An Overview of Health Diagnostic Techniques Applied to In-Service Transformer Oil

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***Abstract*— Transformer is a very important asset in a electrical power network. Its reliable and continuous operation is the key to profitable generation, transmission and distribution of electric power. Failure of a large transformer not only results in the interruption of supply of electricity to the consumers but also it can cause serious damage to other ancillaries in the power system which in turn may result in significant loss of revenue to the electric utility. Replacement or the maintenance of that transformer can take up to days or years if the failure is not disastrous. It is said that life of a transformer is the life of its insulation of which transformer oil is the main ingredient. It is like a blood in the human body, and acts as insulating agent and coolant. During the operation of transformer, the oil insulation is subjected to various stresses like thermal stress, and electrical stress, resulting in degradation of its health which may defeat its purpose. This necessitates its health monitoring and timely reclamation and/ or replacement. From years ago, researchers have been working on various kinds of intrusive and non-intrusive techniques to assess and the health condition of the mineral oil. In this paper, a thorough survey is done on health diagnostic techniques applied to transformer oil. Various methods are studied regarding different viewpoints in this literature. Finally, a couple of thorough comparison is made between the available techniques considering the nature, capabilities, advantages and limitations.**

***Keywords*— Transformer Oil, Diagnostics, Intelligent Techniques,**

I. INTRODUCTION

Transformer establishes a linkage between the generating station and the point of consumption of electricity. In order to achieve a trouble free and consistent supply of electric power, timely maintenance of transformer is very important. It requires a continuous monitoring of the health of its insulation and other components. The main role of transformer oil is to act as an insulating and cooling agent. During the prolonged operation of the transformer, its mineral oil is subjected to the degradation and its insulating properties suffer changes to its disadvantage.

In [1] it has been investigated that how insulating oil in transformers changes and deteriorates with increasing age and what are the impacts on the electrical characteristics such as breakdown voltages. Insulating oil samples were collected from transformers, varying significantly with six manufacturers. Electrical, physical and chemical characteristics were obtained, and the impact of increasing age and the relationships among characteristics were evaluated. The characteristics found to deteriorate with increasing age were volume resistivity, dielectric loss tangents, interfacial tensions, and total acid values. The physical characteristics (kinetic viscosities, densities, and flash points) showed different tendencies depending on the oil type and age. Furthermore, the correlations between characteristics were evaluated.

In [2] the influence of service aging on transformer insulating oil parameters has been discussed. Various properties of transformer insulation oil such as breakdown voltage (BDV), moisture, resistivity, tan delta, interfacial tension and flash point have been measured using different national and international standards. The measured properties of insulating oil have been graphically presented with service aging. It is concluded that most of the properties degraded with respect to service aging.

In [3] researchers have demonstrated the influence of the oil type and oil temperature on the electrical conductivity. Electrical conductivity of insulating oil is a material parameter and differs with oil type and manufacturer. It is strongly dependent on temperature, electrical field strength and the ageing; generally it will increase with advancing ageing. Measurements of electrical conductivity were made for insulating (mineral) oils with test cells according to the IEC 60247 standard for two different oils at temperatures varied between room temperature (22°C) and 90°C. It could be demonstrated, that there is a strong influence of the oil type and oil temperature on the electrical conductivity.

In [4] an experimental study has been presented that is aimed at improving the anti-aging properties of power transformers via using mineral oil/natural ester mixtures (mixed insulating oil). In [5] the authors have investigated the suppression effect of typical additives and the decreasing effect of oil treatment by typical absorbents on the electrostatic charging tendency (ECT) in insulating oil used for power transformer insulation. Both 1, 2, 3-benzotriazol (BTA) and 2, 6-ditertiary-butyl para- cresol (DBPC) are found to suppress the increase in ECT due to sulphide compounds, which are normally contained in new oil. However, only BTA can suppress the increase in ECT due to sulphur oxide compounds, which are not contained in new oil and generated by the oxidation of sulphide compounds. Oil treatment by three types of absorbents such as clay, activated carbon and silica gel is found to have a significant effect of decreasing the ECT of deteriorated oil.

