International Journal of Electrical and Power Engineering 4 (3): 193-197, 2010
ISSN: 1990-7958

Duval Triangle: A Noble Technique for DGA in Power Transformers

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Abstract: Monitoring and fault diagnosis of power transformers has always drawn the attention of all utilities worldwide. It has become important to detect the incipient fault of a power transformer at an early stage, diagnose properly and also to provide the remedies. Dissolved Gas Analyses (DGA) is widely used to detect incipient faults in oil filled power transformers. Various methods are used to interpret DGA results i.e., C.E.G.B. Rogers's ratio, IEC and IEEE ratio codes: Rogers, Dernenburg and Duval triangle methods. In this study, a relationship between the formations of hydrocarbon gases and the specific temperature and their solubility has been presented. For this study, more than couple of 100s of faulty transformer DGA sample reports from the different utilities in India (>10 years) with fault interpretation by different methods are collected. Against the same reports the Duval triangle, a graphical manual and software (MATLAB-7.4) are crossed compared.

Key words: DGA, power transformer, fault diagnosis, TDCG, MATLABs, India

INTRODUCTION

Transformer is one of the most important but complex component of electricity transmission and distribution system. Much attention is needed on maintenance of transformers in order to have fault free electric supply and to maximize the lifetime and efficacy of a transformer. Thus, it is important to be aware of possible faults that may occur. It is equally important to know how to detect them early. Regular monitoring and maintenance can make it possible to detect new flaws before much damage occur.

Formation of gases in transformer oil: Mineral oils (transformer oil) are composed of saturated hydrocarbons called paraffins, whose general molecular formula is C_nH_{2n+2} with n in the range of 20-40. The cellulosic insulation material is a polymeric substance whose general molecular formula is $(C_{12}H_{14}(OH)_6)_n$ with n in the range of 300-750. Gases are formed inside an oil-filled power transformer, in that various gases begin forming at specific temperatures shown in Fig. 1.

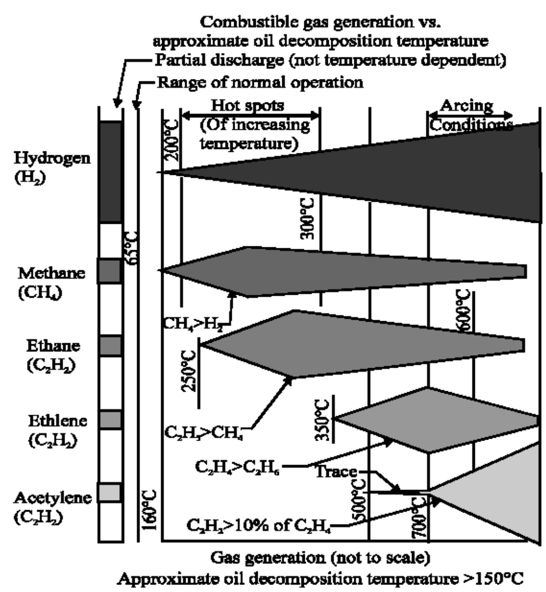

Fig. 1: Gas generation chart

Hydrogen and methane begin to form in small amounts around 150°C. Beyond maximum points, methane (CH_4), ethane and ethylene production goes down as temperature increases. At about 250°C, production of ethane (C_2H_6) starts. At about 350°C, production of ethylene (C_2H_4) begins. Acetylene (C_2H_2) starts between 500 and 700°C. In the past, the presence of only trace amounts of acetylene (C_2H_2) was considered to indicate a temperature of at least 700°C had occurred; however, recent discoveries have led to the conclusion that a thermal fault (hot spot) of 500°C can produce trace amounts (a few ppm). Larger amounts of acetylene can only be produced above 700°C by internal arcing. Between 200 and 300°C, the production of methane exceeds hydrogen. Starting about 275°C and on up, the production of ethane exceeds methane. At about 450°C, hydrogen production exceeds all others until about 750-800°C then more acetylene is produced. It should

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be noted that small amounts of H_2, CH_4 and CO are produced by normal aging. Thermal decomposition of oil-impregnated cellulose produces CO, CO_2, H_2, CH_4 and O_2. Decomposition of cellulose insulation begins at only about 100°C or less. Therefore, operation of transformers at not >90°C is imperative.

Faults will produce internal hot spots of far higher temperatures than these and the resultant gases show up in the DGA.

Solubility of gases in transformer oil: The solubilities of the fault gases in transformer oil as well as their temperature dependence are also important factors for consideration in fault gas analyses.

It should be noted that there are almost two orders of magnitude difference between the least soluble (H_2) and the most soluble (C_2H_2) gas.

The majority of gases that are indicative of faults are also those that are in general the more soluble in the oil.

