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Software Implementation of Duval Triangle Technique for DGA in Power Transformers

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Abstract

Fault diagnosis of power transformers have always drawn the attention among the users, without removing the transformers from the service. Thus it is necessary to detect the incipient fault of a power transformer at an early stage and diagnose properly on optimum way. Dissolved gas analyses (DGA) is widely used to detect incipient faults in oil filled power transformers. Throughout the world, different countries/utilities are using different techniques/tools to diagnose the faults; such as Key gas ratio, Roger's gas ratio and Doernenburg gas ratio and Duval Triangle methods, etc. Also different international/national standards are adopted subjected to country's tropical conditions; ie C.E.G.B. (Central Electricity Generating Board, UK), IEC and IEEE ratio codes and IS standards. Different transformer oil sampling standard practices/procedures are used to minimise the errors and contamination during the whole process of sampling, transportation, preservation and gas extractions at suitable conditions. In this paper, authors have found that Duval Triangle methods' software implementation (in MATLABs) for fault interpretations can provide total solution for any kind of fault exist in the power transformers. The whole Duval triangle interpretations are applied on merely three gases methane (CH_4), ethane (C_2H_4) and acetylene (C_2H_2) after collecting through chromatography. Also for cross verification purposes Duval Triangle's manual (graphical) interpretation is applied. The results show that Duval Triangle interpretation is a robust and optimum technique and does not require much expertise. Software implementation of Duval Triangle also cross verified with other high level languages to emphasise its supremacy.

Keywords: Dissolved Gas Analysis (DGA), Power Transformer, Fault Diagnosis, Total Dissolved Combustible Gases (TDCG), MATLABs.

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 efficiency of a transformer. Thus, it is important to be aware of possible faults those may occur. It is equally important to know how to detect them early. Regular monitoring and their repair/maintenance can make it possible to have flawless electric supply to avoid the catastrophic damage.

Formation of Gases in Transformer Oil [17]

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. Various gases are formed inside an oil-filled power transformer. Gases formation begins at specific temperatures [4] shown in Figure 1. Hydrogen and methane begin to form in small amounts around 150 °C. Notice from the Figure 1 that 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 °C 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 of small amounts of acetylene (a few ppm). Larger amounts of acetylene can only be produced above 700 °C by internal arcing. Notice that between 200 °C 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 °C to 800 °C; then more acetylene is produced. It should 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 more than 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.

