Ageing Estimation Models for Lightly Loaded Distribution Power Transformers

by

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Supervisor: Dr JL Jooste

March 2018

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the authorship owner thereof (unless to the extent explicitly otherwise stated), and that I have not previously, in its entirety or in part, submitted it for obtaining any qualification.

Date: March 2018

Abstract

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Power transformers form an integral part of present day electricity networks. They allow for power to efficiently be transported over vast distances. They are however one of the most expensive assets within the distribution network. In order to maximise return on investment for these assets, transformer owners need to ensure that they operate for as long as possible. The ageing of a transformer is based primarily on the condition of the solid insulation inside the transformer. There are various ageing models which attempt to predict the ageing of a transformer based on parameters such as hot-spot temperature, oxygen and moisture content. Typical distribution networks are designed with transformer redundancy. In these networks, the full load of a substation is typically shared across two or more transformers. This results in individual transformers being lightly loaded (<50%).

This study investigates the accuracy of the ageing models presented on a fleet of twenty distribution power transformers. The study compiles an algorithm which carries out two main functions. The first is to determine the hot-spot temperature based on loading. The second is to predict the loss-of-life based on the various ageing models identified. This predicted loss-of-life value is compared to measured loss-of-life values in order to determine which model produces the most accurate results. Using these results, the study goes further to modify these ageing models in an attempt to improve the accuracy thereof. These modified model's accuracy rates are compared to each other as well as the initial ageing models to identify if any improvement in accuracy is produced.

A modified output model is produced which increases the accuracy of the loss-of-life prediction for lightly loaded transformers. The modified model utilises the historic average hot-spot operating temperature in order to determine the ageing rate. This can be utilised by asset managers of power transformers in distribution networks.

Opsomming

Verouderingsmodelle vir Lig Belaste Distribusie Krag Transformators

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Transformators is integrale komponente van elektriese verspreidingsnetwerke – daarsonder kan elektriese krag nie effektief oor lang afstande gevoer word nie. Transfomators kom egter ook teen ‘n koste wat dit in terme van finansiële bate waarde klassifiseer onder die duurste komponente van ‘n kragstelsel. Dit is in die belang van die bate eienaars dat transformators ‘n lewensduur het wat die belegging nie alleen net regverdig nie, maar maksimeer. Die begrip van veroudering van ‘n transformator word hoofsaaklik gebaseer op die toestand van die elektriese isoleringsmateriaal in vastestof vorm wat intern tot die eenheid gebruik word. Bestaande modelle wat poog om die staat van veroudering te voorspel, is gebaseer op parameters soos warmste temperatuur, suurstof- en voginhoud. Transformator oortolligheid is ingebou die ontwerp van elektriese netwerke en derhalwe word die volle elektriese las tipies tussen twee of meer transformators gedeel. Die resultaat hiervan is dat individuele transformators lig belas word (<50%).

Hierdie studie ondersoek die akkuraatheid van verouderingsmodelle soos toegepas op twintig distribusievlak transformators. ‘n Algoritme word saamgestel wat twee hoofsaaklike funksies uitvoer. Eerstens word ‘n warmste temperatuur bepaal, gebaseer op die belading. Tweedens word die verlies aan lewensduurte voorspel uit die verskillende geïdentifiseerde modelle. Die voorspelde verlies aan lewensduurte word vergelyk met die werklike verlies om sodoende die model met die mees akkurate resultate te identifiseer. Die studie gebruik dan voorts hierdie resultate om die verouderingsmodelle te wysig met die doel om die akkuraatheid daarvan te verbeter. Die mate waartoe die gewysigde modelle se akkuraatheid verander, word met mekaar sowel as met die aanvanklike modelle vergelyk om vas te stel of enige verbetering in akkuraatheid bereik is.

Die resultaat is 'n gewysigde uitset model met verhoogde akkuraatheid in die voorspelde verlies aan lewensduur vir ligbelaste transformators. Die gewysigde model gebruik geskiedenis gemiddelde warmste bedryfstemperatuur om die verouderingstempo te bepaal. Die model vind toepassing in die bestuur van transformator bates in distribusie netwerke.

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The Author

November 2017

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Glossary

Acronyms

DGA	Dissolved Gas Analysis
DP	Degree of Polymerisation
GA	Genetic Algorithm
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
KV	Kilo Volt
LV	Low Voltage
mm	Millimetre
MV	Medium Voltage
MVA	Mega Volt Ampere
ODAF	Oil Directed Air Forced
OFAF	Oil Forced Air Forced
ONAF	Oil Natural Air Forced
ONAN	Oil Natural Air Natural
PPM	Parts Per Million
SANS	South African National Standards
SCADA	Supervisory Control and Data Acquisition
TEMP	Temperature
TRFR	Transformer

Nomenclature

Symbol	Description	Units
g	average winding to average oil gradient at rated current	
H	Hotspot factor	
θ_h	Hot-spot temperature	°C
θ_o	Top oil temperature	°C
V_1	Voltage across winding 1	Volt
V_2	Voltage across winding 2	Volt
N_1	Number of turns in winding 1	
N_2	Number of turns in winding 2	
I_1	Current in winding 1	Amp
I_2	Current in winding 2	Amp
RS	Relative Saturation	%
W_c	Measured moisture content	Parts per million
S_o	Solubility of water in mineral oil	Parts per Million
V	Relative ageing rate	
DP_t	Average degree of polymerisation at time *t*.	
DP_0	Average degree of polymerization at start time.	
t	Time	Minutes
x	Oil exponent	
y	Winding exponent	
K_{11}	Constant	
K_{21}	Constant	
K_{22}	Constant	
τ_o	Time constant	
τ_W	Time constant	
A_T	Constant at temperature, moisture and oxygen for specific interval	
A_{RT}	Constant at reference temperature, moisture and oxygen	
E	Activation Energy	kJ Mol^{-1}
R	Ideal gas constant (8.314 J mol^{-1} K^{-1})	J mol^{-1} K^{-1}
T	Hot-spot temperature	°C
RT	Reference temperature	°C

Chapter 1 Introduction

Power transformers form an integral part of present day electrical networks. They allow for power to be transmitted over vast distances while minimising transmission losses and costs (Heathcote, 2007). They are however one of the most expensive assets within the distribution network (Abu-Elanien & Salama, 2010; Brandtzaeg, 2015; Eskom Holdings Ltd and ABB Powertech, 2008). To maximise the return on investment, the transformers should operate, at minimum, for the duration of their designed lifetime. This lifetime is based on the condition of the solid insulation. Furthermore, the ageing of the solid insulation is primarily based on the hot-spot temperature of the transformer (IEC, 2005; IEEE, 2011). The hot-spot temperature of a transformer is dependent on factors such as ambient temperature, design parameters and load factor. Electricity distribution networks are commonly designed with built in redundancy (Felber Engineering GMBH, 2016). This design philosophy caters for contingencies and results in the loading of transformers below their full load capacity (Felber Engineering GMBH, 2016).

The purpose of this chapter is to provide an introduction to power transformers and their ageing mechanisms. This information provides an overview of the current methodologies and assists with the formation of the research problem. The research problem is broken down into the research question and objectives of this study. The design and methodology of this study is explained in addition to providing an overview of the delimitations and limitations which are applicable to this study. The chapter is concluded with an outline of the study.

1.1. Theoretical Background

Electricity forms an integral part of the world we live in. Humans are surrounded by machines which require electricity, from the devices in their pockets to the machines that manufacture them. This increase in electrical machines has increased the need for electrical energy. Many power systems throughout the world operate with centralised power generation; this is when a small number of high capacity power stations supply the electrical power for the entire system (ABB, 2004). This system requires electrical power to be transported over vast distances from the point of generation to the various points of consumption (ABB, 2004). The pioneers of the electrical power systems identified the transformer as being an important component to this type of network.

A transformer allows voltage and current to be altered with a high level of efficiency (Heathcote, 2007). Different levels of voltage and current are preferred depending on the required purpose. Transmission over large distances is more efficient at a higher voltage. The high voltage reduces the current required to transmit a given amount of power. A reduction in current reduces the ohmic losses across power lines. The reduction in losses increases the efficiency of transport power over large distances (Heathcote, 2007). However, these high voltages are not practical for use at the points of consumption. In order for the power to be safely consumed, the voltage is reduced to a manageable voltage for consumption; facilitated by power transformers (Heathcote, 2007).

Transformers are one of the most expensive assets within a power distribution network. Transformer owners are continuously looking to maximise their return on investment. Unplanned replacement of transformers carries a significant cost, not only in terms of financial expense but also in terms of unserved energy and customer satisfaction (Lapworth & Mcgrail, 1998). To reduce a transformer owner's capital cost and maintain ever increasing capacity requirements, transformers are required to operate beyond their designed lifetime (Dominelli et al., 2004). The condition of the transformer should be known in order to successfully operate a transformer throughout its life time. This has resulted in various asset management methodologies applied to transformers. These methodologies are collectively referred to as equipment health indices (Naderian, et al., 1988; Dominelli, et al., 2004; Jahromi, et al., 2009; Gorgan, et al., 2010; Martins, 2014; Brandtzaeg, 2015; ABB, 2015; Waugh & Muir, 2015). These health indices include various parameters to predict the current health of a transformer which enables transformer owners to plan effectively for replacements.

The life of a transformer is directly linked to the condition of the solid insulation within the transformer windings (IEC, 2005; IEEE, 2011). The solid insulation is used to control the electrical field stress and to prevent flashover inside the transformer (Felber Engineering GMBH, 2016). The degradation of solid insulation occurs via three mechanisms; hydrolytic degradation, oxidative degradation and thermal degradation (Schroff & Stannet, 1985). These mechanisms all result in the breakdown of solid insulation over the lifetime of the transformer.

To determine the design life of a transformer, an end-of-life criterion is required. IEEE (2011) suggests four different end-of-life criteria based on solid insulation which can be seen in Table 1-1 below. The design life can vary significantly depending on the criteria for end-of-life which is used. An accepted criterion for end-of-life is a degree of polymerisation value of 200 (IEC, 2005; IEEE, 2011; Emsley & Stevens, 1994; Martin, et al., 2013; Lungaard, et al., 2002).

Criteria	**Hours**	**Years**
50% retained tensile strength	65 000	7.42
25% retained tensile strength	135 000	15.41
200 retained degree of polymerisation in insulation	150 000	17.12
Interpretation of distribution transformer functional life test data	180 000	20.55

Table 1-1: Normal expected life of well dried, oxygen free thermally upgraded insulation at 110°C (IEEE,2011)

There are various methods for calculating this rate of loss-of-life in solid insulation (IEC, 2005; IEEE, 2011; Emsley & Stevens, 1994; Martin, et al., 2013; Lungaard, et al., 2002). These various ageing methods use a variety of parameters to calculate degradation as can be seen in Table 1-2 below.

	Hot-spot temperature	**Moisture in solid insulation**	**Oxygen in insulating oil**
IEC (2005)	YES	NO	NO
IEEE (2011)	YES	NO	NO
Emsley & Steven (1994)	YES	YES	NO
Lungaard, et al. (2002)	YES	YES	NO
Martin, et al. (2013)	YES	YES	YES

Table 1-2: Comparison of parameters included in ageing methods

These ageing methods can be used to determine the loss-of-life of a transformer dependant on its operating history. However, it is unclear as to which method is the most accurate. The accuracy of the ageing methods is important for the effective management of transformers.

The distribution networks with redundancy typically share the total load of a substation across two or more transformers (Eskom Holdings Ltd and ABB Powertech, 2008). Should one of the transformers be out of service (N-1 condition), the remaining transformers are still capable of supplying the full load of the substation (Eskom Holdings Ltd and ABB Powertech, 2008). This results in transformers operating at below full load capacity under normal network conditions (Eskom Holdings Ltd and ABB Powertech, 2008). A lightly loaded transformer can be considered one which operates at below 50% average loading under normal network conditions (Felber Engineering GMBH, 2016). A reduction in load factor results in a reduction of hot-spot temperature below the rated operating hot-spot temperature (IEC, 2005).

The ageing methods in Table 1-2 all use a reference hot-spot temperature of 98°C or 110°C for their calculations (IEC, 2005; IEEE, 2011; Emsley & Stevens, 1994; Martin, et al., 2013; Lungaard, et al., 2002). However, transformers in distribution networks are typically operated well below these reference temperatures. There is a need to identify the most accurate ageing method for these lightly loaded distribution power transformers in order to effectively manage them throughout their lifetime.

1.2. Problem Statement

To reduce a transformer owner's capital and maintenance cost and maintain an ever-increasing capacity, power transformer owners are required to ensure their transformers are in serviceable condition while minimising costs (Dominelli, et al., 2004). There is thus a need to determine the health condition of the transformer in order to achieve maximum reliability and return on investment irrespective of their operating conditions. The ageing models are primarily for transformers which operate close to their full load capacity (Felber Engineering GMBH, 2016).

The problem is that it is not known how accurate the various ageing models are when applied to lightly loaded transformers.

In order to assist asset management techniques, the ageing model's predictions need to be compared against the actual asset ageing. This is especially important in the case of lightly loaded transformers as they operate at temperatures well below the rated standard.

1.3. Research Questions

Based upon background information, the problem is supported by a primary research question:

What ageing model should be used to obtain the most accurate ageing estimation for lightly loaded transformers?

To support the primary question, the following sub-questions require investigation:

A. What is a lightly loaded transformer?
B. What ageing models exist and how do they compare to each other?
C. What is a suitable end-of-life criteria?
D. Which model produces the most accurate ageing estimation?
E. Can the ageing models be modified to improve accuracy?

1.4. Research Objectives

In order to respond to the research questions, the following objectives are formulated:

1. Establish an overview of transformer thermal considerations and modelling.
2. Establish an overview of transformer ageing factors and mechanics.
3. Establish an end-of-life criteria.
4. Compare the various ageing models currently used.
5. Develop a modified ageing model with an improved accuracy.

This study aims to achieve the above-mentioned objectives.

1.5. Research Design and Methodology Overview

The research questions posed are suited to a comparative research method to be followed. The methodology is summarised in Table 1-3. A literature study is presented in chapter 2 which presents information which is relevant to the study. It also presents ageing models which are suitable to be compared with one another. Chapter 3 presents the research design and methodology. In chapter 4 an algorithm is developed in order to execute the selected ageing models on given data provided of real-world transformers. The algorithm is validated throughout its development against dataset provided by IEC (2005). The results of the data processing are used to carry out a comparison using data analysis. Once the comparison has been completed, an optimisation is performed in chapter 5 to modify an ageing model in order to attempt to increase its accuracy. This ensures that the research problem and objectives are satisfied in a systematic manner.

Phase	**Approach**	**Process**	**Method**	**Chapter**
1	Qualitative	Data Collection	Literature Review	2
2	Quantitative	Data Processing	Algorithm Design	4
		Validation	Known Data	4
3	Quantitative	Data Analysis	Comparative Study	4
4	Quantitative	Model Optimisation	Meta-Heuristic Optimisation	5

Table 1-3: Summary of research methodology

1.6. Delimitations and Limitations

Due to the depth in which this subject can be investigated it is important to set the scope of the study to define its focus. This section presents the limitations as well the delimitations of this study. The following boundaries are noted and addressed accordingly:

- The design of power transformers produces a complex multifaceted problem. This study does not aim to investigate nor improve upon transformer design theory. Certain aspects which are applicable to this study are presented from internationally and locally accepted transformer design methodologies. This may be in the form of national, international or company specific standards such as those developed by the International Electrotechnical Commission (IEC), Institute of Electrical and Electronic Engineers (IEEE) and South African National Standards (SANS).
- Actual transformer specifications and operating conditions may vary from their design specifications as a result of manufacturer tolerances; this study will be delimited to include only the design specifications.
- While there may be additional factors which have a practical implication on power transformer ageing rates, this study will be delimited to factors of moisture, oxygen and temperature.
- This study is delimited to power transformers within the distribution environment. These are transformers with a maximum high voltage rating of 132 kilovolts (kV).
- The study is delimited to lightly loaded distribution power transformers. These are transformers with an annual average loading of less than 50% of its designed rating.
- The information used in this study is limited to the data provided by the transformer owner. The data provided is assumed to be a true representation of the transformer.
- The study sample size is limited to the data provided by the transformer owner.
- The study is limited to modelled hot-spot temperature and not actual measured hot-spot temperature. The transformer owner does not record hot-spot temperature of all transformers as the devices used are still of analogue type.
- This study is limited to a fixed ambient temperature. This data point is not currently collected by the transformer owner. The ambient temperature is fixed at a value defined by transformer design specifications. The algorithm is developed to account for a dynamic ambient temperature, but due to lack of data the ambient temperature is fixed.

- The information used to calculate actual loss-of-life is limited to the Furanic oil tests carried out by the transformer owner. While there are more accurate measurements such as physical paper test, it is not possible due to financial and practical constraints for this study.
- The actual loss-of-life calculated from the Furanic oil test is limited to be a linear function of time.
- A limitation of a genetic algorithm is that it may obtain a slightly different result each time it is executed. This can be due parameters such as initial population, fitness limit and time limits.
- The oil sample results' accuracy will be limited to that which is provided by the transformer owner. The study will not investigate the accuracy of the lab which carries out the oil analysis nor the accreditation of the oil sampler.

1.7. Thesis Outline

An overview of the chapters and their relevance is presented in Table 1-4 below.

Chapter	**Objective**	**Question**
Chapter 1: Introduction		A
Chapter 2: Literature Review	1,2	B
Chapter 3: Research design and methodology	3	C
Chapter 4: Data analysis and interpretation	4	D
Chapter 5: Modified ageing model	5	E
Chapter 6: Conclusion		

Table 1-4: Outline of thesis with the relevant objectives and questions.

1.8. Chapter Summary

Chapter 1 provides the background of this study. Based on the background information, a problem statement is developed. To address the problem statement, research questions and sub-questions are consolidated into research objectives. The main objective of this study is to determine the accuracy of ageing models when used for asset management decision making on lightly loaded transformers. To achieve this objective the research design and methodology is presented. The limitations and delimitations are also discussed to assist the research methodology. In line with the thesis outline, the next chapter provides a literature review of transformers and their associated ageing factors.

Chapter 2 Literature Study

2.1. Introduction

This chapter aims to provide the technical fundamentals and technical background into power transformers. This chapter begins by discussing the theoretical fundamentals of power transformer design and the major components which transformers consists of. A general overview is explored as well as the major components which are found in transformers. The various design parameters are discussed as well as the ageing mechanics and the influence of various parameters. These are then expanded upon to explain the loss-of-life and relative ageing rates as well as various end-of-life criteria. The chapter is concluded with an overview of current condition monitoring and asset health appraisal indexing as well as an introduction to meta-heuristics.

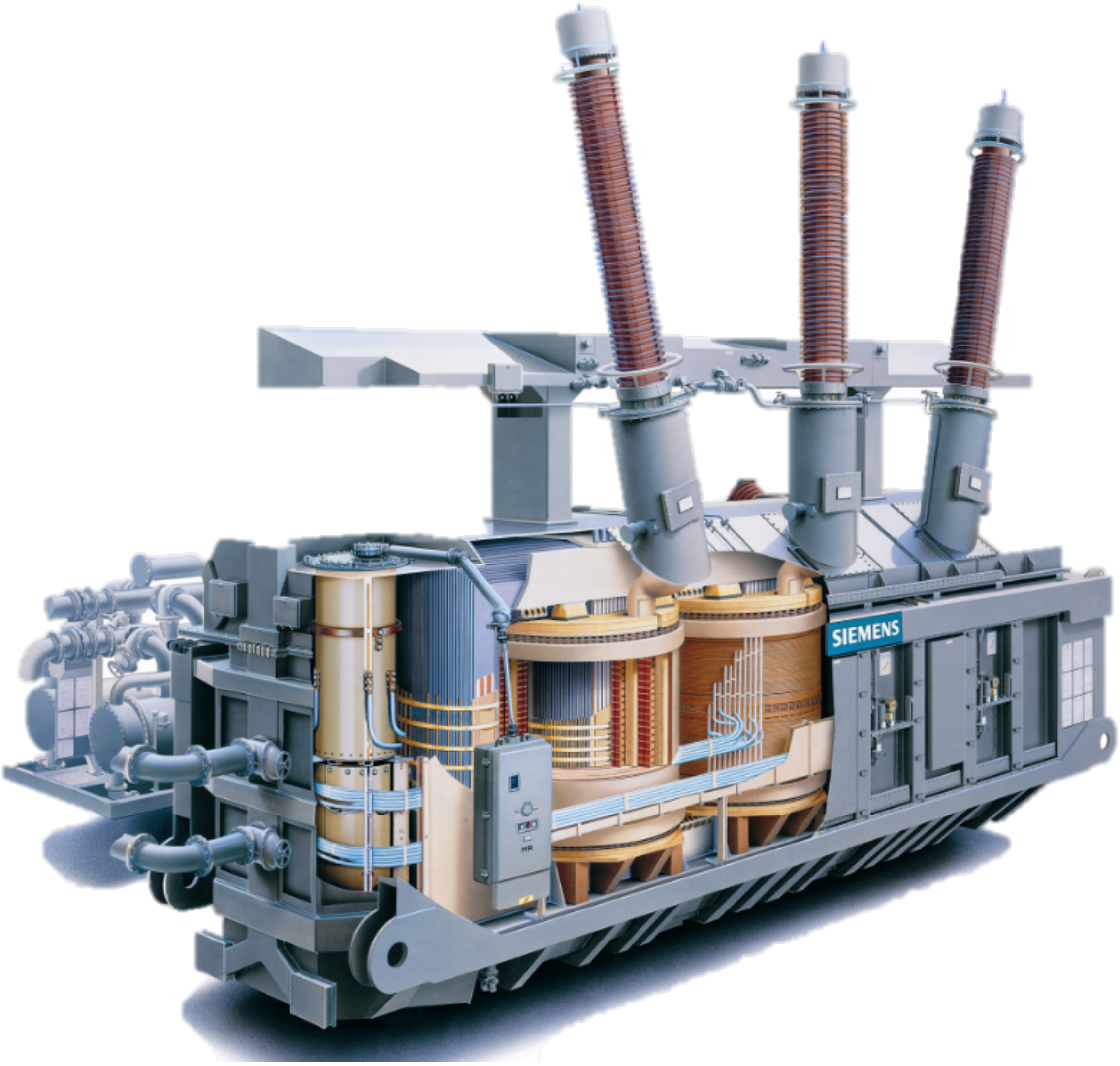

Figure 2-1: Typical power transformer (Adapted from Siemens, 2017)

2.2. Transformer Theoretical Design

Transformers operate on the principle of electromagnetic induction. When an alternating electromotive force is applied to a winding, a current will flow. This alternating current sets up an alternating magnetomotive force and corresponding alternating flux within the core. When a secondary winding is placed within this alternating flux, it results in a corresponding electromotive force being developed in the secondary winding. This electromotive force, if connected to a load will permit current to flow. As current flows in the secondary winding it reduces the total magnetomotive force available. To maintain a balance, the primary current proportionately increases to maintain balance (Heathcote, 2007). As the voltage per turn is constant throughout the windings, a voltage transformation can be created by varying the number of turns on the primary and secondary windings respectively. This relationship for transformers is presented in (2-1) (Sen, 1997):

$$\frac{V_1}{V_2} = \frac{N_1}{N_2} = \frac{I_2}{I_1} \tag{2-1}$$

where

V_1= Voltage across winding 1
V_2= Voltage across winding 2
N_1= Number of turns in winding 1
N_2= Number of turns in winding 2
I_1 = Current in winding 1
I_2 = Current in winding 2

Voltage is stepped up and current is stepped down for the transportation of power over long distances which results in reduced ohmic losses on the power lines (Heathcote, 2007). As the power gets closer to the points of consumption, the voltage is stepped down to levels which can be utilised by the consumer and the current is consequently increased (Heathcote, 2007). The transformer is found throughout power networks and they operate at a high degree of efficiency, with a large majority operating at an efficiency exceeding 90% (Felber Engineering GMBH, 2016).

There are two main types of power transformer designs, namely a *core type* and a *shell type*. In the core type, the windings are wound around two legs of a rectangular magnetic core. Whereas, in the shell type the two windings are wound around the centre of a three-limbed core (Sen, 1997). These two types are illustrated in Figure 2-2. This design requires two main components of a transformer, the first being the core and the second being the winding which is coiled around the core.

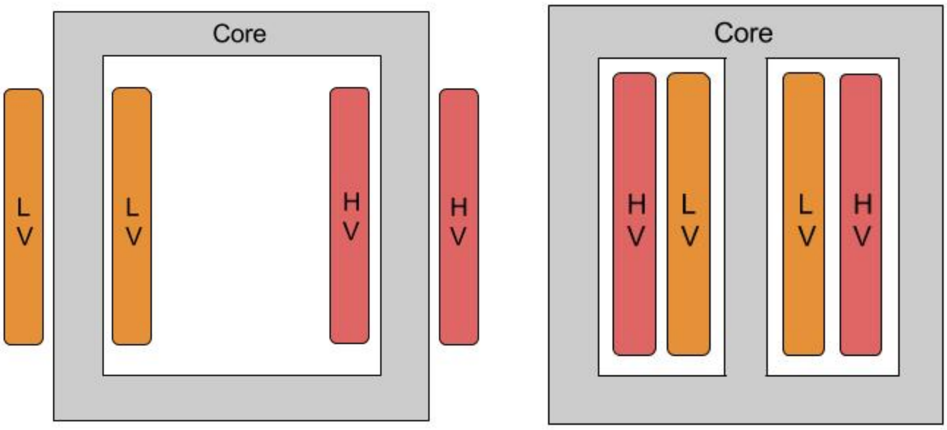

Figure 2-2: Core (left) and Shell type (right) transformer construction

2.3. Transformer Core

The main purpose of the core of a transformer is to provide a low reluctance path in which the magnetic flux can travel between the windings (Heathcote, 2007). There are two main losses which occur in the magnetic core; namely hysteresis and eddy current losses; both of which result in the heating of the core (Sen, 1997). Eddy current losses are related to the frequency at which the unit is operated at and is also directly related to the thickness of the material (Heathcote, 2007). To reduce these losses the majority of power transformer cores are composed of multiple layered stacks of thin laminations (Felber Engineering GMBH, 2016). Another method for reducing core losses is related to the quality and properties of the material. Recent developments in materials employ cold rolled grain orientated material which has fractional losses when compared to the older hot rolled steel (Felber Engineering GMBH, 2016). These losses are known as no-load losses, and are present whenever a voltage is applied across the transformer (Heathcote, 2007).

The flux linkage between the primary and secondary windings through the core is not perfect, which results in a portion of flux becoming stray flux (Heathcote, 2007). This leakage flux is dependent on the physical dimensions of the core (Felber Engineering GMBH, 2016). The leakage flux is used in determining the impedance of the transformer. The impedance of a transformer can be defined as the ratio between stray flux and core flux (2-2). This impedance value is important for the design and operation of a transformer as it can be used to determine the short circuit current which can be expected (Felber Engineering GMBH, 2016).

$$Z(impedance) = \frac{\emptyset stray}{\emptyset core} \tag{2-2}$$

The dimensions of the core influence the stray flux and consequently, the impedance of the transformer. These dimensions are calculated during the design phase to meet the specified impedance requirements. The impedance is specified before the design phase by the end user to align it with the network configuration to which it will be installed.

For transformers to operate, it requires a path for the current to flow through around the core. This is required to setup the flux required for operation; which is achieved in the other major transformer component, namely the transformer windings.

2.4. Transformer Windings

Transformer windings are placed concentrically around the core. These windings provide a path for the alternating current to flow and set up the magnetic flux required for operation. As transformers operate at high voltages, insulation is required in order to ensure that the current flows on the intended path and does not flow to earth via an unintended path (Heathcote, 2007). The insulation around the winding conductors commonly used in power transformers is cellulose paper impregnated with insulating oil (Heathcote, 2007)

The cellulose paper used is commonly referred to as Kraft paper (Lundgaard, et al., 2002). It consists of linear chains of D-glucopyranosyl, multiple of these chains consists of a single cellulose fibre (Shroff & Stannett, 1985). The number of D-glucopyranosyl per chain is referred to the degree of polymerisation (DP) (Lundgaard, et al., 2002). This degree of polymerisation is directly correlated to the mechanical strength which the paper exhibits (Shroff & Stannett, 1985). This cellulose paper is wrapped around the conductors used in the windings, often requiring multiple turns per conductor. This results in a complicated winding arrangement of the cellulose covered conductor. Consequently, the replacement of the paper is a costly activity if such maintenance is required during the lifetime of a power transformer (Nynas, 2013; Meyers, et al., 1981).

The windings are commonly manufactured from copper or aluminium, where copper is still the preferred material for use in high power application due to its increased electrical conductivity over aluminium (Heathcote, 2007). When current is flowing through a conductor there are resultant ohmic losses which are present. These losses are proportional to the load current flowing and are aptly named load losses. These losses manifest as heat within the transformer (Felber Engineering GMBH, 2016).

