Transformer diagnostic

Introduction

Dissolved gas-in-oil analysis (DGA) is a sensitive and reliable technique for the detection of incipient fault condition within oil-immersed transformers. The presence of certain key gases is monitored and quantified.

There are a number of methods developed for analyzing these gases and interpreting their significance: Key Gas, Rogers Ratio, Doernenburg, Logarithmic Nomograph, IEC Ratio, Basic gas ratios and Duval Triangle. This case investigates the accuracy and consistency of these methods in interpreting the transformer condition. Also The mechanical properties of insulating paper can be established by direct measurement of its tensile strength or degree of polymerization (DP). These properties are used to evaluate the end of reliable life of paper insulation. It is generally suggested that DP values of below 200 represent the lower limits for end–of–life criteria for paper insulation; for values < 150, the paper is without mechanical strength.

Analysis of paper insulation for its DP value requires removal of a few strips of paper from suspect sites. This procedure can conveniently be carried out during transformer repairs. The results of these tests will be a deciding factor in rebuilding or scrapping a transformer. Direct measurement of these properties is not practical for in-service transformers. However, it has been shown that the amount of 2-furaldehyde in oil (usually the most prominent component of paper decomposition) is directly related to the DP of the paper inside the transformer.

Paper in a transformer does not age uniformly and variations are expected with temperature, moisture distribution, oxygen levels and other operating conditions. The levels of 2-furaldehyde in oil relate to the average deterioration of the insulating paper. Consequently, the extent of paper deterioration resulting from a hot spot will be greater than indicated by levels of 2-furaldehyde in the oil. For typical power transformer, The evaluation is carried out on DGA and furan data obtained from three different groups of transformers each group are identical in Abu-Sultan steam power plant.

6.2.1 Dissolved gas analysis to diagnose transformer faults

When thermal or electrical stresses, which affect the insulating oil and cellulose material in transformers, are higher than the normal permissible value, then certain combustible gases, referred as fault gases, started to be produced inside the transformer. The most significant fault gases produced by oil decomposition are H_2 (Hydrogen), C_2H_6 (Ethane), C_2H_4 (Ethylene) and C_2H_2 (Acetylene) as well as Carbon monoxide (CO) and carbon dioxide (CO_2) which produce from decomposition of insulated paper (Cellulose).

Table 1 Summary of some diagnostic methods used by a Matlab program

(T.C.G) without C3H6 & C3H8	Hydrogen	Hydrocarbons					Carbon Oxides		Non-fault or atmospheric gases		Diagnoses
	Combustible gases							Non-Combustible gases			
	H2	CH4	C2H2	C2H4	C2H6	C3H6 & C3H8	CO	CO2	O2	N2	
IEEE C57.104- D11d Kay gas % based on total combustible gases without C3H6 & C3H8 ≥											
	4%	16%		62%	18%						pyrolysis in oil
							90%				pyrolysis of cellulose
	86%	12%									corona in oil
	60%	5%	30%	3%	2%						arcing in oil
IEC 60599-2007 Gas limits and generation rate ppm per month											
	L ≥ 150	L ≥ 130	L ≥ 20	L ≥ 280	L ≥ 90		L ≥ 600	L ≥ 14000			fault can be present
	g ≥ 11.25	g ≥ 10.00	g ≥ 0.330	g ≥ 12.10	g ≥ 7.500		g ≥ 88.30	g ≥ 833.3			fault can be present
IEEE C57.104-2008 gas concentration limits											
L ≤ 720	L ≤ 100	L ≤ 120	L ≤ 35	L ≤ 50	L ≤ 56		L ≤ 350	L ≤ 2500			transformer normal
L > 720 L ≤ 1920	L > 100 L ≤ 700	L > 120 L ≤ 400	L > 35 L ≤ 50	L > 50 L ≤ 100	L > 56 L ≤ 100		L > 350 L ≤ 570	L > 2500 L ≤ 4000			fault can be present
L > 1920 L ≤ 4630	L > 700 L ≤ 1800	L > 400 L ≤ 1000	L > 50 L ≤ 80	L > 100 L ≤ 200	L > 100 L ≤ 150		L > 570 L ≤ 1400	L > 4000 L ≤ 10000			high decomposition cellulose and/or oil
L > 4630	L > 1800	L > 1000	L > 80	L > 200	L > 150		L > 1400	L > 10000			excessive decomposition cellulose and/or oil
IEEE C57.104-1999 Gas limits and generation rate											
	L ≥ 100 g ≥ 50	L ≥ 75 g ≥ 38	L ≥ 35 g ≥ 3	L ≥ 75 g ≥ 38	L ≥ 75 g ≥ 38		L ≥ 700 g ≥ 350	L ≥ 7000 g ≥ 3500			fault can be present

facilitate of fault gases, such as Key gases method, Gas limits and generation rate gas concentration limits, these methods are shown in table (1) also Dornenberg method, Roger's ratio method, Basic gas ratios method, C02/CO method, O2/N2 method, and C2H2/H2 method, are shown in table (2) to automate the diagnoses by Matlab program.

6.2.2 Modification of Duval triangle (DGA) diagnostic graph to numerical method

This tool was developed in this thesis only to make the Modification of Duval triangle DGA diagnostic graph to numerical method to be more easy to use and to automate Duval triangle DGA diagnoses by a Matlab program. For example if C2H2 % = 10 % = 0.1, CH4 % = 30 % = 0.3 and C2H4 % = 60% = 0.6 we can use table (3) easy to determine

