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A Review on Ageing of Power Transformer and Insulation Life Assessment

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Abstract: *Power transformer is most important and valuable equipment of electrical transmission and distribution network. In fact, most of power transformer uses paper and oil as the main insulation and the mineral oil play important role of insulating and cooling of it, is similar to the blood in human body. There are mainly few possible mechanisms that subjected to the insulation degradation because of the ageing, high temperature and chemical reactions such as the hydrolysis, oxidation and pyrolysis. The condition of oil has to be checked on the basis of regularly and reclaimed when it necessary, to avoid the sudden failure of transformer. Failures of transformer can have lead to strong effect on security and reliability of power supply and cost. The temperature inside (temperature of oil and winding) a power transformer is varies with the load. Due to that higher operating temperature faster degradation of paper/oil insulation system in transformer and (thermal ageing) leads to change of some insulation characteristics, consequently the remaining life span of the power transformer is degraded.*

In this paper firstly, discussed the different types of insulations system used in transformers such as solid insulation and liquid insulation. Then the ageing process of insulation system used in transformer also has been discussed in detail. Here two parameter are affect the life of insulation of transformer, mainly load and ambient temperature. The estimated load factor and ambient temperature are input and used to find out hotspot temperature using hotspot temperature. Using IEC (international electro technical commission) INTERNATIONAL STANDARD 60076-7 we can easily find out ageing rate and loss of life of insulation. It was shown that the presented method can be used to proposed loss of insulation life in power transformer due to ageing.

1. INTRODUCTION

A power transformer is one of the most expensive and important key component and it represent the largest capital investment in electrical power transmission and distribution substation. For maintaining a reliability and efficiency (electricity power supply to consumer) of power transformer and high price of the insulation system, we have to control the insulation characteristics permanently. Since the power transformer is continuously suffering from the thermal, mechanical, electrical and chemical stress during its operation. It is necessary to several characteristics which can be measured to assess the present condition of the insulation system. [1]

The life of a power transformer is mainly depends on the condition of the insulation system (paper and oil) [3-5]. According to Experience of information the tap-changers and bushing are also contribute the failure the transformer. [2, 6]. However, they can be more easily repaired or replaced than transformer windings and their insulation. In this paper, the transformer life and the remaining lifetime prediction is focused mainly on thermal degradation of its paper insulation. According IEEE standard (ANSI/IEEE–C57.91),[7,8] the normal life time of the power transformer is 19-21 years and according to IEC standard (IEC–354.91) the normal life time of power transformer is not defined by IEC, but it is usually 30 years depending on the ageing rate determining by the hotspot temperature. [9, 10]

The insulation system of the power transformer is completely assembles with help of the dielectric insulating system. This dielectric insulation system cover the supporting structure such as winding wires, insulate the turns in winding from each other, separate different bodies from each other and from the core and tank.

The power transformer insulation system is mainly divided 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) winding and high voltage (HV) winding is subdivided into many oil ducts by means of solid insulating barriers. The insulation system of oil immersed power transformers consists of combination of liquid and solid insulations.

2. TRANSFORMER OIL

The Transformer oil is highly refined insulating oil; mainly it is mainly used for the insulation purpose. This insulating oil normally obtains from the crude petroleum product by fractional distillation process of crude petroleum and also known as the mineral insulating oil. Mineral oil was use as liquid insulators in electrical equipment for over hundred years now. Due to its excellent electrical insulating properties it can withstand at high temperature for an extended period. The availability of variety of synthetic oil and with greater properties, the mineral oil is economical. Mineral oil play two important role for transformer one is the liquid insulation in transformer and second one is the it is dissipate the heat in transformer i.e. act as coolant, is similar to the blood in human body. The mineral oil is also serve other two purpose, it help to protect core and winding as these are fully immersed inside oil and anther essential purpose of this oil is it protect the paper insulation of winding from the direct contact of atmospheric oxygen.

3. COMPOSITION OF OIL

Particular oil will contain a mixture of many different molecular spices and different type of carbon atoms. That difference in chemical composition it results will in different physical properties of the oil. Similarly mineral oil can vary contrast in its composition. Normally all mineral oil has hydrocarbon compound and 25 carbon atom per molecule in the form of composition. Generally two types of mineral oil are used in transformer; one is paraffin base transformer oil and other one is naphtha based transformer oil. This mineral oil is refined product of petrochemical crude. So the mineral oil contain either higher in paraffin compounds or higher in naphtha compounds. In addition the crude oil also contain considerable amount of aromatic and poly aromatic compound. For increasing the dielectric properties of the oil it must necessary to reduce the amount of aromatic and poly aromatic content from the crude.

