CONDITION MONITORING AND ASSESSMENT OF POWER TRANSFORMERS FOR RELIABILITY ENHANCEMENT – A REVIEW

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ABSTRACT

Enhancing the reliability of the transmission and distribution equipment, reducing the operating cost is very much essential in today's deregulated environment. Cellulosic paper and oil are the major insulating materials in transformer and are subjected to different degradation processes during its life. Hence it is necessary to use new monitoring and diagnostic techniques for detecting the incipient fault before catastrophic failure. Currently there are varieties of chemical and electrical diagnostic techniques available for condition assessment of power transformer. In recent times recovery voltage measurement, polarization and depolarization current measurement and partial discharge monitoring using UHF technique are becoming more and more popular. This paper discusses the analysis and interpretation of these techniques in condition assessment of transformer insulation.

***Keywords**: Condition monitoring, dissolved gas analysis (DGA), furan analysis, recovery voltage (RV), polarization and depolarization current (PDC), frequency response analysis (FRA), partial discharge (PD)*

INTRODUCTION

Power transformer is the most important and expensive equipment used in power transmission and distribution system. They are required throughout the modern interconnected power systems. Power transformers are usually very reliable and are expected to operate up to 35years.With proper maintenance the life of the transformer can be extended nearly up to 60 years. Extending the useful life of the power transformer has become the most important utility strategy for increasing the life of power transmission and distribution infrastructure. Monitoring systems can help to increase the transformer life and reliability of power transmission and distribution.

Quality of the electrical insulation is a key element for reliable operation of a power transformer. In transformers, cellulose paper along with oil forms the major insulation, which plays an important role in the life expectancy of the transformer. Insulation system can degrade at higher operating temperature and the degradation is accelerated in presence of moisture and oxygen [1].

During its operation transformers are subjected to various stresses, namely electrical, thermal and mechanical stresses leading to accelerated ageing. These stresses will result in chemical breakdown of the oil or cellulose molecules. The main degradation products are gases which entirely or partially dissolve in the oil. Dissolved gas analysis (DGA) allows one to detect the type of fault by analyzing the composition of gas produced during internal fault [2]. Non-destructive testing techniques such as dielectric response measurements are used to assess the condition of oil/ paper insulation. These methods include polarization and depolarization current (PDC) measurement technique and recovery voltage (RV) measurement [3].

Dielectric faults in the winding can occur due to mechanical displacement during transport or short circuit in power network. Such faults can be detected by frequency response analysis (FRA) [4]. Recently partial discharge (PD) measurements using ultra high frequency (UHF) technique is widely accepted due to its high sensitivity and low signal to noise ratio [5]. Condition monitoring techniques provide information on the developing insulation problems and incipient faults []. Hence it is essential to use monitoring and diagnostic techniques to avoid early failure of the insulation. Due to the complexity of transformer a single diagnostic technique would not give sufficient information on the performance of the insulation system. This paper briefly describes the commonly used condition monitoring techniques and diagnostic methods used in power transformers.

DISSOLVED GAS ANALYSIS

Transformer in service is subjected to several stresses such as electrical or thermal and these stresses along with moisture have a very strong tendency to cause decomposition of insulation leading to the formation of dissolves gases. Such faults can be detected and monitored based on DGA. The main gases formed as a result of electrical and thermal faults and evaluated by DGA are H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, and CO_2, whose relative concentrations depend on the fault type [6]-[7]. The relative ratios and the amount of gas detected in the sample are used to detect problems associated with the insulation structure. DGA is a very effective and reliable tool used for early detection of incipient fault in transformers [8] - [9]. Normally the causes of fault gases are classified into three categories namely corona or partial discharge, thermal heating and arcing [10].Fault analysis is made either on known gases evolved (key gases) or based on ratios of selected gases.

Certain key gas has been correlated with a particular fault and rate of gas production depends on the severity of fault [11]-[12]. The causes of fault that can cause gas generation are classified as corona (partial discharge), thermal heating and arcing [13]. For example, during DGA test of transformer oil hydrogen gas is found in large quantities it is the indication of the corona or partial discharge. CO and CO_2 are found in large quantity and it is predicted that there is thermal decomposition of cellulosic insulation. Heating of oil produces ethylene as the principal gas. Electrical arcing produces large amount of acetylene and hydrogen.

The main diagnostic methods used are:

a) IEEE methods (Dornenburg ratio, Rogers ratio, key gas method)

b) IEC ratio codes

c) Duval Triangle method.

