

University of Southern Queensland
Faculty of Health, Engineering & Sciences

**Effect of Variations in Load Profile on Power Transformer
Cyclic Ratings**

A dissertation submitted by

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in fulfilment of the requirements of

ENG4112 Research Project

towards the degree of

Bachelor of Electrical & Electronic Engineering

Submitted: October, 2014

Abstract

Cyclic rating and demand side management (DSM) schemes are employed by electrical supply authorities to manage peak demand as an alternative to costly network upgrades. This project investigated the currently unknown impact of DSM altered load profiles on the cyclic ratings of power transformers.

In response to electricity price increases, supply authorities are employing cyclic rating and DSM techniques to defer capital expenditure. A cyclic rating exploits transformer thermal inertia to permit loading above nameplate for parts of a 24 hour cycle, compensated for by loading below nameplate at other times such that insulation thermal limits are not exceeded. DSM aims to flatten load profiles commonly by transferring load from peak to off-peak times. Both techniques ensure that existing transformers can supply load peaks. Cyclic ratings achieve this by boosting capacity above demand while DSM reduces demand below capacity. In this way, the two techniques permit deferral of network upgrades. Since DSM alters the load profiles on which cyclic ratings are based, a relationship must exist between the two. The plant rating engineer must understand all such dependencies, hence the need for this project.

Initially, thermal transformer models proposed by various researchers and AS 60076.7 for the purpose of predicting transformer oil and paper temperatures were studied. The AS 60076.7 models and one selected from the literature were then implemented in MATLAB and compared to assess their suitability for use in the project and by plant rating engineers. The selected thermal model then became the basis of a cyclic rating calculator employed to automate the computation of cyclic ratings based on the AS 60076.7 specification. DSM techniques were researched to reveal the load shifting version as the method favoured by supply authorities and a simulator was constructed in MATLAB to modify load profiles accordingly. 12 diverse Ergon Energy transformers

were then selected along with a set of DSM modified load profiles as inputs to the cyclic rating calculator which computed 600 cyclic ratings for analysis. The final phase of the project then involved analysis of the ratings to determine and quantify the effect of DSM caused load profile changes on cyclic ratings.

It was determined that the cyclic ratings of power transformers are negatively affected by load shifting DSM. That is, flattening of load profiles causes reduction in cyclic ratings. The amount by which cyclic ratings change given a change in load profile varies according to several factors including: location, size and cooling mode of the transformer. Regression models for simple but approximate prediction of cyclic rating changes were developed. Generalised expressions for predicting the change in cyclic rating with change in peak load or load factor are:

$$\Delta CRF_d = 0.45 \times \Delta PL_d$$

$$\Delta CRF_d = 0.37 \times \Delta LF_i$$

where: ΔCRF_d is the percentage decrease in CRF;
 ΔPL_d is the percentage decrease in peak load; &
 ΔLF_i is the percentage increase in load factor.

In addition to achievement of the main project objective – determination of the impact on cyclic ratings of load profile changes – a range of other outcomes from the project are useful. These include: a thorough investigation of the techniques and theory involved in transformer thermal modelling, insulation ageing, cyclic rating calculation and DSM; a program which automatically calculates cyclic ratings for power transformers; and a load shifting DSM simulation program, useful for generating altered load profiles for use with the cyclic rating calculator. This collection of knowledge and programs will be of particular use to Ergon Energy, the project sponsor.

The impact of load shifting DSM on cyclic ratings, as identified in this dissertation, has the potential to negatively influence factors such as: peak capacity; transformer lifespan and maintenance; planning and budgeting for network augmentation; reduction of capital expenditure; and the valuation of DSM programs. The results and outcomes of this project have the potential to assist plant rating engineers in their understanding and application of cyclic ratings in the context of changing load profiles such that they may anticipate and therefore prevent many of the negative side-effects identified.

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Acknowledgments

The author would like to acknowledge the assistance and support received throughout the course of this dissertation without which the project could not have been completed. Sincere thanks are offered to the following people:

Mr. Greg Caldwell (Ergon Energy Corporation)

For conceiving the project topic; providing resources; sharing his immense wealth of engineering knowledge; and for his support and guidance. Greg's experience and abilities in the field of plant ratings is truly remarkable.

Dr. Tony Ahfock (USQ)

For his immediate and ongoing enthusiasm; for accommodating an industry project and ensuring academic requirements were fulfilled; for sharing his valuable knowledge and experience; and for his support and guidance. As the head of school, Tony's time is scarce yet he always managed to find time for discussing the project.

My family & friends

For their unwavering and unconditional love, support and guidance. Gratitude and love go to my fiancé Ange; my parents Allan and Julie; my sisters Annette and Danielle; my brothers in law Chris and Mick; and my friend and mentor Trevor Heath.

This thesis was typeset using L^AT_EX 2_ε .

ANDREW PETER ATKINSON

University of Southern Queensland

October 2014

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Glossary

Ageing rate: The loss of life of transformer insulation per unit time (e.g. hours per hour; hours per day).

AS 60076.7: Australian Standard 60076.7:2013 – Power Transformers, Part 7 – Loading guide for oil-immersed power transformers.

Bottom oil: The mineral oil within a transformer present at the bottom of the tank. This oil is at a lower temperature than the oil at the top of the tank due to convection/thermo-siphon effects.

Capacity: The maximum amount of electrical power which can be supplied by the network at some point in time (the time period must be specified).

CAPEX: Capital expenditure. The expense associated with network upgrades and augmentation (installation of new plant).

Cyclic rating: The maximum load that a power transformer can supply at each time interval during a daily cycle. Loads in excess of the nameplate rating can be supplied for certain periods and are compensated for by loading below nameplate during other periods to ensure that temperature rise limits are not exceeded and that excessive ageing of the insulation does not occur.

CRF: Cyclic Rating Factor. The per unit value of the peak of the cyclic rating profile (i.e. $CRF = \text{cyclic rating peak} / \text{nameplate rating}$). Since the cyclic rating varies throughout a loading cycle, the CRF is a convenient, fixed, single value description.

Demand: The amount of electrical power which must be supplied by the network at some point in time (the time period must be specified).

DGA: Dissolved gas analysis. The process of testing a sample of transformer mineral oil to determine the concentrations of particular gases within the oil, thereby obtaining an indirect indication of the transformer condition. The presence of characteristic gas combinations and concentrations points to certain faults within the transformer.

DP: Degree of Polymerisation. A measure of the degradation of insulating Kraft paper within a transformer. Specifically, DP is the average number of glycosidic monomers in each cellulose molecule of the paper.

DSM: Demand side management. Techniques employed to ensure that demand for electricity can be met by attempting to reduce peak demand below existing network capacity. That is, action is from the demand side as opposed to the supply side which requires increasing network capacity.

Flashover: An arcing fault which occurs within a transformer following the reduction in breakdown or dielectric strength of the insulating system caused by the presence of gas bubbles and water droplets in the oil and paper.

HRT: Heat run test. A type test performed by a manufacturer to establish the thermal signature of a transformer. A transformer is loaded in a specific manner and the temperatures of various components (viz. oil and winding) are measured.

Heat transfer theory: The study of the rate of flow of heat energy across a temperature gradient.

Kraft paper: A type of paper wrapped around the windings of a transformer to provide insulation.

Load factor: Ratio of the average load to the peak load occurring during a particular time period (in this dissertation, a 24 hour cycle).

LTEC: Long term emergency cyclic rating. A power transformer cyclic rating which is higher than the NC rating and employed when another network component fails. The LTEC rating results in accelerated ageing but is considered preferable to a network outage.

Nameplate rating: The single value maximum continuous load which can be supplied by a power transformer under standard conditions specified by the manu-

facturer without exceeding temperature rise limits and without excessive ageing of the insulation.

NC: Normal cyclic rating. A power transformer cyclic rating for which the thermal ageing rate is unity (i.e. 24 hours per day).

Oil gradient: The temperature differential between the top oil and the bottom oil.

OPEX: Operational expenditure. The expense associated with maintenance and routine operation of plant.

STEC: Short term emergency cyclic rating. A power transformer cyclic rating higher than the LTEC rating and employed for a very short time in an emergency to maintain supply. Ageing is significant during operation under STEC. STEC ratings are not employed by Ergon Energy Corporation.

Thermal – electrical analogy: The use of an electrical circuit to model a thermal system permitted by the convenient translation of electrical concepts to thermal ones (e.g. a current source is equivalent to a heat source).

Thermally upgraded paper: A type of paper wrapped around the windings of a transformer to provide insulation which thermally decays at a lower rate than Kraft paper.

Top oil: The mineral oil within a transformer present at the top of the tank. This oil is at a higher temperature than the oil at the bottom of the tank due to convection/thermo-siphon effects.

Utilisation: An electricity network performance metric. Utilisation is the ratio of the load being supplied to the rated capacity. Utilisation may apply to an individual asset or the entire network.

WCP: Water content of paper. A percentage measure of the amount of water present within the insulating paper of a transformer.

WHS: Winding hot spot. The portion of a transformer winding which is of higher temperature than the surrounding parts and so causes a greater rate of ageing of the insulating paper in contact with it compared to the surrounding parts.

Winding gradient: The temperature differential between the top of the winding and the bottom of the winding.

Chapter 1

Introduction

1.1 Chapter Overview

This introductory chapter serves to present necessary background information relating to power transformers and the electricity network; justify the need for the project/study; state the project objectives; and describe the structure of the dissertation.

1.2 Background

1.2.1 Power transformers

Power transformers are essential assets in any electrical supply network since they facilitate increases in voltage for the efficient transmission of electrical energy over large distances as well as reductions in voltage to levels which are safer and more easily distributed to the consumer. Power transformers are those typically larger than 500 kVA (Ekanayake 2011*a*, p. 13) and are usually installed in substations. Figure 1.1 shows two examples of typical power transformers. These essential assets represent a high initial outlay of capital (CAPEX) (tens of millions of dollars) and thus are one of the largest portions of a distribution authority's asset base (Iskender & Mamizadeh 2011, p. 9). Transformers also require the ongoing expenditure of significant operational resources (OPEX) to maximise life. In order for there to be a high return on the initial investment, a power transformer must remain in service for as long as possible and

receive minimal maintenance whilst operating as close to its maximum capacity as possible. However, these are conflicting objectives for which the best trade-off must be found. The closer a power transformer is operated to its maximum rating, the greater is the utilisation¹ of the asset and the financial return on the investment but the shorter will be its operational life. In contrast, longevity is improved with movement in the operating point below the maximum rating, but the utilisation of the asset is poor and results in a lower financial return. Operational management of these assets is therefore a complex and critical task.



