

TRANSFORMER LIFE PREDICTION USING DATA FROM UNITS REMOVED
FROM SERVICE

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ABSTRACT

Power transformers are used in the transmission and distribution of electrical power. Installed at power stations, they could be used to raise the voltage from the generators, and transformers at local substations could reduce voltage to supply loads. Power transformers are very important in this day and age, where electricity has almost become a necessity of life. Hence, effort should be taken into studying them and learning all we can about maximizing their efficiency, cost effectiveness, and lifespan. Predicting the lifespan of a power transformer has been considered an important issue for energy companies for some time. Power transformers that reach the end of its life usually do so unexpectedly, causing power reliability problems, which cost a lot of money. Knowing the factors that play part in the degrading process of a power transformer could help power companies determine how long a power transformer have before breaking down, and allow them to perform any necessary action (i.e. replacement) before the power transformer starts giving problems. Applying IEEE transformer loading guide the life consumed during a transformer operation could be assessed by the ambient temperature and loading profile. This helps to understand the "health" condition of a operating transformer and assess the remaining life of the transformer. This project carried out study on thermal modelling of a transformer. Using statistical data of the weather and power system, the power transformer life will be estimated and analysed. This project focuses on the life assessment of the insulation for power transformers by using thermal modelling. Load and ambient temperature are the two important factors that influence the life of insulation in transformers.

ABSTRAK

Kuasa pengubah digunakan dalam penghantaran dan pengagihan kuasa elektrik. Apabila dipasang di stesen jana kuasa, ia boleh digunakan untuk meningkatkan voltan daripada penjana; transformer di pencawang tempatan pula boleh mengurangkan voltan sebelum tiba ke rumah pengguna. Kuasa pengubah sangat penting di zaman ini, di mana tenaga elektrik telah hampir menjadi satu keperluan. Oleh itu, usaha hendaklah diambil dalam mempelajari faktor-faktor yang boleh memaksimumkan kecekapan, keberkesanan kos, dan jangka hayat pengubah. Meramal jangka hayat pengubah telah dianggap sebagai isu penting bagi syarikat-syarikat tenaga. Kuasa pengubah yang mencapai akhir hayat kebiasaannya tidak dapat dijangka. Ini menyebabkan masalah ketiadaan kuasa elektrik yang tidak dirancang terlebih dahulu dan akan mengakibatkan kerugian yang besar. Faktor-faktor yang memainkan peranan dalam proses pengurangan kuasa pengubah perlu dikaji supaya boleh membantu syarikat-syarikat kuasa menentukan berapa lama baki jangka hayat sesebuah transformer kuasa, dan membolehkan mereka melaksanakan apa-apa tindakan yang perlu (seperti penggantian) sebelum pengubah mengalami masalah. Menggunakan IEEE bebanan pengubah membantu menentukan jangka hayat semasa pengubah beroperasi boleh ditaksir dengan suhu ambien dan profil bebanan. Ini dapat membantu memahami keadaan sebuah pengubah yang beroperasi dan menilai baki jangka hayat pengubah. Projek ini menjalankan kajian berdasarkan model terma pengubah. Menggunakan data statistik cuaca dan sistem kuasa, jangka hayat pengubah kuasa akan dianggar dan dianalisis. Projek ini menumpukan kepada penilaian jangka hayat penebatan untuk pengubah kuasa dengan menggunakan model terma. Baban dan suhu ambien ialah dua faktor penting yang mempengaruhi jangka hayat bagi penebatan pengubah.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	-	Constant
B	-	Ageing rate constant
θ_H	-	Hot spot temperature
F_{AA}	-	Ageing acceleration factor
pu	-	Per unit
IEEE	-	The Institute of Electrical and Electronics Engineers
IEC	-	International Electrotechnical Commission
θ_{oil}	-	Top oil temperature
$\Delta\theta_{HR}$	-	Rated hot-spot temperature rise above top oil
I	-	Load current
I_R	-	Rated current
I_{pu}	-	Load current per unit
θ_A	-	Ambient temperature
β	-	Ratio of load to no-load losses
τ_{oil}	-	Top oil time constant
$\Delta\theta_{oil-R}$	-	Rated top oil rise over ambient
$P_{EC-R(pu)}$	-	Rated eddy current loss at the hot spot location
$\Delta\theta_{H-R}$	-	Rated hot spot rise over ambient
τ_H	-	Winding time constant at the hot spot location
L	-	Loss of life
F_{EQA}	-	Per unit loss of life factor
m	-	Winding exponent
n	-	Exponent defines non-linearity

CHAPTER 1

INTRODUCTION

1.1 Introduction

The lifetime of transformers is usually considered to be around 30-50 years. A substantial number of transformers were installed worldwide around the 1950s [1]. Some of them are still in use and most of them were recycled. The reason that some of them are still in use is the cost and the most important of all, good maintenance. According to the guide for loading mineral oil immerse transformers, the life expectancy of a transformer operating at 110°C are at a maximum of 180.000 hours or 7500 days, with a normal percentage loss of life at 110°C for 24h at 0.0133% [2]. This of course varies, depended on the type of the transformer.