When the rates of gas generation are being followed, it is important to take into account the solubility of these gases as a function of temperature (Fig. 2). Over a temperature range of 0-80°C some gases increases in their solubility upto 79% while others decreases their solubility upto 66%.

Dissolved Gas Analysis (DGA): The DGA has become a popular technique and is successfully used for many years. The method is very sensitive and gives an early indication of incipient faults. The insulation oil used in sometimes transformer leads to degradation of insulating transformer is long chain of complex mixture of

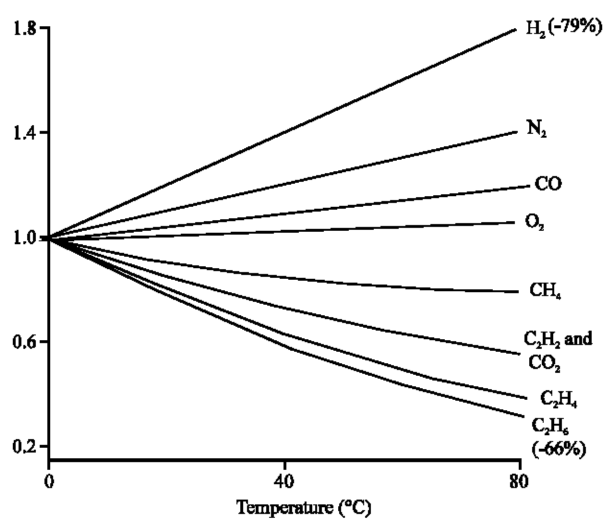

Fig. 2: Relative solubility (Y-axis) as function of temperature °C (X-axis)

hydrocarbon compounds. Failures inside the produced remain in the insulating oil in dissolved state and hydrocarbon compounds. Due to smaller molecular size, many of these compounds are gasses. Types and quantity of hydrocarbon gases formed depends on the nature and intensity of the fault. The gases so if concentration goes beyond saturation level the gases come out and get collected in Bucholzs relay.

Due to dissolved gases in the transformer oil, the insulation property of this oil goes weak and lead to transformer failures. The composition and quantity of the gases generated depend on types and severity of the faults. Both these kinds of information together provide the necessary bases for the evaluation of any fault and the necessary remedial actions. Advantages that dissolved gas analyses can provide:

- Advance warning of developing faults
- Determining warning of the improper use of units
- Status checks on new and repaired units
- Convenient scheduling of repairs
- Monitoring of units under over load

The regular monitoring of these dissolved gases interpret useful information about the condition of the transformer and prior information of the faults by observing the trend of the various gas contents. The relative distribution of the gases is used to evaluate the origin of the production of these gases and the rate at which the gases are formed to assess the intensity and propagation of the gases. A diagnostic code; warnings of any gas concentrations, increments, rates of change or ratios that exceed standard limits and short interpretive remarks and recommendations become proper fault diagnosis. Supported diagnostic methods for transformer DGA include the Duval triangle method and the Rogers, Doernenburg and CIGRE gas ratio diagnostics. The main Interpretation methods in fault diagnosis of power transformers used are:

- The IEC-60599, 1999
- The IEEE methods (Dornenburg, Rogers and key gas methods)
- The Duval triangle
- The IS: 10593 (2006) and IS: 9434 (1992) (Bureau of Indian Standards)

It also needs proper sampling method and can be referred:

- Doble reference book on insulating liquids and gases

Table 1: Key faults in power transformer

Symbols	Faults	Examples
PD	Partial discharges	Discharges of the cold plasma (corona) type in gas bubbles or voids, with the possible formation of X-wax in paper
D1	Discharges of low energy	Partial discharges of the sparking type, inducing pinholes, carbonized punctures in paper Low energy arcing inducing carbonized perforation or surface tracking of paper or the formation of carbon particles in oil
D2	Discharges of high energy	Discharges in paper or oil, with power follow through, resulting in extensive damage to paper or large formation of carbon particles in oil, metal fusion, tripping of the equipment and gas alarms
DT	Thermal and electrical faults	Mixture of thermal and electrical faults
T1	Thermal fault, T<300°C	Evidenced by paper turning brownish (>200°C) or carbonized (>300°C)
T2	Thermal fault, 300<T<700°C	Carbonization of paper, formation of carbon particles in oil
T3	Thermal fault, T>700°C	Extensive formation of carbon particles in oil, metal coloration (800°C) or metal fusion (>1000°C)

- ASTM D 923: Standard practice for sampling electrical insulating liquids
- ASTM D 3613: Standard practice for sampling electrical insulating oils for gas analysis and determination of water content
- IEC 60475: Method of sampling liquid dielectrics
- IEC 60567: Guide for the sampling of gases and of oil from oil-filled electrical equipment and for the analysis of free and dissolved gases
- IS: 1866 (2000): Code of practice for electrical maintenance and supervision of mineral insulating oil in equipment (3rd revision)

Key faults in power transformers (PC57.104/D3.3, 2008; IEC 60599 {Ed.2.1}, 1999) shown in Table 1.