Figure 1.1: Typical power transformers (*Source: G.Caldwell, Ergon Energy*).

1.2.2 Electricity network & pricing

Over the previous decade, reliability has been the driver of upgrades to the electricity network associated with the expenditure of much capital. To ensure reliability, planning thresholds exist which, when encroached by growing load, trigger augmentation and upgrade of the network (Ergon Energy Corporation 2013a, p. 10). With ever growing loads, the size of network asset bases has increased to a point where the unit cost of electricity to the consumer is excessive. In order to place downward pressure on electricity prices, utilities are pursuing multiple strategies. While these strategies have different names and are based on different technologies, they share a common goal – to increase the margin between *load demand* (that which must be supplied) and *network capacity* (the absolute maximum that can be supplied) to alleviate encroachment on the planning thresholds thereby deferring capital expenditure. Of course to be feasible, the cost of the techniques themselves must be less than the cost of the upgrades which

¹ The utilisation metric is defined as: $utilisation = \frac{load\ supplied}{rated\ capacity}$

would otherwise be required due to load growth. Two such initiatives which directly and indirectly affect the capacity and operational management of power transformers are:

1. **Cyclic rating programs** &
2. **Demand side management (DSM) programs.**

These initiatives are thoroughly defined in chapter 2 but at this point it is sufficient to state that cyclic ratings boost network capacity above demand whilst DSM reduces demand below capacity.

1.3 The Need for the Project

Within an electricity utility, plant rating engineers are responsible for specifying maximum operational limits (ratings) for many items of plant including power transformers. Ratings are then employed by an Operational Control Centre (OCC) in the day to day management of network assets. Operation of assets below specified ratings ensures that electricity can be supplied reliably and safely. Exceeding the ratings greatly increases the risks of outages, plant damage and injury to people. Consequently, the role of the plant rating engineer is one of significant responsibility and the individual must possess an in-depth understanding of the rating calculation process and all of the factors which can influence ratings. Compared to the age of the electricity network itself, cyclic rating and DSM techniques are relatively new. With this in mind it is prudent for plant rating engineers to understand how the cyclic ratings of power transformers may be influenced by DSM initiatives – a relationship which has not been investigated to date. This dissertation aims to fill this knowledge gap and therefore facilitate optimisation of power transformer cyclic ratings. In turn this will permit improvements in the operation and management of power transformers as essential components of the electricity network and thereby assist in the reduction of the unit cost of electricity to the consumer.

1.4 Objectives of the Project

The main aim of the research project described in this dissertation was to model and analyse the impact that changes in load profile caused by DSM initiatives have on the cyclic ratings calculated for power transformers. Ideally, the relationship between a change in load profile and the resultant change in transformer cyclic rating was sought. Specifically, the project objectives were as follows (the objectives are also stated in the *Project Specification* located in Appendix A):

1. Research cyclic ratings, their application, determination/calculation and dependence on other parameters.
2. Understand how heat transfer theory is applied to model the thermal behaviour of power transformers.
3. Identify the various forms of DSM, their applications and their effect on load profiles.
4. Analyse the standard methods of transformer cyclic rating calculation as specified in AS 60076.7.
5. Develop numerical power transformer thermal models using heat transfer first principles and two alternative AS 60076.7 methods.
6. Evaluate the accuracy and differences of and between the AS 60076.7 models and the model derived from heat transfer theory and select the most appropriate model to be used as the basis of a cyclic rating calculator.
7. Construct a cyclic rating calculator based on the selected thermal modelling method which is compliant with AS 60076.7.
8. Modify a given set of load profiles to simulate several levels of DSM induced changes.
9. Using the cyclic rating calculator and set of DSM profiles, determine and quantify the changes to cyclic ratings due to alterations in the load profile caused by DSM.

1.5 Overview of the Dissertation

The following descriptions outline the structure of the dissertation:

Chapter 2 – Literature Review: Presentation of all relevant literature for the purpose of defining and calculating power transformer cyclic ratings and DSM. This chapter contains essential information, the understanding of which is a prerequisite to following chapters.

Chapter 3 – Methodology: A statement of the planned approach taken to achieve the project objectives from research, through model development and finally to sensitivity analysis of cyclic ratings.

Chapter 4 – Thermal Model Design & Construction: A detailed description of the design and construction of a thermal model derived from research and heat transfer first principles and two thermal models based on AS 60076.7.

Chapter 5 – Thermal Model Validation: An assessment and discussion of the accuracy and validity of the thermal models through comparison of the outputs with actual recorded data. The validation is used to justify the choice of thermal model used as the basis of the cyclic rating calculator.

Chapter 6 – Cyclic Rating Calculator: A detailed description of the design and construction of the cyclic rating calculator formed by application of the chosen thermal model to the process outlined in AS 60076.7.

Chapter 7 – Demand Side Management Simulation: Presentation of the load profiles to be used as inputs to the cyclic rating calculator, the algorithm employed to simulate DSM modification of the profiles and the results of modification.

Chapter 8 – Sensitivity Analysis: An in-depth analysis and quantification of the effect that changes in load profile produced by DSM simulations have on the cyclic ratings calculated for a sample of power transformers from the Ergon Energy fleet. The results analysed are the outputs of the cyclic rating calculator which accepted the DSM modified profiles and Ergon Energy transformer data as inputs.

Chapter 9 – Conclusions & Further Work: An assessment of the degree of achievement of the objectives, a summary of the important findings and identification of avenues for further research and investigation on the topic.

1.6 Limitations & Restrictions

The following limitations and restrictions apply to the project and dissertation:

- The project is limited to the consideration of power transformers which are:
 - Installed outdoors;
 - Air cooled (natural or forced); &
 - Insulated using mineral oil and Kraft paper (not synthetic fluids and/or thermally upgraded paper).
- To comply with confidentiality and security restrictions, when referring to an Ergon Energy transformer, exact locations and substation names are not revealed. Instead, the name of the town in which the transformer is installed is used.

1.7 Chapter Summary

This chapter has provided background and an introduction to the dissertation. Firstly, the importance of power transformer operational management was discussed in terms of the balance which must be achieved between maximum asset life and maximum utilisation and return on investment. The recent trend in increasing electricity prices as a result of reliability focused capital expenditure and the consequential rise in the use of cyclic rating and DSM programs was also explained. This provided essential background information necessary for fully appreciating the need for the study which was presented next. The need for the project was explained by emphasising the requirement for plant rating engineers to fully appreciate the rating calculation process and identifying the knowledge gap that exists around the effect that DSM may have on transformer cyclic ratings and thus the operational management of these assets. The introduction chapter concluded with a statement of the project objectives (which are frequently referred to throughout the dissertation); applicable limitations and restrictions; and a brief overview of each chapter.

Chapter 2

Literature Review

2.1 Chapter Overview

In chapter 1, it was stated that the main aim of this project was to determine the effect that DSM may have on power transformer cyclic ratings. It is clear that an in-depth understanding of the two techniques is required. This chapter presents the results of extensive research on cyclic ratings and DSM as sections 2.2 and 2.3 respectively.

2.2 Cyclic Ratings

2.2.1 Rating Categories

The rating of a transformer prescribes the maximum power (in MVA or kVA) which can be supplied under certain conditions. It is these conditions which differ between the types of rating. For power transformers, there exist two classes of rating (Ergon Energy Corporation 2013c, p. 8):

1. **Nameplate:**

The nameplate rating is the single value maximum continuous load which can be supplied under standard manufacturer specified conditions without exceeding temperature rise limits and without excessive ageing of the insulation. This value is stamped on the nameplate of the transformer but is not necessarily the

continuous rating which can be achieved in practice.

2. Cyclic:

The cyclic rating is the maximum load that a transformer can supply at each time interval during a daily cycle. The cyclic rating exploits the fact that load varies throughout the loading period to permit loads in excess of the nameplate rating without exceeding temperature rise limits and without excessive ageing of the insulation.

Figure 2.1 displays the difference between cyclic and nameplate ratings. It displays the load profile (i.e. the demand over a cycle of 24 hours); the nameplate rating; and the cyclic rating. It can be seen that the cyclic rating is greater than the nameplate rating for parts of the cycle and lower for other parts. The reasons for this will be explained later. Note that the nameplate and the cyclic rating are applicable to the same transformer and in the case of figure 2.1, it is apparent that use of the transformer to supply the given load is only appropriate using the cyclic rating since the load exceeds the nameplate rating. Herein lies the immense benefit of cyclic ratings eluded to in chapter 1 – the application of a cyclic rating to a transformer, which would otherwise require replacement under the use of the nameplate rating, allows the transformer to remain in service for a longer period and defers the expenditure of millions of dollars. A final note on figure 2.1: a simple manner in which to describe or specify a cyclic rating is using the *cyclic rating factor* (CRF). The CRF is the per unit value of the peak of the cyclic rating profile. In figure 2.1, the peak of the cyclic rating is approximately 78 MVA. The nameplate rating is 55 MVA. Therefore, the CRF is: $78/55 \approx 1.42$.

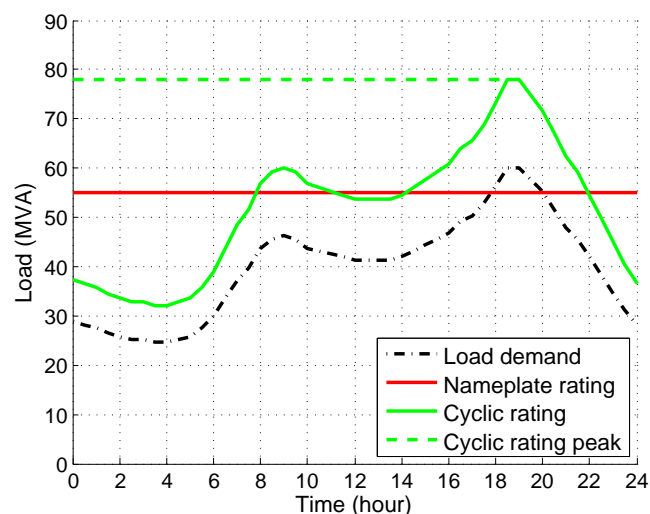


Figure 2.1: Comparison between nameplate and cyclic ratings (*G.Caldwell, Ergon Energy*).

2.2.2 Temperature Rises & Insulation Ageing

The definitions of nameplate and cyclic ratings in section 2.2.1, reveal that *temperature rises* and *insulation ageing* are the limiting factors in the determination of the rating (Ergon Energy Corporation 2013c, p. 8). The former is logical given that the limiting factor for the maximum rating of most items of plant is the highest temperature which can be tolerated by some component(s) within the equipment. The latter concept of insulation ageing requires some further explanation.

