Diagnostic Equipment for Distribution Transformer using IEEE Thermal Model

Major Project Report

Submitted in Partial Fulfillment of the Requirements for the Degree of

MASTER OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

(Electrical Power Systems)

By

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This is to certify that the Major Project Report entitled **Diagnostic Equipment for Distribution Transformer using IEEE Thermal Model** submitted by **Mr. Apurva P. Panchal (14MEEE11)**, towards the partial fulfillment of the requirements for the award of degree in Master of Technology **Master of Technology (Electrical Engineering)** in the field of **Electrical Power Systems** of Nirma University is the record of work carried out by him under our supervision and guidance. The work submitted has in our opinion reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree.

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Abstract

Failure of distribution transformer in grid is one of the major causes of concerns. In India the failure of distribution transformer is around 25% per annum, which is higher compared to developed nations. It is necessary to keep transformer in service for uninterrupted power supply. For uninterrupted operation of the Transformer it is necessary to monitor the health of transformer effectively. The major factor that affects the transformers health is the thermal loading. IEEE has provided guide line for calculation of Transformers health based on hot-spot temperature.

In this project an algorithm is developed for predicting the health of transformer using IEEE thermal model. The developed algorithm is validated using MATLAB simulation and measurement at laboratory. Based on the algorithm a practical tool will be developed for monitoring the health of transformer and tested for its workability at site conditions,

Nomenclature

θ_H .... Hot spot temperature Of the winding

θ_A .... Ambient temperature

θ_{BO} .... Bottom fluid temperature

$\triangle\theta_{WO/BO}$ .... Temperature rise of fluid over bottom oil at hot spot location

$\triangle\theta_{H/WO}$ .... Hot spot temperature rise over oil

$\triangle\theta_{T/B}$ .... Temperature rise of oil at top of radiator over bottom oil

θ_{AO} .... Average oil temperature in tank and radiator

$\theta_{W,1}$ .... Average winding temperature at prior time

$\theta_{W,R}$ .... Average winding temperature at rated load

θ_K .... Temperature factor for resistance correction

$\delta_{DAO,1}$ .... Average temperature of fluid in cooling ducts at prior time

$\delta_{DAO,R}$ .... Average temperature of fluid in cooling ducts at rated load

$\triangle\theta_{DO/BO}$ .... Temperature rise of fluid at top of duct over bottom fluid

$\theta_{TDO,R}$ .... Fluid temperature at top of the duct at rated load

$\theta_{BO,R}$ .... Bottom fluid temperature at rated load

$\theta_{W,O}$ .... Temperature of oil adjacent to winding hot spot

$\theta_{H,R}$ .... Hot spot temperature at rated load

$\theta_{W,R}$ .... Average winding temperature at rated load tested

$\theta_{H,1}$ .... Hot spot temperature at prior time

P_W .... Winding $I^2 Rlosses$

P_E .... Eddy loss of winding

P_C .... Core losses

P_S .... Stray losses

P_T .... Total losses

P_{EHS} .... Eddy loss at rated winding hot spot temperature

E_{HS} .... Eddy loss at winding hot spot location

H_{HS} .... Per unit of winding hot spot location

K_W .... Temperature correction for losses of winding

K .... Per unit load

$\mu_{HS,R}$ .... Viscosity of fluid for hot spot calculation at rated load

$\mu_{HS,1}$ .... Viscosity of fluid for hot spot calculation at rated load

$\mu_{W,R}$ .... Viscosity of fluid for average winding temperature rise at rated load

$\mu_{W,1}$ .... Viscosity of fluid for average winding temperature rise at prior time

$\triangle t$ .... Time increment for calculation

K_{HS} .... Temperature correction for losses at hot spot location

$Q_{GEN,W}$ .... Heat generated by windings

$Q_{LOST,W}$ .... Heat lost by windings

τ_W .... Winding time constant

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Chapter 1

Introduction

Hot spot temperature is the essential parameter for deciding the health and loading capability of transformer. Operating time of transformer is mainly depends upon conditions of insulation of the transformer winding. The main cause of failure in distribution transformer is prolonged overloading and loss of life due to thermal degradation of insulation. so, it is necessary to know about Hot spot temperature at each movement of the transformer performance at different loading condition and different ambient temperature.

The main objective behind this project is to develop a smart monitoring unit which will continuously monitor the health of transformer based on hot spot temperature and provide the loss of life of insulation. Development of this system will results in lower failure rate.

1.1 Block Diagram

The simplified block diagram of smart monitoring unit is presented in Figure 1.1. The system will take load current, top and bottom oil temperature, ambient temperature and design parameters such as type of cooling, type of insulation and eddy current losses at hot spot location, as input. The system will process input and provides ageing rate, remaining life and hot spot temperature as output in display.

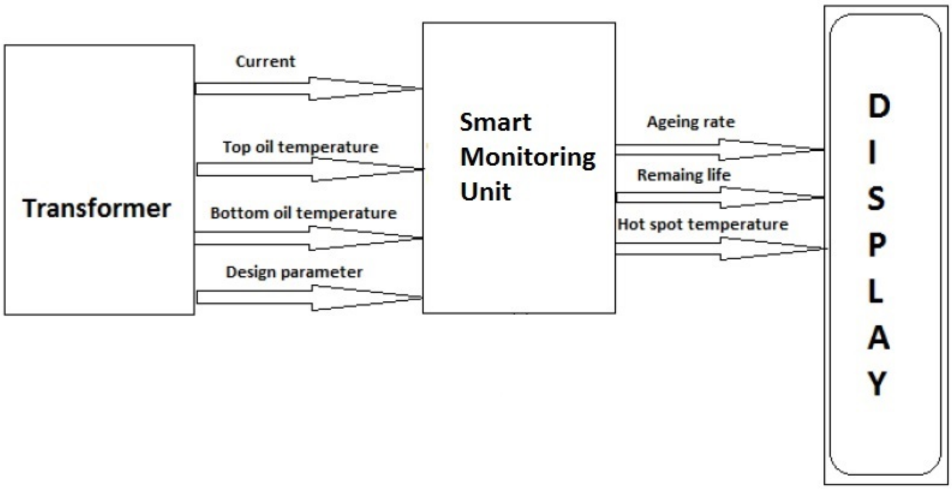

Figure 1.1: Block Diagram

1.2 Literature Review

This paper [1] presents, thermal models to evaluate the hot spot temperature of a transformer winding. The thermal model use top fluid temperature, load current, rated hot spot temperature rise and constant parameters as input. The thermal model can be carry out in an on line monitoring system. The winding hot spot temperature can be used to determine the ageing rate of the insulation, equivalent ageing factor and the loss of life of the insulation.

This paper [2] presents, The IEEE thermal model has been developed for mineral oil immersed transformer. A transformer life span is determine mainly by the solid insulation system. IEEE thermal life consumption model estimate the hot spot temperature in the insulation at given transformer load and ambient temperature which is used to estimate the loss of transformer insulation life.

This standard [3] presents, formation of hot spot in distribution and power transformer. It describes the important criteria to accurately predict the hot spot temperature in the transformer. It also gives guide lines for performing heat run test with direct measurement of the hot spot temperature and also explain the importance of developing an accurate thermal model to properly locate the temperature sensors.

This standard [4] presents, it is applicable for the oil immersed transformer. It describes transformer life operated under various ambient temperature and load condition. It provide the relative aging rate of the insulation based on that it gives the transformer insulation life. It also describe the direct measurement method for hot spot temperature rise.

This standard [5] presents, general recommendation for loading liquid immersed distribution transformer and power transformers. There are two methods of calculating temperature are given in this guide. It contains temperature equation. This equations use the winding hot spot rise over tank top fluid and assumed that the fluid temperature in the cooling ducts is the same as the tank top fluid during overloads. Recent research using imbedded thermocouple and fiber optic detectors indicates that the fluid flow occurring in the windings during transient heating and cooling is an extremely complicated phenomena to describe by simple equations. These recent research have shown that the temperature of the fluid in the winding cooling ducts rises rapidly and exceeds the top fluid temperature in the transformer tank. An alternate set of equations based on this concept is given in this guide. The change of losses with temperature and liquid viscosity effects, and variable ambient temperature was incorporated into the equations. A computer program based on these equations is given for evaluation by the industry.

This standard [6] applies to the insulation system used in all liquid immersed distribution and power transformers. This standard provides the methods to determine the thermal aging characteristics of insulation systems used in liquid immersed distribution or power transformers. The dielectric liquid is part of the insulation system.

Chapter 2

Loading and its Effect

Loading with cyclic variations which is regarded in terms of the accumulated amount of ageing that occurs during the cycle.

Types of loading

a. Normal loading

b. Loading beyond nameplate rating

c. Short time loading

d. Long time loading

e. Transformer size

2.1 Normal loading

Normal loading or a long time loading are also known a cyclic loading. The normal loading of the transformer is continuous loading at rated output when operated under several conditions. It is assumed that the operation in an average ambient temperature of $30°C$ for cooling air or $25°C$ for cooling water is similar to the operation under those conditions. Normal life expectancy will results from operating with a continuous hot spot conductor temperature of $110°C$.

The $110°C$ hot spot temperature is addition of the hot spot rise of $80°C$ and the standard average ambient temperature of $30°C$.

2.2 Loading beyond name plate rating

Increasing load on the transformer above the nameplate rating involves higher risk of failure. The basis for the loading of transformers for many years are aging of the insulation and long time mechanical deterioration of the winding insulation, it is necessary to recognize that there are additional factors that may involve greater risk for transformers of higher MVA and voltage ratings.

