PREDICTING TRANSFORMER END OF LIFE USING TRANSFORMER THERMAL LIFE SIMULATION TECHNIQUE

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ABSTRACT

Large power transformers are key components in power system networks and their correct functioning is vital to system operation. Transformer failures can have enormous impact on security and reliability of supply and cost. In addition, Power transformers ageing are one of the critical issues utilities are facing, since a large number of units are approaching or have exceeded their designed lifetime. Their replacement will involve a considerable amount of time and cost. Therefore, developing a replacement strategy for aged transformer populations is crucial.

This theses presents simulation technique for life assessment of the insulation of the distribution transformer. Load and ambient temperatures are two important factors that influence the life of insulation in transformers. The estimated load factors and ambient temperatures are input to the IEC life consumption models to assess the consumed life of insulation. The simulation is based on IEC 60076-7 Revision 2005 thermal model. Sumer and winter load profiles and ambient temperatures of the transformer in Libya Electricity Company are used as the input for the simulation together with transformer parameters from the heat run test. Hottest spot temperature and loss-of-life are calculated. Besides the temperature, the moisture factor also has been introduced in loss of life calculation.

ABSTRAK

Transformer merupakan komponen yang utama dalam jaringan elektrik kuasa. Keupayaan transformer untuk beroperasi dengan baik sangat penting dalam memastikan sistem operasi elektrik berfungsi dengan baik. Kerosakan kepada transformer boleh memberi kesan kepada sekuriti dan reliabiliti kepada bekalan elektrik serta juga kos untuk menggantinya. Masalah penuaan kepada transformer merupakan isu kritikal yang dihadapi oleh utiliti. Ini adalah kerana hampir keseluruhan transformer akan tamat jangka hayat dalam beberapa tahun lagi dan ada sebahagiannya telah melebihi jangka hanyat yang telah ditetapkan. Keadaan ini akan memberi kesan kepada utiliti kerana penggantian transformer-transformer ini akan melibatkan kos yang tinggi dan juga mengambil masa yang lama. Oleh sebab itu, sangat penting bagi utility untuk membina satu kaedah ataupun strategi untuk menukarkan kesemua transformer ini supaya ia tidak menyebabkan gangguan bekalan elektrik kepada pelanggan.

Tesis ini menerangkan teknik simulasi untuk menentukan jangka hayat untuk transformer yang digunakan dalam pengedaran ekektrik. Dalam simulasi ini, beban elektrik dan suhu udara merupakan dua faktor yang penting dalam menjangka hayat untuk transformer. Simulasi teknik menggunakan transformer model yang terdapat didalam standard antarabangsa IEC 60076-7. Suhu pada musim panas dan musim sejuk untuk transformer di Libya Electircity Company telah digunakan sebagai parameter kepada simulasi yang dijalankan bersama parameter dari heat run test. Suhu transformer yang paling panas digunakan untuk mengira jumlah jangka hayat yang tinggal bagi sesebuah transformer. Selain daripada suhu, faktor air juga telah diambil kira dalam proses mengira jangka hayat untuk transformer bagi mendapat keputusan yang lebih baik

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LIST OF SYMBOLS AND ABBREVIATIONS

AC - Acidity content in paper

AF - Acidity ageing factor

AF_{LL} - Acidity factor for lower limit

AF_{UL} - Acidity factor for upper limit

B - An ageing rate constant

DP - Degree of molecular polymerization

DP_{old} - Final DP value

DP_{new} - Initial DP value

F_{AA} - Ageing acceleration factor

g - Is the average winding to average oil temperature rise at rated load

H - Hotspot factor

HS - Hotspot temperature, ^{0}C

HSR - Winding hotspot rise over top oil temperature, ^{0}C

HSR_R - Winding hotspot temperature rise at rated load, ^{0}C

HSR_1 - Winding temperature rise component 1, ^{0}C

HSR_2 - Winding temperature rise component 2, ^{0}C

I - Current, Amps

K - Load factor, per unit

K_{11},k_{22},k_{21} - Constant

L - Lifetime

m - Mass flow rate kg/s

m - Winding constant (IEEE)

M - A constant

MC - Moisture content in the paper

MF - Moisture ageing factor

MF_{UL} - Moisture ageing factor for upper limit

MF_{LL} - Moisture ageing factor for lower limit

n - Oil constant (IEEE)

OF - The oxygen ageing factor

ONAN - Oil Natural and Air Natural

ONAF - Oil Natural and Air Forced

OFAF - Oil Forced and Air Forced

ODAF - Oil Direct and Air Forced

P - Material constant

P_{EC} - Eddy current losses, Watts

P_T - The total losses in transformer, Watts

P_0 - No-load losses, Watts

P_S - Load losses, Watts

P_{SL} - Stray losses, Watts

Q - Heat flow, Watts

R - Ratio of load loss to no load loss

S - The laplace variable

TA - Ambient temperature, ^{0}C

TO - Top oil temperature, ^{0}C

TOR - Top oil temperature rise over ambient, ^{0}C

TOR_R - The top oil temperature rise over ambient at the rated load, ^{0}C

V - The relative ageing rate

x - The oil constant (IEC)

y - The winding constant (IEC)

Θ - The absolute temperature, k

τ_o - Oil time constant, minute

τ_w - Winding time constant, minute

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CHAPTER 1

INTRODUCTION

1.1 Project Background

A power transformer is a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at same frequency for the purpose of transmitting electrical power (GECOL, 2007).

Power transformers represent the largest portion of capital investment in transmission and distribution substations. In addition, power transformer outages have a considerable economic impact on the operation of an electrical network (Dejan Susa, 2007). The life of a transformer depends mainly on the life of its insulation system and it is primarily depend on transformer operating temperature and time.