The ratio method involves calculating key gas ratios and comparing these ratios with suggested limits. Table II. shows key gas ratios of different DGA interpretation scheme.

TABLE II KEY-GAS RATIOS OF DGA INTERPRETATION SCHEME [14]

Interpretation scheme	Key gas-ratios
Dornenburg ratios	$\frac{CH_4}{H_2};\frac{C_2H_2}{C_2H_4};\frac{C_2H_6}{C_2H_2};\frac{C_2H_2}{CH_4}$
Rogers ratios	$\frac{CH_4}{H_2};\frac{C_2H_6}{CH_4};\frac{C_2H_4}{C_2H_6};\frac{C_2H_2}{C_2H_4}$
Duval triangle	$\%C_2H_2;\%C_2H_4;\%CH_4$
IEC ratios	$\frac{C_2H_2}{C_2H_4};\frac{CH_4}{H_2};\frac{C_2H_4}{C_2H_6}$

One drawback of the gas ratio methods (Dornenburg, Rogers, IEC) is that some DGA results may fall outside the ratio codes and cannot be diagnosed. To overcome this limitation Duval developed the triangle method [15].

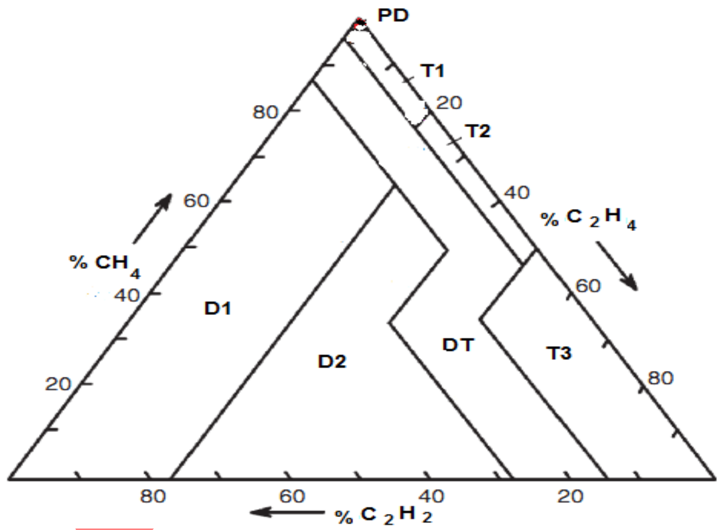

Fig. 1. Duval's triangle [15]

The triangle representation of fault diagnosis is shown in Fig.1.The three sides of the triangle are expressed in triangular coordinates representing the relative proportions of three gases CH_4, C_2H_4 and C_2H_2, from 0% to 100% for each gas. The triangle is divided into several selective regions by drawing lines parallel to the appropriate sides of the triangle and each region represents a particular type of fault depending on the gases detected.

The fault can be identified after DGA analysis as follows:

(1) Partial discharges (PD) –corona type discharge in gas bubbles or voids with possible formation of X-wax in paper.

(2) Discharges of low energy (D1) –partial discharges of the sparking type, low energy arcing

inducing surface tracking of paper or formation of carbon particle in oil.

(3) Discharges of high energy (D2) – discharges in oil resulting in extensive damage to paper, carbonization, metal fusion and possible tripping of the circuit.

(4) Thermal fault at temperature <300^{0}C (T1) – evidenced by brownish coloration of paper followed by carbonization.

(5) Thermal fault at temperature 300^{0}C –700^{0}C (T2) – evidenced by carbonization and particulate contamination in oil.

(6) Thermal fault at temperature >700^{0}C (T3) – extensive formation of carbon and metal particles in oil, metal coloration, fusion.

In addition to the six zones of individual fault mentioned above, an intermediate zone (DT) represents combination of electrical and thermal faults in transformer. Based on DGA results the relative proportions of the three gases are calculated as:

$\% C_2H_2 = \frac{100x}{x+y+z}$; $\% C_2H_4 = \frac{100y}{x+y+z}$; $\% CH_4 = \frac{100z}{x+y+z}$ where x = [C_2H_2] ; y = [C_2H_4]; z = [CH_4] in ppm

Data from DGA can provide warning of incipient fault, presence of fault and conditions during over load. In general by DGA analysis problems can be identified and evaluated at the early stage before catastrophic failure of the transformer.

FURAN ANALYSIS

Paper is a major dielectric within a transformer, used either as conductor wrap and impregnated with oil or as barrier boards. Paper insulation is composed of complex cellulosic molecules containing long chain glucose monomers [16]. The number of monomer units in the polymer is known as degree of polymerization (DP) and the quality of cellulose is measured in terms of DP.