2.2.1 Effects of loading beyond nameplate rating

a. Formulation of free gas from winding insulation and the lead of the conductor gets heated.

b. Evolution of free gas from insulation adjacent to metallic structural part linked by electromagnetic flux produced by winding or lead currents may also reduce dielectric strength.

c. The mechanical strength of conductor and structural parts will reduced due to transformer operation at high temperature. These effects are of major concern during periods of transient overcurrent when mechanical forces reach their highest levels.

d. The main causes of permanent deformation are thermal expansion of conductors, insulating materials, or structural part at high temperatures that could contribute to mechanical or dielectric failures.

e. For current above name plate rating will build up pressure in bushing could result in leaking gasket, loss of oil and ultimate dielectric failure.

f. Increased resistance in the contacts of tap changer can result in leaking gaskets, loss of oil and violent gas evolution.

g. Auxiliary equipment internal to the transformer such as reactors and currents transformers, may also be subject to some the risk identified above.

h. There is a possibility that oil expansion will be greater than the holding capacity of the tank when the temperature of the top oil exceeds $105°C$ and also result in a pressure that causes the pressure relief device to operate and expel the oil.The loss of oil may also create problems with the oil preservation system or expose electrical parts upon cooling.

2.3 Short time loading

Short-time increased loading will result in a service condition having an increased risk of failure. Short-time emergency overloading causes the conductor hot-spot to reach a level likely to result in a temporary eduction in the dielectric strength. However, acceptance of this condition for a short time may be preferable to loss of supply.

The thermal time constant of the whole transformer is bigger than the permissible duration of this load. Before the increase in loading it depends on the operating temperature of the transformer.

2.4 Effects of short time loading

a. The degradation in dielectric strength of oil is due to the presence of gas bubbles in a high electric stress region is the main cause of short time failure. When the temperature of the hot spot exceeds $140°C$ the gas bubbles are appear in the oil.

b. Gas bubbles develop at the surfaces of heavy metallic parts due to the leakage flux and also produced by super-saturation of the oil. However, such bubbles usually develop in regions of low electric stress and have to circulate in regions where the stress is higher before any significant reduction in the dielectric strength occurs.

c. Temporary ageing of the mechanical properties at higher temperatures can reduce the short-circuit strength.

d. Pressure build-up in the bushings may result in a failure due to oil leakage. Gassing in condenser type bushings may also occur if the temperature of the insulation exceeds about 140°C.

e. The expansion of the oil could cause over flow of the oil in the conservator.

f. Breaking of excessively high currents in the tap-changer could be hazardous.

2.5 Long time loading

The long time loading is not a normal operating condition. Occurrence of long time loading is expected to be rare, but it may remains for weeks or months and can lead to ageing of the insulation.

2.5.1 Effects of long time loading

a. At higher temperature the mechanical properties of the insulation will start deteriorate. If this deterioration remains for the long period it may reduce the life of the transformer, and latter it is subjected to system short circuits or transportation events.

b. Other insulation parts, which are baring the axial pressure of the winding block, can also suffer from the increased ageing rates at higher temperature.

c. The contact resistance of the tap-changers can increase at higher currents and temperatures.

d. The gasket materials in the transformer may become more fragile as a result of high temperatures.

2.6 Transformer size

The sensitivity of transformers to load beyond nameplate rating usually depends on their size. as size increases the,

a. The leakage flux density increases.

b. The short circuit forces increases.

c. The mass of insulation which is subjected to a high electric stress is increased.

d. The hot-spot temperatures are more difficult to determine.

Thus, a large transformer could be more vulnerable to loading beyond nameplate rating than a smaller one.

Chapter 3

Relative Ageing Rate and Transformer Insulation Life

3.1 Per Unit Life of the Insulation

Aging of insulation is mainly due to the temperature, moisture and oxygen content. With modern oil preservation systems,the moisture and oxygen contributions to insulation deterioration can be minimized, and temperature is the only controlling parameter by which ageing of the insulation can be control.

In most parts of the transformer temperature distribution is not uniform that part which is working at the highest temperature will ordinarily undergo greater deterioration. Therefore the aging of the insulation produced by the highest temperature needs to be investigated.

The relation between the hot spot temperature of transformer winding and per unit life of the insulation is shown below,

$$Per\ \ unit\ \ life = Ae^{\left(\frac{B}{\theta_H+273}\right)} \tag{3.1}$$

Where,

θ_H = Winding Hot spot Temperature, $^{\circ}C$

A = Constant = 9.8×10^{-18}

B = Constant = 15000

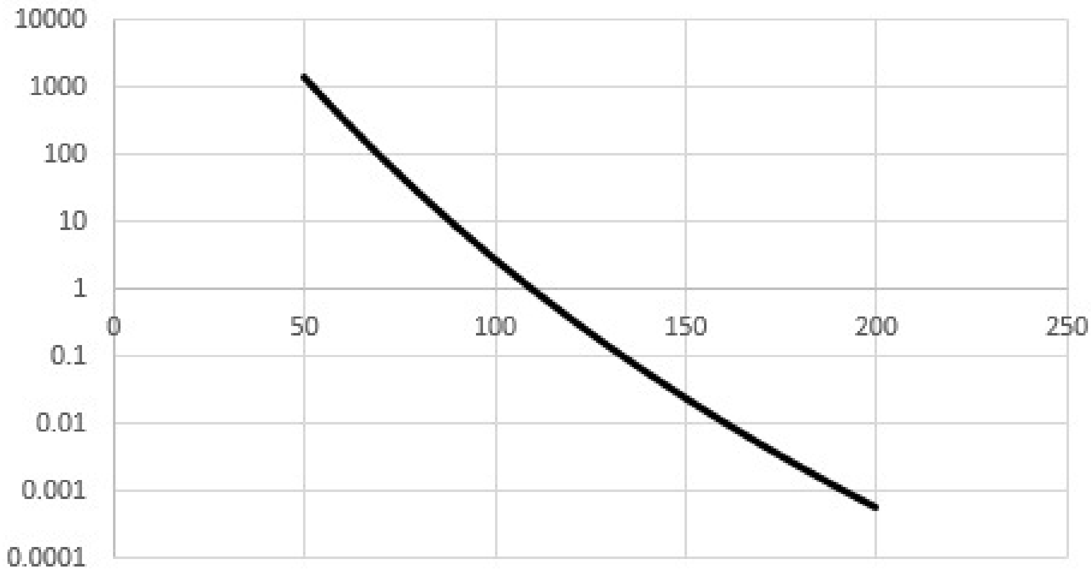

Figure 3.1: Transformer insulation life curve

The relation of per unit life of the transformer insulation to winding hot spot temperature is shown in Figure 3.1. This graph can be used for distribution transformers as well as power transformers because both transformer are manufactured using the same insulating material. It also shows the when the temperature exceeds above the reference temperature of $110°C$ the rate of ageing is accelerated beyond normal and when the temperature goes below the reference temperature of $110°C$ the rate of ageing remains normal.

The per unit insulation life curve of the transformer can be used in the following two ways.

- For a given load and temperature it is use to calculate the ageing acceleration factor.
- It is use to calculate the ageing acceleration factor for a different load pattern and different temperature profile over 24h period.

A graph of F_{AA} Vs. Hot spot temperature is shown in Figure 3.2. It shows that when the hot spot temperature increases the ageing of the winding insulation also increases.

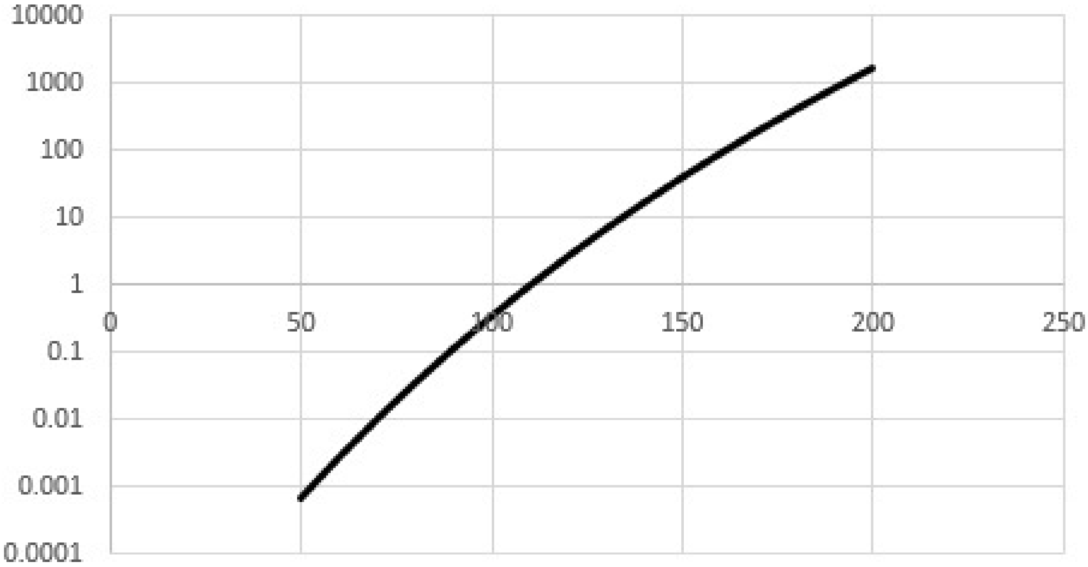

Figure 3.2: Transformer insulation life curve

F_{AA} has value grater than 1 when the winding hot spot temperature exceeds the $110°C$ and less than 1 when the hot spot temperature is below $110°C$.

The equation for ageing acceleration factor is given by,

$$F_{AA} = e^{\left(\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right)} \tag{3.2}$$

The above equation is used to determine ageing acceleration factor of the transformer. Per unit life and aging acceleration factor at various winding hot spot temperatures are as shown in Table I,

The equivalent ageing factor of transformer for a given time period $\triangle t_n$ is,

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA_n} \triangle t_n}{\sum_{n=1}^{N} \triangle t_n} \tag{3.3}$$

Where,

F_{EQA} = Equivalent ageing factor

F_{AA_n} = Ageing acceleration factor

Table I: Per unit life and Ageing acceleration factor at various winding hot spot temperatures

Winding hot spot temperature($T_H^{\circ}C$)	**Per unit life**	**Aging acceleration factor**
90	8.6552	0.1155
100	2.8585	0.3499
110	1.000	1.000
120	0.3692	2.7089
130	0.1432	6.9841

$\triangle t_n$ = Time interval

n = Index of the time interval, t

N = Total number of time intervals

3.2 Percentage loss of Life

The per unit life curve of insulation is used to calculate the age. It is mandatory to determine the life of insulation winding at the reference temperature in hours or years. The loss of life is determined by multiplying the equivalent ageing factor with the time period(t) in hours.

