Design of Online Condition Assessment of Transformer Oil for Incipient Fault Detection

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Abstract — *Different causes and conditions lead to the transformer failure but it is found that the main cause of transformer failure is the damage occurring in insulating oil and paper. Hence to achieve long life of transformer, health monitoring of insulating oil and paper frequently at least on monthly basis is necessary. Condition monitoring increases the transformer life and reliability by making proactive decisions in case of any failures. Also condition monitoring reduces the maintenance cost of the system. Oil of transformer serves as both coolant as well as insulator. Electrical and thermal stresses lead to the degradation of the transformer oil & affect the electrical, chemical and physical properties of the oil. Deterioration of insulating oil and paper leads to the production of gases which gradually get dissolved in oil. The failure in transformers is due to deterioration of insulation overtime. If these failures can be predicted with some degree of confidence, sudden failures and interruption in power supply can be minimized. In this paper various techniques for online condition monitoring of oil and incipient faults detection from the various dissolved gases concentration has been developed. Software implementation of Key gas method, Roger's Ratio method, National Standard method and Duvel's Triangle method is done for the various incipient faults detection.*

Keywords — *Transformer, Key Gas, Roger's Ratio, Duvel's Triangle.*

I INTRODUCTION

Transformer is the most important utility in the power system for the transmission & distribution of electric power to the consumers. Moreover it is one of the critical and costly parts of the whole Power grid, but like all other electrical machines, it has too limited life .Different causes and conditions results in transformer failure but after a lot of survey and analysis it has been found that insulation failure damage the transformer mostly. In dry type transformers generally varnish is used as an insulator. Unimpregnated paper or cloth is used as an insulator in large type transformers to improve the heat transfer characteristic, and the whole assembly of core and windings is poured in the oil tank. The transformer oil serves two purposes.. It has both the properties of an insulator and coolant. The porous insulation surrounding the conductor aids the oil to reach the conductor surface and extract the heat. Insulation used between the windings is annular bakelite the oil to be used as an insulator should be free from moisture or other contamination. Under the influence of high electrical and thermal stresses, oil gets decomposed into some gases which gradually get dissolved in the oil. These gases are known as key gases. The quantity of key gases concentration can help in the identification of various faults.

II PRODUCTION OF GASES IN OIL

High thermal and electrical stresses on transformer oil leads to the breaking of chemical bonds between the atoms that make up the hydrocarbons molecules in the oil. The deterioration of oil and paper under various stresses leads the formation of gases which will gradually dissolve in the oil completely or partially with time [1]. The combustible gases are formed in large quantities due to undesirable faults occurring inside the transformer. These gases formed inside the transformer termed as Key Gases. Several key gases are generated in the transformer oil including Hydrogen (H_2), Methane (CH_4), Ethane (C_2H_6), Ethylene (C_2H_4), Acetylene (C_2H_2), Carbon Dioxide (CO_2) and Carbon Monoxide (CO) There are two kinds of molecular bonds exists between the gases ,one is between carbon and hydrogen atoms and other is between carbon atoms. The energy required to break or create the molecular bonds is different. The energy and temperature required creating or break the bond between same atoms (C-C) is greater than the energy and temperature required for different atoms C-H).Also energy required to make or break triple bonds greater than double and single bonds. Concentration of gases in the oil can detect many incipient faults in the transformer. Normal values of dissolved gases indicate no internal faults but when the concentration of dissolved gases goes beyond the normal limits indicates some incipient faults. The table for the different gases limits is derived from the information provided within ANSI/IEEE C57.104 [2]. Concentration of all the gases is given in ppm level.

TABLE I
Normal and Action limit of Dissolved gases [3]

	H_2	CH_4	C_2H_4	C_2H_2	C_2H_6	CO_2	CO
Normal Limit	150	25	20	15	10	10000	500
Action Limit	1000	80	150	70	55	15000	1000

III. TYPES OF FAULTS DETECTABLE BY INCEPTION OF GASES

Identification of transformer oil gases concentration is the best tool for indicating various types of faults in the transformer. There are various types of internal faults occurred in the transformer.

A. Partial Discharge

The localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress is knows as partial discharge. This type electric breakdown does not bridge the space between two conductors and not visible whereas corona discharges is usually related to a steady glow or brush discharge in air. Partial discharges in an insulating material are generally starts with gas-filled voids within the dielectric. Partial Discharges in transformer oil leads to hydrocarbon cracking. It generates large amount of hydrogen and free radicals.

B. Discharges of Low Energy (D1)

This type of discharges of low energy usually occurs in gas filled voids surrounded by oil. It leads to the carbonization of insulating paper and oil in the transformer .It produces small amount of carbon particles in oil and creates voids in paper insulation.

C. Discharges of High Energy (D2)

The discharges of high energy in the insulting paper and oil in the transformer leads to the high damage to paper or large formation of carbon particles in oil, metal fusion, tripping of equipment and gas alarm.

D. Thermal Fault (T1)

With the increase in temperature, the formation of the degradation gases also increases. The gases changes from methane (CH_4) to ethane (C_2H_6) to ethylene (C_2H_4).Faults which occur at temperature less than 300^{o}Ccategorized as thermal fault, T1.These type of faults can be noticed with change in color of paper. The paper generally turns into brown color and also gets carbonized.