In fact, most of power transformers use paper and oil as the main of insulation. There are three possible mechanisms that contribute to the insulation degradation are hydrolysis, oxidation and pyrolysis. The agents responsible for the respective mechanisms are water, oxygen and heat (temperature) (M.T.Ishak, 2009). Indeed the temperature has been considered as the main parameter affecting the loss-of- life of insulation. Hence, the heat produced (internal temperature) in the transformers as a result of loading and the effect of ambient temperature is the important factor that affecting the life of the transformer.

Since the temperature distribution is not uniform in a transformer, the part that is operating at the highest temperature will usually be considered in estimating transformer insulation life since it will undergo the greatest deterioration. This temperature is referred as hotspot temperature. Therefore, accurate prediction of the hotspot temperature is important for both manufacturers and utilities.

There are a few methods to measure the hotspot temperature, one of which is using fibre optical temperature sensors positioned at the predicted hotspot of the windings. The thermal sensors, attached to the end optical fibre, are usually placed between the insulated conductor and spacer, and their signals via optical fibre transmitted out of the tank. However due to the cost which may be difficult to justify in terms of cost for every new transformer. It is not practical for retro-fitting the existing transformers. The main difficulty with direct measurement technique is how to accurately locate the hotspot and possible the sensors.

Another method to identify the hotspot temperature is by using transformer thermal model or calculation method. The calculation of the internal transformer temperature (Hotspot temperature) is a very complicated and difficult task. However, engineers made simplifying assumptions in the generally accepted methods for calculating the temperature of power transformers as reported in the IEEE and IEC standards (IEEE Standard C57.19, 1995 and IEC Standard, 1991). By using these standards, a computer simulation can be used to calculate the hotspot temperature given the historical loading and ambient temperature profiles are available. Then the life of transformer can be predicted from the calculated temperature.

1.2 Problem Statements

Most of power transformers in Libya today were installed during the 1960s. Although some of these transformers may still be operating satisfactorily, they are approaching or past the designed 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 Project Objectives

The main objectives of this research are listed as follows:

- To carry out literature review on transformer insulation ageing and lifetime assessment.
- To compile data for operation and specifications of transformer (load, ambient temperature, design data).
- To create a simple Simulink/Matlab software for calculate hot-spot temperature and the transformer loss of life. This will be done with the help of IEC standard equations.
- To take in consideration of secondary ageing factors such as moisture and acidity to calculate the transformer loss of life.
- To predict the lifetime of transformers base on their actual loading profiles and ambient temperatures.

1.4 Project Scopes

These scopes of this study are:

- The transformer located in Libya.
- The ambient temperature taken in two period time (summer and winter)

- The data are collected from General Electricity Company of Libya which use scada control program.
- IEC 60076-7:2005 loading guide standard will be used with computer simulation to estimate the transformer end-of-life.

1.5 Outline of thesis

The remainder of this is organized as follows:

- Chapter 2: literature review

In this chapter, an intensive literature review on transformer insulation ageing has been made in this chapter to understand the insulation ageing process. This chapter also presents the simple thermal diagram used to describe the thermal performance of a transformer and the hotspot temperature of winding where the severest ageing process would occur. Different cooling modes available in are also discussed. The last part of this chapter explain IEC60076-7 version 2005 thermal model in details.

- Chapter 3: Methodology

In this chapter the real data of transformer data, loading and ambient temperature from the Libya electricity company and the meteorology office are used in this study. The last IEC60076-7 thermal model is established in Simulink/Matlab by solving the top oil differential equation, hotspot differential equation and loss of life of the transformer using Runge-kutta numerical method.

- Chapter 4: Result and Analysis

In this chapter the hotspot temperature have been calculated as the top oil temperature added to the hotspot temperature rise and ambient temperature. It also calculated the loss of life of the transformer from the hotspot temperature. Besides the temperature, secondary ageing factors such as water and acidity also have been introduced in loss of life calculation, using proposed formulation to represent secondary ageing factor (acidity and water) which increases with life.

- Chapter 5: Conclusion and Recommendation

This chapter gives conclusions of this thesis research and recommendations for future study.

CHAPTER 2

LITERATURE REVIEW

2.1 Transformer insulation life

A transformer cannot wear out in the same way as a rotating machine since it has practically no moving parts, except tap changers or cooling fan and pump. The copper windings, the electric steel core and other metal parts of the transformer can have a very long life if an adequate protection against corrosion is applied. However this is not the case for insulating materials such as both Kraft papers which are mostly made from cellulose materials and insulating oils (M.T. Ishak, 2009).

Since the invention of the power transformer, the conventional conductor insulation has been some from of paper or cloth. The main constituent of these fibrous materials is cellulose, an organic compound whose molecule is made up of long chain of glucose rings, typically numbering in the range from 1000-1400 (S.V.Kulkani and S.A. Khaparde, 2004). It is may be represented simply as $[C_5H_{10}O_5]_n$. Degree of molecular polymerization (DP) is the average number of glucose rings in the molecule. The chemical structure of a portion of a cellulose molecule is shown in Figure 2.1.

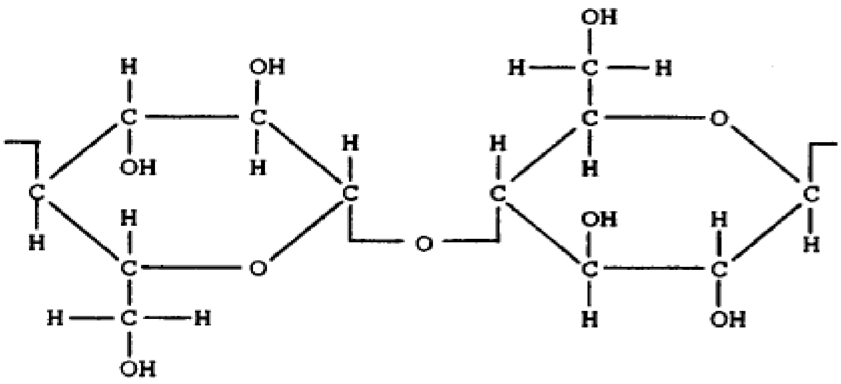

Figure 2.1: Cellulose molecule structure (W.J. Mcnutt, 1993)

A single cellulose fiber is made up of many of these long chains of glucose ring. Since the mechanical strength of the cellulose materials depends on the length and condition of the fibers, the degree of polymerization gives a good measure of retained functionality as transformer insulation ages in service.