Due to overheating the cellulose structure undergoes slow decomposition and splitting of the chain liberates a glucose monomer unit that undergoes further chemical reactions to become furans (furfurals) and other products such as water, carbon oxide gases [17] - [18]. Most often the following five furan compounds are measured [19].

- 2- furaldehyde (2FAL)
- 5- methyl-2-furaldehyde (5M2F)
- 5- hydroxymethyl- 2- furaldehyde (5H2F)
- 2- acetylfuran (2ACF)
- 2-furfurol (2FOL)

Furan formation is related to the degradation of paper and gives information about DP. A reduction in DP value is accompanied by structural changes, reduction in average molecular weight and tensile strength of paper [20].

Normally for a fresh sample of cellulose, the DP is in between 1000 and 2000. As the insulation ages under thermal load, this value continuously decreases and it reaches below 250 indicating an end of life [21].

Burton et al. made a study of rate of furan formation of several furan products over a wide range of temperature (120^0C–350^0C). They observed that the decrease in tensile strength of the paper correspond to an increase in the concentration of the furans in the oil [22]. The rate of rise of percentage of Furfurals products in oil, with respect to time, is used for assessing the condition and remaining life of paper insulation in power transformer. The solubility of these compounds in oil is quite appreciable and their concentration in oil can be detected using High performance Liquid chromatography [23].

DIELECTRIC RESPONSE MEASUREMENT

Dielectric response measurement refers to a family of methods used for characterization of dielectric materials. Conventional methods of measuring dielectric response include capacitance-tan delta measurement and measurement of insulation resistance. Recently, measurement techniques such as return voltage methods (RVM), polarization and depolarization current (PDC) measurements are becoming more and more popular. These methods could be used as an effective tool for transformer condition assessment.

III.1 Return voltage measurement

The degradation of insulation system in a power transformer depends on thermal, electromechanical and chemical stresses. Under these stresses decomposition of cellulose takes place and produces water in the solid insulation, which acts as a catalyst for further degradation. The breakdown voltage of insulating oil and paper is reduced with increase in moisture content of oil. Thus knowledge about moisture content (conductivity) can be used as an important basis for condition assessment of the oil/paper insulation.

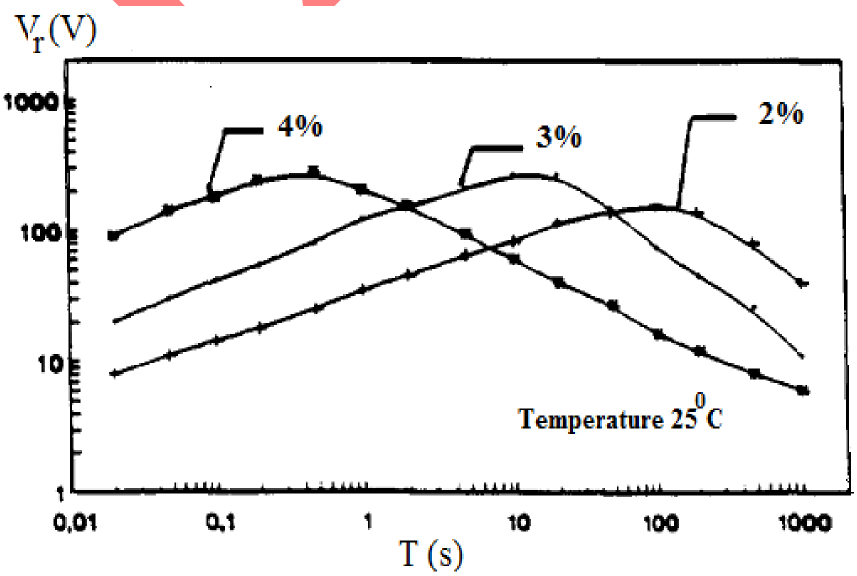

Fig. 2. RV spectra of oil impregnated paper [27]

Recently Return voltage measurement technique is used to detect the water content and ageing process of oil/ paper insulation [24].When a dielectric material is charged with an electric field, it gets polarized. In RV measurement the sample is charged for a long period of time and then the sample is isolated from the high voltage source and short-circuited for a short duration. When the short circuit is removed the charge bounded by the polarization will turn into free charges and voltage will build up between the electrodes on the dielectric and can be measured [25]. The time constant associated with this voltage gives an indication of the condition of the insulation. The relevant parameters associated with this measurement are the maximum value of the voltage, the time to peak value and the initial rate of rise of the return voltage [26]. Fig.2. shows typical RV spectra of oil impregnated .The absorbed moisture and temperature of the oil/paper insulation affect the return voltage measurement. Therefore return voltage measurement is always carried out at ambient temperature (20^0C–30^0C) [28].

