THESIS

STEADY-STATE ANALYSIS OF THE IMPACT OF CLIMATE CHANGE ON DISTRIBUTION TRANSFORMER

Submitted by

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ABSTRACT

STEADY-STATE ANALYSIS OF THE IMPACT OF CLIMATE CHANGE ON DISTRIBUTION TRANSFORMER

Climate change could cause several issues such as decreasing water availability, increasing intensity of storm events, flooding and sea level rise, increasing air, and water temperatures. One aspect of climate change is the increase in ambient temperature. According to, the average global surface temperature is expected to increase around 1.8℃ to 4℃, while the average increase of global ambient temperature is predicted from 1.4℃ to 5.8℃, in the periods of 1990 to 2100.

Climate change can also affect distribution systems in terms of reliability and loadability. A 1℃ rise in global temperature increases peak demand by 4.6%. In 2013, U.S. weather–related power outages may have reached 180 events per year. Further, climate change leads to high temperature, and many factors might change. An increase in ambient temperature leads to increase in transformer loading, which leads to a reduction of lifetime of transformers and low insulation value due to degradation of degree of polymerization. As ambient temperature and operation temperature increase can cause thermal aging of transformers, it is important to control a loaded transformer to mitigate aging effect. Thus, demand response is an important and effective feature of thermal management of a transformer.

Multiple models are discussed and explained to obtain accurate results and a good prediction for the three factors: ambient temperature, operation temperature, and demand response. Therefore, IEEE standard C57.91-2011 is used for calculating thermal characteristics and the loss of life of distribution transformers. It also provides an example using rated parameters of a 25 MVA distribution transformer, real data of temperature, load available in the public domain for

Fort Collins, Colorado, USA. Moreover, demand response is considered in this calculation in order to study the effect of changing load levels on the transformer insulation life and aging acceleration factor. Four scenarios of load levels will be applied as follow: pre-DR, 3%, 6% and 9% peak load reduction.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I

Introduction

1.1 Objective

The main objective of this thesis is to quantify the impact of climate change on distribution transformers and its effect on the electric power system infrastructure. The thesis also explains the hot spot temperature, which consists of ambient temperature, top oil temperature rise over ambient temperature, and hot spot temperature rise over top oil temperature, in detail to illustrate the thermal behavior of a distribution transformer. Another objective of this work is to calculate the insulation level and the aging acceleration factor of a distribution transformer to account for its lifetime. Finally, this thesis examines the effect of demand response (DR) on the aging characteristics of a distribution transformer.

1.2 Motivation

Climate change can affect the reliability and the loadability of electric power systems. The transformer is an important component for maintaining power system reliability. Failure of a transformer could potentially lead to blackouts and economic losses. Hence, power transformer reliability and efficiency are critical concerns in the operation of power system networks. Recent researches state that climate change leads to high temperature, and might change many factors such as the ambient temperature and operation temperature of power system network assets. This could affect the thermal behavior of transformers. According to [1], for each increase of the operating temperature by10°C, the dielectric aging of transformers will be twice as faster and the winding temperature reaches 140°C, the aging acceleration factor would be 100; an hour spent during overloading equals 100 hours at rated operation conditions [2]. As the lifetime of a transformer is controlled by the condition of insulation level that undergoes thermal behavior of operation, studying the thermal operation condition of a distribution transformer with respect to climate change is significant nowadays. Moreover, losing electricity supply due to the failure of a transformer would be costly and will affect power suppliers, consumers, and the electricity market. Examining the thermal behavior of the transformer and demonstrating its lifetime would determine its reliability and efficiency.

1.3 Scope

The scope of this thesis is to investigate a comprehensive model that accounts for the thermal characteristics of a distribution transformer. Further, the model is able to calculate the effect of ambient temperature, operation temperature, and DR in distribution transformer aging. The model is quantified using real data, available in the public domain, of temperature and load corresponding to Fort Collins, Colorado, USA. The model output demonstrates the thermal characteristic of a distribution transformer, the top oil temperature rise over ambient temperature, the hot spot temperature rise over top oil temperature, and the hot spot temperature. Based on the previous, per unit of normal life and aging acceleration factor, as a function of hot spot temperature, are calculated. Furthermore, DR programs are studied in this work by shifting peak demand and load curtailment to explain the benefits of DR in reducing the overall temperature of a transformer.

Several models have many disadvantages such as inadequate data gathering, inadequate fundamental model, incorrect discretization, erroneous data, and selection of training and validation datasets that make it difficult to accurately predict top oil temperature [3]. One of these sources, i.e., inadequate data gathering, can be represented by the absence of many variables needed to precisely calculate top oil temperature, namely, wind velocity and direction, solar radiation, cloud cover, rain or evaporative cooling, humidity, hot spot temperature, internal transformer oil flows, and the status of cooling fans (on or off). Further, an inadequate fundamental model does not accurately account for the impacts of ambient temperature on top oil temperature, and the heat flux is mainly caused by solar radiation. Thus, top oil model can be used to mitigate these effects. Incorrect data considers a source due to quantized measurements, bad measurements such as spikes in top oil temperature, large jumps in ambient temperature or load and incorrect cooling mode information [13]. IEEE Standard C57.91 is used in this work, where it provides a comprehensive model for studying thermal behavior of transformer.

1.4 Literature review

This section outlines the current state of the work in the area of climate change and thermal behavior of a distribution transformer.

a) Climate change and regulations

Global climate change is the meteorological (climatic) variations for an extended period of time due to natural variables and human activities [4]. According to [5], climate and weather disasters in 2012 cost the U.S. economy around $109 Billion as follow: U.S. drought and heat wave ($30 Billion), Superstorm Sandy ($65 Billion), combined severe weather ($11.1 Billion), western wildfires ($1 Billion) and Hurricane Isaac ($2.3 Billion). Carbon pollution is the biggest source of climate change. In essence, total U.S. Greenhouses Gases (GHG) include: carbon dioxide (84%), methane (9%), nitrous oxide (5%) and fluorinated gases (2%) [5]. The large sources of GHG can be divided into three categories: coal burning, natural gas, and oil used for electricity generation and heat production contributes in engendering 41% of GHG. The second contributor of GHG emissions is roads, rails, air and marine transportation in around 22% and industry represents 20% [6]. Climatological changes cause several issues such as decreasing water availability, increasing intensity of storm events, flooding and sea level rise, increasing air, and water temperatures [7]. One aspect of climate change is the increase in ambient temperature. According to [8], the average global surface temperature is expected to increase around 1.8℃ to 4℃, while the average increase of global ambient temperature is predicted from 1.4℃ to 5.8℃, in the periods of 1990 to 2100 [1].

Due to climate change, many policies have been launched to minimize the impact of electric power systems. In December 1997, the Kyoto Protocol to the United Nation Framework Convention on Climate Change (UNFCCC) mandated a reduction in GHG emissions emitted from electric power industry. The U.S. goal targeted a 7% reduction of 1990 levels between 2008 and 2012. Further, President Obama initiated a plan to cut carbon pollution. In June 2014, the U.S. Environmental Protection Agency (EPA) issued regulations, under Clean Air Act section 111(d), for carbon pollution from electric power plant to reduce GHG emissions. There are three regulatory models from which the states can adapt. The models are: 1) command and control, where specific sources are prohibited due to emissions limitation; 2) limitation of carbon pollution by setting an average emission rate; and, 3) cap-and-trade program to limit the electric power industry emissions. In this plan, also, there is an aim to reduce electricity demand by 10%-15% from the targeted levels of 2020. Moreover, the first and second administrations of President Obama supported clean energy initiatives as explained above. Renewables portfolio standard (RPS) requires electricity producers to provide 10% of their generation portfolio from renewable energy sources by 2012 and 25% by 2025. Since the state of California is the largest contributor of GHG in the U.S., California Assembly Bill 32 was approved by the Governor and launched in 2006 to mitigate emissions to 80% below 1990 levels by 2050 by monitoring all electricity consumed in California [9].

b) Electric power system

The electric power system consists of generation, transmission, and distribution components to supply electricity to customers. Such a system should remain within a set of constraints related directly to the reliability of the system such as planning, analysis, operation, and economic characteristics [10]. Power system reliability is the ability of power system to perform its function under various (or changing) operating conditions. Reliability is mandated by federal and state entities and may be the cause of litigation against the supplier by unsatisfied customers, especially when the lack of expected reliability leads to concerns of safety, economics, and general quality of life. The electric power system is faced with many challenges due to the effect of warming global temperature on power infrastructure. This may lead to effects on load profiles, generation heat rate and capacity, warmer wintertime and springtime temperatures, threat to hydroelectric generation patterns, and the effect of increased sea levels and storms on infrastructure including generation stations and substations [11]. All of these may compromise the reliable operation of the electricity grid, a critical infrastructure.

Climate change can also affect distribution systems in terms of reliability and loadability. A 1℃ rise in global temperature increases peak demand by 4.6% [8]. Further, electricity demand for cooling would increase and demand for fuel oil and natural gas demand for heating would decrease due to an increase in temperature. Moreover, temperature increase would increase the risk of physical damage of electrical components because of the hurricanes and storms. Consequently, the number of power outages due to climate change will increase. In 2013, U.S. weather–related power outages may have reached 180 events per year [12].

c) Transformer and DR

Transformers are used to change the voltage of electricity flowing through the electrical power system. Indeed, a step-up transformer is a significant part for power transmission over long distances to reduce power losses. Failure of transformer leads to power supply interruption as well as loss of the capital asset and associated economic loss. Thus, power transformer reliability and efficiency are a critical concern of the power system networks [13]. The operating condition, life cycle, and heating of a power transformer play important roles on power system stability. Thermal management has a great impact in maintaining and managing quality of the transformer by governing a loss of life of a transformer. Key factors used to estimate the lifetime of a transformer are top oil temperature and hot spot temperature. Thus, accurate prediction of the said temperatures allows controlling loss of life with maximal loading [14].

Climate change leads to high temperature, and many factors might change; increasing in ambient temperature causes an increase in operation temperature of the transformer in addition to the impact on demand response. These factors influence the working conditions of a transformer. The thermal behavior of transformers can be affected by external and internal sources. Thus, ambient temperature causes an increase in transformer temperature that might reach 90°Cwith solar radiation instead of 80°C without it [15]. Furthermore, for every increase of temperature by 10°C, the dielectric aging of transformers will be twice faster [1].

A proportional relationship between operating temperature and aging rate of transformers is well known. An increase in ambient temperature leads to increase in transformer loading, which leads to a reduction of lifetime of transformers and low insulation value due to degradation of degree of polymerization [16]. In [2], the aging acceleration factor would be 100, when the winding temperature reaches 140°C. This means that an hour spent during overloading equals 100 hours at rated operation conditions. Consequently, the winding temperature and insulation level could affect the transformer loading capability. As mentioned in [2], ambient temperature increases top oil temperature. Transformer loading increases hot spot temperature. Therefore, loadability and reliability of transformers depend on top oil temperature and hot spot temperature. As a result, transformer overload conditions are governed by ambient temperature and hot spot temperature [2],[17]. Other factors can affect thermal management of a transformer such as loading condition that are classified in [18] into four types of loading:

- Normal life expectancy loading
- Planned overloading
- Long-time overloading
- Short-time overloading.

According to [19], the permissible loading of a transformer for normal life depends on:

- Transformer design
- Temperature rise at rated load
- Cooling temperature
- Duration of the overloads
- Load factor
- Altitude above sea level.

As ambient temperature and operation temperature increase can cause thermal aging of transformers, it is important to control a loaded transformer to mitigate aging effect. Thus, DR is an important and effective feature of thermal management of a transformer. As electricity demand fluctuates by time of day, day of the week, or seasons, balancing supply and demand of electricity requires providing just the right capacity of the electrical supply to match the variations in the demand side [20]. According to [21], DR defines as changes in electric usage by end-users from their normal consumption as a result to the price of electricity changes over time or to incentive payments designed to encourage using lower electricity during high market prices or the system reliability is jeopardized. It is developed by utility in order to increase efficiency as well as increasing flexibility of the demand by reducing or shifting peak demand. The three benefits of demand response to the power grid in general are economic efficiency, system reliability, and environmental benefits. From an economic perspective, DR could lower wholesale market prices by avoiding new capacity construction and shift peak generation by smoothing the demand curve. Further, the reliability and stability of the electric system can be achieved by applying DR resources in the event of emergency, blackouts, and capacity constraints. Additionally, the environmental benefit of DR is in sustainability by displacement of fossil fuel generation, increasing renewable energy penetration, and reducing emissions. DR can be of different types and forms by employing different technologies and strategies. in detail, DR acts as capacity or balancing programs; Incentive-based DR programs include direct load control management, interruptible load, demand bidding and buy back, reserves services, emergency and load as a capacity resource. Time-based programs which include time of use, real time pricing and critical peak pricing [20]. According to [22], DR could reduce investment for new transformers up to 75%. This reduction comes from a reduction in the hot spot temperature.

d) Transformer models

Multiple models are discussed and explained to obtain accurate results and a good prediction for the three factors: ambient temperature, operation temperature, and DR.

1. *IEEE Standard C57.91*

It is the most common model used in calculations germane to distribution transformers. According to this model, the maximum ambient temperature of a transformer is 40℃, and the average ambient temperature should not exceed 30℃. Maximum hot spot temperature should not exceed 110℃, and the average temperature of the winding can not exceed 65℃ over ambient temperature. This model is not accurate as desired, and does not correctly account for the effect of ambient temperature variation and top oil temperature variation on hot spot temperature. It just captures the basic idea, which is a proportional relationship between the loading and transformer temperature. This model is governed by (1), [23, 24]

$$T_h \frac{\boldsymbol{d\theta h}}{\boldsymbol{dt}} + \theta h = \theta_{hu} \qquad (1)$$

The loss of life is given by,

$$LOL=100t\,(10^{-[A+\frac{B}{T}]}) \qquad (2)$$

The aging acceleration factor is calculated using,

$$F_{AA}= e^{[\frac{15000}{383}-\frac{15000}{\theta h+273}]} \qquad (3)$$

Hence, the equivalent life of transformer can be calculated as

$$F_{EQA}=\frac{\sum_{n=1}^{N}(F_{AA,n\Delta t_n})}{\sum_{n=1}^{N}\Delta t_n} \qquad (4)$$

where, A is constant related to the material and their application in the insulation system and B is constant related to the material and their application in the insulation system. T is the time constant, t is the time interval of application of specific load, Δt is the time interval, θfl represents top oil rise over ambient temperature at rated load while θh is hot spot temperature and θh is ultimate hot spot temperature

Several modifications are done to improve the model in [25]. The first model can capture the change in temperature due to the loading, losses in the winding, and naturally changes with cooling mode as shown in (5):

$$T_0 \frac{d\theta top}{dt} = - \theta_{top} + \theta_{amb} + \theta_u \qquad (5)$$

where, θ_{amb} is ambient temperature, θ_{top} is top oil temperature rise and θ_u is hot spot temperature rise

Also, improvements can be made to this model to develop its performance such as thermal radiance to account for solar radiation and thermal time constant. Further, the IEEE model assumes that the hot spot temperature instantaneously changes with top oil temperature.

Another derived model in [26] predicts hot spot temperature based on the heat transfer theory and thermal dynamic electrical analogy. This model is given in (6):

$$\theta_{hs} = \theta_{amb} + \theta_{moil} + \Delta\theta_{toil\text{-}moil} + \Delta\theta_{hs\text{-}toil} \qquad (6)$$

where, θ_{hs} is the hot spot temperature, θ_{amb} is the ambient temperature, θ_{moil} is the bottom oil temperature, $\Delta\theta_{toil\text{-}moil}$ is the temperature difference between top oil and bottom oil and $\Delta\theta_{hs\text{-}toil}$ is the temperature difference between hot-spot and top oil. In this model, the effect of load variation is considered. It also considers the effect of solar radiation and the ambient temperature on the heat dissipation.

In [27], a thermal model of the transformer hot spot temperature is derived from the IEEE standard based on thermal electrical analogy. It depends on heat transfer theory to introduce oil viscosity change and loss variations to reduce the impact of temperature variation. This model is shown in (7)

$$I^2 P_{W,pu}(\theta_{hst}) (\mu_{pu} \theta_{hst,r})^{\frac{1-n}{n}} = (\theta_{hst} - \theta_{oil})^{\frac{1}{n}} + \tau_{hst,r} (\mu_{pu} \theta_{hst,r})^{\frac{1-n}{n}} \frac{d\theta_{hst}}{dt} \quad (7)$$

where, θ_{hst} means the hot spot temperature, θ_{oil} is the top oil temperature τ_{hst} is the hot spot time constants. n means an empirical constant, μ_{pu} is the viscosity of oil and P_W is the power loss

A risk assessment model is derived from the IEEE standard. and represented by (8):

$$\theta_{hst}(t)= \theta_o(t)+ \theta_g(t)+ \theta_{amb}(t) \quad (8)$$

where, θ_{hst} is hot spot temperature, θ_o is the top oil temperature rise, θ_g is the hot spot temperature rise and θ_{amb} is ambient temperature. This model can estimate the transformer thermal loading capability, provide a risk index, and risk calculation [28].

Swift is a modified top oil model that changes allocated oil exponent in the IEEE standard with the equation [29]:

$$T_o \frac{\boldsymbol{d\theta top}}{\boldsymbol{dt}} =-(\theta top - \theta amb)^{\frac{1}{n}} + \theta_u \quad (9)$$

where, θ_{top} is the top oil temperature rise, θ_u is the hot temperature rise and θ_{amb} is ambient temperature. Susa et al. model is a modified top oil model with nonlinear permeability. In this model a similar exponential behavior to the Swift model is showed with retaining oil viscosity as a parameter [30]. The differential equation of this model is:

$$T_o \frac{d\theta top}{dt} =\frac{-(\theta top- \theta amb)\hat{}(1/n)}{\mu \theta fl^{\frac{1-n}{n}}} + \theta_u \quad (10)$$

where, θ_{top} is the top oil temperature rise, θ_u is the hot temperature rise, θ_{amb} is ambient temperature, θ_{fl} is full load temperature and n means an empirical constant

According to [31], the model in [25] is suitable for oil forced air forced cooling but not suitable for no oil-forced air transformers, while Swift model and Susa model are not adequate for either forced oil-forced air or no oil-forced air transformers.

2. *IEC 354 standard*

This model selects a transformer of optimum capacity and checks the operation of an existing transformer. Theoretically, it is shown the software method that used in this model to eliminate the manual calculations is more precise than the manual method. A computer program has to be used to calculate top oil temperature using (11) [32]

$$\Delta\,\theta_{\mathrm{on}} = \Delta\,\theta_{\mathrm{o(n\text{-}1)}}\,(e_{\tau o}^{-t}) + \Delta\,\theta_{\mathrm{oun}}\,(1 - e_{\tau o}^{-t}) \qquad (11)$$

Further, calculating hottest spot temperature can be performed by using (12)

$$\theta_{\mathrm{h}} = \theta_{\mathrm{a}} + \Delta\,\theta_{\mathrm{on}} + \Delta\,\theta_{\mathrm{td}} \qquad (12)$$

where, Δ θtd is temperature deference between hot spot rise and oil temperature rise at end of n^{th}interval, Δ θon is top oil temperature rise at end of n^{th}interval , Δ θo(n-1) is top oil temperature rise at end of $(\mathrm{n}-1)^{\mathrm{th}}$ interval. θa means ambient temperature, θh is ultimate (steady state) hot spot temperature and Δθtd is defined as temperature difference between hot spot and top oil

Simpson’s rule is also used to calculate the aging of transformers according to the equation where V is relative ageing rate [32]

$$\mathrm{LOL} = \frac{h}{3T}\left(\sum 4V_{\mathrm{odd}} + \sum 2V_{\mathrm{even}}\right) \qquad (13)$$

Using a software package to obtain loss of life reduces unexpected damage to the transformer more than following the manual method [33]. This model depends on the analogy between heat exchange and electric circuit laws. The equivalent heat circuit based on thermal model includes heat conductors, heat capacitors, and heat current source. This circuit is used to calculate the transient state temperature and the stationary equilibria of natural oil, ONAN, and forced oil. Furthermore, two important temperature measurements in this model are bottom oil temperature and top oil temperature. They allow simulations of specific load scenarios [34]. The final equation is represented in (14):

$$\theta_{hst}= \theta_{oil\text{-}out}+ \theta_{amb}+\Delta\, \theta_{h}=TOT+\Delta\, \theta_{g}K^{y} \tag{14}$$

where, θhst is the hot spot temperature, $\theta_{oil\text{-}out}$ is the model output in order to obtain the hot spot temperature. $\Delta\, \theta_h$ is hot-spot temperature rise above top oil temperature, θ_g is the hot spot temperature rise and θ_{amb} is ambient temperature. K is ratio of load current to the rated load current and y is exponential power of winding loss

3. *IEC 60076 Standard*

This model provides a guide for the specification and loading of distribution transformer in terms of operating temperatures and thermal aging. Mathematical models are stated to calculate different loading with different temperatures. Dynamic transformer rating (DTR) algorithm is developed based on IEC 60076-7. The inputs and outputs of the DTR algorithm are [35]:

Inputs:

- Transformer load
- Top oil temperature
- Ambient temperature
- Tap position

- Cooling operation

Outputs:

- Dynamic rating
- Hot spot temperature
- Loss of life.