Since the cellulose materials cannot be replaced once the winding are manufactured, the transformer life can be defined as the total time between the initial state for which the cellulose paper is considered new to the final state for which dielectric stress, short circuit stress or mechanical movement which could occur in normal service would cause an electrical failure of cellulose paper. In a brief, when paper insulation fails the transformer life has ended.

2.1.1 Ageing factors:

Insulation paper ageing is a complex and irreversible phenomenon. As cellulose ages thermally in an operating transformer, three possible mechanisms that contribute to the insulation degradation are: hydrolysis, oxidation and pyrolysis (heat) .The agents responsible for the respective mechanisms are water, oxygen and heat (temperature) (M.T.Ishak, 2009). They will be explained in more details.

2.1.1.1 Hydrolysis (water)

The water in the transformer comes from two sources: ingress of water from the atmosphere, and the degradation or ageing of cellulose and oil. Hence, the oxygen bridge between glucose rings is affected by water, causing a rupture of the chain and the formation of two –OH groups, each attached to its monomer. The result is reduction of DP and shortening and weakening of the fiber (W.J. Mcnutt, 1993).

In general, the mechanical life of the non upgraded paper insulation is reduced by half for doubling in water content and in earlier studies by Fabre and Pichon it was found that the rate of thermal deterioration of paper is proportional to its water content. For example, decreasing the water content of the paper from 1.0% to 0.5% doubles the life of that paper. However, later studies found that the rate of degradation for later stages of degradation is in the form of logarithm relationship to moisture level. Recent studies by Lundgaard of SINTEF Energy Research have shown if the normal life is defined as ageing under dry, oxygen free conditions, then a water control of 1% in non upgraded insulation paper can reduce life expectancy to 30% of normal life, whereas for 1% water in the thermal upgraded paper, it will reduce the life expectancy to 60% of the normal life. If the water constant increases to 3-4%, the life expectancy will drop to approximately 10% and 25% of normal life for non upgrade paper insulation and upgraded paper insulation respectively (M.T.Ishak, 2009).

2.1.1.2 Oxidation (oxygen)

Oxygen attacks the carbon atoms in the cellulose molecule to form aldehydes and acids, releasing water, carbon monoxide, and carbon dioxide. The bonds between rings are weakened, leadings to lower DP. Water released by this mechanism can also contribute to the hydrolysis effect previously mentioned (W.J. Mcnutt, 1993).

According to Fabre and Pichon, oxygen increases the rate of degradation of paper in oil containing 0.3%-5% water by a factor of 2.5 for the free breathing transformers. A free breathing transformer is the transformer has vents above the oil that allow air to enter and exit as the oil expands and contracts due to variations in the operation temperature. Reducing the oxygen level from 30,000ppm in oil to less than 300ppm will reduce the ageing factor (M.T. Ishak, 2009).

2.1.1.3 Pyrolysis (heat)

Heat in the extreme will result in charring of the fibers, but at lesser levels it contributes to the breakdown of individual monomers in the cellulose chain. A solid residue is formed and gases are liberated, namely water vapor, carbon monoxide, carbon dioxide, and hydrogen. Again DP is reduced (W.J. Mcnutt, 1993).

The paper insulation deteriorates rapidly if its temperatures are more than 90°C.The winding made of copper can hold their mechanical strength up to several hundred degrees Celsius without deterioration and the transformer oil does not significantly degrade below 140% (M.T. Ishak, 2009).

2.2 IEC thermal ageing equation

The IEC 354 (IEC Standard, 1991) chooses to use the Montsinger rule of thermal degradation which is a simplified expression of the Arrhenius law of thermal degradation. The simple exponential of Montsinger is given as

$$\mathrm{L} = \mathrm{e}^{-\mathrm{p}\theta} \tag{2.1}$$

Where L is lifetime, P is material constant and Θ is the absolute temperature.

Many investigators have not always agreed on the criteria for which L is representative of lifetime. Therefore, the possible way is by changing the equation (2.1) to the rate of ageing. This can be done by inversing of the lifetime, that is

$$\mathrm{V} = \mathrm{M}\ \mathrm{e}^{\mathrm{p}\theta} \tag{2.2}$$

Where V is the rate ageing, M is a constant which is depended on many factors but normally moisture content and oxygen of the insulation. Most important is the fact that the coefficient of temperature variation, P, can be general assumed as a constant over the temperature range of 80^{o}C to 140^{o}C. In this temperature range, the rate of ageing doubles for every 6K temperature rise. This means that if an insulation service life of N years applies for a temperature ϴ^{o}C, the temperature of (ϴ +6) ^{o}C will reduce the life by (N/2) years (M.T.Ishak, 2009).