III.II Polarization and depolarization current measurement

The principle of this measurement is based on the application of a dc voltage across the test object for a long time (`~1000seconds). During this time the polarization current is measured. Then the voltage is removed and the test object is short circuited, and the depolarization current is measured [29]. Fig.3. shows principle diagram of this method. Polarization current is built up of two parts, one part is related to the conductivity of the test object and other is related to the activation of the different polarization processes within the test object. Initial part of the polarization currents depends on the condition of oil and final values are influenced by the condition of solid insulation [31]

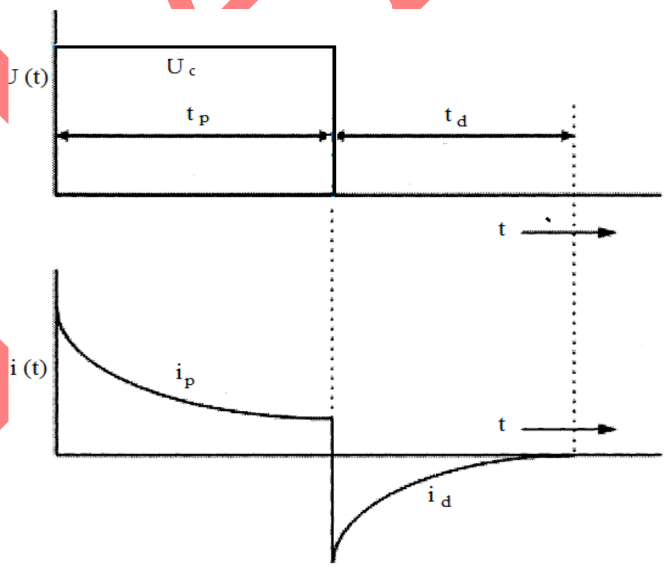

Fig. 3. Principle of polarization and depolarization current measurement [30]

Saha et. al [32] studied the influence of oil and paper conductivities on PDC and concluded that changes in paper conductivity affects the tail of both polarization and depolarization curve and initial higher magnitude of conduction current is due to the higher mobility of charge carriers present in oil . In general it can be concluded that moisture and other contamination tend to increase the paper and oil conductivity and in turn affect the PDC.

FREQUENCY RESPONSE ANALYSIS

During normal operation, transformers are subjected to several short circuit forces that can cause deformation or displacement of the windings as well as changes to winding inductance or capacitance of the transformer. Such small movements may not be detected through conventional condition monitoring techniques. Sweep Frequency Response Analysis (SFRA) has turned out to be a powerful, non-destructive and sensitive method to evaluate the mechanical integrity of core, windings and clamping structures within power transformers by measuring the electrical transfer functions over a wide frequency range [33].

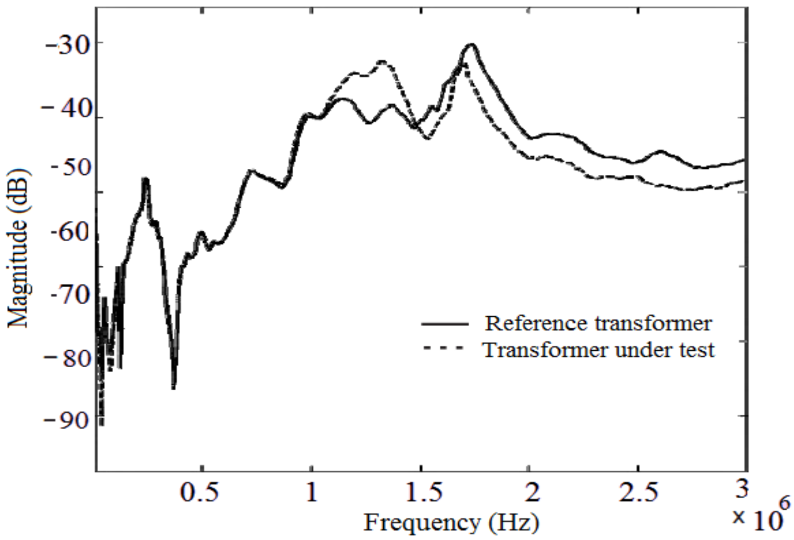

Fig. 5. FRA test results [38]

This technique is based on the principle that every transformer winding has a unique signature of its transfer function that is sensitive to changes in the parameters of windings such as resistance, inductance and capacitance [34]. Difference in signature of the responses may indicate damage to the transformer, which can be investigated further using other techniques or by an internal examination.