The insulation paper that determines aging rates can be calculated in two conditions where thermally upgraded can retain a higher percentage in tensile and strength of insulation paper than non-thermally upgraded [36]. θhst means hot spot temperature :

a) Non-thermally upgraded paper

$$\mathrm{v} = 2^{\frac{\theta h-98}{6}} \tag{15}$$

b) Thermally upgraded paper

$$\mathrm{v} = e^{\frac{15000}{110+273}-\frac{15000}{\theta h+273}} \tag{16}$$

The DTR algorithm sends periodic reports to asset managers on the actual loss of life of insulation paper. Further, this algorithm can calculate various pre loading and overloading scenarios. Moreover, multiple technical challenges may occur in this algorithm such as applying it to all power transformers in the network and the accuracy of the calculated or measured transformer hot spot temperature [36].

Many tests are applied to above models help in obtaining precise results. Even analytical method works in obtaining the probabilistic distribution of hot spot temperature of the transformer. Monte Carlo technique is a developed simulation calculates complicity of a model parameters for estimating the hot spot temperature from various loads. Monte Carlo technique is used due to its mathematical simplicity and its ability to include more probabilistic parameters for ambient temperature and transformer load. Further, through the above technique, the lifetime of the transformer can be addressed [37]. Arrhenius chemical reaction rate law is used to calculate the relationship for thermal aging properties of insulation material. This method states logarithm of time for physical property of the insulation material. Therefore, the aging insulation is governed by chemical process and its reactions vary with time. According to [16] the Arrhenius chemical reaction can be presented as in (17)

$$\log_{10} = \mathrm{A} + \frac{B}{\theta hst + 273} \tag{17}$$

where, *A* and *B* are constants related to the materials and their application in the insulation system

Several thermal models are used for estimating hot spot temperature behavior. Therefore, many devices are used for temperature measurements inside and outside the transformer. Accordingly, specified sensors are needed in these models to get accurate results. Fiber-optic sensor is used due to its accuracy although it takes long acquisition time and has high cost. This sensor is tested on 12 sensing points distributed on several physical locations inside the transformer [38]. This sensor can do several tasks such as detecting loss of cooling and precise alarm and trip function, allow the operators and engineers for better determining the losses of insulation life, real time remote temperature monitoring and contact resistance temperature of circuit breakers connection points [39]. Accordingly, characteristic of this sensor are a 0.1℃ resolution and temperature accuracy of ± 1℃.

1.5 Software tools

MATLAB® was used for all the data analysis, calculations and visualization. All codes are presented in the appendix A of the thesis.

1.6 Organization of thesis

This thesis is organized in four chapters. Chapter I represents an introduction about climate change and literature review. Chapter II describes the developed model. Chapter III illustrates the transformer, Fort Collins's weather data, and loads based on DR and presents the analysis and discussion of the results of the work. Chapter IV concludes the work and presents some avenues of future work.

Chapter II

Thermal Modeling of a distribution transformer according to IEEE Standard C57.91-2011

This chapter presents methods from the literature for calculating thermal characteristics and the loss of life of distribution transformers using IEEE standard C57.91-2011 [1]. It also provides an example using rated parameters of a 25 MVA distribution transformer, real data of temperature, load and DR, shifting peak demand, corresponding to Fort Collins, Colorado, USA

2.1 Introduction

The relationship between transformer lifetime and operating temperatures is well known as explained in chapter I. It is significant for utilities to study the operating temperature of the distribution transformer to establish the aging of such devices. The temperature of the winding and insulation are the basic factors that limit the transformer loading[16]. Therefore, transformer loading is highly dependent upon the operating temperature of the transformer, which means any change in transformer temperature could change the load capabilities and vice versa [40]. Further, temperature and aging of the transformer would affect the insulation level. The heat in the transformer, caused by losses in the transformer, must be transferred to the transformer oil and from the oil to the atmosphere [16]. External conditions such as ambient temperatures, wind velocity and direction, and solar heating affect the heat dissipation from a transformer [41]. Also, ambient temperature versus loading can be drawn for different types of transformer cooling. Based on this, the hot spot temperature and ambient temperature are important factors in determining transformer-aging rate while different load levels affect the aging of the insulation [2]. As mentioned in chapter I, the permissible loading of a transformer for normal life depends on many factors such as the design, the temperature rise at rated load, temperature of the cooling, duration of the overloads in addition to the load factor and the altitude above sea level. The loading conditions of a transformer can be classified into four types: normal life expectancy loading, planned overloading, long-time overloading and short-time overloading.

To explain the relationship between ambient temperature and the transformer loading is such that it causes:

a. An increase in ambient temperature, will result in increased need for loading, and thus increase the supply needed.
b. Ambient temperature is considered in the calculation of hot spot temperature in all transformer thermal models.

The second factor is governed by many influences such as thermal capacity, types of cooling and the effect of altitude. The permissible load for forced-oil-cooled transformer is presented in Table 1

Table 1: Loading capability for forced-oil-cooled transformer [25]

Percent of total coolers used in operation (%)	Permissible load in % of name plate rating
100	100
80	90
60	78
50	70
40	60
33	50

In [19], the average ambient temperature with natural cooling is noted as 30 °C. At this rate of temperature, the loading capability of a transformer is 100 KVA. When ambient temperature increases to 50°C, the permissible load equals 70 KVA and for oil-air-cooled and forced-air-cooled transformers, the permissible load reaches 80 KVA at 50 °C. However, the average ambient temperature for water-cooled transformers is 25 °C with loading capability 100 KVA while the permissible load can reach 85 KVA at 50 °C. Further, oil-water-cooled transformers can work at 50 °C with 90 KVA. Based on overload limitations, hot spot temperature of transformer can be designed to operate either up to 55 °C above ambient temperature or up to 65 °C rise above ambient temperature. In the IEEE standard C57.91, the base ambient temperature rating of a transformer, 24 hour average, is 30 °C while IEC standard considers 20 °C. However, every 1 °C decrease in ambient temperature, the load capacity can increase by 1 % without any loss of life and vice versa [18].

Thermal modeling is a major consideration for utilities to monitor and calculate the distribution transformer operating condition and lifetime. Calculating top oil temperature and HST can give utilities an overview of operating condition of the transformer and then overcome any potential problems such as determining lifetime of the transformer. Thus, it is desirable to have a reliable model to analyze the HST and other factors leading to precise estimation of the lifetime of the transformer.

a) IEEE Std. C57.91-2011

There are several models used for calculating the thermal characteristics of the distribution transformer. IEEE standard C57.91 is one of the most common models used in calculations relevant to distribution transformers. This model deals with the loading and the thermal evaluation of oil-impressed transformers and it uses thermal properties such as top oil rise, the bottom oil rise, and average winding temperature for comparing the loss of life. The model is based on the fact that overall temperature of the transformer is caused by the losses due to increases in the loading current of the transformer [25]. According to this model, the maximum ambient temperature of a transformer is 40 °C, and the average ambient temperature should not exceed 30°C. Maximum HST should not exceed 110 °C, and the average temperature of the winding can not exceed 65 °C over ambient temperature. This model is not accurate as desired, and does not correctly account for the effect of ambient temperature variation and top oil temperature variation on HST. It just captures the basic idea, which is a proportional relationship between the loading and transformer temperature [25]. The standard defines aging acceleration factor as the accelerated rate of transformer insulation aging of a given HST compared to the aging rate at a reference HST. The reference HST is 110 ℃, for 65 ℃ average winding rise, and 95 ℃, for 55 ℃ average winding rise transformers. Percent loss of life is the equivalent aging at the reference HST over a time period divided by the total insulation life at the reference HST. As previously mentioned, the type of cooling affects the loading capability; thus this model suggests exponents for use shown in Table 2 [25].

Table 2: Exponents used in temperature equations [25]

Types of cooling	*m*	*n*
ONAN	0.8	0.8
ONAF	0.8	0.9
Non-directed OFAF or OFWF	0.8	0.9
Directed ODAF or ODWF	1.0	1.0

ONAN: Oil Natural Air Natural
ONAF: Oil Natural Air Force
OFAF: Oil Forced Air Forced
OFWF: Oil Forced, Water Forced
ODWF: Oil Directed Water Forced

Where *m* is an exponent used to calculate the variation of hot spot rise over top oil temperature with different loads and n is an exponent used to calculate top oil rise over ambient temperature with changes in load. However, the four different types of loading condition beyond nameplate, explained in chapter I, have been used in this model as examples. Therefore, they are appropriate for the system development and operation philosophy of some utilities. Table 3 shows maximum temperature limits used in the model for each load condition [25].

Table 3: Maximum temperature limits used in the examples [25]

	Normal life expectancy loading	**Planned loading beyond nameplate rating**	**Long-time emergency loading**	**Short-time emergency loading**
Insulated conductor hot spot temperature (℃)	120	130	140	180
Other metallic hot-spot temperature (℃)	140	150	160	200
Top-oil temperature (℃)	105	110	110	110

b) Hot Spot Temperature Calculation

The HST model in the transformer winding is the sum of the ambient temperature, the top oil rise over ambient temperature, and hot spot rise over top oil temperature. This model is used in determining thermal behavior of the distribution transformer and given in (18) [25]:

$$\theta_{\mathrm{H}} = \theta_{\mathrm{A}} + \Delta\theta_{\mathrm{H}} + \Delta\theta_{\mathrm{Toil}} \tag{18}$$

Where θ_{H} is the winding HST, θ_{A} is the average ambient temperature during the load cycle to be studied. $\Delta\theta_{\mathrm{H}}$ is the winding hot spot rise over top oil temperature and $\Delta\theta_{\mathrm{Toil}}$ is the top oil rise over ambient temperature. The ambient temperature has been taken from the public domain corresponding to Fort Collins, Colorado, USA. Furthermore, the winding hot spot rise, $\Delta\theta_{\mathrm{H}}$, calculates any increase in the oil and winding temperature caused by the losses of the transformer and current increase as shown in (19) [25]:

$$\Delta\theta_{\mathrm{H}} = [\Delta\theta_{\mathrm{Hu}} - \Delta\theta_{\mathrm{Hi}}][1 - e^{-\frac{t}{\tau H}}] + \Delta\theta_{\mathrm{Hi}} \tag{19}$$

$$\tau_H = 2.75 * \frac{\Delta\theta\mathrm{H,R}}{(1+Pe)*S^2} \tag{20}$$

$$\Delta\theta_{\mathrm{Hu}} = \Delta\theta_{\mathrm{H,R}}[\mathrm{K_u}]^{2m} \tag{21}$$

$$\Delta\theta_{\mathrm{Hi}} = \Delta\theta_{\mathrm{H,R}}[\mathrm{K_i}]^{2m} \tag{22}$$

Where $\Delta\theta_{Hu}$ is the ultimate hot spot rise temperature, $\Delta\theta_{Hi}$ is the initial hot spot rise temperature, τ_H is the hot spot time constant, in hours, and *t* is time referenced to the time of the loading, in hours. Further, *S* is the current density in $\frac{A}{mm^2}$ and $\Delta\theta_{H,R}$ is the rated hot spot rise over top oil temperature while P_e is the eddy current losses. K_u is the ratio of ultimate load to rated load in per unit while K_i is the ratio of initial load to rated load in per unit. The top oil rise over ambient temperature, in (23), indicates that an increase in the loading current will result in increase in the overall temperature. This change in temperature depends upon overall thermal time constant [25].

$$\Delta\theta_{TOil}=[\Delta\theta_{TO,u}-\Delta\theta_{TO,i}][1-e^{-\frac{t}{\tau TO}}]+\Delta\theta_{TO,i} \qquad (23)$$

$$\tau_{TO}=\frac{C_{th-oil}*\Delta\theta TO,R}{q_{tot,rated}} \qquad (24)$$

$$\Delta\theta_{TO,u}=\Delta\theta_{TO,R}[\frac{Ku^2R+1}{R+1}]^n \qquad (25)$$

$$\Delta\theta T_{Oi}=\Delta\theta_{TO,R}\,[\frac{\mathrm{Ki}^2R+1}{R+1}]^n \qquad (26)$$

$\Delta\theta_{TOu}$ is the ultimate top oil rise temperature and $\Delta\theta_{TOi}$ is the initial top oil rise temperature. τ_{TO} is the hot spot time constant, in hours, and *t* is duration of load, in hours, while $\Delta\theta_{TO,R}$ is the rated top oil over ambient temperature at rated load. C_{th-oil} is the equivalent thermal capacity that consists of heat capacity of material and the mass while $q_{tot,rated}$ is the total supplied losses. Parameters of in (25) are defined as follow; *R* is the ratio of load losses to rated load, *n* exponent refers to cooling type, 0.9 in this calculations, and $\Delta\theta_{TO,R}$ is the top oil rise over ambient temperature at rated load. As this model considers the HST affects the aging of the distribution transformer. The relation of insulation deterioration to time and hot spot temperature of the transformer is expressed in (27) [25]:

$$\text{Per unit life}=9.8*10^{-18}\,e^{\frac{15000}{\theta\mathrm{H}+273}} \qquad (27)$$

The curve of the transformer per unit insulation life, shown Figure 1, depicts the relation between transformer insulation life and hot spot temperature, regenerated from [25]. It indicates that aging is accelerated above the average for temperature over 110 °C and reduced below normal for temperature under 110°C.

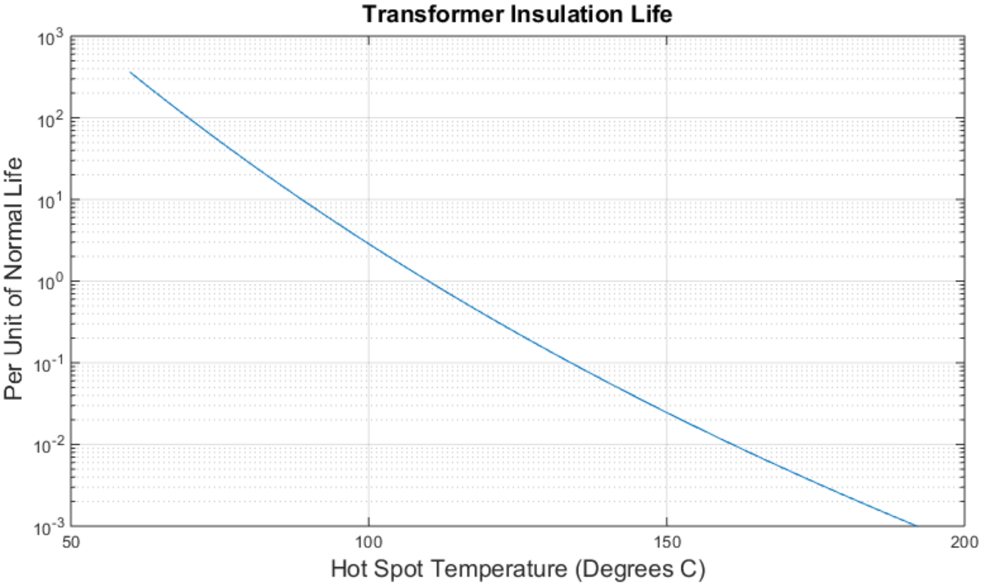

Figure 1: Transformer insulation life

The curve above is used as a basis for calculation of the aging acceleration factor (F_{AA}), shown in (28), for a given load and temperature or for a 25 hour period for load and temperature.

$$F_{AA}= e^{\left[\frac{15000}{383}-\frac{15000}{\theta H+273}\right]} \qquad (28)$$

The equivalent aging factor (F_{EQA}) at the reference temperature in a given time can be used for calculating loss of life as shown in (29):

$$F_{EQA}=\frac{\sum_{n=1}^{N} \mathrm{FAA}\, \Delta tn}{\sum_{n=1}^{N} \Delta tn} \qquad (29)$$

Where Δtn is time interval, N is total number of the time intervals and n is index of the time interval. To determine the percent loss of life, shown in (30), it is necessary to determine the normal insulation life where this model considers 180000 hour or 20.55 year as the normal insulation loss of life [25].

$$\text{LOL }(\%)=\frac{\text{FEQA}*\text{t}*100}{Normal\ insulation\ life} \qquad (27)$$

Many examples based on this model showing the effect of hot spot temperature on lifetime of the transformer. One example by IEEE standard C57.91-2011 on a 100 MVA transformer for a 24 hour period for calculating the equivalent aging factor and the percent loss of life for planned overloading. The load would be used as an input as well as ambient temperature. The input factors vary during a 24 hour period, which might be high during the day and lower during the night. Cumulative age hours, F_{AA}, and HST have been calculated using, this model, during the time period. Table 4 shows the obtained parameters for a 100 MVA transformer. As a result, cumulative age hours show that the F_{EQA} is 1.077 days or 25.848 hours at 110℃ and the percent loss of life amounts to 0.014% based on normal insulation life if the normal life equals 180000 hours [25]. Further, another study on a 630 KVA, 10/0.4 KV transformer using IEEE standard C57.91 shows the F_{EQA} for a 24 hour load profile equals 0.166947 days or 4.00672 hours. The percent loss of life accounts equals 0.002226 %, 12.591 hours, referring to 180000 hours for normal life [42]. Table 5 represents loss of life data for a 630 KVA transformer during a 24 hour period

Table 4: Loss of life data for a 100 MVA transformer during a 24 hour period [25]

Time (h)	Load (p.u.)	HST (℃)	F_{AA}	Cumulative age hours
12:00 AM	0.599	80	0.036	0.036
1:00 AM	0.577	72.8	0.015	0.051
2:00 AM	0.555	72.9	0.015	0.066
3:00 AM	0.544	72.8	0.015	0.081
4:00 AM	0.544	71.8	0.013	0.094
5:00 AM	0.566	71.8	0.013	0.107
6:00 AM	0.655	73	0.015	0.122
7:00 AM	0.844	74.2	0.018	0.14
8:00 AM	0.955	85.1	0.066	0.206
9:00 AM	1.021	92.2	0.148	0.354
10:00 AM	1.054	99.1	0.318	0.672
11:00 AM	1.077	104.6	0.571	1.243
12:00 PM	1.088	109.2	0.921	2.164
1:00 PM	1.099	112.8	1.329	3.493
2:00 PM	1.099	116	1.83	5.323
3:00 PM	1.11	117.8	2.185	7.508
4:00 PM	1.2	125	4.376	11.884
5:00 PM	1.077	130	6.984	18.868
6:00 PM	0.977	125	4.376	23.244
7:00 PM	0.91	114	1.499	24.743
8:00 PM	0.877	104.8	0.583	25.326
9:00 PM	0.866	97.9	0.279	25.605
10:00 PM	0.832	93.2	0.166	25.771
11:00 PM	0.788	87.6	0.088	25.859

Table 5: Loss of life data for a 630 KVA transformer during a 24 hour period [42]

Time (h)	**Load (p.u.)**	**HST (℃)**	**F_{AA}**
12:00 AM	0.78	74.6	0.018526
2:00 AM	0.627	66.1	0.006281
4:00 AM	0.525	58	0.002128
5:00 AM	0.5	55.7	0.001549
6:00 AM	0.515	54.6	0.001329
8:00 AM	0.65	57	0.001855
10:00 AM	0.808	69.5	0.009744
12:00 PM	0.882	79.8	0.115854
2:00 PM	0.96	89.8	0.112973
4:00 PM	1.18	106.2	0.675386
6:00 PM	1.06	107.9	0.805797
8:00 PM	0.9	97.8	0.275661
10:00 PM	0.8	84.5	0.061203
11:00 PM	0.75	74.6	0.018526

IEEE standard C57.91 provides method for calculating thermal characteristics of a distribution transformer. Also, insulation life and aging factor can be analyzed to estimate the loss of life. Next chapter discusses applying this model of a 25 MVA distribution transformer using real weather and load date available in the public domain for Fort Collins, Colorado, USA.

Chapter III

Case Study Using Real Data

3.1 Introduction

This chapter presents results of modeling using real data available in the public domain for Fort Collins, Colorado, USA. The obtainable weather and load data are utilized for calculating the HST of a 25 MVA distribution transformer based on IEEE standard C57.91-2011. DR will be considered in this calculation in order to study the effect of changing load levels on the transformer insulation life and aging acceleration factor. Four scenarios of load levels will be applied as follow: pre-DR, 3%, 6% and 9% peak load reduction.