The Montsinger relation can be used to obtain the relative rate of thermal ageing any hotspot temperature over the reference temperature. For transformers designed in accordance with IEC 60076-2 (IEC 60076-2 standard, 1997), the relative rate of thermal ageing is taken to be equal to unity for a hotspot temperature of 98^{o}C. This corresponds to operation at an ambient temperature of 20^{0}C and hotspot temperature rise of 78^{o}C. The relative ageing rate for non thermal upgraded paper is given by equation (2.3).

$$V = \frac{\text{Ageing rate at HS}}{\text{Ageing rate at 98 C}^{0}} = 2^{(\text{HS}-98)/6} \tag{2.3}$$

For ambient temperature other than 20^{o}C, the hotspot temperature rise has to be modified accordingly. For example, when the ambient temperature is 30 ^{o}C, the allowable hotspot rise is 68^{o}C

2.3 End of life criteria

The general definition of “end of life” for an insulation system is the point at which the insulation no longer performs reasonably; from the viewpoint of insulation’s purpose, it seems only right to consider this point at which the insulation system no longer maintains the majority of its original dielectric strength. However as paper insulation ages, the dielectric strength of the paper does not decrease significantly even well after the paper has become brittle. Therefore, the point at which the paper loses enough strength to withstand the mechanical forces is regarded as the practical point of end of life for insulation system.

To what extent the retention of strength to withstand mechanical forces needs be, is an option in making the definitions of the end of life point and often it is expressed in terms of a measureable physical property. This could be either a mechanical property such as tensile strength, burst strength, elongation to break or abrasion resistance; or it could be a chemical property such as degree of polymerization. The end of life point could be in percentage deterioration or an absolute value of these properties.

Another possible way to define an end point for transformer life is by doing functional life tests on the actual transformers. However this method is only suitable for small transformers not the power transformers because it is not economically practical.

In order to properly predict insulation life, it is critical to understand the basis from which any life reference values are derived. Over the years there have been many studies on insulation ageing which generated significant but often conflicting results and definitions of end of life (M.T .Ishak, 2009).

Table 2.1, in (IEEE Standard C57.19, 1995 and M.T .Ishak, 2009), lists various end of life criteria or normal insulation life for a transformer with thermally upgraded paper, in a well-dried and oxygen free condition at the reference temperature of 110 ^{0}C.

Table 2.1: Normal insulation life value for a well dried oxygen free system at the reference temperature 110 ^{0}C (IEEE Standard C57.19, 1995 and M.T.Ishak, 2009)

Basis	**Normal insulation life**	
	Hours	**Years**
50 % retained tensile strength of insulation (former IEEE std C57.92-1981)	65,000	7.42
25% retained tensile strength of insulation	135,000	15.41
Retained degree of polymerization in insulation, DP=200	150,000	17.12
Interpretation of distribution transformer functional life test data (former std C57.91-1981)	180,000	20.55

Table 2.1, shows that the IEEE (IEEE Standard C57.19, 1995) standard gives the user the freedom to choose end of life criteria base on their requirement which is most applicable to their needs. Therefore we can say that there are no standard values for determining the transformer insulation life end point.

All these normal insulation life definition associate the loss of life with paper losing its ability to withstand mechanical stresses. The main point here is that if the unit is run for 20.55 years (for example) at 110^{0}C hotspot temperature, the life of the insulation will expire. If it runs hotter, the life will expire sooner, and if it runs cooler, the life will extend.

In these theses DP equal 200 is chosen as the end of life criterion and would give the insulation life of 150,000 hours under full load condition for IEEE loading Guide. This method has been suggested by some researches based on the measurement of the degree of polymerization. A new Kraft paper has DP in the ring 1000-1200 after going through the factory drying process. The DP drops to lower value with time.

On contrary, the IEC Loading Guide gives no value for expected life. However, based on design and experience, the life of a transformer has been estimated as 30 years service life of the insulation system with 98^0C for hotspot temperature for Kraft paper by assuming that the insulation system is well preserved (i.e. without oxygen, water or contaminations) (M.T. Ishak, 2009).

2.4 Transformer thermal

2.4.1 Introduction

Transformer losses are produced by the electrical current flowing through the coils and the magnetic field alternating in the core (G. Pop, M. Chindris and R. Bindilu, 2009). The losses are calculated using measured voltage and current. This allows the meter to continue registering Kwh, Kvarh and Kvah (unaffected by compensation). Transformer losses are generally classified into no load losses and load losses as shown in Figure 2.2. Transformer losses can be determinate with the following mathematical expression (G. Pop, M. Chindris and R. Bindilu, 2009).

$$P_T = P_O + P_S \tag{2.4}$$

Where:

P_T: total losses in transformer;

P_O: no-load losses;

P_S: load losses.

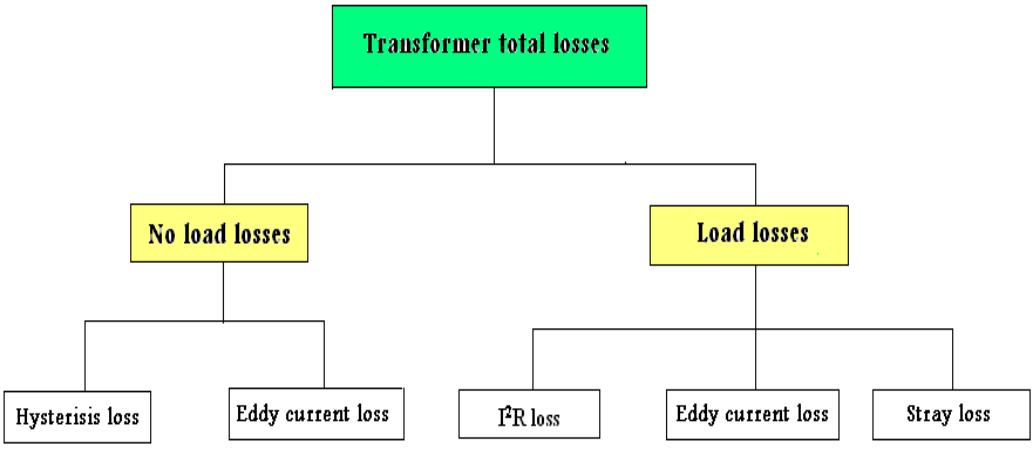

Figure 2.2: Transformer losses classification

The no load losses (referred to as excitation losses, core losses, or iron losses) are a very small part of the power rating of the transformer, usually less than 1%. However, these losses are considered constant over the lifetime of the transformer (do not vary with load), and thus they generally represent a sizeable operating expense, especially if energy costs are high. Therefore, accurate measurements are essential in order to evaluate individual transformer performance accurately. They include losses due to magnetization of the core, dielectric losses in the insulation, and winding losses due to the flow of the exciting current and any circulating currents in parallel conductors. No load losses are the losses in a transformer when it is energized but not supplying load. The no load losses contain tow main components, hysteresis loss and eddy current loss (G. Pop, M. Chindris and R. Bindilu, 2009).