The primary purpose of the insulation around the conductor is to provide a high dielectric strength with the assistance of the insulating oil (Heathcote, 2007). The solid insulation also provides mechanical strength to the transformer windings. This strength is required for the transformer to withstand short circuit events. The magnitude of short circuit current is related to the impedance of a transformer. These short circuit events bring about a large mechanical force because of the increased magnetic field strength during these events (Felber Engineering GMBH, 2016). As the insulation degrades, the degree of polymerisation and mechanical strength of the paper is reduced.

Under short circuit events, the winding is exposed to a large mechanical force in both axial and radial directions. In order to endure these events, the mechanical strength of the paper is required in conjunction with the copper. Should the mechanical strength of the paper be insufficient, a winding shift may take place. This shift may result in the transformer becoming inoperable (Nynas, 2013; Meyers, et al., 1981). The overall insulation system is commonly a two-part system, the first being the solid insulation which comprises of the cellulose paper and the second being the insulating oil. The insulating oil is integral to the insulation but also plays a vital role as a heat transfer fluid within the transformer.

2.5. Insulating Oil

Insulating oil is commonly used in power transformers (Nynas, 2013). The transformer core and windings may be submerged in insulating oil depending on their specific design and construction. The insulating oil has an important role during the lifetime of the transformer as it forms part of the dielectric insulation in conjunction with the cellulose paper. It is also used as a heat transfer medium within the transformer to remove internally generated heat from the transformer losses (Heathcote, 2007).

For the insulating oil to be an effective electrical insulator it needs to be able to withstand electric stress. Insulating oil can withstand electrical stresses in excess of 50 kilovolt (kV) across a 2.5 mm gap. Cellulose paper impregnated with insulating oil is able to exceed this electrical stress (Eskom, 2014). The dielectric strength of the oil is important during the life of a transformer as it forms an overall insulation system.

The main factors which affect the dielectric strength of insulating oil are the moisture content and the particle count (Eskom, 2014). The moisture content and dielectric strength follow an inverse relationship. As the moisture level in the oil increases, the dielectric strength decreases (Nynas, 2013). The particle count follows an inverse relationship. As the particle count increases, the dielectric strength decreases (Eskom, 2014).

There are different types of insulating oil which are suitable for transformers. These include the following types of oil.

- Mineral Oil
- Synthetic Ester Oil
- Natural Ester Oil
- Silicon Oil

The specific requirement of a transformer will influence the oil to be used. Mineral oil is the most commonly used oil (Nynas, 2013; Eskom Holdings Ltd and ABB Powertech, 2008). There are designs which require the use of a different type of oil depending on the specific design and application of the given transformer.

Insulating oil is also used to monitor the condition of a transformer during its life time (Martins, 2014). Oil sampling can be used to monitor the state of the power transformer as well as give an indication of the condition of the solid insulation and the insulating oil (Nynas, 2013; Eskom, 2014). Dissolved Gas Analysis (DGA) is used to identify thermal and electrical faults within the transformer by monitoring the concentration and generation rates of the specific gases dissolved in the insulating oil (ABB Transformer Handbook, 2004; Eskom Holdings Ltd and ABB Powertech, 2008; Nynas 2013; Duval & Lamarre, 2014; IEC, 2015). This analysis can be used to identify if a transformer is operating within its normal limits or if an internal fault may be present. The following gases are used for interpretation during DGA:

- Hydrogen (H_2)
- Carbon Dioxide (CO_2)
- Carbon Monoxide (CO)
- Methane (CH_4)
- Ethane (C_2H_6)
- Ethylene (C_2H_4)
- Acetylene (C_2H_2)

These gases can be interpreted using several methods. The commonly used methods include the Duval Triangle, Duval Pentagon, Rogers Ratio and Doernenburg Ratio (ABB Transformer Handbook, 2004; Eskom Holdings Ltd and ABB Powertech, 2008; Nynas 2013; Duval & Lamarre, 2014; IEC, 2015). These methods all utilised a combination of ratios of the gases to identify specific fault types. These fault types are commonly categorised into one of the following.

- Low temperature thermal fault
- High temperature thermal fault
- Overheating oil
- Arcing
- Cellulose fault

In addition to DGA, Furanic analysis is another test which is carried out in order to predict the degree of polymerisation of the paper insulation within a transformer (Eskom Holdings Ltd and ABB Powertech, 2008). During the breakdown of paper insulation Furans are released into the oil (Gray, 2017.; Mtetwa, 2011). The degree of polymerisation of the paper insulation can be calculated by determining the quantity and type of Furans present in the oil (Eskom Holdings Ltd and ABB Powertech, 2008). The following furan compounds are commonly detected:

- 5-Hydroxymethyl-2-furfural (HMF)
- Furfuryl alcohol (FOL)
- 2-Furfural (FAL)
- Acetyl furan (AF)
- 5-Methyl-2furfural (MF)

The 2-Furfural compound is commonly used to calculate the degree of polymerisation from the sample (Eskom Holdings Ltd and ABB Powertech, 2008; Mtetwa, 2011; Gray, 2017.). The result calculated is the average decomposition of the paper. However, there may however be specific locations which operate under increased temperature, moisture or oxygen and may exhibit increased decomposition (Eskom Holdings Ltd and ABB Powertech, 2008). Furanic analysis is a preferred method in determining the condition of the paper insulation as the required oil sample can be taken with the transformer still being in service (Eskom Holdings Ltd and ABB Powertech, 2008; Mtetwa, 2011; Nynas, 2013; Gray, 2017.;). Furanic oil samples do however come at a financial cost (Eskom Holdings Ltd and ABB Powertech, 2008). In distribution networks with a large amount of transformer this requires a substantial financial budget to be available. An alternative method is to take direct sample of the cellulose paper. While direct paper sampling is more accurate it is more expensive as it requires a more complex process to sample since intrusive maintenance is required (Mtetwa, 2011).

Insulating oil also has needs to have good thermal conductivity properties. While a transformer is in operation it generates heat from the load and no-load losses. This heat needs to be removed away from the core and windings to maintain the designed temperature rise (IEC, 2000). The insulating oil provides this heat transfer medium and is able remove the heat effectively (Nynas, 2013).

As the insulating oil heats up, the volume of the oil increases (Felber Engineering GMBH, 2016) The oil also decreases in volume when the temperature decreases. This results in an oil level which can vary depending on the operating temperature. The expansion and contraction results in transformer "breathing" during operation. When the oil expands air is expelled from the conservator, and when the oil contracts air is pulled into the conservator (Felber Engineering GMBH, 2016). This phenomenon is a possible source of both moisture and oxygen into a transformer (Eskom Holdings Ltd and ABB Powertech, 2008).

For the insulating oil to operate successfully as a heat transfer medium, it requires a cooling system design. Power transformers have various configurations of cooling systems as will be discussed in the following section.

2.6. Cooling system

All transformers operate with losses which manifest as heat. To remove the heat from the transformer, a cooling system is required to allow the transformer to operate at full load while maintaining the temperature as the designed level (Eskom Holdings Ltd and ABB Powertech, 2008). Various cooling methods are available and are selected based on the design characteristics of the transformer. These methods can be identified by a four-letter code as described below (IEC, 2000) and followed by examples in Figure 2-3, Figure 2-4 and Figure 2-5.

First Letter: Internal cooling medium in contact with the windings:

O	mineral oil or synthetic insulating liquid with fire point ≤ 300°C
K	insulating liquid with fire point > 300°C
L	insulating liquid with no measurable fire point

Second Letter: Circulating mechanism for internal cooling medium:

N	natural thermo-siphon flow through cooling equipment and windings.
F	forced circulation through the cooling equipment, thermo-siphon flow in windings.
D	forced circulation through the cooling equipment, directed from the cooling equipment into at least the main windings.

Third Letter: External Cooling Medium

A	Air
W	Water

Fourth Letter: Circulation method for the external cooling medium

N	Natural convection
F	Forced circulation (fans, pumps)

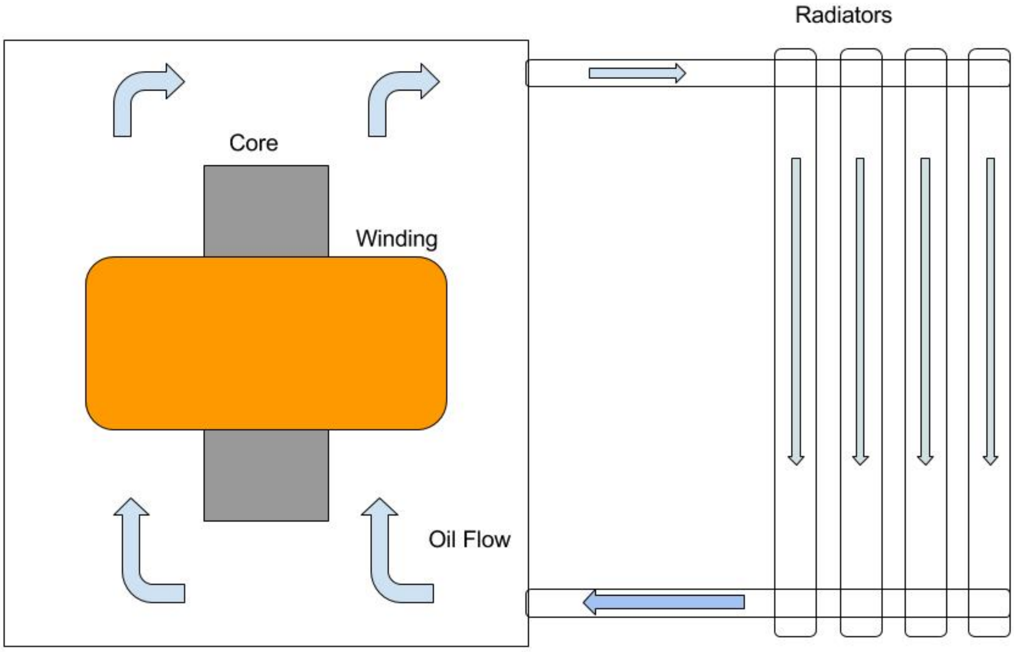

Figure 2-3: ONAN transformer cooling

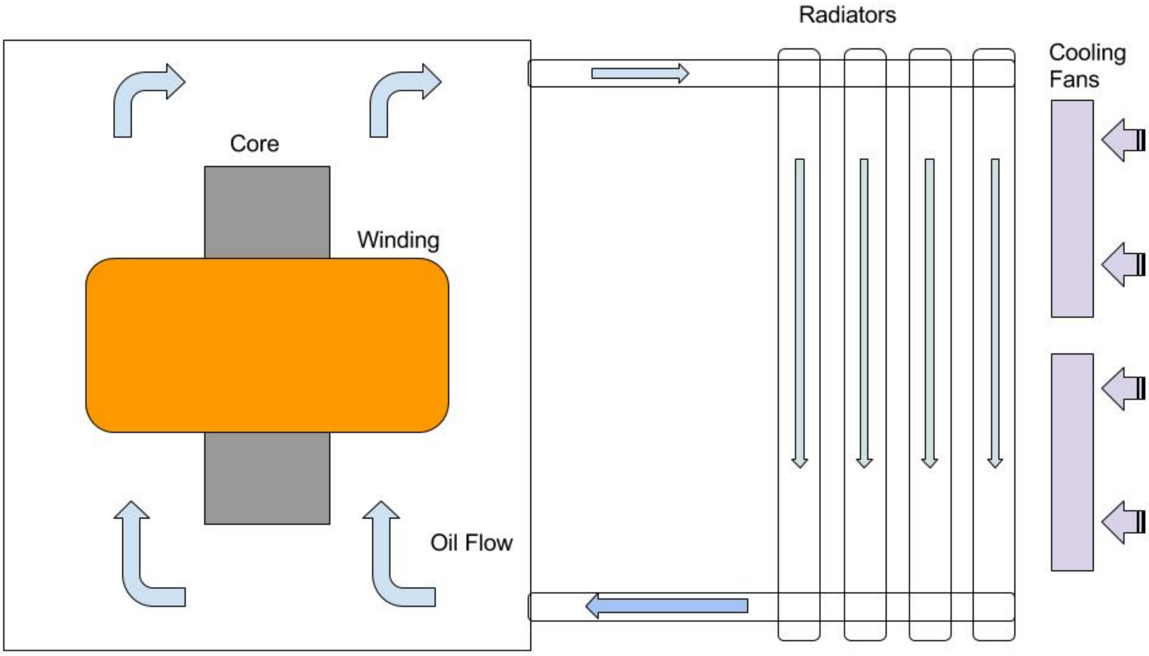

Figure 2-4: ONAF transformer cooling

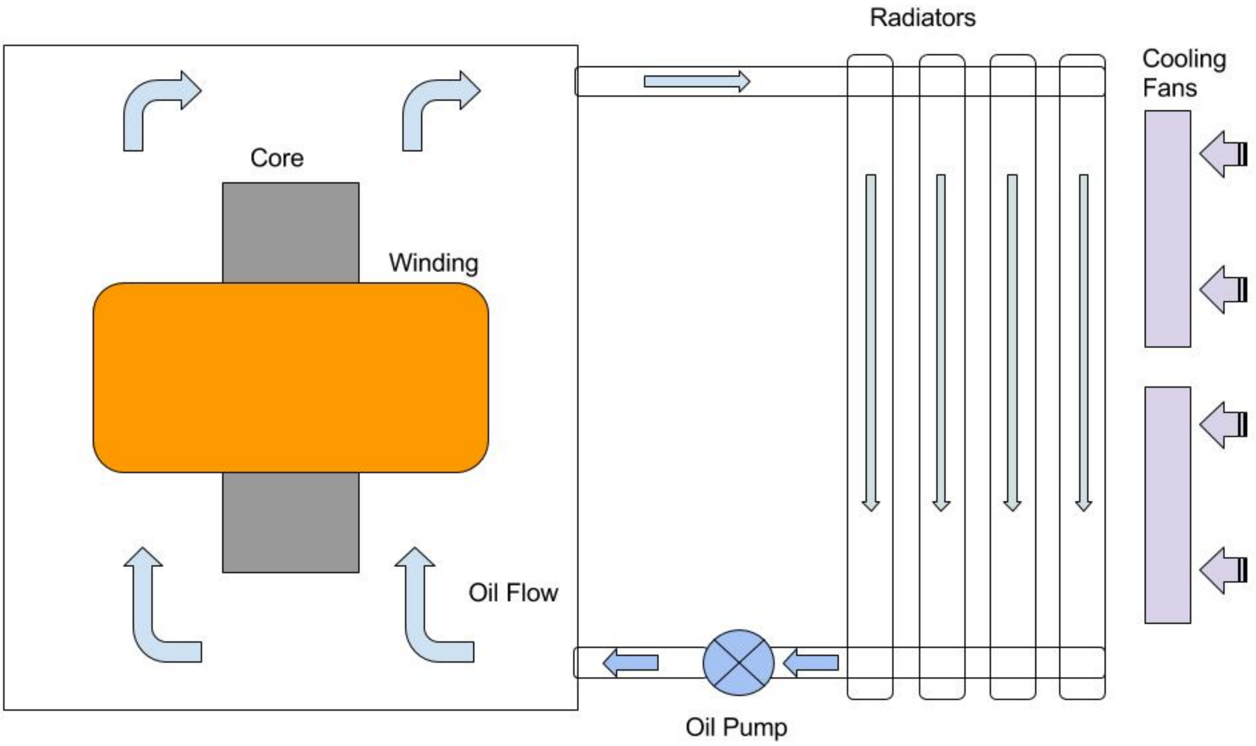

Figure 2-5: OFAF transformer cooling

The oil directed cooling method allows for approximately double the losses to be dissipated when compared to the oil natural method, this is due to the increased oil volume flow (Felber Engineering GMBH, 2016). On small power transformers the ONAN (Oil Natural, Air Natural) is commonly employed, while the medium and large power transformers employ ONAF (Oil Natural, Air Forced), OFAF (Oil Force, Air Forced) or ODAF (Oil Directed, Air Forced) cooling methods (Eskom Holdings Ltd and ABB Powertech, 2008). The use of OFAF and ODAF reduces the overall cooling surface area required, but also necessitates auxiliary equipment such as oil pumps and fans (Eskom Holdings Ltd and ABB Powertech, 2008).

The transformer cooling system design is based on the thermal gradients and specific losses for a given transformer (Felber Engineering GMBH, 2016). The thermal design allows for a specified hot-spot temperature rise above ambient (IEC, 2005). The typical temperature rise found within a transformer is shown in Figure 2-6.

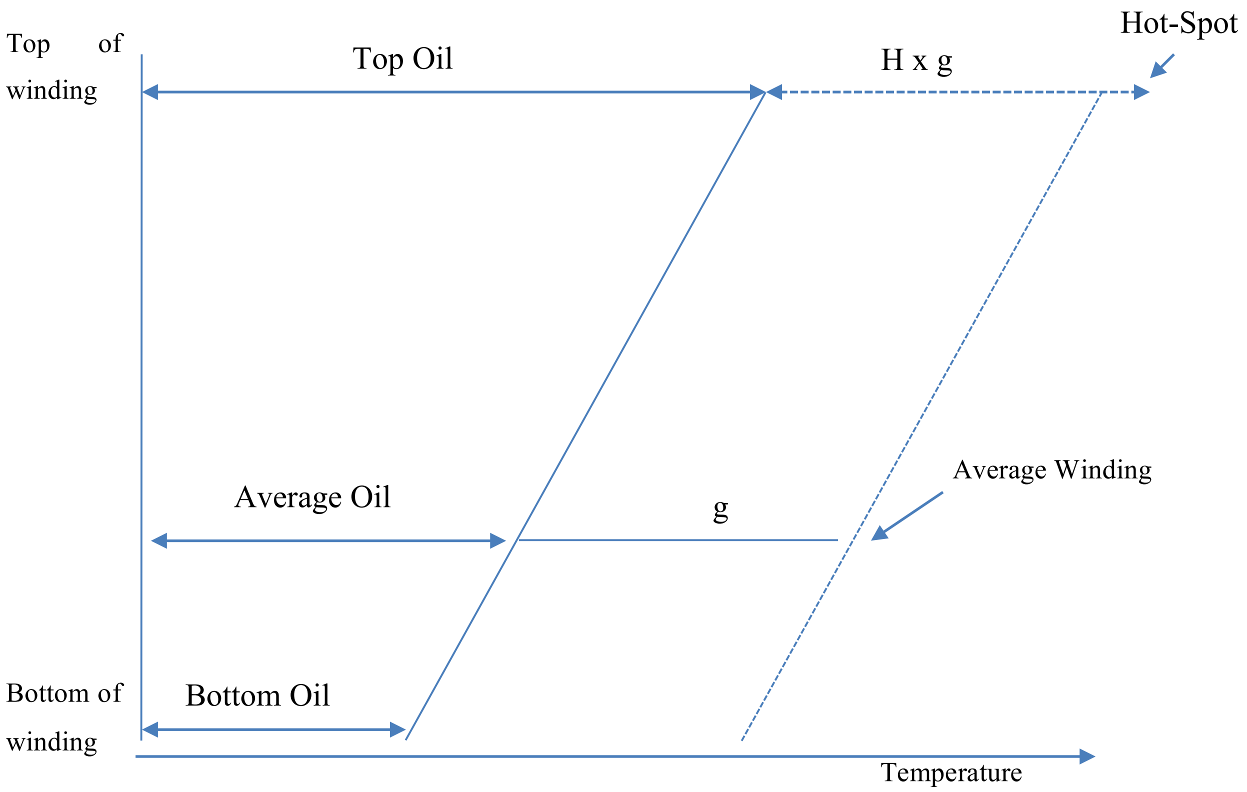

Figure 2-6: A typical thermal design characteristic of a power transformer

where:
g = average winding to average oil gradient at rated current
H = hotspot factor

Figure 2-6 is used during the design process of a power transformer. The limitations of hot-spot temperature affect the other allowable temperature rises (Felber Engineering GMBH, 2016). During operation only the oil at the top and bottom is available to be directly measured. The hot-spot temperature is not easily measurable, but fibre optic technology has allowed for this measurement to be accessible on the new transformer designs (Eskom Holdings Ltd and ABB Powertech, 2008). The historical method of determining hot-spot temperature was to measure the top-oil temperature directly and then add additional heat by means of a current transformer and heater. The current transformer would determine the load current and heat up the oil in proportion to the hot-spot factor H (Comem, 2017).

When a transformer undergoes a step change in loading, there is initially a lag between the measured oil temperature and the actual oil temperature and consequently the hot-spot temperature. This is because of the oil taking time to alter its flow rate based on the new operating temperature (Zhou, et al., 2007). This lag is quantified in IEC (2005) as a function between hot-spot temperature (θ_h) and top-oil temperature (θ_o) at various step load levels (K). This function exhibits set-point overshoot which can be seen in Figure 2-7 for different cooling methods. This overshoot does not represent the hot-spot in relation to its settling point, but instead illustrates the time delay and underestimation which top-oil exhibits in comparison to hot-spot temperature (Nordman, et al., 2003).

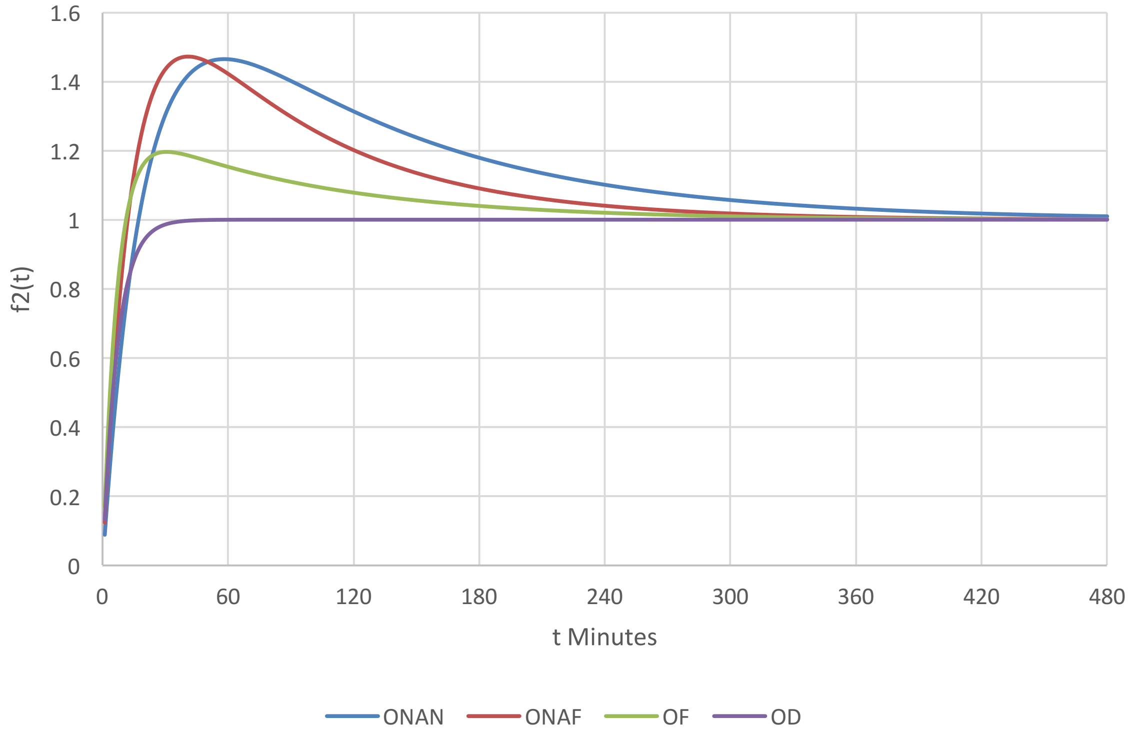

Figure 2-7: Graphical display of set-point overshoot for different transformer cooling methods which occurs between hot-spot and top-oil during a load step change adapted from IEC (2005).

The importance of the cooling system is due to the influence which temperature has on the ageing rate of a transformer cellulose insulation. The ageing factors are discussed in the next section and the importance of operating temperature are explored.

2.7. Ageing Mechanics

The ageing of a transformer is linked to the degradation of the insulation (Meyers, et al., 1981; IEC, 2005; IEEE, 2011). It is important to understand the various factors which affect insulation breakdown. In this section these factors, as well as the mechanics of how the breakdown occurs are explained.

Solid insulation degradation is one of the main factors in transformer ageing (Meyers, et al., 1981; IEC, 2005; IEEE, 2011). This degradation affects the mechanical strength of the solid insulation which can be correlated to the degree of polymerisation of the insulation system (Eskom Holdings Ltd and ABB Powertech, 2008). The life of a power transformer is linked to the condition of the solid insulation as it is not feasible to replace the solid insulation (Meyers, et al., 1981). There are three main mechanisms of degradation which can take place (Shroff & Stannett, 1985), all of which affect the solid insulation. The main mechanisms of solid insulation degradation are:

- Hydrolytic degradation
- Oxidative degradation
- Thermal degradation

These mechanisms all breakdown the chains of cellulose in the insulation. The breakdown of these chains reduces the overall mechanical strength of the paper, which is an irreversible process (Meyers, et al., 1981).

2.7.1. Hydrolytic Degradation

Hydrolytic degradation takes places when there is moisture in the cellulose. Moisture is always found within a power transformer, with majority occurring in the cellulose insulation as opposed to the insulating oil (Griffin, 1996). This occurs since cellulose is hygroscopic, and thus attracts and retains moisture more readily than insulating oil (Meyers, et al., 1981). Insulating oil holds a fraction of the total moisture in a transformer. The moisture within a transformer moves between the solid insulation and the insulating oil via temperature dependant relationship (Griffin, 1996). As the average oil temperature increases, the insulating oil is able to absorb more moisture from the cellulose insulation. As the average oil temperature decreases, the oil returns to the solid insulation. The quantity of water which can be absorbed by the insulating oil is defined as the solubility of water in oil and is dependent on temperature. The solubility of water in oil is governed by equation (2-3) (Griffin, et al., 2008) (Lewand, 2002).

$$\log_{10} S_0 = \frac{-1567}{T} + 7.085 \tag{2-3}$$

Where
S_o = Solubility of water in mineral oil (parts per million = ppm)
T = Absolute temperature in Kelvin

The moisture value in oil can also be expressed as a percentage of the solubility at a given temperature, this percentage is commonly referred to as the relative saturation of water in the insulating oil (Lewand, 2002):

$$RS = \frac{W_c}{S_o} \tag{2-4}$$

Where
RS = Relative Saturation (%)
W_c= Measured moisture content (ppm)
S_o = Solubility of water in mineral oil (ppm)

Equations (2-3) and (2-4) are therefore indicative of the constant movement of moisture between cellulose insulation and the insulating oil which is dependent on temperature (Griffin, 1996). Under stable temperature conditions, an equilibrium will be reached where the quantity of moisture in the oil is constant. It is possible, under these stable equilibrium conditions to estimate the moisture content in the cellulose insulation based on the moisture content in the oil by utilising equilibrium charts such as the Oomen curve (Oomen, 1983), the Fabre-Pichon curves (Fabre & Pichon, 1960) and those curves attributed to Norris (1963). This allows for an estimation of moisture in solid insulation to be calculated without taking a physical cellulose sample. Cellulose sampling is complex and requires the transformer to be removed from service (Eskom Holdings Ltd and ABB Powertech, 2008).

The level of moisture determines the rate at which the degradation occurs. Increased moisture levels result in an increased rate of degradation (Meyers, et al, 1981; Griffin, 1996; Schroff & Stannet, 1985). It is impossible to have a transformer with zero moisture, since the main sources of moisture are residual moisture from manufacturing, moisture from the atmosphere and by-products from insulation degradation (Meyers, et al, 1981; Griffin, et al, 2008).

2.7.2. Oxidative Degradation

Oxidation occurs in the presence of oxygen and is primarily associated with the breakdown of insulating oil but also occurs in cellulose (Meyers, et al., 1981; Shroff & Stannett, 1985). Oxidation of the cellulose breaks down the cellulose rings reducing the degree of polymerisation (Shroff & Stannett, 1985). Oxidation of the insulating oil gives rise to the creation of sludge and increased acidity level of the oil within the transformer (Eskom Holdings Ltd and ABB Powertech, 2008). Sludge settles on the transformer windings and create a blanket effect as it limits the thermal transfer of heat between the conductor and the insulating oil. This effect increases the average temperature which the solid insulation is exposed to (Eskom Holdings Ltd and ABB Powertech, 2008).

To reduce oxidation, manufacturers employ various methodologies to limit the ingress of oxygen into the transformer. One of these methods entail the use of a rubber bladder. This rubber bag prevents air from coming into direct contact with the insulating oil, while still allowing for the expansion and contraction of the oil under various thermal loads (Eskom Holdings Ltd and ABB Powertech, 2008). Small distribution pole mount and ground mount transformers are fully sealed units which are not open to the atmosphere, which also limits the oxygen intake (Felber Engineering GMBH, 2016).

2.7.3. Thermal Degradation

Thermal degradation occurs in the presence of heat. All the losses (no-load losses, load losses and stray losses) which occur within a transformer result in heat being generated within the unit. The transformers' cooling system is designed to ensure that this heat is effectively dissipated. Cellulose is sensitive to thermal degradation, and this is the key parameter used when determining the loss-of-life of a power transformer (Shroff & Stannet, 1985; IEC, 2005; Heathcote, 2007; Meyers, et al., 1981; Eskom Holdings and ABB Powertech, 2008). The expected life of wood pulp, from which cellulose is derived can be seen in Table 2-1.