Companies that use transformers, try to predict their lifetime and use them until the end of their life. An estimation of the lifetime of the transformer is not an easy task since a lot of parameters are involved. If there is an error as far as it concerns the prediction then as a result we have a transformer failure. This, despite the fact that have back up generation and other equipment that support the system serious problems can be caused at the grid, and other piece of equipment that is

connected to the transformer. Multiple transformers where is essential to perform the estimation separately for each transformer.

The condition that limits the transformer loading capabilities is the temperature of the winding and the insulation [3] or more specific, is depended on the average temperature on the hottest spot of the insulation system [4].

1.2 Problem Statement

Most UK transmissions transformer which is currently in service has been installed for 40 or even more years. They are approaching the end of their normal operating lifetime. Ageing equipment is a serious contributing factor to poor system reliability and high operating costs in many utilities. Moreover, simultaneous transformer installation will probably lead to simultaneous failure and replacement in the future. The replacement requires a lot of capital investment and it represents a financial burden for utilities over coming years. Therefore it is important for utilities to know when to replace ageing transformers so that the replacement could be scheduled in a manner to lower the cost and give minimize impact on customers.

1.3 Objective

The main objective of this research is to determine the factors that affect the power transformer life span and to come up with a method of estimating the remaining life of the transformer. Its measureable objectives are as follows:

- Calculate the lifetime of transformer base on their actual loading profiles and ambient temperature data.
- Study the ageing factors which can affect the operation of transformers
- Derive a method to estimate consumed lifetime of an operating transformer

1.4 Scope

These scopes of this study are:

- Literature review of lifetime estimation for transmission transformers; (IEEE & IEC website, searching through key words like “transformer”, “thermal modelling” and “lifetime estimation”).
- Understand ageing factors, loss of life equation of cellulose, transformer thermal design, and loading / ambient conditions.
- Compile data for operation and specifications of transformer.
- Create Matlab programme to calculate the age /loss of life and the temperature critical points monthly and yearly. This will be done with the help of IEC standard equations.
- To discover and examine a new method for calculating the duration of transformers life which will involve the effect of factors such as oxygen, moisture and acid and also be faster using linear / non-linear estimations.

CHAPTER 2

LITERATURE REVIEW

2.1 Transformer background

A transformer consists of the core which provides the path for the magnetic lines of flux, the primary winding which receives energy from the source, the secondary winding which receives energy from the primary and transmits it to the system and finally the enclosure which protects the above from dirt, moisture and mechanical damage [1]. Each winding has a number of turns N which is responsible for the ratio of current and voltage. Equation (2.1) shows the relationship between N , current and voltage.

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} \quad (2.1)$$

Transmission transformers are considered to be the most important apparatus in a power system since without them transmission cannot be achieved.

Many systems throughout the world are still using transformers that have exceeded the expected lifetime. According to “IEC standard” in order to have a relative aging rate of 1.0 and consider a temperature point of 98°C. Lots of engineers developing methods for calculating the loss of life are surprised when they discover for how many years those transformers are in operation. The main reason for their restitution is maintenance.

Other methods were examined in the past regarding the calculation of the loss of life of the transformer. However, ageing models in current international standards, such as IEC and IEEE, do not consider the effect of secondary ageing factor such as moisture and oxygen because of limited data. As a result, the models might not accurately predict the lifetime of the transformer. The high cost and the tremendous consequences, in the case of failure, of the transformer are considered to be the main reasons to predict their lifetime. Engineers are trying to develop an approximation which will allow companies to use the transformer until the end of its life. In the case where a wrong estimation is made and a transformer fails during operation, major problems may occur to the grid and other apparatus of the power system. This is the main reason why transformers are divided into categories according to their characteristics and their operating conditions [3, 4].

2.2 Literature review of insulation

Transformer insulation consists mainly of paper and mineral oil. When talk about “loss of life” of a transformer, is actually mean the loss of life of its insulation. Transformer insulation degrades as a function of time and temperature. Due to the fact that temperature distribution is non-uniform throughout the transformer, in our calculations we are going to use the winding hottest spot temperature which is located at the top middle of it. The main component that composes the insulation from the beginning of the transformer’s birth is cellulose which composes the Kraft paper.

2.2.1 Cellulose structure

“Cellulose ($C_6H_{10}O_5$) is one of many polymers found in nature” [5]. Wood, paper and cotton all contain cellulose. In order to investigate insulation’s life we must have a

clear idea of what cellulose paper is. In Figure 2.1 we can observe the molecular structure and some of its decomposition products.