Insulation & ageing mechanisms

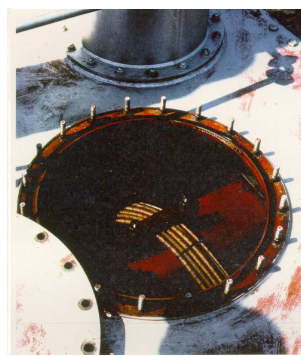
The life of a transformer is generally accepted as the life of its insulation (Feng, Wang & Jarman 2012, p. 540). This life is approximately 30 to 40 years but operation below rated output extends this life considerably (Saha 2011, p. 3). The insulation of a power transformer consists of two parts:

1. **Paper** – wrapped around the windings of the transformer, &
2. **Mineral oil** – contained within the tank in which the windings and the core are submerged.

The paper insulation can be seen in figure 2.2a insulating the windings and the turns of each winding from each other. In figure 2.2b, mineral oil can be seen within the tank of a transformer in which paper insulated conductors are submerged.



(a) Paper insulation wrapped around transformer windings.



(b) Mineral oil within a transformer tank.

Figure 2.2: The insulation system of a transformer (Cigré 2009, p. 44) (Allan 2011, p. 20).

Paper insulation is degraded by the following mechanisms (Saha 2011) (Cigré 2009, p. 13-19):

1. *Thermal scission or Pyrolysis:*

Heat energy from the transformer losses (core and winding) breaks down the cellulose structure (glycosidic bonds) of the paper producing water, carbon dioxide and furans. The effects of pyrolysis on insulating paper can be seen in figure 2.3.

2. *Oxidation:*

Oxygen in the oil causes the breaking of glycosidic bonds within the paper generating water.

3. *Hydrolysis*

Water from the oil along with acids, decomposes the cellulose structure of the paper.

4. *Products of mineral oil decomposition:*

Carbon monoxide, methane and other hydrocarbons generated by degradation of the oil, also affect the paper.

5. *Electrical stress:*

Partial discharge causes localised paper damage.

6. *Mechanical stress:*

Movement of windings due to vibration and large electromagnetic forces during faults damages the paper insulation.



Figure 2.3: Extensive damage to paper insulation caused by pyrolysis (Cigré 2009, p. 16).

A measure of the level of paper insulation degradation is the *degree of polymerisation* (DP) which indicates the average number of glycosidic monomers in each cellulose

molecule (Cigré 2009, p. 10). As paper ageing mechanisms break glycosidic bonds, this average number decreases and so the DP for the paper decreases. New insulating paper possesses a DP of approximately 1200 while the heavily aged paper within a transformer at the end of its life possesses a DP of merely 200 – 250 (Cigré 2009, p. 10) (Ergon Energy Corporation 2013c, p. 11). Depending on the value of DP, an aged transformer may be restricted to operation at nameplate or below (Ergon Energy Corporation 2013c, p. 11).

Mineral oil insulation is degraded by the following mechanisms (Saha 2011) (Cigré 2009, p. 20-27):

1. *Thermal degradation:*

Heat energy from the transformer losses directly breaks down the oil and indirectly causes degradation by accelerating oxidation and hydrolysis.

2. *Oxidation:*

Oxygen enters oil from the air and acts to break down the oil generating water, carbon dioxide, carbon monoxide and other hydrocarbons.

3. *Presence of water:*

Water enters oil from the paper and from the air and drastically reduces the dielectric strength of the oil.

4. *Electrical stress:*

Partial discharge generates hydrogen, methane, carbon monoxide, acetylene, ethylene and ethane from the oil which lower the dielectric strength of the oil and contribute to paper degradation.

From the above, it is apparent that the ageing of transformer insulating paper and oil is a complex thermal and chemical process and that some of the by-products of oil degradation accelerate the degradation of the paper and vice versa (Cigré 2009, p. 8). Since the mineral oil can be replaced when necessary, the life of a transformer is effectively the life of its paper insulation.

Insulation ageing models

The ageing rate of paper insulation depends on (Standards Australia 2013b, p. 16):

- Temperature;
- Moisture content or WCP (water content of paper);
- Oxygen content; &
- Acid content.

However it is common to model the ageing rate of transformer insulation using a function of temperature only in order to reduce complexity (Feng et al. 2012, p. 541). To achieve this, the paper temperature throughout a loading cycle must be known which can be taken as the winding temperature since the paper insulation is in contact with the winding. There always exists a position on the winding of higher temperature than the surrounding parts of the winding which is called the *winding hot spot* (WHS) (Stapleton et al. 2011, p. 60).

Montsinger's Ageing Theory is used by Standards Australia (2013b, p. 16) to model the ageing rate, V , of standard Kraft paper insulation in hours per hour:

$$\boxed{V = 2^{(\theta_h - 98)/6}} \quad (2.1)$$

where: θ_h is the WHS temperature in $^{\circ}C$.

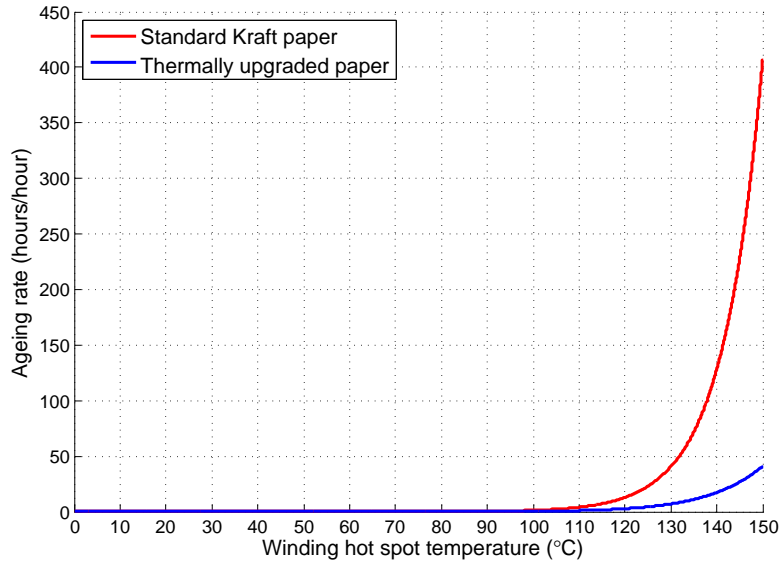
Thermally upgraded paper is available as an alternative to standard Kraft paper. This type of paper has nitrogen based compounds incorporated during manufacture which act to significantly reduce its thermal ageing rate principally by inhibiting oxidation reactions (Cigré 2009, p. 10). Standards Australia (2013b, p. 16) also specify a thermal ageing model for thermally upgraded paper:

$$V = \exp\left(\frac{15000}{110 + 273} - \frac{15000}{\theta_h + 273}\right) \quad (2.2)$$

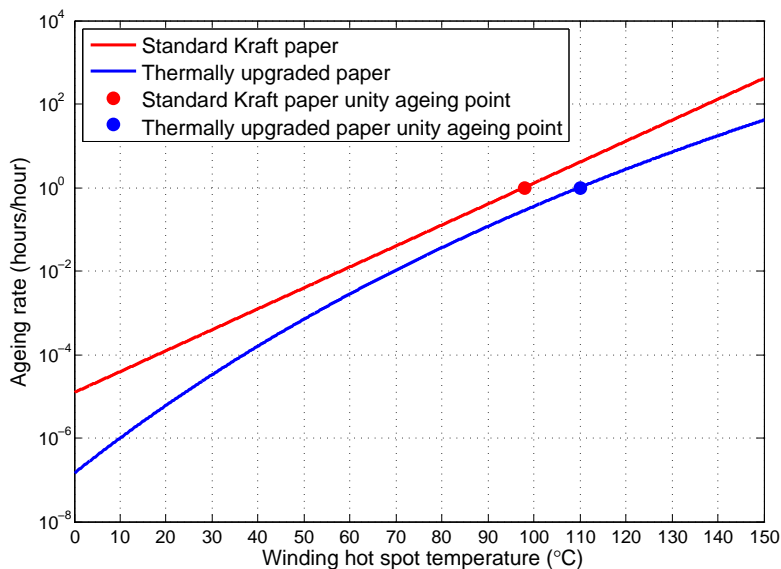
where V and θ_h have identical meanings as for equation (2.1).

Figure 2.4 displays the ageing rate of standard Kraft paper and thermally upgraded paper for different WHS temperatures, calculated using equations (2.1) and (2.2). The

data of both plots is identical but figure 2.4a is plotted on linear axes while figure 2.4b is plotted using a logarithmic ageing rate axis for greater clarity at lower temperatures. It can be seen that the unity ageing rate of standard Kraft paper occurs at a WHS of 98°C while this occurs at 110°C for thermally upgraded paper. New transformers may be manufactured using thermally upgraded paper however older transformers will contain standard Kraft paper and this needs to be taken into account when assessing or calculating ageing or use of insulation life.



(a) Linear axes



(b) Logarithmic ageing rate axis

Figure 2.4: Thermal ageing rates of standard Kraft paper and thermally upgraded paper used as transformer insulation.

As load and therefore WHS temperature (θ_h) changes during a cycle, the ageing rate (V) also varies. Therefore, over the entire cycle, the cumulative ageing of the transformer insulation is given by:

$$L = \int_{t_1}^{t_2} V dt \quad (2.3)$$

where: L is the loss of life in hours (Standards Australia 2013b, p. 17).

More commonly though, the cycle is discretised into intervals and as a result, equation 2.3 becomes a simple summation of the products of the ageing rate for each interval (V_n) and the duration of each interval (t_n):

$$L = \sum_{n=1}^N (V_n \cdot t_n) \quad (2.4)$$

where: N is the total number of intervals in the cycle; &

n is the number of the individual interval

(Standards Australia 2013b, p. 17).