3.2 Weather Data

Fort Collins Weather Station provides hourly weather records for Fort Collins, Colorado. Ambient temperature record for Thursday, March 3, 2016, has been considered is this case study for a 24 hour period, taken from [43]. Ambient temperature is defined according to IEEE standard C57.91-2011 as the average ambient temperature. Hence, 7.5℃ is used as ambient temperature (θ_A) in calculating the HST. Table 6 shows the ambient temperature of Fort Collins.

3.3 Transformer Parameters

In this subsection, we consider a 25 MVA, 66/11kV ideal distribution transformer and the type of cooling is ONAF, taken from [40]. The rated parameters, input model parameters and the losses of this transformer are summarized in Table 7. Additionally, the normal lifetime of the ideal distribution transformer is 20.55 years, $20.55*365*24 \approx 180000$ hours based on IEEE standard C57.91-2011.

Table 6: 24-hour Ambient Temperature Record for Fort Collins [43]

Time (h)	Ambient Temperature (℃)	Time (h)	Ambient Temperature (℃)
12:00 AM	8.4	12:00 PM	11.9
1:00 AM	7.8	1:00 PM	13.1
2:00 AM	4.5	2:00 PM	13.3
3:00 AM	1.2	3:00 PM	14.1
4:00 AM	1.5	4:00 PM	13.7
5:00 AM	1.5	5:00 PM	12.4
6:00 AM	1.8	6:00 PM	10.9
7:00 AM	3.6	7:00 PM	9.1
8:00 AM	5.5	8:00 PM	7.4
9:00 AM	6.7	9:00 PM	5.3
10:00 AM	8.3	10:00 PM	4.6
11:00 AM	9.9	11:00 PM	4.4

Table 7: Rated and thermal parameters and losses of 25 MVA, 66/11 kV transformer [40]

Parameters	Specification	Parameters	Specification
Rated primary voltage (kV)	66	Rated top oil rise over ambient temperature (°C)	38.3
Rated secondary voltage (kV)	11.86	Rated hot spot rise over top oil temperature (°C)	23.5
Rated primary current (A)	218.69	The weight (kg)	10,800
Rated secondary current (A)	1217.01152	Hot spot time constant (min)	7
Oil temperature alarm (°C)	85	Top oil time constant (min)	114
Hotspot temperature alarm (°C)	95	Exponent *n*	0.9
Oil temperature trip (°C)	95	Exponent *m*	0.8
Hotspot temperature trip (°C)	105	Total loss at rated	107,633 W
1st fans group (°C)	55	Ratio of load loss to no load loss	5
2nd fans group (°C)	65		

3.4 Load profile and DR

In order to determine the transformer insulation level and the aging acceleration factor, the load profile corresponding to Fort Collins, is taken, from [44], and normalized on the 25 MVA rating of the distribution transformer. DR has been used to shift peak demand to off-peak periods during a 24 hour cycle. We present the results of calculation, based on IEEE standard C57.91-2011, for four types of loading including: pre-DR, 3%, 6% and 9% DR is recorded from 5 pm until 8 pm. Table 8 shows the load cycle for both scenarios.

Table 8: Load Cycle and DR scenarios of Fort Collins Load [44]

Time (h)	Pre-DR (MW)	3% DR (MW)	6% DR (MW)	9% DR (MW)
12:00 AM	18.30	18.30	18.30	18.30
1:00 AM	17.92	17.92	17.92	17.92
2:00 AM	17.73	17.73	18.08	18.47
3:00 AM	17.86	17.86	18.20	18.51
4:00 AM	18.36	18.36	18.70	19.14
5:00 AM	19.80	19.80	20.14	20.73
6:00 AM	21.99	22.24	22.24	22.80
7:00 AM	22.99	23.24	23.24	22.99
8:00 AM	22.74	22.99	22.99	22.74
9:00 AM	22.68	22.92	22.92	22.68
10:00 AM	22.87	23.11	23.11	22.87
11:00 AM	22.68	22.92	22.92	22.68
12:00 PM	22.81	23.05	23.05	22.81
1:00 PM	22.62	22.86	22.86	22.75
2:00 PM	22.37	22.61	22.61	22.59
3:00 PM	22.24	22.49	22.49	22.63
4:00 PM	22.49	22.74	22.74	22.62
5:00 PM	**23.56**	**22.85**	**23.56**	**22.44**
6:00 PM	**25.00**	**24.25**	**23.50**	**22.75**
7:00 PM	**24.69**	**23.95**	**23.21**	**22.62**
8:00 PM	**24.00**	**23.28**	**22.56**	**22.50**
9:00 PM	22.62	22.86	22.99	22.75
10:00 PM	20.68	20.68	20.68	21.54
11:00 PM	18.86	18.86	18.86	20.03

3.5 Results based on IEEE standard C57.91-2011

The obtained results, using Matlab, of the case study based on IEEE standard C57.91-2011 is presented below. It illustrates the transformer's loading levels and temperatures versus time. For each scenario the load level the top oil rise temperature (delta TOT), the hot spot rise temperature (delta HST) and the HST are calculated. Further, the relationship between insulation level life and aging acceleration factor with respect to HST is presented. Moreover, loss of life, for each scenario, is calculated based on cumulative hours.

c) Pre-DR results

The results pertaining to pre-DR scenario show the peak demand ranges between 5pm to 9pm in the course of the 24 hour load cycle for the date 3/3/2016. Figure 2 shows the transformer peak load is 1 p.u. Top oil rise over ambient temperature is presented in Figure 3, using (23), and Figure 2 shows hot spot rise over top oil temperature where it can be calculated by (19). The analysis of characteristics shows that there is a proportional relationship between thermal behavior of the distribution transformer and a load level. The reason behind having the same shape for the load curve and the temperature curves, in each scenario, is the very small value of the exponential function, almost 0, in (19) and (23). From Figure 3 and 4, maximum temperatures occur at 6:00 pm where the transformer is operating at full load capacity. In Figure 2, the highest delta TOT is 38.3°C while the peak delta HST is 23.5°C as shown in Figure 4.

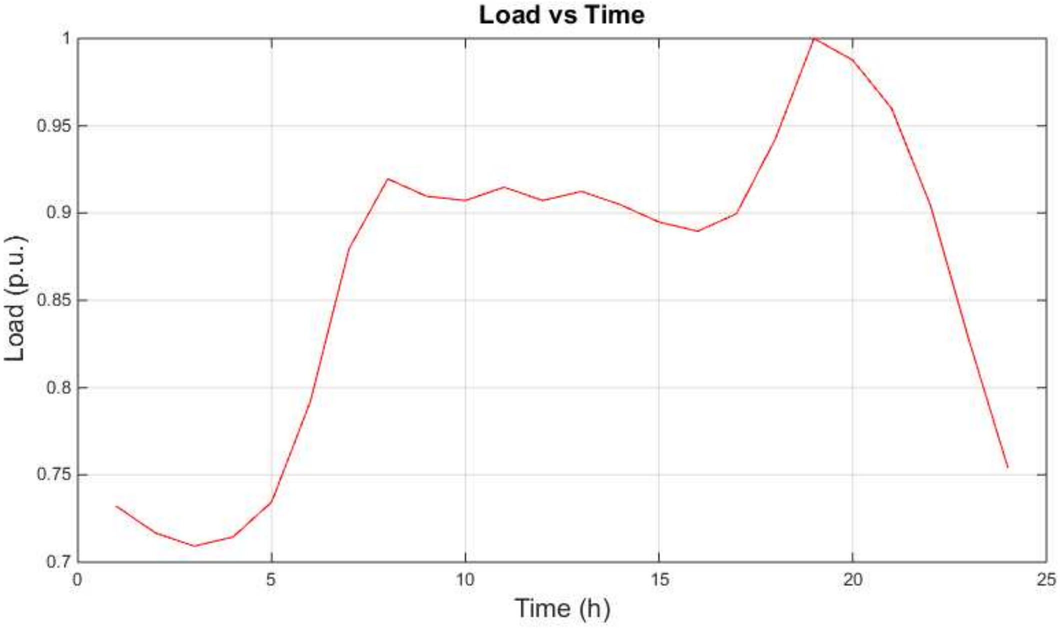

Figure 2: Time versus load of pre-DR scenario for 3/3/2016 in Fort Collins

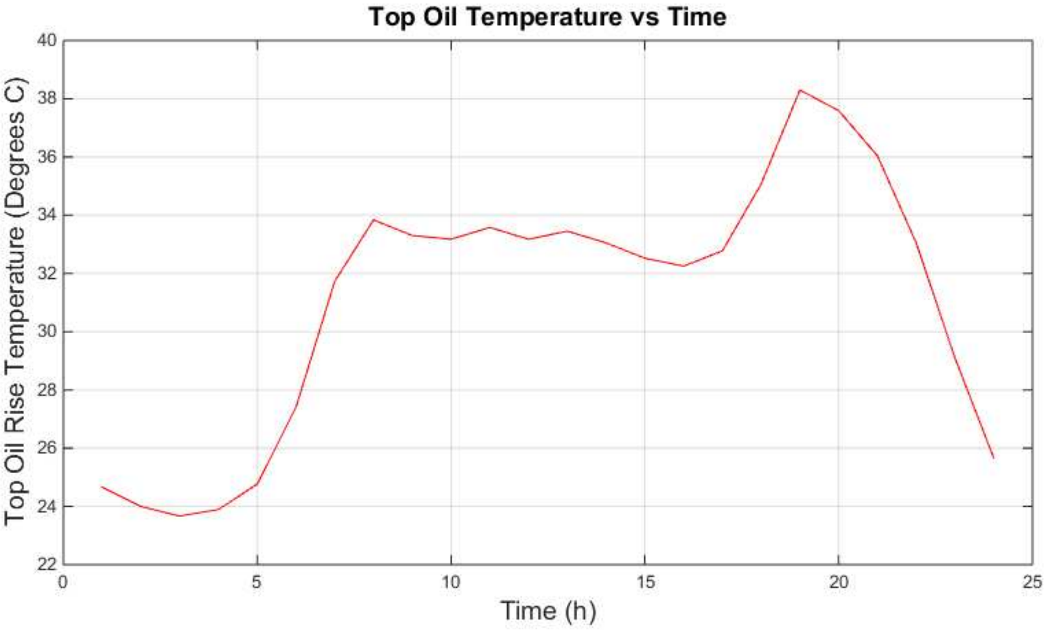

Figure 3: Time versus top oil rise temperature of pre-DR scenario for 3/3/2016 in Fort Collins

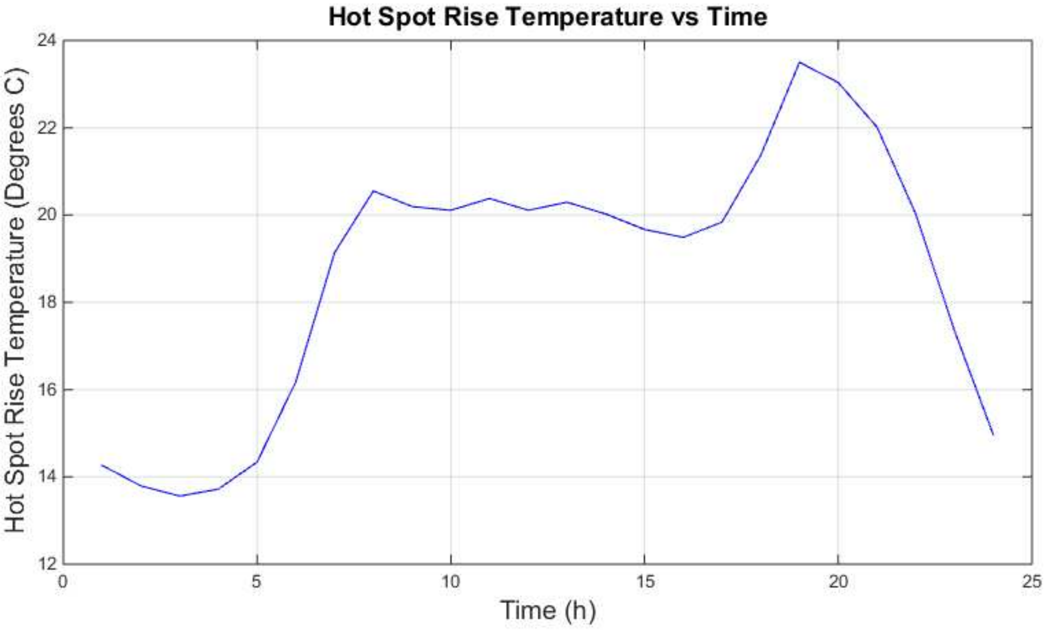

Figure 4: Time versus top oil rise temperature of pre-DR scenario for 3/3/2016 in Fort Collins

According to (18), the HST is calculated by adding the ambient temperature to the delta TOT and the delta HST. Figure 4 illustrates the cumulative temperature of the transformer during the 24 hour load cycle. The curve in Figure 5 explains that the maximum temperature of the transformer reaches 69.3℃ at peak demand under the normal condition. Accordingly, the highest temperature will lead to deterioration of transformer insulation. As a result, Figure 6 relates to the transformer insulation life to the HST, which isolates temperature as the variable affecting insulation life. From Figure 6, it is noticeable that the maximum temperature is below 110℃ which means aging is accelerating underneath normal aging factor. The reason behind this fact is that the transformer has been examined during the winter season with low temperature record.

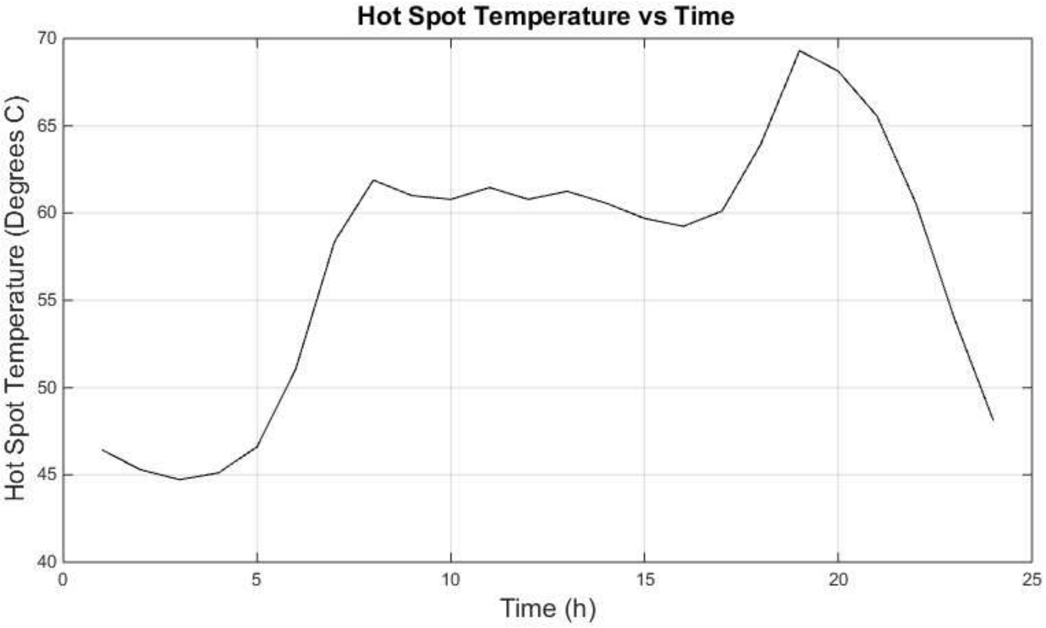

Figure 5: Time versus HST temperature of pre-DR scenario for 3/3/2016 in Fort Collins

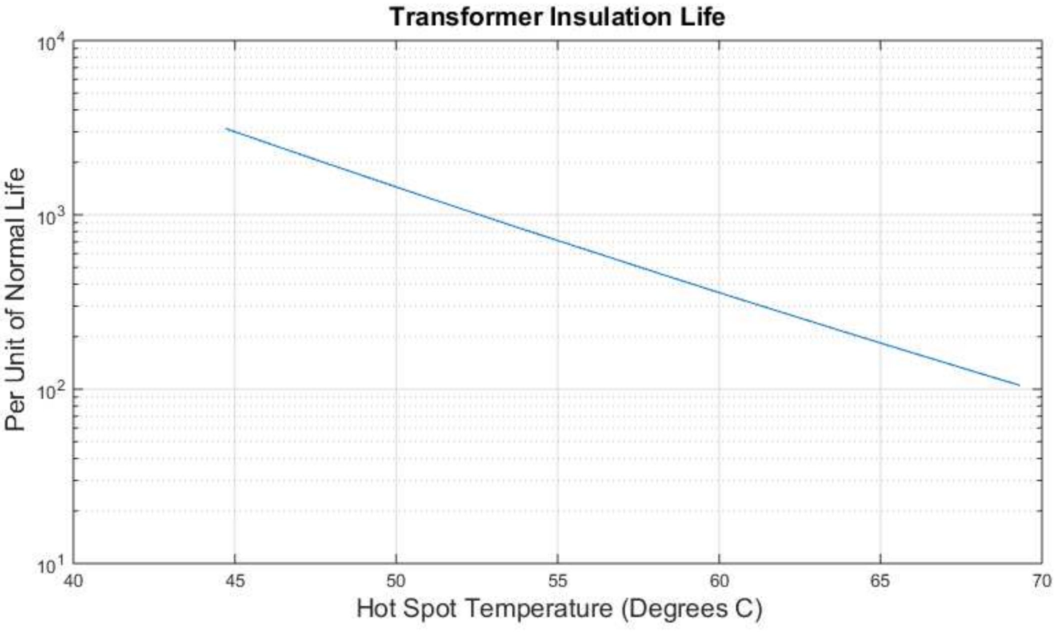

Figure 6: Transformer insulation life curve of pre-DR scenario for 3/3/2016 in Fort Collins

Per unit life insulation, showing in Figure 6, is also used for calculating F_{AA} for a given load and temperature. In (28), F_{AA} is a function of HST where a change in HST will result in a change in F_{AA}. According to IEEE standard C57.91-2011, F_{AA} that has a value greater than 1 means its HST exceeds reference temperature of the standard 110 ℃ and vice versa. In pre-DR, HST ranges between 44.7 to 69.3 ℃ while F_{AA} varies between 0.000320566 to 0.00949732. Figure 7 shows F_{AA} relation with HST based on pre-DR scenario. Accordingly, the equivalent aging factor (F_{EQA}) of pre-DR scenario equals 4.12 minutes and the percent loss of life, using (30), is 3.81462E-05%. This low percent matches with IEEE standard C57.91-2011 because the transformer temperature is below the reference temperature, 110℃.

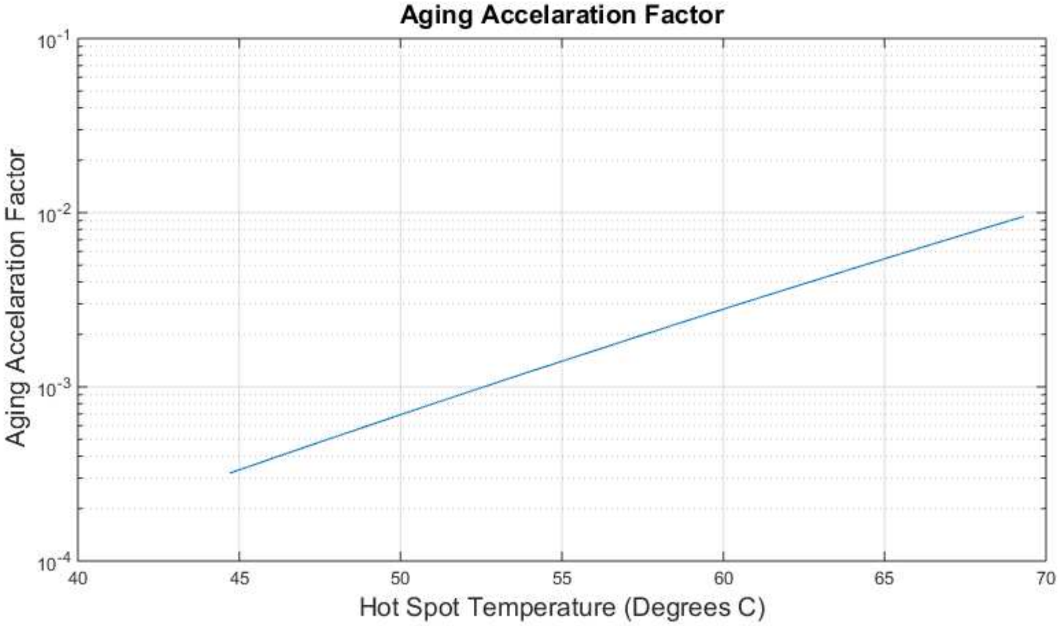

Figure 7: Aging acceleration factor curve of pre-DR scenario for 3/3/2016 in Fort Collins

The results of HST, F_{AA} and cumulative age hours of pre-DR scenario are tabulated in Table 9 as well as the transformer loading profile during the load cycle.