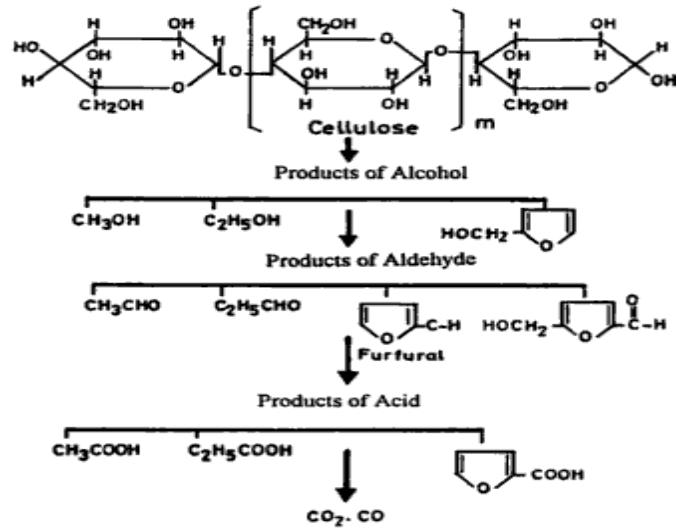


Figure 2.1: Cellulose molecular decomposition [6]

Paper can be affected by the occurrence of three main events. These events are known as hydrolysis, oxidation and the most important of them pyrolysis. Hydrolysis is when the oxygen bridge in the molecular structure of cellulose is affected by water. Oxidation is when oxygen attacks the carbon atoms in the cellulose molecule releasing water, carbon monoxide/dioxide. Pyrolysis is when heat in the extreme will result in charring of the fibers [9]. From the degree of polymerization (DP), which is indicated from the number of cellulose molecules (m) and is usually of the order of 1000-1200 for a brand new cellulose paper, we can have a poor estimation of the lifetime. The critical point where the paper is at the end of its lifetime is when (m) decreases to 200 [6]. The reason why this is a poor estimation, is because surveys have shown that due to the exposure in high temperatures the dielectric strength does not vary much when compared with the degree of polymerization [6].

2.2.2 Mineral oil

Mineral oil in transformers can be used as insulating and cooling medium. In oil filled transformers water, heat and oxygen are considered to be the catalyst, the accelerator and the active reagent in the oxidation of oil. From the oxidation of oil we have products such as acids, esters and metallic soaps that speed up the decomposition of cellulose insulation, therefore decreasing the lifetime of the transformer [7]. In order to minimize the effect of oxidation, the design of the transformer allows the oil to be renewed during maintenance. In figure 1.2 we can observe the structure of mineral oil.

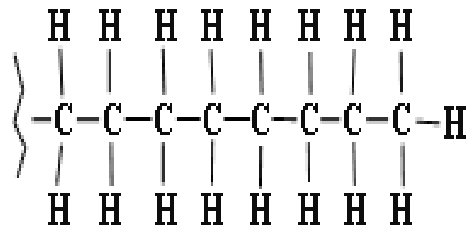


Figure 2.2: Mineral oil structure [8]

2.3 Acidation factor

Factors that affect the oxidation of oil such as moisture-water and oxygen must be taken into consideration while estimating the lifetime of a transformer. Despite the fact that load and temperature are the main factors that affect the loss of life, moisture-water and oxygen have a major contribution to it. Acidation factor is a combination of moisture and oxygen content in oil. We will use it to represent the effect of these secondary factors to the loss of life of the insulation.

2.3.1 Moisture-Water in oil

Transformer's insulating oil has a low comprehensiveness of water. Despite that, with the rise of temperature we can see that the solubility of it increases, making it a large factor that affects the lifetime of the insulation. We can identify the presence of water in three states. Mostly we can find it in a dissolved state, but several measurement techniques have shown that water also exists in the oil firmly bound to the oil molecules. However, the second state has driven to the third. When moisture level in oil exceeds the saturation value, there will be free water in the tank in the form of drops [10].

2.3.2 Moisture-Water in paper

Water and moisture in paper can be found in four forms. "It can be found as vapour, as free water in capillaries, as imbibed free water and it can be absorbed to surfaces"[10]. When compared to oil, paper has larger concentration in moisture therefore the effect in paper is more severe.

2.3.3 Oxygen in insulation

Oxygen in insulation is mostly due to polar compounds found in transformer oil and is responsible for oxidation as mentioned in section 1.3.1 [10]. Actually is considered to be the product of water and moisture.

2.4 Hot-spot Temperature

Knowing the precise temperature of the winding hot spot is the single most critical measurement one can make within a transformer. The common winding temperature indicator does not measure winding hot spot or any winding temperature.