Table (2) summary of some other diagnostic methods used by a Matlab program

R1	R2	R3	R4	R5	R6	Diagnoses
CH4/H2	C2H2/C2H4	C2H2/CH4	C2H6/C2H2	C2H4/C2H6	C2H6/CH4	
IEC 60599-2007 Basic gas ratios						
<0.1	-			<0.2		partial discharges
0.1-0.5	>1.0			>1.0		discharge of low energy
0.1-1	0.6-2.5			>2.0		discharge of high energy
-	-			<1.0		thermal fault of < 300°C
>1.0	<0.1			1.0-4.0		thermal fault 300°C < t < 700°C
>1.0	<0.2			>4.0		thermal fault t > 700°C
IEC 60599-1999 Basic gas ratios						
0.1-1	<0.1			<1.0		normal ageing
<0.1	<0.1			<1.0		partial discharge of low energy density
<0.1	0.1-1			<1.0		partial discharge of high energy density
0.1-1	>0.1			>1.0		discharge of low energy continuous sparking
0.1-1	0.1-1			>3.0		discharge of high energy arc with power flow through
0.1-1	<0.1			1.0-3.0		thermal fault of low temperature <150°C
>1.0	<0.1			<1.0		thermal fault of low temperature range 150-300°C
>1.0	<0.1			1.0-3.0		thermal fault of medium temperature range 300-700°C
>1.0	<0.1			>3.0		thermal fault of high temperature > 700°C
IEEE C57.104- D11d Doernenburg ratios						
>1.0	<0.75	<0.3	>0.4			thermal decomposition
<0.1	insignificant	<0.3	>0.4			partial discharge (low intensity) corona
>0.1 <1.0	>0.75	>0.3	<0.4			partial discharge (high intensity arcing
IEEE C57.104-D11d Rogers ratios						
>0.1 <1.0	<0.5			<1.0	<1.0	normal
≤ 0.1	<0.5			<1.0	<1.0	partial discharge (corona)
≥ 1	<0.5			<1.0	<1.0	slight overheating <150 °C
≥ 1	<0.5			<1.0	≥ 1	slight overheating 150-200 °C
>0.1 <1.0	<0.5			<1.0	≥ 1	slight overheating 200-300 °C
>0.1 <1.0	<0.5			≥ 1.0 ≤ 3.0	<1.0	general conductor overheating
≥ 1.0 <3.0	<0.5			≥ 1.0 ≤ 3.0	<1.0	winding circulating currents
≥ 1.0 ≤ 3.0	<0.5			≥ 3.0	<1.0	core and tank circulating currents, overheated joints
>0.1 <1.0	≥ 0.5 <3.0			<1.0	<1.0	flash, no power follow through
>0.1 <1.0	≥ 0.5			≥ 1	<1.0	arc with power follow through
>0.1 <1.0	≥ 3.0			≥ 3.0	<1.0	continuous sparking to floating potential
≤ 0.1	≥ 0.5			<1.0	<1.0	partial discharge with tracking (note CO)
IEC 60599-2007 Single ratio				**O2/N2**	**C2H2/H2**	
				close to 0.5		may be seal leaks
				≤ 0.3		excessive consumption of oxygen, oil oxidation, paper ageing
					≥ 2.0 ≤ 3.0	may be main tank contamination by O.L.T.C compartment
IEC 60599-2007 and IEEE C57.104- D11d					**CO2/CO**	

Single ratio						
					≥ 3.0 ≤ 11.0	Normal
					< 3.0	paper degradation, Carbonization, t>200°C
					> 11.0	may be seal leaks or/and oil oxidation, t<150°C

Table (3) 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	
0.13 - 1.00	0.00 - 0.87	0.00 - 0.23	Discharge of low energy (electrical fault)

the fault Diagnostic (Thermal fault t > 700°C i.e T3). Another practical examples in our case study, the recent increases of gases for TR2 (37-15 = 22 ppm) of CH4, (12 - 1 = 11 ppm) of C2H4, and (0 - 0 = 0 ppm) of C2H2 from 08/05/2013 to 05/1/2014 i.e (11/33 = 0.333333) CH4, (22/33 = 0.666666) C2H4, and (0/33= 0) C2H2 when we use this method we get from table (6-5) this transformer has (Thermal fault t > 700 °C).

Also the recent increases of gases, for TR4 (61-19 = 42 ppm) of CH4, (6 - 5 = 1 ppm) of C2H4, and (0 - 0 = 0 ppm) of C2H2 from 07/04/2013 to 27/11/2013 i.e (42/43 = 0.9767441) CH4, (1/43 = 0.0232558) C2H4, and (0/43= 0) C2H2 when we use this method we get from (table 6-5) this Transformer has (Thermal fault t < 300 °C).

Also the recent increases of gases for TR6 (12 - 3 = 9 ppm) of CH4, (3 - 2 = 1 ppm) of C2H4, and (0 - 0 = 0 ppm) of C2H2 from 07/04/2013 to 02/04/2014 i.e (9/10 = 0.9) CH4, (1/10 = 0.1) C2H4, and (0/10= 0) C2H2 when we use this method we get from table (3) this transformer has (Thermal fault t < 300 °C).

6.4 Result of diagnostic methods used by a Matlab program

The diagnostic methods for dissolved gas-in-oil analysis and furan are used by a matlab program as shown in the following flow chart Fig. (1). The Matlab program Diagnoses output as shown Fig. (2, 3, 4, 5, 6, 7) for the under evaluation transformers and table (4) shows Summary of the faults diagnosed by various methods which indicate that all transformers are thermal faults.

If % correct diagnoses for method number one is p(A1) and % wrong diagnoses for method number one is p(B1) and % unresolved diagnoses for method number one is p(C1) also If % correct diagnoses for method number two is p(A2) and % wrong diagnoses for method number two is p(B2) and % unresolved diagnoses for method number two is p(C2) and so on then the probability that TR1thermal fault is correct diagnoses is p(A1 U A2 U A3 U A4 U A5) = 99.94 %, for all methods of TR1.

And the probability that TR2 thermal fault is correct diagnoses is p (A1 U A2 U A3 U A4 U A5) = 99.94 %, for all methods of TR2.

And the probability that TR3 thermal fault is correct diagnoses is p (A1 U A2 U A4 U A5) = 99.80 %, for all methods of TR3.

And the probability that TR4 thermal fault is correct diagnoses is p (A1 U A2 U A3 U A4 U A5)= 99.94 %, for all methods of TR4.

And the probability that TR5 thermal fault is correct diagnoses is p (A1 U A2 U A3 U A4 U A5) = 99.85 %, for all methods of TR5.

And the probability that TR6 thermal fault is correct diagnoses is p (A1 U A4 U A5)= 99.12 %, for all methods of TR6.

The fault gases ratios and rate for under evaluation transformers also degree of polymerization are shown in table (5).