Hysteresis losses are caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. Eddy current losses are caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat.

The load losses are commonly called copper losses or short circuit losses. They are in accordance with convention subdivided into I^2R losses, Eddy current losses and stray losses (G. Pop, M. Chindris and R. Bindilu, 2009).

I^2R losses (Dc losses) occur in transformer windings and are caused by the resistance of the conductors. The magnitude of these losses increases with the square of the load current and are proportional to the resistance of the windings.

Eddy current losses due to magnetic fields caused by alternating current, also occur in the windings .Stray losses are due to losses in structures other than windings, such as clamps, tank or enclosure walls, etc.; this can be expressed as (G. Pop, M. Chindris and R. Bindilu, 2009):

$$P_s = I^2 \cdot R + P_{EC} + P_{SL} \tag{2.5}$$

where:

$I^2.R$: losses due value of the current and resistance of the transformer;

P_{EC} : Eddy Current Losses;

P_{SL} : Stray Losses.

All these losses cause heating in all parts of transformer and this heat must be taken away to avoid high temperature because they will cause decrease of insulation and the normal life of transformer (M.T. Ishak, 2009).

2.4.2 Transformer thermal diagram

The temperature distribution inside a transformer is extremely complex and difficult to model accurately, consequently the thermal characteristics of transformers are normally analyzed in the simple thermal diagram. A typical thermal diagram using the IEC 354 and IEEE C57.91-1995 standards is shown in Figure 2.3, (A. Al-Nadabi and H. al-Riyami, 2009).

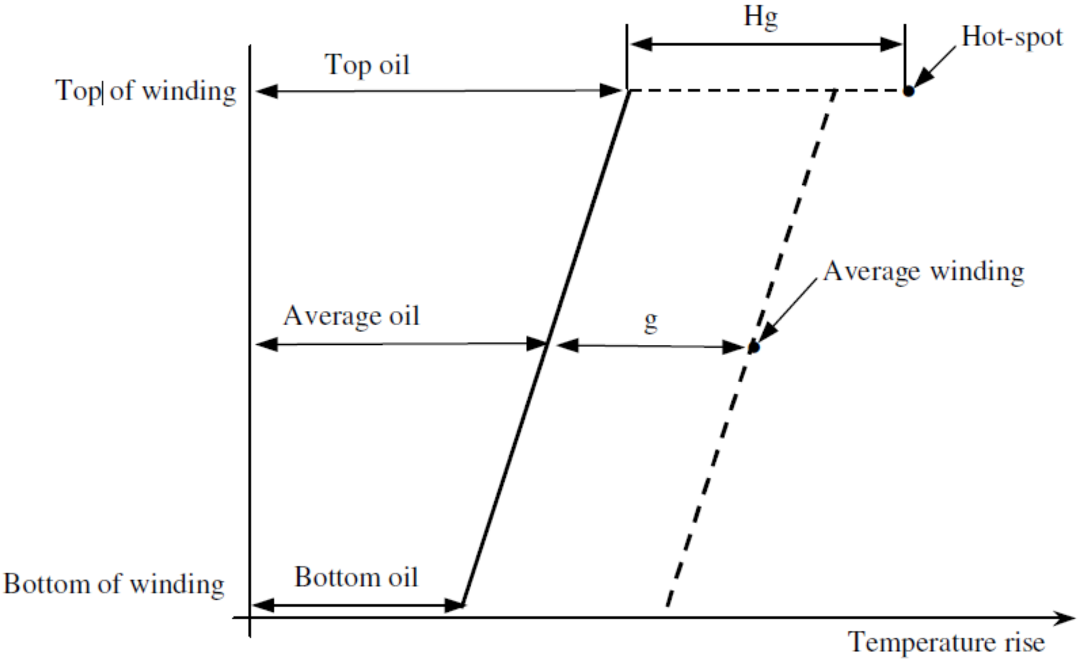

Figure 2.3: Transformer Thermal Diagram (A. Al-Nadabi and H. al-Riyami, 2009).

Several assumptions are made in such a thermal diagram and the assumptions are (A. Al-Nadabi and H. al-Riyami, 2009).

- The change in the oil temperature inside and along the winding is linearly increasing from bottom to top,
- The increase in the winding temperature from bottom to top is linear with a constant temperature difference g,
- At the winding top the hot- spot temperature is higher than the average temperature g rise of the winding,
- The difference in the temperature between the hot-spot and the oil at the of the winding is defined as Hg , where H is a hot-spot factor.

For many years, the value of hot-spot factor, H was taken to be approximately 10% of the average gradient, that is, the maximum gradient was considered to be 1.1 times the average gradient.

CIGRE Working Group12-09 did the thermal tests and collected the data during the tests to quantify the hot-spot factor used in the IEC loading guide (A. A. Elmoudi, 2006). These analysis data showed that the value of the hot-spot factor is 1.1 for distribution transformers and 1.3 for medium and large transformers. These values for the hot-spot factor depending on the transformer size, short circuit impedance and winding design.