The top oil temperature is measured and has an additional temperature gradient added to it which is proportional to the square of the winding load. This additional heat is added with a heater coil wrapped around the top oil temperature probe that adds heat with current set up by a current transformer placed on the transformer bushing. This is defined as the winding hot spot gradient or copper rise and is shown in plot below;

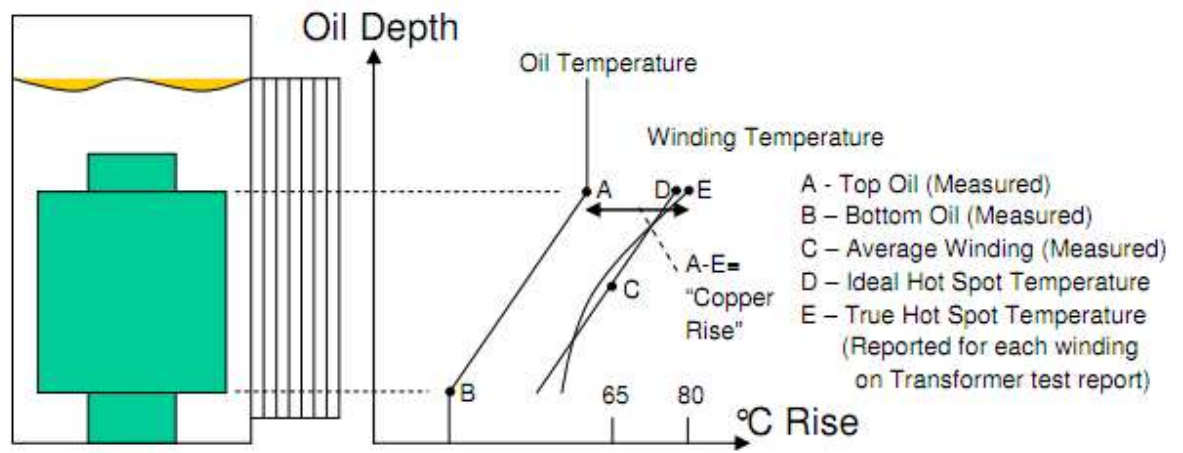


Fig. 2.3: Hot-spot of a power transformer is calculated by first measuring the top-oil temperature.

2.5 Aging of insulation

A power transformer's solid insulation has two essential characteristics: dielectric strength and mechanical strength. Dielectric strength is maintained until the insulation is exposed to certain elevated temperatures. At that point, the insulation also

becomes brittle and loses its mechanical strength. If the elevated temperatures are severe, the insulation will no longer be able to maintain its properties, resulting in insulation failure and ending the useful life of the transformer. Side effects of insulation aging include the formation of water and oxygen. However, with new oil preservation systems, these formations can be minimized, leaving the insulation temperature exposure as the controlling parameter for control personnel. In the late 1940's, it was discovered that the aging of insulation is part of a chemical process. Its reactions vary with temperature according to the Arrhenius equation.

$$K_o = Ae^{B/(\theta+273)} \quad (2.2)$$

The IEEE standard C57.91-1995 translates this equation on a per unit life basis indicated by the curve in Figure 2.3.

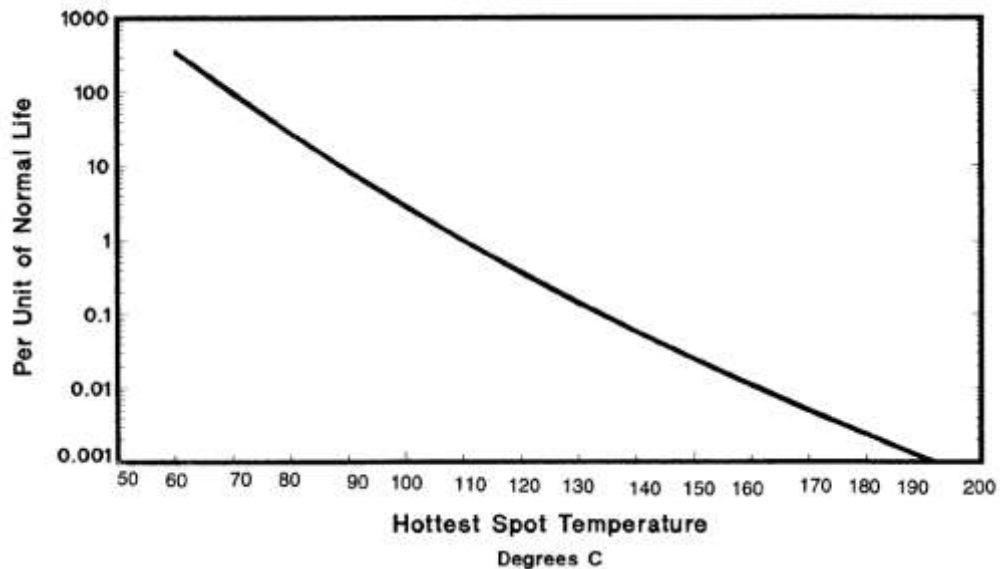


Figure 2.4: Transformer Insulation Life.

The equation for per unit life curve is shown below:

$$\text{Per Unit Life} = 9.80 * 10^{-18} e^{[15000 / (\theta_H + 273)]} \quad (2.3)$$

Where θ_H is the hot spot temperature.