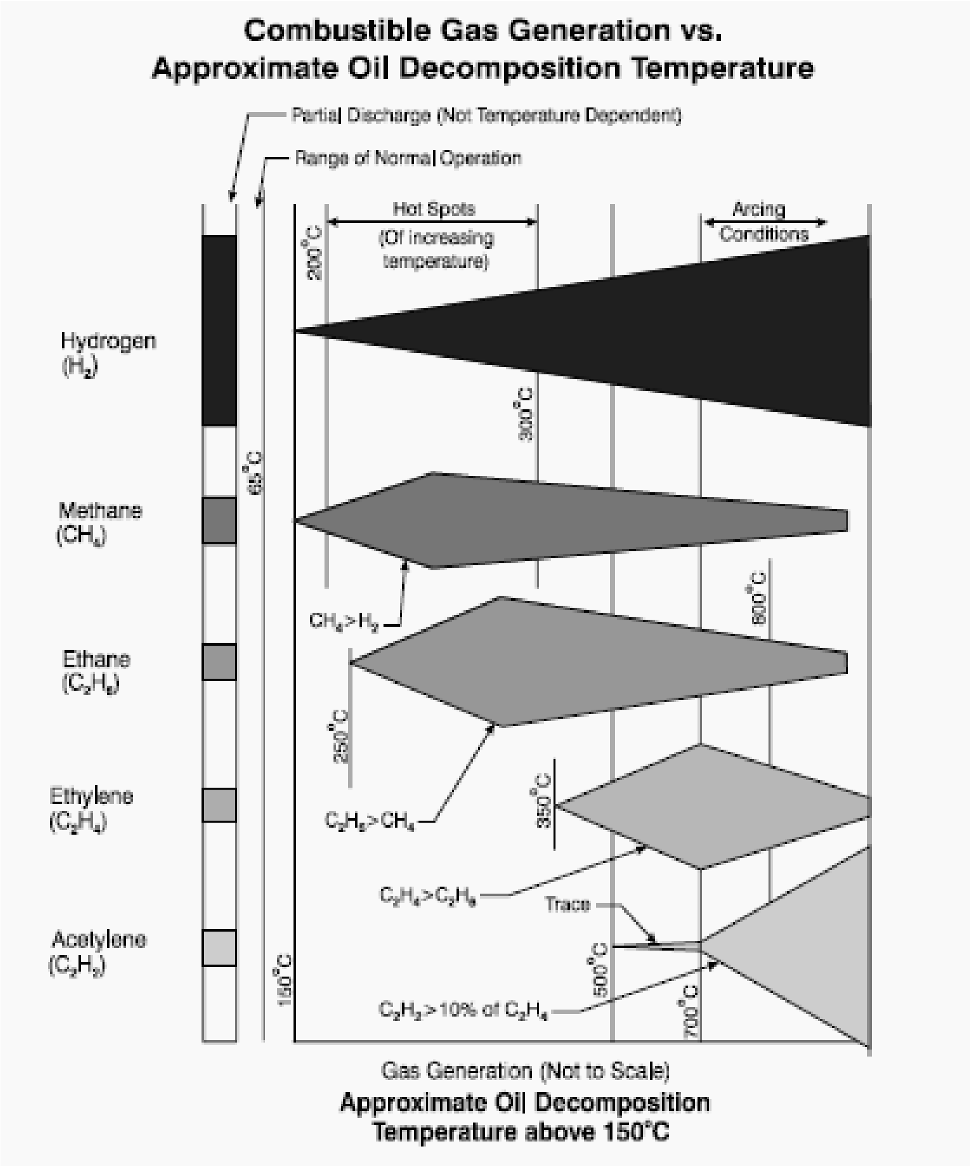

Figure 1: Gas generation chart.

The solubilities of the fault gases in Transformer oil [5] 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 generally 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. Over a temperature range of 0-80^{o}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 transformer is long chain of complex mixture of hydrocarbon compounds. The degradation of insulating hydrocarbon compounds produces smaller molecular size compounds, many of these compounds are gasses. The gases so produced get dissolved into the oil. 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:

1. Advance warning of developing faults
2. Determining warning of the improper use of units
3. Status checks on new and repaired units
4. Convenient scheduling of repairs
5. Monitoring of units under over load.
6. 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 concentration, increments, rates of change of gas concentrations, or ratios that exceed standard limits. Thus short interpretive remarks and recommendations become proper fault diagnosis.

The main interpretation methods in fault diagnosis of power transformers through DGA are:

- The IEC-60599, 2008
- The IEEE Methods (Doernenburg , Roger's and Key gas methods)
- The Duval Triangle
- The IS: 10593 (2006) & IS: 9434 (1992) (Bureau of Indian Standards)

It also needs proper sampling procedures and can be referred from:

- Doble Reference Book on Insulating Liquids and Gases.
- 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 (Third Revision).

Key Faults in power transformers [1], [2] are given in Duval Triangle 1
For Duval triangle 1 method faul**t** interpretation are shown in table -1.

Table 1

Symbol	Fault	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).

Duval Triangles in Dissolved Gas Analyses

Duval Triangle method [6]-[11] shown in figure.3 developed empirically in early 1970s and is used by IEC [2]. 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. More than 100 sample test reports were collected from different utilities in INDIA. Out of those reports, with abnormal gas formations and interpreted faults [1]-[3] are separated with suggested remedial actions.