Paper Type	**Temperature ℃**	**Life – Dry and free from air (Years)**
Wood Pulp	80	118
	90	38
	98	15

Table 2-1: Life of dry and air free paper under various temperatures (Adopted from IEC (2005)

Managing the operating temperature of a transformer is one of the fundamental methods of extending its lifespan (Eskom Holdings Ltd and ABB Powertech, 2008; Felber Engineering GMBH, 2016). The hot-spot operating temperature of a transformer the main parameter used to calculate the loss-of-life of a transformer; this is expanded upon in the following section.

2.8. Transformer Ageing Models

There are various ageing models available for transformers. Some use a single parameter, while others use multiple parameters. There are transformer ageing models specified in IEC (2005) and IEEE (2011). The South African National Standard for transformer loading adopts the models specified in IEC (2005). These models are based on a single parameter only - hot-spot temperature. These models according to IEC (2005) and IEEE (2011) are presented in (2-5) to (2-8). These models provide a relative ageing rate. Relative ageing rate is an equivalent ageing rate when a transformer is operated at a temperature other that rated. The relative ageing rates are given as follows:

IEC non-thermally upgraded insulation – Unity relative ageing is achieved at 98°C

$$V = 2^{(\theta_h - 98)/6} \tag{2-5}$$

where
V = Relative ageing rate
θ_h= Hot-spot temperature in transformer

IEC thermally upgraded insulation – Unity relative ageing rate achieved at 110°C

$$V = e^{\left(\frac{15\,000}{110+273} - \frac{15\,000}{\theta_h+273}\right)} \tag{2-6}$$

where
V = Relative ageing rate
θ_h= Hot-spot temperature in transformer

IEEE non-thermally upgraded insulation – Unity relative ageing rate is achieved at 95°C

$$V = e^{\left(\frac{15\,000}{368} - \frac{15\,000}{\theta_h+273}\right)} \tag{2-7}$$

where
V = Relative ageing rate
θ_h= Hot-spot temperature in transformer

IEEE thermally upgraded insulation – Unity relative ageing rate is achieved at 110°C

$$V = e^{\left(\frac{15\,000}{383} - \frac{15\,000}{\theta_h+273}\right)} \tag{2-8}$$

where
V = Relative ageing rate
θ_h= Hot-spot temperature in transformer

The IEC (2005) and IEEE (2011) relative ageing rates for thermally upgraded insulation are identical, whereas the ageing rate for the non-thermally upgraded insulation is not. The variation between non-thermally upgraded paper from IEC (2005) and IEEE (2011) is due to the reference temperature used in each case. Figure 2-8 illustrates the relative ageing rate.

Another approach to model transformer ageing is by the use of a kinetic equation. The kinetic equation has the Arrhenius form as shown in (2-9). The constant A is a pre-exponential constant. The activation energy is the minimum energy which is required to start the reaction (Martin, et al., 2015). The equation requires temperature to be in Kelvin, a conversion from Celsius to Kelvin is included. R is the ideal gas constant. This equation has been used by several authors who have conducted work with transformer ageing (Emsley & Stevens, 1994; Lundgaard, et al., 2002; Martin, et al., 2015; Martin, et al., 2013; Mtetwa, 2011). Each of the authors however specify different pre-exponent values based on their respective experiments.

$$A \, . \, e^{\frac{-E}{R(T+273)}} \tag{2-9}$$

where
A = Constant determined by experiment
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Temperature (Celsius)

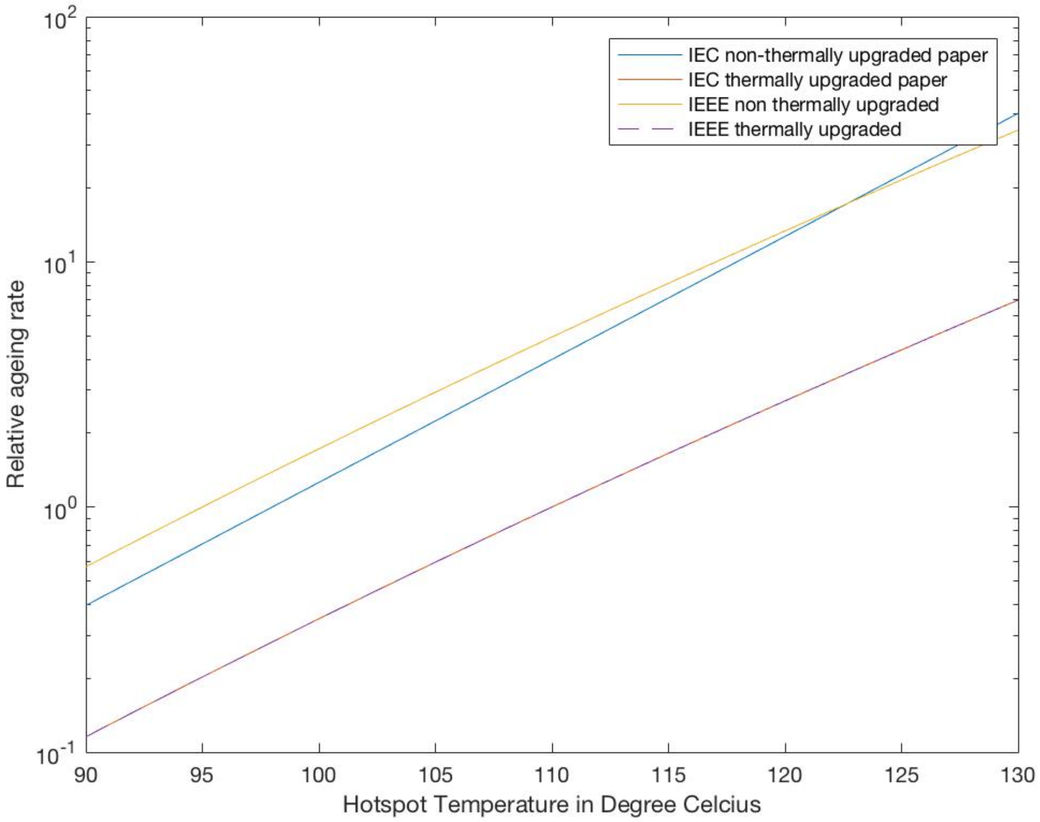

Figure 2-8: Comparison of IEC (2005) and IEEE (2011) relative ageing rates. The thermally upgraded paper equations are identical for IEC and IEEE and.

The various authors each have different values which they use for the constant *A* and the activation energy. The constant *A* is also used to account for additional ageing factors such as moisture and oxygen. This is seen in the work of Martin (2015), Emsley (1994) and Lundgaard (2002). Each author derived their constant *A* based on their individual lab test results thus there are variations between the various authors.

2.9. End-of-Life

The end-of-life of an asset can be viewed from three different perspectives namely, economic, technological and physical (Elanien, 2011). The economic end-of-life refers to the point at which an asset has been fully depreciated. While it may not have a book value, the asset may still be operational. The technological end-of-life refers to the point at which spares are no longer available and retrofits or upgrades are required to extend life, while the asset may still be operational at this point it may require additional investment. The physical end-of-life refers to the point at which the asset is no longer capable of performing its required function (Abu-Elanien & Salama, 2010).

Literature provides various perspectives about the specific physical end-of-life criteria of transformers. Several authors are in agreement that the end-of-life is linked to the condition of the solid insulation (Meyers, et al., 1981; Geldenhuis, 2005; Lundgaard, et al., 2002; Gray, 2017; IEEE, 2011; IEC, 2005; Nynas, 2013). The specific degree of polymerisation for end-of-life condition is however variable. While Gray (2017) uses a degree of polymerisation of 250, Lundgaard, et al.(2002), Geldenhuis (2005), Martin, et al (2015) and Nynas (2013) uses 200 as indicator of end-of-life. IEEE (2011) and IEC (2005) both propose four different end-of-life criteria linked to the degree of polymerisation but does not specify a preferred value. These values are not a definitive end-of-life criterion. Depending on the environment in which a transformer is installed, it may operate for several months with a degree of polymerisation below 200 (Geldenhuis, 2005). IEEE (2011) and IEC (2005) states an expected lifespan of 180 000 hours, which is based on the interpretation of functional test data of transformers.

Literature further reports cases where age limits have been extended well beyond the norm. Figueroa (2009) and Jarman, et al. (2009) report of power transformer operating at 50 years and 70 years, respectively. This is indicative of variation in power transformer ageing, which is dependent on the external operating conditions of the respective transformers.

2.10. Equipment Health Index

The maintenance of power transformers in general has become increasingly important during recent years (Bartley, 2002; Dominelli, et al., 2004). This has been encouraged by the reduction in operating capital and maintenance budgets while the capacity of the networks has increased (Bartley, 2002). Transformers are required to work harder and longer than their initial designs (Dominelli, et al., 2004). This has resulted in various management related measurements being developed in order to determine the health of a power transformer. These can be collectively referred to as transformer health indices (Brandtzaeg, 2015; ABB, 2015; Dominelli, et al., 2004; Jahromi, et al., 2009; Gorgan, et al., 2010; Naderian, et al., 1988; Waugh & Muir, 2015; Augusta Martins, 2014).

These health indices consist of various aspects of the equipment which can be monitored during its life. Thereafter, this information is then collated via algorithms or experts to produce a health rating for each piece of equipment. The general approach of these health indices is to allocate weightings to each aspect, with each aspect being given a rating. The weighted average is calculated to produce a final health index score (Gorgan, et al., 2010; Martins, 2014; Brandtzaeg, 2015; Naderian, et al., 1988; Dominelli, et al., 2004; Jahromi, et al., 2009). The generic format of a health index is given in (2-10).

$$Health\ Index = \frac{\sum_{i=1}^{n} S_i \times W_i}{\sum_{i=1}^{n} W_i} \qquad (2\text{-}10)$$

Where

n = Total number of aspect assessed
S = Individual aspect (*i*) rating
W = Weighting of specific aspect (*i*)

Each health index attributes different weightings to each aspect. These weightings are proprietary and thus not published, especially those of private companies who offer condition monitoring maintenance as a service (ABB, 2015; Dominelli, et al., 2004). Important factors which are taken into account for health indices include (Naderian, et al., 1988; Dominelli, et al., 2004; Jahromi, et al., 2009):

- Dissolved gas analysis
- Electrical test results – tan-delta, insulation resistance, excitation current, winding ratio
- Infrared thermography
- Visual inspections
- Tap changer test and inspections
- Oil quality test – interfacial tension, Furanic, moisture content, dielectric strength
- Degree of polymerisation of paper
- Moisture content of paper
- Load history

Health indices attempt to quantify the condition of power transformers. This is used by transformer owners to focus maintenance, refurbishment and renewal efforts in the most effective manner (Gorgan, et al., 2010; Martins, 2014; Brandtzaeg, 2015; Naderian, et al., 1988; Dominelli, et al., 2004; Jahromi, et al., 2009). The health index is useful to identify units which are high risk to ensure that effective plans are in place to reduce or prevent the cost of transformer failure. In order to use these ageing models and health indices, a decision-making process is required. This is presented in the next section.

2.11. Decision Making

Decisions are made by scientist, managers and engineers throughout the world on a daily basis. The world has grown in complexity in recent times. This has made decision making a bigger challenge than before. In order to ensure a correct decision is made, the decision-making process should be carried out in a logical, rational and optimal manner (Talbi, 2009). Decision making consist of four main steps. These are (Talbi, 2009):

1. Formulation of the problem
2. Modelling of the problem
3. Optimisation of the problem
4. Implementation of the solution

Formulation of the problem is the first step. The problem is identified and an initial formulation of the problem is determined. The formulation will take into account internal and external factors and an outline of the objective is determined. The formulation identifies possible input and output variables (Talbi, 2009).

The second step is to model the problem. This may take the form of a mathematical model or a black-box model. A black box model is one where no analytical formulation exists (Talbi, 2009). A black box model returns a given value *f(x)* for each *x*-value passed to it as can be seen in Figure 2-9. The model or algorithm within the black box is unknown.

Figure 2-9: Representation of a black box problem

The third step is to optimise the problem. Optimisation is related to the selection of input variables which produce the top performing solution (Washington University, 2017) . The selection of the top performing solution can be done through the use of a cost function.

The final step of decision making is the implementation of the selected solution. This is done in order to test the practicality of the solution and to identify if it is an acceptable solution or not. Additional practical constraints may be added to the optimised solution.

This decision-making process can be utilised from basic single variable problems to large multivariable problems (Talbi, 2009). The main difference in solving optimisation problems of various complexities lies in the optimisation model which is used.

2.12. Optimisation Models

The optimisation model forms an integral role in the decision-making process. It is a large field of study and has research dedicated to the development and improvement of optimisation models (Carnegie Mellon University, 2017) (Massachusetts Institute of Technology, 2017). Optimisation methods include exact methods and approximate algorithms (Talbi, 2009).

Exact methods obtain optimal solutions and guarantee optimality, while the approximate methods can generate high quality solutions in a practical amount of time. There is however no guarantee of finding the global optimal solution in approximate methods. Metaheuristics is a form of approximate methods.

Metaheuristics allow for large, complex problems to be optimised while delivering acceptable solutions within a reasonable time (Talbi, 2009). As this is an approximate method, there is no guarantee of obtaining the global optimal solution. The method is suited to solve large and complex problem in a reasonable time frame. Metaheuristics are well suited to black box scenarios. This scenario is presented in Figure 2-10. The metaheuristic search through the domain *x* of input variables and evaluates the quality of (*f(x)*). The metaheuristic uses the quality feedback to direct the search through domain *x* (Talbi, 2009).

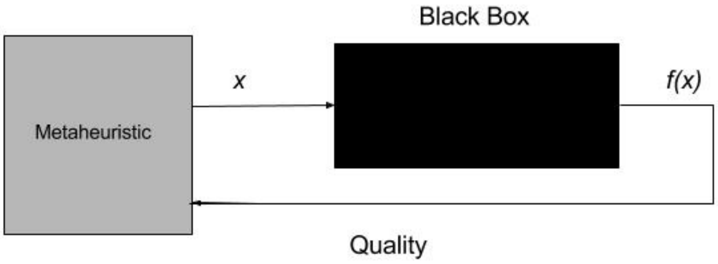

Figure 2-10. Metaheuristic implementation for black box problem

Metaheuristics can be classified into two separate classes. The first is single-solution based metaheuristics and the second is population based metaheuristics (Talbi, 2009). Single-solution metaheuristics look at a single candidate per iteration. A selection process is followed from the current single solution to determine the replacement solution. This process iterates until a solution is found (Talbi, 2009). Population based metaheuristics generates a population of solutions at each iteration.

Each solution is evaluated and a cost is assigned. The generation of the next population generated is based on the specific algorithms cost evaluation criteria. A non-exhaustive list of metaheuristic methods is presented in table 2-2.

Single Solution Based Metaheuristic	**Population Based Metaheuristic**
Local Search	Ant Colony
Simulated Annealing	Particle Swarm
Tabu Search	Genetic Algorithm
Iterated Local Search	Differential Evolution

Table 2-2: Table of single and population based metaheuristics methods. (Talbi, 2009)

The selection of an optimisation method to be used requires the user to look at various aspects such as the complexity of the problem, computational power available and solution accuracy when deciding on a method to utilise.

2.13. Chapter Summary

Chapter 2 provides the background on which this thesis is based. The basic transformer theory provides explanations to illustrate the functioning and importance of the various components of a power transformer. The key component of a transformer is explained as well as the major ageing mechanics. This information is used as basis for the research design and methodology and fieldwork chapters to achieve the required thesis outcomes.

Chapter 3 Experimental Methodology

This chapter presents the research design and methodology. The philosophical worldviews are first discussed followed by the research design and a description of the research methods.

3.1. Introduction

Research approaches are used to plan the steps to be followed during a research investigation. The research approach covers the requirements from the questions and assumptions posed by the researcher, all the way into the methods which are used for collecting and analysing the data. It also provides assistance for the interpretation of the research results (Creswell, 2014). Creswell (2014) discusses three important components to be considered when planning for a study. These three main components are the philosophical worldview, research design and the specific methods of the research (Creswell, 2014). These main components consist of possible options which the researcher is required to select and typical choices are presented in Table 3-1.

Philosophical Worldview	**Strategies of Inquiry**	**Research Methods**
Post Positivist	Quantitative strategies	Questions
Constructivist	Qualitative strategies	Data collection
Transformative	Mixed method strategies	Data analysis
Pragmatic		Interpretation
		Validation

Table 3-1: Three main components for research and some of the possible choices (Creswell, 2009)

Additional considerations should also be made when deciding on a research design. These include

- The research problem.
- Personal experiences of the researcher.
- Audience to which the research is written for.

The purpose of selecting a research design is for a researcher to identify the type of study to be conducted and select the most appropriate research design. Creswell (2014) focuses on three main types designs, namely, qualitative, quantitative and mixed methods. To select the appropriate research design one first needs to select a philosophical worldview.

3.2. Philosophical Worldview

The first step in determining a research design is to select a philosophical worldview. Creswell (2014) discusses four accepted worldviews; which are post-positivism, constructivism, advocacy and pragmatic worldviews. Each worldview allows the researcher a choice of research methods which should be applied. This research is done with a pragmatic worldview. A pragmatic worldview is selected as it emphasis the understanding of the problem. It also emphasises that the problem needs to be understood in order to provide adequate solutions. A pragmatic worldview allows the researcher to use mixed method strategies, if required (Rossman & Wilson, 1985). The pragmatic worldview allows the researcher to direct the inquiry based on the solution to the problems. It focusses more on the understanding of the problem and determining a solution as opposed to focusing more on the design of the method of inquiry (Creswell, 2014).

3.3. Research Design

Creswell (2014) refers to research design as the proposal to conduct research. To decide on a research design the researcher needs to consider philosophy, strategies of inquiry as well as specific methods to be employed in the research. Three additional factors should be considered when deciding on the research design, namely, the research problem, the researcher's personal experience and the audience to which the research will be presented (Creswell, 2014).

A predominantly quantitative design will be adopted for this research. The research questions call for a comparative study to be conducted. A comparison is performed on the selected ageing models to determine their accuracy. A literature review is performed in order to provide background information for this study. It is also used to determine ageing models which are suitable for comparison. The researcher creates an algorithm which is utilised to generate a set of results for comparison. The verification of this model is performed at each step of its development against data provided by IEC (2005) to ensure that the final results are acceptable. The results are compared against a measured value to provide for analysis.

Olsen (2014) recommends the identification of fundamental factors and cases when carrying out comparative studies. The fundamental factors are those which are used during comparison of the cases. This study uses the accuracy of the ageing models as the fundamental factor of comparison. The cases of this study are the different ageing models. These ageing models are applied to the same dataset. The fundamental factor is used to determine which model performs the best. The accuracy is how closely the ageing model compares to the measured loss of DP.

3.4. Additional considerations

Additional considerations identified above need to be identified and addressed as well. The research problem itself is based on a real-world scenario. The data provided by the transformer owner is of transformers which have been in operation for a number of years. The limitations of the data need to be accounted for in the design and methodology. The researcher has several years' experience in the operation and maintenance of transformers. The design and methodology should be done in such a way that this experience does not influence the outcome, but can be used to guide the researcher to provide unbiased results. The study is written for an audience which has some form of technical background. The literature review is done in order to provide the audience with an intimate understanding of the problem and factors which can affect the outcome.

3.5. Research Methodology

In order to achieve the outcomes of this research, four phases of investigation are utilised in this study. The first phase is the literature review which provides the background information required for this study. The literature review also presents ageing models which can be used in the second phase.

The second phase of research is to develop an algorithm which is able to be executed using various selected ageing models presented in literature. The algorithm created is required to be an accurate implementation of ageing models. The various models are required to be normalised in order to provide results which are comparable. The verification and validation of the algorithm is covered in this phase of research as well. The algorithm is verified and validated against known datasets provided by internationally accepted standards (IEC, 2005). The output of the second phase of research is to provide a set of results based on different ageing models.

This set of results will be used in the third phase of research to determine how accurate the various ageing models are. This is done by comparing the calculated loss-of-life to the measured loss-of-life of the transformers. The measured loss-of-life is determined by the Furanic oil samples. Furanic oil samples are the internationally accepted norm for determining the loss-of-life of operational transformers (Eskom Holdings Ltd and ABB Powertech, 2008; Mtetwa, 2011; Nynas, 2013; ABB Transformer Handbook, 2004; Felber Engineering GMBH, 2016). This comparison will provide information which can be used in the final phase of research.

The final phase of research is to modify the ageing models to improve accuracy of their results. This model is based on the modification of a suitable parameter in the ageing models. A summary of the research design and methodology is presented in Table 1-3

3.6. Reasoning

There are two main methods of scientific reasoning which are adopted in the world today; namely inductive and deductive reasoning. Inductive reasoning is when a general conclusion is derived from a large number of observation, whereas deductive reasoning generates predictions of specific results from a general premise (Nickerson, 2010).

This study will use both deductive and inductive reasoning. The general ageing models for transformers will be applied to a fleet of lightly loaded transformers. The calculated results from the general ageing models will be used to determine which model produces the highest degree of accuracy when compared to measured results. This is done in order to determine if these general ageing models are correct.

The second stage uses inductive reasoning. This stage uses meta-heuristics to generate a set of observation based on the fleet of lightly loaded transformers. The observations and patterns are used to determine a general modified ageing model which may be applicable to all lightly loaded transformers.

3.7. Chapter Summary

This chapter provides the research design and methodology which is used for this study. It covers the philosophical worldview adopted by the researcher as well as additional factors which should be considered. This is used to create the research design and methodology which is applied during this study. It also provides a summary of the research methodology applied.

Chapter 4 Data Analysis and Interpretation

Based on the foregoing literature, various theoretical ageing rate equations are proposed. These are primarily based on the hot-spot temperature at which the transformer operates at. Extension of these basic ageing equations take into account moisture and well as oxygen content within the transformer.

This chapter covers the comparative study by looking at the accuracy of the various ageing models. The accuracy of an ageing model is how closely the predicted loss-of-life results compare to the measured loss-of-life from Furanic oil tests. In order to carry this out successfully the following method of approach is followed.

4.1. Method of Approach

In order to achieve the required outcomes, the following needs to be achieved:

1. Simulation of hot-spot temperature based on transformer loading.
2. Selection of relative ageing rates to investigate.
3. Calculation of the various ageing for transformers under investigation.
4. Comparison between the output of ageing against Furanic sample data.

In order to successfully achieve the above, certain parameters need to be identified and held constant in order for the research to provide a meaningful outcome. The parameters which should be constant for the investigation are the following:

- Type of paper: thermally upgraded or non-thermally upgraded paper.
- Transformer life: The lifespan of the transformer under designed operating conditions.
- The end-of-life criteria.
- Transformer design specifications.

Non-thermally upgraded paper more commonly referred to as Kraft paper, is used for this study. Thermally upgraded paper needs to be specified when purchasing new transformers and can add significantly to the cost. The data provided for these transformers does not specify which paper is used inside the transformer. However, since the transformers are older than ten years, the assumption is made that these transformers all have non-thermally upgraded paper as thermally upgraded paper has only been recently introduced into distribution power transformers (Felber Engineering GMBH, 2016). The use of non-thermally upgraded paper also represents the worst-case scenario in comparison to the use of thermally upgraded paper.

The lifespan (180 000 hours) of a transformer which is used for this study is the value quoted by IEEE (2011) and IEC (2005) for the interpretation of transformer functional life data. The end-of-life criteria is fixed at a degree of polymerisation value of 200. This is in accordance with previous research and international standards. The beginning degree of polymerisation value is fixed at 1000.

The design specifications of the transformers under investigation are limited to a common specification. The only important parameters required for this study are the temperature rise limits and parameters. These parameters are used in the calculation of the hot-spot temperature from load factor data. The parameters used are a combination of IEC (2005) recommendations and the transformer owner's parameters. These parameters are stated in the following section when the hot-spot temperature is calculated from transformer loading.

4.2. Dataset Characteristics

This study focuses on the comparison of the calculated ageing rate and the actual ageing based on the Furanic oil samples. In order to gain insight, a dataset of actual transformers in operation is used. The data is provided by a transformer owner in South Africa. The data consists of twenty transformers in total. These twenty transformers are located at ten substations in South Africa. Each substation consists of two sister transformers which operate in parallel. These sister transformers have identical specifications. The data provided contains three elements which are considered for the analysis. The first element is the specifications of the transformers, namely:

- Year of manufacture.
- Substation name.
- Transformer position.
- High voltage rating (kV).
- Medium voltage rating (kV).
- Power rating (MVA).

This information is used to determine the parameters of the transformer. As the power rating and voltages are known, the full load current can be calculated with the use of (4-1).

$$P = \sqrt{3}\,.V\,.I \tag{4-1}$$

This study does not show the actual substation and manufacturer names due to confidentiality and network security requirements. The list of transformers used in this study can be seen in Table A-1.

The second element of data provided is a three-year history of the loading of the transformers. Only three-year data is available at the time interval required. Historical data older than three years is compressed into four-hour averaged data and archived. This data provides the average current at time intervals over the three years. An extract of the format data is seen in Table 4-1. This information only provides transformer current on either the high or medium voltage side of the transformer. The data does not provide ambient temperature as this parameter is not measured and stored for the transformers provided.

Date	MV Current (A)
05/08/2015 18:00	124.21
05/08/2015 18:10	127.89
05/08/2015 18:20	132.01
05/08/2015 18:30	135.68
05/08/2015 18:40	135.31
05/08/2015 18:50	133.94
05/08/2015 19:00	137.41
05/08/2015 19:10	137.41
05/08/2015 19:20	136.25
05/08/2015 19:30	136.11
05/08/2015 19:40	134.18

Table 4-1: Extract of data for transformer theta 2.

In addition, the dataset also includes two newly installed transformers, MEGA 1 and MEGA 2. These new transformers have digital temperature monitors installed and are able to store hot-spot temperature based on direct top oil measurement. This data is only provided for these two transformers and have been limited to a set number of sampled intervals. The digital monitors are capable of storing ambient temperature, but this data is not available for this study as they are not connected to the SCADA system yet.

The third element of data which is required is the oil sample history for the twenty transformers. The oil samples consist of two categories, routine oil samples and special oil samples. Routine oil samples are carried out annually. They analyse the dielectric strength, moisture content, dissolved gases and acidity of the transformer oil.

The special oil samples are carried out between three and five years for each transformer and consist of Furanic analysis in addition to routine analysis. The Furanic analysis generates a predicted average degree of polymerization value by examining the total number of furans in the oil.

The data provided and described up to this point is used to calculate the theoretical ageing of these transformers under their historic operating conditions. The data provided provides sufficient data to calculate the ageing based on the various ageing models. The first step required in this study is to determine the hot-spot temperature based on transformer loading, which is done in the following section.

4.3. Determination of Hot-spot Temperature based on Transformer Loading.

The relative ageing equations (2-5) to (2-8) are primarily based on hot-spot temperature, although certain ageing equations take additional factors such as moisture and oxygen content into account during the calculation. The hot-spot temperature is a key input which is required for all relative ageing equations.

The data which is provided does not record the hot-spot temperature directly. The units under investigation are mature transformers which were only fitted with analogue temperature probes. These temperature probes only have an analogue temperature gauge and have a recording of the maximum temperature for a month. Thus, there is insufficient hot-spot temperature data to be used in the relative ageing equations. The hot-spot temperature, can however be calculated.

The loading of a transformer is recorded at a time interval of 10 minutes via a Supervisory Control and Data Acquisition (SCADA) system and is stored in a digital archive for up to three years at a time. Historic data older than three years is compressed into four-hour averaged data and archived to reduce data storage costs. This information is used to determine the hot-spot temperature of a transformer using the algorithm’s provided by the IEC (2005). The algorithm takes into account transformer loading, ambient temperature and transformer design characteristics to determine a theoretical top oil and hot-spot temperature.

In order to proceed with this investigation, the IEC algorithm is coded in a suitable mathematical platform in order to calculate the hot-spot temperature. It must be noted that this value is a calculated value. The actual hot-spot temperature may differ depending on specific transformer design and operating conditions. However, the model should provide an accurate representation of a working transformers temperatures as it is based on the international standard used in the design of transformers. The model can therefore be checked against existing loading vs temperature data.

For the purpose of this project the model is developed in MATLAB. The algorithm is based on an input file being processed. The input file contains the following data inputs:

1. Date and time
2. Ambient temperature
3. Transformer loading as a percentage of the full load

While ambient temperature is not recorded by the transformer owner, it is a required input to the algorithm. The algorithm should be able to account for a variable ambient temperature, hence the requirement for ambient temperature to be included as a data input.

The algorithm converts the data into a matrix format on which it is able to carry out calculations and access data as required. The transformer design parameters are pre-programmed dependant on the transformer design according to IEC (2005). The calculations are performed in an iterative cycle per time interval. During each iterative step the algorithm determines what the top oil and hot-spot temperatures should be. These calculations are based on the design parameters specified by IEC (2005) and the transformer owner. The output of the algorithm provides both top oil and hot-spot temperatures per time interval and is exported as a CSV file.