The main factors responsible for the deterioration of its insulating property are aging, temperature effects and other chemical reactions taking place inside it. The rate of aging is normally a function of temperature and moisture. Oil will age rapidly at high temperatures whereby the moisture acts as a catalyst for its aging. The present condition of the oil can be assessed by measuring its physical, chemical and electrical characteristics like viscosity, flash point, total acid number, breakdown voltage, dissipation factor etc.

A summary of main characteristics of transformer oil is presented in Table 1. followed by a brief description

Table1

Physical Properties	**Electrical Properties**	**Chemical Properties**
1) Moisture Content 2) Interfacial Tension 3) Flash Point (FP) 4) Kinematic Viscosity 5) Pour Point 6) Density 7) Colour and Appearance	8) Electrical Breakdown Voltage (BDV) 9) Resistivity 10) Tan Delta	11) Neutralization value 12) Corrosive Sulphur 13) Sludge Content

1) *Moisture Content*

Water content in oil is allowed up to 50 ppm as recommended by IS – 335(1993). The accurate measurement of water content is done by Coulometric Karl Fisher Titrator.

2) *Interfacial Tension (IFT)*

The safe limit of IFT for a good new oil sample is about 0.04 N/m at 29.5 ^{0}C.

3) *Flash Point*

For a good transformer oil flash point should be of higher value of about 145 ^{0}C.

4) *Viscosity*

Viscosity of the transformer oil should be very less; a safe permissible value of viscosity is 22 kg/m^3 at 20^0 C.

5) *Pour Point*

For good transformer oil pour point should be low, which say at -6 degree centigrade it starts just flowing.

6) *Density*

Density number should not exceed 900 kg / m^3 at a predetermined temperature of 20°C

7) *Colour and Appearance*

As the oil ages the colour becomes from water clear, to light yellow to dark yellow and brownish yellow.

8) *Electrical Breakdown Voltage (BDV)*

The safe limit of breakdown voltage of a transformer oil is 30 KV/cm. when tested under a pair of electrodes that are fixed at 2.5 mm apart in the oil tester.

9) *Resistivity*

Minimum standard specific resistance of transformer oil at 90°C is 35x10^{12} ohm – cm and at 27°C it is 1500x10^{12} ohm – cm.

10) *Tan Delta*

It is desirable to have a small tan δ value. Tan delta at 90 degree C is 0.20 as per IS – 1874.

11) *Neutralization Value/ Acidity*

For good transformer oil total acidity should be low. It should be about 0.2 mg KOH/gm. as per IS – 1872

12) *Corrosive Sulphur*

Crude petroleum contains sulphur compounds. Presence of corrosive sulphur results in pitting and black deposit on the surface of the bare copper which hinders the heat dissipation ability.

13) *Sludge Content*

Sludge forms from the degradation of the oil and paper insulation due to stressors such as oxygen and temperature and catalysts such as copper. [8].

II. CLASSIFICATION OF DIAGNOSTIC METHODS

In recent years, researchers have been interested in condition monitoring of transformer oil insulation. This is due to the reason of growing numbers of aged population of transformers across the world. Therefore, assessment of the insulation condition of the transformer is of great interest [7]. Various insulation diagnostic techniques have been developed over the years by the scientists and researchers. There are varieties of chemical and electrical diagnostic techniques available for insulation condition monitoring of transformers. In recent times, a number of electrical diagnostic techniques like return voltage measurement, polarisation/depolarisation current measurement and frequency domain dielectric spectroscopy at low frequencies have gained importance and are widely being used. Some other diagnostic techniques for oil are: dissolved gas analysis (DGA), moisture, tan-delta, resistivity, breakdown voltage (BDV), acidity, flash point, interfacial tension (IFT) etc.