E. Thermal Fault (T2)

Faults which occur at temperature greater than 300^{O}C but less than 700^{O}C are categorized as thermal fault, T2.High temperature results in generation of carbon particles in both paper and oil. Higher temperatures (>300deg/C) leads to the production of more ethylene. The production of ethylene increases with the increase in temperature.

F. Thermal Fault (T3)

Faults which occur at temperature greater than 700^{o}C are categorized as thermal faults T3 .These leads to the generation of excess carbon particles in insulating paper and oil.

G. Thermal and Electrical Fault (DT)

Sometimes both electrical and thermal faults occurs inside the transformers. These faults accelerate the degradation of oil and paper.

IV FAULT DETECTION METHODS

At initial stage generally low energy faults at low temperature occur but failure of early detection of the faults leads to the conversion of low energy faults into high energy serious faults. The detection of the faults at the early stage can prevent the transformer from getting shut down from the service. If we are able to find out the trend of rate of increase in individual gases and the faults, information about the health of transformer can be collected. Different methods such as Key gas method, ratio method and Duvel's triangle method can be implemented for the detection of faults based on the concentration of gases.

A. The Duvel's Triangle

Michel Duval of IREQ have developed the Duval's Triangle diagnostic method for oil insulated high-voltage transformers in 1974 [11].In this method triangular coordinate system is used. The triangular chart is subdivided into fault zones. The three sides of triangular chart represents concentrations of %CH_4, %C_2H_4, %C_2H_2in ppm to the percentages of total(CH_4 + C_2H_4 + C_2H_2) respectively. The intersections of three line parallel to the adjacent axis gives a point in the triangle. The triangle is divided into various fault zones. The location of the point in a specific fault zone represents the fault type. When the gas concentrations are well above the detection limit concentrations, DGA diagnostic methods, including the Duval Triangle, should be applied. It is advisable to subtract out the background concentrations, if stable concentrations of the gases were present before the commencement of the various incipient faults. The recently formed gases should be considered for the analysis through Duvel's triangle. Misleading results can be found if we are including pre-fault gas in the diagnostic calculations .Almost all the incipient faults such as Partial Discharge (PD), Low range thermal fault (T1) (T1<300^{O}c), Medium range thermal fault (T2) (300^{o}C<T2<700^{o}C,) High range thermal fault (T3) (>700^{O}c), Low energy electrical discharge (D1,) High energy electrical discharge and intermediate electrical and thermal faults can be determined through Duvel's triangle method.

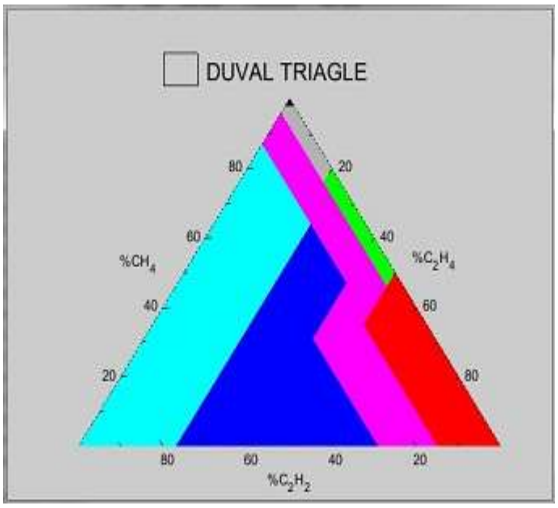

Fig. 1 The Duvel's triangle

B. Key Gas Method

The gases generated in the transformer oil are known as key gases. In the key gas method, faults can be determined based on which gas is present in high quantity. The gas present in high percentage will indicate specific faults.

TABLE II
Fault Indicator Gases [7]

Gas detected	Fault detected
H_2	Corona effect arcing, overheated oil
CH_4	Arcing, serious overheated oil
C_2H_6	Thermal faults like corona & overheated oil
C_2H_4	Thermal fault, local or overheated oil, corona & arcing
C_2H_2	Electric fault like corona & sparking, severely overheated oil
CO	Overheated cellulose decomposition arcing if fault involves cellulose
CO_2	Cellulose decomposition
O_2 & N_2	Indicator of system leaks over pressurization or changes in temperature

C. Ratios Method or Basic Gas Ratio Method

The International Electro Technical Commission (IEC) Standard recognized this basic gas ratio method. Three ratios of gases are used for the detection of faults. In key gas method single gas present in high percentage determines the faults.

Whereas in ratio method three ratios of gases will be considered for the fault detection. The three gas ratios are acetylene/ethylene, ethylene/ethane and methane/hydrogen.

TABLE III
IEC Gas Ratio Table [1]

Characteristics Faults	C_2H_2 / C_2H_4	C_2H_2 / C_2H_6	CH_4 / H_2
Partial discharges (PD)	NS	<0.2	<0.1
Discharges of low energy (D1)	>1	>1	0.1 – 0.5
Discharges of high energy (D2)	0.6 – 2.5	>2	0.1 – 1.0
Thermal fault (T1) (T < 300 °C)	NS	<1	>1
Thermal fault (T2) (300 °C T < 700 °C)	<0.1	<1	>1
Thermal fault (T3) (T > 700 °C)	<0.2	>4	>1

NS No Significance

The ratio CO_2/CO indicates thermal decomposition of paper. The ratio CO_2/CO should be greater than 7 for normal operation as the rate of production of carbon dioxide is 7 to 8 times greater than carbon monoxide. In case the ratio goes below or equal to 5 there must be some problem occurring in the cellulose. It indicates that severe thermal deterioration of cellulose.