The three sides of the Triangle are expressed in triangular coordinates (X, Y, Z) representing the relative proportions of CH_4, C_2H_4 and C_2H_2, from 0% to 100% for each gas. In order to display a DGA result in the Duval Triangle as shown in Figure 2 , one must start with the concentrations of the three gases, (CH_4) = A, (C_2H_4) = B and (C_2H_2) = C, in ppm. The Dissolved gas analysis by Duval triangle involves percentage of gas (CH_4, C_2H_4 and C_2H_2) ratios in graphical presentation. Where,

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

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

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

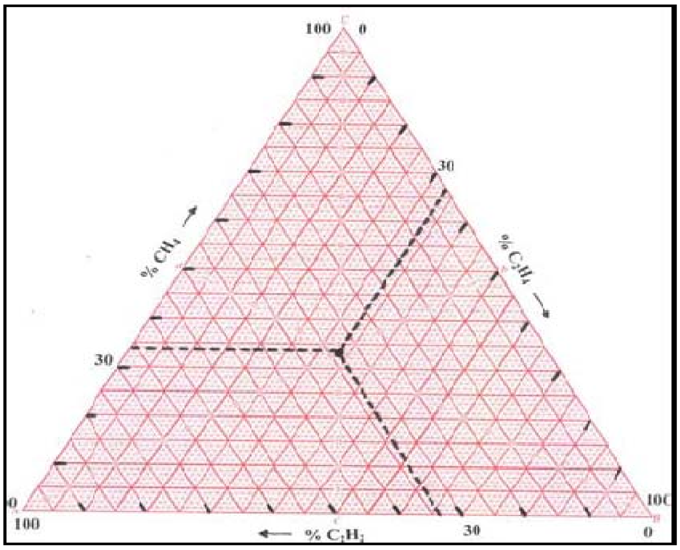

Figure 2: Duval Triangle Graphical Plot.

First calculate the sum of these three values: (CH_4 + C_2H_4 + C_2H_2) = S, in ppm, then, calculate the relative proportion of the three gases, in %:

X = % CH_4 = 100 (A/S), Y = % C_2H_4 = 100 (B/S), Z = % C_2H_2 = 100 (C/S).

X, Y and Z are necessarily between 0 and 100%, and (X + Y + Z) should always = 100 %.

Use of Duval Triangle

There are two different procedures to use DTMs are as follows;

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

By the use of DTMs above procedures indicate the same fault.

Graphical fault interpretation

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% to 100% for each gas. Numerical boundary zones for 7 key faults are shown in Table 2. To find the faults graphically (manual), first calculate the percentage of each gas as per above equations (1)-(3). Then 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 on the specially supplied graphical sheets. Thus drawn intersection of all three lines would indicate the fault responsible for the DGA results in the transformer. Such verification of faults by Duval Triangle (manual) DGA has been done (for more than 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=56ppm, C_2H_4=55ppm and C_2H_2=43ppm, manually calculated result D2 displayed in Figure 3**.**

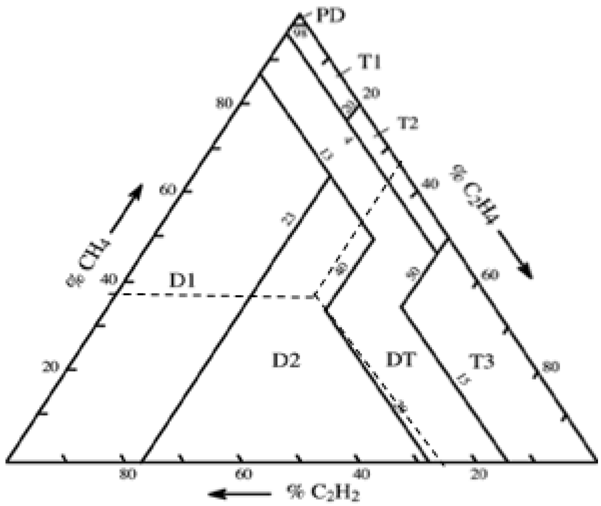

Figure 3: Graphical analyses on Duval Triangle 1.

Software based fault interpretations:

Following steps are used for fault interpretations

Step 1: In this research work, firstly, polygon coordinates for the numerical zone boundaries of seven key faults of Duval Triangle1 have been generated in terms of percentages of CH_4, C_2H_4 and C_2H_2, from 0% to 100% respectively shown in Table 2.