The hot spot temperature is normally located at the top of winding this is due to leakage flux concentration near to the top of the winding which increase the eddy current losses and in consequence, the temperature. The hot spot temperature for a transformer under any load k is equal to the sum of the ambient temperature, the top oil temperature rise over ambient and the hot spot temperature rise over top oil. This can be expressed by the equation below:

$$HS = TA + TO + HSR \qquad (2.6)$$

Where:

TA is the ambient temperature, (^{o}C)
TO is the oil temperature rise over ambient, (^{o}C)
HSR is the hot spot temperature rise over top oil temperature, (^{o}C)
HS is the ultimate hot spot temperature, (^{o}C)

The top oil temperature rise over ambient temperature is given by the following equation:

$$TO = TOR_R \left[\frac{1+RK^2}{1+R}\right]^n \qquad (2.7)$$

where:

TOR_R is the top oil temperature rises over ambient at rated load.
R is the ratio of load losses at rated current to no load losses.
K is the load factor.
n is an empirically derived exponent that depends on the cooling method.

The hot spot temperature rise over top oil temperature is given by the following equation:

$$HSR = H.g.K^{2m} \qquad (2.8)$$

where:

H is the hot spot factor.
g is the average winding to average oil temperature rise at rated load.
m is an empirically derived exponent that depends on the cooling method.

The exponent n and m approximately account for changes in load loss and oil viscosity because of the change in temperature. These exponents are different for different cooling modes as shown in Table 2.2, (M.T. Ishak, 2009).

Table 2.2: Exponents used in temperature calculation (M.T.Ishak, 2009)

standard	IEC		IEEE	
Type of cooling	x	Y=2m	n	m
ONAN	0.8	1.6 (0.8)	0.8	0.8
ONAF	0.9	1.6 (0.8)	0.9	0.8
OFAF	1.0	1.6 (0.8)	0.9	0.8
ODAF	1.0	1.0 (2.0)	1.0	1.0

2.5 Direct hotspot measurement

The direct temperature measurement techniques using fibre optic sensors are currently available and are in use for some larger power transformers. Ideally, this is the best method is to directly measure the winding hot spot temperature (A. A. Elmoudi, 2006). In this method a sensor, made of photo-luminescent material and attached to the end of optical fiber (S.V.Kulkani and S.A. Khaparde, 2004). These devices are capable of indicating the temperature only at the spots where sensors are located. The sensors are usually placed between insulated conductor and radial spacer. CIGERE Working Group (CIGRE Working Group12-09 survey, 1995) suggests the eight sensors would be adequate if placed in the winding location where the highest temperatures are expected. However due to the cost which may be difficult to justify in terms of cost for every new transformer and also it is not practical for retro-fitting the existing transformers.

2.6 Transformer cooling system

The heat produced in a transformer must be dissipated to an external cooling medium in order to keep the temperature in a specified limit. If transformer insulation is experienced higher temperatures than the allowed value for a long time, it will cause rapid degradation of insulation and hence severely affect the transformer life.

A cooling system of transformers increases the load capacity of a transformer by improving its ability to dissipate the heat generated by electric current. In other words, good cooling systems allow a transformer to carry more of a load than it otherwise could without reaching critical hot spot temperatures.

In oil cooled transformers, the oil provides a medium for both cooling and insulation. Heat from core, windings and structural components is dissipated by the process of the oil circulation. The heat is finally transmitted either to atmospheric air or water. The process of transferring heat from a transformer involves three different heat transfer mechanisms which are conduction, convection and radiation (M.T.Ishak, 2009). In the oil cooled transformers, convection plays the most important role and conduction the least important (S.V.Kulkani and S.A. Khaparde, 2004). The conduction is the transfer of heat through a material by direct contact, whereas the convection is the transfer of heat in a fluid (oil) as a result of the movement of the fluid itself. The radiation is the transfer of heat via electromagnetic waves through space. There are four common types of cooling are:

1- Oil Natural and Air Natural cooling (ONAN)
2- Oil Natural and Air Forced Cooling (ONAF)
3- Oil Forced and Air Forced Cooling (OFAF)
4- Oil Direct and Air Forced cooling (ODAF)

They have been used in the industry and will be explained in more details.

2.6.1 Type of cooling transformer

2.6.1.1 Oil Natural and Air Natural Cooling (ONAN)

This type of cooling is most common used in the practice. The ONAN cooling transformers have their windings and core cooled by oil naturally circulation (thermosiphon effect). The oil is then cooled by air which is naturally cooled. Moreover, Oil is kept in circulation by the gravitational buoyancy in the closed-loop cooling system as shown in Figure 2.4.

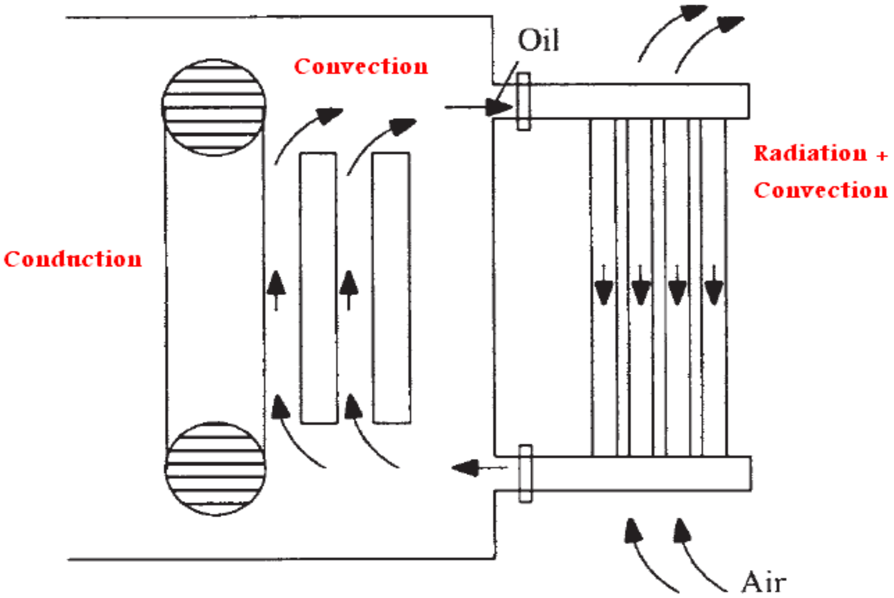

Figure 2.4: ONAN cooling diagram (S.V.Kulkani and S.A. Khaparde, 2004)

The heat developed in active parts is passed on to the surrounding oil through the surface transfer (convection) mechanism. The oil temperature increases and its specific gravity drops, due to which it flows upwards and then into the coolers. The oil heat gets dissipated along the colder surfaces of the coolers which increase its specific gravity, and it flows downwards and enters the transformer tank from the inlet at the bottom level (S.V.Kulkani and S.A. Khaparde, 2004).