For the development of the algorithm the parameter values in Table 4-2 are kept constant for the calculation of the hot-spot temperature. These are variables which are taken into account by the IEC (2005) algorithm when calculating the hot-spot temperature from the loading factor. The parameters are fixed according to the recommended values from IEC (2005). These parameters are applicable based on the type of cooling used on a specific transformer.

Parameter	**ONAN**	**ONAF**
Oil exponent x	0.8	0.8
Winding exponent y	1.3	1.3
Constant K_{11}	0.5	0.5
Constant K_{21}	2.0	2.0

Constant K_{22}	2.0	2.0
Time constant τ_o	210	150
Time constant τ_W	10	7

Table 4-2: Values for parameters which are kept constant for calculating hot-spot temperature based on load factor (Adopted from IEC 2005)

The following parameters are provided by the transformer owner. These parameters relate to the allowable temperature rise specifications which they specify when ordering transformers. These specifications account for the local operating conditions in South Africa. The parameters are used to design for nominal ageing to occur at 98°C.

- Ambient operating temperature: 25°C
- Top oil temperature at rate current: 55°C
- Hot-spot to top oil gradient at rated current: 18°C

A graphical representation of the algorithm is presented in Figure 4-4 and the MATLAB code is presented in section B.1. The algorithm imports the data file from a comma separated value or Excel file and stores the contents in a local matrix. Thereafter, the algorithm then calculates the initial conditions of the top oil and hot-spot temperatures at t = 0. The algorithm enters an iterative loop. Each time the loop is executed, the algorithm determines the change in the top oil and hot-spot temperature based on the imported data of ambient temperature and load factor. The calculated values are stored in a temperatures database after each iteration. Figure 4-4 also includes the calculation of the ageing in each time interval which is discussed in section 4.5.

4.4. Validation of Hot-Spot Temperature Calculation

A two-step process is performed to validate the output hot-spot temperatures. The first step is to verify the algorithm against a data set provided by IEC (2005). The IEC data set provides transformer loading and ambient temperature data with a set of design parameters as well as the calculated hot-spot temperature. This dataset is run through the algorithm developed in section 4.3. The algorithm output is compared to the IEC specified output. The comparison results are illustrated in Figure 4-1 and Table 4-3. The algorithm calculated hot-spot temperature has a deviation of 0.31% in comparison to the IEC stated results.

Based on the verification, the model proves to be acceptable for this study according to the results provided. The next step in the validation process is to validate the model against available operational data. In order to perform this step out, a data set is required from the field which has transformer loading, ambient temperature, top oil and hot-spot temperature recorded. Transformers recently installed in the transformers owners network are fitted with a device which is capable of recording the required parameters. There are, however, very few currently in operation and data retention is limited as it is not connected to the SCADA system yet for archiving.

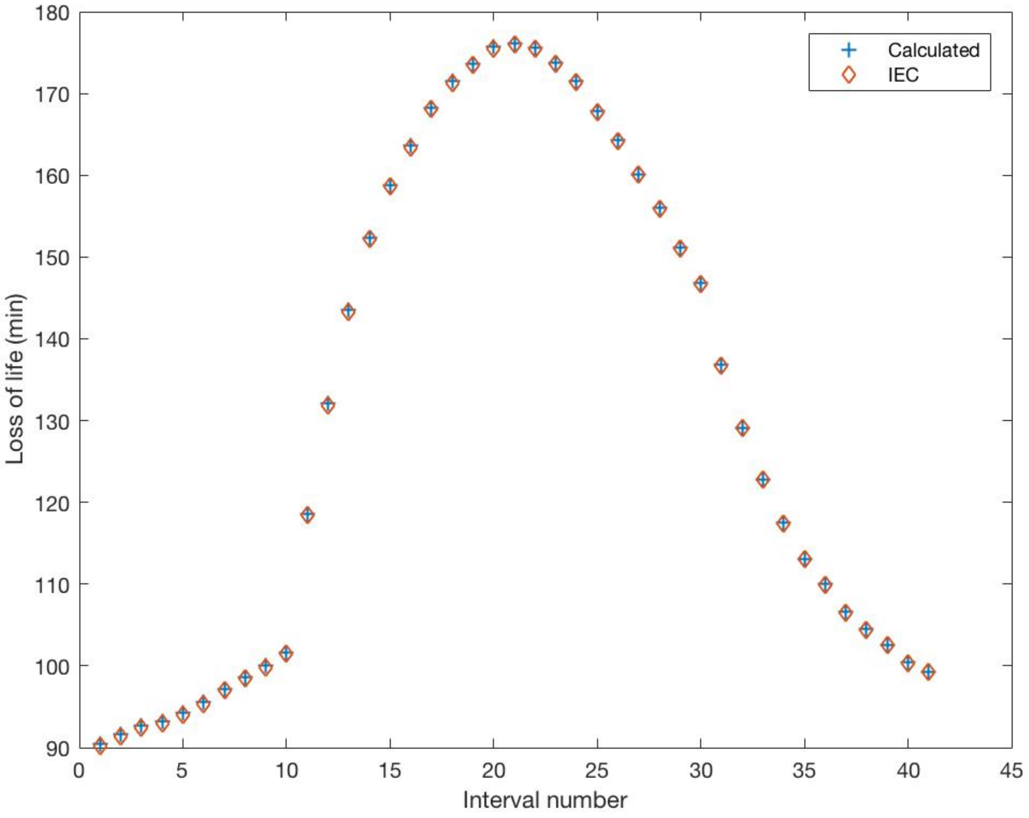

Figure 4-1: Showing calculated and IEC stipulated averages of hot-spot temperature

	Calculated	IEC	Deviation
Average of Hot-spot	131.542	131.688	0.11%
Standard Deviation	30.982	30.962	0.06%

Table 4-3 Showing calculated and IEC stipulated averages of hot-spot temperature

The data set for two transformers, MEGA 1 and MEGA 2 are obtained. These data sets contain the following parameters; (1) transformer current, (2) top oil and (3) hot-spot temperature. In order to further validate the model, this data is processed through the model with input parameters given. The output of the model is then compared against the actual measured hot-spot temperatures recorded. This validation is required to authenticate the model against actual transformer data because the calculated hot-spot temperatures would form the basis of the relative ageing equations. However, the limitation with this dataset is that the ambient temperature information is unavailable. In order to overcome this, the ambient temperature is fixed to the specified design value of 25 degrees Celsius.

The absence of the ambient temperature is an important point as the other dataset which are to be used also do not have ambient temperature data available. The results of transformer MEGA 1 and MEGA 2's validation against the model are presented in Table 4-4, Table 4-5, Figure 4-2 and Figure 4-3. On average, the calculated values are two degrees Celsius higher than the measured counterpart. It can also be seen in the graph comparison that a time delay appears to be prevalent. This can be attributed to the lack of ambient temperature data. The ambient temperature plays a role in the calculation of the top oil and hot-spot temperature.

As the calculated values are higher than the measured values, this would result in the calculated ageing values providing a higher ageing estimate, since the ageing rate is proportional to the hot-spot temperature. It must be noted that power transformers for the specific transformer owner are specified to operate at a higher ambient temperature than specified in IEC (2005). The specified ambient temperature for this transformer owner is 25°C while IEC provides an ambient temperature of 23°C. This variation between IEC specification and transformer owner specification may account for the difference in the measure and calculated hot-spot temperatures.

There is also a noticeable variation in the standard deviation between calculated and measured temperatures. This can be attributed to the oil time constant. The measured hot-spot temperature is calculated from the measurement of top oil temperature. The hotspot of a transformer can heat up quickly, however there is a time delay in heating up the oil. If the hotspot temperature is reduced before the oil heats up, the measuring system will not detect the full magnitude of the hot-spot rise. This is not as prevalent is the calculated temperature. This time delay can account for the reduced standard deviation. The contribution of this oil time constant to standard deviation is similar for both transformers. This model is for the determination of the hot-spot temperature. The algorithm is tested against a dataset provided by IEC (2005). This algorithm is accepted for the purpose of this study as it provides a low deviation of error when compared to stipulated values from IEC (2005). The hot-spot algorithm can be used to provide input into the transformer ageing algorithms. The effect of the variation of parameters such as ambient temperature and loading can be addressed when looking at the ageing models. The method used to calculate the ageing estimation is explained in the next section.

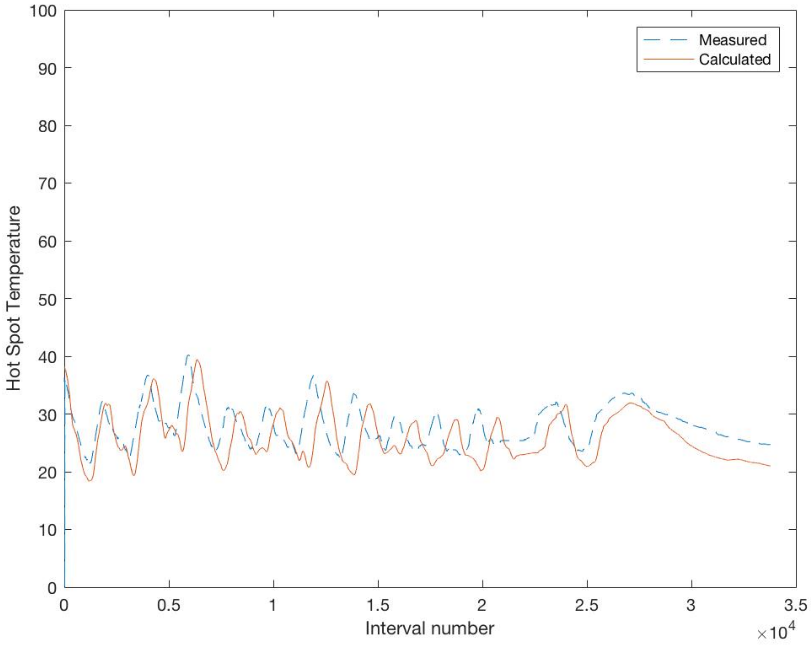

Figure 4-2: Comparison between measured and calculated hot-spot temperature for transformer MEGA1

	Calculated	Measured	Deviation
Average of Hot-spot temperature	27.90	25.98	7%
Standard Deviation	4.10	3.51	16%

Table 4-4 Showing calculated and measured averages of hot-spot temperature for transformer MEGA 1

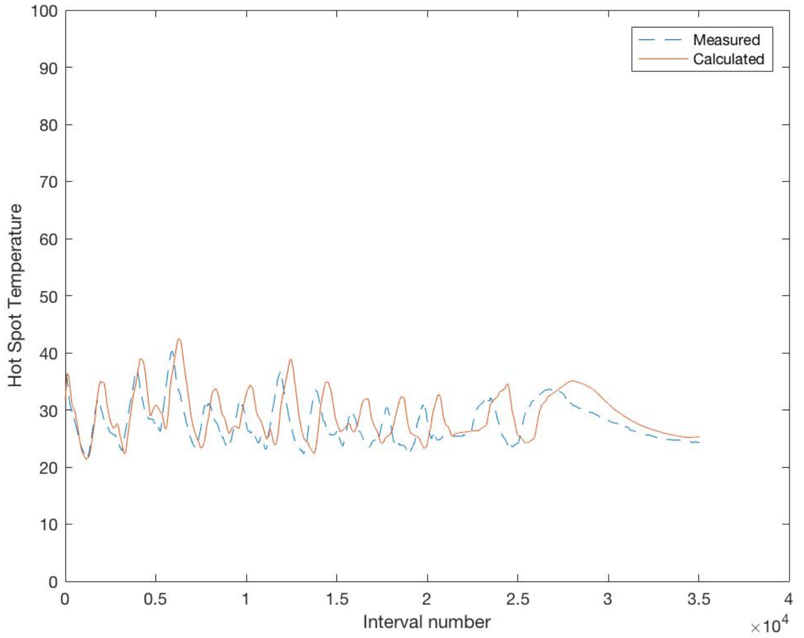

Figure 4-3: Comparison between measured and calculated hot-spot temperature for transformer MEGA 2

	Calculated	Measured	Variation
Average of Hot-spot temperature	29.1742	27.780	5%
Standard Deviation	4.057	3.482	16%

Table 4-5: Table showing calculated and measured averages of hot-spot temperature for transformer MEGA 2

4.5. Ageing Estimations

Ageing estimations models are presented in literature for power transformers, the models presented are assumed to be applicable to any power transformer. The models take into account various parameters. The most commonly used parameter is that of hot-spot temperature. The algorithm to determine hot-spot temperature is presented in section 4.3. The output of this model, hot-spot temperature is used as one of the inputs into the ageing estimation algorithm. The ageing models increase in complexity as more variables are taken into account. This increase in complexity is used as a comparison mechanism once the results are obtained. The ageing estimations are performed using three categories of ageing models.

- Hot-spot temperature only
- Hot-spot temperature and paper moisture content
- Hot-spot temperature, paper moisture and oil oxygen.

These models are selected as they have been acceptable by previous research. The models build up levels of complexity from a single input variable to multiple variable inputs. All the models which are used require as a minimum the hot-spot temperature at which the transformer is operating at. The results from section 3.10. is used as the hot-spot temperature input. The multi variable model requires further information about moisture and oxygen content in the transformer. The paper moisture content and oxygen information is obtained from oil sample results provided. These oil samples are taken on an annual basis. In order to utilise this information, the results are used as input variables for the ageing estimation algorithm. The ageing models investigated are provided in Table 4-6.

Category	**Model Reference**
Hot-spot temperature	IEC (2005)
Hot-spot temperature and paper moisture	Emsley & Stevens, (1994); Lungaard, et al (2002)
Hot-spot temperature, paper moisture and oxygen in oil	Martin, et al. (2015)

Table 4-6: References for the models under investigation

The hot-spot model used is the model presented by IEC (2005) for kraft paper. This ageing model is based on relative ageing rate and can be used directly: The model to be used is presented in (4-2).

$$V = 2^{(\theta_h - 98)/6} \tag{4-2}$$

The IEEE (2011) ageing model is presented here for completeness, but will not be used in this study as it relates to a different reference hot-spot temperature. The IEEE (2011) ageing model is also a relative ageing equation as can be seen in (4-3).

$$V = e^{\left(\frac{15\,000}{110+273} - \frac{15\,000}{\theta_h+273}\right)} \tag{4-3}$$

IEC (2005) and IEEE (2011) provide relative ageing rates while Emsley & Stevens (1994), Lungaard, et al. (2002) and Martin, et al (2015) all provide kinetic equations. To be able to compare these different models the kinetic equations are converted to a relative ageing rates. The conversion to relative ageing rates is performed by normalising the kinetic equations to a similar reference temperature used by IEC (2005) and IEEE (2011). This normalisation is performed utilising equation (4-4).

$$\frac{A_T\,.e^{\frac{-E}{R(T+273)}}}{A_{RT}\,.e^{\frac{-E}{R(RT+273)}}} \tag{4-4}$$

Where

A_T = Constant at temperature, moisture and oxygen for specific interval
A_{RT} = Constant at reference temperature, moisture and oxygen
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius)

This can be simplified to the following form which represent the relative ageing rate using kinetic equations. When compared to relative ageing rates of thermally upgraded paper (2-8) in IEC (2005) and IEEE (2011) a similarity of the form is clear. The relative ageing rates presented by IEC (2005) and IEEE (2011) in (2-6) and (2-8) are normalised kinetic equations with a specific activation energy value of 124 710 joules with constant pre-exponent (A) values.

$$\frac{A_T}{A_{RT}}\,.\,e^{\left(\frac{E}{R(RT+273)} - \frac{E}{R(T+273)}\right)} \tag{4-5}$$

Where

A_T = Constant at temperature, moisture and oxygen for specific interval
A_{RT} = Constant at reference temperature, moisture and oxygen
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius)

The ageing models can now be placed in an algorithm which will calculate the ageing for the data provided. The overall ageing modelling algorithm can be seen in Figure 4-4. The full algorithm is presented in Appendix B.1 The ageing calculation for each time interval is based on equation (4-6). At each time interval, the loss-of-life is calculated based on the applicable input parameters such as hot-spot temperature, moisture in paper and oxygen. The loss-of-life during each time interval is calculated based on the product of the time interval and the relative ageing rate for that time period. A summation of the loss-of-life is stored in the ageing database.

$$\boldsymbol{Loss\ of\ life\ (t) = Relative\ ageing\ rate\ (t) \times time\ interval\ (t)} \tag{4-6}$$

The hot-spot and ageing algorithms are then combined into one. The program in Figure 4-4 can now determine the hot-spot temperature as well as calculate the loss-of-life based on the various ageing models. To be able to utilize the model, it needs to be verified against a known dataset. This dataset is provided by IEC (2005). The ageing model is executed utilising this input data and compared to the output data provided by IEC (2005).

4.6. Validation of Ageing Algorithm

In order to validate the suitability of the algorithm developed, an existing data set is required. IEC (2005), provides the required dataset. IEC (2005) provides the input data for the ageing calculations as well as the expected output of the calculation based on their relative ageing rates. The algorithm developed is executed on this input data and the output is then compared to the IEC (2005) output.

The results of this comparison can be seen in Figure 4-5. The final loss-of-life which is calculated by the developed algorithm is 4423.482 minutes, while the IEC provides a final loss of 4470 minutes. The final value deviates by 1% between algorithm output and IEC (2005) output. The deviation can be due to the decimal points used. The algorithm calculates to the fourth decimal place, while IEC (2005) round off at each iteration to the nearest whole number. The algorithm successfully calculates the age of a transformer. Given these results, the algorithm developed is accepted to be adequately suitable to carry out the various ageing models. The next step is to determine if there is sufficient data available to execute the algorithm successfully using all the ageing models.

4.7. Input Parameters for the Ageing Algorithm

The algorithm is accepted as suitable for calculating the loss-of-life of a transformer. The ageing models which are assessed are provided in Table 4-6. The first category of models, which are hot-spot temperature dependent only, can be directly implemented using the given algorithm. The second and third category models require additional parameters to be provided for the models. These parameters are moisture content in paper and the oxygen in oil. This information is extracted from the routine samples provided by the transformer owner.

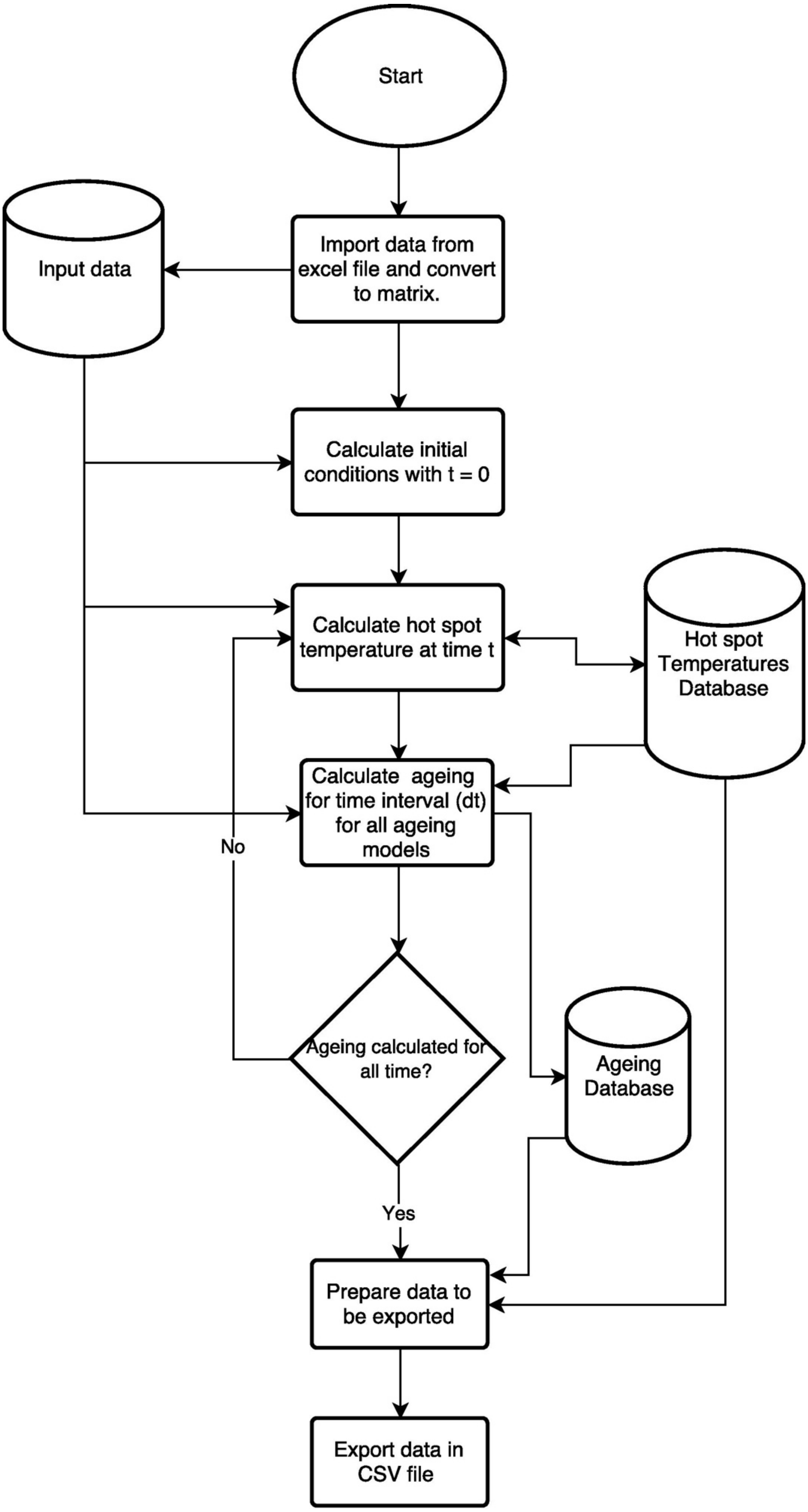

Figure 4-4: Graphical representation of algorithm used to determine hot-spot temperature and model transformer ageing.

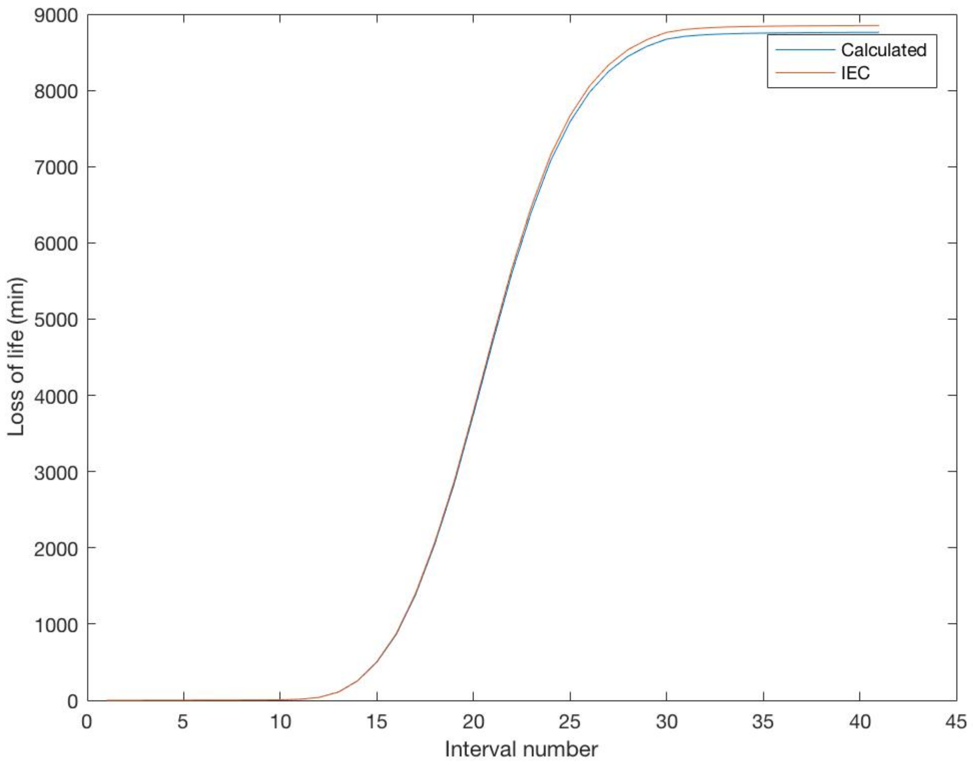

Figure 4-5: Comparison of calculated loss-of-life to IEC presented loss-of-life.

	Calculated	IEC	Variation
Loss-of-life	4423.482 min	4470 min	1%

Table 4-7: Comparison of calculated loss-of-life and IEC presented loss-of-life

The moisture in paper determination is carried out using the equilibrium curves. A set of equilibrium curves based on Oomen (1983) and Fabre-Pichon (1960) are being used by the transformer owner. These curves are used to determine the moisture content in paper based on the moisture content in insulating oil and the oil temperature. These curves provided by the transformer owner is used to determine the moisture in paper content based on the annual oil samples results. These curves cannot be included are they are proprietary information. Based on the data provided, there is only a moisture in paper data point once a year. This limit's the accurate modelling of the moisture dynamics which occurs in the transformers. The moisture in paper content is assumed to be linear between two data points as there is insufficient data points to derive a more accurate model for moisture in paper. Oxygen content in insulating oil is a parameter directly measured during routine oil samples. Once again, a data point for oxygen in oil is only available once a year. The oxygen content is also assumed to be linear between two data points.

The input file to the algorithm contains the following parameters. These are required to execute the algorithm completely based on all ageing models under investigation.

• Date and time stamp	(YYYY/MM/DD HH:MM)
• High Voltage Current	(Amps)
• Ambient Temperature	(°C)
• Load factor	(%)
• Moisture in paper	(%)
• Oxygen content	(parts per million - ppm)

This data is a combination of the available information provided by the transformer owner. An input file is created for each transformer under investigation. Each file consists of three years' worth of data for each transformer. These files, in conjunction with the ageing model parameters are used by the algorithm to calculate the transformer ageing.

4.8. Ageing Model Parameters

The ageing models under investigation have certain parameters which have to be decided upon prior to execution. These parameters are only applicable to the kinetic equations which have been converted to relative ageing rates. Using the derived relative ageing rate in equation (4-5) the following parameters are required to be selected:

- Activation energy
- Reference Temperature
- A_T (Pre-exponent at current temperature, moisture and oxygen for specific interval)
- A_{RT} (Pre-exponent at reference temperature, moisture and oxygen.)

The activation energy value selected is the value accepted in literature across the various sources (Emsley & Stevens, 1994 ; Lungaard, et al 2002; Martin, et al. 2015). The selected value for activation energy was determined by experimental methods to be 111kJ/mole as determined by Emsley & Stevens (1994). This value is also accepted by Lungaard et al (2002) and Martin et al (2015).

The reference temperature used is 98 °C. This corresponds to non-thermally upgraded paper. This value is selected, since majority of the transformers under investigation are mature units. The transformer owner confirmed that they have only recently started specifying the use of thermally upgraded on specific transformers.

The pre-exponent A_{RT} value is different for each of the kinetic equation ageing models. This is done to ensure the kinetic equations are normalised correctly. Each author has specific different pre-exponent values depending on the moisture and oxygen content. The A_{RT} value selected for each model is based on kraft paper with a low moisture (< 0.5%) and oxygen (<7000 ppm) content. The reference A_{RT} selected for the various models is seen in Table 4-8.

Model	**A_{RT} (Kraft paper, Moisture < 0.5%, Oxygen < 7000 ppm)**
Emsley & Stevens (1994)	1.07×10^8
Lungaard, et al (2002)	2.00×10^8
Martin, et al (2015)	$0.5^2 \times (1.78 \times 10^{12}) + 0.5 \times (1.10 \times 10^{10}) + 5.28 \times 10^7$

Table 4-8: Selected value of A_{RT} for these investigations (Emsley & Stevens, 1994 ; Lungaard, et al 2002; Martin, et al. 2015)

The values for A_T are also required to be fixed prior to the execution of the algorithm. These values are taken from the relevant authors literature and are presented in Table 4-9 (Emsley & Stevens, 1994; Lungaard, et al 2002; Martin, et al. 2015). These values are based on the moisture content for Emsley & Steven (1994) and Lungaard, et al (2002). The value of A_T for Martin, et al. (2015) are based on both the moisture content as well as the oxygen content, as shown in Table 4-10.

Model	**Kraft Paper + 1% Moisture**	**Kraft Paper + 2% Moisture**	**Kraft Paper + 3% Moisture**	**Kraft Paper + 4% Moisture**
Emsley & Stevens (1994)	3.5×10^8	7.8×10^8	35×10^8	35×10^8
Lungaard, et al (2002)	6.2×10^8	6.2×10^8	21×10^8	21×10^8

Table 4-9: Selected values of A_T for ageing models (Emsley & Stevens, 1994 ; Lungaard, et al 2002)

Martin, et al (2015)	**A_T**
Low oxygen (<7000ppm)	$(1.78 \times 10^{12})w^2 + (1.10 \times 10^{10})w + 5.28 \times 10^7$
Medium Oxygen (7 000 – 14 000 ppm)	$(2.07 \times 10^{12})w^2 + (5.61 \times 10^{10})w + 2.31 \times 10^8$
High oxygen (> 14 000 ppm)	$(2.29 \times 10^{12})w^2 + (9.78 \times 10^{10})w + 3.86 \times 10^8$

Table 4-10: Selected values of A_T for ageing models (Martin, et al, 2015). Where w is moisture content in percentage.