Percent loss of life is the ratio of product of life of insulation and 100 to the rated life of insulation.

$$\%Loss\ of\ life = \frac{F_{EQA} \times t \times 100}{Normal\ insulation\ life} \tag{3.4}$$

Chapter 4

Hot Spot Temperature

4.1 Introduction

Hot spot temperature is define as the maximum or hot test spot temperature rise of winding. The hot spot temperature is naturally occurring event due to the generation of losses and the heat transfer phenomena. It is the highest temperature inside the transformer winding and leads which is greater than measured average winding temperature. This chapter describes different methods to determine the hot spot temperature.

4.2 Methods for determination of the Hot spot temperature

The different methods for evaluating the Hot spot temperatures are,

a. Direct hot spot measurement

b. Mathematical models to predict temperature distribution and hot spot rises

- Thermal model I
- Thermal model II

4.2.1 Direct hot spot measurement

Temperature of the winding is the important parameter which affect the ageing rate of winding insulation. As the temperature of the winding increases the strength of the insulation decreases. Hence, it is important to determine winding temperature in order to predict life of the insulation as well as life of the transformer.

The hot spot temperature appear at winding turns in the upper part of the transformer because of,

a. Top oil temperature is higher than the bottom oil temperature.

b. The loss density in the winding is higher at the top of the transformer as compared to bottom because of eddy loss due to radial leakage field.

c. At top of the winding an extra insulation may have provided to line and turns.

In this method a sensor made of photo-luminescent material and attached to the end of optical fiber is in thermal contact with the winding. The sensor is usually placed between insulated conductor and radial spacer. The fiber optic cable is brought out of the tank up to the instrument through a hole made in the tank with a proper fluid sealing arrangement. A pulse of light from the light emitting diode(LED) in the instrument is sent to the sensor through the fiber optic cable, which stimulates the sensor material to fluorescent. Depending on the decay time of the returning fluorescent signal, which is a function of conductor temperature.

Hot spot temperature can be accurately measure by using fiber optic sensor but the insertion od sensor is difficult.

The hot spot temperature measured at various critical locations by direct hot spot measurement technique should be approximately equal to the calculated values.

4.2.2 Mathematical models to predict temperature distributions and hot spot rises

Thermal model or mathematical model is used to calculate the winding hot spot temperature. The two case studies are performed through simulation namely.

Figure 4.1: Fiber Optic Sensor

a. Case study I : Thermal model I

b. Case study II : Thermal model II

Case study I : Thermal model I

In this model the top fluid temperature, load current, rated hot spot temperature rise and other constant parameters are used as input to calculate the winding hot spot temperature.

The hot spot temperature is given by,

$$\frac{I_{pu}^2[K_\theta + \frac{P_{EC-R}}{K_\theta}]}{1 + P_{EC-R}}[\triangle\theta_{H-R}]^{\frac{1}{m}} = \tau_H \frac{d\theta_H}{dt} + [\theta_H - \theta_o]^{\frac{1}{m}} \tag{4.1}$$

The value of "m" is decided based on the type of cooling. The below table gives the value of "m" for different cooling system,

The simplified block diagram to determine the hot spot temperature of the winding is shown in Figure 4.1.

Table I: Different value of m for different type of cooling mode

OA	0.8
FA	0.8
FOA or FOW	0.8
DFOA or DFOW	1.0

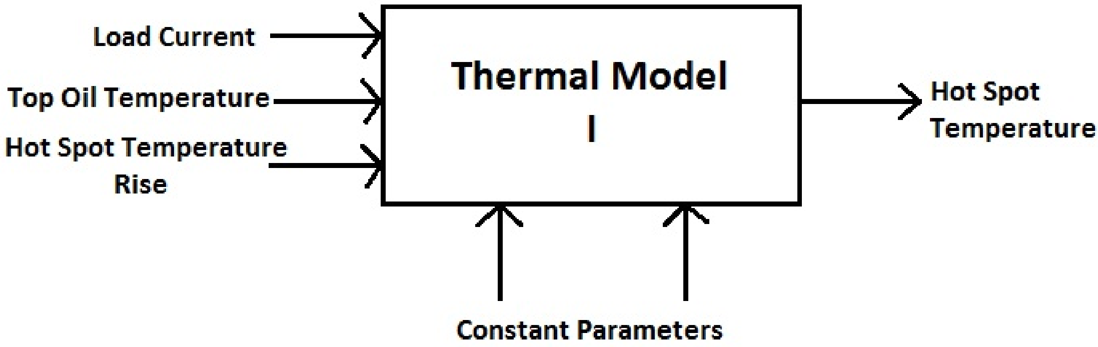

Figure 4.2: Block diagram of the thermal model I

Runge-kutta method is use to solve this equation.

The winding hot spot temperature is determine by the this thermal model model. Load current, top oil temperature and other constants parameters are used as input.

Simulation Model

The modelling and simulation of thermal model 1 is made in MATLAB and results of simulations are presented in figure 4.5

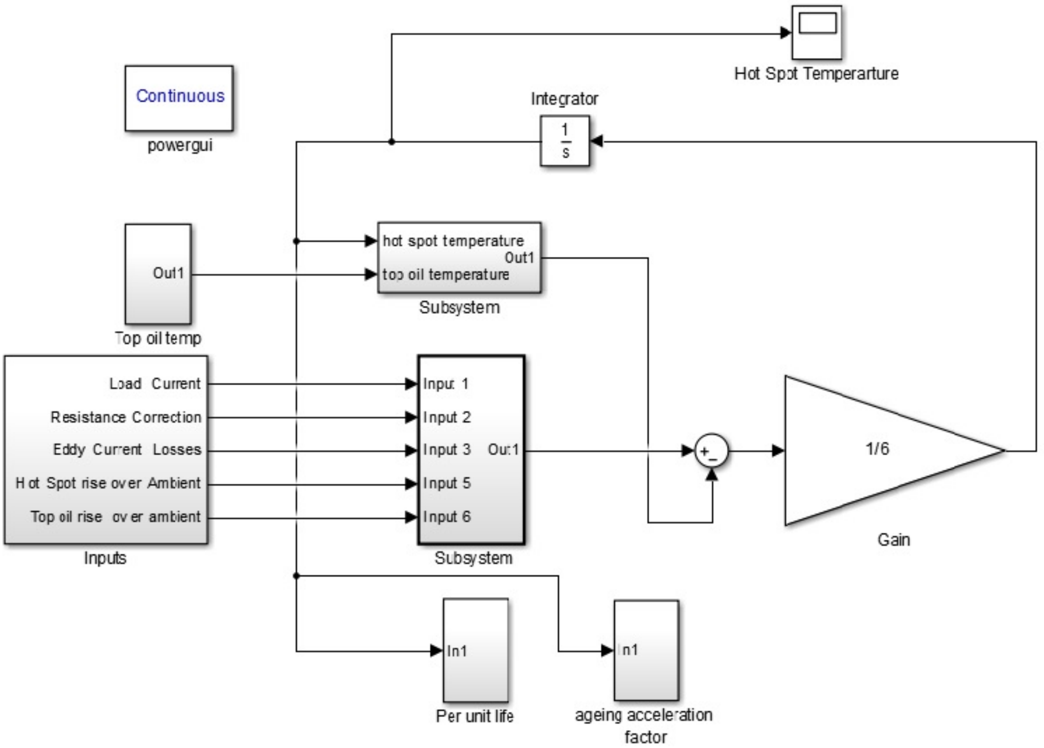

Figure 4.3: Simulation model in the matlab

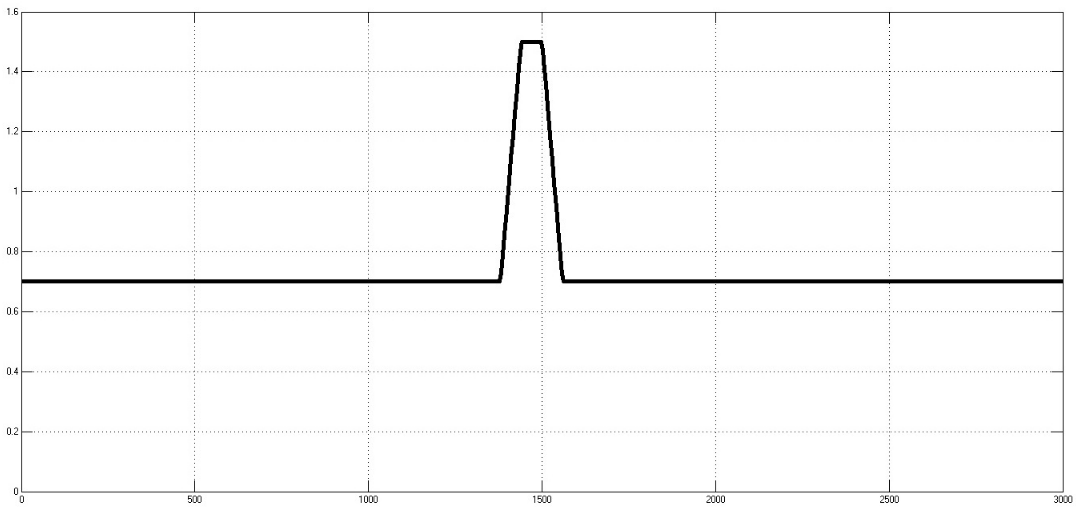

Figure 4.4: Input load current (pu)