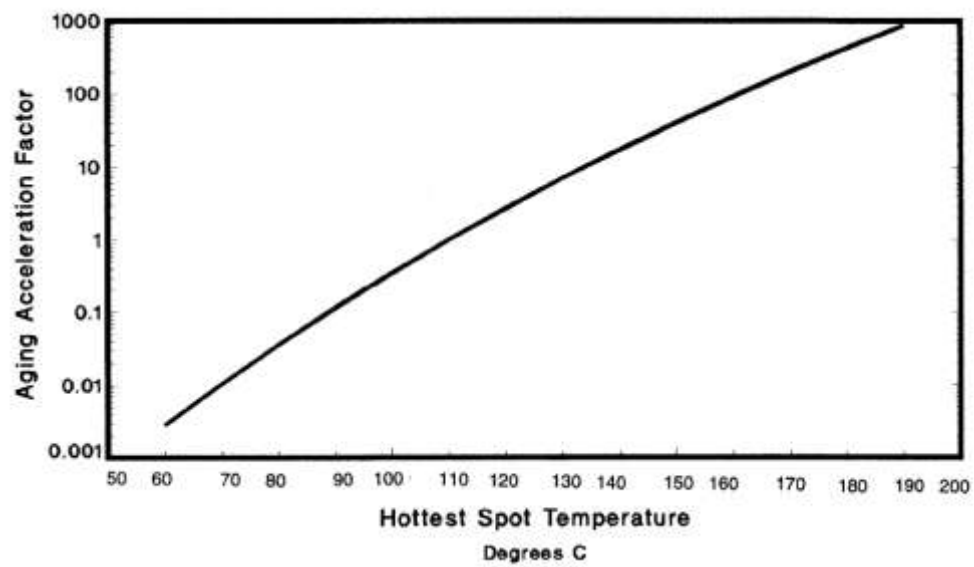


Figure 2.5: Aging Accelerator Factor.

The aging accelerating factor is calculated using the following equation:

$$F_{AA} = e^{\left[\frac{B}{383} - \frac{B}{\theta_H + 273}\right]} \text{ pu} \quad (2.4)$$

where B is a constant.

2.6 Transformer winding hot spot determination

Loading capability of power transformers is limited mainly by winding temperature. As part of acceptance tests on new units, the temperature rise test is intended to demonstrate that, at full load and rated ambient temperature, the average winding temperature will not exceed the limits set by industry standards. However the temperature of the winding is not uniform and the real limiting factor is actually the hottest section of the winding commonly called winding hot spot. This hot spot area is located somewhere toward the top of the transformer, and not accessible for direct measurement with conventional methods.

The temperature of solid insulation is the main factor of transformer aging. With temperature and time, the cellulose insulation undergoes a depolymerization process. As the cellulose chain gets shorter, the mechanical properties of paper such as tensile strength and elasticity degrade. Eventually the paper becomes brittle and is not capable of withstanding short circuit forces and even normal vibrations that are part of transformer life. This situation characterizes the end of life of the solid insulation. Since it is not reversible, it also defines the transformer end of life.

Wet transformers (solid insulation showing more than 2% water content) incur an additional risk when operating at high temperature. It has been shown that the residual water trapped in paper may reach bubbling conditions and escape from paper under the form of water vapor bubbles. These bubbles may move with the oil flow, or get trapped in the winding and in both cases create a threat for insulation breakdown. No wonder that the transformer operator attempts to control the winding hot spot temperature with the best mean available.

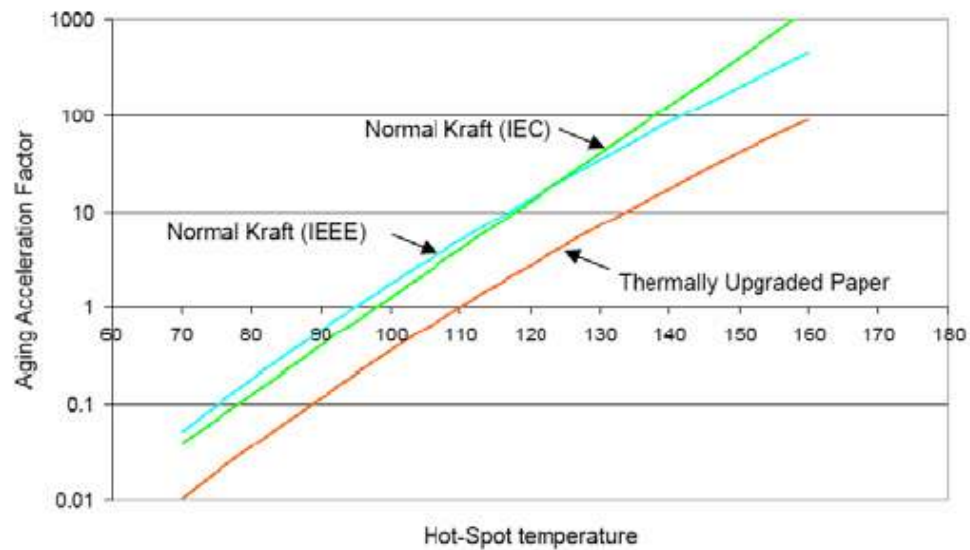


Figure 2.6: Effect of temperature on paper aging rate

For several decades IEEE and IEC loading guides have been providing guidelines for the calculation of the winding hottest spot temperature from data that can be conveniently measured and parameters derived from temperature rise test or manufacturer calculations. The basic calculation method relies on the measurement of oil temperature at the top of the transformer tank and a calculation of the temperature difference between the winding hottest spot and the top oil. This temperature rise is provided by the manufacturer, based on his modeling of oil flow and losses distribution in the winding. Thereafter the hot-spot temperature can be computed for any load using the standard relation:

$$\theta_H = \theta_{oil} + \Delta\theta_{HR} \left(\frac{I}{I_R}\right)^{2m} \quad (2.5)$$

