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Experimental Investigation Regarding Prediction of Residual Life of Transformer Using Fuzzy Method

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Abstract— **An efficient intelligent system (FUZZY LOGIC) for the power transformer residual life assessment is presented in this paper. In the fuzzy method, different inputs and one output is used, that strictly depends on the number of membership function and their rule base and the type of the defuzzification method. The residual life of the transformers greatly influenced by the condition of the transformer insulation system. The insulation of winding de-teriorates during the normal ageing of the transformers. Paper insulation that contains cellulose molecules degrades due to heating or electrical breakdown dissolved in the transformer oil. Hence, the analysis of the Transformer oil gives correct evidence of variation in the property of the winding insulation during operation. Deterioration in transformer oil-paper insulation decreases both its electrical and mechanical strength that influence the age of the transformer. This paper presents a fuzzy logic method that has been implemented on three samples of power transformer oil for the residual life assessment of the transformers.**

***Keywords*— Transformer oil, Condition Monitoring, Ageing, Parameters of transformer oil, and fuzzy logic controller.**

I. Introduction

Transformers are the heart of the power system networks. Thus the health of the transformer is the key factor for the normal operation of it. The health of the transformer basically depends upon the insulation condition of it that is oil & paper. Transformer ageing is a process involving chemical, physical & electrical changes in the properties of the oil-paper insulation system. Deterioration of both the paper and transformer oil is caused by oxidation accelerated by high temperatures, moisture. The oil oxidation will lead to acids and par- oxides production & these are introduced into the transformer oil.

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Transformer oil acts as insulating material & heat transfer media. The main requirements of insulating oil are to provide insulation, to withstand electric stresses imposed in service as the oil has high dielectric strength and low dissipation factor, to transfer heat and to provide cooling. For the good residual life of the transformers, oil needs to have the following properties:

- Dielectric breakdown strength of the oil should be high.
- IFT of the transformer oil should be high.
- Flash point of the transformer oil should be high.
- Viscosity should be low.
- The Oxidation Stability of the oil must be high to reduce oxidation process in service, which degrades the oil, producing sludge and acids.
- The oil must have a low Particle Size and low fiber content as the presence of these contaminants, especially in the presence of moisture; it can considerably reduce the electric strength.

Monitoring of such characteristics, which concern in the failure of machine is necessary when safe and reliable operation is required [1]. Selection of suitable diagnostic methods is the first important objective during the design of monitoring system. As the aging of transformer insulation system is affected mainly by changes of temperature and electrical operation characteristics, the observation of these characteristics is included in our monitoring system [2]. The fuzzy logic modeling and analysis has been carried out to get better asset's remnant life estimation. To estimate the age of a power transformer fuzzy logic based approach is useful [3, 4].
For analysis of residual life of power transformers, we collected oil sample of power transformer. The rating of Power Transformer was 40 MVA, 132/33kV. Following tests have been performed on sampled oil.

II. A Brief Description of Tests to be Performed

A. *Moisture Analysis in transformer oil*

Moisture in the transformer is the main cause of problems in transformer & its operation. It affects both solid & liquid insulation because moisture is interrelated in both insulation.

Breakdown voltage of the oil is affected with increase or decrease in the moisture content of the oil & also it affects the ageing of the insulation & so the ageing of the transformer. In the extreme case, transformers can fail because of excessive water in the insulation. For these reasons it is important to have a means of assessing the moisture content of transformer systems and to maintain transformers in a reasonably dry state. Water can exist in several different states within the transformer. There are three basic types of water associated with transformer oil [4]:

- Dissolved water is hydrogen bonded to the hydrocarbon molecules of which oil is composed.
- Emulsified water is supersaturated in solution but has not yet totally separated from the oil. It usually gives oil a milky appearance.
- Free water is also supersaturated in solution but in a high enough concentration to form water droplets and separate from the oil.