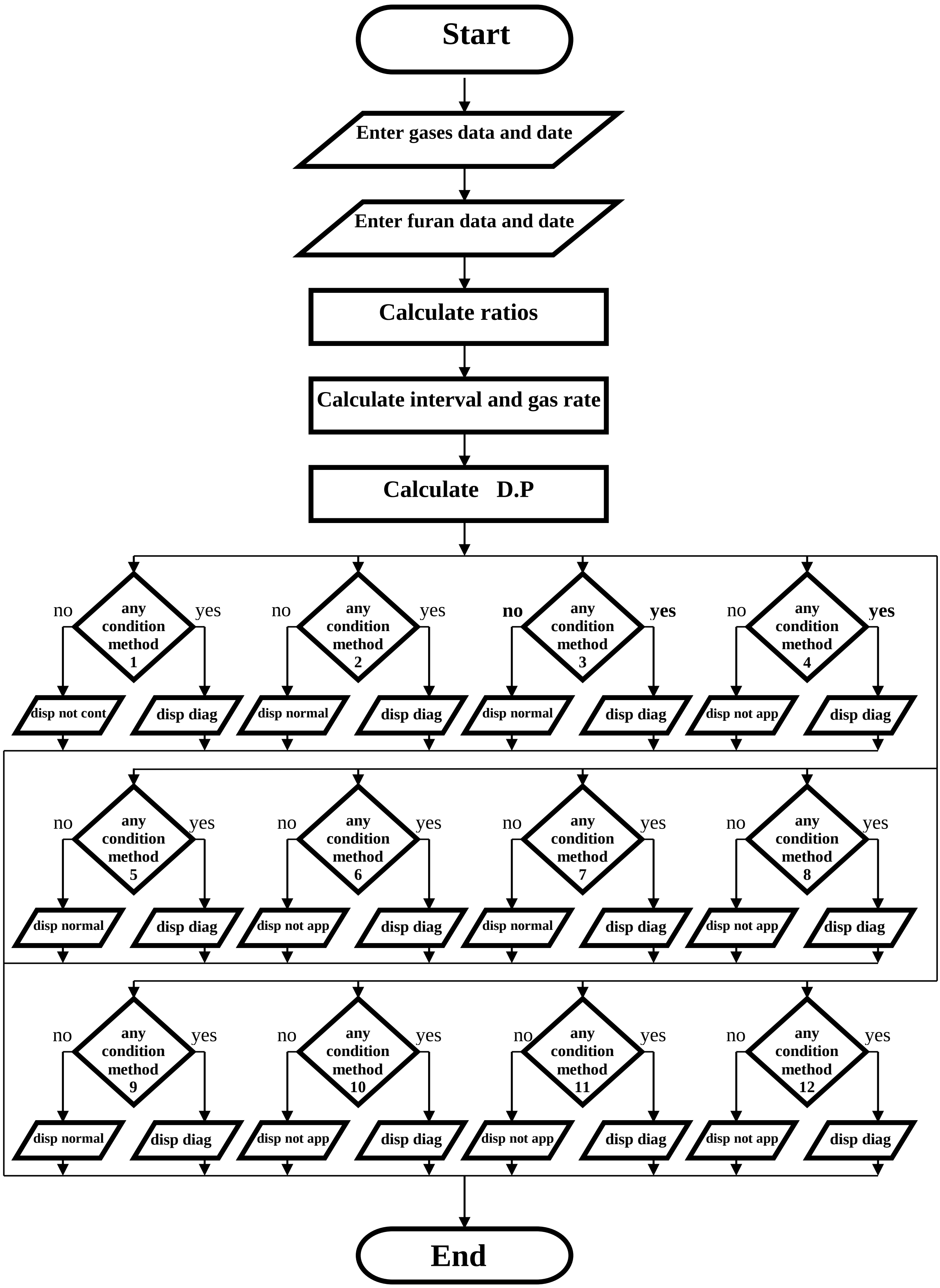

Fig. (1) transformer diagnostic using dissolved gases and furan analysis flow chart

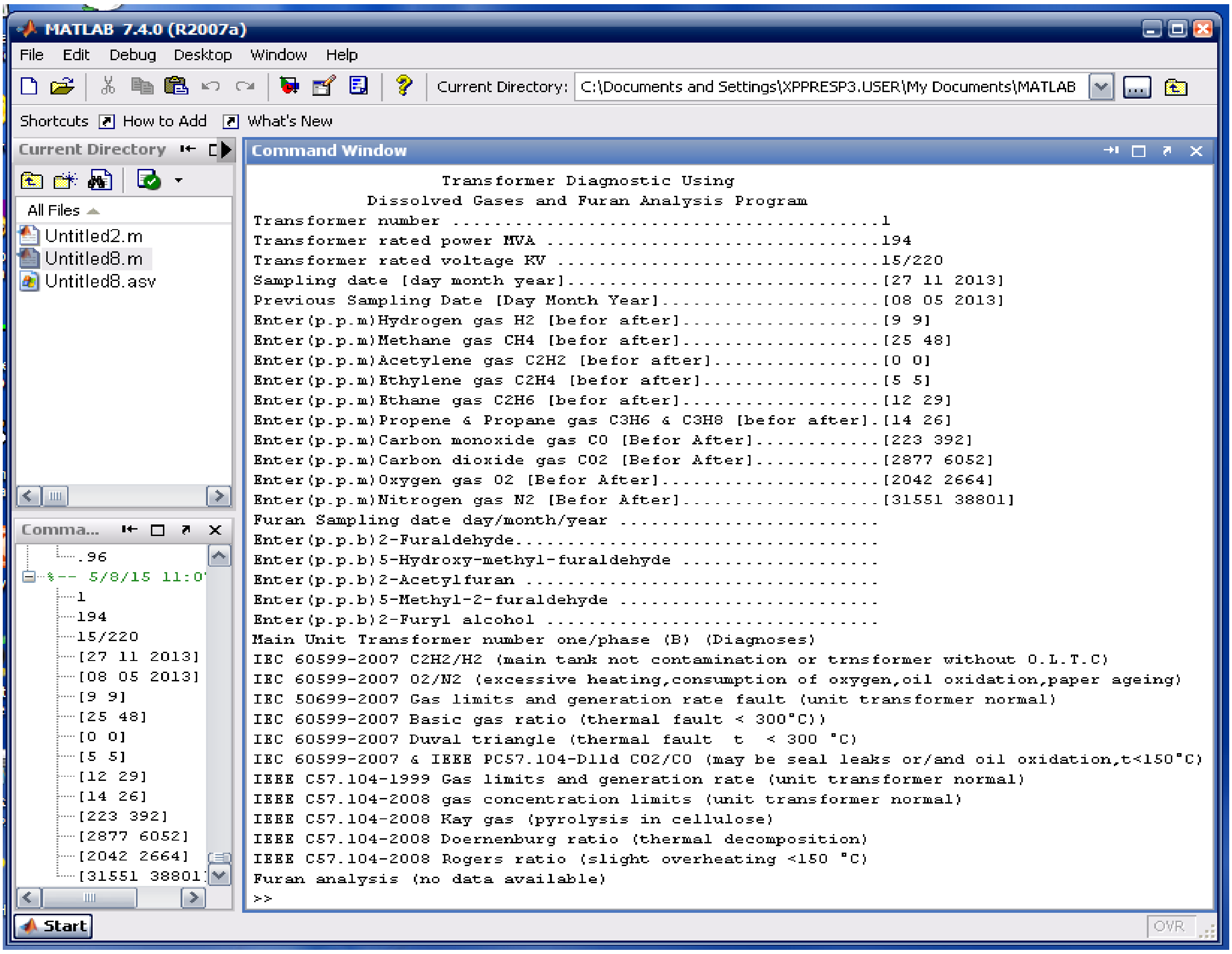

Fig. (2) transformer number one/phase (B) diagnoses

Main Unit Transformer number one/phase (B) (Diagnoses)
IEC 60599-2007 C2H2/H2 (main tank not contamination or transformer without O.L.T.C)
IEC 60599-2007 O2/N2 (excessive heating, consumption of oxygen, oil oxidation, paper ageing)
IEC 50699-2007 Gas limits and generation rate fault (unit transformer normal)
IEC 60599-2007 Basic gas ratio (thermal fault < 300°C))
IEC 60599-2007 Duval triangle (thermal fault < 300°C)
IEC 60599-2007 & IEEE PC57.104-D11d CO2/CO (may be seal leaks or/and oil oxidation, t<150°C)
IEEE C57.104-1999 Gas limits and generation rate (unit transformer normal)
IEEE C57.104-2008 gas concentration limits (unit transformer normal)
IEEE C57.104-2008 Kay gas (pyrolysis in cellulose)
IEEE C57.104-2008 Doernenburg ratio (thermal decomposition)
IEEE C57.104-2008 Rogers ratio (slight overheating <150 °C)
Furan analysis (no data available)

g = 0 3.5 0 0 2.6 1.8 25.5 478.6 93.8 1093 (ppm/month)

r = 5.3333 0 0 Inf 0.1724 0.6042

s = 0 15.4388 0.0687

t = 6.63 (month)