(1) Electrical Breakdown Voltage Strength (BDV) Test

Electrical breakdown strength is basic parameter for insulating system design of the transformer. Transformer oil should have higher breakdown voltage strength. If the transformer oil has lower strength (lower BDV value) it indicates the presence of the contaminating agents like moisture, fibrous materials, carbon particles, perceptible sludge and sediments. Break down voltage is measured by observing at what voltage, sparking starts between two electrodes immersed in the oil, separated by a specific gap. For measuring BDV of transformer oil, portable BDV measuring kit is generally available at site. In this kit, oil is kept in a pot in which one pair of electrodes are fixed with a gap of 2.5 mm (in some kit it is 4 mm) between them as shown in Fig.1.

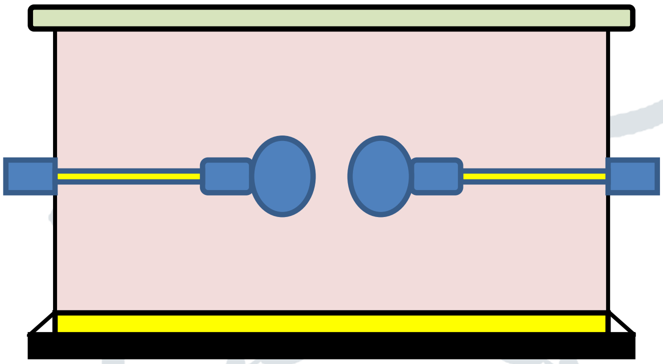

Fig.1.1 2.5 mm Gap Electrodes in BDV Tester

(2)Tan Delta Test

. High resistive insulation is a good insulation. it is desirable to have loss angle as small as possible, which means tan δ value will also be small. High value of tan δ is an indication of presence of contaminants in transformer oil. Hence there is a clear relationship between tan δ and resistivity of insulating oil. If resistivity of the insulating oil is decreased, the value of tan δ increases and vice versa. So both resistivity test and tan δ test of transformer oil are not normally required for the same sample of insulating oil. It can be said that tan δ is a measure of imperfection of dielectric nature of insulating materials, like transformer oil.

(3) Neutralization Value Test

It is the measure to determine the free organic and inorganic acids present in the oil expressed in terms of milligrams of KOH required to neutralize the total free acids in one gram of oil. Oxidation in the transformer oil is due to reaction between the hydrocarbons present in the oil and air. Copper present in the copper acts as catalyst to this reaction. The products of oxidation are injurious to the insulation system of the transformer and corrode the transformer components. So measurement of the total acidity is the tool to determine the capability of oil for non-formation of acids during the life. For good transformer oil total acidity should be low.

(4)Dissolved Gas Analysis (DGA)

Dissolved gas analysis is one of the most important test to determine the condition of a transformer. Different kinds of gaseous products are liberated from transformer oil under abnormal electrical or thermal stresses. The deterioration of paper insulation and mineral oil generates gaseous hydrocarbons that remains dissolved in transformer oil. The gases generated are H_2, CO, CO_2, CH_4, C_2H_6, C_2H_4, C_2H_2, O_2 and N_2 [8]. In the past certain key gases have been correlated with fault type and the rate of gas production correlated with fault severity. IEEE standard [12] with an extensive literature list discusses key gas method in detail with relative proportions of gases for the general types of fault. The composition of these gases depends upon the type of fault like partial discharge (corona), over-heating and arcing [9]. It is commonly found that H_2 gas is produced due to the corona effect and it is the main gas produced in all types of faults. Non- fault gases like N_2 and O_2 are also generated. Formation of gaseous products is summarized as follows. Age deterioration of insulating paper is responsible for generation of CO and CO_2. Hydrocarbon gases and H_2 are generated by decomposition of insulating oil and paper materials. At low temperature, CH_4 and C_2H_6 are not generated but C_2H_4 and C_2H_2 are generated. Oxidation deterioration also give rise to generation of C_2H_6 and H_2. In particular H_2 is generated by other causes than deterioration alone [10,11]. Fuzzy logic approach to develop a computer based intelligent interpretation of transformer faults was developed to demonstrate the detection and verification of faults [16].