The analysis of moisture in oil performed in the laboratory is performed by Karl Fischer titration described in ASTM Test Method D 1533 or IEC Method 60814.It involves a coulometric titration technique involving the reduction of an iodine- containing reagent. The methods are used to determine the amount of water in an oil sample on a weight-to-weight (mg/kg) basis or what is commonly known as ppm (parts per million). Online analysis of moisture in transformer oil is performed by the DOBLE moisture-in-oil sensor. The domino measures water in oil in terms of relative saturation (%RS) which can be determined as follows: relative saturation indicates the amount of moisture in oil in the scale of 0-100%RS. In this scale, 0%RS is an indication of completely water free oil & 100%RS is an indication of oil fully saturated with water & may be present in free form.

Solubility is defined as the total amount of water that can be dissolved in the oil at a specific temperature. It is not constant in oil but changes due to temperature. As the temperature increases, the level of water in oil also increases. The increase is not linear but exponential function. The solubility for mineral oil can be calculated using Arrhenius equation (1):

$$\text{Log } S = -P/T + Q \qquad (1)$$

Where: “S” is the solubility of water in mineral oil & “T” is the temperature in Kelvin (°C + 273). “P” & “Q” are constants.

Water in oil solubility as a function of oil is shown in the Table. I, [4].

B. *Breakdown Strength Test*

Breakdown voltage (BDV) is defined as the voltage at which breakdown occurs between the electrodes when oil is subjected to an electric field under prescribed conditions. It is very important parameter for insulation system design of a transformer. It is used to indicate the presence of moisture, fibrous materials, carbon particles & sediments [5]. Test cells are used for conducting the BDV test. There are two methods are available for BDV test:-

- ASTM D 877
- ASTM D 1816

In ASTM D 877 two flat electrodes are used spaced inches apart & rate of increase of voltage is 3kv/sec. In ASTM D 1816 two spherical electrodes are used spaced either at 1mm or 2mm. It is much more sensitive towards moisture & polar compounds. The rate of rise of voltage is reduced to 500V/sec. Automatic BDV test setup is used to know the BDV of the insulating oil. The test voltage required for this test is nearly 100kv as the spacing between the electrodes is very small.

TABLE I. WATER IN OIL SOLUBILITY AS A FUNCTION OF TEMPERATURE

Oil Temperature	Water Content in Oil, ppm
0°C	22
10°C	36
20°C	55
30°C	83
40°C	121
50°C	173
60°C	242
70°C	331
80°C	446
90°C	592
100C	772

C. *Interfacial Tension (IFT) Test*

IFT is defined as the molecular attractive force between oil & water molecules at their interface. It gives a suitable means of detecting soluble polar compounds that decreases the molecular attractive force between oil & water. Thus it indicates the degree of sludging of oil. IFT test is performed by INTERFACIAL TENSION ANALYSER. It is measured in mN/meter or dynes/cm. For new highly refined transformer oil, IFT ranges from 45 to 50 mN/meter. When the transformer oil is installed in the transformer, IFT reduces to 5 to 10 mN/m as oil picks up contaminants from the new equipment. IFT is greatly influenced by the moisture content in the transformer oil, increasing moisture level decreases the value of IFT , thus reducing the residual life of the transformers. The IFT test is a powerful tool for determining the performance of insulating oil and how much life is left in the oil before maintenance is required to prevent sludge. Transformer oil classification based on IFT test is shown in Table. II, [6].

TABLE II. TRANSFORMER OIL CLASSIFICATION BASED ON IFT

1.	Good Oils IFT 30.0 - 45.0
2.	Marginal Oils IFT 24.0 - 27.0
3.	Bad Oils IFT 18.0 - 23.9
4.	Very Bad Oils IFT 14.0 - 17.9
5.	Extremely Bad Oils IFT 9.0 - 13.9

