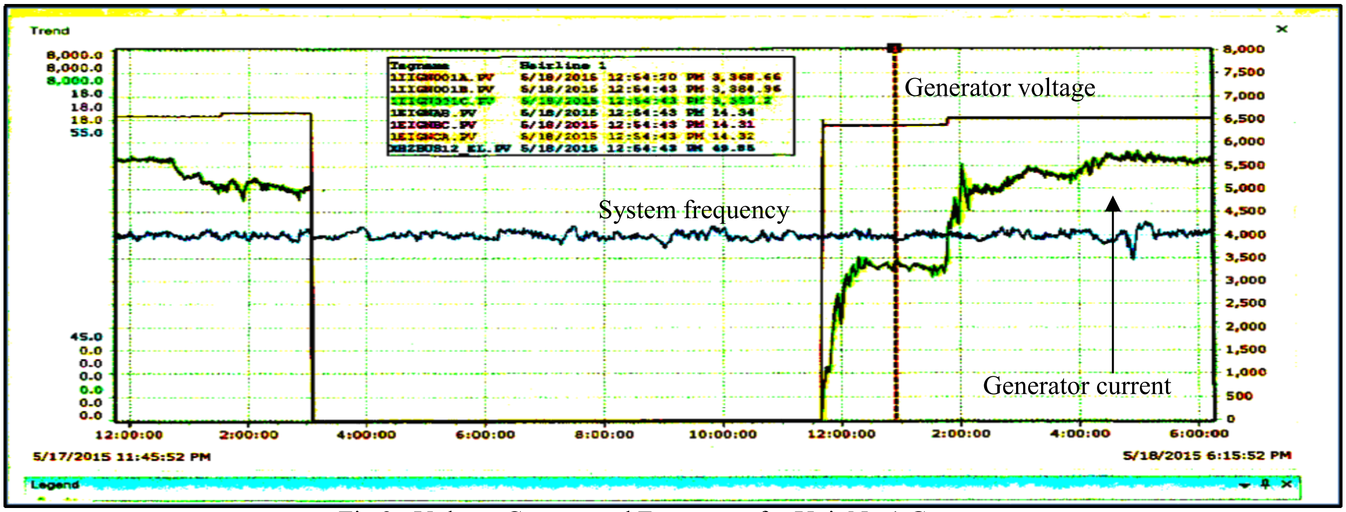

Fig 3. Voltage Current and Frequency for Unit No.1 Generator

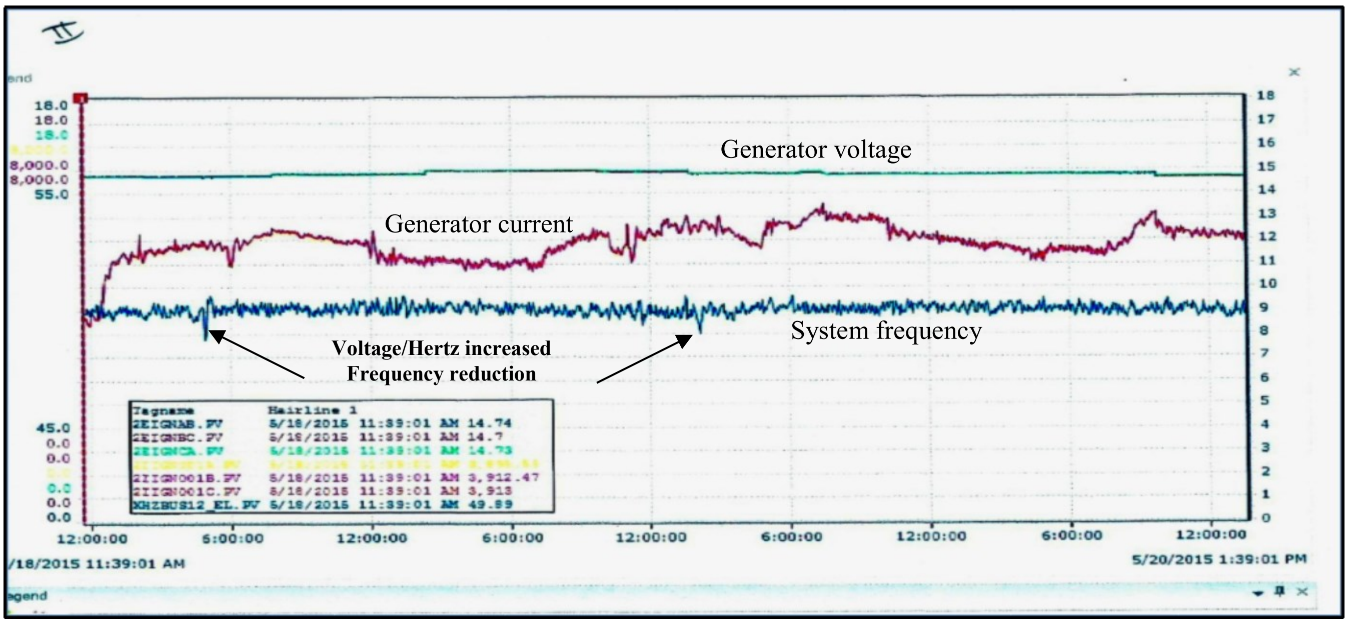

Fig 4. Repeating Disturbances in Power System Frequency

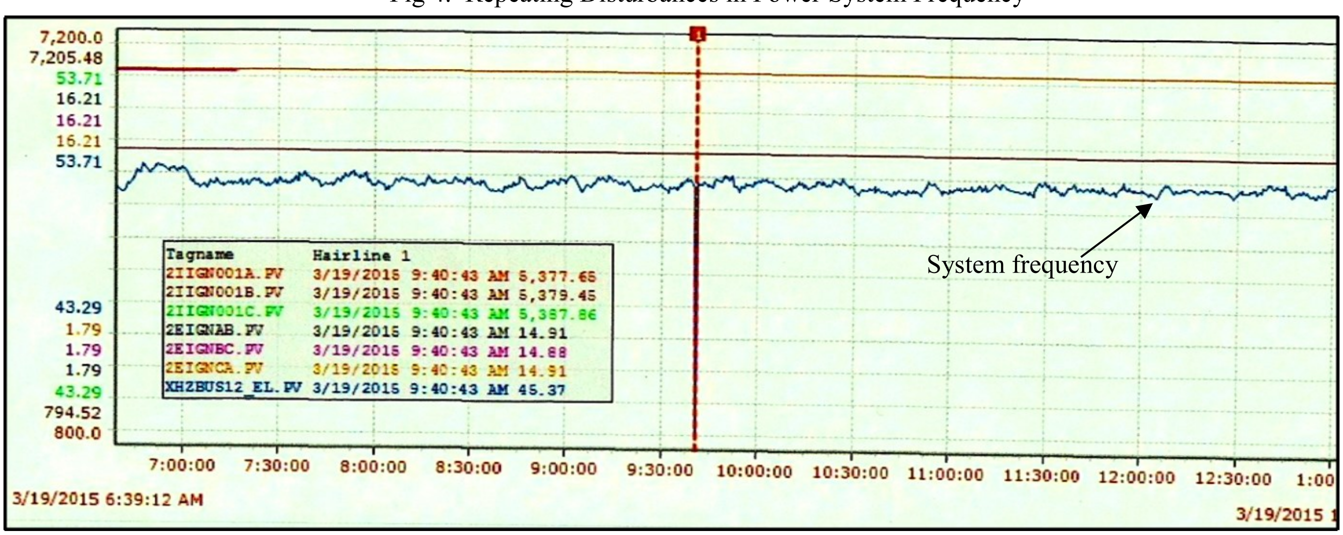

Fig 5. Instantaneous Decrease in Power System Frequency

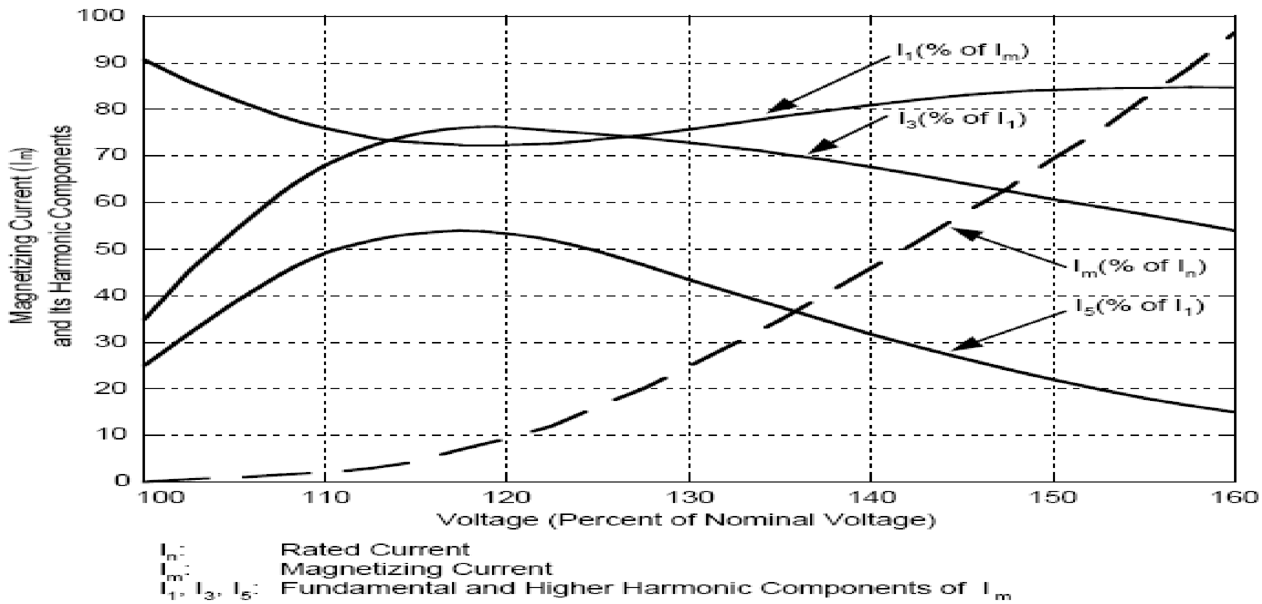

Fig 6. Voltage Increased, at Rated Frequency Exciting Current Increase

TABLE VI.
CAUSES OF THERMAL FAULTS, NORMAL AND ACCELERATED AGING

				Tr1	Tr2	Tr3	Tr4	Tr5	Tr6
Normal aging due to dynamic load cycle	Over Temperature	Fault currents							
		Overload &Unbalanced load							
		Cooling system failure							
		Increased Oil viscosity							
	Over excitation	Unit startup	maintain the set point voltage at low frequency	X	X			X	X
		Unit shutdown	field breaker fails to open when the generator trips	X	X			X	X
		Over Voltage At rated frequency	The charging current for a high-voltage transmission line.	X	X	X	X	X	X
		Power system disturbance	Loss of some units During operation or suddenly heavy load	X	X	X	X	X	X