Flashover

In addition to causing ageing of transformer insulation, temperature has a more short term effect which must be taken into account when determining cyclic ratings. During periods of loading above nameplate rating, temperature rises can cause the generation of gases. Overheated mineral oil generates mainly ethylene gas, whilst overheated paper generates mainly carbon monoxide gas (Ekanayake 2011b, p. 51). Additionally, water within the paper and dissolved in the oil may form water vapour bubbles or water droplets (Cigré 2009, p. 27). The presence of these gases dramatically reduces the insulating capability (breakdown strength) of the insulation system which can lead to arcing and failure (Cigré 2009, p. 27). The effect is known as *flashover*. Consequently, the temperature at which flashover is likely should be known in order to safely apply a cyclic rating to a transformer. According to Standards Australia (2013b, p. 18) flashover is likely when the WHS temperature exceeds $140^\circ C$ and/or the oil temperature exceeds $115^\circ C$. These temperatures are indicative and in practice the flashover temperature may be significantly higher or lower than these values depending on the condition of the paper and the oil. Assessing the condition of the paper within an on-load transformer is very difficult, however the mineral oil can be easily sampled and

tested through a procedure called *dissolved gas analysis* (DGA). From an oil sample, DGA reveals the amounts of water, oxygen, acids, furans and various hydrocarbon gases including methane, ethane, ethylene and acetylene within the transformer (Ergon Energy Corporation 2013c, p. 10). In addition to revealing the condition of the oil, DGA results are used to predict WCP and DP via a range of mathematical formulae which are beyond the scope of this literature review (incidentally there is no industry accepted method for calculation of WCP and DP from DGA results and so utilities commonly calculate the parameters using a range of methods and average the results) (Ergon Energy Corporation 2013c, p. 10). With the results of DGA and the predicted WCP and DP, it is then possible (via further formulae) to calculate the flashover temperature for an individual transformer which must not be exceeded during the loading cycle (Ergon Energy Corporation 2013c, p. 10). Flashover temperatures are highly variable with very small changes in WCP. A WCP of $\approx 2\%$ usually results in a flashover temperature above 140°C , while a WCP of $\approx 4\%$ results in this temperature decreasing below 100°C (Ergon Energy Corporation 2013c, p. 10). A flashover temperature this low would place serious restrictions on the cyclic rating and operation of a transformer.

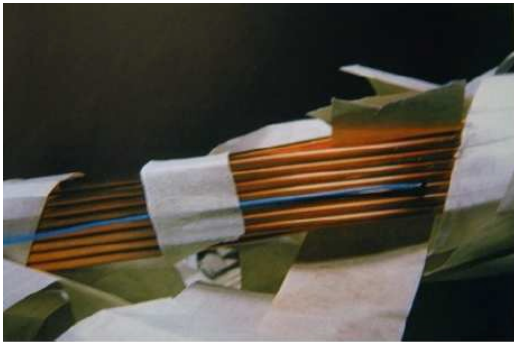
2.2.3 Principles of thermal modelling

In section 2.2.2, the thermal factors and effects which influence the cyclic rating calculated for a particular transformer were outlined. In summary, the cyclic rating can be thought of as the maximum load which can be supplied by a transformer before oil and paper temperatures reach flashover point at some stage in the loading cycle and before the cumulative ageing of the insulating paper exceeds a predefined limit. Obviously then, determination of the cyclic rating of a transformer requires knowledge of the critical temperatures throughout the loading cycle. This can be achieved in two ways:

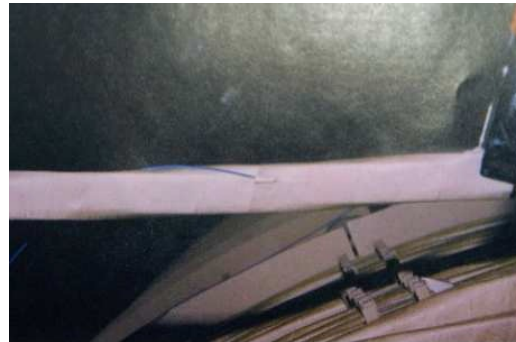
1. Direct measurement; or
2. Mathematical modelling.

The direct measurement of oil temperatures is relatively straightforward and can be accomplished using a probe inserted in an easily accessible oil flow pipe. In contrast, the measurement of WHS temperature is more difficult, requiring installation of fibre

optic temperature sensors within the transformer winding (Elmoudi et al. 2006, p. 214) (Feng et al. 2012, p. 541). Figure 2.5 shows a fibre optic sensor embedded in the insulating paper of a transformer winding for WHS temperature measurement. These fibre optic sensors are difficult to retrofit into existing older transformers and are costly to have installed at manufacture (Elmoudi et al. 2006, p. 214). Even when installed, it can never be guaranteed that the sensor is actually measuring the hottest spot (Tan et al. 2012, p. 1). For these reasons, mathematical prediction via the use of a thermal model is much more common. The use of a thermal model also allows cyclic ratings to be calculated for a future loading period, whereas real-time measurements - while they can be stored for future use - are mainly employed for on-load operational monitoring.



(a) Installation beneath paper



(b) Restoration of paper insulation

Figure 2.5: Installation of a fibre optic temperature sensor within the insulating paper of a transformer winding (Ekanayake 2011b, p. 14).

Heat transfer theory

A thermal transformer model is created using *heat transfer theory* which is defined by Çengel (2008, p. 5) as the study of the rate of flow of heat energy across a temperature gradient. The two main principles of heat transfer theory are (Çengel 2008, p. 5):

1. The rate of energy transfer into a system equals the rate of increase in energy of the system; &
2. Heat energy always flows from a higher temperature region to a lower temperature region.

Figure 2.6 illustrates the heat flow which occurs within an operating transformer. The fixed core losses and the variable winding losses generate heat which increase the tem-

perature of the paper and oil insulation. The oil circulates through radiators and heat is transferred to the surrounding air. If the load is constant, eventually, the oil and paper will reach steady state temperatures. If the load is variable, the oil and paper temperatures will be dynamic.

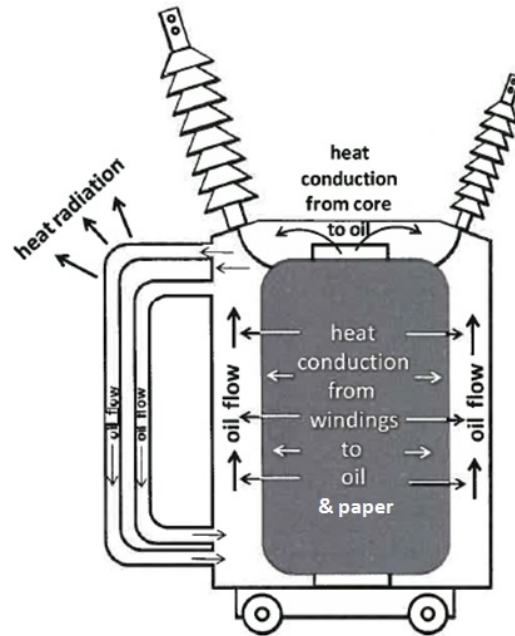


Figure 2.6: A simplified model of the heat transfer which occurs in an operating transformer (Stapleton et al. 2011, p. 56).

Transformer cooling modes

Since the flow of heat is dependent upon the flow rates of the oil within the transformer and the air outside the transformer, enhancing these flow rates achieves greater heat transfer. In turn, this enables operation of the transformer at higher loads. As such, there exists a range of different cooling methods for transformers. Standards Australia (2013a, p. 8-9) along with IEEE (2010, p. 8) have standardised transformer cooling methods using a four letter designation:

- *First letter: Internal cooling medium:*
 - O** Mineral oil (fire point $< 300^{\circ}\text{C}$)
 - K** Insulating liquid with fire point $> 300^{\circ}\text{C}$
 - L** Insulating liquid with no measurable fire point

- *Second letter: Circulation method for internal cooling medium:*
 - N** Natural thermo-siphon flow through windings and radiators
 - F** Forced circulation (pumped) through radiators, thermo-siphon flow through windings
 - D** Forced circulation through radiators, directed flow through windings

- *Third letter: External cooling medium:*
 - A** Air
 - W** Water

- *Fourth letter: Circulation method for external cooling medium:*
 - N** Natural convection
 - F** Forced circulation (fans, pumps)

Most transformers are capable of operating in two cooling modes and some possess three cooling modes. The most common transformer cooling designations (particularly within Ergon Energy) include:

- ONAN/ONAF
- ONAN/OFAF
- ONAN/ODAN
- ONAN/ODAF
- ONAN/ONAF/ODAF

For an individual transformer, associated with the cooling mode specifications are corresponding nameplate power ratings. An improved cooling mode increases the nameplate rating of a transformer. For example, a transformer with a nameplate rating of 30 MVA using ONAN cooling may have this rating increased to 40 MVA when operating in ONAF cooling mode (i.e. external fans operating to increase the flow of air across the radiators). Compared to ONAN cooling, the use of fans to increase air flow

and/or pumps to increase oil flow rates results in greater thermal gradients and hence enhanced heat flow from winding and core to paper and oil, and from oil to the external environment. Clearly then, the cooling mode in which a transformer is operating has an effect on the temperatures of the oil and paper and is therefore an important variable in a transformer thermal model.

Transformer thermal model nomenclature

For ONXX type cooling (i.e. ONAN or ONAF) it was stated above that the oil flows through the windings and radiators of the transformer by natural thermo-siphon action (Standards Australia 2013a, p. 8-9). This implies that there is a pressure gradient across which the oil flows. From figure 2.6, it can be seen that this thermo-siphon flow is from the bottom of the transformer tank, through the windings, into the radiators via the upper outlet and back into the tank through the lower inlet. The pressure differential is caused by a difference in temperature between the oil at the base of the transformer tank - called the *bottom oil temperature* - and the oil at the top of the tank - called the *top oil temperature* (Stapleton et al. 2011, p. 59). It is therefore the top oil temperature which must be modelled since this oil will suffer the greatest thermal effects during the loading cycle. The temperature differential between top oil and bottom oil is classified as the *oil gradient* (Stapleton et al. 2011, p. 59). Similarly, the winding temperature is lowest at the base and greatest at the top and is classified as the *winding gradient*. These gradients can be visualised by examination of figure 2.7 in which the vertical axis indicates position (in the tank or on the winding) from bottom to top and the horizontal axis indicates temperature. The linear temperature gradients displayed in figure 2.7 are an assumption however empirical evidence has shown this to be acceptable (Stapleton et al. 2011, p. 59). Other assumptions made with respect to figure 2.7 include: specification of a constant difference between the oil and winding temperature gradients, given the symbol g ; and the application of a constant multiplier H (usually equal to 1.3) to the top winding temperature to calculate WHS temperature (Standards Australia 2013b, p. 21-22). The ambient temperature is also included in figure 2.7 as a vertical line at a temperature below the oil and winding gradients and has an important contribution to any thermal model as will soon be discussed. The concept of the WHS, as the position on the winding of greatest localised heating, has already been introduced in section 2.2.2 and is also included in figure 2.7.