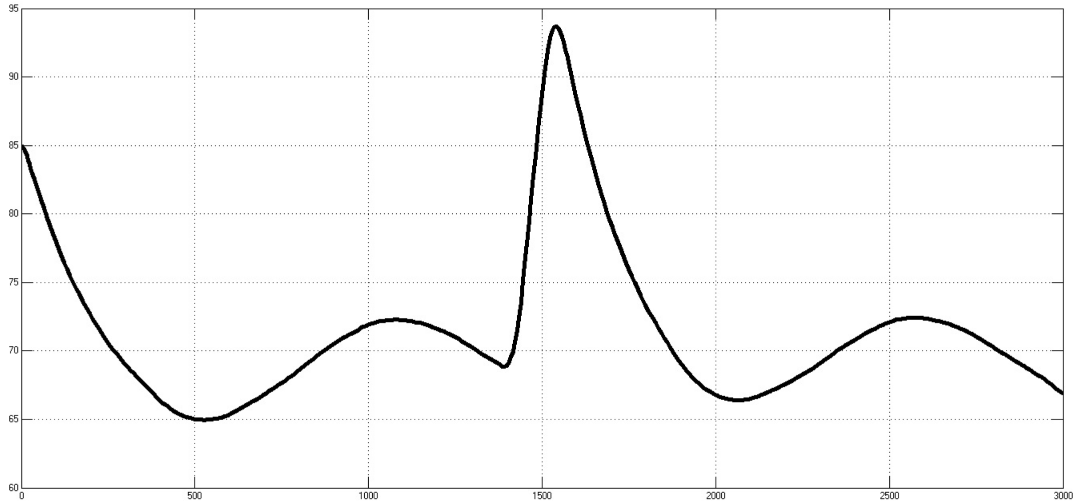

Figure 4.5: Top oil temperature

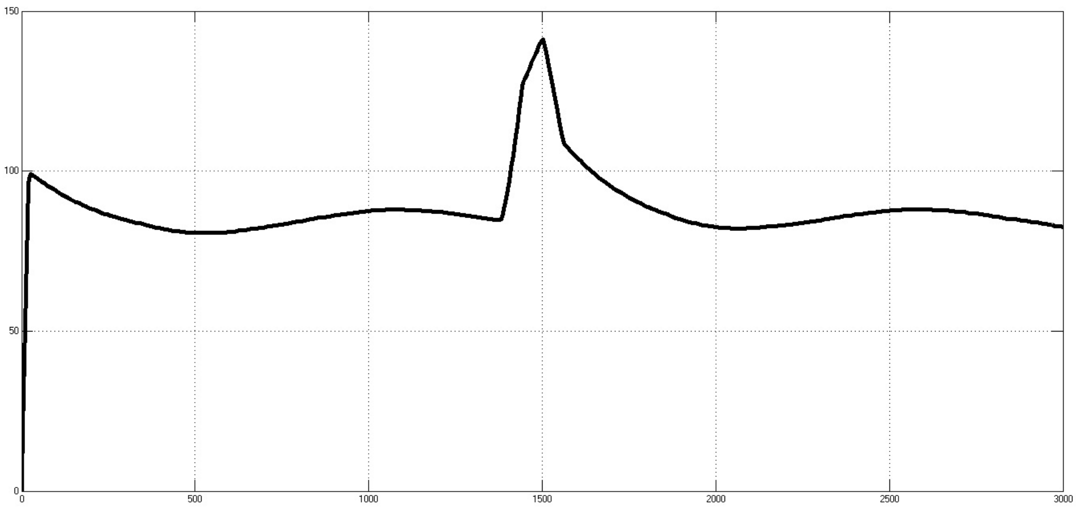

Figure 4.6: Hot Spot temperature

Case Study II : Thermal model II

Alternate Hot spot temperature calculation method

The hot spot temperature and oil temperature are obtained from equations for the conservation of energy during a small instant of time △t. The equation consist a transient forward-marching finite difference calculation procedure.

For temperatures acquire from the calculation at the prior time t_1 are used to calculate the temperatures at the next instant of time $t_1 + \triangle t$ or t_2. The time is incremented again by △t and the last calculated temperatures are used to calculate the temperature for the next time step.

For the load and corrected for the resistance change with temperature losses are calculated at each steps.

By using this method the required accuracy is obtain by taking a small value for the time increment △t.

The Hot spot temperature is made up of the following components.

$$\theta_H = \theta_A + \theta_{BO} + \theta_{WO/BO} + \theta_{H/WO} \tag{4.2}$$

The top fluid temperature and bottom fluid temperature are calculated by using the following equations,

$$\theta_{TO} = \theta_{AO} - \frac{\triangle\theta_{T/B}}{2} \tag{4.3}$$

$$\theta_{BO} = \theta_{AO} + \frac{\triangle\theta_{T/B}}{2} \tag{4.4}$$

The simplified block diagram to determine the hot spot temperature is shown in figure 4.6

In order to determine the Hot spot temperature this model make use of three equations namely,

a. Winding duct oil equation

b. Average winding equation

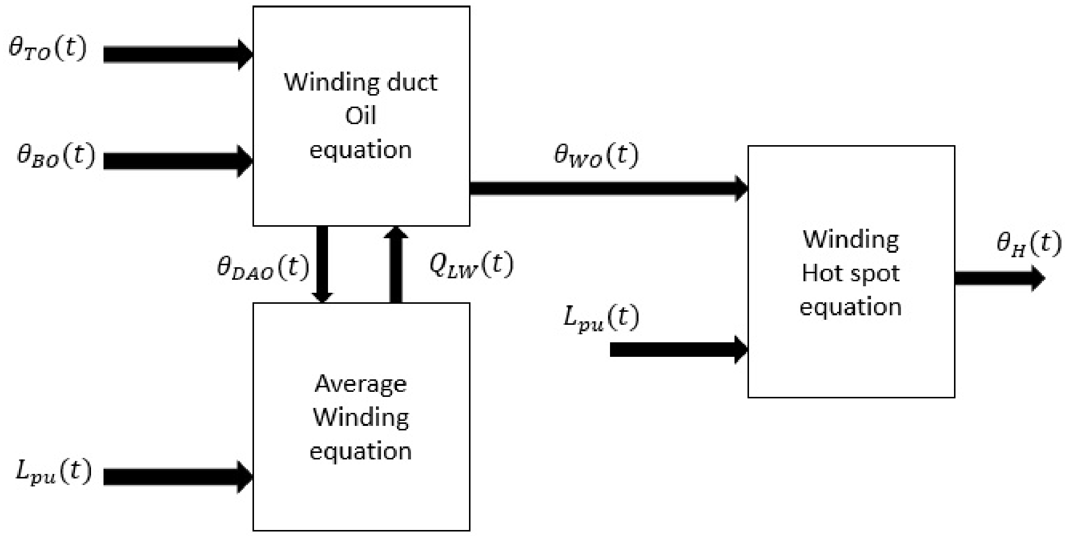

Figure 4.7: Block diagram of hot spot model

c. Winding hot spot equation

Average winding temperature

The heat produced by the windings during the time t_1 - t_2 is

$$Q_{GEN,W} = K^2[P_W K_W + \frac{P_E}{K_W}]\triangle t \tag{4.5}$$

Where,

$$K_W = \frac{\theta_{W,1} + \theta_K}{\theta_{W,R} + \theta_K} \tag{4.6}$$

The heat lost by the windings is given by,(For OA, FA, NDFOA)

$$Q_{LOST,W} = [\frac{\theta_{W,1} - \theta_{DAO,1}}{\theta_{W,R}} - \theta_{DAO,R}](P_W + P_E)\triangle t \tag{4.7}$$

From the winding time constant the mass and thermal capacitance of the winding can be estimated. The winding time constant may be determine from the heat run test or approximate values may be used.

$$M_W C_{P_W} = \frac{(P_W + P_E)\tau_W}{\theta_{W,R} - \theta_{DAO,R}} \tag{4.8}$$

The average winding temperature at time t = t_2 is,

$$\theta_{W,2} = \frac{Q_{GEN,W} - Q_{LOST,W} + M_W C_{P_W} \theta_{W,1}}{M_W C_{P_W}} \tag{4.9}$$

Winding duct oil temperature rise over bottom fluid

$$\triangle\theta_{DO/BO} = \theta_{TDO} - \theta_{BO} = [\frac{Q_{LOST,W}}{(P_W + P_E)\triangle t}]^x (\theta_{TDO,R} - \theta_{BO,R}) \tag{4.10}$$

x = 0.5 for OA, FA, NDFOA

x = 1.0 for DFOA

The duct fluid temperature at rated load, $\theta_{TDO,R}$ is assumed to the tank top fluid temperature.(For OA, FA, DFOA)

If the duct top fluid temperature at rated load is not known for NDFOA, it can be assumed to be around equal to the average winding temperature at rated load.

Table II: Types of cooling mode

Cooling modes	**Description**
OA	Natural convection flow of oil through winding and radiators. Natural convection flow of air and tank radiators.
FA	Natural convection flow of oil through winding and radiators. Forced convection flow of air over radiators by fans.
DFOA	Forced oil flow of oil through winding and radiators or heat exchange by pumps. The oil is directed from the radiators or heat exchanger by fans.
NDFOA	Forced oil flow through the radiators by one or more pumps. The oil if forced to flow into the tank by the pumps. however the main forced oil flow in the tank bypasses the windings. the air is forced over the radiators or heat exchanger by fans.

At hot spot the fluid temperature is given by,

$$\triangle\theta_{WO/BO} = H_{HS}(\theta_{TDO} - \theta_{BO}) \tag{4.11}$$

$$\theta_{WO} = \theta_{BO} + \triangle\theta_{WO/BO} \tag{4.12}$$

The fluid temperature close to the hot spot is assumed equal to the top fluid temperature when the winding duct fluid temperature is less than the fluid in the tank.

