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Remaining Life Assessment of Power Transformer

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Abstract Power Transformers are the most vital components in a sub-station / Receiving station. Failure of a Transformer leads to loss of revenue besides affecting reliability of power supply to consumers. It can lead to non-availability of the transformer for long durations. In this paper, an approach to evaluate transformer‘s aging condition is introduced based on multi-parameters. Firstly, the different types of insulations in transformers like solid insulation and liquid insulation have been discussed. Later, the ageing process of these insulations used in transformer has been illustrated in detail. Different condition monitoring techniques used for transformer are included to assess the life of insulating material. A program is developed in Visual Basic Software which is very user friendly software. Through the developed program, we can predict the remaining life of transformer. Moreover, a software system based on transformer’s electrical and thermal parameters is developed correspondingly, by using a multi- parameters analytic approach. This system is expected to help in planned maintenance of transformer on fields. This can help the utilities in making optimum use of the transformers and also taking timely decisions regarding refurbishment / replacement of transformers. Various transformer insulation properties like electrical properties, oil quality and temperature are considered in assessment of remaining life of transformer.

Keywords: *transformer insulation, insulation aging, condition monitoring, dissolve gas analysis*

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1. Introduction

Being one of the most expensive and important equipment in electrical power transmission and distribution (T&D) system, power transformer plays a vital role in maintaining a reliable and efficient electricity supply. Since transformer is continuously subjected to thermal, electrical, mechanical and chemical stresses etc. during its operation, it is necessary to include comprehensive parameters when establishing aging assessment system [1].

In order to ensure that Power Transformers provide long and trouble-free service, several diagnostic tests are carried out and remedial actions initiated throughout their operational lifetime. For the oil-filled Transformers, more particularly which are in service for more than fifteen years, it is advisable that we should also estimate the residual life of the transformers. It can be done by assessing the extent of degradation of the insulation used in transformer. This calculation considers not only typical test results such as dissolved gas analysis (DGA), oil quality, and dissipation factor, but also other parameters such as top oil temperature and hot spot temperature estimation.

The insulation system of a power transformer is understood as the complete internal assembly of dielectric insulating materials. This includes parts and supporting structures that cover the winding wires, insulate the turns from each other in each winding, separate different winding bodies from each other and from the core and tank.

The transformer insulation system can be categorized into major insulation system & and minor insulation system. The major insulation consists of insulation between windings, between windings and limb/yoke, and between high voltage leads and ground. The minor insulation consists of basically internal insulation within the windings, viz. inter-turn and inter-disk insulation.

The gap between low voltage (LV) and high voltage (HV) windings is subdivided into many oil ducts by means of solid insulating barriers. The insulation system of oil cooled power transformers consists of combination of oil and solid insulations (paper and pre-compressed board).

1.1. Transformer Oil

Transformer oil comes under liquid insulation. Mineral oil is the major type of liquid insulation used in electrical equipment. Oil used for insulation in transformers is mineral oil and it is obtained by refining crude petroleum. Mineral oils were in use as liquid dielectrics in electrical equipments for over hundred years now. Despite the availability of variety of synthetic oil, with far more superior properties, mineral oil held its way due to their abundant availability and economy. Particular oil will contain a mixture of many different molecular species and types of carbon atoms. The differences in the chemical composition will result in differences in physical properties and in the chemical behavior of the oils. The chemical composition has profound effects on the physical characteristics of the oil.

2. Composition of Oil

Mineral oil can vary greatly in its composition. All mineral oils are mixtures of hydrocarbon compounds with about 25 carbon atoms per molecule. Crude oils from some sources are higher in *paraffinic* compounds, whereas others are higher in *naphthenic* compounds. Crude oils also contain significant amounts of aromatic and poly aromatic compounds. The refining of crude oil for the production of dielectric fluids reduces the aromatic and poly aromatic content to enhance the dielectric properties and stability of the oil.

3 Insulating Paper

Oil impregnated paper, Kraft paper, pressboards, etc come under solid insulation of transformer. Power transformer windings are most commonly insulated with multiple layers of Kraft paper immersed in mineral oil. The paper insulation is required to withstand both electrical and mechanical stress. The oil provides both insulation and cooling. Paper and pressboard insulations are made from organic materials called cellulose fibers obtained from vegetable sources including cotton, hemp, manila, straw, wood and coniferous/ deciduous trees because the cell of such plants consist mainly of cellulose. These sources therefore felted to form a fabric, a mat, a web or a sheet of paper according to their application. The Kraft process reduces unwanted constituents of wood pulp such as lignin and hemicelluloses. The main constituent of Kraft paper is cellulose and the remaining components of the paper consist of lignin, hemicelluloses. The insulation is dried after winding. The dried paper is impregnated with insulating oil, which increases its dielectric strength and also serves to cool the windings.