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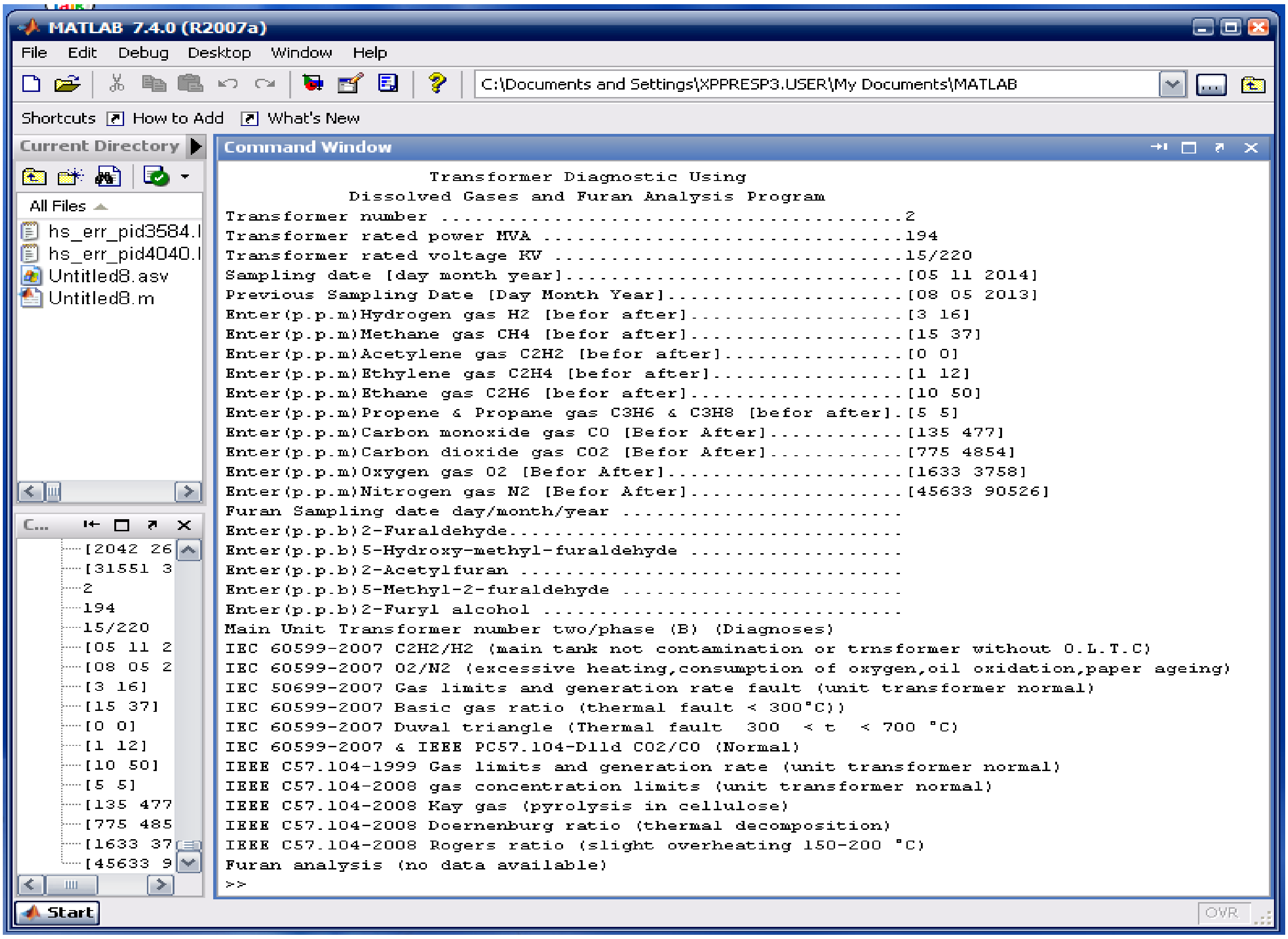

Fig. (3) transformer number two/phase (B) diagnoses)

Main Unit Transformer number two/phase (B) (Diagnoses)
IEC 60599-2007 C2H2/H2 (main tank not contamination or transformer without O.L.T.C)
IEC 60599-2007 O2/N2 (excessive heating , consumption of oxygen, oil oxidation, paper ageing)
IEC 50699-2007 Gas limits and generation rate fault (unit transformer normal)
IEC 60599-2007 Basic gas ratio (thermal fault < 300°C))
IEC 60599-2007 Duval triangle (Thermal fault 300 < t < 700 °C)
IEC 60599-2007 & IEEE PC57.104-D11d CO2/CO (Normal)
IEEE C57.104-1999 Gas limits and generation rate (unit transformer normal)
IEEE C57.104-2008 gas concentration limits (unit transformer normal)
IEEE C57.104-2008 Kay gas (pyrolysis in cellulose)
IEEE C57.104-2008 Doernenburg ratio (thermal decomposition)
IEEE C57.104-2008 Rogers ratio (slight overheating 150-200 °C)
Furan analysis (no data available)

g = 0.7 1.2 0 0.6 2.2 0 19.1 227.9 118.7 2508 (ppm/month)

r = 2.3125 0 0 Inf 0.2400 1.3514

s = 0 10.1761 0.0415

t = 17.9000 (month)