4. INSULATING PAPER

For solid insulation purpose mainly Kraft paper, oil impregnated paper, pressboard paper etc. used in transformer. The winding of the power transformer cover with the multiple layers of Kraft paper (insulation) and transformer winding is immersed in mineral oil. The electrical and mechanical strength of the paper is mainly depend on the operating load, ambient temperature, winding temperature, different chemical and physical process of power transformer. The paper insulation must be withstood in front of all parameter which are above defined. The insulation strength is quantified from the dielectric properties of the paper. The transformer insulation paper and pressboard was not based on waste (used paper) paper or cotton waste but it is made from the high grade of cellulose [17]; cellulose is an organic material which is obtain from the vegetable sources such as cotton, hemp, manila, straw, wood and coniferous/deciduous tree because of it consist mainly of cellulose molecules [5]. The insulation paper is made by the delignification of wood pulp by the Kraft process. It mainly contains about 90% cellulose, 6-7 % lignin and the balance is hemicelluloses [22]. For improving insulation capacity of Kraft paper is completely dried after winding. The dried paper is impregnated with insulation oil, which increases its dielectric strength.

5. CELLULOSE

Cellulose insulation is primarily used in oil-filled transformer from distribution to large power transformer. The cellulose is an organic compound whose cell is made up of long chain of glucose rings. The cellulose is polymer of glucose unit's link to one another in a special manner which is shown in Fig. 1 (chemical structure of the cellulose). This is simply representing as a $[C_5H_{10}O_5]_n$, where n is the degree of polymerization (DP). Degree of molecular polymerization is nothing but the average number of glucose rings in the molecule [3]. The life of power transformer can be defined as for a given temperature of the transformer insulation, the total time between the initial states, for which the insulation is considered new and final state for which dielectric stress, short circuit stress, or mechanical movement which could occur in normal service, and could cause an electrical failure. So it must to be necessary to choose good cellulose paper which having good mechanical strength [22]. Because of the end life of the power transformer is equal to the end life of the insulation paper.

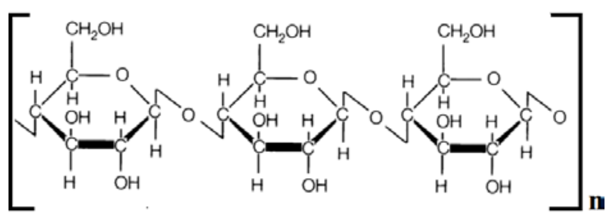

Fig. 1: Structure of Cellulose

6. INSULATION AGEING FACTOR AND THEIR EFFECT

Since the cellulose materials cannot be replaces once the winding are manufactured. For oil-immersed transformer the insulation system is oil impregnated paper (cellulose). The dielectric strength of the oil-impregnated paper is mainly dependent on temperature, moisture content, oxygen content, and acid content. The temperature of the insulation paper is main factor for ageing [11]. That temperature is maximum temperature in the winding insulation; use for calculation of ageing of insulation [11].

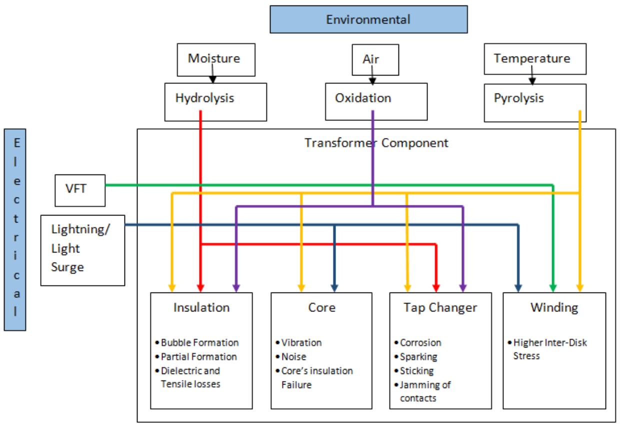

Fig. 2: Ageing factors & their effect on the main transformer components

When sudden increase in load results in increase in hot-spot temperature and causes the thermal decomposition of cellulose. Oxygen and water are the primary component that degrades in cellulose insulation life.