Table 9: Loss of life data for 24 hour load cycle of pre-DR

Time (h)	Load (p.u.)	HST (℃)	F_{AA}	Cumulative age hours (h)
12:00 AM	0.731998542	46.42757609	0.00041199	0.00041199
1:00 AM	0.716798572	45.29129863	0.000348403	0.000760393
2:00 AM	0.709198587	44.72987415	0.000320566	0.001080959
3:00 AM	0.714398577	45.11352196	0.000339347	0.001420306
4:00 AM	0.734398537	46.60861949	0.000423096	0.001843402
5:00 AM	0.791998422	51.08581579	0.000809134	0.002652536
6:00 AM	0.879598248	58.37247339	0.002238853	0.004891389
7:00 AM	0.919598168	61.88725686	0.003600427	0.008491816
8:00 AM	0.909598188	60.99768035	0.003195535	0.011687351
9:00 AM	0.907198193	60.78525818	0.003105496	0.014792847
10:00 AM	0.914798178	61.45935826	0.003399906	0.018192753
11:00 AM	0.907198193	60.78525818	0.003105496	0.021298249
12:00 PM	0.912398183	61.24603315	0.003303968	0.024602217
1:00 PM	0.904798198	60.57325324	0.003018053	0.02762027
2:00 PM	0.894798218	59.69439756	0.00268002	0.03030029
3:00 PM	0.889598228	59.24026527	0.002519843	0.032820132
4:00 PM	0.899598208	60.1153421	0.002837144	0.035657277
5:00 PM	0.942398123	63.94243541	0.004731565	0.040388842
6:00 PM	0.999998008	69.29979008	0.009497321	0.049886163
7:00 PM	0.987598033	68.12659722	0.008168629	0.058054792
8:00 PM	0.959998088	65.55437456	0.005848686	0.063903478
9:00 PM	0.904798198	60.57325324	0.003018053	0.066921531
10:00 PM	0.827198352	53.94530225	0.001212898	0.068134429
11:00 PM	0.754398497	48.13452883	0.000528797	0.068663226

d) 3% DR results

In this subsection, the peak load has been shifted by 3%. Figure 8 shows that reduction in the peak load of the transformer. The maximum load reduces from 1 to 0.97 p.u. while the entire energy consumed remains the same. The shifted load is moved to off peak period starting form early morning. This minimized percentage of DR leads a reduction of the transformer temperatures as well as loss of life and F_{AA}. Delta TOT declines by 1.7℃ to reach 36.6℃ and delta HST decreases from 23.5℃ to 22.3℃ due to shifting the peak demand. Figure 9 represents delta TOT reduction while Figure 10 illustrates the relationship between time and delta HST with respect to DR.

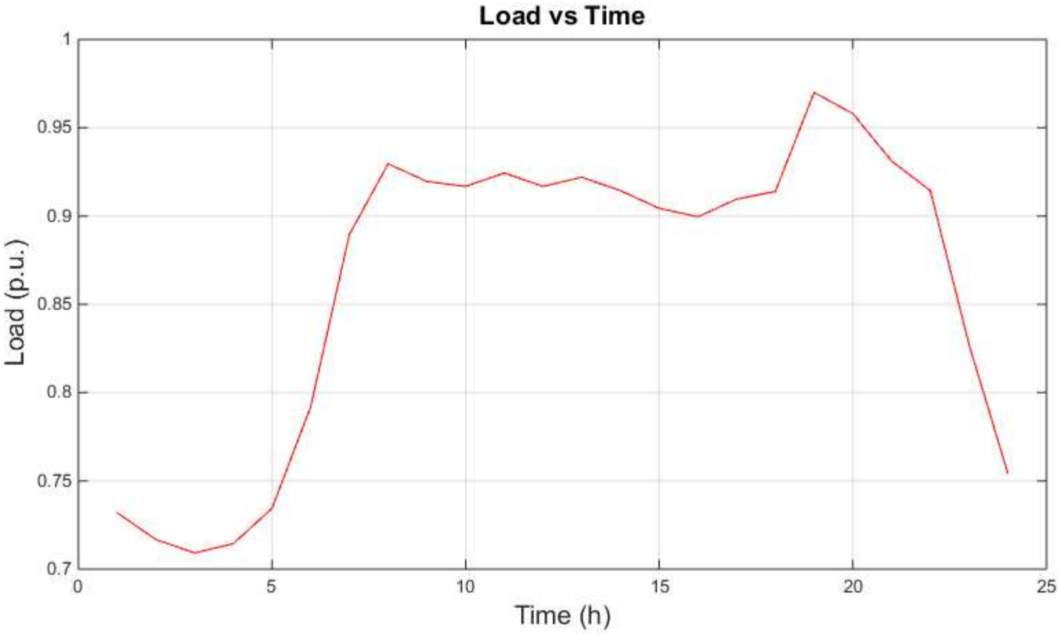

Figure 8: Time versus load of 3 % DR scenario for 3/3/2016 in Fort Collins

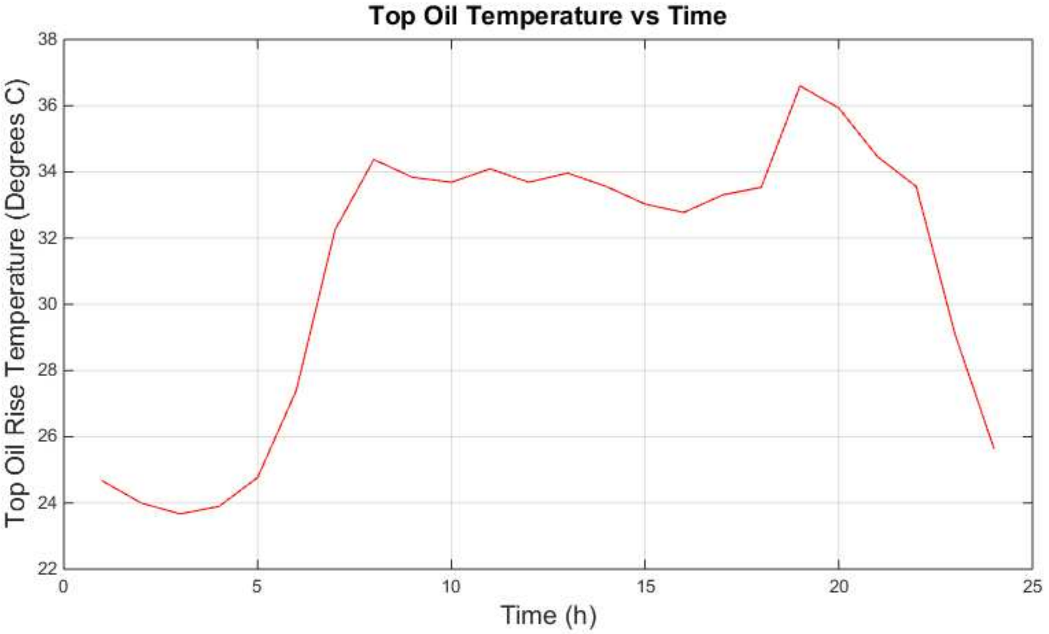

Figure 9: Time versus top oil rise temperature of 3% DR scenario for 3/3/2016 in Fort Collins

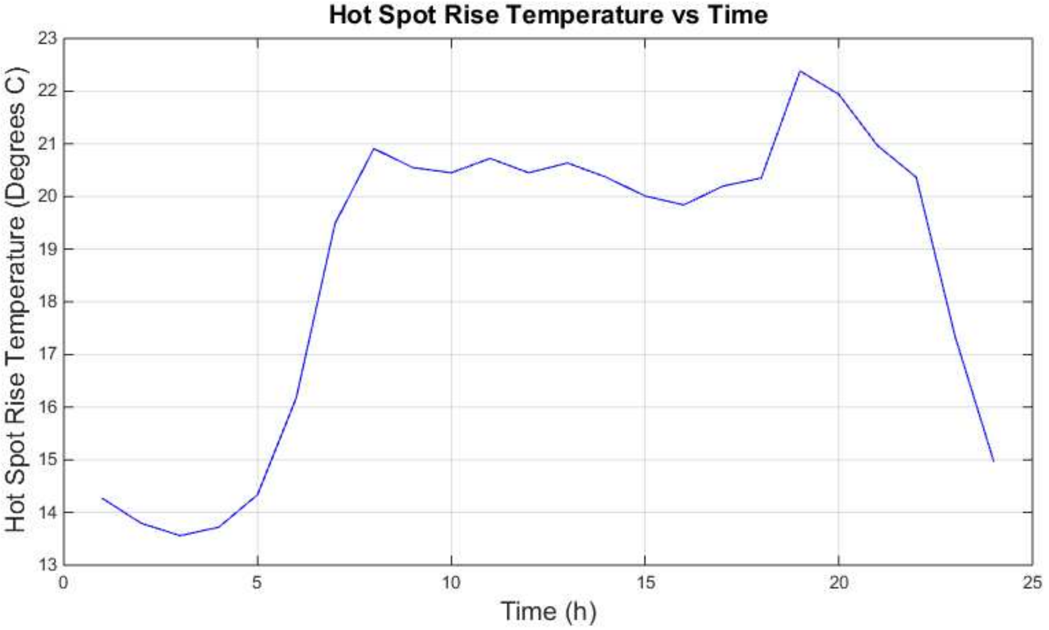

Figure 10: Time versus hot spot rise temperature of 3% DR scenario for 3/3/2016 in Fort Collins

Another benefit of DR, besides the benefits mentioned in chapter I, is a reduction of the overall temperature of the transformer. Figure 11 shows HST curve versus time 3% DR decreases HST from 69.3℃ to 66.4℃. From this curve, the overall temperature ranges between 44.7℃ to 66.4℃. Consequently, this drop in the temperature leads to maximizing insulation life from 105.3 p.u. in the previous scenario to hit 151.6 p.u. in the current scenario. Figure 12 explains impact of the 3% DR on insulation life of the transformer. Moreover, F_{AA} has minimized from 0.009497321 to 0.006599762 as shown in Figure 13. This improvement can reduce loss of life of the transformer to 3.59287E-05% whereas the F_{EQA} reduces to 3.88 minutes

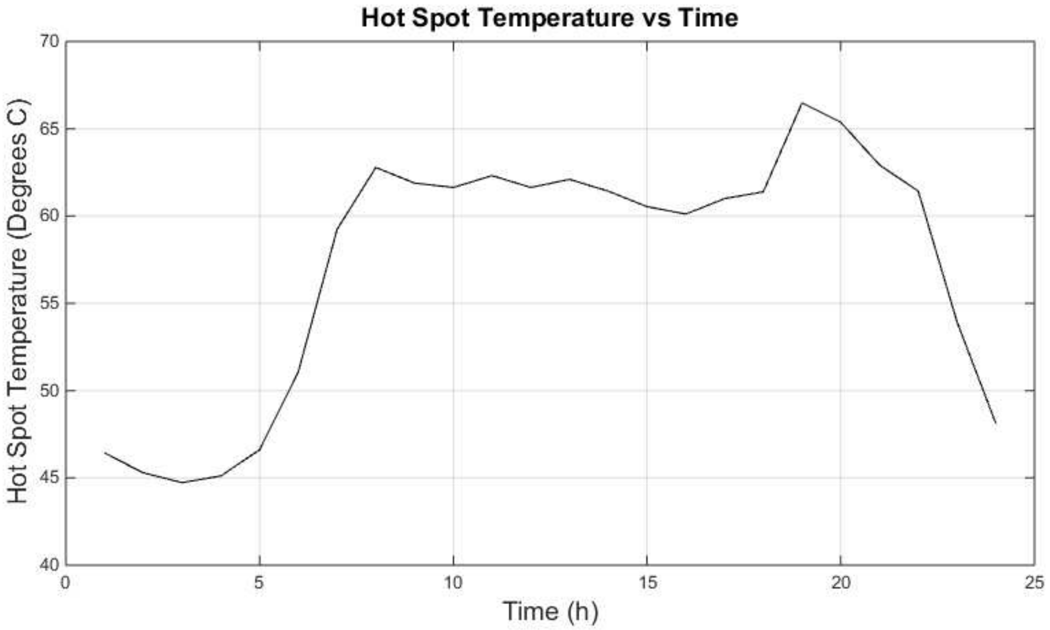

Figure 11: Time versus HST temperature of 3% DR scenario for 3/3/2016 in Fort Collins

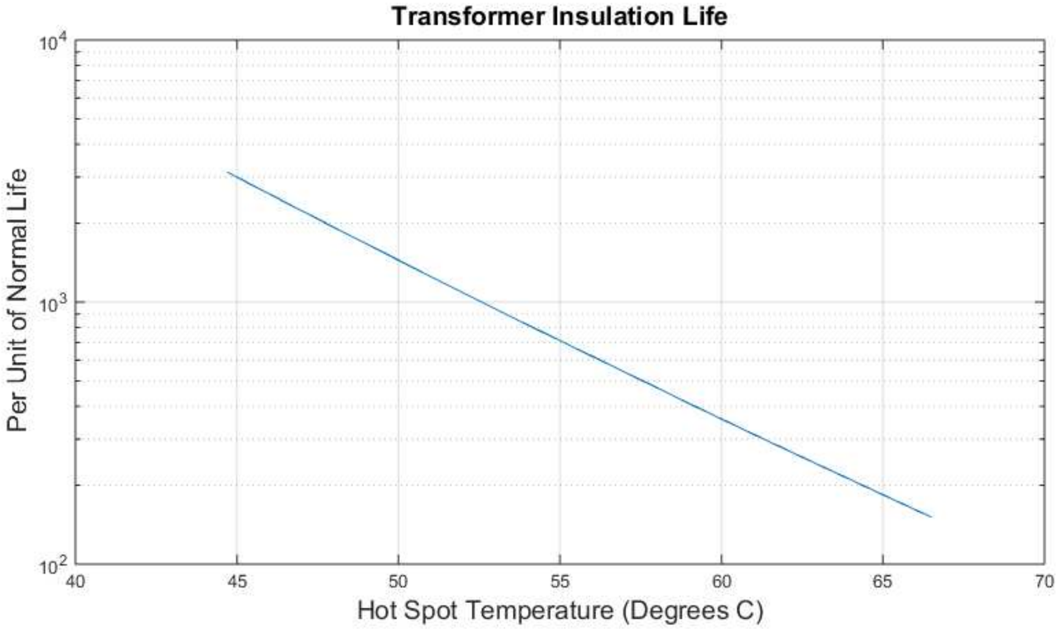

Figure 12: Transformer insulation life curve of 3% DR scenario for 3/3/2016 in Fort Collins

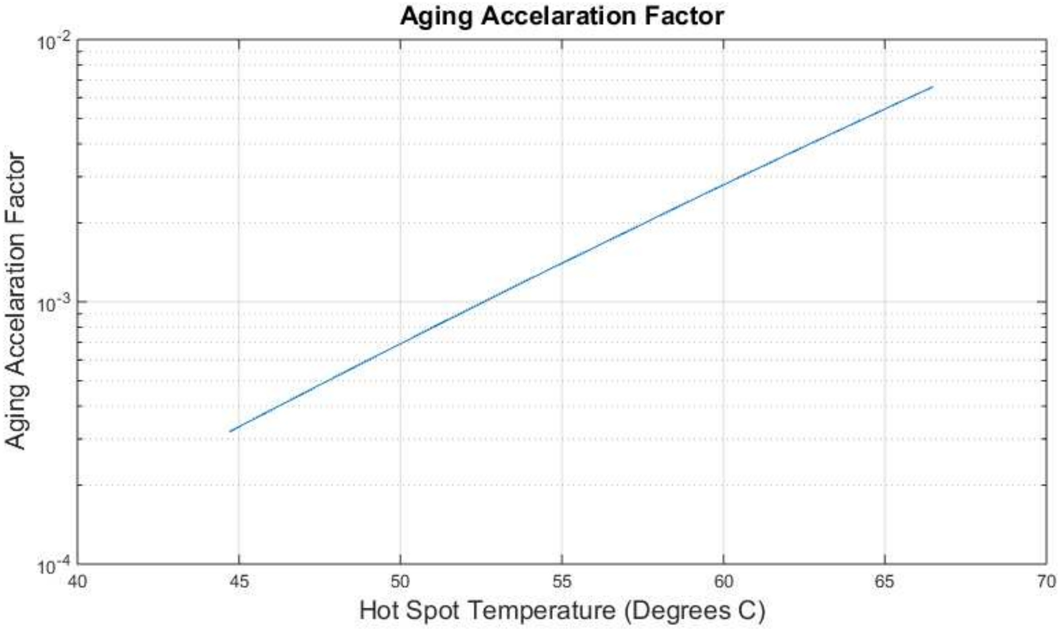

Figure 13: Aging acceleration factor curve of 3% DR scenario for 3/3/2016 in Fort Collins

Table 10 represents the results of HST, F_{AA} and cumulative age hours relating to 3% DR scenario with respect to the transformer loading profile during the 24 hour period.

Table 10: Loss of life data for 24-hour load cycle of 3% DR

Time (h)	Load (p.u.)	HST (℃)	F_{AA}	Cumulative age hours (h)
12:00 AM	0.731998542	46.42757609	0.00041199	0.00041199
1:00 AM	0.716798572	45.29129863	0.000348403	0.000760393
2:00 AM	0.709198587	44.72987415	0.000320566	0.001080959
3:00 AM	0.714398577	45.11352196	0.000339347	0.001420306
4:00 AM	0.734398537	46.60861949	0.000423096	0.001843402
5:00 AM	0.791998422	51.08581579	0.000809134	0.002652536
6:00 AM	0.889598228	59.24026527	0.002519843	0.005172379
7:00 AM	0.929598148	62.78404881	0.004057951	0.009230329
8:00 AM	0.919598168	61.88725686	0.003600427	0.012830756
9:00 AM	0.916798174	61.63744715	0.00348203	0.016312786
10:00 AM	0.924398159	62.3168179	0.003813062	0.020125848
11:00 AM	0.916798174	61.63744715	0.00348203	0.023607878
12:00 PM	0.921998163	62.10182974	0.003705185	0.027313063
1:00 PM	0.914398179	61.42377516	0.00338372	0.030696783
2:00 PM	0.904398198	60.53795967	0.003003727	0.03370051
3:00 PM	0.899598208	60.1153421	0.002837144	0.036537654
4:00 PM	0.909598188	60.99768035	0.003195535	0.03973319
5:00 PM	0.913998179	61.38820362	0.003367614	0.043100803
6:00 PM	0.969998068	66.48009124	0.006599762	0.049700565
7:00 PM	0.957998092	65.37008572	0.005709242	0.055409807
8:00 PM	0.931198145	62.9282036	0.00413649	0.059546297
9:00 PM	0.914398179	61.42377516	0.00338372	0.062930018
10:00 PM	0.827198352	53.94530225	0.001212898	0.064142915
11:00 PM	0.754398497	48.13452883	0.000528797	0.064671713

e) 6% DR results

The transformer thermal and lifetime characteristics have improved when the maximum load reduces by 6%, which leads the load profile to range between 0.45 p.u. to 0.94 p.u. Figure 14 shows the reduction in the peak load based on 6% DR. From this figure, the maximum load starts from 7 am and continues fluctuating until 8 pm while the highest load occurs at 6 pm. As a result, delta TOT and delta HST increase at 5 am till 7 am due to shifting the peak load. However, delta TOT is minimized by 3.3°C in comparison with the original load as shown in Figure 15. Delta HST decreases from 23.5°C to 21.2°C based on the results from the first scenario as illustrated in Figure 16.