Where:

θ_H = Hot-spot temperature

θ_{oil} = Top-oil temperature

$\Delta\theta_{HR}$ = Rated hot-spot temperature rise above top oil

I = Load current

I_R = Rated current

m = Winding exponent

This simple formula was completed with an exponential function to account for the thermal inertia of the winding when a sudden load increment is applied.

2.7 Thermal model and life loss equations

The top oil thermal model is based on the equivalent thermal circuit theory proposed by G.Swift. The differential equation for the equivalent circuit is;

$$\frac{I^2\beta+1}{\beta+1} \cdot [\Delta\theta_{oil-R}]^{\frac{1}{n}} = \tau_{oil} \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_A]^{\frac{1}{n}} \quad (2.6)$$

Where,

I_{pu} is the load current per unit.

θ_A is the ambient temperature, °C.

θ_{oil} is the top oil temperature, °C.

β is the ratio of load to no-load losses.

τ_{oil} is the top oil time constant, min.

$\Delta\theta_{oil-R}$ is the rated top oil rise over ambient, K.

n is the exponent defines non-linearity.

As the same mentioned method, the differential equation used to calculate the hot spot temperature is;

$$\frac{I^2[1+P_{EC-R}(pu)]}{1+P_{EC-R}(pu)} [\Delta\theta_{H-R}]^{\frac{1}{m}} = \tau_H \frac{d\theta_H}{dt} + [\theta_H - \theta_{oil}]^{\frac{1}{m}} \quad (2.7)$$

Where,

θ_H is the hot spot temperature, °C.

$P_{EC-R}(pu)$ is the rated eddy current loss at the hot spot location

$\Delta\theta_{H-R}$ is the rated hot spot rise over ambient, K.

τ_H is the winding time constant at the hot spot location, min.

It is assumed that insulation deterioration can be modelled as a per unit quantity for a reference temperature of 110°C, the equation for accelerated aging is;

$$\text{Accelerated Ageing} = e^{\left[\frac{B}{383} - \frac{B}{\theta_H + 273}\right]} \text{ pu} \quad (2.8)$$

where B is the ageing rate constant.

The loss of life over the given load cycle can be calculated by;

$$L = \int F_{AA} dt \quad (2.9)$$

The per unit loss of life factor is;

$$F_{EQA} = \frac{\sum_{n=1}^N F_{AA,n} \Delta t_n}{\sum_{n=1}^N \Delta t_n} \quad (2.10)$$

Percentage loss of life is;

$$\% \text{ Loss of Life} = \frac{F_{EQA} \times 24 \times 100}{\text{Normal Insulation Life}} \quad (2.11)$$

The model created for oil-immersed power transformer has the following specifications. (ONAF – 250MVA). Parameters of the power transformer were taken in the IEEE Loading Guide and are shown in Table 2.1.

Table 2.1: 250MVA Transformer Parameters

No Load	78100 W
P_{dc} losses ($I^2 R_{dc}$)	411780 W
Eddy losses	41200 W
Stray losses	31660 W
Rated top oil rise over ambient	38.3 °C
Rated hot spot rise over top oil	20.3 °C
Ratio of load losses to no load losses	6.20
pu eddy current losses at hot spot location, LV	0.65
pu eddy current losses at hot spot location, HV	0.3
Top oil time constant	170 min
Hot spot time constant	6 min
Exponent n	0.9
Exponent m	0.8

2.8 Description of Previous Methods in Transformer Life Estimation

2.8.1 Thermal Aging of Distribution Transformers

There are two standards in which a power transformers thermal aging can be measured, IEEE Standard and IEC Standard. IEEE states that a power transformer would normally have 180000 hours of life, whereas IEC has no defined total transformer life, though it is most often mentioned that the transformer life is 30 years. The difference between these two standards is mainly caused by the hot spot temperature at which there is normal aging (110°C according to IEEE and 98°C according to IEC).