There are two different testing techniques- Sweep frequency response analysis (SFRA) and impulse frequency response analysis (IFRA) [35]. SFRA is usually done by injecting a sinusoidal signal of variable frequency into one terminal of a transformer winding and measuring the response signal on other terminal .With impulse response analysis, a pulse signal is applied to HV winding and response is recorded in the other winding. In general FRA technique is a comparative method in which measurements are made over a wide range of frequency from 50Hz to 5MHz and compares the results with a finger print measurement or with a reference response taken during installation [36]. Tenbohlen et.al [37] made a comparative study of the two FRA methods and proved that sweep frequency method is superior to low voltage impulse method in detecting mechanical damage to transformer winding. Fig.5 shows a typical FRA curve, with and without fault.

ON LINE PARTIAL DISCHARGE DETECTION METHODS

Partial discharges are localized electrical discharges within the insulation system and can deteriorate the insulation and cause complete failure of the system and hence it is desirable to monitor on line. The following are the various types of defects causing partial discharges (PD)

1. Impact of moving particles on the enclosure or on the insulation surface
2. Electrode protrusions
3. Fixed particles on an insulating surface
4. Floating electrodes causing a very large energy PD
5. Voids in solid insulation

PD activity is associated with both physical phenomena and chemical changes within the insulating material. During PD can cause transmission of electrical, chemical, acoustic and optical energy [39]. Conventional method of identifying incipient discharge is through measuring the degradation products produced during discharges, identification of luminous discharges and by measuring the partial discharge magnitudes. DGA results alone cannot establish the location of fault.

Conventional electrical method according to IEC 60270 of PD detection is based on the measurement of apparent charges generated due to different defects. This method has certain limitations such as low sensitivity and poor signal to noise ratio when applied to on line PD monitoring [40]. PD detection and location in oil paper insulation systems were achieved by the use of High Frequency Current Transformer (HFCT) and Inductive Loop Sensor (ILS) [41].

Currently onsite PD detection with high measurement sensitivity are gaining importance and this can be achieved by UHF or acoustic emission (AE) techniques.

Acoustic detection of PD is based on the retrieval and analysis of ultrasonic pressure pulses (20 kHz – 1.5 MHz) propagating through insulation due to partial discharges [42]-[43]. These pressure waves propagate through the medium and interact with the walls of the equipment and setup small amplitude vibrations. The signals thus generated can be detected by appropriate acoustic sensors mounted outside the transformer tank.

PD detection and localization in oil filled transformer was carried out by Lu et.al [44]. Sakoda et.al [45] made an attempt to detect corona discharges in oil using AE sensors placed outside the tank. The detected AE signals were analyzed by Fast Fourier Transform (FFT). It is a non-destructive testing technique and which can be applied to on line PD monitoring. Also location of PD defective site is possible using multiple sensors placed at different locations but this method of PD detection is limited by signal attenuation.

PD injected current pulses have duration of the order of 1ns or less, accompanied by electromagnetic radiation in ultra-high frequency range of 300MHz -3GHz.The resulting UHF radiation can be coupled to a designed capacitive device [46]. The UHF technique is being increasingly applied to the diagnosis of defects in gas insulated system and recently in case of power transformers and it is proved to be much more efficient than acoustic emission when the signal path passes through the solid insulation [47]. Judd et al. [48] conducted studies on PD activity using UHF sensor on a 18MVA, single phase 132/25kV traction transformer

UHF sensors must have a broad band response because the frequency content of the signals from defective site can vary considerably depending on its location and signal path [49].

CONCLUSION

In this paper an attempt has been made to understand the diagnostic techniques commonly used in power transformers. With regular monitoring and diagnosis it is possible to extend the life of a transformer. Among the chemical methods used DGA is the most widely used method for investigating incipient faults. Furan analysis is used to investigate cellulose ageing phenomena and it is related to degree of polymerization. Dielectric response measurement techniques such as FRA technique are suitable in finding the winding displacement or deformation. Recovery voltage measurements with the help of dielectric theory and polarization and depolarization measurements are good in investigating the moisture content of oil/paper insulation. Recently on line PD measurement is possible with the help of UHF sensor which is a broad band sensor gaining more importance due to its high sensitivity and less signal to noise ratio.

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