These parameters are fixed to the constants in Tables 4-8, 4-9 and 4-10. The next step is to execute the algorithm based upon all the data provided and to collate the results. This is performed in the following section.

4.9. Ageing Results for Loss-of-life

The developed algorithm is executed on the full dataset available. The algorithm is executed on a total of twenty transformers, with data available for three years on each transformer. The ageing models is executed on this data set and the results are collated in Table A-2. A summary of the transformer parameters during the period under investigation are presented in Table 4-11. All transformers under investigation are regarded to be lightly loaded as they all, on average, operate below 50% loading.

SUBSTATION	POSITION	MEAN LOAD	MEAN TEMP	MEAN MOISTURE	MEAN OXYGEN	TOTAL TIME
ALPHA	1	25.84%	44.880	0.021	8698.60	1580600
ALPHA	2	26.44%	45.179	0.025	2006.80	1580600
THETA	1	18.85%	41.554	0.028	18886.00	1580500
THETA	2	47.56%	59.379	0.021	16502.00	1580600
DELTA	1	44.02%	50.265	0.034	17126.00	1580500
DELTA	2	43.89%	50.070	0.034	18044.00	1580500
ZETA	1	22.41%	42.128	0.032	19952.00	1580000
ZETA	2	22.94%	42.366	0.032	20064.00	1580000
KAPPA	1	31.56%	56.403	0.026	23873.00	1580500
KAPPA	2	31.78%	56.997	0.025	14100.00	1580500
PHI	1	22.94%	47.480	0.026	19404.00	1580500
PHI	2	37.61%	64.522	0.029	16404.00	1580500
LAMBDA	1	25.95%	41.443	0.030	20537.00	1580500
LAMBDA	2	24.76%	42.296	0.031	21643.00	1580000
SIGMA	1	42.23%	62.174	0.032	20253.00	1580500
SIGMA	2	42.31%	62.268	0.040	19141.00	1580500
RHO	1	27.40%	41.547	0.022	25978.00	1580500
RHO	2	27.34%	41.763	0.030	26204.00	1580600
TAU	1	28.56%	45.553	0.032	1575.60	1580500
TAU	2	30.26%	47.147	0.032	1638.70	1580500

Table 4-11: Summary of transformer parameter for period under investigation.

The results provided are the equivalent minutes of loss-of-life which the transformer has theoretically aged, based on its operating history. The average hot-spot temperature is also provided. The results are based on the implementation of the aforementioned ageing models. The loss-of-life minutes can further be equated to a loss of degree of polymerisation. This is done based on the methods from literature and is discussed in the next section.

4.10. Loss of Degree of Polymerisation

The results from the ageing models provide a loss-of-life of the transformer in minutes. To compare the models to the actual Furanic oil samples a loss of degree of polymerisation is required. The conversion from loss-of-life minutes to degree of polymerisation is done via (4-7) (IEC,2005; IEEE, 2011).

$$DP\ loss\ per\ minute = \frac{DP_{Start} - DP_{end}}{expected\ life(minutes)} \tag{4-7}$$

The three parameters required for the conversion are kept constant as follow, according to IEC (2005) and IEEE (2011 are presented in Table 4-12.

Degree of Polymerisation of new transformer	1000
Degree of Polymerisation at end-of-life:	200
Expected life of transformer (IEC, 2005; IEEE, 2011)	180 000 hours or 10.8x10^6 min

Table 4-12: Parameters held constant for the conversion of loss-of-life in minutes to DP loss.

By using these parameters, the DP loss per minute is calculated as:

$$DP\ loss\ per\ minute = \frac{1000 - 200}{10.8 \times 10^6}$$

$$DP\ loss\ per\ minute = 7.41 \times 10^{-5}$$

By using this DP loss per minute value, the calculated DP loss for the investigation period is calculated according to equation (4-8) with the results presented Table A-3

$$DP\ loss = 7.41 \times 10^{-5} \times loss\ of\ life\ (minutes) \tag{4-8}$$

These values are compared to measured DP values. The measured DP values is calculated from the Furanic oil sample history. The Furanic oil sample method is a universally accepted method for determining the DP value of a given transformer. The measured DP loss from Furanic oil sample is calculated by determining the linear DP loss per operating minute between two Furanic oil samples. This value is multiplied by the total time (minutes) to determine the measured DP loss over the investigation period. The results are used to determine which ageing model provides the most accurate loss of DP prediction. This is performed in the following section.

Substation	Transformer position	Total Time (Minutes)	Measured DP loss from Furanic Oil samples	IEC Kraft Paper DP Loss	Emsley DP Loss	Lungaard DP Loss	Martin DP Loss
ALPHA	1	1580600	88.571	0.27307	5.0893	1.7987	3.7643
ALPHA	2	1580600	59.048	0.28675	2.3984	1.0226	3.1982
THETA	1	1580500	120.304	0.25512	2.0208	0.86158	8.8667
THETA	2	1580600	122.465	17.006	91.011	33.009	117.33
DELTA	1	1580500	19.596	0.67864	5.9814	2.5502	27.468
DELTA	2	1580500	23.515	0.93058	7.0392	3.0012	38.074
ZETA	1	1580000	46.426	0.19156	1.5498	0.65716	8.0959
ZETA	2	1580000	43.695	0.19724	1.6032	0.67983	8.4056
KAPPA	1	1580500	56.455	2.0102	16.818	7.1703	67.885
KAPPA	2	1580500	39.173	2.0631	17.247	7.3531	53.812
PHI	1	1580500	70.428	5.0269	32.122	13.695	129.93
PHI	2	1580500	45.593	80.885	265.59	113.23	904.34
LAMBDA	1	1580500	65.115	0.17776	1.4039	0.59855	6.6999
LAMBDA	2	1580000	10.515	0.20432	2.0101	0.81035	8.4166
SIGMA	1	1580500	23.833	7.4218	54.169	23.095	306.78
SIGMA	2	1580500	29.157	7.4559	198.13	65.474	424.67
RHO	1	1580500	25.034	0.18523	2.9836	1.0718	4.9888
RHO	2	1580600	25.128	0.19383	1.5524	0.66188	7.3608
TAU	1	1580500	74.768	0.81337	4.7943	1.9925	8.103
TAU	2	1580500	74.763	2.3087	9.1313	3.8931	16.233

Table 4-13: Table of ageing model DP results and measured DP results.

4.11. Results Interpretation

The results from the ageing models are presented in Table 4-13. These results are interpreted in this section. The interpretation is based on the comparison factor identified in section 3.4. The fundamental comparison factor is how closely the ageing models can predict the loss of DP in comparison to the measured loss of DP.

The ageing models' results are compared to the measured values. A percentage variation factor is derived from these results using (4-9). The percentage values given indicate how closely the ageing models match the measured results. A variation percentage of zero indicates that the ageing model and the measured results are identical. A value less than zero indicates and underestimation, and values greater that zero indicate overestimation. The results are presented in Table 4-14.

$$\% \, Variation = \frac{DP_{Predicted} - DP_{Measured}}{DP_{Measured}} \tag{4-9}$$

Substation	Transformer position	IEC KRAFT % VARIATION	EMSLEY % VARIATION	LUNGAARD % VARIATION	MARTIN % VARIATION
ALPHA	1	-100%	-94%	-98%	-96%
ALPHA	2	-100%	-96%	-98%	-95%
THETA	1	-100%	-98%	-99%	-93%
THETA	2	-86%	-26%	-73%	-4%
DELTA	1	-97%	-69%	-87%	40%
DELTA	2	-96%	-70%	-87%	62%
ZETA	1	-100%	-97%	-99%	-83%
ZETA	2	-100%	-96%	-98%	-81%
KAPPA	1	-96%	-70%	-87%	20%
KAPPA	2	-95%	-56%	-81%	37%
PHI	1	-93%	-54%	-81%	84%
PHI	2	77%	483%	148%	1884%
LAMBDA	1	-100%	-98%	-99%	-90%
LAMBDA	2	-98%	-81%	-92%	-20%
SIGMA	1	-69%	127%	-3%	1187%
SIGMA	2	-74%	580%	125%	1356%
RHO	1	-99%	-88%	-96%	-80%
RHO	2	-99%	-94%	-97%	-71%
TAU	1	-99%	-94%	-97%	-89%
TAU	2	-97%	-88%	-95%	-78%
AVERAGE ACCURACY		-86%	-9%	-65%	190%

Table 4-14: Table showing the percentage variation of the various ageing models on the fleet of transformers. The average accuracy for each model is also indicated.

It appears from the average results that Emsley ageing model produces the most consistent accuracy. However, looking at the results in more depth, it is clear that the results contains upper and lower extreme values. The average value is this case is not a good representation of the results. In order to better comprehend the results, they are organised into a frequency plot. The frequency plot counts the number of results which fall into one of the following absolute variation presented in Figure 4-6. Low variation category is any results which falls within ±20% variation. The medium category is from -20% to -100% and +20% to +100% variation. The high category is for results less than -100% and greater than +100%. This plot is presented in Figure 4-7 and Table 4-15. This presents the results in a clearer manner. It is clear from this plot that a majority of the ageing models fall into the medium variation category. With either under or overestimate the age of a transformer. The accuracy band of -20% to 20% contain very few results, with Martin et. Al. producing only 10% of its estimations in this band.

< -100%	-100%	-80%	-60%	-40%	-20%	0%	20%	+40%	+60%	+80%	+100%	> +100%
High	Medium				Low			Medium				High

Figure 4-6: Figure describing the categories for classification of results. The percentage value refers to the % variation.

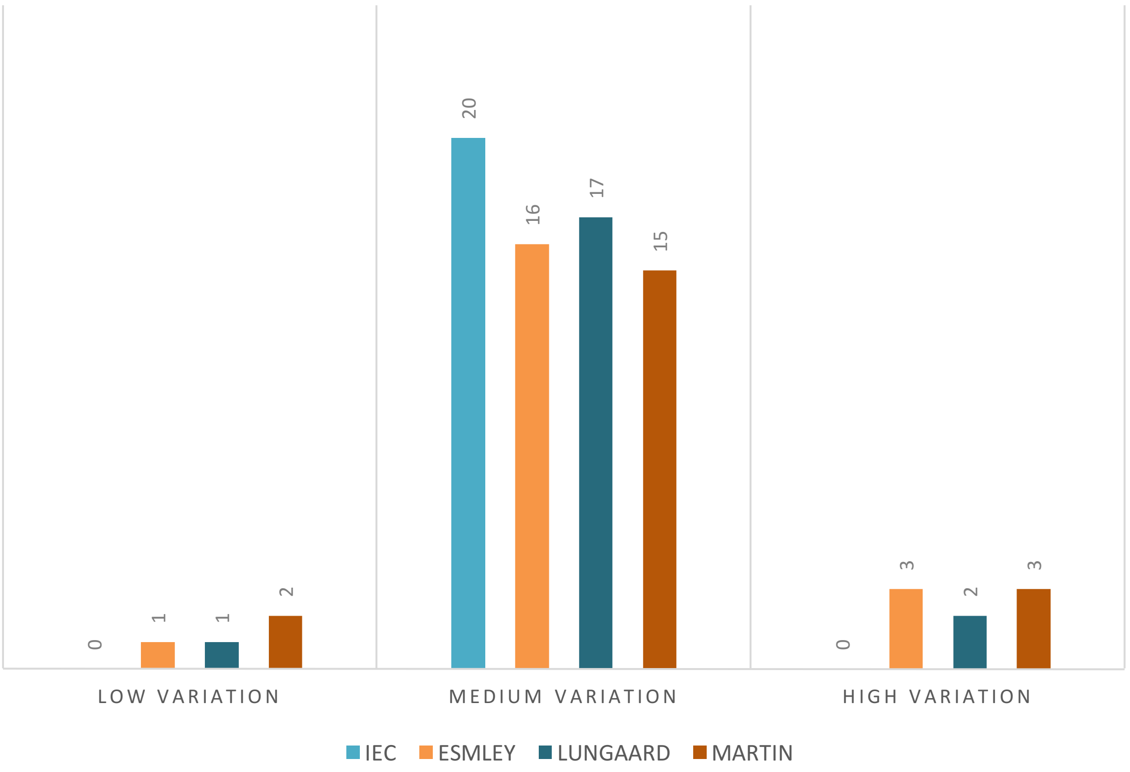

Figure 4-7: The figure shows the number of results which fall into the specific variation category. Based on ageing results.

Variation	IEC	ESMLEY	LUNGAARD	MARTIN
Low	0	1	1	2
Medium	20	16	17	15
High	0	3	2	3

Table 4-15: Table showing the number of results which fall into each accuracy category.

It is evident that none of the ageing models consistently produce high accuracy ageing estimations. There are isolated cases where Martin, et al (2015) produces predictions within 20% variation. The ageing models do however exhibit an increase in accuracy as more ageing factors are taken into account. When hot-spot temperature is the sole parameter, the majority of the predictions are underestimations. When moisture is also taken into account, the prediction accuracy increases slightly. Martin, et al (2015) which account for hot-spot temperature, moisture and oxygen increases the accuracy further.

The ageing models produced results which tend to underestimate the loss-of-life. This outcome can be due to the low operating temperature which the transformers operate at. These transformers operate at a low hot-spot temperature due to limited loading which they are subjected to. The low loading is due to the distribution network configuration which caters for contingencies. This typically results in two transformers sharing a load; but one transformer is able to handle the full load in isolation if required. Based on the ageing models, for approximately every decrease of 6 °C of the hot-spot temperature, the ageing rate of paper halves as seen in Table 4-16. The highest average temperature of the transformers under investigation is 66°C. This is well below the rated operating temperature of 98°C. Based on the relationship above, the ageing of the paper would be at 0.03125 of the rated ageing.

An increase in the number of ageing factors which are taken into account increases the accuracy of the loss-of-life prediction in this cases. The temperature only model is limited to a single ageing mechanism. When temperature and moisture are taken into account the accuracy increases as the algorithm now account for two separate ageing mechanisms. The last ageing model accounts for all three ageing mechanisms, namely, temperature, moisture and oxygen content. When taking all three ageing mechanisms into account, the accuracy of the model is improved compared to the other models. However, the models do not produce accurate results consistently across the various transformers.

Hot-spot temperature (°C)	Relative ageing rate – Kraft paper, IEC (2005)
80	0.125
86	0.25
92	0.5
98	1
104	2
110	4
116	8

Table 4-16: Relative ageing rates at different temperatures. (IEC, 2005)

A modification to the ageing models may provide a more accurate estimation across the various transformers. The main parameter which can be altered for the ageing models is the pre-exponent values. The experiments used to determine the pre-exponent value for the ageing models are all based on accelerated ageing experiments. The accelerated ageing experiment exposes kraft paper to temperatures of at least 80°C. Lightly loaded transformers rarely see these high temperatures in operation.

4.12. Chapter Summary

Chapter 4 presents the bulk of the field work based on ageing models found in literature. An algorithm is developed and implemented which simulated hot-spot temperature from transformer loading information. The accuracy of this model on its own is validated against an available dataset of in-service transformers. This algorithm is then adapted to carry out the loss-of-life calculation based on the selected ageing models. The ageing models are used to predict a loss-of-life in DP of the individual transformers. The ageing model output is then compared to the measured loss-of-life measured from Furanic oil samples.

The comparison between predicted DP loss from the ageing models and the measured DP loss from the oil samples are compared to demine the accuracy of the various ageing models. The ageing models, under most cases produces low accuracy estimations. The accuracy increases as the number of ageing mechanic variables are taken into account based on the results presented. The chapter concludes with an interpretation of the results obtained as well as possible reasons for the low accuracy of the ageing models. The next chapter looks at a modified ageing models in a bid to improve the accuracy of the model.

Chapter 5 Modified Ageing Model

The ageing models investigated produce low accuracy rates. The possible reason for the inaccuracy is also presented. In order to create improved ageing estimations, this chapter attempts to improve the accuracy for lightly loaded transformers which operate below their designed hot-spot temperature rating.

The ageing models presented have three main variables which can be selected by the user, namely, the activation energy, pre-exponent constant, *A,* and the reference temperature for ageing. The activation energy has been accepted by several authors to be a value of 111 000 J/Mol (Emsley & Stevens, 1994; Lungaard, et al 2002; Martin, et al. 2015; IEC, 2005; IEEE, 2011). This activation energy value is accepted to be independent of the quantity of moisture, oxygen or hot-spot temperature in the transformer (Emsley & Stevens, 1994; Lungaard, et al 2002; Martin, et al. 2015; IEC, 2005; IEEE, 2011). Thus, the authors therefore aimed to determine the value of the pre-exponent constant, *A*. The constant, *A,* is used to account for accelerated ageing depending on the moisture and oxygen content within the transformer. The second variable which is investigated is the reference temperature (*RT*). In the case of kraft paper, the reference temperature is 98°C. This value increases to 110°C for thermally upgraded paper.

To improve the accuracy of the ageing models two variables are investigated. The first is the reference temperature (*RT*), the second, is the constant, *A*. The search for the optimal *RT* and *A* values is carried out in this chapter.

5.1. Method of Approach

To determine if the models can be improved upon, an optimisation process is required. The variables to be optimised are the reference temperature (*RT*) and pre-exponent *A*. The optimisation is performed using three ageing models. The optimisation equation takes the Arrhenius form. This is similar to the form used by IEEE (2011), Emsley & Stevens (1994), Lungaard et al. (2002) and Martin et al. (2015) models. The models all have a similar equation form. However, each model cited in literature uses a different pre-exponent value.

The process involves the investigation of three separate ageing models. The models to be investigated are presented in Table 5-1. Case One only looks at the hot-spot temperature. Case Two includes oxygen content. Case Three accounts for moisture content. The basic form of the ageing model which is investigated is presented in (5-1). The parameters which are held constant for the duration of this investigation are presented in Table 5-2. These parameters are held at similar constant values to that in section 4.3. The three cases investigated takes the form of relative ageing rates.

Case	**Temperature**	**Oxygen**	**Moisture**
1	Yes	No	No
2	No	Yes	No
3	No	No	Yes

Table 5-1: Table of ageing models to be investigated and the ageing factors which they include.

$$\frac{A_T}{A_{RT}} . e^{\left(\frac{E}{R(RT+273)} - \frac{E}{R(T+273)}\right)} \tag{5-1}$$

A_T = Constant at temperature, moisture and oxygen for specific interval
A_{RT} = Constant at reference temperature, moisture and oxygen
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius)

Parameter	**Fixed Value**
Activation Energy (E)	111 000 J.mol^{-1}
Reference Temperature (RT)	98°C
Constant at reference temperature, moisture and oxygen (A_{RT})	1
Ideal gas constant	8.314 J mol^{-1} K^{-1}

Table 5-2: Table of parameter which are held constant for duration of investigation

5.2. Case One Design

Case One serves to identify if the reference ageing temperature should be altered to decrease the percentage variation of the loss-of-life estimate. The first case looks at the hot-spot temperature as the sole influence on transformer ageing. IEC (2005) and IEEE (2011) operate on a similar principle. This ageing equation solely looks at the hot-spot temperature in comparison to the reference temperature. Case One looks at a single variable to be optimised, namely the reference temperature. The model to be used for Case One is equation (5-2). The variable which will be optimised is the reference temperature (*RT*). The parameters A_{RT} and A_T are fixed at a value of one for this case. The genetic algorithm is used to solve for variable *RT* which produces the most accurate ageing estimation.

$$\left(e^{\frac{E}{R(RT+273)}} - e^{\frac{E}{R(T+273)}}\right) \tag{5-2}$$

Where:

E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius)

5.3. Case Two Design

The second case incorporates oxygen content. The reference temperature in this case is held constant at 98°C. This case uses a form similar to Martin et al. (2015). The values for the pre-exponents presented by Martin et al. (2015) are based on a combination of moisture and oxygen content. In this case, the pre-exponent, A_T, is a based only on the oxygen content during a given time period. The values for the A_T and the limits used are presented in Table 5-3.For Case Two, equation (5-3) will be utilised in this case. A total of three variables are to be optimised in this case.

Oxygen Content (PPM)	A_T
<1000	A_{RT}
≥ 1000 < 7000	A_A
≥ 7000 <16500	A_B
≥ 16500	A_C

Table 5-3: Table of pre-exponents used in Case Two with their oxygen limits

$$\frac{A_T}{A_{RT}} \cdot \left(e^{\frac{E}{R(RT+273)}} - e^{\frac{E}{R(T+273)}}\right) \tag{5-3}$$

where:
A_T = Constant at oxygen content for specific interval from Table 5-3
A_{RT} = Constant at reference temperature, moisture and oxygen
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius)

5.4. Case Three Design

Case Three examines the moisture content in isolation to reference temperature and oxygen content. The reference temperature in this case is held constant at 98°C. This case uses a similar case to that of Emsley & Stevens (1994) and Lungaard et al. (2002). Pre-exponent values, which take into account accelerated ageing due to moisture content within the paper, were produced by Emsley & Stevens (1994) and Lungaard et al. (2002). Case Three will look at the optimisation of four. The four variables are pre-exponent values and are based on the moisture content in the paper. Similar to that of Emsley & Stevens (1994), Lungaard et al. (2002). The pre-exponent value is dependent on the moisture content within the paper. The moisture limits are specified in Table 5-4. For Case Three, the equation (5-4) is used. A_{RT} in this case is held constant at a value of one which is the reference for this case.

Moisture in Paper (%)	A_T
<1%	A_{RT}
≥1% <2%	A_w
≥2% <3%	A_x
≥3% <4%	A_y
≥4%	A_Z

Table 5-4: Moisture content categories for Case Three

$$\frac{A_T}{A_{RT}} \cdot \left(e^{\frac{E}{R(RT+273)}} - e^{\frac{E}{R(T+273)}} \right) \tag{5-4}$$

where:
A_T = Constant at moisture content for specific interval (A_w, A_x, A_y or A_z)
A_{RT} = Constant at reference temperature, moisture and oxygen
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius)

5.5. Optimisation Execution

The optimisation is executed with the premise that the ageing models are black-box problems. Values for the variables can be passed into the ageing model and the model produces an accuracy value. This accuracy value is used as the cost function for the optimisation model. The number of variables for each case are one, three and four respectively. An approximate optimisation method is utilised as the problem does not exist within the scope of a simple mathematical model.

The purpose of this study is to investigate the ageing model of transformers pragmatically therefore metaheuristic optimisation algorithms fall outside the scope of this study. Thus, the models are optimised using a metaheuristic population-based search algorithm. For the purpose of this investigation, a genetic algorithm is selected for the following reasons:

- The genetic algorithm works with black box problems.
- It can be directly implemented in MATLAB with minor modification to the code.
- The problem under investigation is a dynamic optimisation problem.
- The problem under investigation is non-linear.

In order to carry out the optimisation, the case algorithms B.4, B.5, and B.6 are passed to the genetic algorithm B.3. The genetic algorithm is able to vary the specified number of variables in each case algorithm. The genetic algorithm evaluates the accuracy of the model at each iteration to determine its next step. The algorithm terminates when it finds a solution which satisfies the exit requirements. This algorithm operates with the specified cost function in (5-5) and it aims to minimise the cost function to a specified fitness limit.

$$\boldsymbol{Cost = Absolute\ (Predicted\ DP - Actual\ DP)} \tag{5-5}$$

A genetic algorithm by its nature may produce slightly different result each time it is executed. In order to overcome this, the genetic algorithm is executed five times for each case. The results are then averaged out to obtain a final value.

MATLAB has a built in Genetic Algorithm optimisation tool which is accessible and can be readily implemented for the existing ageing model algorithm. However, there are preliminary parameters which need to be specified prior to the execution of the genetic algorithm. These are parameters which are held constant throughout the various cases and is presented in Table 5-5. The parameters which are altered depending on the case under investigation is presented in Table 5-6. The MATLAB algorithms used are found in appendix B.3, B.4, B.5 and B.6

Parameter	Value	Description
Fitness Limit	2	Minimum cost function value for the algorithm to terminate.
Maximum Iterations	100	Maximum number of iterations to complete

Lower Bound	0	Lower bound of variables
Upper Bound	1000	Upper bound of variables
Population Count	50	Population size per iteration
Elite Count	3	Number of elite individuals
Crossover Count	40	Number of crossover individuals
Mutation Count	7	Number of mutated individuals

Table 5-5: Table of parameters which are held constant through all case investigations.

Parameter	**Case One Value**	**Case Two Value**	**Case Three Value**
Number of variables	1	4	3
Fitness Function	ageing_calc_case1	ageing_calc_case2	ageing_calc_case3

Table 5-6: Table of parameter which are altered depending on which case is under investigation.

Upon completion of the optimisation process, the results from each case are presented, interpreted and a new ageing model is produced from the results. The full dataset is used in the optimisation and model building process in order to develop a general model for lightly loaded transformers. The use of the full dataset takes into account the variations between different lightly loaded transformers. The final step is to execute these three new general ageing models on the same dataset and to identify if any improvement in accuracy is observed.

5.6. Case One Modified Ageing Model

Case One was executed five times with the genetic algorithm as presented in section 5.5. The full results can be found in Table A-4. The output of each iteration produces a reference temperature for the transformers which produce a predicted DP value equal to the measured DP value. These results are averaged out across all the iterations to produce a specific reference temperature for each transformer.

The results presented in Figure 5-1 shows the relationship between the calculated reference temperature and the average hot-spot temperature of the transformers. The reference temperature presented in IEC (2005) and IEEE (2011) are both recommended at 98°C. This data shows that a reduction in the reference temperature may result in better accuracy.

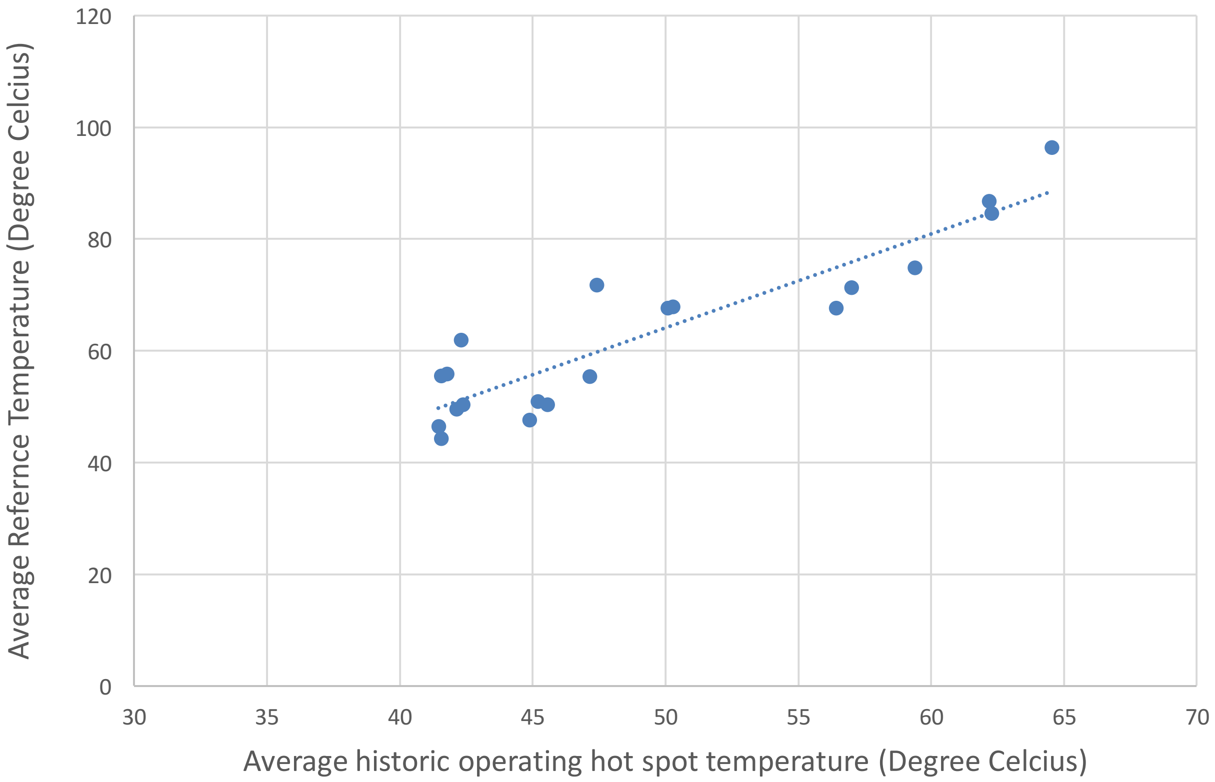

Figure 5-1:Case One results. Average operating hot-spot temperature plotted against the average reference temperature as determined by genetic algorithm search.

The two variables, average reference temperature and average operating hot-spot temperature are analysed using correlation analysis to determine if the two variables are correlated. The results from the correlation indicate a positive correlation with value of 0.912. This value of correlation is interpreted to mean that the two variables can be linked by an equation. The relationship presented in Figure 5-1 indicates that the reference temperature for ageing can be based on the average operating hot-spot temperature. A three-year average is used in this case.