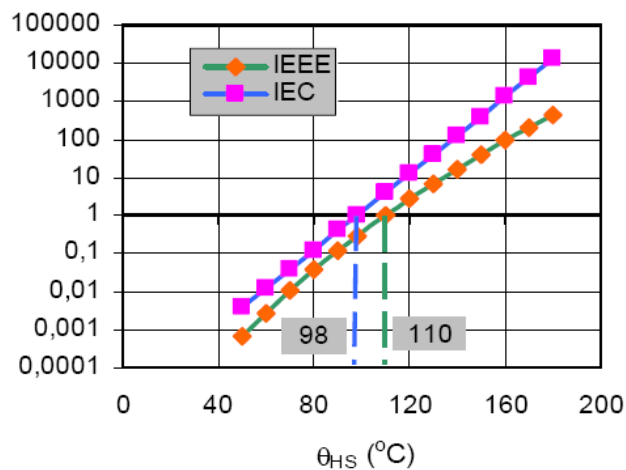


Figure 2.7: Aging rate (p.u) depending on the hot spot temperature according to IEEE and IEC.

Comparing the two standards for determining loss of life requires the following assumptions be made:

- The transformer has a normal aging rate at 98°C,
- The normal ambient temperature is 20°C,
- Normal aging rate is 30 years,
- Same load cycle and ambient temperature.

The comparison held the following results:

Table 2.3: Loss of life determined according to IEEE and IEC at same input data.

	IEEE	IEC
Hot-spot temperature	114.17 (°C)	108.6 (°C)
Maximal ageing rate	3.04 (p.u)	6.478 (p.u)
Loss of Life	0.5246 (p.u) = 12.591 (hours)	0.5209 (p.u) = 12.502 (hours)

The analysis shows that the loss of life of the transformer when using IEEE and IEC standards is not that different.

2.8.2 Loading of transformers beyond nameplate rating

The rating of a distribution transformer is usually assigned for continuous operation at that value. However, extraordinary events, such as overvoltages, short-circuit in the system and emergency loading can affect the life of a transformer to a high degree [9].

Consequences of loading a transformer beyond name-plate rating can be as follows:

- 1) The temperatures of windings, insulation, oil etc. increase and can reach unacceptable levels.
- 2) The leakage flux density outside the core increases, causing additional eddy current heating in metallic parts linked by the flux.
- 3) The moisture and gas content in the insulation and in the oil increase with the temperature increase.
- 4) Bushings, tap-changers, cable-end connections and current transformers are exposed to higher stresses.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Life consumption of insulation in transformers is governed by several factors. The main factors are load and the ambient temperature. In order to assess the life consumed in an interval due to the loading and ambient conditions that have to identify from historical data, the present and the future load and ambient profile.

If the hourly load and ambient values are known, then the IEEE models in [5] can be used to calculate the consumed life at any point in time. The first challenge therefore is the accurate prediction of the load profile and the ambient temperature profile. The output current and ambient temperature data from a GSU transformer are showcased below to illustrate our method.

Transformer loss-of-life calculation needs the operating history of a transformer, mainly the loading and the ambient temperature data. In attempts to compensate the lacking of the exact data, some researchers [17, 78] used limited data obtained from power system operators and meteorology office and developed a method based on statistical analysis.

3.2 Loss of life calculation

The calculation of the loss of life is based on an ageing model taken from the IEC standard “Loading guide for oil-immersed power transformers” which has as main parameter the winding hot-spot temperature. As mentioned in the introduction the main factors that can affect the lifetime of the transformer are ambient temperature and load. We consider that these two factors affect a specific temperature point in the transformer which is called “winding hot-spot” (Θ_H). According to the IEC standard, that temperature point controls the loss of life through the following equation:

$$V = 2^{(\Theta_H - 98)/6} \quad (3.1)$$

Where,

V = Relative ageing rate

Θ_H = Winding hot spot temperature

98°C = Temperature point where the IEC standard considers V to be 1.0

6°C = It represents the rate of deterioration of mechanical properties that is doubled for each 5-10°C increase in temperature. The doubling factor is not a constant. Is considered to be 6°C and 8°C for temperature range of 100-110°C and above 120°C respectively [7]. For the scope of the project is considering it to be constant at 6°C.

By calculating V can use the equation shown below in order to find the loss of life of a transformer over a certain period of time:

$$LOL = \int_{t_1}^{t_2} V dt \quad (3.2)$$

Θ_H is not a direct measurement but in order to be able to estimate the loss of life of a transformer Θ_H have to be calculate. Θ_H is considered to be a temperature point which is located at the top middle of the transformer. Due to the fact that the circulating hot oil in the transformer seats at the bottom, the hot air produced by it, is concentrated at the top middle where its considered to be the hottest spot.

3.3 Mathematical equations explanation

In order to be able to calculate the loss of life the equation (3.1) will be use and moreover have to be able to calculate the winding hot-spot temperature Θ_H . Θ_H is considered to be the sum of the top-oil temperature (in the tank) at a certain load (Θ_0) and the hot-spot to top-oil (in tank) gradient at a certain load ($\Delta\Theta_H$) [11].

$$\theta_H = \theta_0 + \Delta\theta_H \quad (3.3)$$

From the above equation we can therefore deduce that in order for Θ_H to be calculated first the two other factors that compose equation (3.3).