In terms of equation,

$\theta_{TDO} < \theta_{TO} THEN \theta_{WO} = \theta_T$

Winding Hot spot temperature

At the hot spot temperature to determine the additional heat generated, it is require to correct the losses of the winding from the average winding temperature to the hot spot temperature by using following equations,

$$P_{HS} = (\frac{\theta_{H,R} + \theta_K}{\theta_{W,R} + \theta_K})P_W \tag{4.13}$$

$$P_{EHS} = E_{HS}P_{HS} \tag{4.14}$$

If E_{HS} is not known it may be determine.

$$Q_{GEN,HS} = K^2[P_{HS}K_{HS} + \frac{P_{EHS}}{K_{HS}}]\triangle t \tag{4.15}$$

Where,

$$K_{HS} = \frac{\theta_{H,1} + \theta_K}{\theta_{H,R} + \theta_K} \tag{4.16}$$

Viscosity correction is use For the OA,FA and NDFOA cooling modes

At the hot spot location heat lost is given by,

Table III: Calculation of Viscosity

Viscosity term	Equation
$\mu_{W,R}$	$\frac{\theta_{W,R}+\theta_{DAO,R}}{2}$
$\mu_{W,1}$	$\frac{\theta_{W,1}+\theta_{DAO,1}}{2}$
$\mu_{HS,R}$	$\frac{\theta_{H,R}+\theta_{DAO,R}}{2}$
$\mu_{HS,1}$	$\frac{\theta_{H,R}+\theta_{DAO,1}}{2}$

$$Q_{LOST,HS} = [\frac{\theta_{H,1} - \theta_{WO}}{\theta_{H,R} - \theta_{WO,R}}]^1.25[\frac{\mu_{HS,R}}{\mu_{HS,1}}]^0.25(P_{HS} + P_{EHS})\triangle t \tag{4.17}$$

Viscosity correction is not use for the DFOA cooling mode since the oil is pumped At the hot spot location heat lost is given by,

$$Q_{LOST,HS} = [\frac{\theta_{H,1} - \theta_{WO}}{\theta_{HS,R} - \theta_{WO,R}}](P_{HS} + P_{EHS})\triangle t \tag{4.18}$$

The winding hot spot temperature at time t_2 is,

$$\theta_{H,2} = \frac{Q_{GEN,HS} - Q_{LOST,HS} + M_W C_{P_W} \theta_{H,1}}{M_W C_{P_W}} \tag{4.19}$$

Simulation

In this thermal model algorithm is developed in matlab software, which calculate the hot spot temperature using various inputs.

```
xkva1 = xlsread('input.xlsx','B1:B1')
xkva2 = xlsread('input.xlsx','B2:B2')
tkva1 = xlsread('input.xlsx','B3:B3')
thkva2 = xlsread('input.xlsx','B4:B4')
pw = xlsread('input.xlsx','B5:B5')
pe = xlsread('input.xlsx','B6:B6')
ps = xlsread('input.xlsx','B7:B7')
pc = xlsread('input.xlsx','B8:B8')
thewa = xlsread('input.xlsx','B9:B9')
thehsa = xlsread('input.xlsx','B10:B10')
thetor = xlsread('input.xlsx','B11:B11')
```

```
tar = xlsread('input.xlsx','B12:B12')
puelhs = xlsread('input.xlsx','B13:B13')
tauw = xlsread('input.xlsx','B14:B14')
hhs = xlsread('input.xlsx','B15:B15')
wcc = xlsread('input.xlsx','B16:B16')
wtank = xlsread('input.xlsx','B17:B17')
gfluid = xlsread('input.xlsx','B18:B18')
mcore = xlsread('input.xlsx','B19:B19')
timcor = xlsread('input.xlsx','B20:B20')
pcoe = xlsread('input.xlsx','B21:B21')
thebor = xlsread('input.xlsx','B22:B22')
ma = xlsread('input.xlsx','B23:B23')
mpr1 = xlsread('input.xlsx','B24:B24')
dtp = xlsread('input.xlsx','B25:B25')
lcas = xlsread('input.xlsx','B30:B30')
pa = xlsread('input.xlsx','B32:B32')
pb = xlsread('input.xlsx','B33:B33')
jj = xlsread('input.xlsx','B26:B26')
tim = xlsread('input.xlsx',2,'A:A');
amb = xlsread('input.xlsx',2,'B:B');
pul = xlsread('input.xlsx',2,'C:C');
tim = 60 * xlsread('input.xlsx',2,'A:A');
m = [tim,amb,pul]
pt = pw + pe + ps + pc
conductor = input('Winding conductor is:')
if (conductor == 1)
'conductor == copper'
tk1 = xlsread('input.xlsx','F2:F2')
cpw1 = xlsread('input.xlsx','G2:G2')
else
'conductor == aluminum'
```

```
tk3 = xlsread('input.xlsx','F3:F3')
cpw2 = xlsread('input.xlsx','G3:G3')
end
fluid = input('Cooling fluid is:')
if (fluid == 1)
'fluid == transformer oil'
cpf = xlsread('input.xlsx','F6:F6')
rhof = xlsread('input.xlsx','G6:G6')
c = xlsread('input.xlsx','H6:H6')
b = xlsread('input.xlsx','I6:I6')
elseif(fluid == 2)
'fluid == silicon'
cpf = xlsread('input.xlsx','F7:F7')
rhof = xlsread('input.xlsx','G7:G7')
c = xlsread('input.xlsx','H7:H7')
b = xlsread('input.xlsx','I7:I7')
else(fluid ¿ 2)
'fluid == HTHC'
cpf = xlsread('input.xlsx','F8:F8')
rhof = xlsread('input.xlsx','G8:G8')
c = xlsread('input.xlsx','H8:H8')
b = xlsread('input.xlsx','I8:I8')
end
coolingmode = input('Cooling mode is:')
if (coolingmode == 1)
'coolingmode == OA'
x = xlsread('input.xlsx','F11:F11')
y = xlsread('input.xlsx','G11:G11')
z = xlsread('input.xlsx','H11:H11')
'thedor == thetor'
thedor = xlsread('input.xlsx','B11:B11')
```

```
end
if (coolingmode == 2)
'coolingmode == FA'
x = xlsread('input.xlsx','F12:F12')
y = xlsread('input.xlsx','G12:G12')
z = xlsread('input.xlsx','H12:H12')
'thedor == thetor'
thedor = xlsread('input.xlsx','B11:B11')
end
if (coolingmode == 3)
'coolingmode == NDFOA'
x = xlsread('input.xlsx','F13:F13')
y = xlsread('input.xlsx','G13:G13')
z = xlsread('input.xlsx','H13:H13')
'thedor == thewa'
thedor = xlsread('input.xlsx','B9:B9')
end
if (coolingmode == 4)
'coolingmode == DFOA'
x = xlsread('input.xlsx','F14:F14')
y = xlsread('input.xlsx','G14:G14')
z = xlsread('input.xlsx','H14:H14')
'thedor == thetor'
thedor = xlsread('input.xlsx','B11:B11')
end
twr = tar + thkva2
twrt = tar + thewa
thsr = tar + thehsa
ttor = tar + thetor
tbor = tar + thebor
ttdor = thedor + tar
```

```
twor = (hhs*(ttdor-tbor))+tbor
tdaor = (ttdor + tbor)/2 tfaver = (ttor + tbor)/2 xk2 = (xkva2/xkva1)^2 tk2 = (tk1
+ twr)/(tk1 + tkva1)
pw1 = xk2 * pw * tk2
pe1 = xk2 * (pe/tk2)
ps1 = xk2 * (ps/tk2)
pt1 = pw1 + pe1 + ps1 + pc
if(pe/pw > puelhs)
puelhs = pe/pw
end
tkhs = (thsr + tk1)/(twr + tk1)
pwhs = tkhs * pw
pehs = puelhs * pwhs
if(mcore < 1)
disp('CORE OVEREXCITATION DOES NOT OCCUR')
end
if(mcore > 1)
disp('CORE OVEREXCITATION OCCUR AT')
disp('CORE OVEREXCITATION LOSS IS')
end
if(mpr1 < 1)
timcor = 60 * timcor
end
dt = xlsread('input.xlsx','B27:B27')
if(tauw/dt > 9)
xmcp = ((pe1 + pw1)*tauw)/(twrt - tdaor)
wwind = xmcp/cpw1
else
dt = dt/2
end
if(wwind > wcc)
```

```
disp(' winding time constant to high')
end
cpst = xlsread('input.xlsx','B28:B28')
wcore = wcc-wwind
wfl = gfluid*231*rhof
summcp = (wtank*cpst) + (wcore*cpst) + (wfl*cpf)
visr = (twrt + tdaor)/2
vihsr = (thsr + twor)/2
tmp = xlsread('input.xlsx','B29:B29')
if(mpr1 < 1)
dtp = 15
else
dtp = 60
end
kk = (tim(jj)/dtp + 0.1)
for k = 1:1:kk
tmp = tmp + dtp
timp = tmp
end
if(mpr1 <= 1)
if(lcas == 1)
ths(1) = thsr
tw(1) = twrt
tto(1) = ttor
ttdo(1) = ttdor
tbo(1) = tbor
asum(1) = 0
mpr = mpr1
tfave(1) = (tto(1) + tbo(1))/2
two(1) = tbo(1) + (hhs*(ttdo(1)-tbo(1)))
jlast = 1;
```

jjj = 1

end

end

if(jjj == 2)

mpr = mpr1

end

for i = 1:1:2940

thsmax(i) = ths(i) timhs = 0

ttomax(i) = tto(i)

timto = 0

tims = 0

timsh = 0

asm(i) = asum(i)

k = 1

tims = tims + dt

$if(tims > tim(i+1))$

i = i+1

end

timsh = tims/60

if(abs(tim(i+1) - tim(i)) ¡ 0.01)

i = i+1

end

sl(i) = (pul(i+1) - pul(i))/(tim(i+1) - tim(i))

slamb(i) = (amb(i+1) - amb(i))/(tim(i+1) - tim(i))

tdao(i) = (ttdo(i) + tbo(i))/2

tkw(i) = (tw(i) +tk1)/(twr + tk1)