In a transformer normally many ageing processes occur. Insulation paper ageing is not uniform or complex process in transformer. In this paper mainly focus on the insulation of the transformer. In Fig. 2, the insulation of the transformer can be suffers from the environmental and electrical process; environmental factors such as pyrolysis (thermal degradation), oxidation (oxygen in the oil), and hydrolysis (moisture in the oil). These are the main factors which promote paper degradations.

Hydrolysis (Water)

The main sources of water comes in transformer are ingress of water from the atmosphere and the ageing in cellulose and oil. The oxygen bridge between glucose rings is affected by water, causing the break of the chains and result in reduction of DP and weakening of fiber [14].

Oxidation (Oxygen)

Oxygen attacks the carbon atom in the cellulose molecule to form aldehydes, acids, CO, CO_2. The main source of oxygen comes in transformer either from the atmosphere or from the thermal degradation of cellulose. The bond between glucose rings is wakened; result in degradation of DP [13].

Pyrolysis (Heat)

The main source of heat generation in transformer is maximum temperature of winding is known as hotspot temperature. This heat will contribute to the breakdown of individual cell of the cellulose chain. Sometimes due to the high temperature within a power transformer can cause the cellulose insulation to get reduce in size and become brittle; and the reduction in the DP of cellulose [12].

7. KRAFT PAPER AND THERMALLY UPGRADED INSULATION PAPER

Previously the transformer insulation paper and pressboard are made from the unbleached cellulose material by Kraft chemical process. Since the 1960's this type of Kraft paper has been used as transformer solid insulation [15]. Due to cheap and even it can meet the specific physical, chemical and electrical properties; up to present most of power transformer manufactures design to use Kraft paper as solid insulation [15,17].

But in order to increase the transformer insulation life since mid of 1960's especially thermally upgraded paper used in high rated transformer [17]. The purpose of thermally upgrading is to neutralize the acids and enhance thermal resistance. The hydrolysis effect could be reduce by neutralize the acid and the result in insulation ageing rate is reduced by the factor of 1.5% -3% [16, 18].

Thermally upgrade paper has much higher percentage of their tensile strength and bursting strength. Additionally, it is more reliable. In [19, 20] Fig. 3 it is shown that depolymerisation process with time in thermally upgraded paper is much slower than non-thermally paper (Kraft paper).

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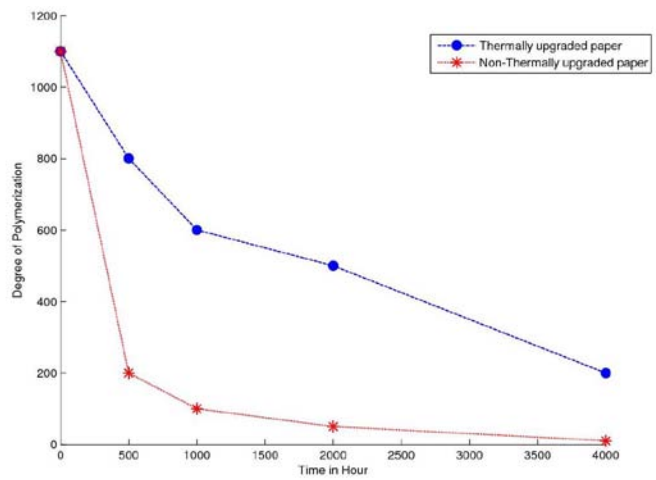

Fig. 3 Sealed tube accelerated ageing in mineral oil at 150 °C [21]

Transformer Relative Ageing Rate

The ageing of insulation is a time function of temperature, moisture content, oxygen content and acid content. The distribution of the temperature is not uniform. So, relative ageing rate is the rate at which the degradation of the cellulose (insulation paper) for a hot-spots temperature is reduced or accelerated compared with the degradation rate at a reference hotspot temperature [21].

For thermally upgraded paper, equation 1; which is neutralize the acid content to improve the stability of the cellulose structure, the relative aging rate V_{TUP} is

$$V_{TUP} = e^{\frac{15000}{110+273} - \frac{15000}{\theta_h+273}} \quad (1)$$

Where,

110 ℃ is the rated reference hot-spot temperature for thermally upgraded paper.

θ_h is the hot-spot temperature in ℃ .