D. *Acidity Test*

The total acidity of the transformer oil is measured in mgKOH/g and it is another indication of the deterioration of the transformer's overall insulation system. Total acidity increases continuously with extended service periods of the transformer oil, thus it can be used to indicate the health of the oil [8]. The deterioration of the paper insulation also increases the acidity in the transformer oil [9]. Acidity of oil is the measure of the acidic constituents in the transformer oil. Its value, negligible in an unused oil and increase as a result of oxidation. Transformer Oil with high neutralization value affects the winding & paper in the transformer. Normally the transformer have uninhibited oil but sometimes inhibited oil is used. The inhibitor breaks the chain reaction by which sludge and acids are produced. If sludge is produced in oil, the oil changes its color and become darker and turbid. The sludge can be removed by filtration. The oil exchange should be carried out when transformer is warm and oil viscosity is in low range. New transformer oils have practically no acids if properly refined. The acidity test measures the content of acids formed during oxidation. The oxidation byproducts polymerize to form sludge which then precipitates out. Acids react with the metals on the surface in-side the tank and form metallic soaps and another form of sludge.

E. *Resistivity Test*

The resistivity of transformer oil is a measure of its electrical insulating properties under conditions comparable to those of the tests. High resistivity shows low value of free ions and ion-forming particles and normally shows a low concentration of conductive contaminants. These parameters are very sensitive to the presence in the transformer oil of soluble contaminants and ageing by-products. Resistivity is normally carried out at ambient temperature but useful information can be obtained if the test is carried out at ambient temperature and a higher temperature such as 90 degrees Celsius. Unsatisfactory results at these temperatures indicate a greater extent of contamination than a poor value at the lower temperature only.

III. Residual Life Assessment of Transformer Using Fuzzy Method

A. *Overview of Fuzzy Logic*

Fuzzy sets has been originated in the year 1965 and the concept of fuzzy sets was proposed by Lofti A. Zadeh. It is an expert system that does not use the Boolean logic but it uses a collection of fuzzy membership functions and rules. It provides an inference morphology that enables approximate human reasoning capabilities that can be applied to knowledge-based systems. Fuzzy logic theory gives a mathematical strength to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning. This system is suitable for approximate reasoning, especially for the system that have a mathematical model which is difficult to derive. Fuzzy logic allows decision making with estimated values under incomplete or uncertain information. The fuzzy expert system uses rules that are in the form of like: If p is low and q is high then r = medium where p and q are input variables & z is an output variable, "low" is a membership function defined on p, "high" is a membership function defined on q, and "medium" is a membership function defined on r. Membership function is defined as the degree of truth or the degree of compatibility. It is a very crucial component of the fuzzy set. That is why every operation on fuzzy sets is defined based on it's membership functions. The membership function represents the participation of magnitude of each input. The rules in the fuzzy expert system use the input membership values as weighting factors to determine their influence on the fuzzy output sets. The fuzzy expert system uses different sets of rules that are known as the rule base or knowledge base. The block diagram of fuzzy system architecture is shown in the "Fig. 1".The components of the block diagram are Inputs, Fuzzification, Inference, Defuzzification, Output & Rule Base.

A.1). Fuzzification

The membership functions that are defined on the different input variables are applied to their actual values for the determination of the degree of truth for each rule premise under the fuzzification. The aim of fuzzification is to map the inputs from a set of variables to values from 0 to 1 using a set of input membership functions.

A.2). Fuzzy Inference System

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It is the process of formulating the mapping from the given input to the output using fuzzy logic. To compute the output of this fuzzy inference system for the given inputs there are six steps:

- Determining a set of fuzzy rules.
- Fuzzifying the inputs using the input membership functions.
- Combining the fuzzified inputs according to the fuzzy rules to establish rule strength.
- Finding the consequence of the rule by combining the rule strength and the output membership function.
- Combining the consequences to get an output distribution, and
- Defuzzifying the output distribution.

Fuzzy inference system has been applied in fields such as fault diagnosis, data classification, decision analysis & expert systems.