$qwgen(i) = pul(i)^2 * ((tkw(i) * pw1) + (pe1/tkw(i))) * dt$

$if(tw(i) < tdao(i))$

qwlost == 0

end

vis(i) = (tw(i) + tdao(i))/2

$qwlost(i) = ((tw(i) - tdao(i))/(twrt - tdaor))^1.25 * (visr/vis(i))^0.25 * (pw1 + pe1) * dt$

$if(tw(i) < tbo(i))$

tw(i) = tbo(i)

end

$dtdo(i) = (ttdor - tbor) * (qwlost(i)/((pw1 + pe1) * dt))^x$

tkhs(i) = (ths(i) + tk1)/(thsr + tk1)

$if((ttdo(i) + 0.1) < tto(i))$

two(i) = tto(i)

end

$if(ths(i) < tw(i))$

ths(i) = tw(i)

end

$if(ths(i) < two(i))$

ths(i) = two(i)

end

qhsgen(i) = pul(i)*pul(i) * ((tkhs(i) * pwhs) + (pehs/tkhs(i))) * dt

vishs(i) = (ths(i) + two(i))/2

$qlhs(i) = ((ths(i) - two(i))/(thsr - twor))^1.25 * (vihsr/vishs(i))^0.25 * (pwhs + pehs) * dt$

$qs(i) = ((pul(i)^2 * ps1)/tkw(i)) * dt$

$qlostf(i) = ((tfave(i) - amb(i))/(tfaver - tar))^(1/y) * pt1 * dt$

$if(mcore < 1)$

qc = pc * dt

end

$if(tims < timcor)$

qc = pc * dt

end

qc = pcoe*dt

tfave(i+1) = (qwlost(i) + qc + qs(i) - qlostf(i) +(summcp * tfave(i)))/summcp

$dttb(i) = ((qlostf(i)/(pt1 * dt))^z) * (ttor - tbor)$

tto(i+1) = tfave(i) + (dttb(i)/2)

tbo(i+1) = tfave(i) - (dttb(i)/2)

```
tw(i+1) = (qwgen(i) - qwlost(i) +(xmcp * tw(i)))/xmcp
ttdo(i+1) = tbo(i) + dtdo(i)
tdao(i+1) = (ttdo(i) + tbo(i))/2
two(i+1) = tbo(i) + (hhs * dtdo(i))
ths(i+1) = (qhsgen(i) - qlhs(i) + (xmcp * ths(i)))/xmcp
if(tbo(i) < amb(i))
tbo(i) = amb(i)
end
if(ttdo(i) < tbo(i))
ttdo(i) == tbo(i)
end
l(i) = (pb/(ths(i)+273))
l1(i) = exp(l(i))
life(i) = pa * l1(i)
ax(i) = (pb/383) - (pb/(ths(i) + 273))
a(i) = exp(ax(i))
asum(i+1) = asm(i) + (a(i) * dt)
if(ths(i) > thsmax(i))
thsmax(i) = ths(i)
timhs = timsh
end
if(tto(i) > ttomax(i))
ttomax(i) = tto(i)
timto = timsh
end
tims = tims - dt
asum(i+1) = asm(i)/60
aeq(i) = asm(i)/timsh
i = i+1
end
```

Load current , Top oil temperature, and Ambient temperatures are use as input and output of the simulation is hot spot temperature.

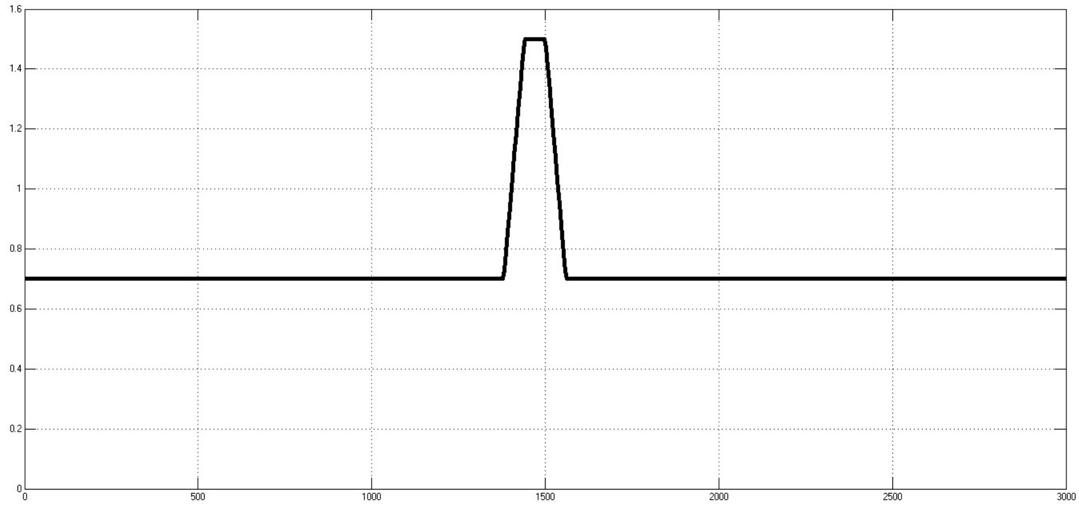

Figure 4.8: Load current

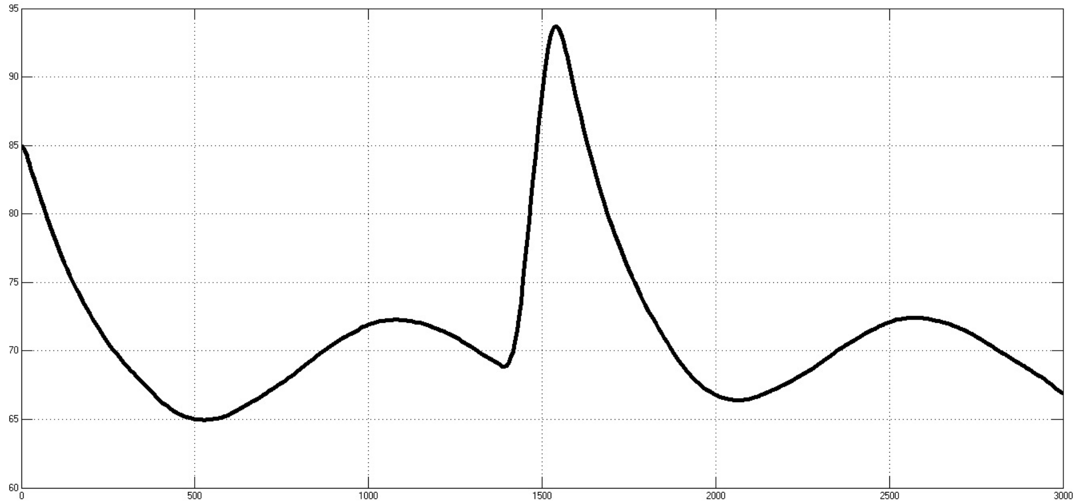

Figure 4.9: Top oil temperature

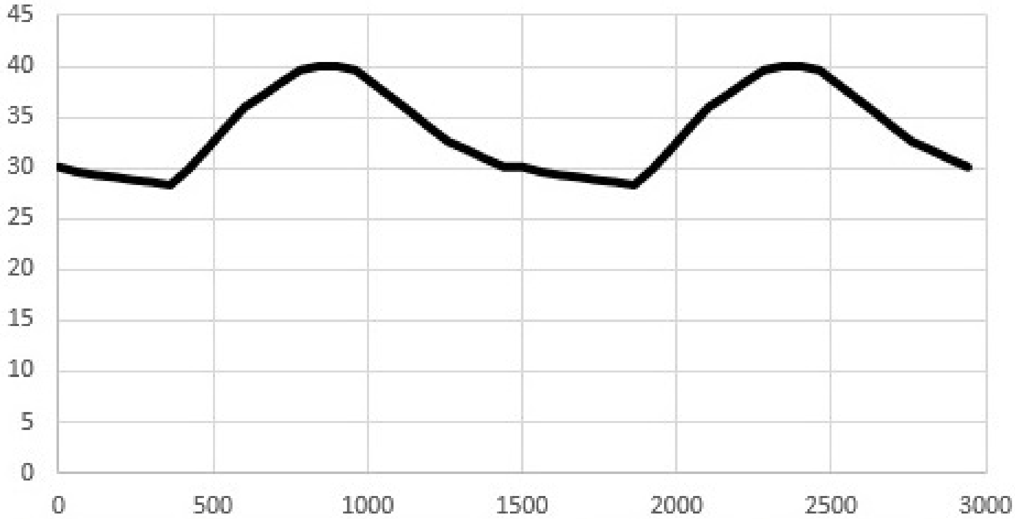

Figure 4.10: Ambient temperature

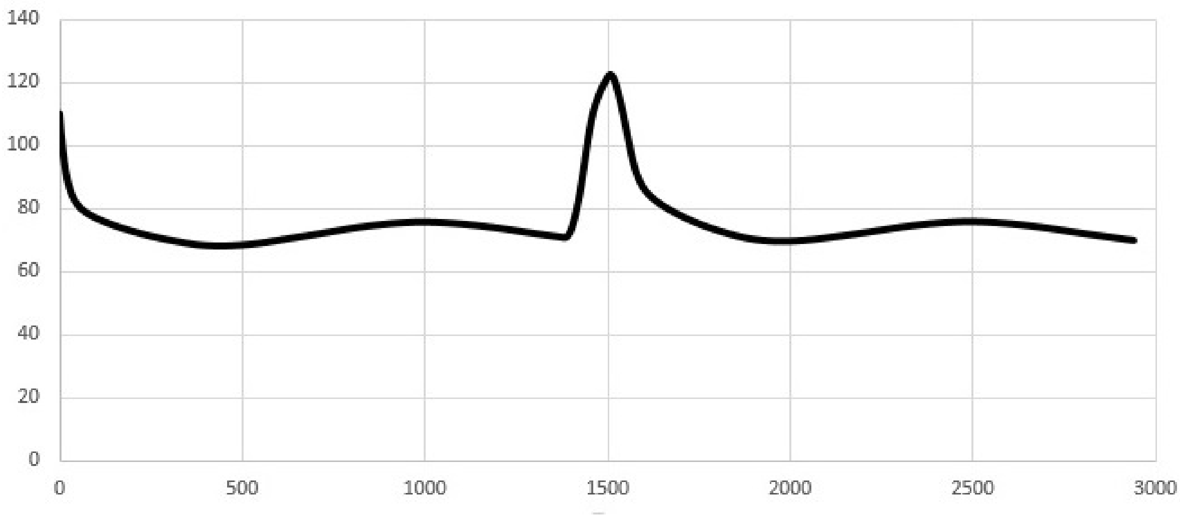

Figure 4.11: Hot spot temperature

Chapter 5

Validation and its Results

5.1 Thermal Model I

5.1.1 20% and 40% Loading

Transformer is rated for 100kVA, 11/0.433kV, Dyn 11 used for determining the hot spot temperature for various loading condition. In the first phase only 20% and 40% loading is being done to determine the hot spot temperature and percentage loss of the life practically determine using Thermal model I and afterwards this data will be compared with the calculated one.