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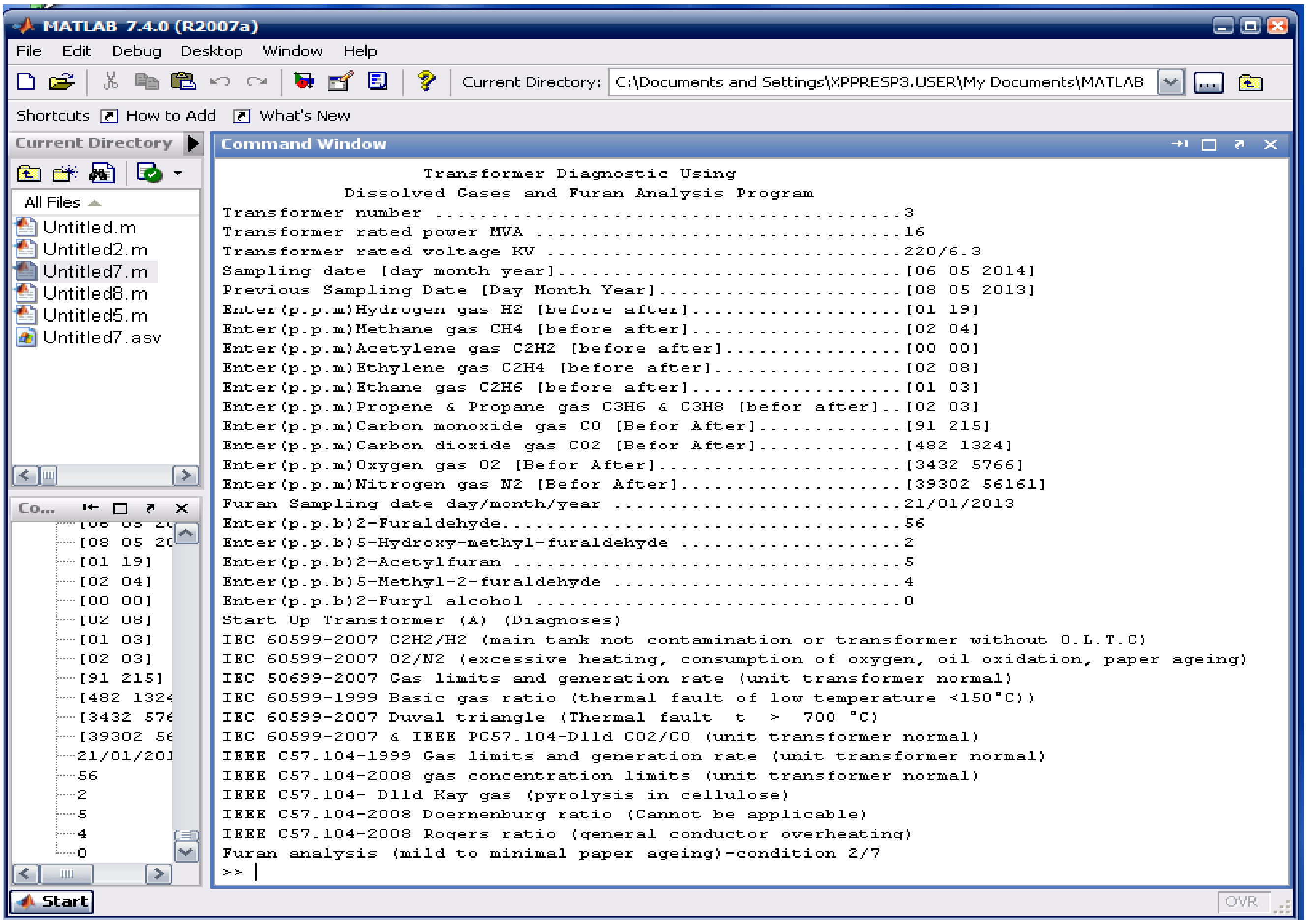

Fig. (4) Start Up transformer (A) Diagnoses

Start Up Transformer (A) (Diagnoses)
IEC 60599-2007 C2H2/H2 (main tank not contamination or transformer without O.L.T.C)
IEC 60599-2007 O2/N2 (excessive heating, consumption of oxygen, oil oxidation, paper ageing)
IEC 50699-2007 Gas limits and generation rate (unit transformer normal)
IEC 60599-1999 Basic gas ratio (thermal fault of low temperature <150°C))
IEC 60599-2007 Duval triangle (Thermal fault t > 700 °C)
IEC 60599-2007 & IEEE PC57.104-D11d CO2/CO (unit transformer normal)
IEEE C57.104-1999 Gas limits and generation rate (unit transformer normal)
IEEE C57.104-2008 gas concentration limits (unit transformer normal)
IEEE C57.104- D11d Kay gas (pyrolysis in cellulose)
IEEE C57.104-2008 Doernenburg ratio (Cannot be applicable)
IEEE C57.104-2008 Rogers ratio (general conductor overheating)
Furan analysis (mild to minimal paper ageing)-condition 2/7

g = 1.5 0.2 0 0.5 0.2 0.1 10.4 70.6 195.6 1412.8 (ppm/month)

r = 0.2105 0 0 Inf 2.6667 0.7500

s = 0 6.1581 0.1027

t = 11.9333 (month)

DP = 630.6766

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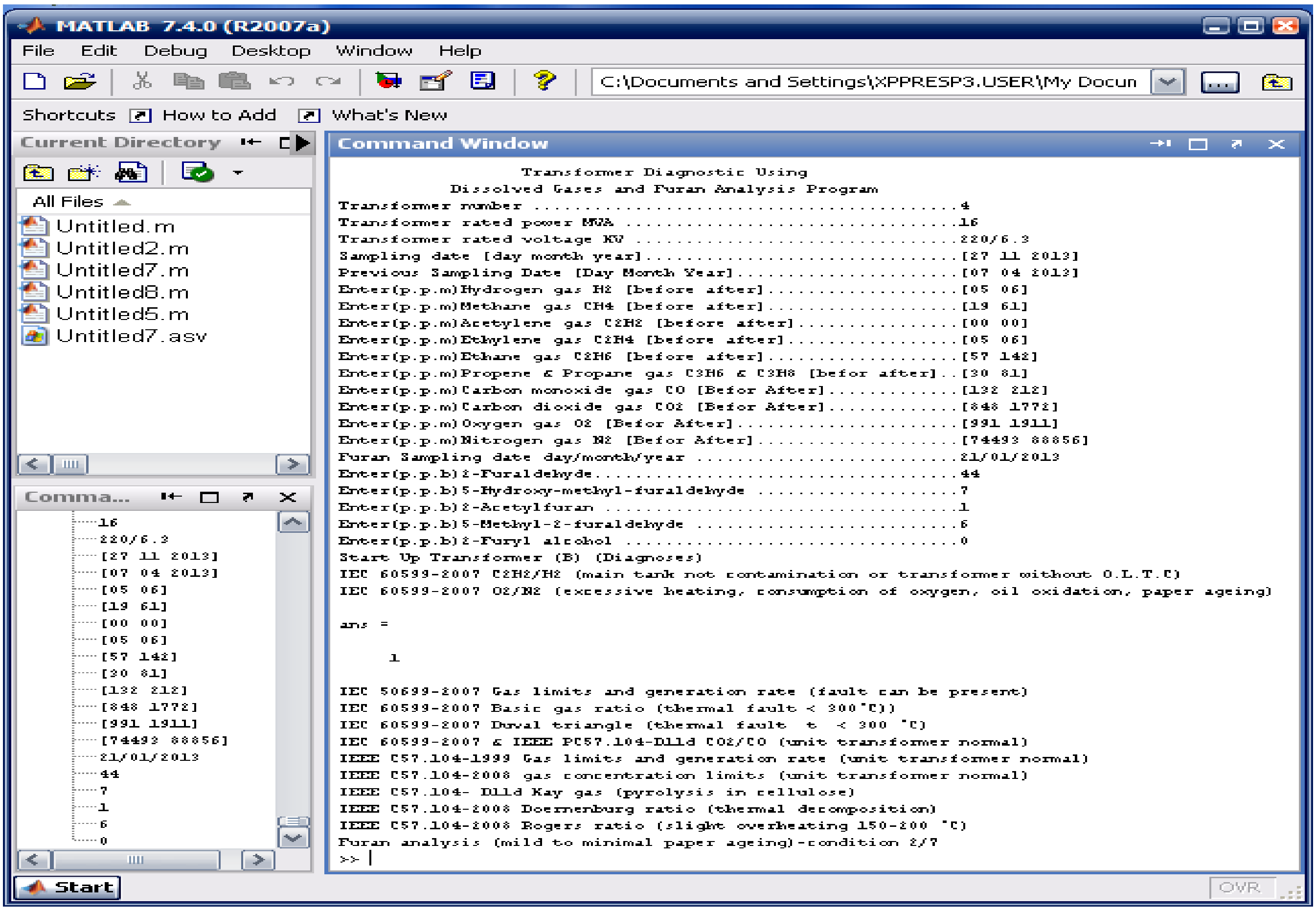