Table 2: Triangular coordinates for Duval Triangle 1 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

Step 2: A flow-chart for software development of Duval triangle 1 on MATLAB is developed and shown in Figure 4. Software implementation of Duval triangle 1carried out for all the samples on MATLABs 7.4 and cross verified. To define each polygon, the defined points are converted to Cartesian coordinates for percentage of gases for type of fault. Same report as analysed manually has been analysed by software on MATLAB-7.4 and provides the same result D2 in Figure 5. All the comparative fault analysis between manual and software implementation of Duval triangle 1 along with the fault analysis with other diagnostic techniques (faults analyzed by the respective authorities and utilities) are prepared and a comparative study carried out for this research.

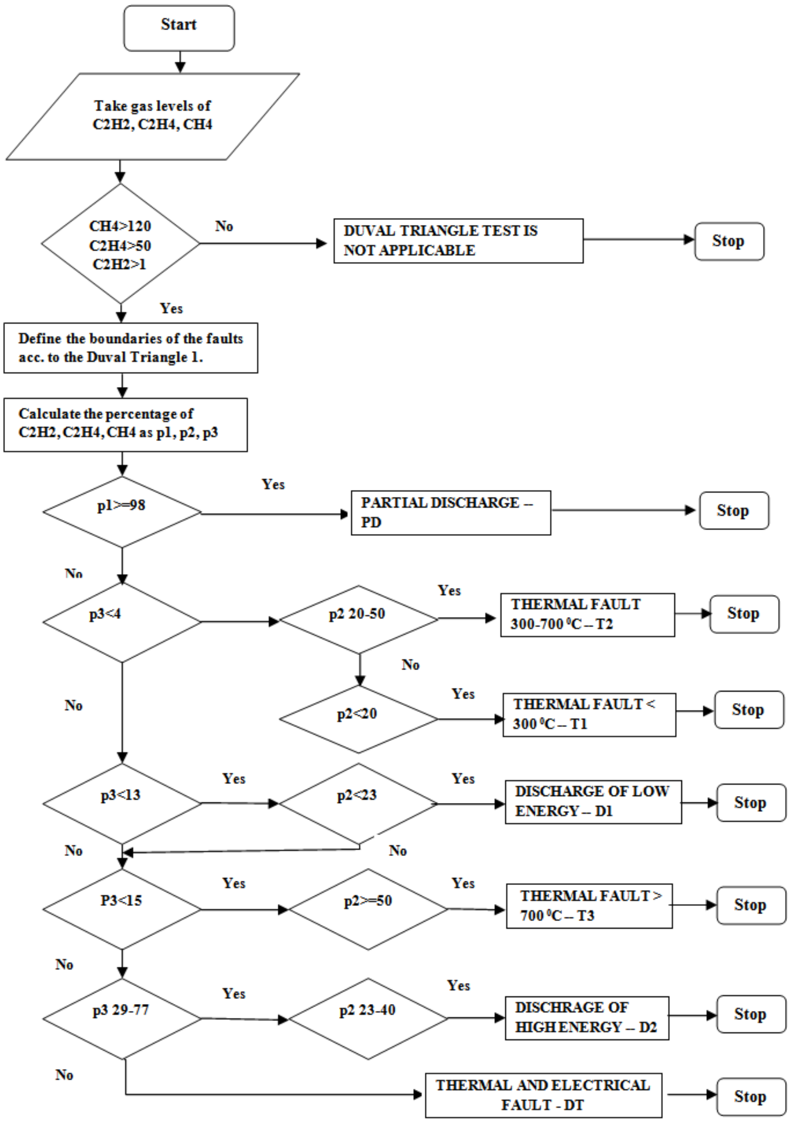

Figure 4: Flow-chart of Duval triangle 1.