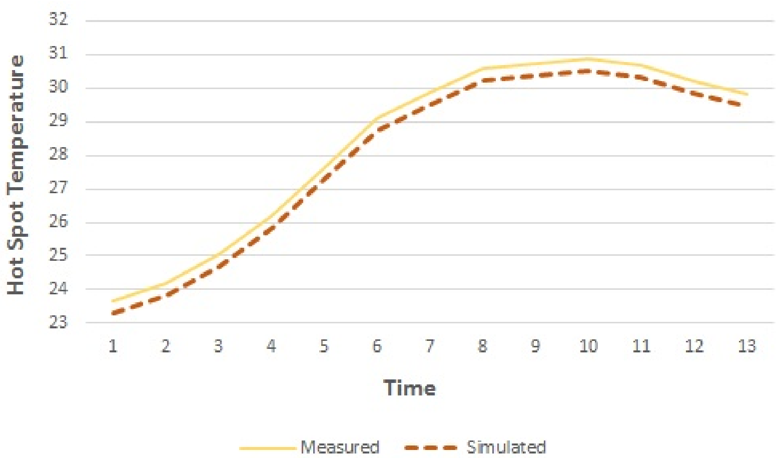

Figure 5.1: Measured & Simulated Hot Spot Temperature for 20% and 40% Loading

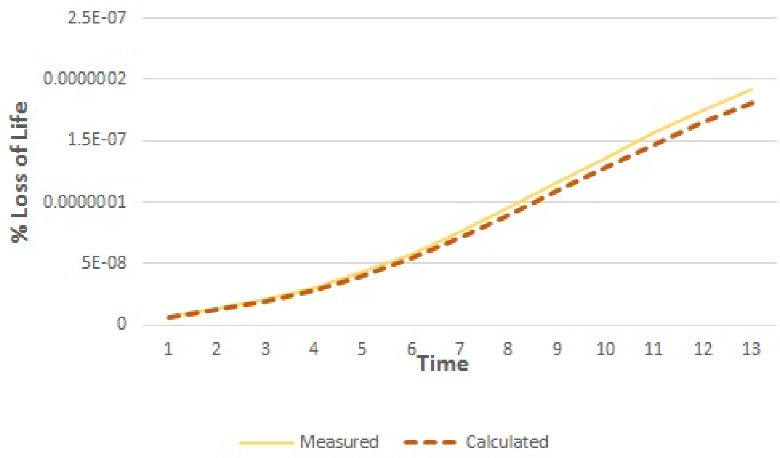

Figure 5.2: Measured & Simulated Percentage Loss of Life for 20% and 40% Loading

It is observed that the results obtain through simulation and calculation are almost similar.

5.1.2 60% and 80% Loading

Transformer is rated for 100kVA but only 60% and 80% loading is being done in first phase to determine the hot spot temperature and percentage loss of the life practically determine using Thermal model I and afterwards this data will be compared with the calculated one.

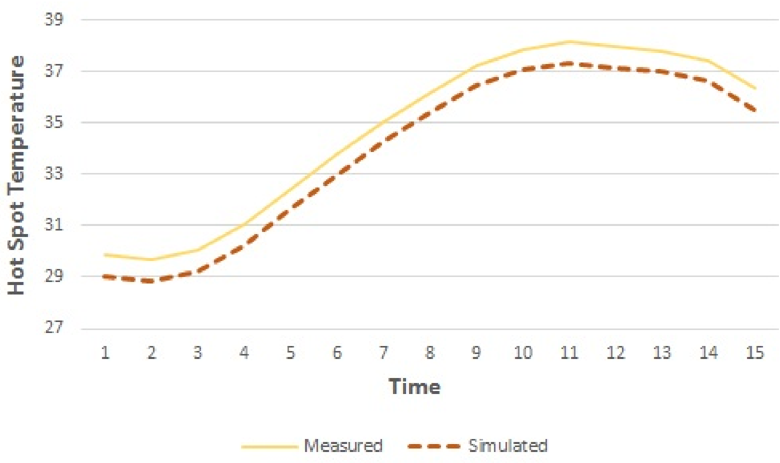

Figure 5.3: Measured & Simulated Hot Spot Temperature for 60% and 80% Loading

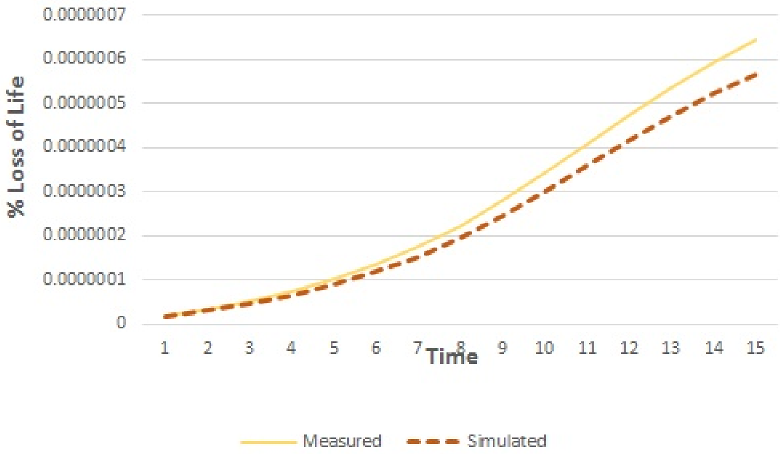

Figure 5.4: Measured & Simulated Percentage Loss of Life for 60% and 80% Loading

Both the results of simulation and calculation are to be same.

5.1.3 100% Loading

Transformer is rated for 100kVA but only 100% loading is being done in first phase to determine the hot spot temperature and percentage loss of the life practically by using Thermal model I and afterwards this data will be compared with the calculated one.

It is observed that the results obtain through simulation and calculation are almost similar.

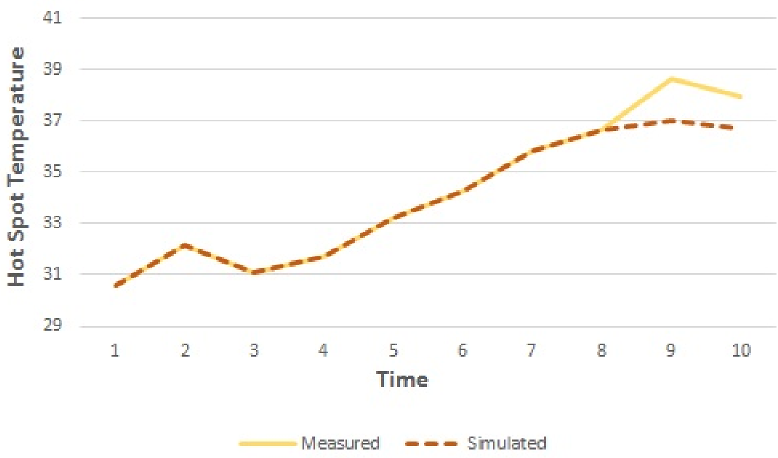

Figure 5.5: Measured & Simulated Hot Spot Temperature for 100% Loading

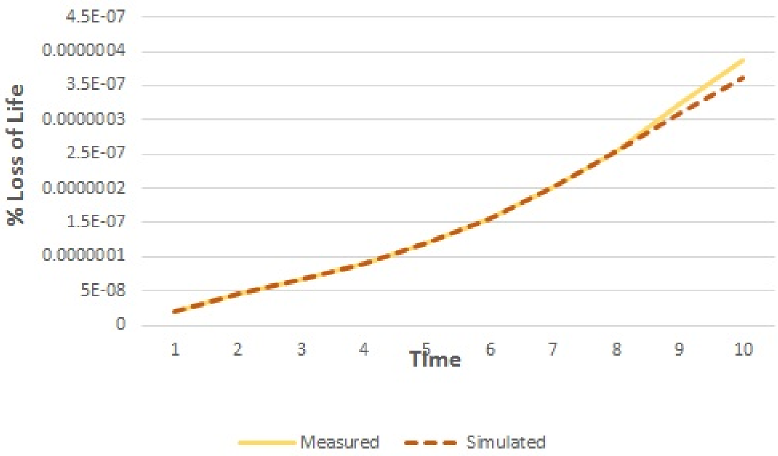

Figure 5.6: Measured & Simulated Percentage Loss of Life for 100% Loading

5.2 Thermal Model II

5.2.1 20% and 40% Loading

Transformer is rated for 100kVA but only 20% and 40% loading is being done in first phase to determine the hot spot temperature and percentage loss of the life practically by using Thermal model II and afterwards this data will be compared with the calculated one.