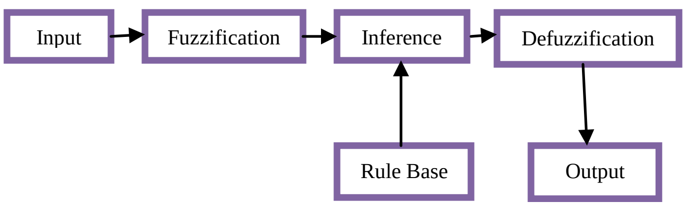

Figure 1. Block diagram of typical fuzzy system architecture and the general inference process.

A.3). Defuzzification

Finally the defuzzification is used to convert the fuzzy output set to a crisp number. There are number of defuzzification methods are available (at least 30). Two of the more common techniques are the MAXIMUM & CENTROID methods. The CENTROID method is known as the Centre of gravity or the Centre of area method. It obtains the Centre of area occupied by the fuzzy set. The crisp value of the output variable is computed by finding the variable value of the center of gravity of the membership function for the fuzzy value in the CENTROID method. One of the variable values on that the fuzzy subset has its maximum truth value is chosen as the crisp value for the output variable in the MAXIMUM method. Moisture, IFT, BDV , acidity & resistivity of the oil has serious impact on the performance and life of the transformers. The fuzzy logic modeling and analysis has been done to get better residual life estimation. "Fig 2". represents the FIS editor showing 5-input variables and 1- output variable. "Fig 3to7". represents the Moisture, BDV, IFT, Acidity & Resistivity membership function plot for the input variable. "Fig 8". represents the membership function plot for the output variable age and "Fig 9". represents the rule view of input and output variable.

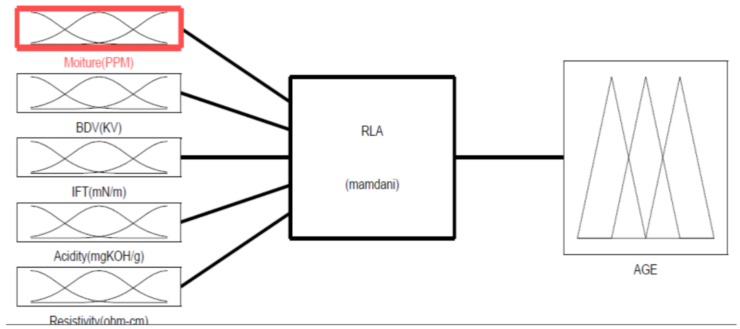

Figure 2. FIS editor showing 5-input variables and 1-output variable.

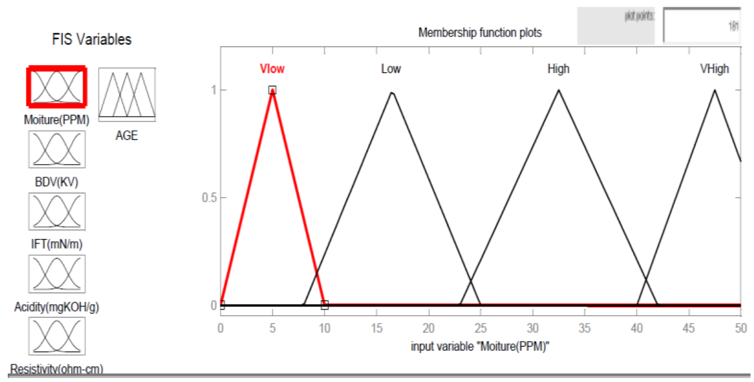

Figure 3. FIS editor showing membership function plot for "Moisture".

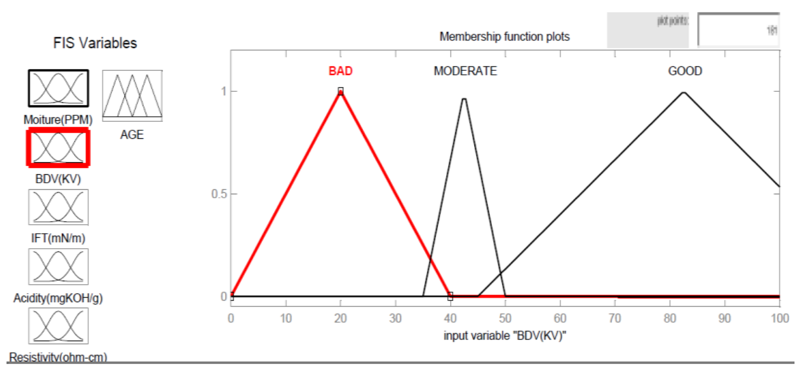

Figure 4. FIS editor showing membership function plot for "BDV".