Fig. (5) Start Up transformer (B) diagnoses

Start Up Transformer (B) (Diagnoses)
IEC 60599-2007 C2H2/H2 (main tank not contamination or transformer without O.L.T.C)
IEC 60599-2007 O2/N2 (excessive heating, consumption of oxygen, oil oxidation, paper ageing)
IEC 50699-2007 Gas limits and generation rate (fault can be present)
IEC 60599-2007 Basic gas ratio (thermal fault < 300°C))
IEC 60599-2007 Duval triangle (thermal fault t < 300 °C)
IEC 60599-2007 & IEEE PC57.104-D11d CO2/CO (unit transformer normal)
IEEE C57.104-1999 Gas limits and generation rate (unit transformer normal)
IEEE C57.104-2008 gas concentration limits (unit transformer normal)
IEEE C57.104- D11d Kay gas (pyrolysis in cellulose)
IEEE C57.104-2008 Doernenburg ratio (thermal decomposition)
IEEE C57.104-2008 Rogers ratio (slight overheating 150-200 °C)
Furan analysis (mild to minimal paper ageing)-condition 2/7

g = 0.1 5.5 0 0.1 11.1 6.7 10.4 120.5 120 1873.4 (ppm/month)

r = 10.1667 0 0 Inf 0.0423 2.3279

s = 0 8.3585 0.0215

t = 7.6667 (month)

DP = 631.5920

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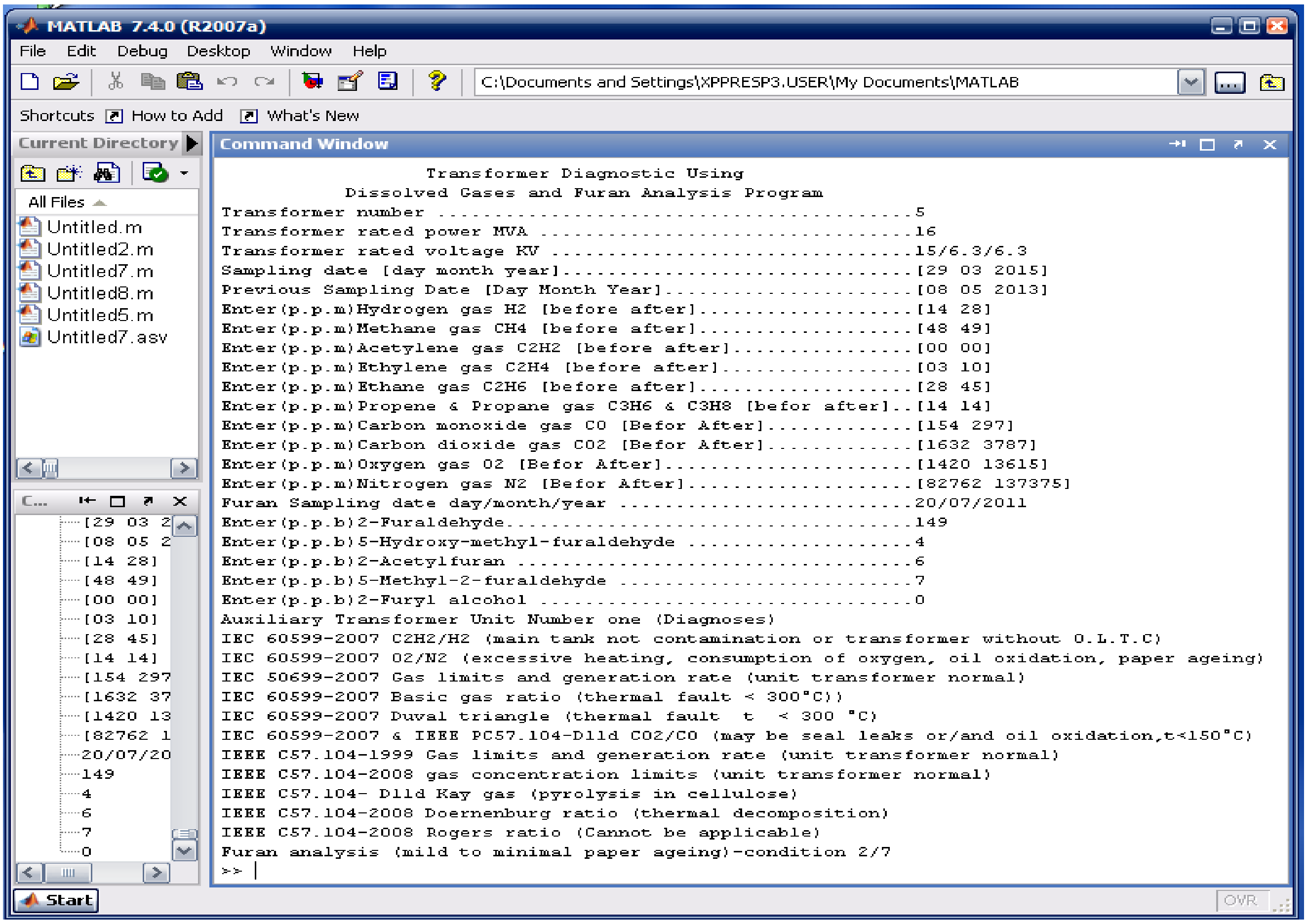