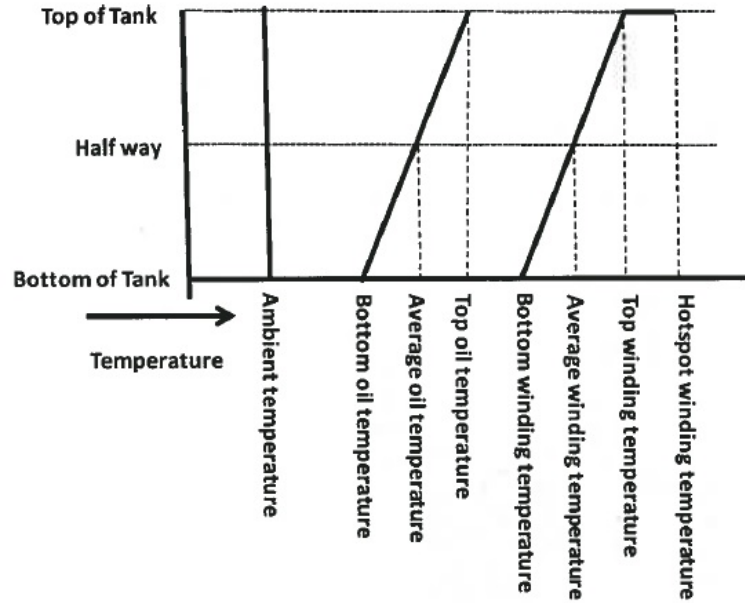


Figure 2.7: Graphical representation of the thermal gradients existing within an operating transformer (Stapleton et al. 2011, p. 60).

Heat run tests (HRT)

To model the top oil and WHS temperatures throughout the loading cycle using pure heat transfer theory would be an almost impossible exercise since it would be necessary to obtain knowledge of every aspect, feature and dimension of a transformer. Factors inhibiting the direct application of heat transfer theory are:

- The complex structure of the transformer – multiple materials are present including steel, copper, mineral oil and paper – all with different thermal properties;
- The range of heat transfer mechanisms at play – conduction (from winding to paper), convection (from paper to oil, from core to oil, from oil to steel, from steel to air) and radiation (from steel to the environment);
- The variability of the environment in which the transformer operates – solar heating effects, natural wind, rain etc.; &
- The fact that a transformer represents a 3-D heat transfer problem (e.g. thermal modelling of cables is simpler since a 2-D cross section only need be analysed).

Added to the above complexities in the thermal modelling of individual transformers is the fact that a typical utility owns many hundreds of transformers across its network, all

of which require a cyclic rating to be determined. A unique model for every transformer is not feasible in this situation and a more universal method is required.

To simplify the task of thermal modelling, manufacturers carry out *temperature rise tests*, also called *heat run tests* (HRT), on their transformers before delivery to the customer. Temperature rise tests are but one of the compulsory tests manufacturers must carry out as specified by Standards Australia (2005, p. 25-26). A HRT involves applying rated losses to a transformer for an extended period of time and measuring the top oil temperature rise above ambient temperature and the top winding temperature rise above the top oil temperature at regular intervals (Standards Australia 2013a, p. 14-15). The rated losses are applied using either a short circuit test or back-to-back test configuration until the measured temperature rises have reached steady state (Standards Australia 2013a, p. 14-15). The transformer is then de-energised and measurements are recorded as it cools (Standards Australia 2013a, p. 14-15). The HRT results state the increase in oil and winding temperatures which can be expected during operation at rated (nameplate) loads. A HRT essentially yields the thermal signature of a particular transformer which can then be used to model the temperature rises during operation at loads other than nameplate.

Ambient temperature

A final factor affecting thermal modelling is the *ambient temperature*. A maximum rating must always be qualified by a statement of the ambient temperature at which the rating applies. For example, a transformer may have been determined to possess a continuous nameplate rating of 50 MVA at an ambient temperature of 20°C and therefore cannot be operated continuously at 50 MVA in another location where the ambient temperature is 30°C . This is because the initial rating was determined by loading the transformer until the oil and paper temperatures reached their limiting values. At the different location and at the same load, the oil and paper temperature *rises* above ambient will be the same, however the oil and paper temperature limits will be exceeded by 10°C due to the higher ambient temperature. This effect of ambient temperature is also apparent as the seasons change. Cold weather in winter facilitates higher loading while high summer temperatures limit ratings significantly in some cases. Ambient temperature is therefore another important consideration in thermal modelling.

Thermal modelling parameters

In summary, as a result of the discussion in previous sections, it can be stated that any transformer thermal model must accommodate the following parameters as inputs:

1. **Nameplate rating and data**
2. **Load profile**
3. **Cooling mode**
4. **Heat run test data**
5. **Ambient temperature**

2.2.4 Thermal transformer models

A range of transformer thermal models have been presented in the literature. Different models target different applications and attempt to address the complexities of the transformer as a thermal system in different ways. From the utility perspective, some of the models are more appropriate due to their combination of resource requirements and ease of application. The thermal models which have been analysed are:

1. Swift, Molinski & Lehn (2001)
2. Susa et al. (2005)
3. Iskender & Mamizadeh (2011)
4. Tang, Wu & Richardson (2004)
5. Elmoudi et al. (2006)
6. Tan et al. (2012)
7. Susa & Lehtonen (2006)
8. Standards Australia (2013*b*)

Common to all of the models are the following two concepts:

1. Non-linearity

Non-linearity exists in transformer thermal modelling due to the nature of convection. For an ONAN transformer, an increase in load not only causes an increase in the thermal gradient across the oil to air interface, but results in a rise in the rate of air flow across the radiator surface (Swift, Molinski & Lehn 2001, p. 172). These effects cause an increase in the rates of both conduction and convection and thus a non-linearly proportional rise in heat transfer (Swift, Molinski & Lehn 2001, p. 172). A similar effect occurs at the paper to oil and core to oil interfaces where an increase in load causes both an increase in thermal gradient and a rise in oil flow rate. For a transformer with forced cooling however (e.g. ONAF, OFAF, ODAN or ODAF), the flow rate of the air and/or oil are fixed and hence the system becomes linear (Swift, Molinski & Lehn 2001, p. 172).

2. Thermal – electrical analogy

A useful technique for thermal modelling involves creating a ‘thermal circuit’ with circuit elements that possess similar behaviour to their electrical circuit counterparts. Table 2.1 defines these component analogies.

Table 2.1: Thermal and electrical circuit analogies (Susa et al. 2005, p. 198) (Swift, Molinski & Lehn 2001, p. 171).

Thermal circuit element	Analogous electrical circuit element	Description
Heat source [W]	Current source [A]	Used to represent core and winding losses.
Temperature differential [$^{\circ}C$]	Voltage source [V]	Used to account for ambient temperature in oil model or oil temperature in WHS model.
Thermal resistance [$^{\circ}C/W$]	Electrical resistor [Ω]	Models the material opposition to heat flow (paper, oil, steel, air).
Thermal capacitance [$J/^{\circ}C$]	Electrical capacitor [F]	Models the material’s ability to store thermal energy (paper, oil, steel).

Each model is now evaluated in turn.

Swift, Molinski & Lehn (2001)

Swift, Molinski & Lehn (2001, p. 172), using thermal – electrical analogy, have developed models for the top oil and WHS temperatures. The top oil model, displayed in figure 2.8, is discussed first. Note that core losses are represented by iron loss (*Fe loss*) and winding losses are represented by copper loss (*Cu loss*).

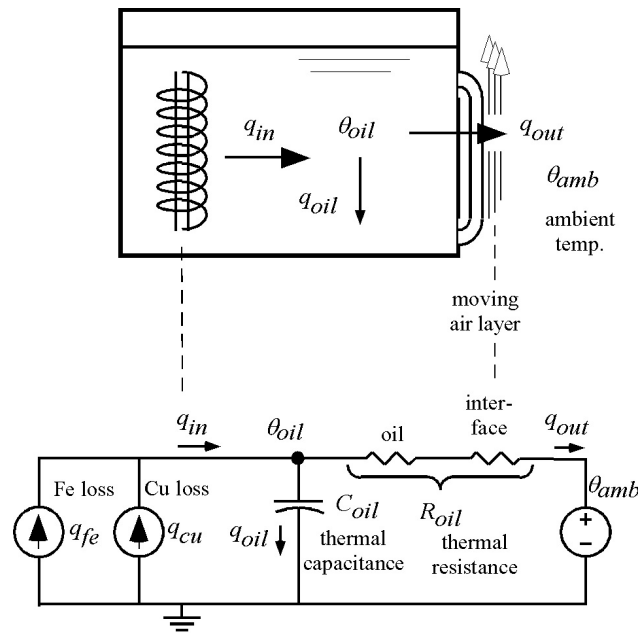


Figure 2.8: Transformer top oil thermal model developed by Swift, Molinski & Lehn (2001, p. 172-173).

The top oil thermal model can be described by the following differential equation:

$$q_{fe} + q_{cu} = C_{oil} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{1/n}}{R_{oil R}} \quad (2.5)$$

- where:
- q_{fe} is the core or iron loss [W];
 - q_{cu} is the winding or copper loss [W];
 - C_{oil} is the thermal capacitance of mineral oil [$J/^\circ C$];
 - θ_{oil} is the top oil temperature [$^\circ C$];
 - θ_{amb} is the ambient temperature [$^\circ C$];
 - $R_{oil R}$ is the thermal resistance of mineral oil at rated load [$^\circ C/W$]; &
 - n is the non-linearity exponent; $n = 0.8$ for ONAN cooling; $n \approx 1$ for ONAF cooling.

Some issues that cause equation (2.5) to be difficult to apply in its current form are:

- Copper losses (q_{cu}) are not known for loads other than the rated load (iron losses can be assumed fixed);
- Thermal capacitance of the mineral oil (C_{oil}) is usually not known;
- Thermal resistance of the mineral oil at rated load ($R_{oil R}$) is usually not known.