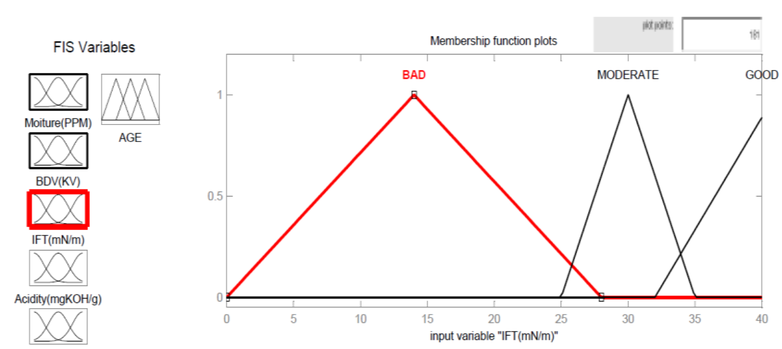

Figure 5. FIS editor showing membership function for "IFT".

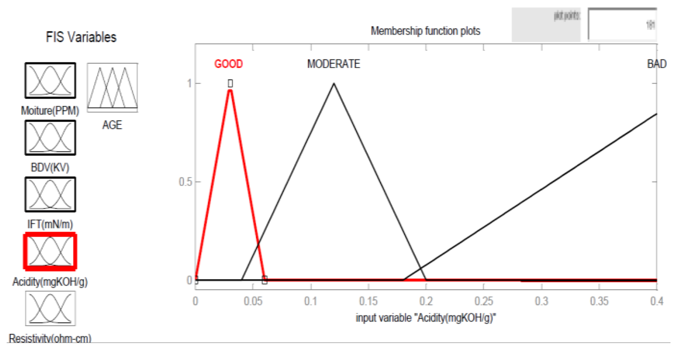

Figure 6. FIS editor membership function plot for "Acidity".

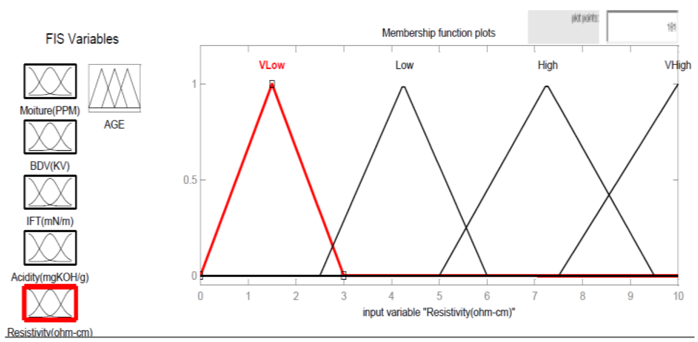

Figure 7. FIS editor membership function plot for "Resistivity".

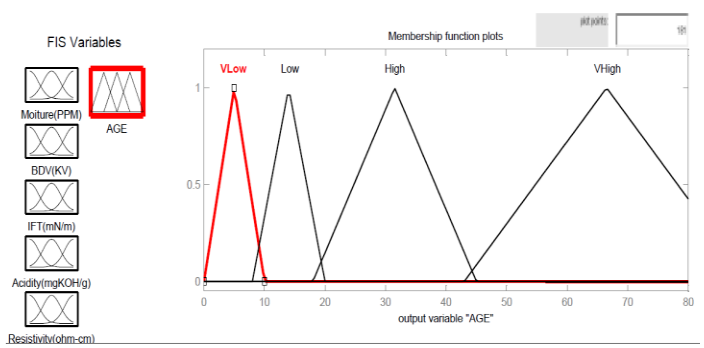

Figure 8. FIS editor showing membership function plot for "Age."