Duval triangle in dissolved gas analyses: Duval triangle method (Duval, 2003, 2008; Singh, 2008a, b; Akbari *et al.*, 2008; Duval and Dukarm, 2005) shown in Fig. 3 developed empirically in early 1970s and is used by IEC (IEC 60599 {Ed.2.1}, 1999). It is based on the use of three gases methane (CH_4), ethane (C_2H_4) and acetylene (C_2H_2), corresponding to the increasing energy levels of gas formation. About 1000 sample test reports were collected from different utilities in India. Out of those reports, with abnormal gas formations and interpreted faults (PC57.104/D3.3, 2008; IEC 60599 {Ed.2.1}, 1999) are separated with suggested remedial actions. The dissolved gas analysis by Duval triangle involves percentage of gas (CH_4, C_2H_4 and C_2H_2) ratios in graphical presentation:

$$CH_4\% = \frac{100x}{x+y+z} \quad \text{for, } x = [CH_4] \text{ in ppm} \qquad (1)$$

$$C_2H_4\% = \frac{100y}{x+y+z} \quad \text{for, } y = [C_2H_4] \text{ in ppm} \qquad (2)$$

$$C_2H_2\% = \frac{100z}{x+y+z} \quad \text{for, } z = [C_2H_2] \text{ in ppm} \qquad (3)$$

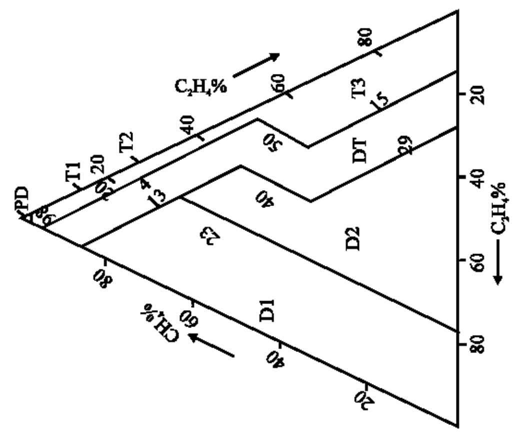

Fig. 3: Duval triangle

Key faults presented in Duval triangle (Table 2).

How to use Duval triangle?: There are two different procedures to use this Novel method:

- By using total accumulated gas
- By using total increase between conjugative samples

By the use of this method both the procedures indicate the same fault.

A procedure to use the Duval triangle: Graphical use of Duval triangle is very simple. Consider the three side of triangle in triangular coordinates (x, y and z) representing the relative proportion of CH_4, C_2H_4 and C_2H_2, from 0-100% for each gas.

To find the faults graphically (manual), first calculate the percentage of each gas as per Eq. 1-3. Then the draw the lines CH_4% quantity parallel to C_2H_2 line, C_2H_4% quantity parallel to CH_4 line and C_2H_2% quantity parallel to CH_4. Thus, drawn intersection of all three lines would indicate the fault for the GA results in the transformer.

Table 2: Key faults in Duval triangle

Faults	Limits of zones				
PD	98% CH_4	-	-	-	-
D1	23% C_2H_4	13% C_2H_2	-	-	-
D2	23% C_2H_4	13% C_2H_2	40% C_2H_4	29% C_2H_2	-
DT	40% C_2H_4	50% C_2H_4	04% C_2H_2	13% C_2H_2	15% C_2H_2
T1	04% C_2H_2	20% C_2H_4	-	-	-
T2	04% C_2H_2	10% C_2H_4	50% C_2H_4	-	-
T3	15% C_2H_2	50% C_2H_4	-	-	-

Table 3: Triangular coordinates for Duval triangle zones

Area	Points	CH_4 (%)	C_2H_4 (%)	C_2H_2 (%)
PD	PD1	98	2	00
	PD2	100	00	00
	PD3	98	00	2
D1	D11	0	0	100
	D12	0	23	77
	D13	64	23	13
	D14	87	00	13
D2	D21	00	23	77
	D22	0	71	29
	D23	31	40	29
	D24	47	40	13
	D25	64	23	13
DT	DT1	00	71	29
	DT2	00	85	15
	DT3	35	50	15
	DT4	46	50	4
	DT5	96	00	4
	DT6	87	00	13
	DT7	47	40	13
	DT8	31	40	29
T1	T11	76	20	4
	T12	80	20	00
	T13	98	2	00
	T14	98	00	2
	T15	96	00	4
T2	T21	46	50	4
	T22	50	50	00
	T23	80	20	00
	T24	76	20	4
T3	T31	00	85	15
	T32	00	100	00
	T33	50	50	00
	T34	35	50	15

For example, Fig. 4 indicates a fault and such verification of faults by Duval triangle (manual) DGA has been done (for >100 fault reported transformers).