4. Cellulose

The cellulose fibers consist of a bundle of cellulose molecules of different lengths which lay side by side. They are held together by hydrogen bonds involving the hydroxyl group (-OH group) on the adjacent molecules as in Figure 1. Cellulose itself is a linear polymer construct by a long straight chain of anhydrous glucose units which are linked together through the glycoside bond. The letter ‘n’ from Figure 1 represents the length of cellulose molecule and is measured in terms of the degree of polymerization (DP).

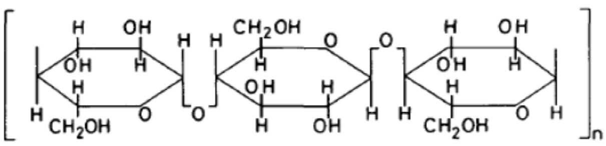

Figure 1. Structure of Cellulose

5. Ageing of Transformer Insulation

Most transformer failures can eventually be related to the deterioration of insulation with time. For liquid-filled transformers, the traditional insulation system is oil impregnated (cellulose) paper. The dielectric strength of the oil-impregnated paper is greatly affected by water contamination. The cellulose insulation must also maintain its tensile strength to be able to withstand the stresses that occur with surges, and must be able to withstand detrimental chemical transformations. Oxygen and water are the primary agents that degrade cellulose insulation. Heat acts as catalysts and accelerates the reactions in producing various oil-degradation products.

Paper aging in transformers is not uniform and follows thermal and moisture gradients. In addition, external layers are more exposed to higher concentrations of oxygen and the byproducts of aging in the oil. There are three main factors which promote paper degradations, which are thermal, oxidative and hydrolytic i.e.:

1. Hydrolysis
2. Oxidation
3. Pyrolysis

Historically, the loss of life of insulating paper has been determined by the reduction of its tensile strength. A 50% reduction of tensile strength has been used as the criteria for a long period of time. However, this has produced very conservative results. An alternative method using the degree of polymerization (DP) of the insulating paper has also been used to determine the electrical insulation life. Most recently, the relative dielectric constant and loss tangent methods are also being investigated by monitoring changes in capacitance and conductance as a function of frequency to determine the thermal age of a power as stated in the IEEE Standard C57.91-1995[41. Transformer insulation deteriorates as a function of time and temperature. Since the temperature distribution in most transformers is not uniform, the most common practice is to consider the aging effects produced by the hottest-spot temperature (θ_{hs}). Various transformer temperatures such as top oil, radiator surfaces, and cooling medium can be measured directly to estimate the transformer hottest spot temperature. Normal life expectancy is said to occur when transformers with a rated average winding rise of 65°C are operated continuously with hottest spot temperatures of 110°C. This value, (θ_{hs}) can be expressed in two different ways. It is based on the sum of the ambient temperature ($\theta_{a)}$ and the average winding temperature rise ($\Delta\theta_w$) and the hottest spot temp. rise margin above the average winding temp. rise ($\Delta\theta_1$). Hence,

$$\theta_{hs} = \theta_a + \Delta\theta_w + \Delta\theta_1 \qquad (1)$$

$\Delta\theta_1$ = 15°C for 65° average winding temperature rise.

To estimate accurately the hot-spot, winding and oil temperatures, one needs to consult the loading guides. There are two popular guides: the IEEE guide and the IEC guide. The IEC guide is applicable mainly for the non-thermally upgraded paper and the hot spot temperature is limited to 98°C at 20°C ambient temperature (78°C hot spot rise). The guide briefly mentions, without any further details, the use of thermally upgraded paper for 110°C hot spot temperature. Both standards utilize the top-oil temperature and the hotspot rise over top-oil for the calculation of the hot-spot temperature. However, the IEC uses the bottom-oil instead of the top-oil for direct-forced-oil flow transformers. The IEC has a limited discussion on loss-of-insulation-life and there is only relative-aging rate that is used to compare aging due to overload [6].

6. Condition Monitoring Methods for Power Transformer

The condition monitoring of transformer cab be carried out using following methods:

6.1. Measurement of dissipation factor (tan δ) and capacitance

The dissipation factor of power factor is an important source of data to monitor transformer and bushing conditions. This test is performed to determine the condition of capacitive insulation between different winding and compartments.

6.2. Dissolved Gas Analysis (DGA)

It is widely used to detect incipient faults in transformers. The main gases formed by decomposition of oil and paper are hydrogen, methane, ethane, ethylene, acetylene, carbon monoxide, carbon dioxide, oxygen and nitrogen. These gases dissolve in oil or accumulate above it and are analyzed by DGA. Some laboratories also report the contents of C3 and C4 hydrocarbon gases formed. DGA is the most widely used technique for detecting and monitoring faults in electrical equipment.

6.3. Insulation Resistance

Insulation resistance measurement may be the simplest field testing but also useful one that could determine whether tested object is integrally moistened or inter-connectively deteriorated. Generally, R_{60}, which is equal to resistance value of insulation after applied potential is subjected for 60 seconds, is an integrant; additionally absorptance (Ka) and polarization index (PI) are also needed to have an overall judge. It is worth noting that temperature translation is necessary before ranking to get normalized values.