And for non-thermally upgraded paper, equation 2; the relative ageing rate V_{NTP} is

$$V_{NTP} = 2^{(\theta_h - 98)/6} \quad (2)$$

Where,

98 ℃ is the rated reference hot-spot temperature for non-thermally upgraded paper.

θ_h is the hot-spot temperature in ℃.

In Equation (1), the relative aging rate for the thermally upgraded paper is higher than one for hot-spot temperatures greater than 110℃, and it is less than one for hot-spot temperatures less than 110℃ [21].

Table 1: Relative ageing rates due to hot-spot temperature [21]

Hot-spot Temperature In Degree C	Non-Upgraded Paper VNTP	Thermally Upgraded Paper VTUP
80	0.125	0.036
86	0.25	0.073
92	0.5	0.145
98	1	0.282
104	2	0.536
110	4	1
116	8	1.83
122	16	3.29
128	32	5.8
134	64	10.1
140	128	17.2

Additionally in Equation (2), the relative aging rate for the non-thermally upgraded paper is higher than unity for hot-spot temperatures which are greater than 98℃, and it is less than unity for hot-spot temperatures which are less than 98℃ [21].

Equation (1) and Equation (2) are very sensitive to the hot-spot temperature that can be seen in table 1.

From the table 1 conclude that the relative ageing rate of non-thermally upgraded paper is higher than the thermally upgraded paper for their respective temperature. So, most of the transformer manufacturer uses thermally upgraded paper for increasing the life time of the paper insulation; the result in increasing life span of the transformer. Fig. -4 indicates the characteristic of relative ageing rate with respect to the hot-spot temperature [21].

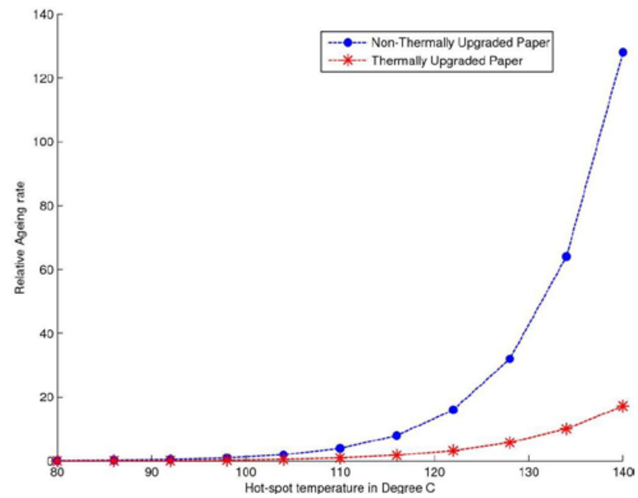

Fig. 4 Characteristic of relative ageing rate with respect to hot-spot temperature for thermally upgrade paper and non-non-upgrade paper

8. LOSS OF INSULATION LIFE CALCULATION

The loss of life over a certain time period is equivalent to life consumed by the insulation in hours or days during that time. Mathematically it is calculated by integrating the relative ageing rate over certain period of time.

The loss of life L in continuous-time [21] from over a period of time, say from t_1 to t_2, is

$$L = \int_{t_1}^{t_2} V \, dt \quad (3)$$

And, in discrete-time form [21] and over a certain number of time intervals, it is

$$L = \sum_{n=1}^{N} V_n * t_n \quad (4)$$

Where,
V_n = relative aging over a certain period of time n,
t_n= time interval of the period,
N = total number of intervals.

9. NEW IDEA TOWARD INSULATION LOSS OF LIFE CALCULATION

In this paper we consider a variable current source for calculating the hot-spot temperature. The output of the variable current source is 4-20 ma range and also the output of the temperature sensor in the range of 4-20 ma. So right now in this paper we consider variable current source beside of temperature sensor.

Before we are going to implementation on any Hardware or MCU (Microcontroller Unit) we have a first implemented equation (1) and equation (4) [21] in C programming. For implementation in C language we consider the hot-spot temperature ranges from 50-200℃ and the value of the current is the 4-20 ma. So if the value of current is set to 4 ma, the value of the hot-spot temperature is 50 ℃ similarly, if the value of current is the 20 ma, the value of the hot spot temperature is 200 ℃ ; this mathematical equation is implemented with the help of linear equation y=MX + C.