V HARDWARE DESCRIPTION

Fig. 2 Transmitter section

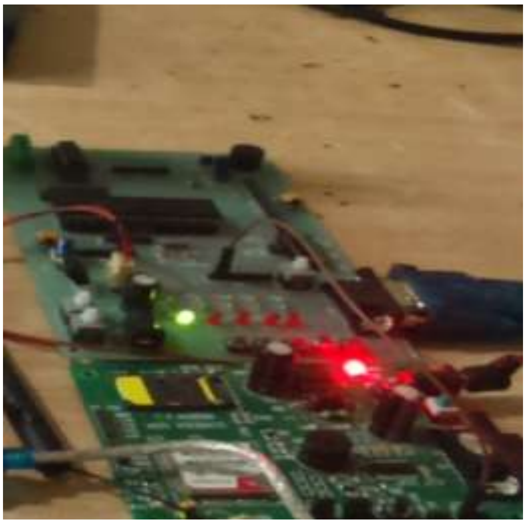

Fig. 3 Receiver section

A. ATMEGA16 Microcontroller

The ATmega16 microcontroller is used in this design. It consist of 512 bytes EEPROM ,On-chip debugging support and programming, 16 Kbytes of in-system programmable flash program memory with Read-While-Write capabilities, three flexible Timer/Counters with compare modes, , 1 Kbyte SRAM, a JTAG interface for Boundary scan, a byte oriented
two-wire serial interface ,32general purpose I/O lines, 32 general purpose working registers, Internal and External Interrupts, a serial programmable USART, an SPI serial port , an 8-channel 10-bit ADC with optional differential input stage with programmable gain, a programmable watchdog timer with internal oscillator, and six software selectable power saving modes. The AVR core consists of a rich instruction set with 32 general purpose working registers. All the 32 registers are directly connected to the Arithmetic Logic Unit (ALU).It permits two independent registers to be accessed in one single instruction executed in one clock cycle. The resulting architecture achieves throughputs up to ten times faster than conventional CISC microcontrollers and is more code efficient. Atmel's high density non-volatile memory technology is used for the manufacture of the device. The allows The program memory is reprogrammed in-system through an SPI serial interface with the help of On chip ISP Flash and a conventional non-volatile memory programmer, or by an On-chip Boot program running on the AVR core. The Atmel ATmega16 provides a highly-flexible and cost-effective solution to many embedded control applications. The ATmega16 AVR is supported with a full suite of program and system development tools including: C compilers macro assemblers, program debugger/simulators, in-circuit emulators, and evaluation kits.

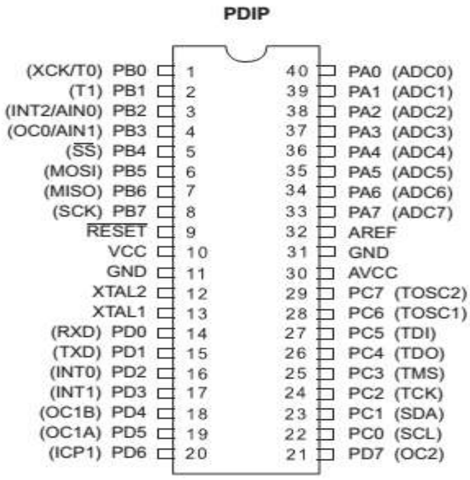

Fig. 4 Pin Diagram of ATMEGA16

B. Temperature Sensor

The temperature sensor used in this work is LM35.The output voltage of LM35 series are directly related to the Celsius temperature. They are also known as precision integrated-circuit temperature sensors as the user is not required to subtract a large constant voltage from its output to obtain the respective Centigrade scaling. Output impedance of LM35 is low, output voltage is linear, and precise inherent calibration makes interfacing to readout or control circuitry especially easy. LM35 sensors also finds their application in single power supplies and plus and minus supplies. 60 µA current is drawn by LM35 from its supply, which is really very low value. Self-heating is nearly less than 0.1°C in still air, which is very low. -55° to +150°C is the operating temperature range of LM35.

C. MQ-5 Gas Sensors

The main composition of MQ-5 Gas sensor consist of micro ceramic tube made up of AL_2O_3,a sensitive layer composed of tin dioxide, measuring electrode and a heater made up of plastic and stainless steel net are fixed into a crust. The main function of heater is to provide necessary work conditions for the smooth working of sensitive components. The enveloped MQ-5 gas sensor consists of total 6 pins. 4 pins them are used to fetch signals and 2 pins are used for providing heating current. Resistance of MQ-5 gas sensor is different to various types and various concentration gases. Sensitivity adjustment is very necessary when we are using these components. Calibration of the detector for 1000ppm of H_2 or LPG concentration in air is done usually. Load resistance (RL) is of about 20 KΩ (10KΩ to 47KΩ). The proper alarm condition for the gas detector should be determined after taken into account the temperature and humidity interference.