6.4. Leakage Current

Leakage current measurement has the same testing circuit as insulation resistance measurement, but with much higher applied voltage and higher sensitivity which are easier to detect insulating defects and deterioration.

7. System Flow Chart

Figure 2 provides a summary of the scoring system and a flowchart of the main condition parameters that are used in this study for aging condition assessment. Figure 3 depicts result of developed software system for assessment of remaining life of new power transformer whose expected remaining life is 100% ideally. In the software developed in Visual Basic, standard acceptable values of different parameters related to testing of transformer insulation are considered. The testing considers electrical testing, oil testing, oil quality, temperature. An algorithm is able to calculate remaining life of transformer in hours or in percentage considering different parameters related to its insulation. It is observed that the remaining life of a new transformer is 99.99% (ideally 100%) considering all the insulation testing parameters as per standard requirement.

The same software system can be used to judge remaining life of any transformer on site. As well, same system is able to predict remaining life of same transformer even if some of testing parameters are not available considering the weighting factors for other available parameters in increased proportion.

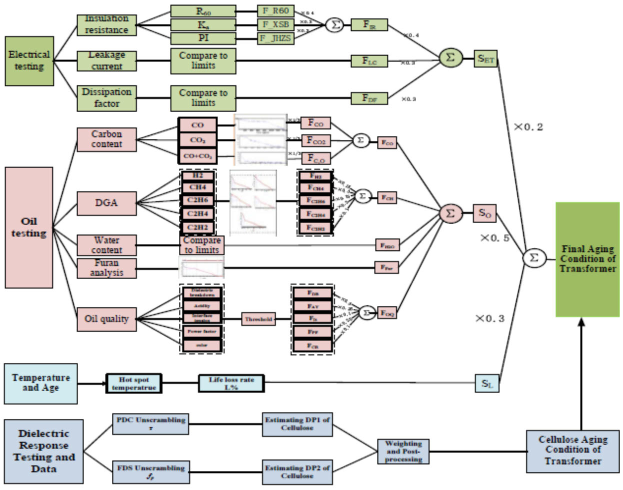

Figure 2. Flowchart for assessment of transformer aging with multi parameters [1]

Table 1. Standard Value Of Various Parameters Related To Power Transformer

Properties	U≤66kV	66<U≤22kV	U>220kV	Score
Dielectric strength(kV)	≥40	≥47	≥50	100
	35-40	42-47	45-50	80
	30-35	35-40	40-45	60
	<30	<35	<40	40
Acidity (mg(KOH/g))	≤.05	≤0.04	≤0.03	100
	0.05-0.1	0.1-0.15	0.03-0.07	80
	0.1-0.2	0.1-0.15	0.07-0.1	60
	≥0.2	≥0.15	≥0.1	40
IFT(25®C)	≥25	≥30	≥35	100
	20-25	23-30	25-35	80
	15-20	19-23	20-25	60
	<15	<19	<20	40
Tan δ	<1.5	<1	<0.5	100
	1.5-3	1-1.5	0.5-1	80
	3-4	1.5-3	1-2	60
	≥4	≥3	≥2	40
Colour	Light yellow			100
	Yellow			80
	Dark yellow			60
	Chocolate brown			40
Leakage current	100µA			
Power factor	0.8			

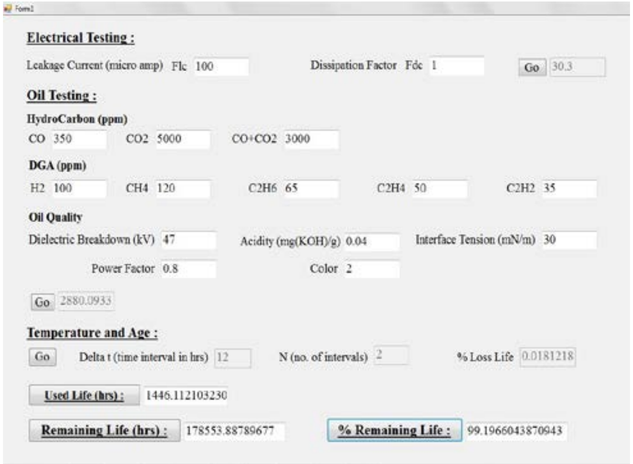

Figure 3. Result for remaining life of new transformer

8. Conclusion

In this paper, an approach to evaluate aging condition of power transformer is introduced based on multi-parameters. 'Aging Index' as a useful tool combines not only electrical testing and oil quality testing but also hot spot temperature to estimate transformer's aging rate. A corresponding software system is developed to help make condition based maintenance plan and replacement of transformers. Various transformer insulation properties like electrical properties, oil quality and temperature are considered in assessment of transformer's life. Weighting factors is a useful tool which combines not only electrical testing, oil quality testing but also hot spot temperature to estimate transformer's aging rate. The final total score represents aging condition of transformer. This assessment of remaining life of transformer helps us to predict the time duration for which a transformer has left in service.

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