Fig. (6) auxiliary transformer unit number one diagnoses

Auxiliary Transformer Unit Number one (Diagnoses)
IEC 60599-2007 C2H2/H2 (main tank not contamination or transformer without O.L.T.C)
IEC 60599-2007 O2/N2 (excessive heating, consumption of oxygen, oil oxidation, paper ageing)
IEC 50699-2007 Gas limits and generation rate (unit transformer normal)
IEC 60599-2007 Basic gas ratio (thermal fault < 300°C))
IEC 60599-2007 Duval triangle (thermal fault t < 300 °C)
IEC 60599-2007 & IEEE PC57.104-D11d CO2/CO (may be seal leaks or/and oil oxidation,t<150°C)
IEEE C57.104-1999 Gas limits and generation rate (unit transformer normal)
IEEE C57.104-2008 gas concentration limits (unit transformer normal)
IEEE C57.104- D11d Kay gas (pyrolysis in cellulose)
IEEE C57.104-2008 Doernenburg ratio (thermal decomposition)
IEEE C57.104-2008 Rogers ratio (Cannot be applicable)
Furan analysis (mild to minimal paper ageing)-condition 2/7

g = 0.6 0 0 0.3 0.7 0 6.3 94.9 537.2 2405.9 (ppm/month)

r = 1.7500 0 0 Inf 0.2222 0.9184

s = 0 12.7508 0.0991

t = 22.7000 (month)

DP = 623.6127

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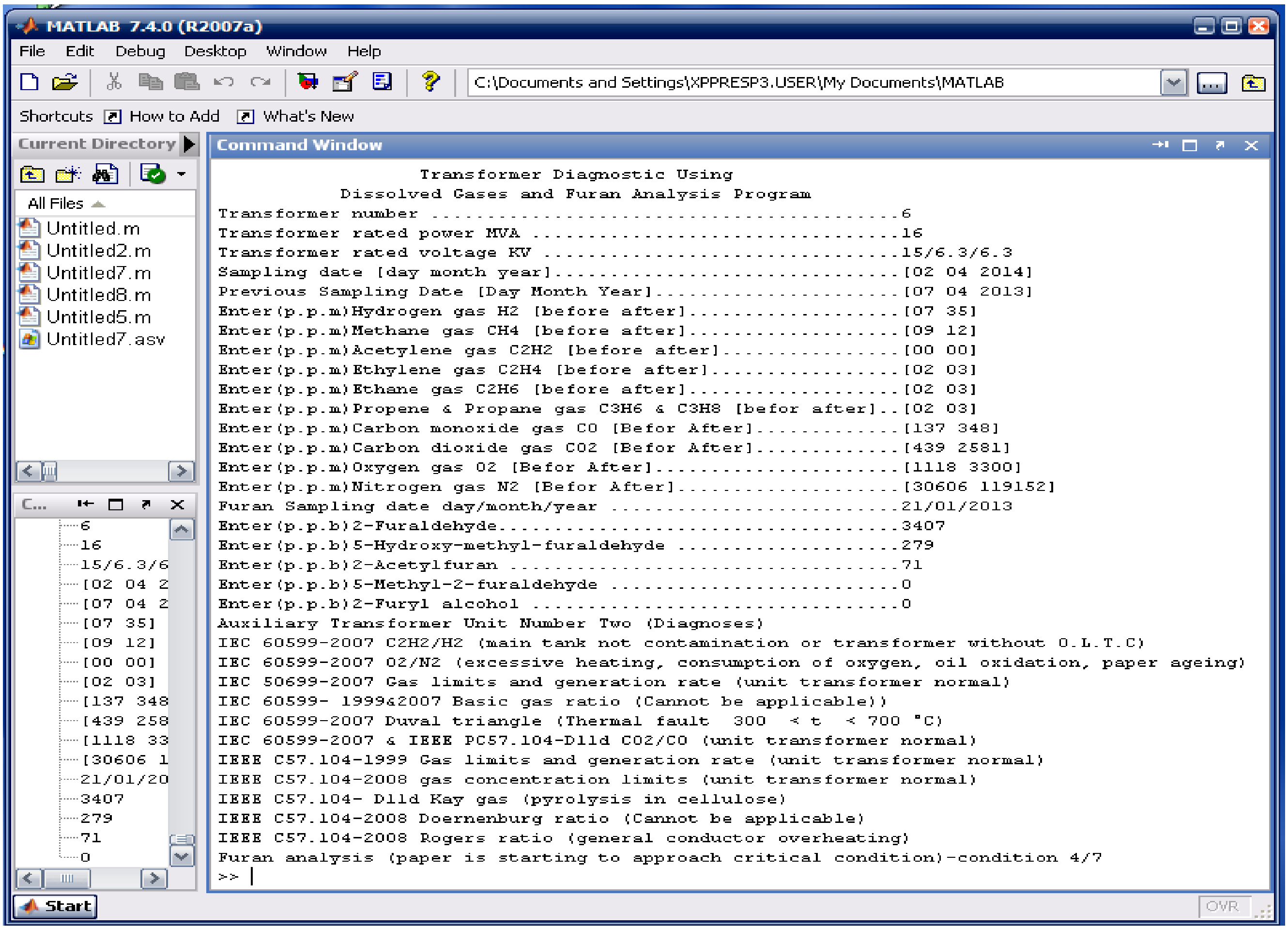

Fig. (7) auxiliary transformer unit number two diagnoses

Auxiliary Transformer Unit Number Two (Diagnoses)
IEC 60599-2007 C2H2/H2 (main tank not contamination or transformer without O.L.T.C)
IEC 60599-2007 O2/N2 (excessive heating, consumption of oxygen, oil oxidation, paper ageing)
IEC 50699-2007 Gas limits and generation rate (unit transformer normal)
IEC 60599- 1999&2007 Basic gas ratio (Cannot be applicable))
IEC 60599-2007 Duval triangle (Thermal fault 300 < t < 700 °C)
IEC 60599-2007 & IEEE PC57.104-D11d CO2/CO (unit transformer normal)
IEEE C57.104-1999 Gas limits and generation rate (unit transformer normal)
IEEE C57.104-2008 gas concentration limits (unit transformer normal)
IEEE C57.104- D11d Kay gas (pyrolysis in cellulose)
IEEE C57.104-2008 Doernenburg ratio (Cannot be applicable)
IEEE C57.104-2008 Rogers ratio (general conductor overheating)
Furan analysis (paper is starting to approach critical condition)-condition 4/7

g = 2.4 0.3 0 0.1 0.1 0.1 17.8 181 184.4 7482.8 (ppm/month)

r = 0.3429 0 0 Inf 1.0000 0.2500

s = 0 7.4167 0.0277

t = 11.8333 (month)