(5) Moisture Content

Electric conductivity and dissipation factor of insulation materials increase as the water content increases which in turn reduces electric strength. Moisture content in oil is commonly measured the by the Karl Fischer titration method [13]. There are several direct measurement methods reported in the literature. The authors in [22] put forward a moisture detection method based on the ultrasonic transit time difference. The ultrasonic velocity of oil is closer to the water, but has a relatively large difference with ice; the oil-water mixture is frozen to enable the water to become ice. Because different moisture content will lead to change of propagation time, the moisture content will be obtained from ultrasonic transit time difference. A thin film capacitive humidity sensor was tested for moisture sensing in transformer oil [14]. The near infrared spectroscopy for the determination of moisture content in oil impregnated paper was investigated. Their results showed that NIR spectroscopy along with their developed multivariate modelling have resulted in accurate estimation of moisture [15]. It has been found that equilibrium in oil-paper insulation depends upon temperature and the condition of power transformer. A balance charts exists for the percent of moisture in oil or paper insulation at different temperatures in steady state but the dynamical relationship is very complex [17].

(6) Furan Analysis

The major degradation products of insulation paper are Furans that remain present in the insulation oils of operational transformers. Analysis of Furan provides a convenient method of analysis on insulation paper [18]. It is reported that 2-furfuraldehyde is formed from the degradation of cellulose insulation paper. In accelerated ageing experiments approximately logarithmic relationship has been found to exist between the concentration of 2-furfuraldehyde in the oil and the degree of polymerisation of cellulose [19].

(7) Degree of Polymerisation

Degree of polymerisation is a measure of the quality of the cellulose in the insulation paper. The length of the cellulose chain is measured by the average degree of polymerisation based on viscosity method. It is denoted by DP_V and has been used as a diagnostic tool to determine the condition of transformers by several workers [14,19,20]. New Kraft paper has an average chain length of 1000 to 1500. After a long period of service under the condition of temperature with high content of water and oxygen DP_V goes down to 150 to 200 which may reduce the mechanical strength of paper to 20% of its initial value and this condition is regarded as the end of life for transformer insulation [19].

(8) UV-Spectroscopy

UV/VIS spectrophotometer to determine the dissolved decay products in mineral insulating oils for transformer remnant life estimation with ANN has emerged as powerful tool. UV-Spectrophotometer response which is a nonintrusive test, can show only pictorial information of the age of the oil hence an Artificial Neural Network (ANN) method to determine the health assessment of the transformer oil was introduced [25]. In an air environment, during accelerated ageing the oil is subjected to oxidation and turned brown in colour. But in a nitrogen environment there was found to be no change in the colour of the oil. To monitor any changes, the absorbance of the oil was examined by UV-visible spectroscopy for the samples aged at 145^0C [21].

(9) Return voltage Measurement

Return voltage measurement (RVM) has been used as a reliable tool for evaluating moisture content in transformer insulation. In this study, voltage response measurements were performed on various transformers with different voltage grades, various operating periods, different moisture contents and aging degrees on site. Derived moisture contents from return voltage measurement were compared with the 27 corresponding moisture contents obtained from the analysis of oil samples. Based on on-site experiments and theoretical analysis, the criteria for insulation state of transformer were proposed, and a good correlation between aging degree and the return voltage initial slopes of the aged transformers are established [23].

(7)Temperature Dependent Dielectric Spectroscopy

Researchers have presented the advantages offered by the Temperature Dependent Dielectric Spectroscopy (TDDS) in frequency domain, as a possible diagnostic tool for power transformer life-time prediction. Characterization of the insulating oil has been carried out for a wide selection of transformers and their gas concentrations were monitored. The work correlates (Gas Chromatography) data to the dielectrometery ones [24].