Accelerating aging	normal operating Temperature 80 - 120 °C.	Moisture	Oxidation of the insulation and oils forms acids, Acid attacks cellulose and accelerates insulation degradation, with moisture (PD) Electrical stress can occur and more insulation degradation						X
		Oxygen							X
		Acidity							X

VI. CONCLUSION.

Modification of Duval triangle DGA diagnostic graph to numerical method is easy to use for diagnoses and a Matlab program. Transformer thermal faults during dynamic load cycle due to temperature increase from over load, cooling system failure or trouble, fault currents and /or over excitation condition.

Over excitation, damage usually occurs during periods of off-frequency operation such as start up or shut down for unit transformer. In addition, the fault gases can be generated due to oil decomposing effected by transformer over excitation.

Transformers and generators can be subject to repeated over excitation by inappropriate operating practices or operator error without a disruption to operations. It's can be concluded also, the resulting thermal faults lead to oil decomposing to generate fault gases H2, CH4 at temperature 120°C, C2H6 at temperature 150°C, C2H4 at temperature 300°C, and C2H2 at temperature 700°C.

The gas type and gas quantity depends on the intensity and duration of Over-excitation. Transformer diagnostic thereby results depends on the events inside evaluation interval or before evaluation time.

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Control of electric machines; Vector control, nonlinear control, adaptive control, model predictive control, double feed induction motors ,DTC -Power electronic converters, two-level and multilevel, matrix converter, ZS-Artificial Intelligence in machines and power electronics control, Fuzzy logic, neural networks -Renewable energy conversion for PV and wind systems, maximum power point tracking -Fault detection Diagnosis in electrical machines and drives.

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