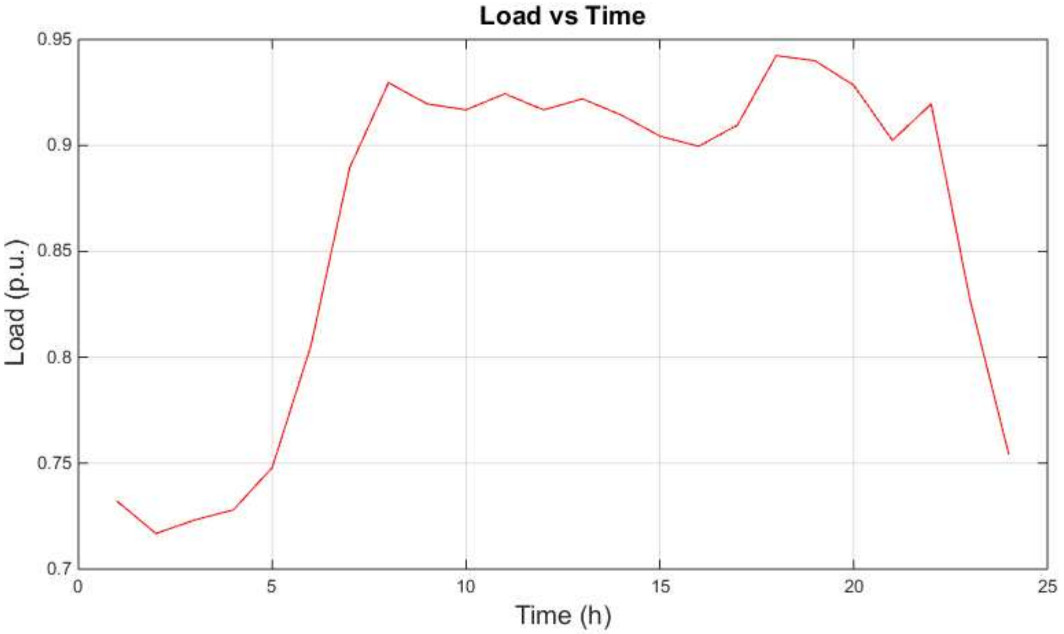

Figure 14: Time versus load of 6% DR scenario for 3/3/2016 in Fort Collins

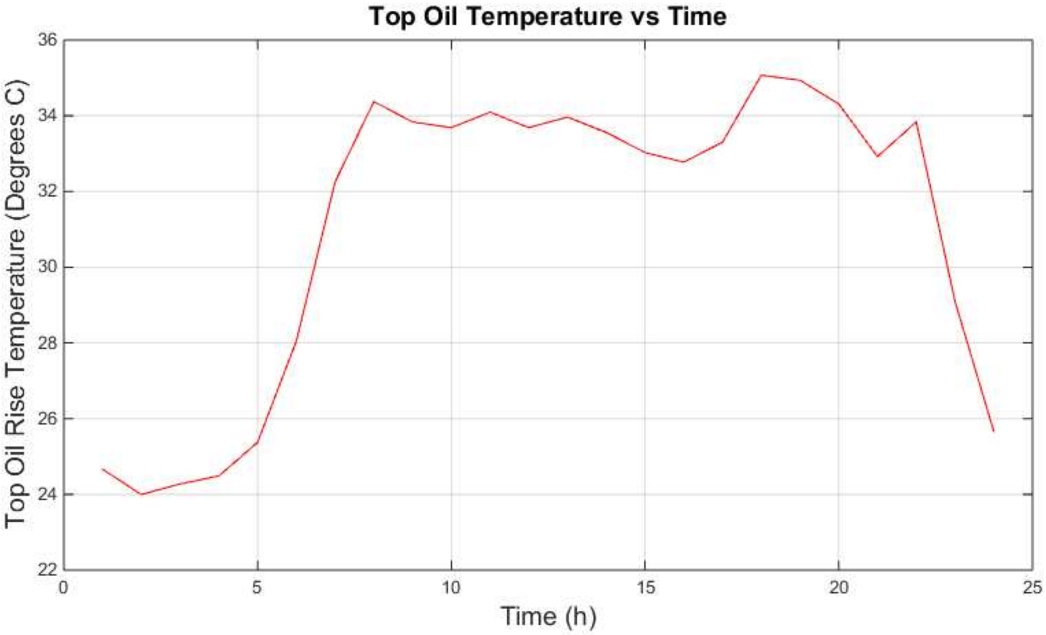

Figure 15: Time versus top oil rise temperature of 6% DR scenario for 3/3/2016 in Fort Collins

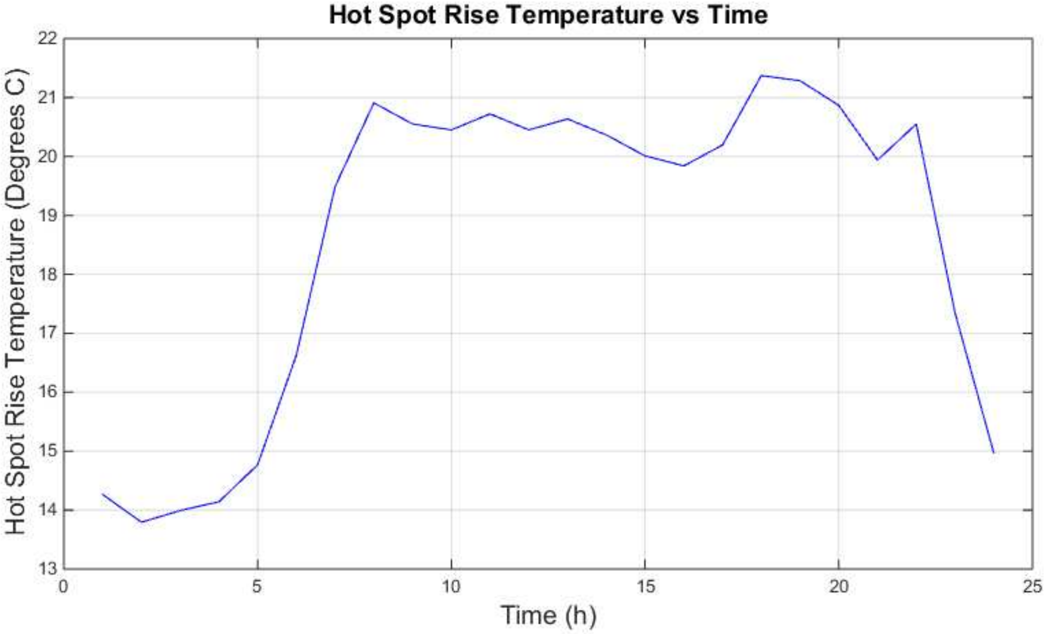

Figure 16: Time versus hot spot rise temperature of 6% DR scenario for 3/3/2016 in Fort Collins

The transformer overall temperature reduces by 5.6℃ in this calculation as Figure 17 denotes. Hence, this could improve insulation life of the transformer and then reduces deterioration of the transformer insulation level. We notice that the insulation life is 105.3 p.u. in pre-DR scenario while this value increases to 217 p.u. by moving 6% of the highest load as Figure 18 expresses. In Figure 19, the maximum F_{AA} occurs in this scenario is around 48% lower than the normal load. This reduction in aging factor will result in decreasing loss of life caused by high thermal characteristics. From (29), the F_{EQA} of this scenario reaches 3.69 minutes and the percent loss of life amounts to 3.42504E-05% based on normal insulation life of 180000 hours

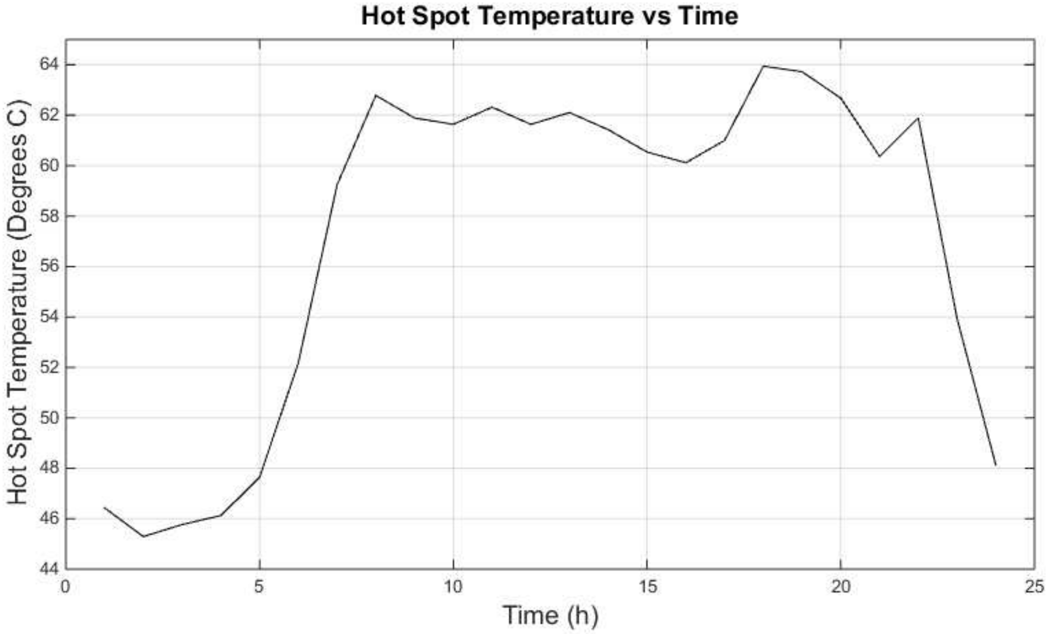

Figure 17: Time versus HST of 6% DR scenario for 3/3/2016 in Fort Collins

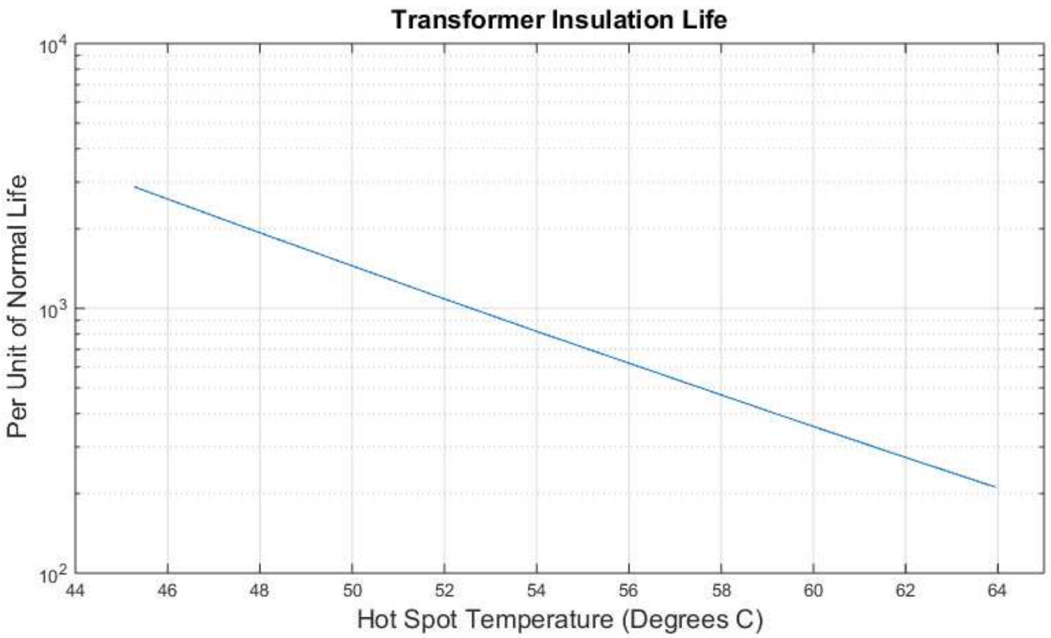

Figure 18: Transformer insulation life of 6% DR for 3/3/2016 in Fort Collins

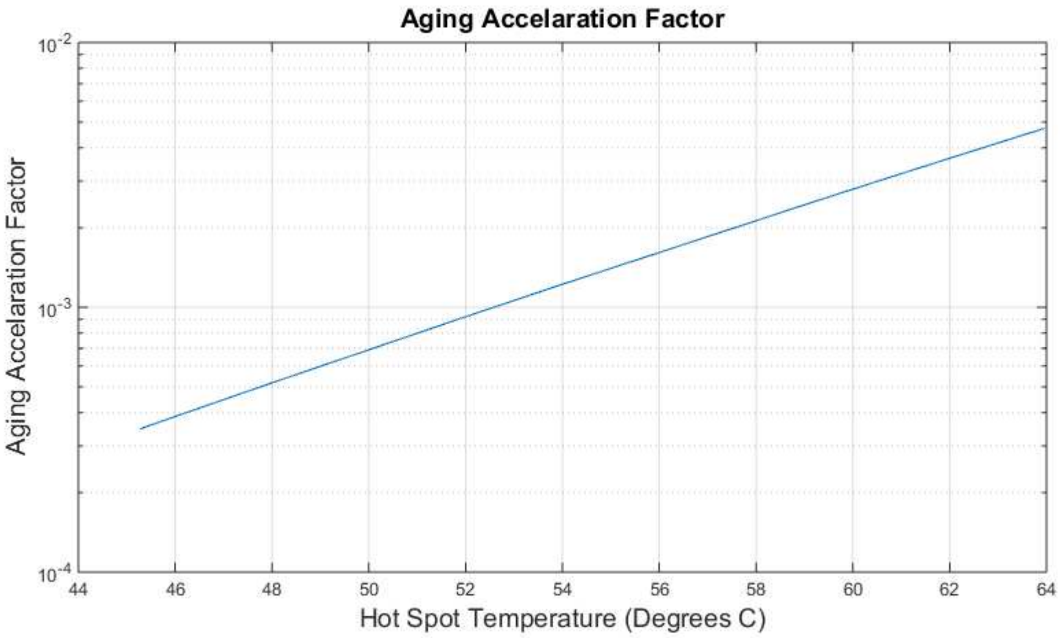

Figure 19: Aging acceleration factor of 6% DR for 3/3/2016 in Fort Collins

To explain the improvements is the transformer thermal and insulation performance, Table 11 shows the transformer loading profile, HST, F_{AA} and F_{EQA} of this scenario are tabulated during the load period.

Table 11: Loss of life data for 24 hour load cycle of 6% DR

Time (h)	Load (p.u.)	HST (℃)	F_{AA}	Cumulative age hours (h)
12:00 AM	0.7319985	46.42757609	0.000412	0.00041199
1:00 AM	0.7167986	45.29129863	0.0003484	0.000760393
2:00 AM	0.7231986	45.76755309	0.0003738	0.001134211
3:00 AM	0.7279985	46.12682419	0.0003942	0.001528367
4:00 AM	0.7479985	47.64290035	0.0004923	0.002020617
5:00 AM	0.8055984	52.17961512	0.0009454	0.002966055
6:00 AM	0.8895982	59.24026527	0.0025198	0.005485898
7:00 AM	0.9295981	62.78404881	0.004058	0.009543848
8:00 AM	0.9195982	61.88725686	0.0036004	0.013144275
9:00 AM	0.9167982	61.63744715	0.003482	0.016626305
10:00 AM	0.9243982	62.3168179	0.0038131	0.020439367
11:00 AM	0.9167982	61.63744715	0.003482	0.023921397
12:00 PM	0.9219982	62.10182974	0.0037052	0.027626582
1:00 PM	0.9143982	61.42377516	0.0033837	0.031010303
2:00 PM	0.9043982	60.53795967	0.0030037	0.034014029
3:00 PM	0.8995982	60.1153421	0.0028371	0.036851174
4:00 PM	0.9095982	60.99768035	0.0031955	0.040046709
5:00 PM	0.9423981	63.94243541	0.0047316	0.044778274
6:00 PM	0.9399981	63.72434239	0.0045971	0.049375358
7:00 PM	0.9283982	62.67605355	0.004	0.053375405
8:00 PM	0.9023982	60.36166586	0.0029331	0.056308537
9:00 PM	0.9195982	61.88725686	0.0036004	0.059908964
10:00 PM	0.8271984	53.94530225	0.0012129	0.061121861
11:00 PM	0.7543985	48.13452883	0.0005288	0.061650658

f) 9% DR results

The advantage of applying 9% DR is more obvious where the peak load reduces to 0.91 p.u. Figure 20 shows the new load of the transformer varies between 0.70 p.u. to 0.91 p.u. during the time period. Additionally, delta TOT reduces by 4.5℃ of the normal load, which reaches 33.8℃ in this scenario. Figure 21 illustrates that the 9% DR scenario provides the lowest value of delta TOT among all scenarios. Further, delta HST is also decreased to 20.5 ℃ as a result of shifting the peak load by 9%. Figure 22 demonstrates that delta HST exceeds 20 ℃ at 6 pm is still fluctuating until 9 pm.

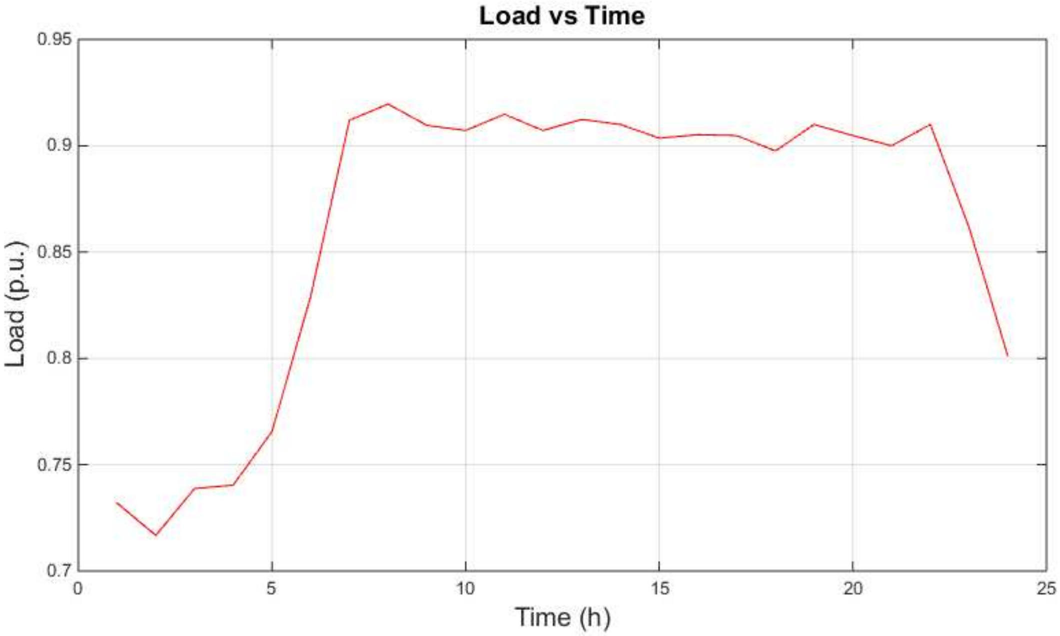

Figure 20: Time versus load of 9% DR scenario for 3/3/2016 in Fort Collins

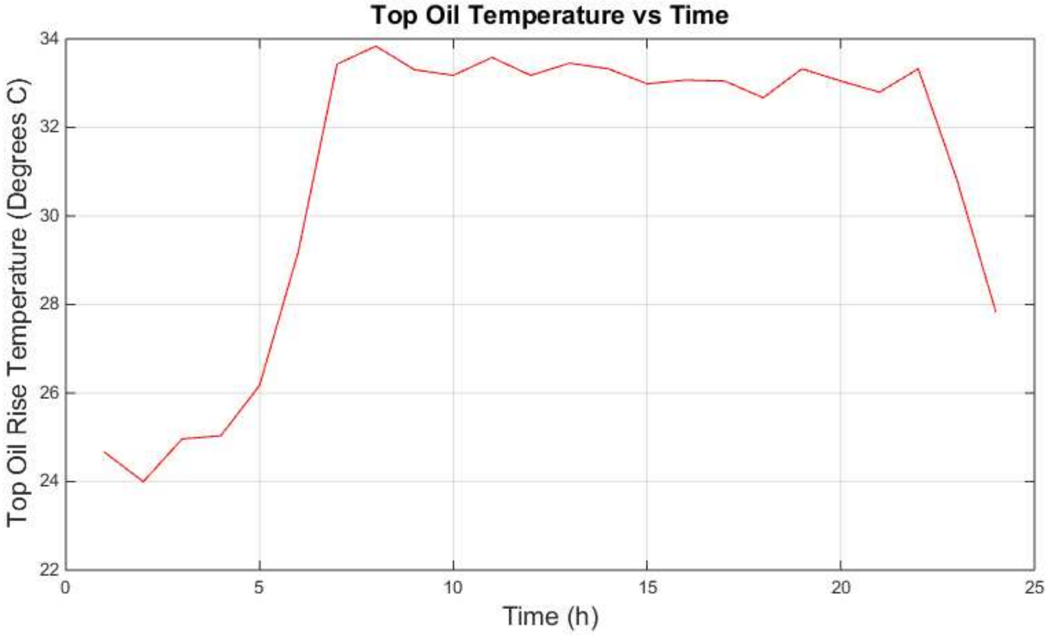

Figure 21: Time versus tot oil rise temperature of 9% DR scenario for 3/3/2016 in Fort Collins

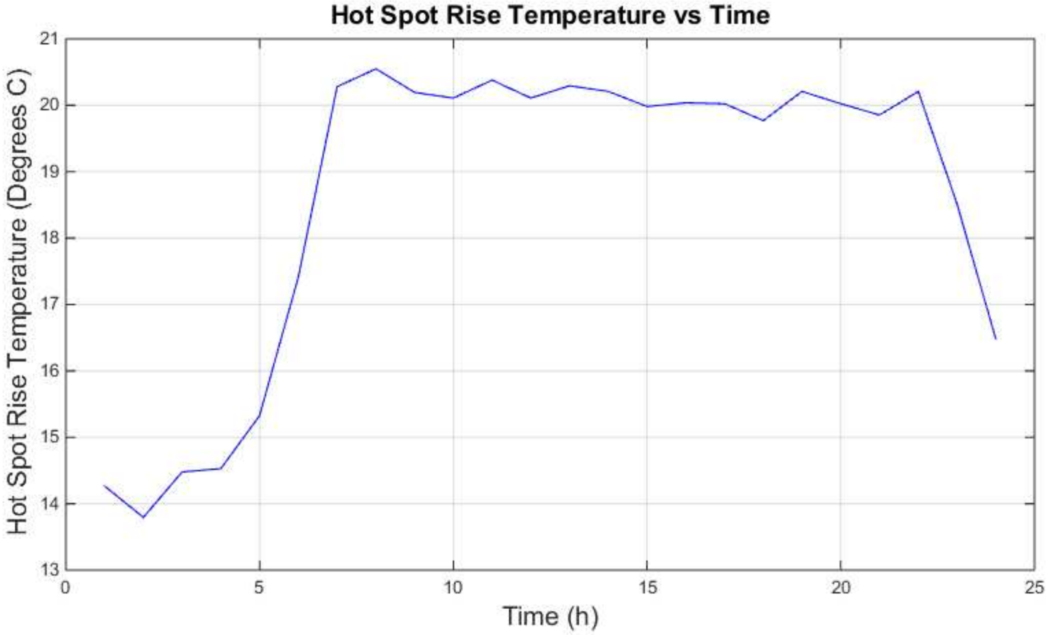

Figure 22: Time versus hot spot rise temperature of 9% DR scenario for 3/3/2016 in Fort Collins

As a result of shifting the peak demand with keeping the same entire load, the overall temperature of the transformer drops where HST declines by 8.3℃ of the normal load, as Figure 23 displays. This reduction has an impact of insulation life and aging factor, which leads to less loss of life of the transformer. The transformer per unit insulation life rises to 311.6 p.u. instead of 105.3 p.u. where Figure 24 describes this development in the insulation life. Also, Figure 25 shows that F_{AA} response to the reduction in the peak load by decreasing aging factor to 0.003210801 while the F_{EQA} decreases to 3.39 minutes. Based on the previous outcomes, the percent loss of life of the transformer reduces to 3.13916E-05 %.