D. NCP-180 Acetylene Gas Sensors

The Nemoto NCP-180-A is a special application acetylene gas sensor. This is a catalytic (pellistor) gas sensor which is supplied as a matched pair of elements embedded on aTO4 size headers. These are flammable in nature. A metal can is provided in order to protect the gas sensor. The sensor is used for the detection of acetylene in air in the range of 0-100%.The main disadvantage of the pellistors used for monitoring acetylene levels is that they face technical problems due to acetylene's ability to poison catalytic gas sensors, which results in reduced sensor lifetime. This drawback is eliminated in the NCP-180-A pellistor, which does not get poisoned by acetylene, and operates reliably in this application. The device is highly compatible with a wide range of gas detection Systems available on commercial scale. They are also compatible with remote flammable gas detection heads.

E. CO1224T Carbon Monoxide Detector

Carbon monoxide detector is an electrochemical sensing cell which is used to provide early warning of dangerous CO levels. They are highly reliable and accurate. The detector is composed of a sounder and a trouble relay. The detector base is of such type that it can be directly mount to a wall or it can be mount to a single gang electrical box. Dual color LED indication is used to indicate the normal standby, alarm and end of life. When the sensor is found to be in some trouble condition, the detector will send a trouble signal to the panel. When a trouble or end of life signal is given by the detector, it should be replaced by a fresh one immediately.

F. Power Supply

It is an electronic device which supplies electrical energy to electrical load. In this work, dc power supply as battery is used as power source for all components. Regulated power supply is used as an input circuit supply. The 230V ac supply is first step down with the help of step down transformer to 12V and is then it is fed to a rectifier. The output obtained from the rectifier gives an output dc voltage of pulsating nature. The pulsating output voltage of rectifier is fed to a filter to remove any ac components present even after rectification and to get a pure dc voltage. Pure constant dc voltage is obtained after passing the voltage through voltage regulator. In this work a voltage regulator IC 7805 is used with 12 V battery to give power supply of 5 V which is required by the microcontroller.

VI CIRCUIT DIAGRAM

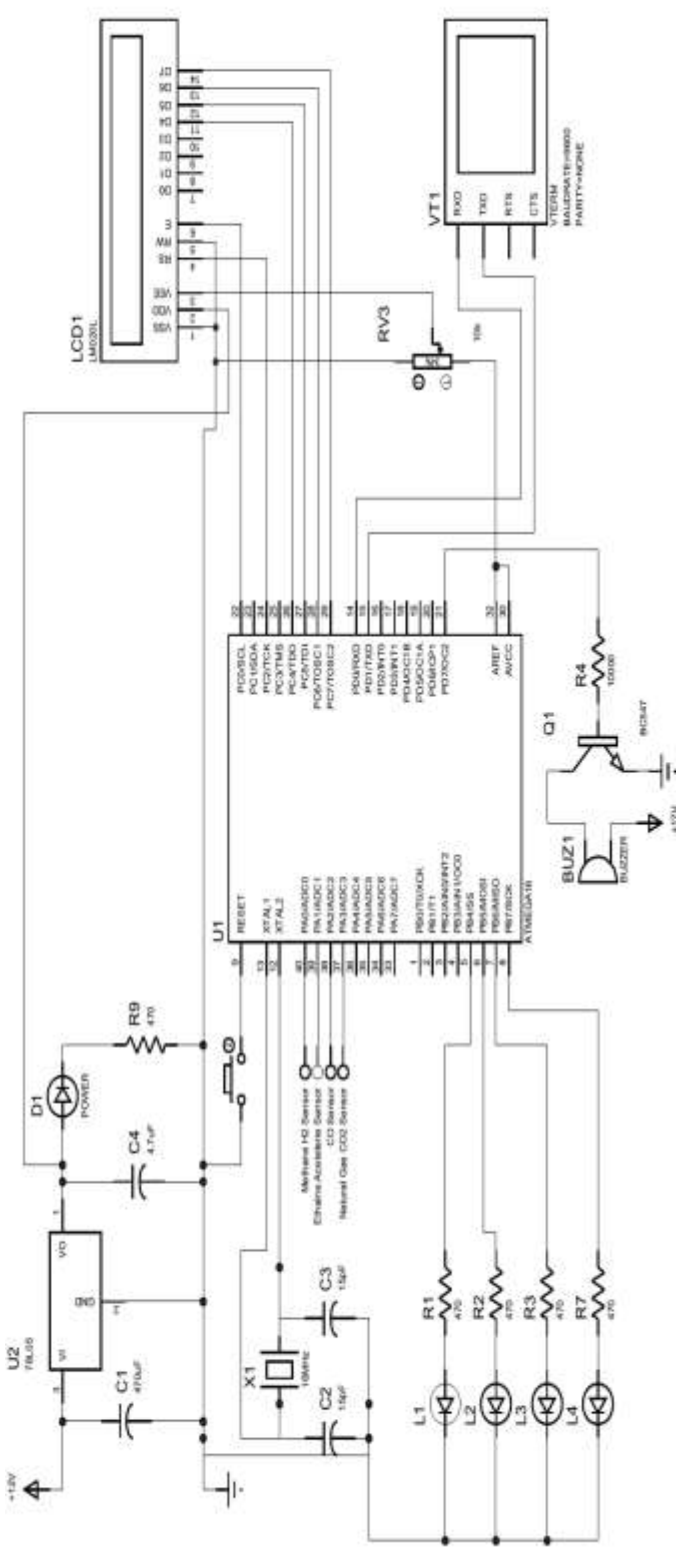

Fig. 5 Circuit diagram of design of online condition assessment of transformer oil.