In ONAN cooling system of transformers there is a big difference between the temperatures of top and bottom oil because the oil velocity is slow between the transformer and radiators (M.T. Ishak, 2009). The ONAN cooling has the following advantages. They are (S.V.Kulkani and S.A. Khaparde, 2004).

- It is more reliable as no cooler controls are involved and it requires less maintenance.
- The cost increase due to extra radiators is, to a large extent, compensated by the reduction in cost due to the absence of fan and control system.
- It is particularly useful when low noise transformers are required. Absence of fans makes it easier to achieve the required low noise level.
- There is no cooler loss.
- Winding losses also reduce because of lower winding.

2.6.1.2 Oil Natural and Air Forced Cooling (ONAF)

As the transformer losses increases, the number and size of the radiators that are required to cool the oil must increase. Eventually, a point is reached where air and natural convection are not adequate to remove the heat and air must be forced through the radiators by motor- driven fans (John J. Winder, Jr, 2002), This type of cooling is termed as ONAF (Oil Natural and Air Forced) cooling, as shown in Figure 2.5.

These fans generate forced air flow in the radiators to increase the oil circulation rate from tank to radiators. This type of cooling improves the efficiency of the transformer to increase the capability to operate at a high load, but this flow rate is relatively low. Because of this, the heat carrying (or dissipating) capacity of the oil is low. The heat carrying capacity can be defined as (S.V.Kulkani and S.A. Khaparde, 2004).

$$Q = m\,C_P\,(T_{Out} - T_{In}) \qquad (2.9)$$

where Q is heat flow in W, m is mass flow rate in kg/s, Cp is specific heat in J/ (kg ° C) and temperatures Tout and Tin are in °C. For the given transformer oil inlet (Tin) and top oil (Tout) temperatures,

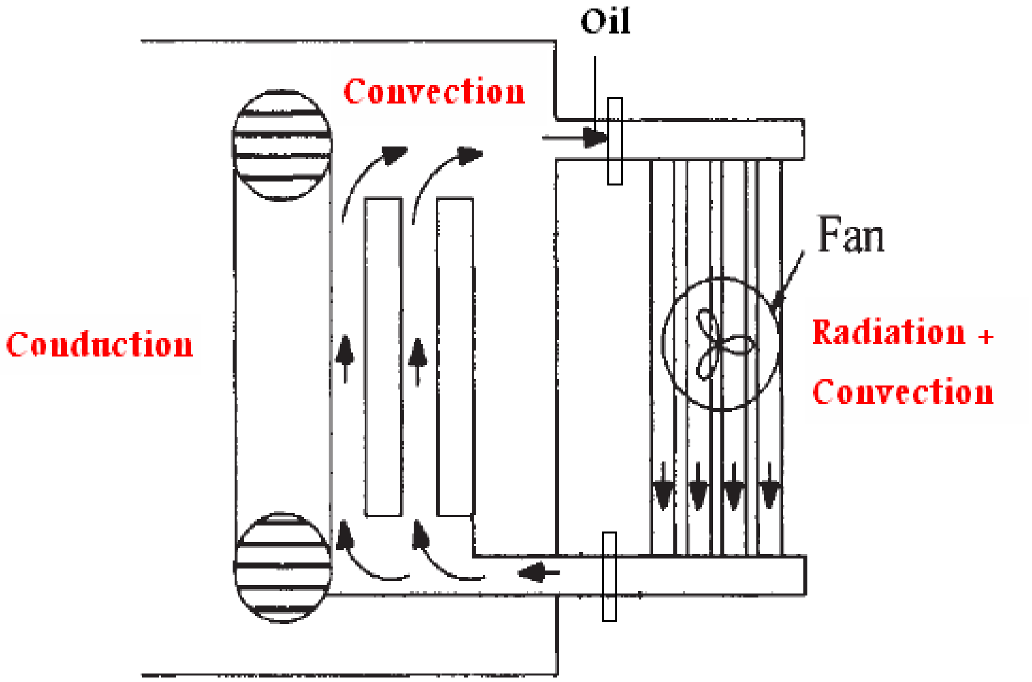

Figure 2.5: ONAF cooling diagram (S.V.Kulkani and S.A. Khaparde, 2004)

2.6.1.3 Oil Forced and Air Forced Cooling (OFAF)

Although the cooling capacity is greatly increased by the use of forced air, increasing the loading to take advantage of the increased capacity will increase the temperature gradients within the transformers. A point is reached where the internal temperature gradient limit the ability to increase load any further. The solution is to increase the oil velocity by pumping oil as well as forcing air through the radiators. This type of cooling called OFAF (Oil Forced and Air Forced) cooling. The usual pump placement is at the bottom of the radiators as shown in Figure 2.6, forcing oil from the radiator outlets into the bottom of the transformer tank in the Sam direction as natural circulation but at a much higher velocity (John J. Winder, Jr, 2002). By direction the flow of oil within the transformer windings, reduce considerably the temperature between the top and the bottom of the radiators (M.T. Ishak, 2009).