To rectify these issues, the following relationships (equations (2.6) to (2.10)) are employed:

$$\tau_{oil} = R_{oil R} \cdot C_{oil} \quad (2.6)$$

where: τ_{oil} is the thermal time constant of the oil in seconds.

$$\beta = \frac{q_{cuR}}{q_{fe}} \quad (2.7)$$

where: β is the ratio of rated copper losses to iron losses;
 q_{cuR} is the copper (winding) loss at *rated* load; &
 q_{fe} is the fixed iron (core) loss.

$$I_{pu} = \frac{I}{I_R} \quad (2.8)$$

where: I_{pu} is the per unit load current at the present operating point;
 I is the load current at the present operating point; &
 I_R is the load current at *rated* load.

$$\frac{q_{cu}}{q_{cuR}} = \frac{I^2}{I_R^2} \quad (2.9)$$

$$\therefore q_{cu} = q_{cuR} \cdot I_{pu}^2 \quad (2.10)$$

Multiplying by $R_{oil R}$, equation (2.5) can now be rewritten as:

$$(q_{fe} + q_{cu}) R_{oil R} = R_{oil R} \cdot C_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \quad (2.11)$$

Substituting equation (2.6) into equation (2.11) gives:

$$(q_{fe} + q_{cu}) R_{oil R} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \quad (2.12)$$

When approaching steady state at *rated* load, q_{oil} in figure 2.8 approaches zero and thus:

$$(q_{fe} + q_{cu_R}) R_{oil\ R} = \Delta\theta_{oil\ R}^{1/n} \quad (2.13)$$

where: $\Delta\theta_{oil\ R}$ is the top oil temperature rise above ambient at rated load [$^{\circ}C$].

Inverting equation (2.13) for $R_{oil\ R}$ and substituting into equation (2.12) yields:

$$(q_{fe} + q_{cu}) \frac{\Delta\theta_{oil\ R}^{1/n}}{q_{fe} + q_{cu_R}} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \quad (2.14)$$

$$\frac{q_{fe} + q_{cu}}{q_{fe} + q_{cu_R}} \cdot \Delta\theta_{oil\ R}^{1/n} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \quad (2.15)$$

Equation (2.10) can now be employed to simplify equation (2.15):

$$\frac{q_{fe} + q_{cu_R} \cdot I_{pu}^2}{q_{fe} + q_{cu_R}} \cdot \Delta\theta_{oil\ R}^{1/n} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \quad (2.16)$$

$$\frac{1 + \frac{q_{cu_R} \cdot I_{pu}^2}{q_{fe}}}{1 + \frac{q_{cu_R}}{q_{fe}}} \cdot \Delta\theta_{oil\ R}^{1/n} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \quad (2.17)$$

Finally, substitution of equation (2.7) into equation (2.17) yields the final differential equation modelling the **top oil temperature**:

$$\boxed{\left(\frac{1 + I_{pu}^2 \beta}{1 + \beta} \right) \cdot \Delta\theta_{oil\ R}^{1/n} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n}} \quad (2.18)$$

The WHS thermal model, displayed in figure 2.9, is similar to the top oil model apart from the following differences:

- Only copper losses are taken into account (i.e. Swift, Molinski & Lehn have assumed that core losses do not contribute to heating of the winding and paper); &
- Ambient temperature is no longer considered since the WHS temperature is modelled as a rise above top oil temperature which has already been calculated using equation (2.18).

The WHS thermal model can then be described by the following differential equation:

$$q_{cu} = C_{hs} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{1/m}}{R_{hs\ R}} \quad (2.19)$$

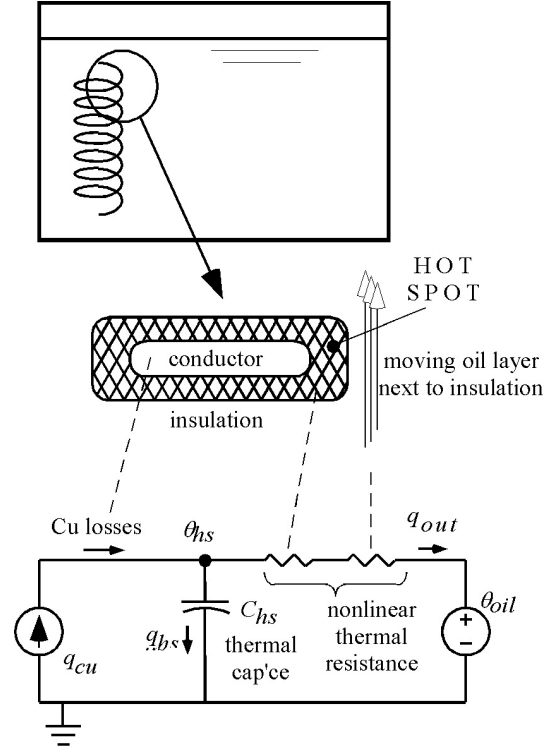


Figure 2.9: Transformer WHS thermal model developed by Swift, Molinski & Lehn (2001, p. 172-173).

where: C_{hs} is the thermal capacitance of the winding [$J/^\circ C$];
 θ_{hs} is the WHS temperature [$^\circ C$];
 $R_{hs R}$ is the thermal resistance of the winding at rated load [$^\circ C/W$]; &
 m is the non-linearity exponent; not defined by Swift, Molinski &
 Lehn.

Using a similar procedure to that of the top oil model, equation (2.19) is modified:

$$q_{cu} = C_{hs} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{1/m}}{R_{hs R}} \quad (2.20)$$

$$q_{cu} \cdot R_{hs R} = R_{hs R} \cdot C_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{1/m} \quad (2.21)$$

$$\Delta\theta_{hs}^{1/m} = \tau_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{1/m} \quad (2.22)$$

$$\Delta\theta_{hs R}^{1/m} \cdot \left(\frac{q_{cu}}{q_{cu R}} \right) = \tau_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{1/m} \quad (2.23)$$

$$\Delta\theta_{hs R}^{1/m} \cdot \left(\frac{q_{cu R} \cdot I_{pu}^2}{q_{cu R}} \right) = \tau_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{1/m} \quad (2.24)$$

Therefore, the final differential equation modelling the **WHS temperature** is:

$$\Delta\theta_{hs R}^{1/m} \cdot I_{pu}^2 = \tau_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{1/m} \quad (2.25)$$

Validation of the top oil thermal model (but not the WHS model) is carried out in a companion paper (Swift, Molinski, Bray & Menzies 2001). $\Delta\theta_{oil}$ (top oil temperature rise above ambient temperature) and $\Delta\theta_{hs}$ (WHS temperature rise above top oil temperature) are easily obtained from transformer heat run tests. The two models are combined as shown in figure 2.10. θ_{oil} and θ_{hs} can then be calculated for every time step in a loading cycle using equations (2.18) and (2.25).

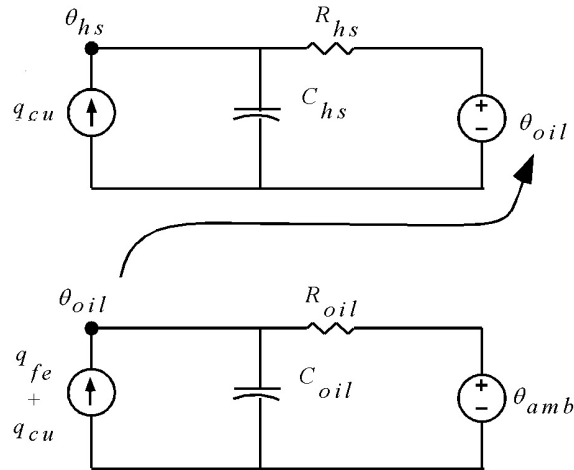


Figure 2.10: The complete transformer thermal model developed by Swift, Molinski & Lehn (2001, p. 174).

This model by Swift, Molinski & Lehn (2001) has the advantages of being simple (it is the simplest model discovered), however its disadvantage is that it accounts for the non-linearity of the thermal behaviour by raising the temperature differentials to the n and m exponents which is only an approximation. It is actually the thermal resistances R_{oil} and R_{hs} which are non-linear. These thermal resistances can be modelled as non-linear elements for improved accuracy, which is performed by Susa et al. (2005) in the next model to be examined.

Susa et al. (2005)

Susa et al. (2005, p. 197) justify the use of two time constants in the thermal transformer model. They state that many older models (pre-2005) in the literature and standards disregard the winding time constant because compared to the oil time constant, it is negligible (minutes compared with hours) (Susa et al. 2005, p. 197). It is important to note however, that despite being published in 2001, the model by Swift, Molinski

& Lehn (2001) (examined above) did not make this assumption. The use of only one time constant meant that in these older models, the WHS temperature varied in phase with the load (i.e. it was assumed there was no delay in WHS temperature variations). This assumption was shown to be inaccurate by Nordman et al. (2003). It can be seen from figure 2.11 that the WHS temperature does in fact lag the changes in load by a significant amount (a different amount for different transformers) and as a consequence, the winding time constant should be included in thermal models.

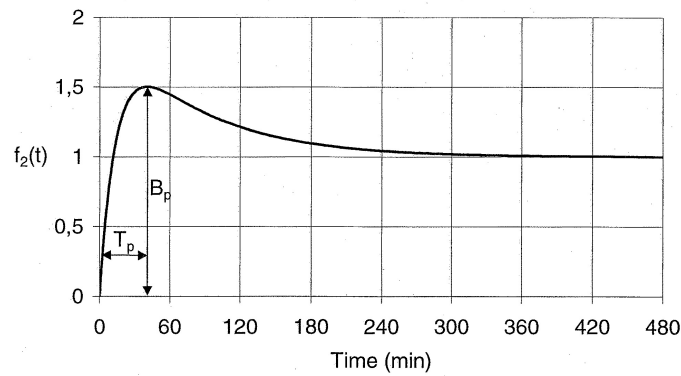


Figure 2.11: Normalised variation in WHS temperature as a response to a step change in load for a particular transformer Nordman et al. (2003, p. 1111).

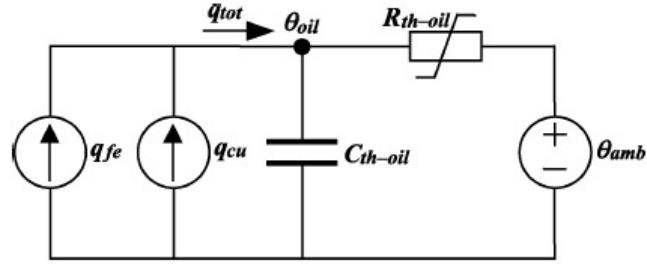
Susa et al. (2005) propose a thermal transformer model based on thermal – electrical analogy which is very similar to that of Swift, Molinski & Lehn (2001) as can be seen from figure 2.12. However the model by Susa et al. (2005) differs from that of Swift, Molinski & Lehn (2001) by including the following features:

- Non-linearity is modelled using a non-linear thermal resistance as opposed to the application of a non-linear exponent to a temperature differential; &
- The variation in oil flow rate with temperature due to changes in oil viscosity is considered.