3.3.1 Derivation of θ_0

In order to avoid complexity need to make an approximation that the non-linear relationship affects only the final value of any temperature change that occurs, and that the time function is still exponential whatever cooling system use [11]. The following differential equation shows the relationship between inputs K, Θ_A and output Θ_0 .

$$\left(\frac{1+K^2R}{1+R}\right)^x \times \Delta\theta_{or} = k_{11}\tau_0 \times \frac{d\theta_0}{dt} + [\theta_0 - \theta_\alpha] \quad (3.4)$$

Where:

K = Load factor

R = Ratio of load losses

x = Exponential power of total losses (oil exponent)

$\Delta\Theta_{or}$ = Top-oil temperature rise in steady state at rated losses

k_{11} = Thermal model constant

τ_o = Average oil time constant

θ_a = Ambient temperature

The differential equation (4) can be written as the following difference equation:

$$D\theta_o = \frac{Dt}{k_{11}\tau_o} \times \left(\frac{1+K^2R}{1+R}\right)^x \times [\Delta\theta_{or} - (\theta_o - \theta_a)]$$

(3.5)

“The “D” operator implies a difference in the associated variable that corresponds to each time step Dt . Therefore at each time step the n th value of $D\theta_o$ is calculated from the $(n-1)$ th value using”[11]:

$$\theta_o(n) = \theta_o(n-1) + D\theta_o(n)$$

(3.6)

From the equations (3.4), (3.5), (3.6) therefore can calculate the top-oil temperature.

3.3.2 Derivation of $\Delta\Theta_H$

The remaining factor of equation (3.3) is $\Delta\Theta_H$ which is defined as the hot spot to top oil gradient (in tank) at a certain load [11]. $\Delta\Theta_H$ is considered to be the difference of $\Delta\Theta_{H1}$ and $\Delta\Theta_{H2}$ [11].

$$\Delta\Theta_H = \Delta\Theta_{H1} - \Delta\Theta_{H2}$$

(3.7)

$\Delta\Theta_{H1}$ and $\Delta\Theta_{H2}$ are considered to be two differential equations where the sum of them can give the hot-spot temperature rise (input K , output $\Delta\Theta_H$).

The two differential equations that are related with $\Delta\Theta_{H1}$ and $\Delta\Theta_{H2}$ are the following:

For $\Delta\Theta_{H1}$ [11]:

$$k_{21} \times K^y \times (\Delta\Theta_{Hr}) = k_{22} \times \tau_w \times \frac{d\Delta\Theta_{H1}}{dt} + \Delta\Theta_{H1} \quad (3.8)$$

Where:

K_{21}, k_{22} = Thermal model constant

y = Winding exponent

$\Delta\Theta_{Hr}$ = Hot-spot to top oil gradient at rated current

τ_w = Winding time constant

For $\Delta\Theta_{H2}$ we have [11]:

$$(k_{21} - 1) \times K^y \times (\Delta\Theta_{Hr}) = \left[\frac{\tau_o}{k_{22}} \times \frac{d\Delta\Theta_{H2}}{dt} \right] + \Delta\Theta_{H2} \quad (3.9)$$

All the variables of equation (9) are defined above. Next, in order to derive an equation that we can use throughout the process we must therefore convert them into difference equations. After the conversion of equations (8), (9) we came up with the following difference equations:

$$D\Delta\Theta_{H1} = \frac{Dt}{k_{22}\tau_w} \times [k_{21} \times \Delta\Theta_{Hr} K^y - \Delta\Theta_{H1}] \quad (3.10)$$

$$D\Delta\Theta_{H2} = \frac{Dt}{(1/k_{22})\tau_o} \times [(k_{21} - 1) \times \Delta\Theta_{Hr} K^y - \Delta\Theta_{H2}] \quad (3.11)$$

Finally can say that the total hot-spot temperature, rise at the n^{th} time step, since the n^{th} values are calculated in a similar way as in previous section, is given by:

$$\Delta\Theta_{H(n)} = \Delta\Theta_{H1(n)} - \Delta\Theta_{H2(n)} \quad (3.12)$$

From sections 3.2.1 and 3.2.2 have derived and illustrated the equations that are associated with the estimation of θ_H (winding hot-spot temperature). Values for the variables in the equations are taken from test reports [12] and from the manufacturer of the specific transformer.

3.3.3 Relative ageing rate (V) calculation

As mentioned at the chapter 2 the relative ageing rate is:

$$V = 2^{(\theta_H - 98)/6} \quad (3.13)$$

The only variable in equation (3.13) is θ_H which is derived in sections 3.2.1 and 3.2.2. In order now to find V, have to enter the estimated value of θ_H in Celsius and find a value of V. Then use:

$$LOL = \sum_{n=1}^N V_n \times t_n \quad (3.14)$$

or

$$LOL = \int_{t_1}^{t_2} V dt \quad (3.15)$$

Where:

N = total number of intervals during the period considered

t_n = the n_{th} time interval

n = number of each time interval

V_n = relative aging rate during the interval n according to equation (1)

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