In order to use this correlation, the next step is to carry out regression analysis to determine the equation linking the two variables. This equation can be used in the modified ageing model. This result can be returned to a relative ageing formula as presented in equations (5-6) and (5-7).

$$\left(e^{\frac{E}{R(RT+273)}} - e^{\frac{E}{R(T+273)}}\right) \tag{5-6}$$

$$RT = [B \times (average\ historic\ operating\ hot\ spot\ temperature)] + A) \tag{5-7}$$

where
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius) (5-7)
B = Regression slope
A = Regression intercept

The regression slope and intercept values are calculated using Microsoft Excel built in regression tool in the Data Analysis toolbox. The tool provides a linear regression model based on the variables plotted in Figure 5-1. In order to accept the regression model, the following hypotheses is utilised with an alpha value of 0.05.

$$H_0: {\sigma^2}_{Regression} \leq {\sigma^2}_{Residual}$$
$$H_1: {\sigma^2}_{Regression} > {\sigma^2}_{Residual}$$

(5-8) Hypothesis testing setup for regression

This can be achieved by using a F test. The Excel regression tool provides both the F value as well as the critical value of F. If the F value is greater than the critical value of F, H_0 will be rejected. The second stage is to determine if the coefficients of *A* and *B* which are calculated by the regression model are acceptable or not. This is done using *t-tests*. Should the *P-value* be smaller than alpha (0.05), H_0 will be rejected. Otherwise H_0 will not be rejected.

$$H_0: \beta \leq 0$$
$$H_1: \beta > 0$$

(5-9) Hypothesis testing setup for regression slope

$$H_0: \alpha = 0$$
$$H_1: \alpha \neq 0$$

(5-10) Hypothesis testing setup for regression intercept.

The regression model is executed on the full data set Table A-4. The model produced a R^2 value of 0.831. The regression model produced the results presented in Table 5-7 and Table 5-8. With a P-value of 0.037 and 0.00000002162 for intercept and average historic hot-spot operating temperature respectively, the null hypothesis is rejected for both. It can be concluded that (5-11) is an acceptable representation of the relationship.

	F	*Critical F*
Regression	89.053	0.00000002162

Table 5-7: ANOVA Analysis for full data set

	Coefficients	*P-value*
Intercept	-19.996	0.037
Average historic hot-spot operating temperature	1.682	0.00000002162

Table 5-8: Regression model results based on full dataset.

The relationship is defined in (5-11), which in conjunction with (5-6) is the modified ageing model for Case One.

$$RT = [1.682 \times (average\ historic\ operating\ hot\ spot\ temperature)] - 19.996) \qquad (5\text{-}11)$$

5.7. Case Two Modified Ageing Model

Case Two was executed five times using the genetic algorithm. The complete set of results can be found in Table A-5, Table A-6 and Table A-7. These results are executed using correlation analysis. However, there is no significant correlation (>0.5) consistently found between the variables A_A, A_B and A_C and the input parameters load, hot-spot temperature or moisture. A weak correlation is found between A_A, A_C and average oxygen content. The application of these results will differ to what has been carried out for Case One.

	A_A	A_B	A_C	*LOAD*	*TEMP*	*MOISTURE*	*OXYGEN*
A_A	1						
A_B	0.142	1.000					
A_C	-0.425	0.486	1.000				
LOAD	0.046	-0.429	-0.521	1.000			
TEMP	-0.048	-0.471	-0.553	0.770	1.000		
MOISTURE	0.005	0.201	-0.195	0.224	0.122	1.000	
OXYGEN	0.636	-0.070	-0.651	0.018	0.010	0.061	1

Table 5-9: Correlation coefficient for Case Two results.

In order to utilise these results correctly, the minimum and maximum oxygen values for each transformer are derived. The minimum and maximum value is used to classify which results from the genetic algorithm should be accepted. If the oxygen content of a transformer never enters any of the three categorisation limits, then that results are neglected. A summary of this is presented in Table

5-10. If a transformer operates within the range of a category, a one is attributed, otherwise a zero is assigned.

Substation	**TRFR**	**Minimum O2**	**Maximum O2**	**A_A**	**A_B**	**A_C**
				<7000	**7000-16500**	**>16500**
ALPHA	1	785	24057	1	1	1
ALPHA	2	845	3856	1	0	0
THETA	1	14429	23654	0	1	1
THETA	2	8816.4	18981	0	1	1
DELTA	1	16119	25664	0	1	1
DELTA	2	17093	27638	0	0	1
ZETA	1	15986	30740	0	1	1
ZETA	2	16128	30936	0	1	1
KAPPA	1	21087	25460	0	0	1
KAPPA	2	9740	25679	0	1	1
PHI	1	15250	23347	0	1	1
PHI	2	15381	24293	0	1	1
LAMBDA	1	16358	22491	0	1	1
LAMBDA	2	15199	24815	0	1	1
SIGMA	1	17902	25449	0	0	1
SIGMA	2	17866	22033	0	0	1
RHO	1	24440	30592	0	0	1
RHO	2	25721	29530	0	0	1
TAU	1	1037	2057	1	0	0
TAU	2	973	2165	1	0	0

Table 5-10: Table showing minimum and maximum oxygen levels. The oxygen categories are included. If a transformer operates within the range of a category, a one is attributed, else a zero is attributed.

The complete set of results, in conjunction with the operating oxygen range, is used to determine the final variables A_A, A_B and A_C. In order to determine the value of these variables, the following steps are carried out:

1. Calculate the average variable (A_A, A_B and A_C) value per transformer from the five iterations output. (Based on Table A-5, Table A-6 and Table A-7)
2. Using Table 5-10, calculate the overall average of the variable if the transformer operates within given categories.

3. These results are placed back in the modified ageing equation for Case Two.

The calculation is provided for A_A. The first step is to calculate the average value per variable from the five iterations. The first step is presented in Table 5-11. This table also contains the selection criteria based on Table 5-10.

Substation	**Position**	**Average results of five iterations (A_A)**	**Transformer operates is category?**
ALPHA	1	159.98	1
ALPHA	2	176.66	1
THETA	1	214.53	0
THETA	2	435.95	0
DELTA	1	93.03	0
DELTA	2	518.51	0
ZETA	1	365.65	0
ZETA	2	582.89	0
KAPPA	1	498.14	0
KAPPA	2	374.01	0
PHI	1	176.89	0
PHI	2	138.19	0
LAMBDA	1	454.33	0
LAMBDA	2	489.29	0
SIGMA	1	462.51	0
SIGMA	2	314.26	0
RHO	1	485.93	0
RHO	2	395.38	0
TAU	1	195.93	1
TAU	2	105.35	1

Table 5-11: Results used for calculation of A_A

The second step is to take the average only if the transformer operates within the category constraints. For A_A only transformers Alpha 1, Alpha 2, Tau 1 and Tau 2 satisfy this constraint. The final value is determined to be the average of these four transformers. The final value for A_A is calculated at 159.47. The remaining variables A_B and A_C are calculated in a similar manner. The final results are presented in Table 5-12. These values, in conjunction with equation (5-3) are the modified ageing model for Case Two.

Oxygen Content	A_T	**Value**
<1000	A_{RT}	1
>1000 <= 7000	A_A	159.47
>7000 <=16500	A_B	235.27
> 16500	A_C	128.63

Table 5-12: Final Pre-exponent values for Case Two.

5.8. Case Three Modified Ageing Model

The results from Case Three are arranged in a similar manner to that of Case Two. Case Three results also showed low rates of correlation as presented in Table 5-13

	A_X	A_Y	A_Z	A_W	*LOAD*	*TEMP*	*MOISTURE*	*OXYGEN*
A_X	1							
A_Y	-0.120	1.000						
A_Z	0.031	-0.160	1.000					
A_W	0.264	-0.389	0.489	1.000				
LOAD	-0.404	0.153	-0.267	-0.424	1.000			
TEMP	-0.278	0.099	-0.029	-0.341	0.770	1.000		
MOISTURE	0.123	0.598	-0.421	-0.238	0.224	0.122	1.000	
OXYGEN	-0.279	0.001	-0.282	-0.035	0.018	0.010	0.061	1

Table 5-13: Correlation coefficients for Case Three result

In Case Three there are four variables. The method to determine the pre-exponent constant are the same as described in section 5.7 using the results found in Table A-8 through Table A-11 and Table 5-14. If a transformer operates within the range of a category, a one is attributed, else a zero is assigned.

Substation	**Transformer**	**Min H20**	**Max H20**	A_W	A_X	A_Y	A_Z
				1-2%	**2-3%**	**3-4%**	**>4%**
ALPHA	1	0.014721	0.0255	1	1	0	0
ALPHA	2	0.0217	0.02826	0	1	0	0
THETA	1	0.022401	0.03118	0	1	1	0
THETA	2	0.0124	0.0234	1	1	0	0
DELTA	1	0.030003	0.0363	0	0	1	0

DELTA	2	0.023077	0.0363	0	1	1	0
ZETA	1	0.023401	0.04048	0	1	1	1
ZETA	2	0.023401	0.04048	0	1	1	1
KAPPA	1	0.0218	0.0274	0	1	0	0
KAPPA	2	0.023	0.02784	0	1	0	0
PHI	1	0.023	0.0288	0	1	0	0
PHI	2	0.0265	0.0301	0	1	1	0
LAMBDA	1	0.02376	0.03228	0	1	1	0
LAMBDA	2	0.015601	0.03582	1	1	1	0
SIGMA	1	0.029	0.03552	0	1	1	0
SIGMA	2	0.03536	0.0452	0	0	1	1
RHO	1	0.0188	0.0265	1	1	0	0
RHO	2	0.027	0.0312	0	1	1	0
TAU	1	0.011202	0.035	1	1	1	0
TAU	2	0.020721	0.03582	0	1	1	0

Table 5-14: Table showing minimum and maximum moisture levels. The moisture categories are included. If a transformer operates within the range of a category, a one is attributed, else a zero is attributed.

The final pre-exponent values for Case Three are presented in Table 5-15. These value, in conjunction with equation (5-4) form the modified ageing model for Case Three.

Moisture	A_T	Value
<1%	A_{RT}	1
>=1% <2%	A_w	243.15
>=2% <3%	A_x	133.08
>=3% <4%	A_y	143.13
>4%	A_Z	1058.60

Table 5-15: Final pre-exponent values for Case Three.

5.9. Ageing Model Results

The results from the modified ageing models are compared to that of the four ageing models used in section 4.10. A modified algorithm (B.2) is used to include the new modified ageing models. The full set of DP loss results for the seven models can be found in Table A-12. The percentage variation results are presented in Table 5-16. The results are from the execution of the three modified ageing models (1) Case One (2) Case Two (3) and Case Three, which were run in the algorithm as used in section 4.10. The modified algorithm included the three new ageing models; which can be found in appendix B.2; with the parameters as defined in sections 5.6, 5.7 and 5.8. The results of the initial four ageing models calculated in section 4.10 are also included.

SUBSTATION + POSITION	IEC KRAFT % VARIATION	EMSEY % VARIATION	LUNGAARD % VARIATION	MARTIN % VARIATION	CASE ONE % VARIATION	CASE TWO % VARIATION	CASE THREE % VARIATION
ALPHA 1	-100%	-94%	-98%	-96%	-63%	-37%	-39%
ALPHA 2	-100%	-96%	-98%	-95%	-45%	-11%	-26%
THETA 1	-100%	-98%	-99%	-93%	-51%	-69%	-69%
THETA 2	-86%	-26%	-73%	-4%	-67%	950%	762%
DELTA 1	-97%	-69%	-87%	40%	48%	718%	501%
DELTA 2	-96%	-70%	-87%	62%	51%	430%	484%
ZETA 1	-100%	-97%	-99%	-83%	-15%	-39%	-35%
ZETA 2	-100%	-96%	-98%	-81%	-12%	-34%	-28%
KAPPA 1	-96%	-70%	-87%	20%	-55%	427%	445%
KAPPA 2	-95%	-56%	-81%	37%	-41%	1118%	706%
PHI 1	-93%	-54%	-81%	84%	291%	1448%	1413%
PHI 2	77%	483%	148%	1884%	105%	18397%	10753%
LAMBDA 1	-100%	-98%	-99%	-90%	-36%	-61%	-59%
LAMBDA 2	-98%	-81%	-92%	-20%	292%	202%	218%
SIGMA 1	-69%	127%	-3%	1187%	20%	3921%	4320%
SIGMA 2	-74%	580%	125%	1356%	-3%	3204%	21506%
RHO 1	-99%	-88%	-96%	-80%	72%	4%	34%
RHO 2	-99%	-94%	-97%	-71%	72%	9%	16%
TAU 1	-99%	-94%	-97%	-89%	-26%	29%	13%
TAU 2	-97%	-88%	-95%	-78%	11%	168%	126%
AVERAGE VARIATION	-86%	-9%	-65%	190%	27%	1539%	2052%

Table 5-16: Table of results for all seven ageing models under investigation. The results shown are the percentage variation.

As previously discussed, the use of the average variation value is not a good representation of the results. The extreme values influence the average variation value. The results are grouped into three categories as presented in Figure 4-6. A summary of the categorisation is presented in Figure 5-2 and Table 5-17.

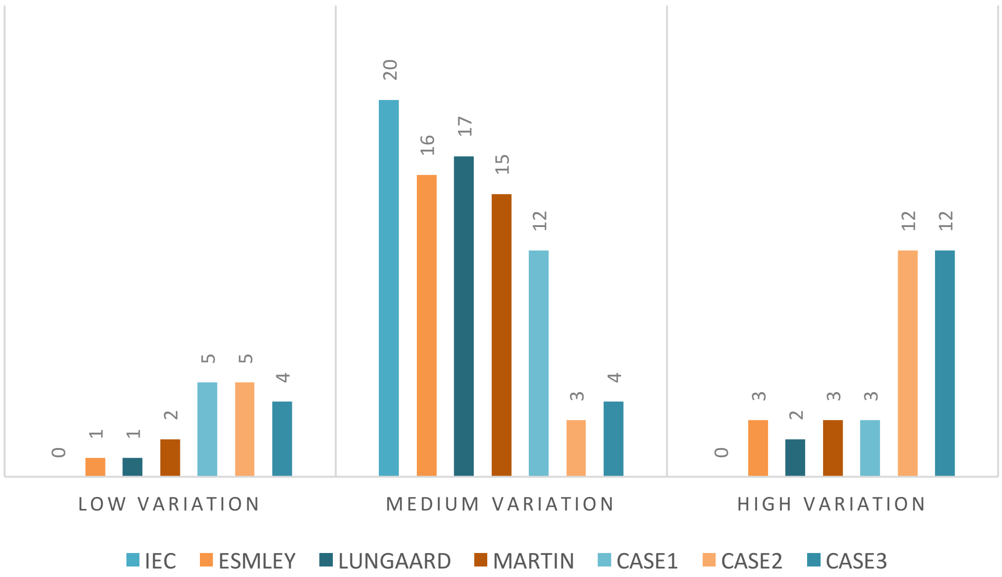

Figure 5-2: Figure which displays the number of transformers per ageing model which fall into the various variation categories.

Variation	**IEC**	**ESMLEY**	**LUNGAARD**	**MARTIN**	**CASE1**	**CASE2**	**CASE3**
Low	0	1	1	2	5	5	4
Medium	20	16	17	15	12	3	4
High	0	3	2	3	3	12	12

Table 5-17: Table showing the final results which fall into the specific accuracy categories as specified in Figure 4-6

In order to gain further insight, the results are further categorised. The categories consider whether the predicted value is an over or under estimation of the measured value. The categories are defined based on the percentage variation as the following:

< -50%	-50% to +50%	>50%
Underestimation	Acceptable	Overestimation

Figure 5-3: Limits used for under and overestimation categories.

Variation	**IEC**	**ESMLEY**	**LUNGAARD**	**MARTIN**	**CASE1**	**CASE2**	**CASE3**
Underestimation	19	14	17	10	2	2	1
Acceptable	0	3	1	5	12	7	8
Overestimation	1	3	2	5	6	11	11

Table 5-18: Table showing the final results which fall into the specific accuracy categories as specified in Figure 5-3.

5.10. Sensitivity Analysis

A limitation of this study is the absence of ambient temperature data. The algorithm developed, which can account for variation in ambient temperature, uses a fixed ambient temperature of 25°C in this study. This is the value used during the design of these power transformers. In order to test the robustness of the results, a sensitivity analysis is carried out. The analysis is carried out for extreme cases of ±15°C change in the fixed ambient temperature. The model results are shown in in tables 5-19 to 5-21.

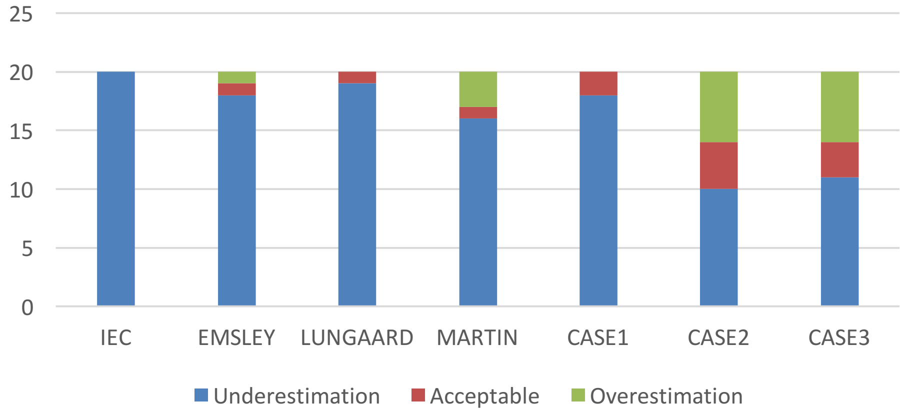

Figure 5-4: Chart showing the results which fall into the specific accuracy categories as specified in Figure 5-3 for a fixed ambient temperature of 10°C

Variation	IEC	ESMLEY	LUNGAARD	MARTIN	CASE1	CASE2	CASE3
Underestimation	20	18	19	16	18	10	11
Acceptable	0	1	1	1	2	4	3
Overestimation	0	1	0	3	0	6	6

Table 5-19: Table showing the results which fall into the specific accuracy categories as specified in Figure 5-3 for a fixed ambient temperature of 10°C

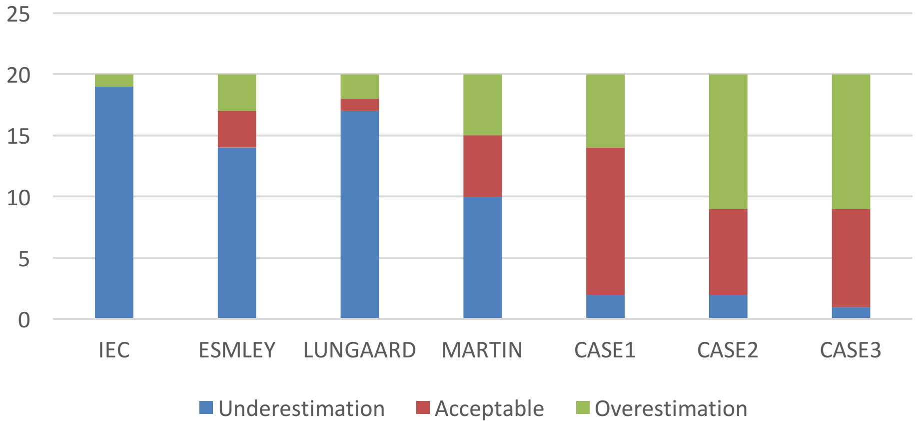

Figure 5-5: Chart showing the results which fall into the specific accuracy categories as specified in Figure 5-3 for a fixed ambient temperature of 25°C

Variation	IEC	ESMLEY	LUNGAARD	MARTIN	CASE1	CASE2	CASE3
Underestimation	19	14	17	10	2	2	1
Acceptable	0	3	1	5	12	7	8
Overestimation	1	3	2	5	6	11	11

Table 5-20: Table showing the final results which fall into the specific accuracy categories as specified in Figure 5-3 for a fixed ambient temperature of 25°C

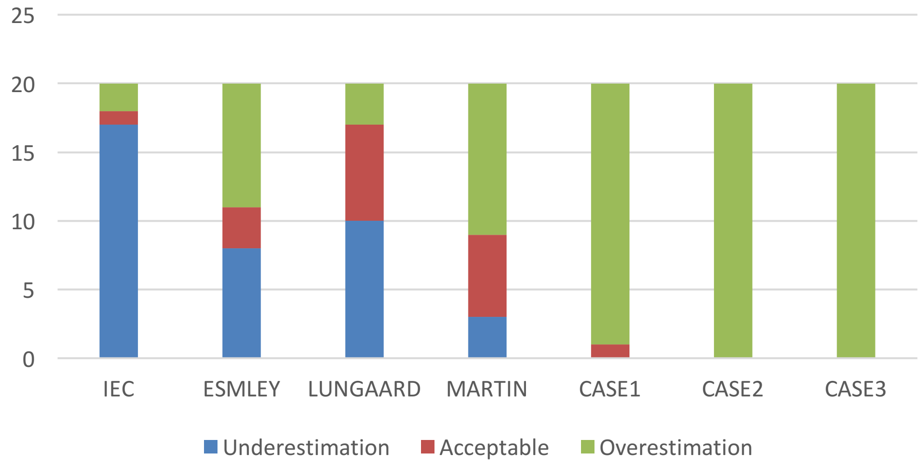

Figure 5-6: Chart showing the results which fall into the specific accuracy categories as specified in Figure 5-3 for a fixed ambient temperature of 40°C

Variation	IEC	ESMLEY	LUNGAARD	MARTIN	CASE1	CASE2	CASE3
Underestimation	17	8	10	3	0	0	0
Acceptable	1	3	7	6	1	0	0
Overestimation	2	9	3	11	19	20	20

Table 5-21: Table showing the final results which fall into the specific accuracy categories as specified in Figure 5-3 for a fixed ambient temperature of 40°C

The results show that all the models are sensitive to the ambient temperature. At 10°C all of the models exhibit an underestimation tendency. As the ambient temperature is increased the results move towards overestimations. IEC (2005), however, still has a majority underestimations in the results even at the 40°C ambient temperature. These results show that all the models are influenced by the ambient temperature. The sensitivity analysis indicates that further improvements to the model can be achieved with the incorporation of actual ambient temperature data. This data can be used to determine a more robust ageing model.

5.11. Ageing Model Interpretation

The results from the modified ageing models are presented in section 5.9. The modified ageing models produce more results in the low variation range in comparison to the initial four models used. Case One and Case Two presents the highest number in this category; which now account for 25%. Case Three also has results in this category which account for 20% respectively. Case One does however have more results within the medium variation category in comparison to Case Two. In addition, the new modified ageing models have a higher tendency to overestimate the age in comparison to the original four models which predominantly underestimated ageing.

When considering the three modified ageing models, Case One produces the largest improvement in the age estimation results. Its improvement lies in the number of predictions in the low variation category when compared to IEC, Emsley, Lungaard and Martin ageing model. In addition, the ageing model described by Case One is the simplest of the three modified models. It only accounts for hot-spot temperature, but it however reduces the reference temperature for ageing. This also makes the model easily implementable in practice. Furthermore, the formula uses the reduction of the reference ageing temperature to account for moisture and oxygen content above baseline.

The ageing estimation are to be used in the asset management of power transformers. Table 5-18 presents valuable information in this regard. It shows that while IEC, Emsley and Lungaard primarily produce results which underestimate the ageing of a transformer, Case One shifts the results into the categories of *reasonable* and *overestimation*. In terms of an asset management, an underestimation may result in no action being taken on the specified asset which may result in an unplanned breakdown. This can be due to lack of action as it is assumed the asset does not require any intervention. An overestimation, will however start off a further investigation process. In terms of power transformers, further investigation can entail oil and paper Furanic tests. This will confirm whether action is required or not.

The sensitivity analysis presented results which indicates the challenge when ambient temperature data is not available. All the ageing algorithms are dependent on the ambient operating temperature. The sensitivity analysis does indicate that the Case One model still produces better estimations which compared to other models. This also provides scope for further refinement of the modified ageing models in future work. If ambient temperature data is available in the future, a relook at the modified ageing models can be carried out to determine the optimal model which would be less sensitive to variations in ambient temperature. This is however still a case of a fixed ambient temperature. A real-world asset is subjected to a dynamic ambient temperature.

The Case One ageing model is recommended to be better suited for lightly loaded transformers when compared to the original four ageing models investigated. Case One improves the number of cases with a low variation and it also reduces the number of underestimations. This can allow asset managers to take proactive measures in order to reduce unplanned breakdowns.

5.12. Chapter Summary

This chapter produced three modified ageing models in a bid to improve the ageing estimation accuracy. The three ageing models are based on temperature, oxygen and moisture respectively. These models are designed and their relevant parameters are selected using a genetic algorithm optimisation method for each transformer. Using the generated results, a general ageing model is produced for each of the three cases. These three modified ageing models are executed through the same algorithm as was done with the initial four ageing models. Thereafter, the results of the modified ageing models are compared to the original four ageing models. These results indicate that the modified ageing models perform better when compared to the original models under investigation. The Case One model is selected to produce the most improvement in ageing estimation.

Chapter 6 Conclusions and Recommendations

The previous chapters have concluded the field work, presented results as well as interpretation thereof. This final chapter aims to summaries the study, its methodology and the outcome. Contributions to practice are also discussed. The chapter concludes with recommendations and future work which are possible based on the work done in this study.

6.1. Conclusion

This study set out to investigate the accuracy of ageing models when applied to lightly loaded distribution power transformers. The study begins with a literature study looking at the basics of transformer designs. The literature study presents the internal components and construction of a transformer. A transformer is made of two main components, the winding and the core. The core is covered with solid insulation; Kraft paper is a commonly used solid insulation.

The loss-of-life of a transformer is linked to the condition of the solid insulation as it is not ordinarily feasible to replace the solid insulation during the life of a transformer. The strength of solid insulation is measured via the Degree of Polymerisation of the paper (DP). This value is directly related to the physical strength of the solid insulation. The ageing mechanics are presented, which includes hydrolytic degradation, oxidative degradation and thermal degradation. These mechanics all degrade the strength of the solid insulation inside a transformer. A transformer degrades via these mechanics until it reaches the end-of-life criteria. A widely accepted physical end-of-life criteria is when the degree of polymerisation of the paper is equal to 200 or less.

Ageing models are presented which vary in the number of degradation factors which they take into account. These models vary from a single factor like hot-spot temperature, to multi factor models which take into account hot-spot temperature and moisture content, as well as hot-spot temperature, moisture content and oxygen content.

An algorithm is produced and validated using a known dataset as well as real world data which determines hot-spot temperature from transformer loading. It then calculates the loss-of-life of the transformer based on the ageing models selected. This algorithm is executed on a dataset of twenty transformers from a local transformer owner and operator. The data provided has certain limitations which is discussed and addressed. These twenty transformers are all lightly loaded transformers because they operate below 50% average loading.

The output of the ageing models selected are compared to the measured loss of Degree of Polymerisation. The measured value is determined by Furanic oil samples. Furanic oil sampling is an accepted method of determining the DP value of a transformer. This is a non-intrusive method of determining the current DP value of a transformer. While direct paper sampling is available, it is a complex process and requires a transformer to be removed from service.

The results from section 4.10 indicate that the available ageing models produce results with a high degree of variation between predicted and measured DP values. The majority of the results produced from the four selected ageing models produce underestimations of the transformer age. In order to produce a higher degree of accuracy, the study presents three new ageing models which may provide a lower degree of variation.

Three cases for modified ageing models are used. The first attempts to find the optimal reference temperature. The second model examines incorporating the oxygen content during the calculation of transformer ageing. The third model investigates the influence of moisture on the ageing of transformers. The three models undergo an optimisation process using a genetic algorithm to determine a general ageing model for each case. The three ageing models, in their general forms are executed on the full set of transformers to determine the accuracy of the new models in comparison to the original four models.

The modified models appear to generate ageing estimations with a lower variation rate in comparison to the four models originally selected. Case One ageing model produces the largest improvement and is based solely on the operating hot-spot temperature of a transformer. This ageing model reduces the reference temperature used for ageing. The new temperature is based on a function of the historical average hot-spot operating temperature of a transformer. The Case One ageing model is presented in (6-1) and (6-2). This is in the form of a relative ageing rate.

$$\left(e^{\frac{E}{R(RT+273)}} - e^{\frac{E}{R(T+273)}}\right) \tag{6-1}$$

$$RT = [1.682 \times (AHST)] - 19.996) \tag{6-2}$$

where
E = Activation Energy
R = Ideal gas constant (8.314 J mol^{-1} K^{-1})
T = Hot-spot temperature (Celsius)
RT = Reference temperature (Celsius) (6-2)
B = Regression slope
A = Regression intercept
AHST = Average historic operating Hot-spot temperature (3-year average)

6.2. Contributions to Practice

The modified ageing model presented reduce the variation between predicted and measured DP values when compared to other models investigated. However, this model is only applicable to lightly loaded transformers. This model can be used to improve the asset management of distribution of transformer.