VII RESULTS

A. MATLAB GUI

The above MATLAB GUI shows the Key gases concentrations dissolved in oil in ppm. The values are monitored by engineers at regular basis. No faults takes place if the gases are in normal limits but if the gases goes beyond the normal limits they leads to serious incipient faults. So if the concentration of gases is higher, then faults will be detected by using various methods. If the faults are predicted successfully at very early stage, insulation life and hence transformer age can be increased.

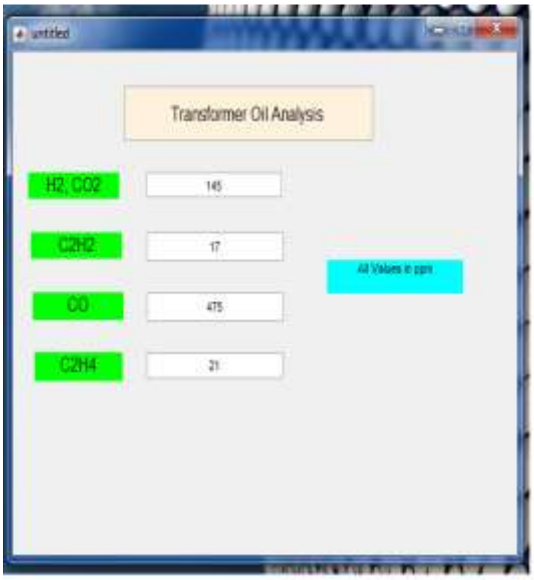

Fig. 6 MATLAB GUI showing concentration of gases in ppm.

B. Key Gas Method

Following figure shows the detection of the incipient faults in the transformer according to the Key Gas Method.

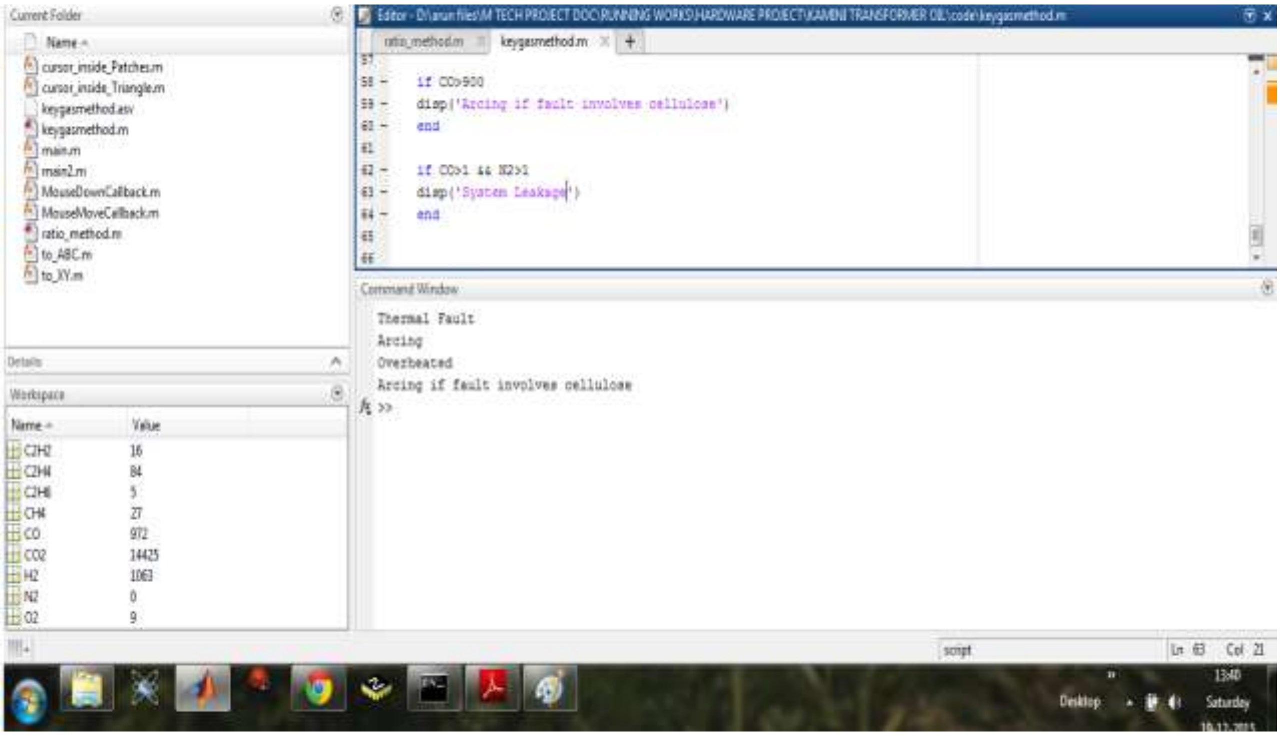

Fig. 7 Fault detection according to key gas method.