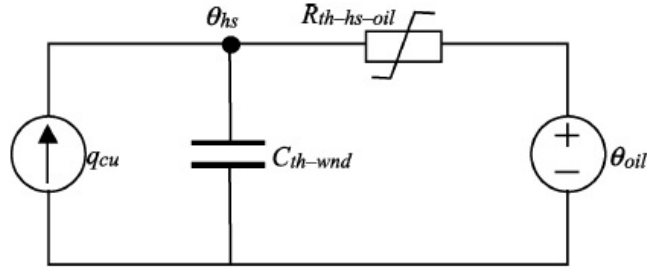
Although Susa et al. (2005) utilise slightly different variable symbols in their model (as can be seen in figure 2.12) the symbols from the Swift, Molinski & Lehn (2001) model will be retained here for ease of comparison. The top oil model will be considered first.

By inspection of figure 2.12a, a differential equation model can be written as follows:

$$q_{fe} + q_{cu} = C_{oil} \cdot \frac{d\theta_{oil}}{dt} + \frac{\theta_{oil} - \theta_{amb}}{R_{oil}} \quad (2.26)$$



(a) Top oil model.



(b) WHS model.

Figure 2.12: Top oil and WHS models proposed by Susa et al. (2005).

Note that equation (2.26) includes no exponents. The non-linearity for the Susa et al. (2005) model is inherent in the non-linear thermal resistance (R_{oil}). From heat transfer theory, convection is the transfer of thermal energy from a surface to a moving fluid (Çengel 2008, p. 382). For the Susa et al. (2005) model, the non-linear thermal resistance associated with convection at the oil/steel to air interface is described by the following relationship (Çengel 2008, p. 404):

$$R_{oil} = \frac{1}{hA} \quad (2.27)$$

where: h is the empirically determined heat transfer coefficient [$W/m^2/^\circ C$]; &
 A is surface area through which heat transfer by convection occurs [m^2].

Natural convection is modelled in heat transfer theory by employing the following well known empirical relationship (Çengel 2008, p. 618):

$$Nu = C (Gr \cdot Pr)^n \quad (2.28)$$

where: Nu is the Nusselt number;
 Gr is the Grashof number;
 Pr is the Prandtl number;
 n is an exponent equal to 1/4 for laminar flow and 1/3 for turbulent flow; &
 C is a constant.

The *Nusselt number* is the ratio of heat transfer by convection to heat transfer by conduction and is given by (Çengel 2008, p. 528):

$$Nu = \frac{hL_c}{k} \quad (2.29)$$

where: h is the heat transfer coefficient [$W/m^2/^\circ C$];
 L_c is the characteristic dimension; &
 k is the thermal conductivity [$W/m/^\circ C$].

The *Grashof number* is a dimensionless quantity representing natural convection effects and is given by (Çengel 2008, p. 617):

$$Gr = \frac{g \cdot B \cdot \Delta T \cdot L_c^3}{\nu^2} \quad (2.30)$$

where: g is the acceleration due to gravity ($\approx 9.8m/s^2$);
 B is the coefficient of volume expansion [$^\circ C^{-1}$];
 ΔT is the temperature differential [$^\circ C$];
 L_c is the characteristic dimension; &
 ν is the kinematic viscosity of mineral oil [m^2/s].

The *Prandtl number* is the ratio of molecular diffusivity of momentum to the molecular diffusivity of heat and is given by (Çengel 2008, p. 535):

$$Pr = \frac{\mu \cdot c_p}{k} \quad (2.31)$$

where: μ is the absolute viscosity of oil [Ns/m^2]; &
 c_p is the specific heat capacity of mineral oil [$J/kg/^\circ C$].

Since kinematic viscosity and absolute viscosity are related by the density of mineral oil, ρ , according to $\nu = \frac{\mu}{\rho}$ (Çengel 2008, p. 536), equation (2.30) becomes:

$$Gr = \frac{g \cdot B \cdot \Delta T \cdot L_c^3 \cdot \rho^2}{\mu^2} \quad (2.32)$$

Substituting equations (2.29), (2.31) and (2.32) into equation (2.28) and realising that $\Delta T = \Delta\theta_{oil}$ yields:

$$\frac{hL_c}{k} = C \left(\frac{g \cdot B \cdot \Delta\theta_{oil} \cdot L_c^3 \cdot \rho^2}{\mu^2} \cdot \frac{\mu \cdot c_p}{k} \right)^n \quad (2.33)$$

It can be shown experimentally, that apart from h , $\Delta\theta_{oil}$ and μ , all of the variables in equation (2.33) can be considered constant with changes in temperature (Susa et al.

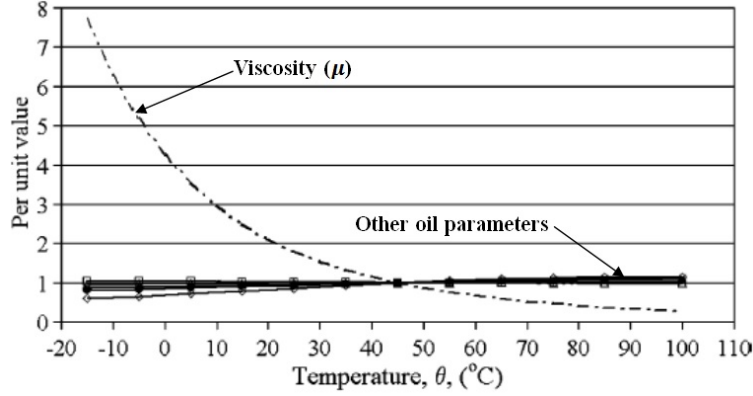


Figure 2.13: Negligible variation in oil parameters relative to that of absolute viscosity with change in temperature (Susa et al. 2005, p. 200).

2005, p. 199). This can be seen in figure 2.13 in which compared to viscosity (the dot-dash line), the other parameters change very little over a large range of temperatures.

For this reason, equation (2.33) can be modified as follows:

$$h = \frac{Ck}{L_c} \left(\frac{g \cdot B \cdot \Delta\theta_{oil} \cdot L_c^3 \cdot \rho^2 \cdot c_p}{k \cdot \mu} \right)^n \quad (2.34)$$

$$= \frac{Ck}{L_c} \left(\frac{g \cdot B \cdot L_c^3 \cdot \rho^2 \cdot c_p}{k} \right)^n \cdot \left(\frac{\Delta\theta_{oil}}{\mu} \right)^n \quad (2.35)$$

$$= C' \cdot \left(\frac{\Delta\theta_{oil}}{\mu} \right)^n \quad (2.36)$$

where: $C' = \frac{Ck}{L_c} \left(\frac{g \cdot B \cdot L_c^3 \cdot \rho^2 \cdot c_p}{k} \right)^n = \text{a constant.}$

Substituting equation (2.36) into equation (2.27) then gives:

$$R_{oil} = \frac{1}{C' \cdot A} \cdot \left(\frac{\mu}{\Delta\theta_{oil}} \right)^n \quad (2.37)$$

Substitution of equation (2.37) into equation (2.26) yields a new version of the top oil differential equation containing the non-linear thermal resistance (R_{oil}) as a function of oil viscosity (μ) and the top oil temperature rise above ambient temperature ($\Delta\theta_{oil}$):

$$q_{fe} + q_{cu} = C_{oil} \cdot \frac{d\theta_{oil}}{dt} + C' \cdot A \cdot \left(\frac{\Delta\theta_{oil}}{\mu} \right)^n \cdot [\theta_{oil} - \theta_{amb}] \quad (2.38)$$

Since $\theta_{oil} - \theta_{amb} = \Delta\theta_{oil}$, equation (2.38) becomes:

$$q_{fe} + q_{cu} = C_{oil} \cdot \frac{d\theta_{oil}}{dt} + \frac{C' \cdot A}{\mu^n} \cdot [\theta_{oil} - \theta_{amb}]^{n+1} \quad (2.39)$$

$$\frac{\mu^n}{C' \cdot A} \cdot (q_{fe} + q_{cu}) = \frac{\mu^n}{C' \cdot A} \cdot C_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{n+1} \quad (2.40)$$

Now utilising the form of equation (2.37), the thermal resistance of the oil at *rated* load ($R_{oil\ R}$) is:

$$R_{oil\ R} = \frac{1}{C' \cdot A} \cdot \left(\frac{\mu_R}{\Delta\theta_{oil\ R}} \right)^n \quad (2.41)$$

where: μ_R is the oil viscosity at rated load; &
 $\Delta\theta_{oil\ R}$ is the top oil temperature rise above ambient temperature at rated load (from HRT data).

Since the viscosity of the mineral oil at a particular load (μ) is the product of viscosity at rated load (μ_R) and per unit viscosity (μ_{pu}), (i.e. $\mu = \mu_R \cdot \mu_{pu}$), equation (2.41) becomes:

$$R_{oil\ R} = \frac{1}{C' \cdot A} \cdot \left(\frac{\mu}{\mu_{pu}} \right)^n \cdot [\Delta\theta_{oil\ R}]^{-n} \quad (2.42)$$

$$\frac{\mu^n}{C' \cdot A} = R_{oil\ R} \cdot \mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n \quad (2.43)$$

Now, substituting equation (2.43) into equation (2.40) gives:

$$[R_{oil\ R} \cdot \mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n] \cdot (q_{fe} + q_{cu}) = [R_{oil\ R} \cdot \mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n] \cdot C_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{n+1} \quad (2.44)$$

The rated load oil time constant is given by: $\tau_{oil\ R} = R_{oil\ R} \cdot C_{oil}$, where $C_{oil\ R} = C_{oil} = c_p \cdot m_{oil}$ since both c_p (specific heat capacity of mineral oil) and m_{oil} (mass of mineral oil) are constants (Tan et al. 2012, p. 3). Therefore, equation (2.44) becomes:

$$[R_{oil\ R} \cdot \mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n] \cdot (q_{fe} + q_{cu}) = [\mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n] \cdot \tau_{oil\ R} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{n+1} \quad (2.45)$$

Recalling from equation (2.10) (in the Swift, Molinski & Lehn model) that: $q_{cu} = q_{cu\ R} \cdot I_{pu}^2$, equation (2.45) is altered to:

$$[R_{oil\ R} \cdot \mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n] \cdot (q_{fe} + q_{cu\ R} \cdot I_{pu}^2) = [\mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n] \cdot \tau_{oil\ R} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{n+1} \quad (2.46)$$

Dividing equation (2.46) by $[\mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n]$ results in:

$$R_{oil\ R} \cdot (q_{fe} + q_{cu\ R} \cdot I_{pu}^2) = \tau_{oil\ R} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n} \quad (2.47)$$