IV. Results

The residual life of 40 MVA, 132/33 kV power transformer is evaluated using the developed algorithms. Three tests have been conducted on the three samples. Conducted tests results are shown in Table III. In the fuzzy system triangular membership functions have been used [7, 8]. Table IV shows residual life of the transformer that is evaluated in single stroke using the developed fuzzy logic algorithm.

TABLE III. TESTS CONDUCTED ON THREE SAMPLES OF TRANSFORMER OIL

Test	First Oil Sample	Second Oil Sample	Third Oil Sample
BDV	72.5 kv (rms)	68.2 kv (rms)	65.6 kv (rms)
Moisture	4 PPM	5 PPM	9 PPM
IFT	45.2 mN/m	33.7 mN/m	27.0 mN/m
Acidity	0.03 mg KOH/G	0.04 mg KOH/G	0.05 mg KOH/G
Resistivity	$10x10^{14}$ ohm-cm	$9.6x10^{14}$ ohm-cm	$9.2x10^{14}$ ohm-cm

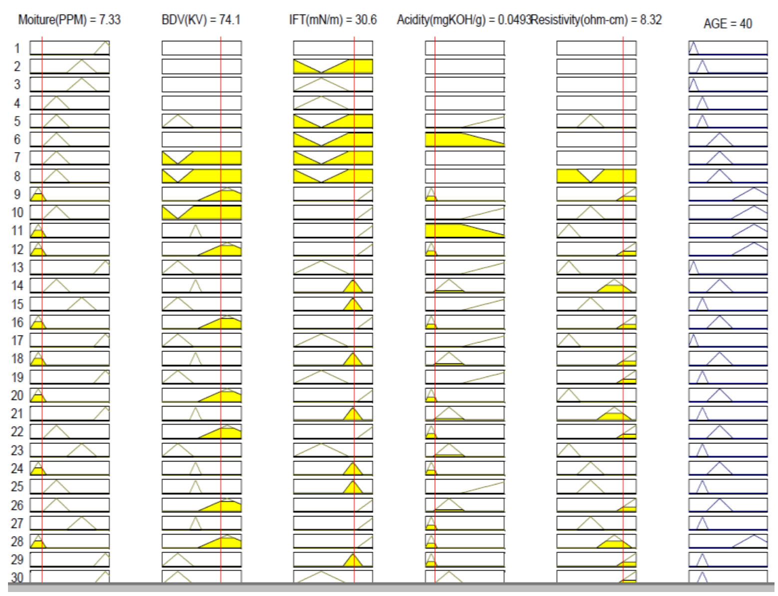

Figure 9. Showing the rule view of input and output variable.

TABLE IV. RESIDUAL LIFE OF TRANSFORMER EVALUATED USING FUZZY LOGIC

Samples	Residual Life of Transformer (In Years)
First Sample	51.9
Second Sample	50
Third Sample	30

V. Conclusion

The Residual life assessment is very important as the risks in the transformer can be eliminated and the life of transformer can be extended. The satisfactory operation of large power transformers can be achieved if the condition of the insulating oil is maintained within the prescribed limits. Moisture in the transformer oil is the most dangerous contaminant. It can be seen as ten parts per million by volume may lower the BDV of the oil below its acceptable value. This in turn can lead to deteriorates cooling conditions and higher temperature leading to shorter lives of the transformer. The oil must have a high value of IFT and low value of the moisture medium range of the temperature as the presence of such contaminants can considerably reduce the electric strength of the insulating oil. From the rules developed in this paper, it is clear that the residual life of the transformer is much more depend upon the values of the moisture content in the transformer oil and the IFT of the oil. The residual life assessment model of transformer presented in this paper with the use of fuzzy logic controller because of simplicity and accuracy of the fuzzy method.

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