C. Ratio Method

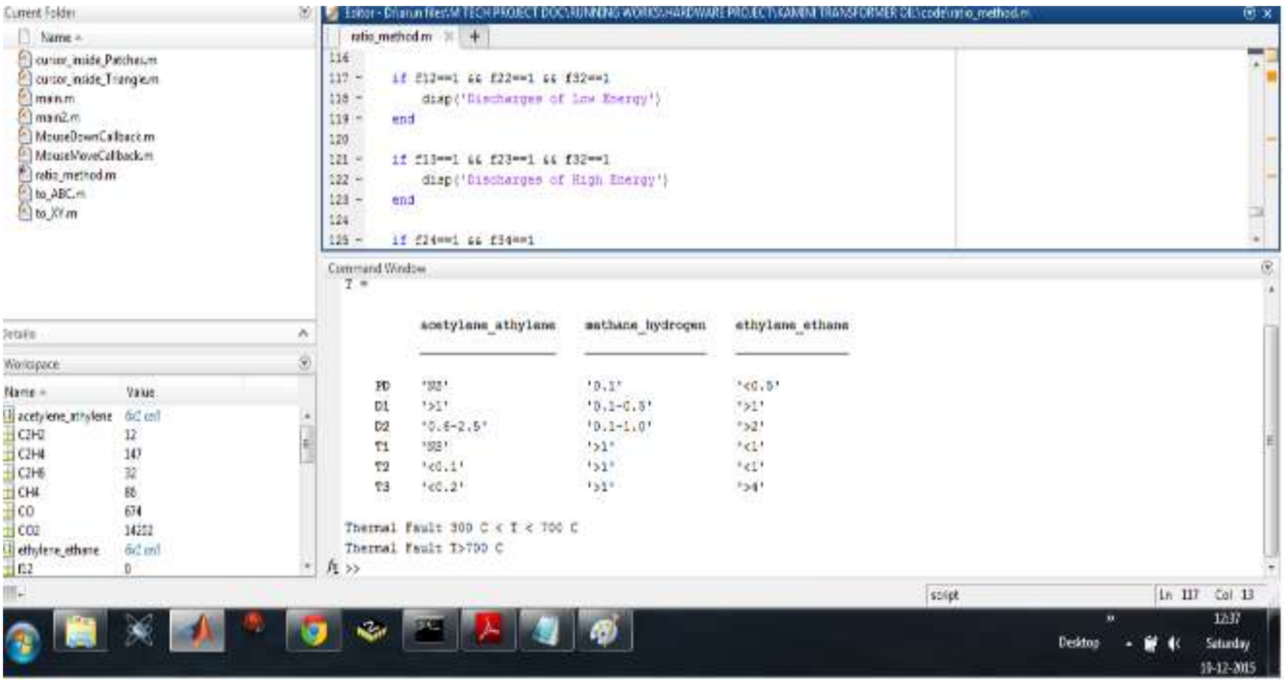

Fig. 8 Fault detection according to ratio method

D. Duvel's Triangle

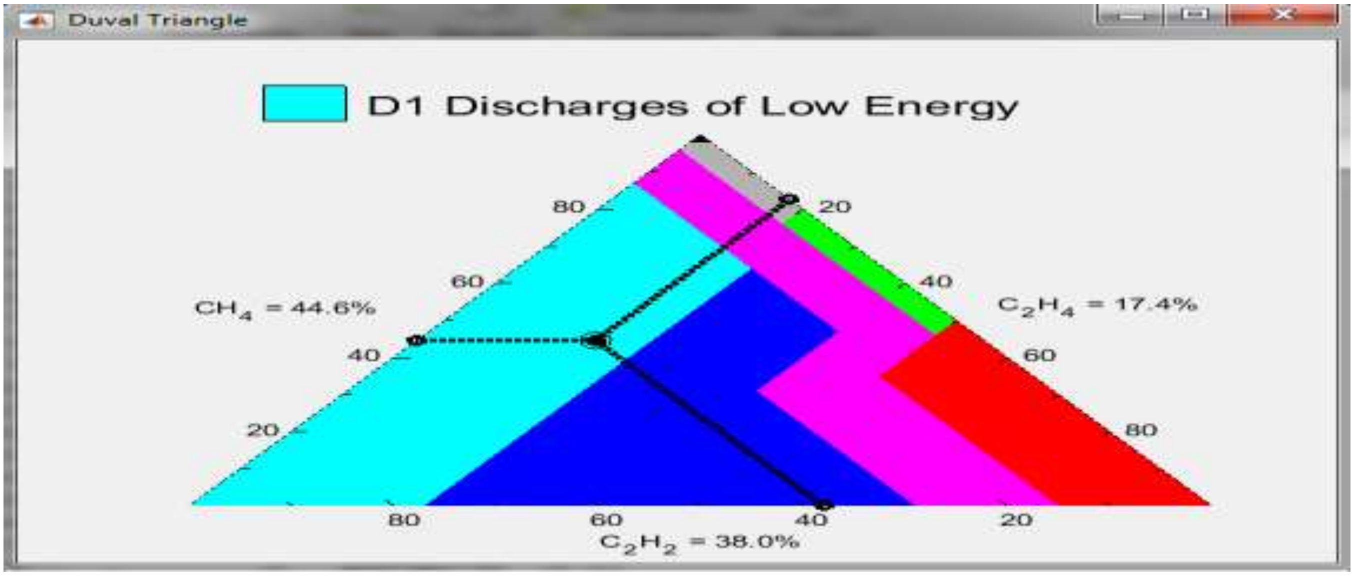

Fig. 9 Discharges of low energy fault detection by Duvel's triangle

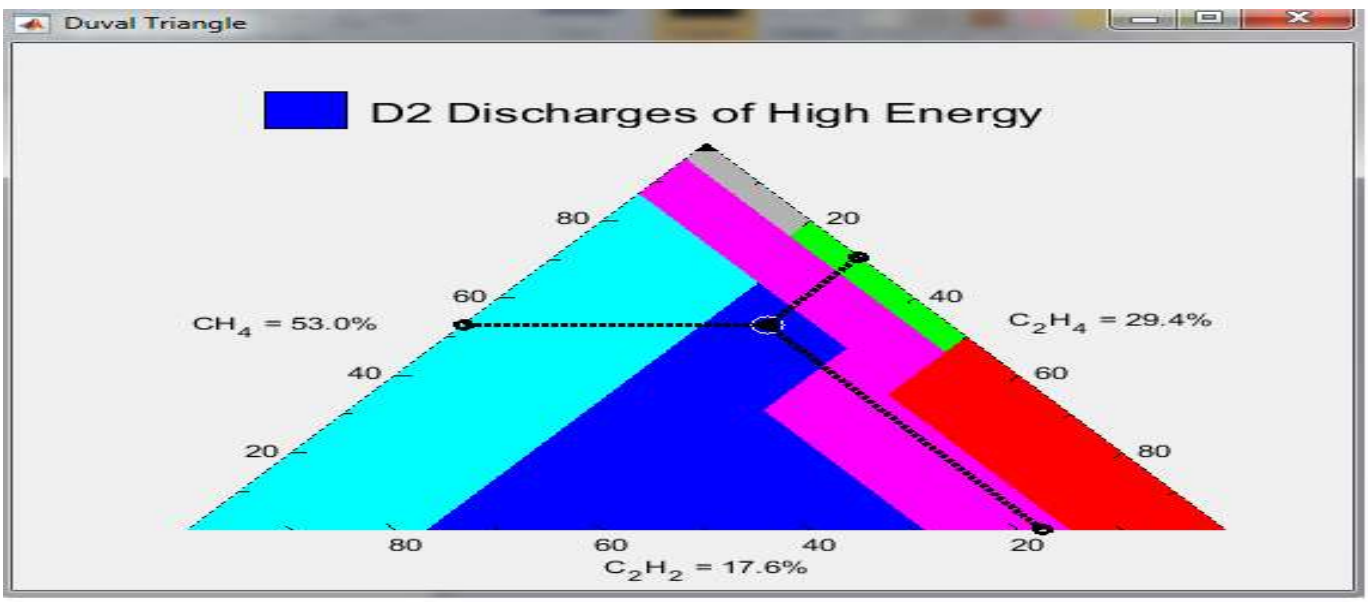

Fig. 10 Discharges of high energy fault detection by Duvel's triangle

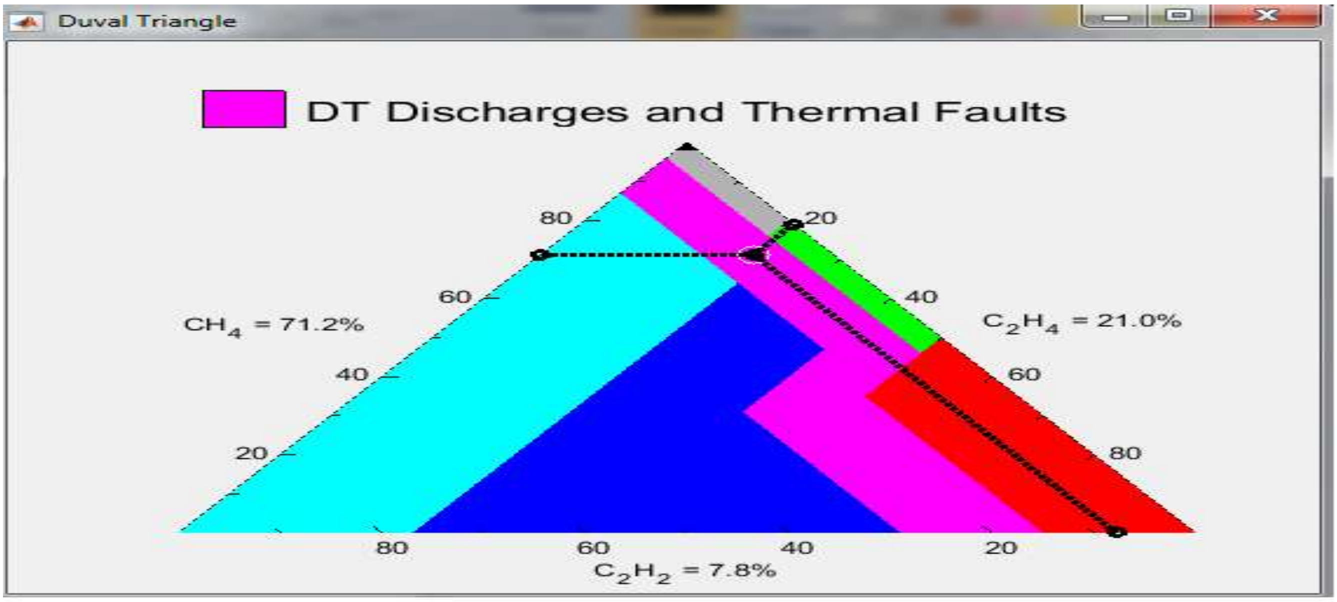

Fig. 11 Discharges and Thermal Faults detection using Duvel's triangle.

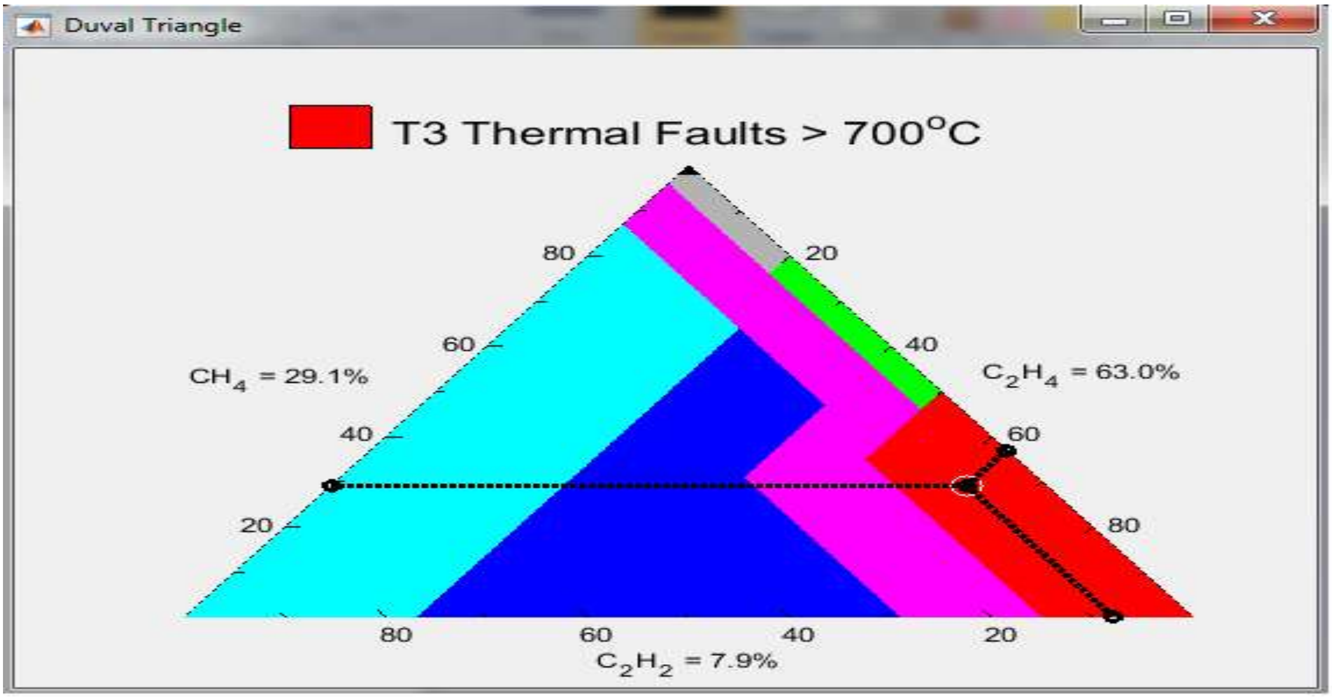

Fig. 12 Thermal faults > 700 °C detection using Duvel's triangle.

VIII CONCLUSION

Monitoring of transformer oil is very effective tool to increase transformer life because transformer is the most expensive and important equipment of the power system. It plays an important role in transmitting and distributing electrical power at low voltage and high voltage to the consumers. Frequent replacement of transformer because of insulation failure is not the better choice. Provisions should be make for the frequent condition assessment of insulating material. Offline methods including gas chromatography test of insulating oil sample in the laboratories is an inconvenient method and does not provide accurate results. Moreover it leads to the wastage of time .In the work online gas monitoring through various gas sensors gives accurate and fast results. The inconveniency of sending the oil samples to the laboratories and waiting for the results is totally eliminated by using online techniques.

Moreover the sensors used in the work gives a better alternative to other online gas monitors available in the market like Hydran sensor and Morgan Schaffer Calesto. These online sensors are not compatible to all the combustible gases. Combination of gas sensors serves the purpose of online monitors with less cost. Software implementation of key gas method, Roger's Ratio method and Duvel''s triangle increases the accuracy as compare to the manual method. No human errors will be encountered as the results are through computer programming. Routine checkup of transformer oil can be performed very easily in a short interval of time with great accuracy. Hence this method is more reliable and accurate as compare to other conventional offline method of gas monitoring.

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