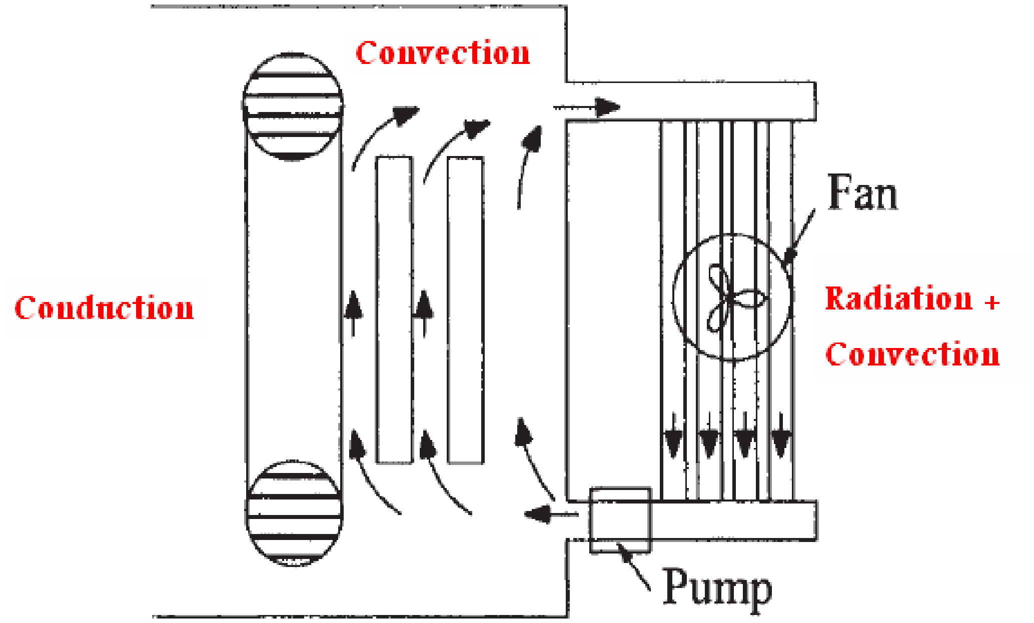

Figure 2.6: OFAF cooling diagram (S.V.Kulkani and S.A. Khaparde, 2004)

2.6.1.4 Oil Direct and Air Forced Cooling (ODAF)

In OFAF cooling type the oil forced from the pump into the transformer, its flow is governed by the least resistance path as well as the buoyancy. Hence, part of the oil may not enter either windings or core, and may from parallel path outside these two. Thus, the top oil temperature may reduce because of the mixture of hot oil coming from the windings and the cool oil coming from the pump. This in turn reduces the effectiveness of radiators. The solution is to improve the heat dissipation rate by the oil forced and directed in the windings through the paths. This type of cooling called

ODAF (Oil Direct and Air Forced) cooling, as shown in Figure 2.7, (S.V.Kulkani and S.A. Khaparde, 2004).

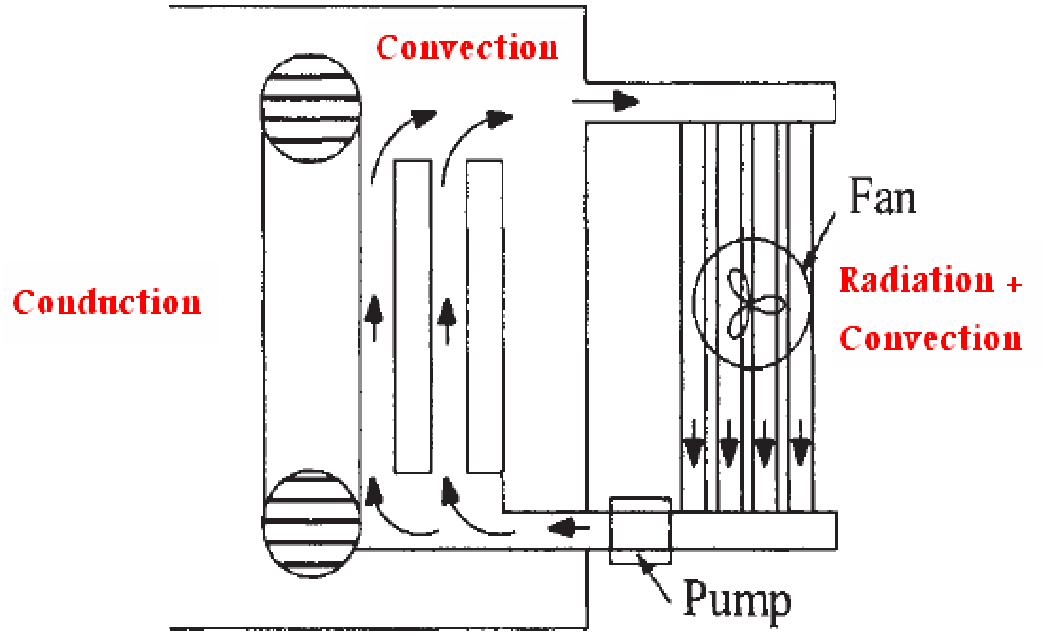

Figure 2.7: ODAF cooling diagram (S.V.Kulkani and S.A. Khaparde, 2004)

ODAF type of cooling is used in most of the large rating transformer .one disadvantages of ODAF cooling is the increased pressure loss because of the ducting system used for directing the oil flow (S.V.Kulkani and S.A. Khaparde, 2004).

2.7 IEC 60076- 7 thermal models

Most of transformers around the world including Libya are designed according to the IEC standard. Therefore, in order to investigate the temperature related loss of life for transformers designed according to IEC standard, it is appropriates to use the IEC thermal model. The latest IEC 60076-7 thermal model (IEC 60076-2, 2005),

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