DP = 409.9619

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Table (4) Summary of the fault diagnosed by various methods

Transformer no.	Furan analysis	IEC 60599		IEEE C57.104		
		Duval's triangle 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	no data available	thermal fault t < 300°C	thermal fault t < 300°C	thermal decomposition	slight overheating t < 150 °C	pyrolysis in cellulose
TR2	no data available	Thermal fault 300 < t < 700 °C	thermal fault t < 300°C	thermal decomposition	slight overheating 150-200 °C	pyrolysis in cellulose
TR3	mild to minimal paper ageing condition 2/7	Thermal fault t > 700 °C	thermal fault of low temperature t < 150°C	Cannot be applicable	general conductor overheating	pyrolysis in cellulose
TR4	mild to minimal paper ageing condition 2/7	thermal fault t < 300 °C	thermal fault t < 300°C	thermal decomposition	slight overheating 150-200 °C	pyrolysis in cellulose
TR5	mild to minimal paper ageing condition 2/7	Thermal fault t > 700 °C	thermal fault t < 300°C	thermal decomposition	Cannot be applicable	pyrolysis in cellulose
TR6	paper is starting to approach critical condition condition 4/7	Thermal fault 300 < t < 700 °C	Cannot be applicable	Cannot be applicable	general conductor overheating	pyrolysis in cellulose

Table (5) the fault gases ratios and rate for under evaluation transformers

Ratios and Gases		TR1	TR2	TR3	TR4	TR5	TR6
R1	CH4/H2	5.3333	2.3125	0.2105	10.1667	1.7500	0.3429
R2	C2H2/C2H4	0	0	0	0	0	0
R3	C2H2/CH4	0	0	0	0	0	0
R4	C2H6/C2H2	Inf	∞	Inf	∞	Inf	∞
R5	C2H4/C2H6	0.1724	0.2400	2.6667	0.0423	0.2222	1.0000
R6	C2H6/CH4	0.6042	1.3514	0.7500	2.3279	0.9184	0.2500
Gas generation rate (ppm) / month							
g1	H2/month	0	0.7	1.5	1	0.6	2.4
g2	CH4/month	3.5	1.2	2	5.5	0.0	0.3
g3	C2H2/month	0	0	0	0	0.0	0.0
g4	C2H4/month	0	0.6	5	1	0.3	0.1
g5	C2H6/month	2.6	2.2	2	11.1	0.7	0.1
g6	C3H6&C3H8/month	1.8	0	1	6.7	0.0	0.1
g7	CO/month	25.5	19.1	10.4	10.4	6.3	17.8
g8	CO2/month	478.6	227.9	70.6	120.5	94.9	181
g9	O2/month	93.8	118.7	195.6	120	537.2	184.4
g10	N2/month	1093	2508	1412.8	1873.4	2405.9	7482.8
Single ratios							
S1	C2H2/H2	0	0	0	0	0	0
S2	CO2/CO	15.4388	10.1761	6.1581	8.3585	12.7508	7.4167

S3	**O2/N2**	**0.0687**	**0.0415**	**0.1027**	**0.0215**	**0.0991**	**0.0277**
Degree of polymerization		**-**	**-**	**630.6766**	**631.5920**	**623.6127**	**409.9619**
t (month)		**6.63**	**17.9000**	**11.9333**	**7.6667**	**22.7000**	**11.8333**

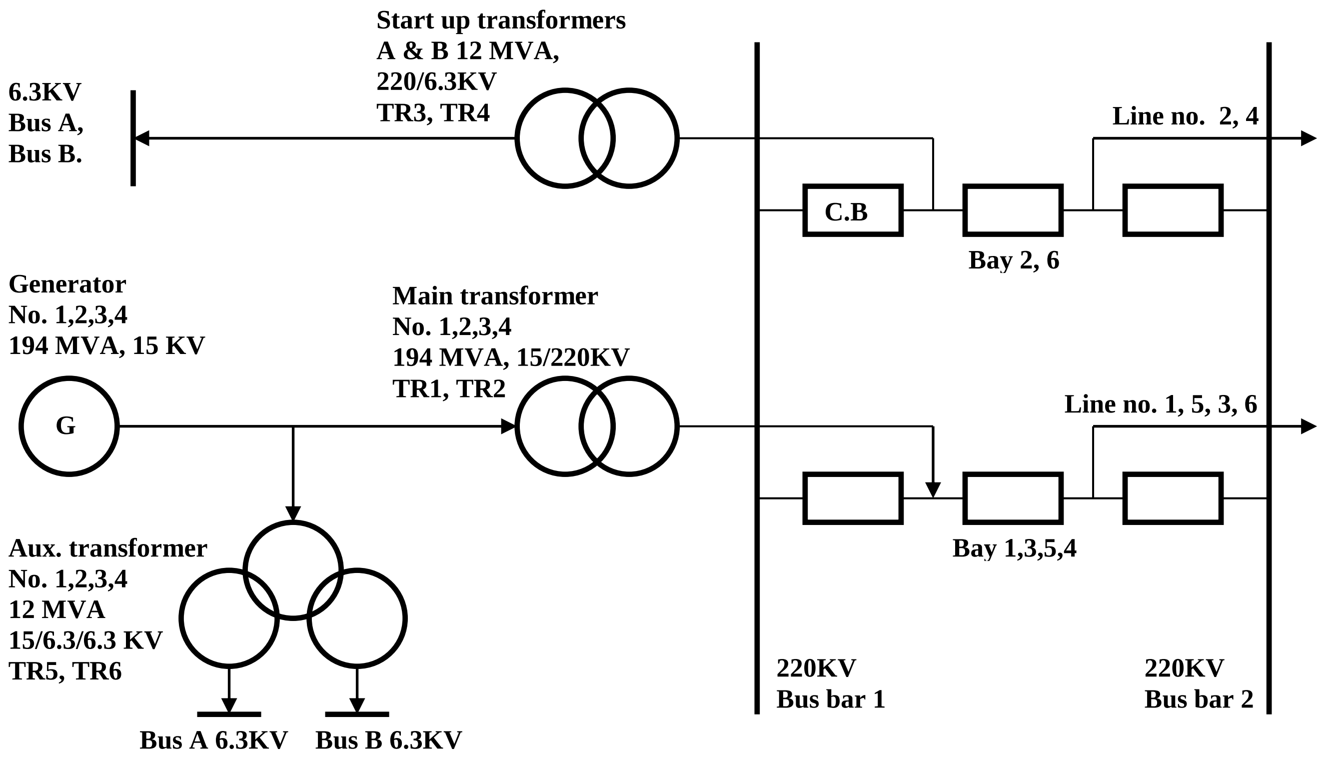

Fig. (8) Schematic diagram for transformers under evaluation