Furanic oil sample comes with a financial cost associated to it. This model will be able to produce a basic prediction based on available information. This prediction can be used to optimise the selection of transformers which need to undergo Furanic sampling. This can increase the efficiency of transformer asset management while minimising the cost and without increasing transformer risk.

The ageing model presented is suitable for practical implementation due to its simplified format. The model only requires the hot-spot operating temperature, current and historic.

The modified ageing models provides evidence that increasing the number of variables taken into account does not necessarily improve the accuracy of the ageing model. Case One uses a single variable, hot-spot temperature, and it exhibits improvements over multivariable ageing models.

6.3. Recommendations and Future Work

The sample size is limited due to the data provided by the transformer owner. This is identified as a limitation in section 1.6. It is recommended that the selected ageing model be applied to a larger fleet of lightly loaded distribution power transformers. This will allow for the presented model to be tested further.

Future work can be carried out on the basis of this investigation to determine what the optimal time period for the historic hot-spot temperature should be. This work may further improve the accuracy of this ageing model.

A further in-depth study on a lightly loaded transformer with digital recordings of the hot-spot temperature, moisture and oxygen measurements can be used to further validate the modified ageing models.

Further work should be carried out with dynamic ambient temperature included in order to determine if the model presented still maintains its improvement with the additional data.

Appendix A Tables of Results

Substation	**Transformer position**	**IEC**	**Cooling type**	**Power rating (MVA)**	**High voltage rating (kV)**	**Medium voltage rating (kV)**	**High voltage full load current (amps)**	**Medium voltage full load current (amps)**
ALPHA	1	2003	ONAF	160	132	66	700	1400
ALPHA	2	2003	ONAF	160	132	66	700	1400
THETA	1	1993	ONAN	20	66	11	175	1050
THETA	2	1993	ONAN	20	66	11	175	1050
DELTA	1	1991	ONAN	20	66	11	175	1050
DELTA	2	1991	ONAN	20	66	11	175	1050
ZETA	1	1989	ONAN	10	132	22	44	263
ZETA	2	1989	ONAN	10	132	22	44	263
KAPPA	1	1970	ONAN	10	66	11	88	525
KAPPA	2	1970	ONAN	10	66	11	88	525
PHI	1	1988	ONAN	2	66	11	18	105
PHI	2	1988	ONAN	2	66	11	18	105
LAMBDA	1	1989	ONAN	10	66	11	88	525
LAMBDA	2	1989	ONAN	10	66	11	88	525
SIGMA	1	1989	ONAN	2	66	11	18	105
SIGMA	2	1989	ONAN	2	66	11	18	105
RHO	1	2014	ONAF	45	132	66	197	393
RHO	2	2014	ONAF	45	132	66	197	393
TAU	1	1999	ONAF	40	132	11	174	2100
TAU	2	1999	ONAF	40	132	11	174	2100
MEGA	1	2012	ONAN	20	132	11	88	1050
MEGA	2	2012	ONAN	20	132	11	88	1050

Table A-1: Transformer parameters used in study.

				Loss-of-life minutes			
Substation	**Transformer position**	**Total Time (Minutes)**	**Average Hot-spot temperature**	**IEC Kraft Paper Age (Minutes)**	**Emsley Age (Minutes)**	**Lungaard Age (Minutes)**	**Martin Age (Minutes)**
ALPHA	1	1580600	44.88	3686.5	68706	24282	50818
ALPHA	2	1580600	45.179	3871.2	32379	13805	43176
THETA	1	1580500	41.554	3444.1	27281	11631	1.20E+05
THETA	2	1580600	59.379	2.30E+05	1.23E+06	4.46E+05	1.58E+06
DELTA	1	1580500	50.265	9161.6	80750	34428	3.71E+05
DELTA	2	1580500	50.07	12563	95030	40516	5.14E+05
ZETA	1	1580000	42.128	2586.1	20923	8871.7	1.09E+05
ZETA	2	1580000	42.366	2662.8	21644	9177.7	1.13E+05
KAPPA	1	1580500	56.403	27138	2.27E+05	96799	9.16E+05
KAPPA	2	1580500	56.997	27851	2.33E+05	99268	7.26E+05
PHI	1	1580500	47.480	67863	4.34E+05	1.85E+05	1.75E+06
PHI	2	1580500	64.522	1.09E+06	3.59E+06	1.53E+06	1.22E+07
LAMBDA	1	1580500	41.443	2399.7	18953	8080.4	90448
LAMBDA	2	1580000	42.296	2758.3	27137	10940	1.14E+05
SIGMA	1	1580500	62.174	1.00E+05	7.31E+05	3.12E+05	4.14E+06
SIGMA	2	1580500	62.268	1.01E+05	2.67E+06	8.84E+05	5.73E+06
RHO	1	1580500	41.547	2500.6	40279	14470	67349
RHO	2	1580600	41.763	2616.7	20958	8935.3	99370
TAU	1	1580500	45.553	10980	64724	26898	1.09E+05
TAU	2	1580500	47.147	31168	1.23E+05	52557	2.19E+05

Table A-2: Transformer ageing calculated in loss-of-life in minutes

Substation	**Transformer position**	**Total Time (Minutes)**	**Measured DP loss from Furanic Oil samples**	**IEC Kraft Paper DP Loss**	**Emsley DP Loss**	**Lungaard DP Loss**	**Martin DP Loss**
ALPHA	1	1580600	88.571	0.27307	5.0893	1.7987	3.7643
ALPHA	2	1580600	59.048	0.28675	2.3984	1.0226	3.1982
THETA	1	1580500	120.304	0.25512	2.0208	0.86158	8.8667
THETA	2	1580600	122.465	17.006	91.011	33.009	117.33
DELTA	1	1580500	19.596	0.67864	5.9814	2.5502	27.468
DELTA	2	1580500	23.515	0.93058	7.0392	3.0012	38.074
ZETA	1	1580000	46.426	0.19156	1.5498	0.65716	8.0959
ZETA	2	1580000	43.695	0.19724	1.6032	0.67983	8.4056
KAPPA	1	1580500	56.455	2.0102	16.818	7.1703	67.885
KAPPA	2	1580500	39.173	2.0631	17.247	7.3531	53.812
PHI	1	1580500	70.428	5.0269	32.122	13.695	129.93
PHI	2	1580500	45.593	80.885	265.59	113.23	904.34
LAMBDA	1	1580500	65.115	0.17776	1.4039	0.59855	6.6999
LAMBDA	2	1580000	10.515	0.20432	2.0101	0.81035	8.4166
SIGMA	1	1580500	23.833	7.4218	54.169	23.095	306.78
SIGMA	2	1580500	29.157	7.4559	198.13	65.474	424.67
RHO	1	1580500	25.034	0.18523	2.9836	1.0718	4.9888
RHO	2	1580600	25.128	0.19383	1.5524	0.66188	7.3608
TAU	1	1580500	74.768	0.81337	4.7943	1.9925	8.103
TAU	2	1580500	74.763	2.3087	9.1313	3.8931	16.233

Table A-3: Transformer ageing calculated in loss-of-life in DP

Substation	Transformer	Execution Iteration					Average Result	Average Load	Average Hot-spot temperature
		1	2	3	4	5			
ALPHA	1	47.857	47.351	47.471	47.762	47.616	47.6114	26%	44.88
ALPHA	2	51.016	51.232	50.799	51.119	51.002	51.0336	26%	45.179
THETA	1	44.52	44.317	44.311	44.264	44.391	44.3606	19%	41.554
THETA	2	74.88	74.925	74.784	75.139	74.943	74.9342	48%	59.38
DELTA	1	67.294	68.126	69.1	67.662	67.569	67.9502	44%	50.264
DELTA	2	68.745	67.478	67.368	67.38	67.573	67.7088	44%	50.07
ZETA	1	49.533	49.931	49.785	49.738	49.208	49.639	22%	42.128
ZETA	2	49.963	50.867	49.876	50.858	50.228	50.3584	23%	42.366
KAPPA	1	67.483	67.775	67.682	67.649	67.696	67.657	32%	56.401
KAPPA	2	71.242	70.677	71.399	71.746	71.529	71.3186	32%	56.995
PHI	1	71.967	71.909	71.667	71.904	71.778	71.967	23%	47.408
PHI	2	96.558	96.021	96.166	96.746	96.551	96.4084	38%	64.522
LAMBDA	1	46.585	46.179	46.321	46.632	46.662	46.4758	26%	41.443
LAMBDA	2	62.777	62.674	62.356	61.473	60.836	62.0232	25%	42.296
SIGMA	1	86.227	87.259	86.931	86.542	86.944	86.7806	42%	62.174
SIGMA	2	85.057	84.595	83.712	85.197	84.381	84.5884	42%	62.268
RHO	1	55.282	54.62	56.056	55.558	56.197	55.5426	27%	41.547
RHO	2	55.249	55.759	56.945	55.894	55.778	55.925	27%	41.763
TAU	1	50.26	50.314	50.403	50.405	50.465	50.3694	29%	45.553
TAU	2	55.583	55.315	55.402	55.59	55.57	55.492	30%	47.147

Table A-4: Table of result from Case One investigation.

Substation	**TRFR**	EXECUTION ITERATION				
		1	2	3	4	5
ALPHA	1	150.71	209.53	279.69	1.4051	158.54
ALPHA	2	185.65	173.71	169.62	169.79	184.51
THETA	1	40.575	396.28	341.52	137	157.25
THETA	2	816.6	0	2	474.48	886.68
DELTA	1	3.1666	0.060791	398.39	1.0792	62.442
DELTA	2	574.65	998.53	576.59	368.42	74.374
ZETA	1	0	839.48	541.8	170.47	276.5
ZETA	2	18.563	880.97	665.89	900.59	448.44
KAPPA	1	448.94	973.16	469.01	528.29	71.289
KAPPA	2	22.12	1.3521	853.39	128.07	865.14
PHI	1	309.84	1.8307	494.75	75.762	2.25
PHI	2	1.1234	687.54	0.029568	1	1.2795
LAMBDA	1	309.43	395.67	519.83	357.05	689.65
LAMBDA	2	617	714.7	411.76	203.14	499.83
SIGMA	1	868.29	517.43	926.83	0	0
SIGMA	2	1	668.16	327.43	433.24	141.46
RHO	1	934.21	84.375	685.78	501.45	223.85
RHO	2	356.56	730.79	90.674	679.85	119.04
TAU	1	212.26	209.45	186.12	185.91	185.91
TAU	2	102.76	104.09	110.62	110.85	98.421

Table A-5 Table of results for Case Two variable A_A

Substation	**TRFR**	EXECUTION ITERATION				
		1	2	3	4	5
ALPHA	1	345.21	238.76	298.11	77.197	765.94
ALPHA	2	756.46	515.82	201.07	4.0224	804.7
THETA	1	975.23	180.37	117.48	319.77	219.82
THETA	2	13.064	13.573	0.27811	6.3934	10.29
DELTA	1	1.1846	0	0	0	0
DELTA	2	2	76.636	499.74	207.41	508.11
ZETA	1	233.83	0.14842	990.94	923.52	352.26
ZETA	2	52.024	296.31	645.37	539.05	214.32
KAPPA	1	752.85	70.423	832.26	646.05	833.62
KAPPA	2	0	26.381	24.102	27.381	24.004
PHI	1	1	119.79	39.573	31.211	107.03
PHI	2	1.25	1.25	0.12261	1	1
LAMBDA	1	846.24	813.63	629.67	372.13	958.95
LAMBDA	2	104.89	5.2236	34.518	476.45	462.59
SIGMA	1	1	483.18	0.3035	0	0
SIGMA	2	812.11	2.3681	868.79	328.74	751.4
RHO	1	338.39	717.52	512.69	212.95	432.05
RHO	2	429.45	233.1	846.46	532.25	855.88
TAU	1	240.2	659.55	449.39	858.52	836.72
TAU	2	423.96	612.76	480.65	403.11	765.05

Table A-6 Table of results for Case Two variable A_B

Substation	**TRFR**	EXECUTION ITERATION				
		1	2	3	4	5
ALPHA	1	218.24	781.08	559.35	903.91	600.83
ALPHA	2	74.449	725.78	673.1	403.17	453.68
THETA	1	463.37	454.25	444.69	455.34	384.22
THETA	2	12.655	28.731	50.997	0	1
DELTA	1	50.37	74.482	79.037	68.267	61.645
DELTA	2	24.727	19.826	28.549	24.384	28.962
ZETA	1	216.77	167.5	178.41	252.83	223.24
ZETA	2	198.24	188.25	179	201.79	225.48
KAPPA	1	22.924	26.349	26.231	23.054	25.618
KAPPA	2	0	0	0.92247	0.17674	56.37
PHI	1	0.3642	2.5811	2.5959	0	3.5
PHI	2	1.4761	2	27.612	1.0625	1.4216
LAMBDA	1	326.73	348.36	326.57	329.35	326.01
LAMBDA	2	9.6736	11.65	47.457	48.427	27.217
SIGMA	1	3	3	2.852	3.1072	3
SIGMA	2	3.25	3.9812	4	3.5	3.5
RHO	1	99.665	104.54	97.803	126.9	106.17
RHO	2	95.661	100.15	95.306	101.51	96.525
TAU	1	460.56	793.63	715.85	223.14	508.88
TAU	2	166.93	148.89	189.48	832.52	381.02

Table A-7 Table of results for Case Two variable A_C

Substation	**Transformer**	EXECUTION ITERATION				
		1	2	3	4	5
ALPHA	1	463.4	668.03	372.74	92.206	1
ALPHA	2	21.845	257.7	385.16	435.37	7054.8
THETA	1	730.47	9.5558	886.03	840.71	4260.9
THETA	2	27.371	30.233	9.75	0	4
DELTA	1	54.836	185.5	1.5293	6.2428	3.5625
DELTA	2	978.42	713.3	564.82	621.73	2663.2
ZETA	1	401.26	992.43	406	712.61	6577.9
ZETA	2	55.94	553	56.749	827.33	6730.9
KAPPA	1	172.01	3.9922	267.72	351.63	3422.4
KAPPA	2	462.68	34.51	845.26	258.25	10.75
PHI	1	0.015231	988.93	768.81	330.16	1.8032
PHI	2	434.89	1.25	584.84	0	6673.8
LAMBDA	1	710.88	84.609	793.18	697.91	4395.5
LAMBDA	2	971.17	0.21167	0	55.094	1.2529
SIGMA	1	0.83236	234.81	522.87	238.11	2
SIGMA	2	0.5625	1.1296	0.28421	155.94	3
RHO	1	218.04	328.08	83.04	267.1	419.22
RHO	2	0.15529	620.41	566.58	26.644	0
TAU	1	820.99	473.54	462.19	310.05	0
TAU	2	11.265	187.74	975.46	486.78	8055

Table A-8: Table of results for Case Three variable A_W

Substation	**Transformer**	EXECUTION ITERATION				
		1	2	3	4	5
ALPHA	1	190.43	83.622	232.37	392.49	426.01
ALPHA	2	200.59	184.33	186.81	190.43	197.59
THETA	1	470.54	371.82	351.02	489.87	306.66
THETA	2	0.00024414	0	12.054	18.959	14.943
DELTA	1	682.08	30.929	6.619	3.8281	2073.6
DELTA	2	203.27	170.44	80.311	2.8595	13
ZETA	1	548.39	478.87	83.511	564.4	466.06
ZETA	2	85.303	386.54	206.44	167.79	90.298
KAPPA	1	22.393	22.303	23.902	22.461	22.438
KAPPA	2	18.432	14.954	14.517	18.21	15
PHI	1	3.5	3.25	3.25	3.2812	3.5593
PHI	2	1	0.75	1	0.98301	1
LAMBDA	1	386.94	139.84	231.95	355.86	416.48
LAMBDA	2	0	123.56	125.15	102.05	0.78196
SIGMA	1	0	16.934	1.364	1.5	0.97016
SIGMA	2	1.0222	851.57	600.15	0.234	5360
RHO	1	43.794	0.060706	104.01	41.613	0
RHO	2	0	126.44	110.02	48.7	0
TAU	1	135.41	224.99	372.34	11.495	438.74
TAU	2	107.19	34.495	86.793	71.101	32.429

Table A-9 Table of results for Case Three variable A_X

Substation	**Transformer**	EXECUTION ITERATION				
		1	2	3	4	5
ALPHA	1	839.75	241.32	358.67	120.1	1095.7
ALPHA	2	252.74	238.8	487.6	851.41	3949.2
THETA	1	247.59	698.17	860.94	177.54	1106.5
THETA	2	0.53705	149.64	6.5	242.93	1.3281
DELTA	1	27.841	18.578	18.125	17.938	18.062
DELTA	2	0.49265	7.3152	20.875	25.656	20.875
ZETA	1	61.087	90.775	285.19	44.232	82.505
ZETA	2	233.87	83.132	207.73	226.08	148.18
KAPPA	1	5.7253	4.4164	515.06	295.03	2.25
KAPPA	2	518.37	402.03	827.4	915.08	8596.1
PHI	1	1.6865	313.85	377.69	1	1359.3
PHI	2	1.4996	2.3125	1.25	1.1736	1.1944
LAMBDA	1	299.73	490.74	420.9	311.31	319.75
LAMBDA	2	1.8756	2.5107	0.75402	46.818	73.858
SIGMA	1	4.647	0.66405	2.8727	3.2591	3
SIGMA	2	19.202	2.6592	10.195	12.844	4.25
RHO	1	12.936	195.72	999.63	117.29	0.099901
RHO	2	269.35	62.1	86.418	217.25	200.36
TAU	1	204.19	163.79	19.575	353.34	0.25
TAU	2	74.036	265.1	166.78	187.96	264.31

Table A-10 Table of results for Case Three variable A_Y

Substation	**Transformer**	EXECUTION ITERATION				
		1	2	3	4	5
ALPHA	1	536.82	109.26	3.101	634.76	2352.1
ALPHA	2	556.04	994.15	783.94	501.82	7377.1
THETA	1	406.95	928.63	237.54	667.44	4727.3
THETA	2	985.53	704.13	720.5	76.857	1.1434
DELTA	1	487.64	590.75	172.2	3.2837	1.188
DELTA	2	119.48	70.378	82.382	998.52	7463.8
ZETA	1	853.93	531.69	460.94	492.54	1473.6
ZETA	2	693.93	855.16	327.94	326.54	9853.3
KAPPA	1	253.55	8.4191	499.41	161.45	4
KAPPA	2	510.19	208.29	753.84	418.08	8726.6
PHI	1	2.3904	511.07	29.751	0.26299	7262.1
PHI	2	1	0.25	688.24	0	5995.6
LAMBDA	1	762.35	105.12	552.59	234.32	369.24
LAMBDA	2	0	0	688.66	834.62	5855.1
SIGMA	1	623.64	150.8	85.665	182.47	2
SIGMA	2	0	3.5	1.5	1.4358	3.0512
RHO	1	733.73	0.60193	297.37	526.93	5162
RHO	2	1	400.5	343.02	487.9	5203.8
TAU	1	152.67	132.22	963.81	282.23	3063.8
TAU	2	627.19	859.14	302.96	83.996	62.356

Table A-11: Table of results for Case Three variable A_Z

Substation	Transformer position	Measured DP loss	IEC Kraft Paper DP Loss	Emsley DP Loss	Lungaard DP Loss	Martin DP Loss	Case One DP Loss	Case Two DP Loss	Case Three DP Loss
ALPHA	1	88.571	0.273	5.089	1.799	3.764	32.927	56.153	54.051
ALPHA	2	59.048	0.287	2.398	1.023	3.198	32.520	52.603	43.898
THETA	1	120.304	0.255	2.021	0.862	8.867	58.965	37.893	37.490
THETA	2	122.465	17.006	91.011	33.009	117.330	41.022	1286.200	1055.500
DELTA	1	19.596	0.679	5.981	2.550	27.468	29.000	160.390	117.740
DELTA	2	23.515	0.931	7.039	3.001	38.074	35.460	124.530	137.270
ZETA	1	46.426	0.192	1.550	0.657	8.096	39.273	28.146	30.256
ZETA	2	43.695	0.197	1.603	0.680	8.406	38.615	28.792	31.297
KAPPA	1	56.455	2.010	16.818	7.170	67.885	25.211	297.520	307.810
KAPPA	2	39.173	2.063	17.247	7.353	53.812	23.163	477.050	315.660
PHI	1	70.428	31.860	58.223	24.823	241.540	275.690	1090.300	1065.600
PHI	2	45.593	80.885	265.590	113.230	904.340	93.372	8433.400	4948.400
LAMBDA	1	65.115	0.178	1.404	0.599	6.700	41.956	25.172	26.766
LAMBDA	2	10.515	0.204	2.010	0.810	8.417	41.235	31.780	33.431
SIGMA	1	23.833	7.422	54.169	23.095	306.780	28.635	958.290	1053.500
SIGMA	2	29.157	7.456	198.130	65.474	424.670	28.314	963.280	6299.800
RHO	1	25.034	0.185	2.984	1.072	4.989	42.936	25.993	33.517
RHO	2	25.128	0.194	1.552	0.662	7.361	43.306	27.464	29.206
TAU	1	74.768	0.813	4.794	1.993	8.103	55.264	96.592	84.251
TAU	2	74.763	2.309	9.131	3.893	16.233	82.637	200.270	169.170

Table A-12: Table of results for all ageing models including the three cases of modified ageing models.

Appendix B MATLAB Code

This appendix contains the MATLAB code developed and used for this study.

B.1 AGEING_CALV_FINALV.m

```
%%12 sorted out most hotspot bugs.
%13 changed output to include input.
%14 auto naming of output file + calculation of total time in minutes.
%15 output final data plus time. and estimated dp loss based on 180
%000hours with dpstart and dpend
%16 include martin and lungaard ageing moisture calc
%17 modify transformer parameters to that of medium size distribution -
%Note for ONAF
%18 add in protection limit of 150 celcius
%18.1
%20 try to normalise kinetic to ageing. Solved
%30 modify activation energy value.
%40 optimise activation energy.
%50 CHANGED OR STATEMENT TO AND. Calculates all transformers at once

clearvars;

%filename = input('File to load?','s');
global transformers;
global cooling;
global dp_estimate;


for tr = 1:20
filename = transformers(tr)
%trfrtype = input('Cooling type?','s')
trfrtype = cooling(tr);
K = xlsread(filename); %K =     %load factor load/rated load
intr = size(K,1);
intc = size(K,2);


for a = 1:intr
    K(a,intc+1) = K(a,1) + 693960; % modifier to make MATLAB date = excel date
    date(a) = K(a,intc+1);
    load(a) = K(a,4);
    moisture(a) = K(a,5);
    oxy(a) = K(a,6);

end

 t21=datevec(K(2,intc+1));
 t11=datevec(K(intr,intc+1));
 totalt = etime(t11,t21);
 totalt = totalt/60;    %total minutes covered

 data(1) = totalt;
 %Transformer Characteristic Design variables
if  (trfrtype == 'ONAN')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=210;
    tw=10;
elseif(trfrtype == 'ONAF')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=150;
    tw=7;
end

dpstart=1000;
dpend=200;
```

```
act_energy = -111000; %non rearragned equation.

paper = 98; %paper ageing temp 110 for upgraded 98 for normal

%initial conditions
top_oil(1) = ((((1+(K(1,4).^2*R))/(1+R))^x) * Or) + Oa;   %C1 initial condition
h1(1) = k21 * K(1,4).^y * hr; %C3 initial value
h2(1) = (k21-1) * K(1,4).^y * hr; %C4 initial value

losslife_IEC_IEEE(1) = 0;
losslife_iec_ntu(1)=0;
losslife_rated(1)=0;
losslife_martin(1)=0;
losslife_emsley(1)=0;
losslife_lungaard(1)=0;
count =1;

    k_martin_110_05 = ((1.78e12)*0.005^2 + 1.10e10*0.005+5.28e7)*exp(act_energy/(8.3145*(273+110)));
    k_martin_98_05 = ((1.78e12)*0.005^2 + 1.10e10*0.005+5.28e7)*exp(act_energy/(8.3145*(273+98)));

    k_emsley_upgraded_110 = 3.65e7 * exp(act_energy/(8.3145*(273+98)));
    k_emsley_dry_kraft_98 = 1.07e8 * exp(act_energy/(8.3145*(273+98)));

    k_lungaard_upgraded_110 = 6.7e7 * exp(act_energy/(8.3145*(273+98)));
    k_lungaard_dry_kraft_98 = (2e8 * exp(act_energy/(8.3145*(273+98))));

    hotspot_rise(1) = h1(1) - h2(1);
    hotspot = top_oil(1) + hotspot_rise(1);

    %itirative calculation
    for t = 2:intr

        t2=datevec(K(t,intc+1));
        t1=datevec(K(t-1,intc+1));

        deltat = etime(t2,t1);
        deltat = deltat/60;

        deltatage = deltat;
        if deltat >=60 deltat=60 ;
        end

        delta_oil_top(t) = (deltat/(k11*t0)) * ((((1+K(t,4).^2*R)/(1+R))^x)*Or  - ((top_oil(t-1) -K(t,3)))
);
        top_oil(t) = top_oil(t-1) + delta_oil_top(t);
        delta_h1(t) = (deltat/(k22*tw))   *   (k21*hr*K(t,4)^y - h1(t-1));
        h1(t) = h1(t-1) + delta_h1(t);
        delta_h2(t) = (deltat/((1/k22)*t0))     *   ((k21-1)*hr*K(t,4)^y - h2(t-1));
        h2(t) = h2(t-1) + delta_h2(t);
        hotspot_rise(t) = h1(t) - h2(t);
        hotspot_cal(t) = hotspot_rise(t) + top_oil(t);

        if (hotspot_cal(t) >160)
            hotspot(t) = 160;
        elseif(hotspot_cal(t)<10)
            hotspot(t) = 10;
        else hotspot(t) = hotspot_cal(t);
        end

        %Ageing at rated rate
        losslife_rated(t) = losslife_rated(t-1) + deltatage;

        %loss-of-life calculation IEEE and IEC thermally upgraded
        deltalosslife_IEC_IEEE(t) = (deltatage) * (exp((15000/(110 + 273))-(15000/(hotspot(t)+273))));
        losslife_IEC_IEEE(t) = losslife_IEC_IEEE(t-1) + deltalosslife_IEC_IEEE(t); %min

        %loss-of-life IEC non thermally upgraded
        deltalosslife_iec_ntu(t) = (deltatage) * 2.^((hotspot(t)-98)/6);
        losslife_iec_ntu(t) = losslife_iec_ntu(t-1) + deltalosslife_iec_ntu(t); %min

        %Martin et al updated model to determine the life remaining of
        %transoformer
        water(t) = K(t,5);
        oxygen(t) = K(t,6);

        if (oxygen(t) < 7000)
            %low oxygen(t) - water(t)(t) input
            k_martin_temp = ((1.78e12)*water(t)^2 + 1.10e10*water(t) +
5.28e7)*exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (oxygen(t) >=7000 && oxygen(t) < 16500)
            %Medium oxygen(t) - water(t)(t) input
            k_martin_temp = ((2.07e12)*water(t)^2 + 5.61e10*water(t) +
2.31e8)*exp(act_energy/(8.3145*(273+hotspot(t))));
        else (oxygen(t) >= 16500);
            %High oxygen(t) - water(t) input
            k_martin_temp = ((2.29e12)*water(t)^2 + 9.78e10*water(t) +
3.86e8)*exp(act_energy/(8.3145*(273+hotspot(t))));
```

```
        end

        deltalosslife_martin(t) = deltatage* (k_martin_temp/k_martin_98_05);
        losslife_martin(t) = losslife_martin(t-1) + deltalosslife_martin(t);

        %Emsley
        if (water(t) <0.01)
            k_emsley_temp = 1.07e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t) >= 0.01 && water(t) < 0.002)
            k_emsley_temp = 3.5e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t)>=0.02 && water(t) <0.04)
            k_emsley_temp = 7.78e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        else (water(t) >= 0.04);
            k_emsley_temp = 3.47e9 * exp(act_energy/(8.3145*(273+hotspot(t))));
        end
        deltalosslife_emsley(t) = deltatage* (k_emsley_temp/k_emsley_dry_kraft_98);
        losslife_emsley(t) = losslife_emsley(t-1) + deltalosslife_emsley(t);

        %Lungaard
        if (water(t) <0.01)
            k_lungaard_temp = 2e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t) >= 0.01 && water(t) < 0.002)
            k_lungaard_temp = 6.2e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t)>=0.02 && water(t) <0.04)
            k_lungaard_temp = 6.2e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        else (water(t) >= 0.04);
            k_lungaard_temp = 21e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        end
        deltalosslife_lungaard(t) = deltatage* (k_lungaard_temp/k_lungaard_dry_kraft_98);
        losslife_lungaard(t) = losslife_lungaard(t-1) + deltalosslife_lungaard(t);

    end

data(2) = losslife_iec_ntu(intr);
data(3) = losslife_IEC_IEEE(intr);
data(4) = losslife_rated(intr);
data(5) = losslife_martin(intr);
data(6) = losslife_emsley(intr);
data(7) = losslife_lungaard(intr);
data(8) = 1;
data(9) = 1;

%store final data to be able to do direct comparison


%dDp loss - Loss-of-life is done per hour.
dploss = (dpstart-dpend)/(180000); % PER HOUR

%Export data
%output = [date.',load.',moisture.',oxy.',hotspot.', losslife_iec_ntu.',
losslife_IEC_IEEE.',losslife_rated.',losslife_martin.',losslife_emsley.',losslife_lungaard.'];
optimise(tr,1) = data(1); % Total time;
optimise(tr,2) = (data(2)/60)*dploss;
optimise(tr,3) = (data(3)/60)*dploss;
optimise(tr,4) = (data(4)/60)*dploss;
optimise(tr,5) = (data(5)/60)*dploss;
optimise(tr,6) = (data(6)/60)*dploss;
optimise(tr,7) = (data(7)/60)*dploss;
optimise(tr,8) = mean(load);
optimise(tr,9) = mean(hotspot);
optimise(tr,10) = mean(water);
optimise(tr,11) = mean(oxygen);
oxyt=sort(oxygen(:));
optimise(tr,12) = oxyt(2);
% optimise(tr,12) = min(oxygen);
optimise(tr,13) = max(oxygen);
wtr =sort(water(:));
optimise(tr,14) = wtr(2);
optimise(tr,15) = max(water);
ld = sort(load(:));
optimise(tr,16) = ld(2);
optimise(tr,17) = max(load);
optimise(tr,18) = min(hotspot);
optimise(tr,19) = max(hotspot);
optimise(tr,20) = dp_estimate(tr);
optimise(tr,21) = data(1); % Total time;
optimise(tr,22) = data(2);
optimise(tr,23) = data(3);
optimise(tr,24) = data(4);
optimise(tr,25) = data(5);
optimise(tr,26) = data(6);
optimise(tr,27) = data(7);

count = count +1;

clearvars K intr intc oxy oxygen moisture water;
```

```
cooling =
["ONAF","ONAF","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","
ONAN","ONAF","ONAF","ONAF","ONAF"];
transformers = ["BELHAR T1","BELHAR T2","BELHAR T11","BELHAR T12","BLACKHEATH T1", "BLACKHEATH
T2","BUFFELSPOORT T1", "BUFFELSPOORT T2", "CALEDON T1", "CALEDON T2","HAMMANSHOF T1","HAMMANSHOF T2","HEX
T11","HEX T12","KLIPDALE T1","KLIPDALE T2","KLIPDRIFT T1","KLIPDRIFT T2","RIETVLEI T1","RIETVLEI T2"];
dp_estimate = [88.57 59.05 120.30 122.47 19.60 23.52 46.43 43.69 56.46 39.17 70.43 45.59 65.11 10.51 23.83
29.16 20.2 20.5 74.77 74.76];

end
file_output = "AGEING_OUTPUT_FINAL_V2"
%xlswrite(file_output,data)
xlswrite(file_output,optimise)
%csvwrite(file_output,data)
```