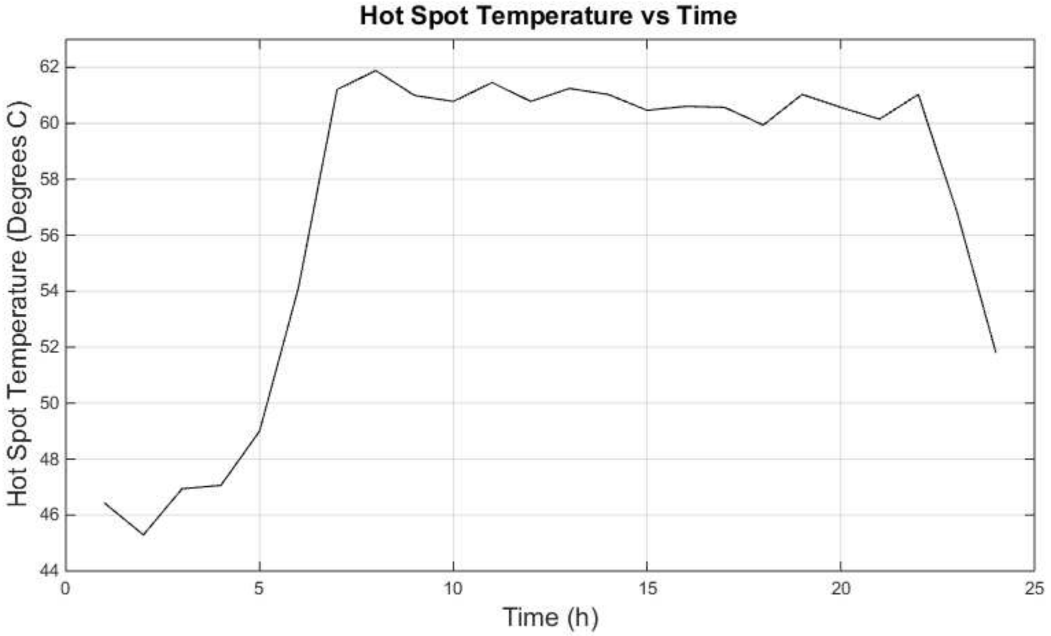

Figure 23: Time versus hot spot temperature of 9% DR scenario for 3/3/2016 in Fort Collins

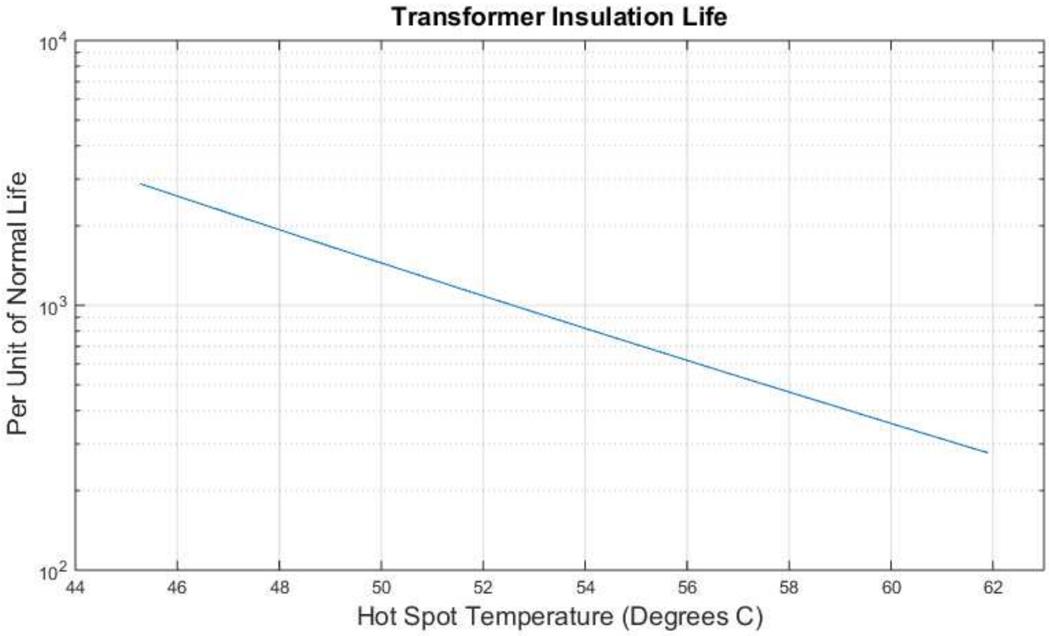

Figure 24: Transformer insulation life of 9% DR for 3/3/2016 in Fort Collins

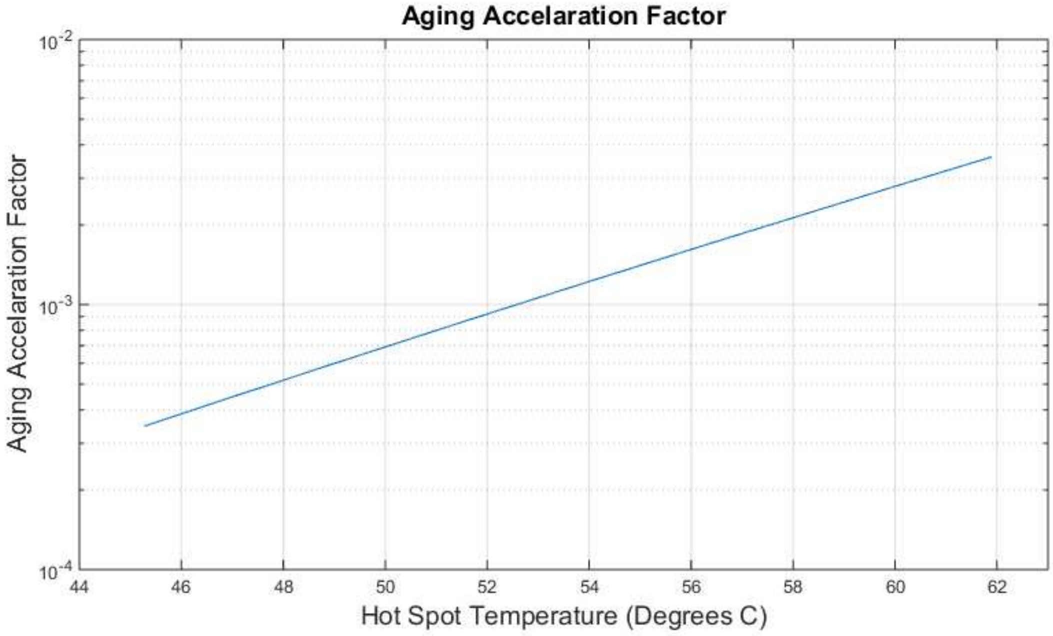

Figure 25: Aging acceleration factor of 9% DR for 3/3/2016 in Fort Collins

The relationship between the transformer thermal and insulation performance and loading is tabulated in Table 12. This table shows the transformer loading profile during the load cycle, HST, F_{AA} and F_{EQA} of 9% DR scenario.

Table 12: Loss of life data for 24 hour load cycle of 9% DR

Time (h)	Load (p.u.)	HST (℃)	F_{AA}	Cumulative age hours (h)
12:00 AM	0.731998542	46.42757992	0.000411991	0.000411991
1:00 AM	0.716798572	45.29130247	0.000348403	0.000760394
2:00 AM	0.738798528	46.94168825	0.000444281	0.001204675
3:00 AM	0.740398525	47.063172	0.000452258	0.001656933
4:00 AM	0.765598475	49.00241044	0.000599742	0.002256675
5:00 AM	0.829198348	54.1105556	0.001241338	0.003498013
6:00 AM	0.911998183	61.21052329	0.003288252	0.006786265
7:00 AM	0.919598168	61.8872607	0.003600429	0.010386694
8:00 AM	0.909598188	60.99768419	0.003195537	0.01358223
9:00 AM	0.907198193	60.78526201	0.003105497	0.016687728
10:00 AM	0.914798178	61.45936209	0.003399908	0.020087635
11:00 AM	0.907198193	60.78526201	0.003105497	0.023193133
12:00 PM	0.912398183	61.24603699	0.00330397	0.026497103
1:00 PM	0.909998187	61.03312843	0.003210801	0.029707904
2:00 PM	0.9035982	60.46741117	0.002975284	0.032683188
3:00 PM	0.905198197	60.60856224	0.003032452	0.035715639
4:00 PM	0.904798198	60.57325708	0.003018055	0.038733694
5:00 PM	0.897598212	59.93974891	0.00277056	0.041504254
6:00 PM	0.909998187	61.03312843	0.003210801	0.044715055
7:00 PM	0.904798198	60.57325708	0.003018055	0.04773311
8:00 PM	0.899998207	60.1505002	0.002850659	0.050583769
9:00 PM	0.909998187	61.03312843	0.003210801	0.05379457
10:00 PM	0.861598284	56.82888639	0.001811435	0.055606005
11:00 PM	0.801198404	51.82422185	0.000898907	0.056504912

g) Comparison of results

This subsection offers a comparison between the four scenarios previously explained. Figure 26 shows a differentiation of the transformer load profile levels. From the figure below, we notice that the transformer load decreases from 1 to around 0.91 p.u. among the four scenarios. The red curve demonstrates the normal load of the transformer and we realize the decreases in the peak load from the green curve by applying some DR mechanism for shifting peak demand. Moreover, Figure 27 represents the relation of delta TOT for different load levels. The highest calculated delta TOT quantities to 38.3℃**,** at the normal load, whereas this temperature declines to 33.8℃ when exercising a 9% DR. Similarly, applying lower load levels leads to reducing delta HST where the temperature reacts to thermal modeling of the transformer as stated in Figure 28.

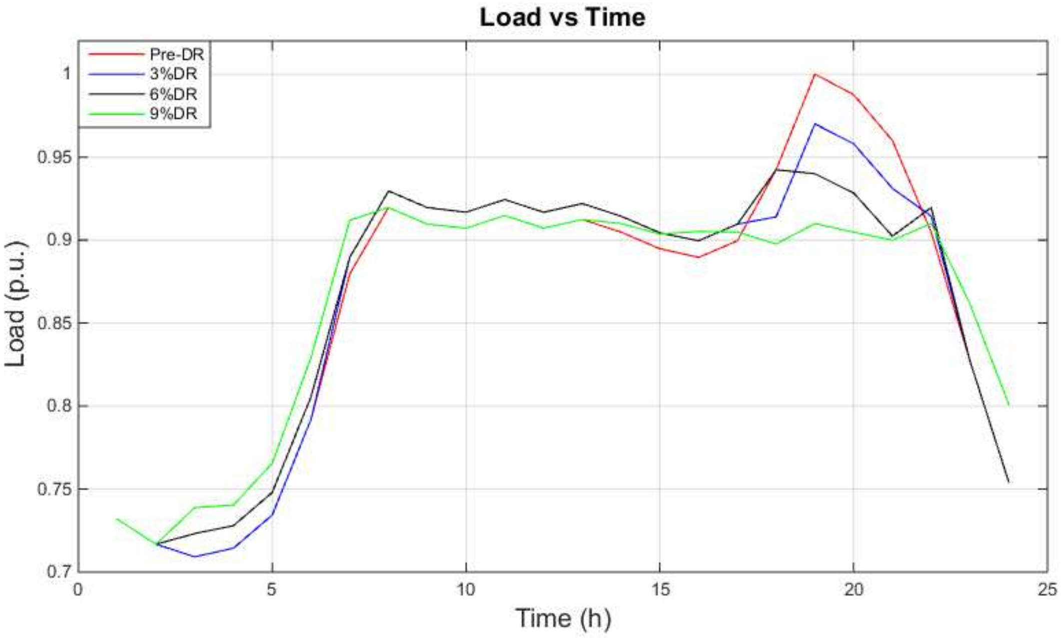

Figure 26: Comparison between load levels for 3/3/2016 in Fort Collins

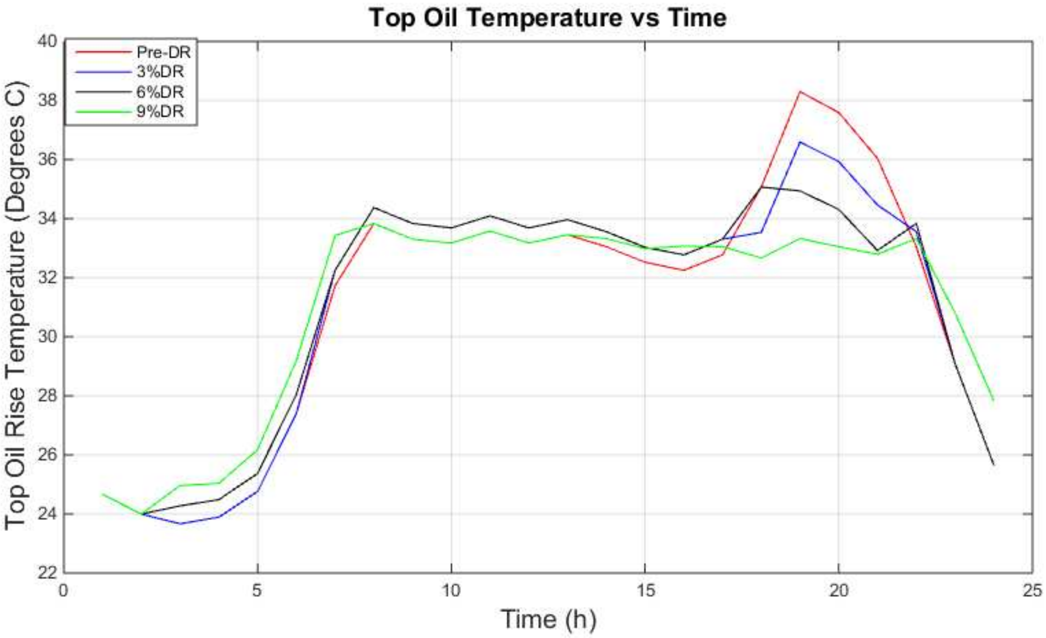

Figure 27: Comparison between top oil rise temperatures for 3/3/2016 in Fort Collins

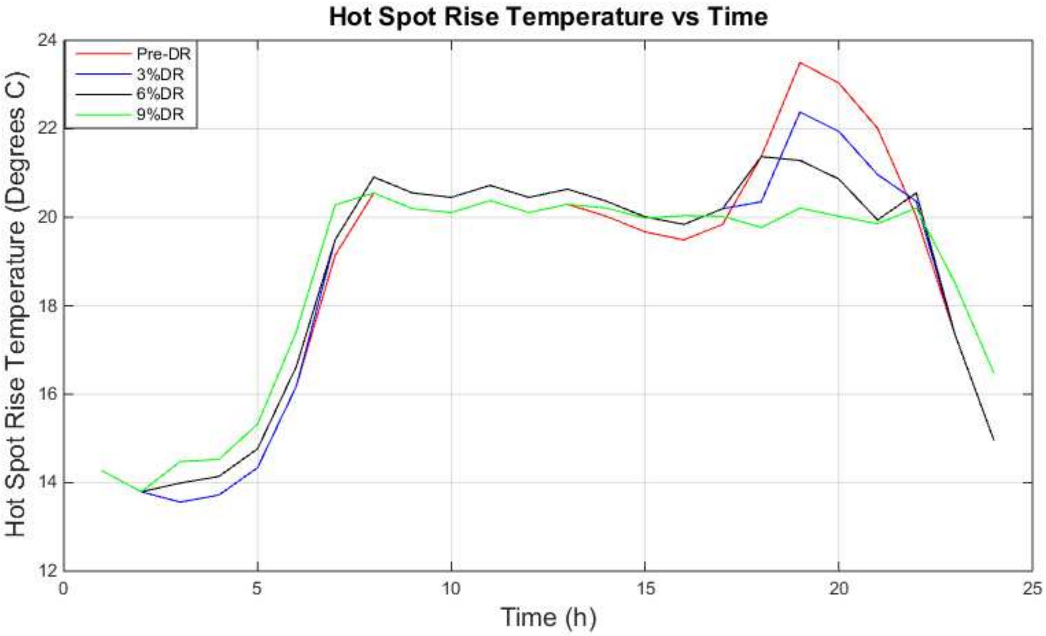

Figure 28: Comparison between hot spot rise temperatures for 3/3/2016 in Fort Collins

Figure 29 shows thermal behavior of the transformer. The curves explain the effect of DR on the distribution transformer. The black curve provides the highest reduction in the tranformer loading levels, with respect to the percent of DR, where it shows 8% drop in the overall operating temperature. Consequently, This decline in the themperature explains the thermal limitation of the transformer loading as well as increases the transforemr insulation life. Figure 30 shows a comparison between the transformer insulation life curves. We notice that the green curve demonestrates the minimum effect of the transformer thermal charactristics due to a reduction in the temperature obtained by the 9% DR scenario. Furthermore, Figure 31 accounts for the relationship between aging factor with respect to load levels. It is obvoius that an increase in temperature will result in an increase in aging factor. However, the green curve in the same figure indicates a smooth relationship between aging factor and the operation temperature of the transformer as it also represents lowest F_{AA} result.