Step3: Software Development in MATLAB

a. To develop this software, from the numerical zone boudaries of Duval Triangle 1 two dimentional cartecian coordinates are fixed for Duval triangle key faults using simple trignometry in a equivilateral ABC triangle in X-Y plane. Considering vertex A (0,0) meeting point of CH_4 and C_2H_2 in Duval triangle. Taking each side (L) of the triangle is divided in100% of the gas as shown in Duval triangle 1.

b. To mark any point in the triangle, such as to calculate cartecian coordinate of point R(Rx, Ry) which are obtained from the fractions of the the gases CH_4, C_2H_4 and C_2H_4 the points are calculated as below given equations:

$$Ry = 0 + CH_4 * \cos 30^0 \quad (4)$$

$$Rx = 0 + (C_2H_4 + CH_4 * 0.5) \quad (5)$$

Keeping in view that all the length of sides of the triangle are equal.

c. Software is developed according to equations (4)-(5) in MATLAB according logic to Flow–chart is given in Figure 4 above and data entered as shown below:

enter the value of Methane=56

enter the value of Ethylene=55

enter the value of Acetylene=43

"Duval Triangle Test is Applicable"
""""""DUVAL TRIANGLE RESULTS"""
MIXTURE OF THERMAL & ELECTRICAL FAULTS -- DT

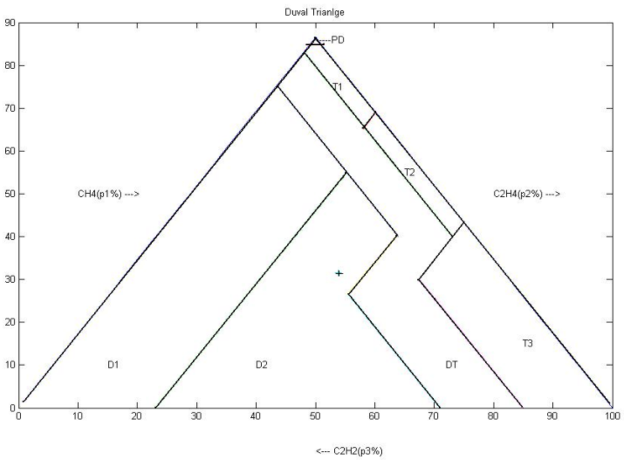

Figure 5: Duval Triangle Software analyses using MATLAB.

Conclusions

The software implementation for Duval triangle techniques on MATLAB have satisfied all the fault diagnoses on the collected samples and produced more accurate results. Even the traces of one of the three gases can interpret some of the faults to detect at early stage. There are rare chances of wrong fault diagnosis. This software tool found to be optimum by the authors in terms of time taken, simplicity, accuracy compare to other conventional diagnostic tools. Thus in this paper, it emphasises that manual and software implementations to interpret the faults in power transformers by Duval Triangle method for DGA provide the best results. Software can be easily developed with the knowledge of computer graphics and any other high level computer language (ie. C, C++, Java, FOTRON, MATLABs, etc).

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Sukhbir Singh received degree in Electrical Engineering in 1987 and his Master of Engineering (C&I) in 1993 (Delhi College of Engineering, Delhi, (D.U.)). Continuing Ph D. research work from NIT Kurukshetra, INDIA on a topic “Fault Diagnosis on Power Transformer” since August 2006. He has worked in Indian Air Force as a combatant member for long 15 years in the engineering field and since 1993 onwards in teaching in India and abroad. He also has an interest in Fuzzy and Nuero systems.

Dr. Dheeraj Joshi received M. Tech. (Gold Medalist) from IIT Roorkee, India and Ph. D. from NIT Kurukshetra, India. He has been teaching UG and PG students various subjects at NIT Kurukshetra and other places for last 10 years in electrical engineering departments. He has published number of research papers in international and national journals/conferences. He holds the life memberships of many professional bodies and has the research interest in the areas: Induction Generators, Nonconventional Energy Sources, Artificial Intelligence and Optimization.

Dr. M. N. Banddhyopadhyay received his Ph.D. from Jadhavpur University, Kolkatta, in 1976. He has more than 40 years of experience in industry, research and teaching. He has visited various countries in the world for his research papers presentations and other assignments. He has authored many books in the disciplines of Electrical and Electronics Engineering. He has received various prizes and prestigious awards like “Socrates International Award” for his contributions.