B.2 MODIFIED_AGEING_ALL.m

```
%%12 sorted out most hotspot bugs.
%13 changed output to include input.
%14 auto naming of output file + calculation of total time in minutes.
%15 output final data plus time. and estimated dp loss based on 180
%000hours with dpstart and dpend
%16 include martin and lungaard ageing moisture calc
%17 modify transformer parameters to that of medium size distribution -
%Note for ONAF
%18 add in protection limit of 150 celcius
%18.1
%20 try to normalise kinetic to ageing. Solved
%30 modify activation energy value.
%40 optimise activation energy.
%50 CHANGED OR STATEMENT TO AND. Calculates all transformers at once

clearvars;

%filename = input('File to load?','s');
global transformers;
global cooling;
global dp_estimate;
global RT;


for tr = 1:20
filename = transformers(tr)
%trfrtype = input('Cooling type?','s')
trfrtype = cooling(tr);
K = xlsread(filename); %K =     %load factor load/rated load
intr = size(K,1);
intc = size(K,2);
rt = RT(tr);


for a = 1:intr
    K(a,intc+1) = K(a,1) + 693960; % modifier to make MATLAB date = excel date
    date(a) = K(a,intc+1);
    load(a) = K(a,4);
    moisture(a) = K(a,5);
    oxy(a) = K(a,6);

end

 t21=datevec(K(2,intc+1));
 t11=datevec(K(intr,intc+1));
 totalt = etime(t11,t21);
 totalt = totalt/60;    %total minutes covered

 data(1) = totalt;
 %Transformer Characteristic Design variables
if  (trfrtype == 'ONAN')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=210;
    tw=10;
elseif(trfrtype == 'ONAF')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
```

```
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=150;
    tw=7;
end

dpstart=1000;
dpend=200;
act_energy = -111000; %non rearragned equation.

paper = 98; %paper ageing temp 110 for upgraded 98 for normal

%initial conditions
top_oil(1) = ((((1+(K(1,4).^2*R))/(1+R))^x) * Or) + Oa;   %C1 initial condition
h1(1) = k21 * K(1,4).^y * hr; %C3 initial value
h2(1) = (k21-1) * K(1,4).^y * hr; %C4 initial value

losslife_IEC_IEEE(1) = 0;
losslife_iec_ntu(1)=0;
losslife_rated(1)=0;
losslife_martin(1)=0;
losslife_emsley(1)=0;
losslife_lungaard(1)=0;
losslife_case1(1)=0;
losslife_case2(1)=0;
losslife_case3(1)=0;
count =1;

    k_martin_110_05 = ((1.78e12)*0.005^2 + 1.10e10*0.005+5.28e7)*exp(act_energy/(8.3145*(273+110)));
    k_martin_98_05 = ((1.78e12)*0.005^2 + 1.10e10*0.005+5.28e7)*exp(act_energy/(8.3145*(273+98)));

    k_emsley_upgraded_110 = 3.65e7 * exp(act_energy/(8.3145*(273+98)));
    k_emsley_dry_kraft_98 = 1.07e8 * exp(act_energy/(8.3145*(273+98)));

    k_lungaard_upgraded_110 = 6.7e7 * exp(act_energy/(8.3145*(273+98)));
    k_lungaard_dry_kraft_98 = (2e8 * exp(act_energy/(8.3145*(273+98))));

    k_case2_base =(1)*exp(act_energy/(8.3145*(273+98)));
    k_case3_base = (1)*exp(act_energy/(8.3145*(273+98)));

    hotspot_rise(1) = h1(1) - h2(1);
    hotspot = top_oil(1) + hotspot_rise(1);

    %itirative calculation
    for t = 2:intr

        t2=datevec(K(t,intc+1));
        t1=datevec(K(t-1,intc+1));

        deltat = etime(t2,t1);
        deltat = deltat/60;

        deltatage = deltat;
        if deltat >=60 deltat=60 ;
        end

        delta_oil_top(t) = (deltat/(k11*t0)) * ((((1+K(t,4).^2*R)/(1+R))^x)*Or  - ((top_oil(t-1) -K(t,3)))
);
        top_oil(t) = top_oil(t-1) + delta_oil_top(t);
        delta_h1(t) = (deltat/(k22*tw))   *   (k21*hr*K(t,4)^y - h1(t-1));
        h1(t) = h1(t-1) + delta_h1(t);
        delta_h2(t) = (deltat/((1/k22)*t0))     *   ((k21-1)*hr*K(t,4)^y - h2(t-1));
        h2(t) = h2(t-1) + delta_h2(t);
        hotspot_rise(t) = h1(t) - h2(t);
        hotspot_cal(t) = hotspot_rise(t) + top_oil(t);

        if (hotspot_cal(t) >160)
            hotspot(t) = 160;
        elseif(hotspot_cal(t)<10)
            hotspot(t) = 10;
        else hotspot(t) = hotspot_cal(t);
        end

        %Ageing at rated rate
        losslife_rated(t) = losslife_rated(t-1) + deltatage;

        %loss-of-life calculation IEEE and IEC thermally upgraded
        deltalosslife_IEC_IEEE(t) = (deltatage) * (exp((15000/(110 + 273))-(15000/(hotspot(t)+273))));
        losslife_IEC_IEEE(t) = losslife_IEC_IEEE(t-1) + deltalosslife_IEC_IEEE(t); %min

        %loss-of-life IEC non thermally upgraded
        deltalosslife_iec_ntu(t) = (deltatage) * 2.^((hotspot(t)-98)/6);
        losslife_iec_ntu(t) = losslife_iec_ntu(t-1) + deltalosslife_iec_ntu(t); %min

        %Martin et al updated model to determine the life remaining of
```

```
        %transoformer
        water(t) = K(t,5);
        oxygen(t) = K(t,6);

        if (oxygen(t) < 7000)
            %low oxygen(t) - water(t)(t) input
            k_martin_temp = ((1.78e12)*water(t)^2 + 1.10e10*water(t) +
5.28e7)*exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (oxygen(t) >=7000 && oxygen(t) < 16500)
            %Medium oxygen(t) - water(t)(t) input
            k_martin_temp = ((2.07e12)*water(t)^2 + 5.61e10*water(t) +
2.31e8)*exp(act_energy/(8.3145*(273+hotspot(t))));
        else (oxygen(t) >= 16500);
            %High oxygen(t) - water(t) input
            k_martin_temp = ((2.29e12)*water(t)^2 + 9.78e10*water(t) +
3.86e8)*exp(act_energy/(8.3145*(273+hotspot(t))));
        end

        deltalosslife_martin(t) = deltatage* (k_martin_temp/k_martin_98_05);
        losslife_martin(t) = losslife_martin(t-1) + deltalosslife_martin(t);

        %Emsley
        if (water(t) <0.01)
            k_emsley_temp = 1.07e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t) >= 0.01 && water(t) < 0.002)
            k_emsley_temp = 3.5e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t)>=0.02 && water(t) <0.04)
            k_emsley_temp = 7.78e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        else (water(t) >= 0.04);
            k_emsley_temp = 3.47e9 * exp(act_energy/(8.3145*(273+hotspot(t))));
        end
        deltalosslife_emsley(t) = deltatage* (k_emsley_temp/k_emsley_dry_kraft_98);
        losslife_emsley(t) = losslife_emsley(t-1) + deltalosslife_emsley(t);

        %Lungaard
        if (water(t) <0.01)
            k_lungaard_temp = 2e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t) >= 0.01 && water(t) < 0.002)
            k_lungaard_temp = 6.2e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif (water(t)>=0.02 && water(t) <0.04)
            k_lungaard_temp = 6.2e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        else (water(t) >= 0.04);
            k_lungaard_temp = 21e8 * exp(act_energy/(8.3145*(273+hotspot(t))));
        end
        deltalosslife_lungaard(t) = deltatage* (k_lungaard_temp/k_lungaard_dry_kraft_98);
        losslife_lungaard(t) = losslife_lungaard(t-1) + deltalosslife_lungaard(t);

         %loss-of-life calculation CASE ONE RESULTS
        deltalosslife_case1(t) = (deltatage) * (exp((-act_energy/(8.3145*(rt + 273)))-(-
act_energy/(8.3145*(hotspot(t)+273)))));
        losslife_case1(t) = losslife_case1(t-1) + deltalosslife_case1(t); %min


        %CASE TWO 3 variable
        if ((oxygen(t) < 7000))%low oxygen(t) - water(t)(t) input
            k_case2= 159.47 * exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif ((oxygen(t) >=7000) && (oxygen(t) < 16500))%Medium oxygen(t) - water(t)(t) input
            k_case2=235.27 * exp(act_energy/(8.3145*(273+hotspot(t))));
        else ((oxygen(t) >= 16500)); %High oxygen(t) - water(t) input
            k_case2=128.63 * exp(act_energy/(8.3145*(273+hotspot(t))));
        end
        deltalosslife_case2(t) = deltatage* (k_case2/k_case2_base);
        losslife_case2(t) = losslife_case2(t-1) + deltalosslife_case2(t);

                %loss-of-life calculation CASE THREE 4 variable RESULTS
        if ((water(t) >=0.01 && water(t) <0.02))
                k_case3 = (243.15)*exp(act_energy/(8.3145*(273+hotspot(t))));
            elseif ((water(t) >=0.02 && water(t) <0.03))
                k_case3 = (133.08)*exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif ((water(t) >=0.03 && water(t) <0.04))
                k_case3 = (143.13)*exp(act_energy/(8.3145*(273+hotspot(t))));
        else (water(t) >=0.04);
            k_case3 = (1058.60)*exp(act_energy/(8.3145*(273+hotspot(t))));
        end
        deltalosslife_case3(t) = deltatage* (k_case3/k_case3_base);
        losslife_case3(t) = losslife_case3(t-1) + deltalosslife_case3(t);

    end

data(2) = losslife_iec_ntu(intr);
data(3) = losslife_IEC_IEEE(intr);
data(4) = losslife_rated(intr);
data(5) = losslife_martin(intr);
data(6) = losslife_emsley(intr);
data(7) = losslife_lungaard(intr);
data(8) = losslife_case1(intr);
data(9) = losslife_case2(intr);
```

```
data(10) = losslife_case3(intr);

%store final data to be able to do direct comparison


%dDp loss - Loss-of-life is done per hour.
dploss = (dpstart-dpend)/(180000); % PER HOUR

%Export data
%output = [date.',load.',moisture.',oxy.',hotspot.', losslife_iec_ntu.',
losslife_IEC_IEEE.',losslife_rated.',losslife_martin.',losslife_emsley.',losslife_lungaard.'];
optimise(tr,1) = data(1); % Total time;
optimise(tr,2) = (data(2)/60)*dploss;
optimise(tr,3) = (data(3)/60)*dploss;
optimise(tr,4) = (data(4)/60)*dploss;
optimise(tr,5) = (data(5)/60)*dploss;
optimise(tr,6) = (data(6)/60)*dploss;
optimise(tr,7) = (data(7)/60)*dploss;
optimise(tr,8) = (data(8)/60)*dploss; %CASE1
optimise(tr,9) = (data(9)/60)*dploss; %CASE2
optimise(tr,10) = (data(10)/60)*dploss; %CASE3
optimise(tr,11) = mean(oxygen);
oxyt=sort(oxygen(:));
optimise(tr,12) = oxyt(2);
% optimise(tr,12) = min(oxygen);
optimise(tr,13) = max(oxygen);
wtr =sort(water(:));
optimise(tr,14) = wtr(2);
optimise(tr,15) = max(water);
ld = sort(load(:));
optimise(tr,16) = ld(2);
optimise(tr,17) = max(load);
optimise(tr,18) = min(hotspot);
optimise(tr,19) = max(hotspot);
optimise(tr,20) = dp_estimate(tr);

count = count +1;

clearvars K intr intc oxy oxygen moisture water;

cooling =
["ONAF","ONAF","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","ONAN","
ONAN","ONAF","ONAF","ONAF","ONAF"];
transformers = ["BELHAR T1","BELHAR T2","BELHAR T11","BELHAR T12","BLACKHEATH T1", "BLACKHEATH
T2","BUFFELSPOORT T1", "BUFFELSPOORT T2", "CALEDON T1", "CALEDON T2","HAMMANSHOF T1","HAMMANSHOF T2","HEX
T11","HEX T12","KLIPDALE T1","KLIPDALE T2","KLIPDRIFT T1","KLIPDRIFT T2","RIETVLEI T1","RIETVLEI T2"];
dp_estimate = [88.57 59.05 120.30 122.47 19.60 23.52 46.43 43.69 56.46 39.17 70.43 45.59 65.11 10.51 23.83
29.16 20.2 20.5 74.77 74.76];

end
file_output = "AGEING_MODIFIED_ALL_V2"
%xlswrite(file_output,data)
xlswrite(file_output,optimise)
%csvwrite(file_output,data)
```

B.3 OPTIMISATION.m

```
global K;
global dpesti;
global UB;
global LB;
global transformers;
global dp_estimate;

LB = [0 0 0 0];           %Lower bound for each variable
UB = [1000 1000 1000 1000];      % upper bound for each variable

fit = @ageing_calc_case1; % fitness function

for int = 1:5

for tr = 1:20 %transformers to go through.
filename = transformers(tr);
options = optimoptions('ga','FitnessLimit',2,'MaxGenerations',100);
K = xlsread(filename);
dpesti = dp_estimate(tr);

    [x,Fval] = ga(fit,1,[],[],[],[],LB,UB,[],[],options);
    fval(int) = Fval
    v(tr,:)= x
    val(tr,int) = Fval;
    dp(tr,int) = dpesti;

end
```

```
file_output = "OPTIMISATION_OUTPUT_CASE1_Hammans" + int;
xlswrite(file_output,[v,val,dp])
clearvars v val dp
end
```

B.4 AGEING_CALC_CASE1.m

```
function accuracy = ageing_calc_case1(w)
%AGEING CALCULATION BASED ON ARHHNIEUS EQUATION FORM
% FROM 10 TO 200
% filename = input('File to load?','s');
% trfrtype = input('Cooling type?','s');
% dpesti = input('Estimated DP Loss');

%filename = 'KLIPDALE T2';
%trfrtype = 'ONAN';
%dpesti = 29;


global K;
global trfrtype;
global dpesti;
%K = xlsread(filename); %K =     %load factor load/rated load

intr = size(K,1);
intc = size(K,2);

%Water factor

for a = 1:intr
    K(a,intc+1) = K(a,1) + 693960; % modifier to make MATLAB date = excel date
    date(a) = K(a,intc+1);
    load(a) = K(a,4);
    moisture(a) = K(a,5);
    oxy(a) = K(a,6);

end

 t21=datevec(K(2,intc+1));
 t11=datevec(K(intr,intc+1));
 totalt = etime(t11,t21);
 totalt = totalt/60;     %total minutes covered

 data(1) = totalt;
 %Transformer Characteristic Design variables
if  (trfrtype == 'ONAN')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=210;
    tw=10;
elseif(trfrtype == 'ONAF')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=150;
    tw=7;
end

dpstart=1000;
dpend=200;

paper = 98; %paper ageing temp 110 for upgraded 98 for normal

%initial conditions
top_oil(1) = ((((1+(K(1,4).^2*R))/(1+R))^x) * Or) + Oa;   %C1 initial condition
h1(1) = k21 * K(1,4).^y * hr; %C3 initial value
h2(1) = (k21-1) * K(1,4).^y * hr; %C4 initial value

losslife_opti(1) = 0;
losslife_iec_ntu(1)=0;
```

```
losslife_rated(1)=0;
count =1;

act_energy= 111000; %using rearragned equation
RT = w(1);
k_martin_98_05 = 1*exp(act_energy/(8.3145*(273+98)));


    hotspot_rise(1) = h1(1) - h2(1);
    hotspot = top_oil(1) + hotspot_rise(1);

    %iterative calculation
    for t = 2:intr

        t2=datevec(K(t,intc+1));
        t1=datevec(K(t-1,intc+1));

        deltat = etime(t2,t1);
        deltat = deltat/60;

        deltatage = deltat;
        if deltat >=60 deltat=60 ;
        end

        delta_oil_top(t) = (deltat/(k11*t0)) * ((((1+K(t,4).^2*R)/(1+R))^x)*Or  - ((top_oil(t-1) -K(t,3)))
);
        top_oil(t) = top_oil(t-1) + delta_oil_top(t);
        delta_h1(t) = (deltat/(k22*tw))   *   (k21*hr*K(t,4)^y - h1(t-1));
        h1(t) = h1(t-1) + delta_h1(t);
        delta_h2(t) = (deltat/((1/k22)*t0))     *   ((k21-1)*hr*K(t,4)^y - h2(t-1));
        h2(t) = h2(t-1) + delta_h2(t);
        hotspot_rise(t) = h1(t) - h2(t);
        hotspot_cal(t) = hotspot_rise(t) + top_oil(t);
        hotspot(t) = hotspot_cal(t);


        deltalosslife_opti(t) = (deltatage) * (exp((act_energy/(8.3145*(RT + 273)))-
(act_energy/(8.3145*(hotspot(t)+273)))));

%         deltalosslife_opti(t) = deltatage* (k_martin_temp/k_martin_98_05);
        losslife_opti(t) = losslife_opti(t-1) + deltalosslife_opti(t);



    end
dploss = (dpstart-dpend)/(180000);
dploss_calc = (losslife_opti(intr)/60)*dploss

accuracy = dploss_calc - dpesti
accuracy = abs(accuracy);

end
```

B.5 AGEING_CALC_CASE2.m

```
function accuracy = ageing_calc_case2(w)
%AGEING CALCULATION BASED ON ARHHNIEUS EQUATION FORM
% FROM 10 TO 200
% filename = input('File to load?','s');
% trfrtype = input('Cooling type?','s');
% dpesti = input('Estimated DP Loss');

%filename = 'KLIPDALE T2';
%trfrtype = 'ONAN';
%dpesti = 29;


global K;
global trfrtype;
global dpesti;
%K = xlsread(filename); %K =     %load factor load/rated load

intr = size(K,1);
intc = size(K,2);

%Water factor

for a = 1:intr
    K(a,intc+1) = K(a,1) + 693960; % modifier to make MATLAB date = excel date
    date(a) = K(a,intc+1);
    load(a) = K(a,4);
    moisture(a) = K(a,5);
    oxy(a) = K(a,6);
```

```
end

 t21=datevec(K(2,intc+1));
 t11=datevec(K(intr,intc+1));
 totalt = etime(t11,t21);
 totalt = totalt/60;     %total minutes covered

 data(1) = totalt;
 %Transformer Characteristic Design variables
if  (trfrtype == 'ONAN')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=210;
    tw=10;
elseif(trfrtype == 'ONAF')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=150;
    tw=7;
end

dpstart=1000;
dpend=200;

paper = 98; %paper ageing temp 110 for upgraded 98 for normal

%initial conditions
top_oil(1) = ((((1+(K(1,4).^2*R))/(1+R))^x) * Or) + Oa;   %C1 initial condition
h1(1) = k21 * K(1,4).^y * hr; %C3 initial value
h2(1) = (k21-1) * K(1,4).^y * hr; %C4 initial value

losslife_opti(1) = 0;
count =1;

act_energy= -111000;
k_martin_98_05 = 1*exp(act_energy/(8.3145*(273+98)));

    hotspot_rise(1) = h1(1) - h2(1);
    hotspot = top_oil(1) + hotspot_rise(1);

    %iterative calculation
    for t = 2:intr

        t2=datevec(K(t,intc+1));
        t1=datevec(K(t-1,intc+1));

        deltat = etime(t2,t1);
        deltat = deltat/60;

        deltatage = deltat;
        if deltat >=60 deltat=60 ;
        end

        delta_oil_top(t) = (deltat/(k11*t0)) * ((((1+K(t,4).^2*R)/(1+R))^x)*Or  - ((top_oil(t-1) -K(t,3)))
);
        top_oil(t) = top_oil(t-1) + delta_oil_top(t);
        delta_h1(t) = (deltat/(k22*tw))   *   (k21*hr*K(t,4)^y - h1(t-1));
        h1(t) = h1(t-1) + delta_h1(t);
        delta_h2(t) = (deltat/((1/k22)*t0))     *   ((k21-1)*hr*K(t,4)^y - h2(t-1));
        h2(t) = h2(t-1) + delta_h2(t);
        hotspot_rise(t) = h1(t) - h2(t);
        hotspot_cal(t) = hotspot_rise(t) + top_oil(t);
        hotspot(t) = hotspot_cal(t);

        water(t) = K(t,5);
        %oxygen(t) = K(t,6);

        if ((water(t) >=0.01 && water(t) <0.02))
                k_martin_temp = (w(1))*exp(act_energy/(8.3145*(273+hotspot(t))));
            elseif ((water(t) >=0.02 && water(t) <0.03))
                k_martin_temp = (w(2))*exp(act_energy/(8.3145*(273+hotspot(t))));
        elseif ((water(t) >=0.03 && water(t) <0.04))
                k_martin_temp = (w(3))*exp(act_energy/(8.3145*(273+hotspot(t))));
```

```
        else (water(t) >=0.04);
            k_martin_temp = (w(4))*exp(act_energy/(8.3145*(273+hotspot(t))));
        end

        deltalosslife_opti(t) = deltatage* (k_martin_temp/k_martin_98_05);
        losslife_opti(t) = losslife_opti(t-1) + deltalosslife_opti(t);

    end
dploss = (dpstart-dpend)/(180000);
dploss_calc = (losslife_opti(intr)/60)*dploss

accuracy = dploss_calc - dpesti
accuracy = abs(accuracy);

end
```

B.6 AGEING_CALC_CASE3.m

```
function accuracy = ageing_calc_case31(w)
%AGEING CALCULATION BASED ON ARHHNIEUS EQUATION FORM
% FROM 10 TO 200
% filename = input('File to load?','s');
% trfrtype = input('Cooling type?','s');
% dpesti = input('Estimated DP Loss');

%filename = 'KLIPDALE T2';
%trfrtype = 'ONAN';
%dpesti = 29;


global K;
global trfrtype;
global dpesti;
%K = xlsread(filename); %K =     %load factor load/rated load

intr = size(K,1);
intc = size(K,2);

%Water factor

for a = 1:intr
    K(a,intc+1) = K(a,1) + 693960; % modifier to make MATLAB date = excel date
    date(a) = K(a,intc+1);
    load(a) = K(a,4);
    moisture(a) = K(a,5);
    oxy(a) = K(a,6);

end

 t21=datevec(K(2,intc+1));
 t11=datevec(K(intr,intc+1));
 totalt = etime(t11,t21);
 totalt = totalt/60;     %total minutes covered

 data(1) = totalt;
 %Transformer Characteristic Design variables
if  (trfrtype == 'ONAN')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=210;
    tw=10;
elseif(trfrtype == 'ONAF')
    R = 6;     %ration of losses at rated current to no load
    Or= 55;    %Top oil temp rise in steady state, given
    Oa= 18;    %ambient temp
    hr = 26;
    x= 0.8;
    y = 1.3;
    k11=0.5;
    k21=2;
    k22=2;
    t0=150;
    tw=7;
end

dpstart=1000;
dpend=200;
```

```
paper = 98; %paper ageing temp 110 for upgraded 98 for normal

%initial conditions
top_oil(1) = ((((1+(K(1,4).^2*R))/(1+R))^x) * Or) + Oa;   %C1 initial condition
h1(1) = k21 * K(1,4).^y * hr; %C3 initial value
h2(1) = (k21-1) * K(1,4).^y * hr; %C4 initial value

losslife_opti(1) = 0;
losslife_iec_ntu(1)=0;
losslife_rated(1)=0;
count =1;

act_energy= -111000;
RT = w(1);
k_opti_dry_kraft_98 = 1*exp(act_energy/(8.3145*(273+98)));
%k_martin_98_05 = ((1.78e12)*0.005^2 + 1.10e10*0.005+5.28e7)*exp(act_energy/(8.3145*(273+98)));
k_martin_98_05 = 1*exp(act_energy/(8.3145*(273+98)));


    hotspot_rise(1) = h1(1) - h2(1);
    hotspot = top_oil(1) + hotspot_rise(1);

    %iterative calculation
    for t = 2:intr

        t2=datevec(K(t,intc+1));
        t1=datevec(K(t-1,intc+1));

        deltat = etime(t2,t1);
        deltat = deltat/60;

        deltatage = deltat;
        if deltat >=60 deltat=60 ;
        end

        delta_oil_top(t) = (deltat/(k11*t0)) * ((((1+K(t,4).^2*R)/(1+R))^x)*Or  - ((top_oil(t-1) -K(t,3)))
);
        top_oil(t) = top_oil(t-1) + delta_oil_top(t);
        delta_h1(t) = (deltat/(k22*tw))   *   (k21*hr*K(t,4)^y - h1(t-1));
        h1(t) = h1(t-1) + delta_h1(t);
        delta_h2(t) = (deltat/((1/k22)*t0))     *   ((k21-1)*hr*K(t,4)^y - h2(t-1));
        h2(t) = h2(t-1) + delta_h2(t);
        hotspot_rise(t) = h1(t) - h2(t);
        hotspot_cal(t) = hotspot_rise(t) + top_oil(t);
        hotspot(t) = hotspot_cal(t);

        water(t) = K(t,5);
        oxygen(t) = K(t,6);

        if ((oxygen(t) < 7000))%low oxygen(t) - water(t)(t) input
            k_martin_temp= 1 * exp(act_energy/(8.3145*(273+hotspot(t))));


        elseif ((oxygen(t) >=7000) && (oxygen(t) < 16500))%Medium oxygen(t) - water(t)(t) input
            k_martin_temp=w(1) * exp(act_energy/(8.3145*(273+hotspot(t))));

        else ((oxygen(t) >= 16500)); %High oxygen(t) - water(t) input
            k_martin_temp=w(2) * exp(act_energy/(8.3145*(273+hotspot(t))));
        end

        deltalosslife_opti(t) = deltatage* (k_martin_temp/k_martin_98_05);
        losslife_opti(t) = losslife_opti(t-1) + deltalosslife_opti(t);


    end
dploss = (dpstart-dpend)/(180000);
dploss_calc = (losslife_opti(intr)/60)*dploss

accuracy = dploss_calc - dpesti
accuracy = abs(accuracy);

end
```

Appendix C References

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