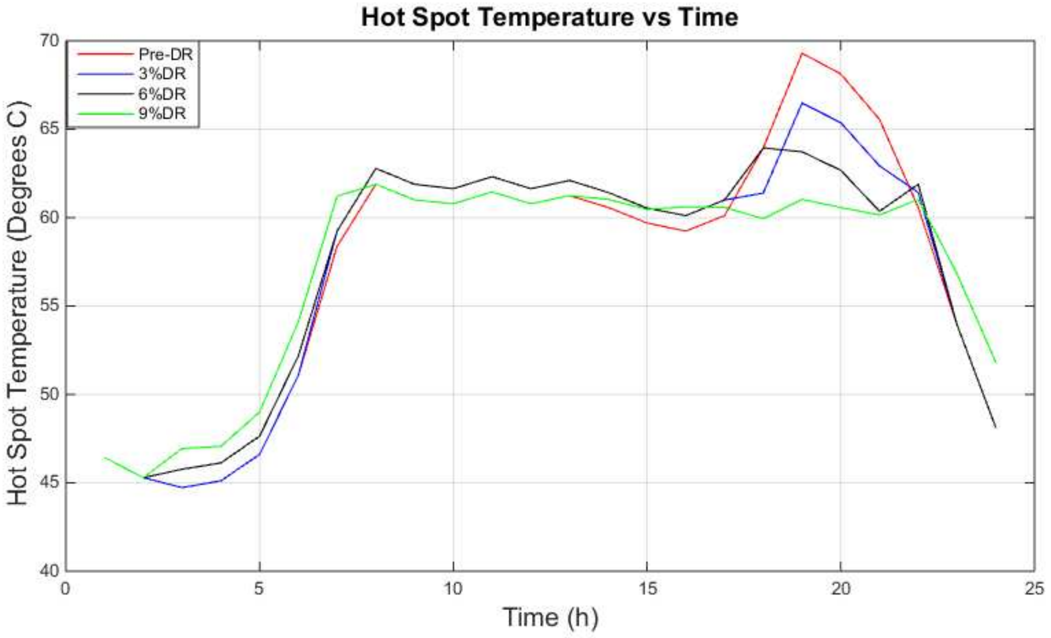

Figure 29: Comparison between hot spot rise temperatures for 3/3/2016 in Fort Collins

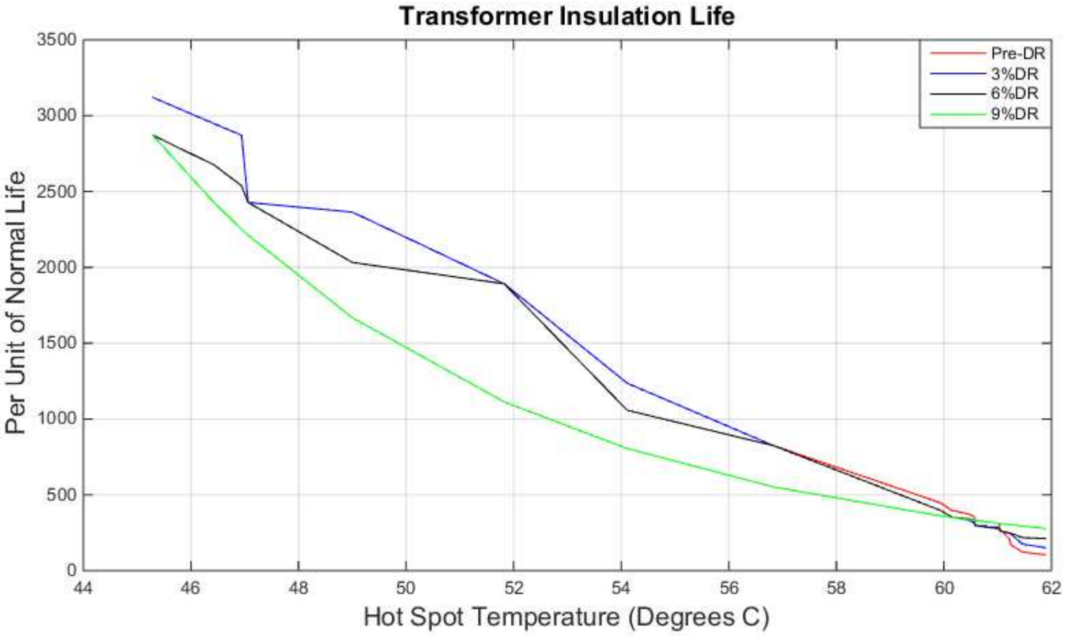

Figure 30: Comparison between the transformer insulation life for 3/3/2016 in Fort Collins

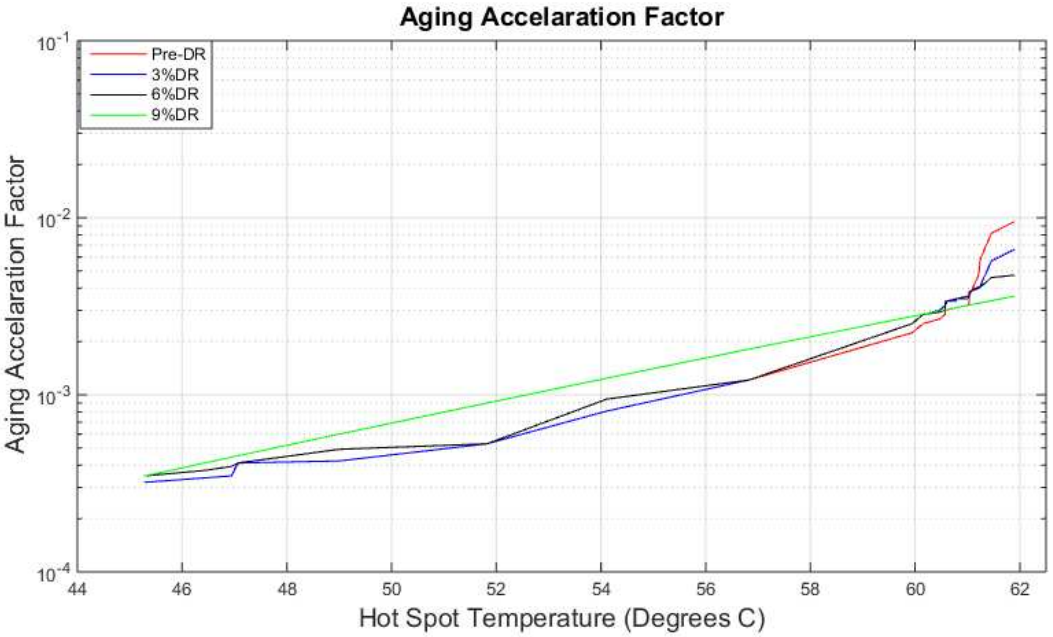

Figure 31: Comparison between the transformer aging acceleration factors for 3/3/2016 in Fort Collins

The objective of this study is investigating the impact of the operating temperature on the transformer lifetime. Form the above, it is well known that LOL is directly dependent on ambient temperature and HST. Figure 32 displays the relationship of the transformer loss of life (LOL) during the load cycle. From this figure, the transformer is gradually losing its normal life for different scenarios.

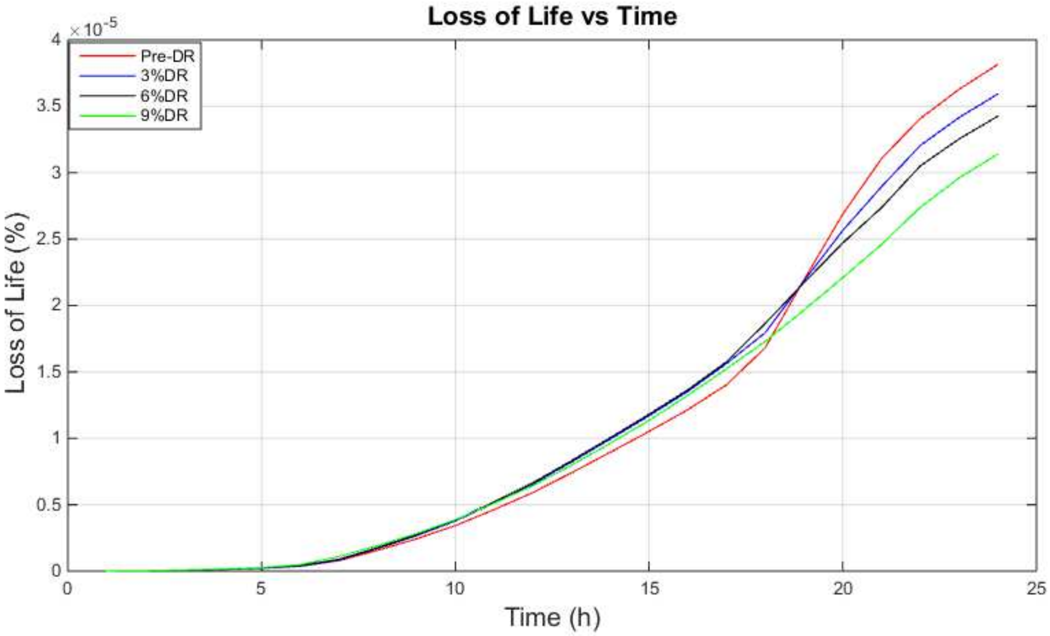

Figure 32: Comparison between the transformer losses of life for 3/3/2016 in Fort Collins

Besides, Table 13 indicates to the peak load, the operation temperature, F_{AA} and LOL for each scenario.

Table 13: The results of the both scenarios during 24 hour period

Scenario	Max. Load (p.u.)	Max. HST (℃)	Max. F_{AA}	LOL (%)
Pre-DR	1	69.29	$9.5*10^{-3}$	$3.8*10^{-5}$
3% DR	0.97	66.48	$6.6*10^{-3}$	$3.6*10^{-5}$
6% DR	0.94	63.72	$4.6*10^{-3}$	$3.4*10^{-5}$
9% DR	0.91	61.03	$3.2*10^{-3}$	$3.1*10^{-5}$

This case study discussed thermal modeling of the 25 MVA using IEEE standard C57.91. Further, loss of life of the transformer is estimated using the results obtained from insulation life and the aging factor calculations. Conclusion of this work and the future path is presented in next chapter.

Chapter IV

Conclusion and Future Work

In this thesis, some methods for basic modeling the heating of a distribution transformer with respect to load changes are presented. The IEEE standard C57.91-2011 was used for studying the thermal characteristics and the loss of life of the 25 MVA distribution transformer under some special conditions such as DR.

4.1 Conclusion

Climate change could affect insulation life and aging factor of transformers and in turn decrease the lifetime of a transformer. In this work, the effect of increasing ambient temperature on distribution transformers was investigated. Recommendations from the IEEE standard C57.91-2011 were applied, using MATLAB, for calculating the HST that includes the sum of ambient temperature, delta TOT and delta HST. Also, this model was employed for analyzing the insulation life and aging acceleration factor of an ideal 25 MVA distribution transformer to estimate the lifetime of the transformer. Further, four scenarios of load levels were utilized for showing the effect of DR in improving the transformer lifetime. The four scenarios are pre-DR, 3%, 6%, and 9% peak load reduction.

A case study based on real data for weather and loads for Fort Collins, Colorado, USA, available in the public domain, was implemented on the 25 MVA distribution transformer. The results obtained for 24 hours of data demonstrate that the overall temperature of the transformer is directly affected by ambient temperature and load level. In detail, the peak demand of pre-DR scenario was between 5 pm and 9 pm. The HST for the 24-hour load cycle reached 69.3℃. Moreover, it is observed that the HST decreases to 66.4℃ by reducing the peak demand by 3%. Also, the calculations were implemented for a 6% reduction in the maximum load cycle of the same day and the outcome of this reduction was minimizing the HST by 5.4°C from the base case. Further, the HST decreases by 8.3°C from the base case to reach 61°C as a result of diminishing the peak load by 9%.

The main aim of these calculations was to obtain the impact of the overall temperature on loss of life of the transformer. Hence, insulation life and aging factor calculations were used for each scenario to study the reduction in lifetime of the transformer based on the comprehensive temperature. The results confirm that the insulation life and aging factor directly depend on the HST. In the pre-DR scenario, i.e., the base case, the minimum insulation life equals 105.3 p.u. at the maximum temperature while the highest aging factor accounted for $9.5*10^{-3}$ p.u.

However, an advantage of applying DR is the increase in insulation life and aging acceleration factor. The highest temperature observed with a 3% reduction in the peak demand raises the insulation life to 151.6 p.u. and decreases the F_{AA} to $6.6*10^{-3}$ p.u. Further, a 6% reduction in the maximum load resulted in an improvement in the insulation life by 48.4% and lowering the F_{AA} by 48% compared to the first scenario. The last scenario was reducing the peak load by 9% in order to obtain the improvement in the insulation life and aging factor. The results of the calculations showed that the insulation life increased to 277.8 p.u. and the F_{AA} fell to $2.3*10^{-3}$ p.u as a result of reducing the overall temperature of the transformer. However, a longer study is required to comprehensively establish the relationship between the cooling facilitated by the change in nighttime loading. The relationship between operating temperature and transformer lifetime is well known in our calculations since the analysis of the characteristics show that the winding temperature is dependent on the transformer loading level. Therefore, the percent loss of life is directly related on the HST.

4.2 Future Work

The results from the work presented here show the effect of climate change, especially ambient temperature, on the ideal distribution transformer. But, studying an ideal distribution transformer would not be sufficient for determining the loss of life of such a transformer. Power quality issues could cause loss of life as well. Harmonic distortion in a distribution transformer can lead to power loss and heating in transformer components, which will cause a reduction in their life expectancy. Our future path is considering the presence of non-sinusoidal load currents. Additionally, the influence of harmonic current on copper loss, eddy current loss and stray loss will be studied. Also, top oil rise over ambient temperature will be affected by harmonic loading which in turn would increase the total losses. Finally, the future work will include cooling characteristics in addition to the aging and power quality costs as harmonic distortion occurs in a distribution transformer.

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Appendix A

a. Pre-DR Matlab code

```
%% Identifying the constants of the model
t= 1:24;
TOT_rated=38.3; % Intial Temp Rise
TOT_fl=85; % Full-load Temp Rise
Tau=24; % Time Constant
R=5; % Ratio of load losses at rated load to no load loss.
n=0.9; % Forced Cooling
Tau_Rated=((5184*38.3)/107633); % Rated Time Constant
P_rated=25e6; % Rated Power in MW %that is based on the assumption that
P.F=1, so S=P.
V=11.86e3; % 11.86 KV
I_Rated=2107.93; % Amp
P_t=[18.30 17.92 17.73 17.86 18.36 19.80 21.99 22.99 22.74 22.68 22.87 22.68
22.81 22.62 22.37 22.24 22.49 23.56 25.00 24.69 24.00 22.62 20.68
18.86]*10^6; % instantenious Load Power
I=P_t/V;
K_t=I/I_Rated;
%K=P_t/P_rated
% Calculating initial TOT
[~,c] = size(K_t);
TOT_initial_t=zeros(1,c);
TOT_initial_t_new=zeros(1,c);
for i=1:c

   TOT_initial_t(1,i)=TOT_rated*((K_t(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        TOT_initial_t_new(1,1) = TOT_initial_t(1,1);
    else
   TOT_initial_t_new(1,i)= TOT_initial_t(1,i-1);
    end
end

% Calculating ultimate TOT
TOT_ult_t=TOT_rated*((K_t.^2*R+1)/(R+1)).^n;
% Calculating Top Oil Transformer Temp
Delta_TOT=((TOT_ult_t)-(TOT_initial_t_new(1,i)))*(1-exp(-
(Tau/Tau_Rated)))+TOT_initial_t_new(1,i);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% HST_Int=60; % Intial HS Temp
HST_Rated=23.5; % Rated-load HST Temp
% HST_Int=55; % Intial HS Temp
% HST_Rated=59; % Rated-load HST Temp
T_HST=7; % HST Time Constant
m=0.8; % Forced Cooling
```

```
Tau_H=2.75*((HST_Rated)/(1+10960)*2.5^2); % Rated Time Constant
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Calculating initial HST
HST_initial_t=zeros(1,c);
HST_initial_t_new=zeros(1,c);
for i=1:c

   HST_initial_t(1,i)=HST_Rated*((K_t(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        HST_initial_t_new(1,1) = HST_initial_t(1,1);
    else
   HST_initial_t_new(1,i)= HST_initial_t(1,i-1);
    end
end
% Calculating ultimate HST
HST_ult_t=HST_Rated*(K_t.^(2*m));
% Calculating Hot Spot Temp Transformer Temp
Delta_HST=(HST_ult_t-HST_initial_t_new)*(1-exp(-
(Tau/Tau_H)))+HST_initial_t_new;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Ambient Temp
Ambient_Temp= [7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5
7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% The Cumulative Thermal Model

Cumulative_Temp= Ambient_Temp+Delta_HST+Delta_TOT;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

[~,c] = size(Cumulative_Temp);
Faa=zeros(1,c);
FAA_Cum=zeros(1,c);
Feqa=zeros(1,c);
LOL=zeros(1,c);

% Calculating the Aging Acceleration Factor
for i=1:c
    Faa(1,i)=(exp((15000/383)-(15000/(Cumulative_Temp(1,i)+273))));
end
[CT_sort,id] = sort(Cumulative_Temp, 'ascend');
% Sort eigenvector accordingly
Faa_new = Faa(:,id);
% Calculating Cumulatiave Aging Hours
for i=1:c
    if i == 1
        FAA_Cum(1,1) = Faa(1,1);
```

```
    else
    FAA_Cum(1,i)= FAA_Cum(1,i-1)+Faa(1,i);
    end
end

% Calculating the Equivalent Aging Factor
for i=1:c
    Feqa(1,i) = FAA_Cum(1,i)/24;
end

% Calculating the Percent Loss of Life
for i = 1:c
    LOL(1,i) = ((Feqa(1,i)*(i)*100) / 180000);
end

% Calculating Tranformer's Isolation Loss of Life
for i = 1:c
    PUL(1,i) = (9.80*(10^-18))*(exp((15000/(273+Cumulative_Temp(1,i)))));
end
[CT_sort,id] = sort(Cumulative_Temp, 'ascend');
% Sort eigenvector accordingly
PUL_new = PUL(:,id);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Faa (1,c)
FAA_Cum (1,c);
Feqa (1,c)
LOL (1,c)
PUL(1,c);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,K_t,'r');
% legend('15%DR');
hold on
grid;
xlabel('Time (h)');
ylabel('Load (p.u.)');
title('Load vs Time');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,Delta_TOT,'r');
% legend('Delta-TOT');
hold on
grid;
xlabel('Time (h)');
ylabel('Top Oil Rise Temperature (Degrees C)');
title('Top Oil Temperature vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot(t,Delta_HST,'b');
% legend('Delta-HST');
hold on
grid;
```

```
xlabel('Time (h)');
ylabel('Hot Spot Rise Temperature (Degrees C)');
title('Hot Spot Rise Temperature vs Time');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot ( t,Cumulative_Temp,'k');
% legend('Cumulative-Temp');
grid;
xlabel('Time (h)');
ylabel('Hot Spot Temperature (Degrees C)');
title('Hot Spot Temperature vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
figure
plot(t,LOL)
% legend('Loss of life');
grid;
xlabel('Time (h)');
ylabel('Loss of Life (%)');
title('Loss of Life vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
semilogy(CT_sort,PUL_new)
% legend('Per Unit life');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Per Unit of Normal Life');
title('Transformer Insulation Life');
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
semilogy(CT_sort,Faa_new)
% legend('Aging Accelaration Factor');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Aging Accelaration Factor');
title('Aging Accelaration Factor');

fname = strcat('my',datestr(now, 'yyyymmddTHHMMSS' ));
xlswrite(fname,[{'Time (h)','Load (p.u.)','HST (Degrees C)'  ,'FAA
(p.u.)','Cumulative age hours (h)'}]);
xlswrite(fname,[t', K_t', Cumulative_Temp', Faa', FAA_Cum'],'A2:E25');
```