These results were verified with DGA interpretation for total dissolved combustible gases by other procedures used by different utilities in India. Example: CH_4 = 56 ppm, C_2H_4 = 55 ppm and C_2H_2 = 43 ppm, manually calculated result D2 shown in Fig. 4.

Software implementation of Duval triangle DGA carried out for the same samples on MATLAB 7.4 and cross verified. Used software can be obtained on request. This software is developed with the knowledge of computer graphics and by fixing the points for fault zones coordinates (polygons) (Table 3). To define each polygon, the defined points are converted to Cartesian

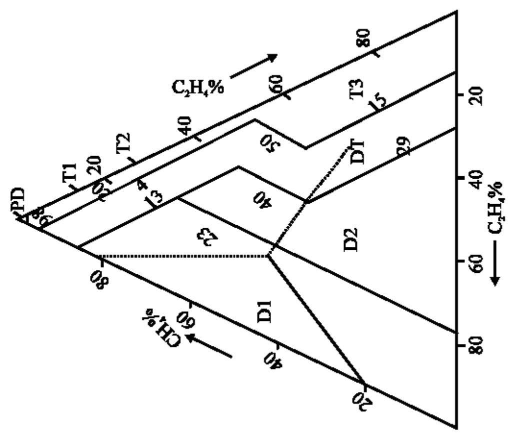

Fig. 4: Graphical analysis on Duval triangle responsible

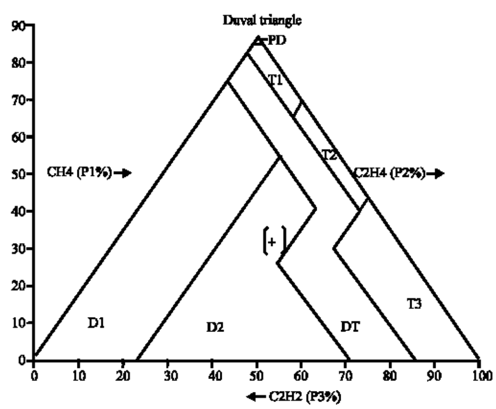

Fig. 5: Software analysis on MATLAB

coordinates (Duval, 2002) for percentage of gases for type of fault. Same example analysed by software on MATLAB-7.4 and provides the same result D2 in Fig. 5.

RESULTS AND DISCUSSION

In this study, manual and software implementations of Duval triangle for DGA provides the following results:

- Duval triangle method for DGA fault interpretations in power transformers is very simple (with three gases only) and consuming less time

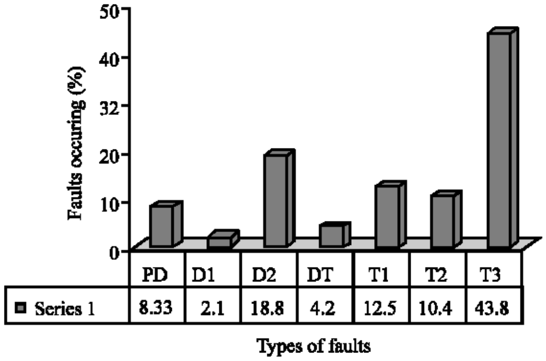

Fig. 6: Comparative fault analysis for power transformers (India)

- This method has satisfied the fault diagnosis (both manual and software implementation) >95% accurate than any other method of diagnostics
- Traces of one of the three gases can provide the quick fault diagnosis to a little experienced worker on the power transformers
- This method always provides a diagnosis with a very low percentage of wrong diagnosis
- Duval triangle representation also allows to follow graphically in a very easy way and the evaluation of faults with time visually
- Software can be easily developed with a small knowledge of computer graphics and any high level computer language (i.e., C, C++, Java, FOTRON, MATLABs, etc.)
- DGA fault diagnostics by different interpretation diagnostic tools (used by various organizations) proved that T3 is the maximum faults occurring in power transformers in the existing environmental conditions and service procedures followed in India

A comparative chart from DGA fault reports is given in Fig. 6.

CONCLUSION

The results show that Duval triangle interpretation is a robust technique and does not require much expertise. Software implementation for Duval triangle can be done on the computer with many high level languages. Also, it is found from existing fault diagnostics tools for Indian conditions, the maximum fault occurring is T3 (44%).

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