So here for this paper we found a linear equation from the calculation is

$$Temperature = \frac{75X + 100}{8} \quad (5)$$

Where, X is a value of current

With the help of the above equation (5) calculated value of the hot-spot temperature by putting the value of the current.

For implementation of the programming in the C language the value of the current, (from equation 4) the value of the time interval (sampling time t_n), and the value of number of samples (N) is enter by the user.

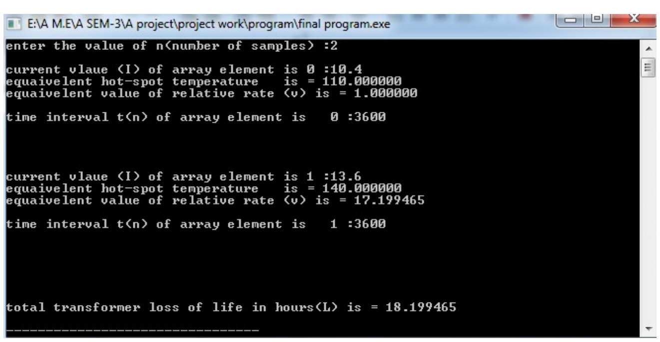

Fig. 5: Final output for the loss of life calculation using C programming

The below Fig. -5 show that the output window of the C language. From the Fig. -5, conclude that operating time of the controller is only 2 hours but the loss of life of power transformer from the total life is 18 hours, which was because of the hot-spot temperature. During the 2nd sample the value of the relative ageing rate is exceed from the unity for the value of the hot-spot temperature 140℃ . And one more thing is in this paper we have an implement this C program for the thermally upgrade paper because of the insulation life for the transformer is greater than the non-thermally upgraded paper.

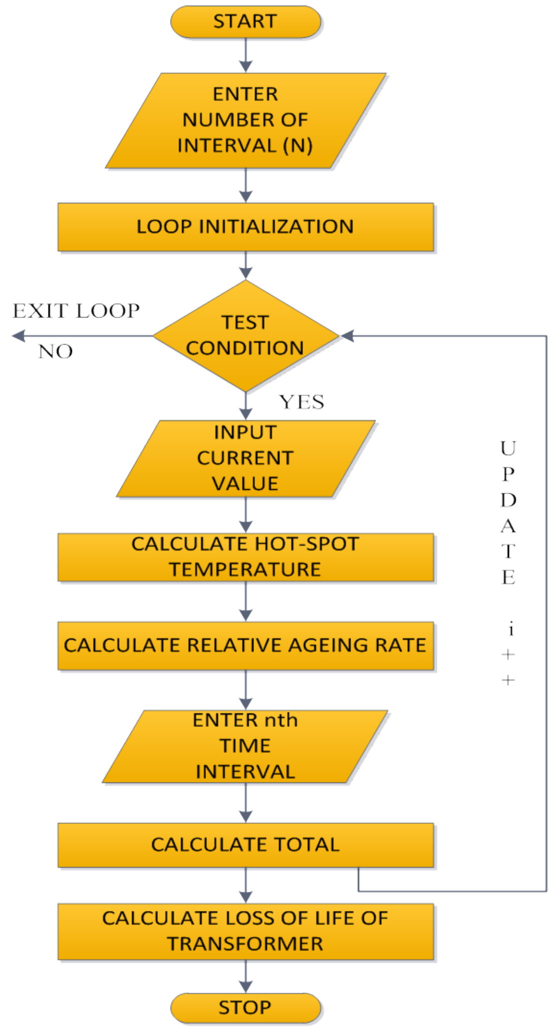

Fig. 6: Flow Chart of the C programming

10. CONCLUSION

In this paper, described various insulation systems that are used in the power transformer. The strength of insulation systems are described by the dielectric properties and mechanical strength of it. The dielectric properties of transformer paper insulation are mainly determined by the environmental ageing factor. So, the insulation ageing of power transformer is determined by temperature, moisture and oxidation. In the Fig. -3 show that thermal upgrading paper agents is used to extend the life of power transformer. We observed that the relative ageing rate of the insulation system increases when the rapidly, as the increase in the temperature.

The final score of output of C window represent that the transformer operating hours are only 2 hours and loss of life in power transformer is 18 hours. So finally we conclude from this output is that if the value of relative ageing rate of insulation paper exceeds from the unity it can create the bad impact on life of power transformer.

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