b. 3% DR Matlab code

```
%% Identifying the constants of the model with Demand Response by 3%
t= 1:24;
TOT_rated=38.3; % Intial Temp Rise
TOT_fl=85; % Full-load Temp Rise
Tau=24; % Time Constant
R=5; % Ratio of load losses at rated load to no load loss.
n=0.9; % Forced Cooling
Tau_Rated=((5184*38.3)/107633); % Rated Time Constant
P_rated=25e6; % Rated Power in MW %that is based on the assumption that
P.F=1, so S=P.
V=11.86e3; % 11.86 KV
I_Rated=2107.93; % Amp
P_t5=[18.30 17.92 17.73 17.86 18.36 19.80 22.24 23.24 22.99 22.92 23.11 22.92
23.05 22.86 22.61 22.49 22.74 22.85 24.25 23.95 23.28 22.86 20.68
18.86]*10^6; % instantenious Load Power
I_t5=P_t5/V;
K_t5=I_t5/I_Rated;
%K=P_t/P_rated
% Calculating initial TOT
[~,c] = size(K_t5);
TOT_initial_t5=zeros(1,c);

TOT_initial_t5_new=zeros(1,c);
for i=1:c

   TOT_initial_t5(1,i)=TOT_rated*((K_t5(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        TOT_initial_t5_new(1,1) = TOT_initial_t5(1,1);
    else
   TOT_initial_t5_new(1,i)= TOT_initial_t5(1,i-1);
    end
end

% Calculating ultimate TOT
TOT_ult_t5=TOT_rated*((K_t5.^2*R+1)/(R+1)).^n;
% Calculating Top Oil Transformer Temp


 Delta_TOT5 =((TOT_ult_t5)-(TOT_initial_t5_new(1,i)))*(1-exp(-
(Tau/Tau_Rated)))+TOT_initial_t5_new(1,i);




%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% HST_Int=60; % Intial HS Temp
HST_Rated=23.5; % Rated-load HST Temp
% HST_Int=55; % Intial HS Temp
```

```
% HST_Rated=59; % Rated-load HST Temp
T_HST=7; % HST Time Constant
m=0.8; % Forced Cooling
Tau_H=2.75*((HST_Rated)/(1+10960)*2.5^2); % Rated Time Constant
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Calculating initial HST
HST_initial_t5=zeros(1,c);
HST_initial_t5_new=zeros(1,c);
for i=1:c

   HST_initial_t5(1,i)=HST_Rated*((K_t5(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        HST_initial_t5_new(1,1) = HST_initial_t5(1,1);
    else
   HST_initial_t5_new(1,i)= HST_initial_t5(1,i-1);
    end
end
% Calculating ultimate HST
HST_ult_t5=HST_Rated*(K_t5.^(2*m));
% Calculating Hot Spot Temp Transformer Temp



   Delta_HST5=(HST_ult_t5-HST_initial_t5_new)*(1-exp(-
(Tau/Tau_H)))+HST_initial_t5_new;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Ambient_Temp= [7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5
7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% The Cumulative Thermal Model

Cumulative_Temp5= Ambient_Temp+Delta_HST5+Delta_TOT5;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

[~,c] = size(Cumulative_Temp5);
Faa5=zeros(1,c);
FAA_Cum5=zeros(1,c);
Feqa5=zeros(1,c);
LOL5=zeros(1,c);

% Calculating the Aging Acceleration Factor
for i=1:c
    Faa5(1,i)=(exp((15000/383)-(15000/(Cumulative_Temp5(1,i)+273))));
end
[CT_sort,id] = sort(Cumulative_Temp5, 'ascend');
```

```
% Sort eigenvector accordingly
Faa_new5 = Faa5(:,id);
% Calculating Cumulatiave Aging Hours
for i=1:c
    if i == 1
        FAA_Cum5(1,1) = Faa5(1,1);
    else
    FAA_Cum5(1,i)= FAA_Cum5(1,i-1)+Faa5(1,i);
    end
end

% Calculating the Equivalent Aging Factor
for i=1:c
    Feqa5(1,i) = FAA_Cum5(1,i)/24;
end

% Calculating the Percent Loss of Life
for i = 1:c
    LOL5(1,i) = ((Feqa5(1,i)*(i)*100) / 180000);
end

% Calculating Tranformer's Isolation Loss of Life
for i = 1:c
    PUL5(1,i) = (9.80*(10^-18))*(exp((15000/(273+Cumulative_Temp5(1,i)))));
end
[CT_sort,id] = sort(Cumulative_Temp5, 'ascend');
% Sort eigenvector accordingly
PUL5_new5 = PUL5(:,id);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Faa5 (1,c)
FAA_Cum5 (1,c);
Feqa5 (1,c)
LOL5 (1,c)
PUL5(1,c);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,K_t5,'r');
% legend('15%DR');
hold on
grid;
xlabel('Time (h)');
ylabel('Load (p.u.)');
title('Load vs Time');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,Delta_TOT5,'r');
% legend('Delta-TOT');
hold on
grid;
xlabel('Time (h)');
ylabel('Top Oil Rise Temperature (Degrees C)');
title('Top Oil Temperature vs Time');
%
```

```
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot(t,Delta_HST5,'b');
% legend('Delta-HST');
hold on
grid;
xlabel('Time (h)');
ylabel('Hot Spot Rise Temperature (Degrees C)');
title('Hot Spot Rise Temperature vs Time');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure
plot ( t,Cumulative_Temp5,'k');
% legend('Cumulative-Temp');
grid;
xlabel('Time (h)');
ylabel('Hot Spot Temperature (Degrees C)');
title('Hot Spot Temperature vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
figure
plot(t,LOL5)
% legend('Loss of life');
grid;
xlabel('Time (h)');
ylabel('Loss of Life (%)');
title('Loss of Life vs Time');

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
semilogy(CT_sort,PUL5_new5)
% legend('Isolation loss of life');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Per Unit of Normal Life');
title('Transformer Insulation Life');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
CT_sort
Faa_new5
semilogy(CT_sort,Faa_new5)
% legend('Aging Accelaration Factor');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Aging Accelaration Factor');
title('Aging Accelaration Factor');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% visualizing the data in a table
fname = strcat('my',datestr(now, 'yyyymmddTHHMMSS' ));
xlswrite(fname,[{'Time (h)','Load (p.u.)','HST (Degrees C)'  ,'FAA
(p.u.)','Cumulative age hours (h)'}]);
xlswrite(fname,[t', K_t5', Cumulative_Temp5', Faa5', FAA_Cum5'],'A2:E25');
```

c. 6% DR Matlab code

```
%% Identifying the constants of the model with 6 % Demand Response

t= 1:24;
TOT_rated=38.3; % Intial Temp Rise
TOT_fl=48; % Full-load Temp Rise
Tau=24; % Time Constant
R=5; % Ratio of load losses at rated load to no load loss.
n=0.9; % Forced Cooling
Tau_Rated=((5184*38.3)/107633); % Rated Time Constant
P_rated=25e6; % Rated Power in MW %that is based on the assumption that
P.F=1, so S=P.
V=11.86e3; % 11.86 KV
I_Rated=2107.93; % Amp
P_t10=[18.30 17.92 18.08 18.20 18.70 20.14 22.24 23.24 22.99 22.92 23.11
22.92 23.05 22.86 22.61 22.49 22.74 23.56 23.50 23.21 22.56 22.99 20.68
18.86]*10^6; % instantenious Load Power Power
I_t10=P_t10/V;
K_t10=I_t10/I_Rated;
%K=P_t/P_rated
% Calculating initial TOT
[~,c] = size(K_t10);
TOT_initial_t10=zeros(1,c);
TOT_initial_t10_new=zeros(1,c);
for i=1:c

   TOT_initial_t10(1,i)=TOT_rated*((K_t10(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        TOT_initial_t10_new(1,1) = TOT_initial_t10(1,1);
    else
   TOT_initial_t10_new(1,i)= TOT_initial_t10(1,i-1);
    end
end

% Calculating ultimate TOT
TOT_ult_t10=TOT_rated*((K_t10.^2*R+1)/(R+1)).^n;
% Calculating Top Oil Transformer Temp
Delta_TOT10=((TOT_ult_t10)-(TOT_initial_t10_new(1,i)))*(1-exp(-
(Tau/Tau_Rated)))+TOT_initial_t10_new(1,i);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% HST_Int=60; % Intial HS Temp
HST_Rated=23.5; % Rated-load HST Temp
% HST_Int=55; % Intial HS Temp
% HST_Rated=59; % Rated-load HST Temp
T_HST=7; % HST Time Constant
m=0.8; % Forced Cooling
Tau_H=2.75*((HST_Rated)/(1+10960)*2.5^2); % Rated Time Constant
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Calculating initial HST
HST_initial_t10=zeros(1,c);
HST_initial_t10_new=zeros(1,c);
for i=1:c

   HST_initial_t10(1,i)=HST_Rated*((K_t10(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        HST_initial_t10_new(1,1) = HST_initial_t10(1,1);
    else
   HST_initial_t10_new(1,i)= HST_initial_t10(1,i-1);
    end
end
% Calculating ultimate HST
HST_ult_t10=HST_Rated*(K_t10.^(2*m));
% Calculating Hot Spot Temp Transformer Temp
Delta_HST10=(HST_ult_t10-HST_initial_t10_new)*(1-exp(-
(Tau/Tau_H)))+HST_initial_t10_new;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Ambient_Temp= [7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5
7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% The Cumulative Thermal Model

Cumulative_Temp10= Ambient_Temp+Delta_HST10+Delta_TOT10;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

[~,c] = size(Cumulative_Temp10);
Faa10=zeros(1,c);
FAA_Cum10=zeros(1,c);
Feqa10=zeros(1,c);
LOL10=zeros(1,c);

% Calculating the Aging Acceleration Factor
for i=1:c
    Faa10(1,i)=(exp((15000/383)-(15000/(Cumulative_Temp10(1,i)+273))));
end
[CT_sort,id] = sort(Cumulative_Temp10, 'ascend');
% Sort eigenvector accordingly
Faa_new10 = Faa10(:,id);
% Calculating Cumulatiave Aging Hours
for i=1:c
    if i == 1
        FAA_Cum10(1,1) = Faa10(1,1);
    else
    FAA_Cum10(1,i)= FAA_Cum10(1,i-1)+Faa10(1,i);
    end
end
```

```
% Calculating the Equivalent Aging Factor
for i=1:c
    Feqa10(1,i) = FAA_Cum10(1,i)/24;
end

% Calculating the Percent Loss of Life
for i = 1:c
    LOL10(1,i) = ((Feqa10(1,i)*(i)*100) / 180000);
end

% Calculating Tranformer's Isolation Loss of Life
for i = 1:c
    PUL10(1,i) = (9.80*(10^-18))*(exp((15000/(273+Cumulative_Temp10(1,i)))));
end
[CT_sort,id] = sort(Cumulative_Temp10, 'ascend');
% Sort eigenvector accordingly
PUL10_new = PUL10(:,id);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Faa10 (1,c)
FAA_Cum10 (1,c);
Feqa10 (1,c)
LOL10 (1,c)
PUL10(1,c);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,K_t10,'r');
% legend('15%DR');
hold on
grid;
xlabel('Time (h)');
ylabel('Load (p.u.)');
title('Load vs Time');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,Delta_TOT10,'r');
% legend('Delta-TOT');
hold on
grid;
xlabel('Time (h)');
ylabel('Top Oil Rise Temperature (Degrees C)');
title('Top Oil Temperature vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot(t,Delta_HST10,'b');
% legend('Delta-HST');
hold on
grid;
xlabel('Time (h)');
ylabel('Hot Spot Rise Temperature (Degrees C)');
title('Hot Spot Rise Temperature vs Time');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
figure
plot ( t,Cumulative_Temp10,'k');
legend('Cumulative-Temp');
grid;
xlabel('Time (h)');
ylabel('Hot Spot Temperature (Degrees C)');
title('Hot Spot Temperature vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
figure
plot(t,LOL10)
legend('Loss of life');
grid;
xlabel('Time (h)');
ylabel('Loss of Life (%)');
title('Loss of Life vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
semilogy(CT_sort,PUL10_new)
% legend('Isolation loss of life');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Per Unit of Normal Life');
title('Transformer Insulation Life');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure
CT_sort
Faa_new10
semilogy(CT_sort,Faa_new10)
% legend('Aging Accelaration Factor');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Aging Accelaration Factor');
title('Aging Accelaration Factor');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


% visualizing the data in a table
fname = strcat('my',datestr(now, 'yyyymmddTHHMMSS' ));
xlswrite(fname,[{'Time (h)','Load (p.u.)','HST (Degrees C)'  ,'FAA
(p.u.)','Cumulative age hours (h)'}]);
xlswrite(fname,[t', K_t10', Cumulative_Temp10', Faa10',
FAA_Cum10'],'A2:E25');
```

d. 9% DR Matlab code

```
%% Identifying the constants of the model with Demand Response by 9%
t= 1:24;
TOT_rated=38.3; % Intial Temp Rise
TOT_fl=85; % Full-load Temp Rise
Tau=24; % Time Constant
R=5; % Ratio of load losses at rated load to no load loss.
n=0.9; % Forced Cooling
Tau_Rated=((5184*38.3)/107633); % Rated Time Constant
P_rated=25e6; % Rated Power in MW %that is based on the assumption that
P.F=1, so S=P.
V=11.86e3; % 11.86 KV
I_Rated=2107.93; % Amp
P_t15=[18.30 17.92 18.47 18.51 19.14 20.73 22.80 22.99 22.74 22.68 22.87
22.68 22.81 22.75 22.59 22.63 22.62 22.44 22.75 22.62 22.50 22.75 21.54
20.03]*10^6; % instantenious Load Power
I_t15=P_t15/V;
K_t15=I_t15/I_Rated;
%K=P_t/P_rated

% Calculating initial TOT
[~,c] = size(K_t15);
TOT_initial_t15=zeros(1,c);
TOT_initial_t15_new=zeros(1,c);
for i=1:c

   TOT_initial_t15(1,i)=TOT_rated*((K_t15(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        TOT_initial_t15_new(1,1) = TOT_initial_t15(1,1);
    else
   TOT_initial_t15_new(1,i)= TOT_initial_t15(1,i-1);
    end
end

% Calculating ultimate TOT
TOT_ult_t15=TOT_rated*((K_t15.^2*R+1)/(R+1)).^n;
% Calculating Top Oil Transformer Temp
Delta_TOT15=((TOT_ult_t15)-(TOT_initial_t15_new(1,i)))*(1-exp(-
(Tau/Tau_Rated)))+TOT_initial_t15_new(1,i);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% HST_Int=60; % Intial HS Temp
HST_Rated=23.5; % Rated-load HST Temp
% HST_Int=55; % Intial HS Temp
% HST_Rated=59; % Rated-load HST Temp
T_HST=7; % HST Time Constant
m=0.8; % Forced Cooling
Tau_H=2.75*((HST_Rated)/(1+10960)*2.5^2); % Rated Time Constant
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% Calculating initial HST
HST_initial_t15=zeros(1,c);
HST_initial_t15_new=zeros(1,c);
for i=1:c

   HST_initial_t15(1,i)=HST_Rated*((K_t15(1,i)^2*R+1)/(R+1))^n;

end
for i=1:c
    if i == 1
        HST_initial_t15_new(1,1) = HST_initial_t15(1,1);
    else
   HST_initial_t15_new(1,i)= HST_initial_t15(1,i-1);
    end
end
% Calculating ultimate HST
HST_ult_t15=HST_Rated*(K_t15.^(2*m));
% Calculating Hot Spot Temp Transformer Temp
Delta_HST15=(HST_ult_t15-HST_initial_t15_new)*(1-exp(-
(Tau/Tau_H)))+HST_initial_t15_new;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Ambient_Temp= [7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5
7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5 7.5];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% The Cumulative Thermal Model

Cumulative_Temp15= Ambient_Temp+Delta_HST15+Delta_TOT15;
% [CT_sort,id] = sort(Cumulative_Temp15, 'ascend');
% % Sort eigenvector accordingly
% Cumulative_Temp15_new = Cumulative_Temp15(:,id);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

[~,c] = size(Cumulative_Temp15);
Faa15=zeros(1,c);
FAA_Cum15=zeros(1,c);
Feqa15=zeros(1,c);
LOL15=zeros(1,c);

% Calculating the Aging Acceleration Factor
for i=1:c
    Faa15(1,i)=(exp((15000/383)-(15000/(Cumulative_Temp15(1,i)+273))));
end
[CT_sort,id] = sort(Cumulative_Temp15, 'ascend');
% Sort eigenvector accordingly
Faa_new15 = Faa15(:,id);
% Calculating Cumulatiave Aging Hours
for i=1:c
    if i == 1
        FAA_Cum15(1,1) = Faa15(1,1);
    else
    FAA_Cum15(1,i)= FAA_Cum15(1,i-1)+Faa15(1,i);
```

```
    end
end
% Calculating the Equivalent Aging Factor
for i=1:c
    Feqa15(1,i) = FAA_Cum15(1,i)/24;
end

% Calculating the Percent Loss of Life
for i = 1:c

LOL15(1,i) = ((Feqa15(1,i)*(i)*100) / 180000);
end

%Integraion of Faa
% L = zeros(1,c);
% Lt = zeros(1,c);
% Lf = zeros(1,c);
% for i = 1:c
%     func = @(t) Faa15(1,i)*t.^0;
%     L(1,i) = integral(func,1,24);
%     func = @(t) t.^0;
%     Lt(1,i) = integral(func,1,24);
%     Lf(1,i) = L(1,i) / Lt(1,i);
% end

% Calculating Tranformer's Isolation Loss of Life
for i = 1:c
    PUL15(1,i) = (9.80*(10^-18))*(exp((15000/(273+Cumulative_Temp15(1,i)))));
end
[CT_sort,id] = sort(Cumulative_Temp15, 'ascend');
% Sort eigenvector accordingly
PUL15_new = PUL15(:,id);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Faa15 (1,c)
FAA_Cum15 (1,c);
Feqa15 (1,c)
LOL15 (1,c)
PUL15(1,c);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,K_t15,'r');
% legend('15%DR');
hold on
grid;
xlabel('Time (h)');
ylabel('Load (p.u.)');
title('Load vs Time');

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot (t,Delta_TOT15,'r');
% legend('Delta-TOT');
hold on
grid;
xlabel('Time (h)');
```

```
ylabel('Top Oil Rise Temperature (Degrees C)');
title('Top Oil Temperature vs Time');
%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot(t,Delta_HST15,'b');
% legend('Delta-HST');
hold on
grid;
xlabel('Time (h)');
ylabel('Hot Spot Rise Temperature (Degrees C)');
title('Hot Spot Rise Temperature vs Time');
% %
% % %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
plot ( t,Cumulative_Temp15,'k');
% legend('Cumulative-Temp');
grid;
xlabel('Time (h)');
ylabel('Hot Spot Temperature (Degrees C)');
title('Hot Spot Temperature vs Time');

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
figure
plot(t,LOL15)
% legend('Loss of life');
grid;
xlabel('Time (h)');
ylabel('Loss of Life (%)');
title('Loss of Life vs Time');

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure
semilogy(CT_sort,PUL15_new)
% legend('Isolation loss of life');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Per Unit of Normal Life');
title('Transformer Insulation Life');
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure
CT_sort
Faa_new15
semilogy(CT_sort,Faa_new15)
%xlim([60,200])
% xlabel('Hottest Spot Temperature','FontSize',20)
% ylabel('Aging Acceleration Factor','FontSize',20)
% grid on
% plot(CT_sort,Faa_new15)
% legend('Aging Accelaration Factor');
grid;
xlabel('Hot Spot Temperature (Degrees C)');
ylabel('Aging Accelaration Factor');
title('Aging Accelaration Factor');
```

```
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
figure
plot(t,Lf)
legend('Loss of life');
grid;
xlabel('Time (h)');
ylabel('Loss of Life (pu)');
title('Loss of Life vs Time');
% % % %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %
figure
plot(t,L)
legend('Loss of life');
grid;
xlabel('Time (h)');
ylabel('Loss of Life (%)');
title('Loss of Life vs Time');
% % %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% figure
% plot(t,Faa)

T = table(CT_sort',Faa_new15', 'VariableNames',{'Temperature_degC'
'Age_Factor'})

% visualizing the data in a table
fname = strcat('my',datestr(now, 'yyyymmddTHHMMSS' ));
xlswrite(fname,[{'Time (h)','Load (p.u.)','HST (Degrees C)'  ,'FAA
(p.u.)','Cumulative age hours (h)'}]);
xlswrite(fname,[t', K_t15', Cumulative_Temp15', Faa15',
FAA_Cum15'],'A2:E25');
```

List of Abbreviations

A	Constant related to the material and their application in the insulation system
B	Constant related to the material and their application in the insulation system
Delta TOT	Top oil temperature rise
Delta HST	hot spot temperature rise
$C_{t_{h-oil}}$	Equivalent thermal capacity that consists of heat capacity of material
EPA	Environmental protection agency
F_{AA}	The aging acceleration factor
F_{EQA}	The factor of equivalent aging
GHG	Greenhouse gas
HST	Hot spot temperature
I	Ratio of load to rated load
K	Ratio of load at rated load
K_i	Ratio of initial load to rated load
K_u	Ratio of final load to rated load

LOL	Losses of life of the transformer
n	Exponent refers to cooling type
m	Exponent refers to cooling type
ODWF	Oil Directed Water Forced
OFAF	Oil forced Air Forced
OFWF	Oil Forced Water Forced
ONAF	Oil natural air forced
ONAN	Oil Natural Air Natural
p	The number of delay lines
R	Ratio of load losses to rated load
RPS	Renewable portfolio standard
TOT	Top oil temperature
T	Time constant
t	Time interval of application of specific load
UNFCCC	United nation framework convention on climate change
V	Relative aging rate
X	Demand in kVA
x2	The load

y	The output of the model
Δt	The time interval
$\Delta\theta_{H}$	Top oil temperature rise
$\Delta\theta_{Hi}$	Hot spot initial temperature
$\Delta\theta_{Hu}$	Hot spot final temperature
$\Delta\ \theta oun$	Ultimate oil temperature rise at end of n^{th}interval
$\Delta\ \theta on$	Top oil temperature rise at end of n^{th}interval
$\Delta\ \theta o(n-1)$	Top oil temperature rise at end of $(n-1)^{th}$interval
$\Delta\ \theta td,g$	Temperature difference between HST and TOT
$\Delta\theta_{TOil}$	Top oil temperature rise
$\Delta\theta_{TOi}$	Top oil Initial temperature
$\Delta\theta_{TO,R}$	Top oil rise over ambient temperature at rated load
$\Delta\theta_{TOu}$	Top oil final temperature
$\theta amb, x1$	Ambient temperature
θfl	Top oil rise over ambient temperature at rated load
$\theta hst, H$	Hot spot temperature
θhu	Ultimate hot spot temperature

$\Delta\theta TO,i$	Rated top oil over ambient temperature at rated load
$\theta toil - moil$	The difference between top oil and bottom oil
μ	Oil viscosity
τ_H	Hot spot time constant
τ_{To}	Top oil time constant