(10) Intelligent Techniques

ANN models have ability to learn from experience but the learning process can be too long and also does not guarantee a success. Fuzzy approach is user friendly and intelligent approach with simplicity, but it is hard to develop models from fuzzy systems. Neuro-Fuzzy computing which is judicious integration of the merits of neural and fuzzy logic, enables one to build more intelligent decision-making systems. This incorporates the generic advantages of artificial neural networks like massive parallelism, robustness, and learning in data-rich environments into the system.

In recent times, a number of intelligent methods based on Artificial Intelligence (AI), Artificial Neural Network, Fuzzy Logic, Neuro-fuzzy and their other hybrid methods have been used to predict incipient faults in high voltage transformers that are based on insulation studies under various conditions of stresses. Neural networks have been used to solve a wide variety of problems that are hard to solve using ordinary rule-based programming. Artificial neural networks and fuzzy logic are the most commonly used artificial intelligence techniques for transformer insulation condition assessment. In [26] the hybrid tool has been developed to diagnose faults in power transformers through the analysis of dissolved gases in oil. The well-known traditional criteria of the dissolved gas analysis based on artificial neural network and fuzzy logic have been used for fault diagnosis [27, 28]. To detect faults in oil filled power transformer based on dissolved gas analysis, a two-step neural network method has been used and a good diagnosis accuracy has been achieved [29].

A brief summary of the comparison of diagnostic techniques is summarised in Table2

Table2

Diagnostic Method	Nature/Type	Standards	Remarks
1. BDV Test	Electrical	IS:6792, IEC: 60156	Needs to be done periodically to ensure health of the oil, safe limit is 35 kv/cm (D877-ASTM)
2. Tan Delta Test	Electrical	IS:6262, IEC: 60247	The dissipation factor of new oil should not exceed 0.05% at 25^0C
3. Neutralization Value	Chemical	IS: 1448(P-2) IEC:62021	It should never exceed 0.25 mg KOH/mg oil
4. DGA	Chemical	IS:9434	Enough useful information can be derived from nine gases so additional gases are usually not examined
5. Moisture Content	Electrical and Chemical	IS:13567, IEC: 60814	Safe level is 30-35 ppm
6. Furan Analysis	Chemical	IEC:61198	Furan content above 2500 ppb indicates that the transformer is about to fail.
7. DP	Chemical	IEEE C57 140	DP value range is 1200 to 100 for new to aged paper It reflects degradation level of paper insulation
8. UV Spectroscopy	Electrical	ASTM D-6802	Provides a provides a platform for visual identification of age of oil
9. RVM	Electrical	----	A non-destructive technique for moisture and aging condition assessment of transformer oil –paper.
10. AI Techniques	Electrical/Chemical	-----	Useful when mathematical models not available and applicable for non linear problems.

III. CONCLUSION AND FUTURE TRENDS

In this paper, various physical, chemical and electrical characteristics of transformer oil insulation have been classified and explained. Effect and causes of aging phenomenon on transformer oil insulation properties have also been briefly discussed. Permissible values of characteristic parameters have also been highlighted. Different diagnostic techniques and their international standards used for testing purpose have also been presented. An in-depth analysis and comparison is done among various diagnostic techniques. In models based on AI techniques it is highlighted that fuzzy rules and training patterns are quite promising and deserves serious implementation due to its robustness, generalization of results, and our own choice of set rules. Different soft computing methods can be used in parallel for enhancing the performance of the AI models. A more reliable parameter for ascertaining the oil quality may be established in terms of health index, that may be based on some oil characteristics, their correlation and in-service life of the transformer oil. There is a high scope in exploring alternative liquids, and some additives to improve oil condition. Today, coconut oil with some improvisation in its characteristic or in conjunction with some additives, is being thought of a promising alternative. Online monitoring and diagnostic tools with usage of advanced sensors could be highly effective solution to the science of insulation diagnosis.

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