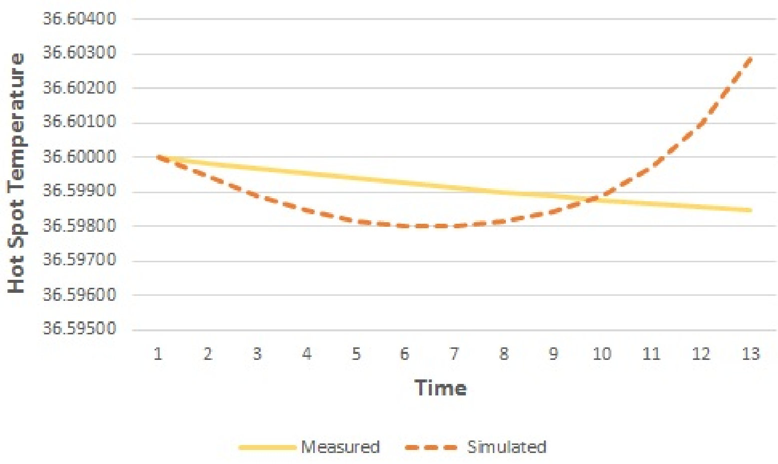

Figure 5.7: Measured & Simulated Hot Spot Temperature for 20% and 40% Loading

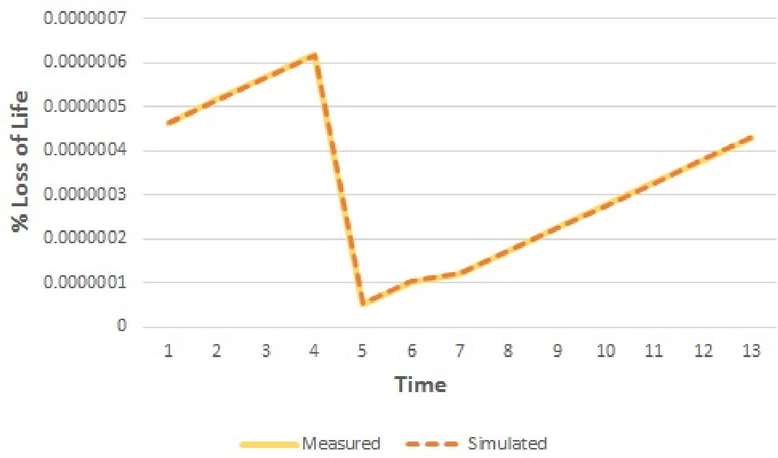

Figure 5.8: Measured & Simulated Percentage Loss of Life for 20% and 40% Loading

It is observed that the results obtain through simulation and calculation are almost similar.

5.2.2 60% and 80% Loading

Transformer is rated for 100kVA but only 60% and 80% loading is being done in first phase to determine the hot spot temperature and percentage loss of the life practically by using Thermal model II and afterwards this data will be compared with the calculated one.

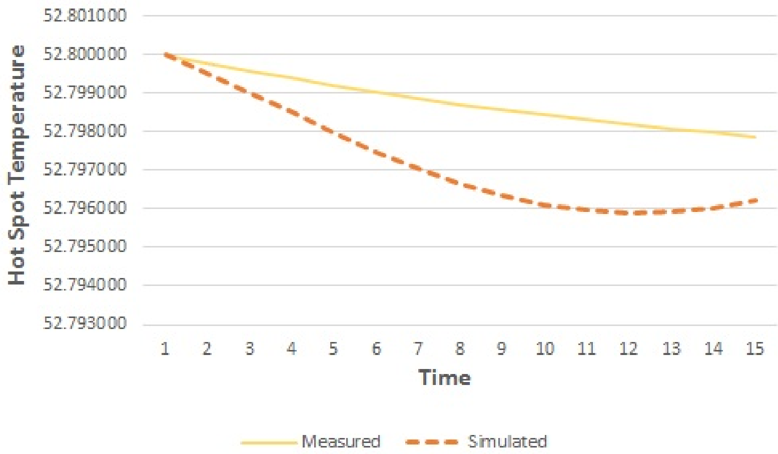

Figure 5.9: Measured & Simulated Hot Spot Temperature for 60% and 80% Loading

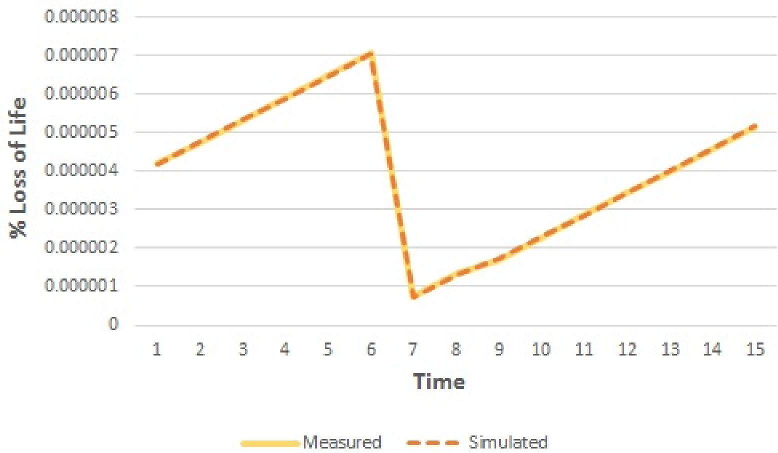

Figure 5.10: Measured & Simulated Percentage Loss of Life for 60% and 80% Loading

It is observed the the results obtain through simulation and calculation are almost similar.

5.2.3 100% Loading

Transformer is rated for 100kVA but only 100% loading is being done in first phase to determine the hot spot temperature and percentage loss of the life practically by using Thermal model I and afterwards this data will be compared with the calculated one.

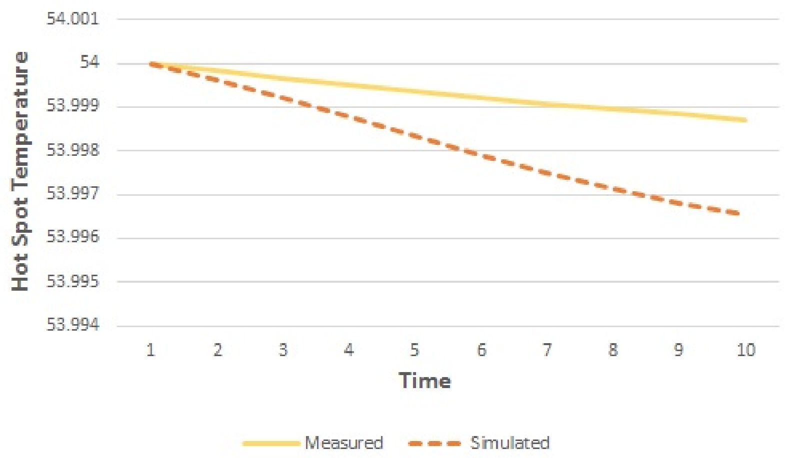

Figure 5.11: Measured & Simulated Hot Spot Temperature for 100% Loading

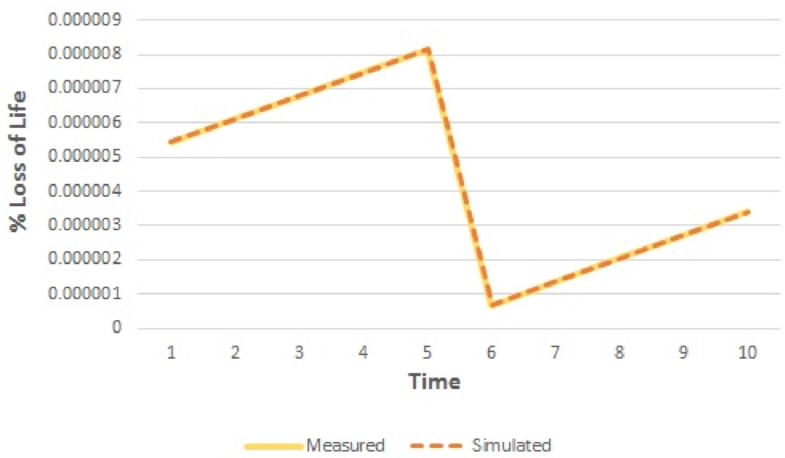

Figure 5.12: Measured & Simulated Percentage Loss of Life for 100% Loading

It is observed the the results obtain through simulation and calculation are almost similar.

Chapter 6

Conclusion

- Thermal model I and Thermal model II is used to determine Hot spot temperature. Both Thermal model are simulated in MATLAB. Based on the simulation it is observed that the value found in Thermal model I is more when compared to Thermal model II.

- Validation is done for 100kVA transformer by using both Thermal model. Thermal models are validate for various loading conditions. Based on the results it is observed that the results obtain through measurement and simulation are almost similar.

Chapter 7

Future Scope

In this project the algorithm is being developed for determine the hot spot temperature. After completion of this project one can implement this algorithm in prototype. One can also provide the trip signal to circuit breaker when hot spot temperature exceeds the permissible limit.

References

[1] "Transformer Winding Hot Spot Temperature Modeling and Simulation" A.Elmoudi

[2] "Diagnostic and Prognostic Models for Generator Step-up Transformers" Vivek Agarwal, Nancy J. Lybeck and Binh T.Pham.

[3] "IEEE Guide for Determination of Maximum Winding Temperature Rise in Liquid-Filled Transformers" (IEEE Std 1538-2000)

[4] "Loading Guide for Oil-immersed power Transformers" (IEC 60076-7:2005)

[5] "IEEE Guide for Loading Mineral Oil Immersed Transformers"(IEEE Std C57.91-1995)

[6] "IEEE Stndard Test Procedure for Thermal Evaluation of Insulation System for Liquid Immersed Distribution and Power Transformer"(IEEE Std C57.100-2011)