Referring to figure 2.12a, it can be seen that as steady state is approached at *rated* load, $\Delta\theta_{oil\ R} = R_{oil\ R} \cdot (q_{fe} + q_{cu\ R})$. Thus, $R_{oil\ R} = \frac{\Delta\theta_{oil\ R}}{q_{fe} + q_{cu\ R}}$, which when substituted into

equation (2.47) yields:

$$\frac{\Delta\theta_{oil R}}{q_{fe} + q_{cu R}} \cdot (q_{fe} + q_{cu R} \cdot I_{pu}^2) = \tau_{oil R} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil R}^n} \quad (2.48)$$

$$\frac{q_{fe} + q_{cu R} \cdot I_{pu}^2}{q_{fe} + q_{cu R}} \cdot \Delta\theta_{oil R} = \tau_{oil R} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil R}^n} \quad (2.49)$$

Finally, applying the definition: $\beta = \frac{q_{cu R}}{q_{fe}}$ to equation (2.49) generates the final version of the **top oil temperature** differential equation:

$$\boxed{\frac{1 + I_{pu}^2 \beta}{1 + \beta} \cdot \Delta\theta_{oil R} = \tau_{oil R} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil R}^n}} \quad (2.50)$$

In the Susa et al. (2005) model, the WHS differential equation is formulated in much the same way except it is assumed that only copper losses contribute to heating of the winding and paper. Referring to figure 2.12b, again employing identical variable symbols to those of the Swift, Molinski & Lehn (2001) model, the initial differential equation describing the WHS temperature is:

$$q_{cu} = C_{hs} \cdot \frac{d\theta_{hs}}{dt} + \frac{\theta_{hs} - \theta_{oil}}{R_{hs}} \quad (2.51)$$

In equation (2.51), R_{hs} is the non-linear thermal resistance of the heat path from the WHS to the winding insulation to the oil. That is: $R_{hs} = R_{winding} + R_{insulation} + R_{oil}$ (Susa et al. 2005, p. 201). It is assumed by Susa et al. (2005, p. 201) that: $R_{oil} \gg R_{winding}$ and $R_{oil} \gg R_{insulation}$. Therefore, $R_{hs} \approx R_{oil}$ which from the top oil model equation (2.37) implies that:

$$R_{hs} = \frac{1}{C' \cdot A} \cdot \left(\frac{\mu}{\Delta\theta_{hs}} \right)^n \quad (2.52)$$

Equation (2.52) is now substituted into equation (2.51) and the same process as for the top oil model is followed:

$$\begin{aligned} q_{cu} &= C_{hs} \cdot \frac{d\theta_{hs}}{dt} + C' \cdot A \cdot \left(\frac{\Delta\theta_{hs}}{\mu} \right)^n \cdot [\theta_{hs} - \theta_{oil}] \\ q_{cu} &= C_{hs} \cdot \frac{d\theta_{hs}}{dt} + \frac{C' \cdot A}{\mu^n} \cdot [\theta_{hs} - \theta_{oil}]^{n+1} \\ \frac{\mu^n}{C' \cdot A} \cdot q_{cu} &= \frac{\mu^n}{C' \cdot A} \cdot C_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{n+1} \\ [R_{hs R} \cdot \mu_{pu}^n \cdot \Delta\theta_{hs R}^n] \cdot q_{cu} &= [R_{hs R} \cdot \mu_{pu}^n \cdot \Delta\theta_{hs R}^n] \cdot C_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{n+1} \\ R_{hs R} \cdot q_{cu R} I_{pu}^2 &= \tau_{hs R} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{hs R}^n} \\ \frac{\Delta\theta_{hs R}}{q_{cu R}} \cdot q_{cu R} I_{pu}^2 &= \tau_{hs R} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{hs R}^n} \end{aligned}$$

Thus the final version of the **WHS temperature** differential equation is:

$$\Delta\theta_{hs R} \cdot I_{pu}^2 = \tau_{hs R} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{hs R}^n} \quad (2.53)$$

In a separate, more recent publication, Susa & Nordman (2009) present an empirical relationship between absolute viscosity (μ) in *kg/s* and temperature (θ_μ):

$$\mu = 1.36 \times 10^{-3} \cdot \exp\left[\frac{2797.3}{\theta_\mu + 273}\right] \quad (2.54)$$

where: $\theta_\mu = (\theta_{hs} + \theta_{amb}) / 2$

When modelling transformer temperatures, equation (2.54) can be employed along with equations (2.50) and (2.53) to calculate μ_{pu} which is itself calculated as: $\mu_{pu} = \mu / \mu_R$.

Combination of the models can be accomplished in the same manner as for Swift, Molinski & Lehn (2001) which is displayed in figure 2.10. These models were validated by Susa et al. (2005) through the process of loading several transformers, measuring the oil and WHS temperatures and then comparing these measurements with those predicted by the models. Oil flow within the transformer and air flow through the radiators of the transformer were assumed to be *laminar* and so $n = 0.25$ was employed (Susa et al. 2005, p. 200). Since it is based on natural convection heat transfer theory, the model can only be accurately applied to ONAN transformers.

Iskender & Mamizadeh (2011)

Iskender & Mamizadeh (2011) develop thermal transformer models for both outdoor and indoor installation conditions but only for the top oil temperature. The two environments are significantly different predominantly because air flow is restricted in the indoor situation (Iskender & Mamizadeh 2011, p. 14).

For the outdoor transformer thermal model, Iskender & Mamizadeh (2011) begin with a more complex thermal – electrical analogy than for the previous models. This thermal circuit, shown in figure 2.14, is a more detailed representation of the losses within a transformer, incorporating stray losses in addition to winding and iron losses (Iskender & Mamizadeh 2011, p. 11-12). The circuit also incorporates thermal capacitances of

windings, core, tank and other metal components as well as thermal resistances between tank and oil, core and oil, winding and oil and oil and air (Iskender & Mamizadeh 2011, p. 11-12). However, the authors then simplify the model to that studied for the previous models by combining the various thermal capacitances and resistances. From this point, Iskender & Mamizadeh (2011) follow a similar process to Susa et al. (2005) and arrive at the same modelling differential equation (2.50).

The indoor transformer model for top oil temperature is displayed in figure 2.15. This model is significantly more complex as it incorporates additional heat sources such as indoor switch gear and the heat transfer properties of structures such as doors, walls, ceiling and vents (Iskender & Mamizadeh 2011, p. 15). In terms of its application to this project, the indoor model is less relevant since the majority of Ergon Energy transformers are installed outdoors. Additionally, Iskender & Mamizadeh (2011) do not develop a modelling equation to a form which can be easily solved. The equation presented is similar in form to equation (2.50) but incorporates thermal capacitance and resistance representative of the building enclosing the transformer as expected.

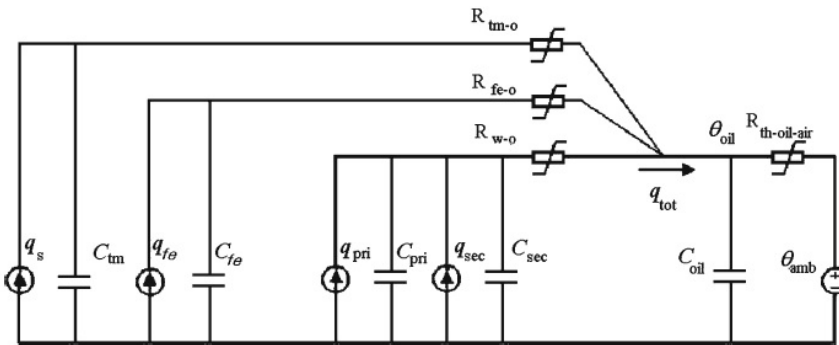


Figure 2.14: Outdoor transformer top oil model by Iskender & Mamizadeh (2011, p. 12).

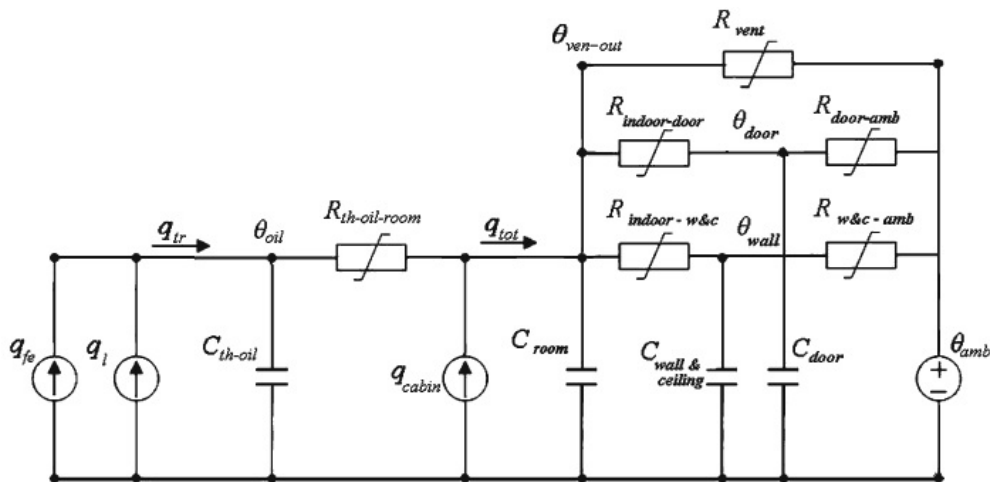


Figure 2.15: Indoor transformer top oil model by Iskender & Mamizadeh (2011, p. 15).

Tang, Wu & Richardson (2004)

The model created by Tang et al. (2004) is based on similar heat transfer theory and thermal – electrical analogy as has been described for the previous models. Where this model differs from others is in the use of a *genetic algorithm* (GA) to obtain optimised thermal parameters for a transformer (Tang et al. 2004, p. 1115). A GA is an interesting combination of optimising mathematics and genetics whereby estimates of parameters are modified and the best combined to produce ever more optimised parameters using techniques reminiscent of ‘mutation’ and ‘reproduction’ (Tang et al. 2004, p. 1115). To obtain a set of optimised thermal parameters, the GA requires the input of real-time oil and winding temperatures from the transformer being modelled (Tang et al. 2004, p. 1116). This means that the model is optimised for a single transformer and is not universal.

Elmoudi et al. (2006)

Elmoudi et al. (2006) base their model on the differential equations proposed by Swift, Molinski & Lehn (2001). A *finite element* numerical technique is then employed to model the leakage flux over the transformer windings which enables calculation of winding eddy current losses and thus a more accurate solution (Elmoudi et al. 2006, p. 215). The results of the finite element method also enable accurate prediction of the WHS location as displayed in figure 2.16. As for the Tang et al. (2004) model, this model is specific to a particular transformer and is not universal (to be applicable to other transformers, the finite element analysis would have to be repeated).

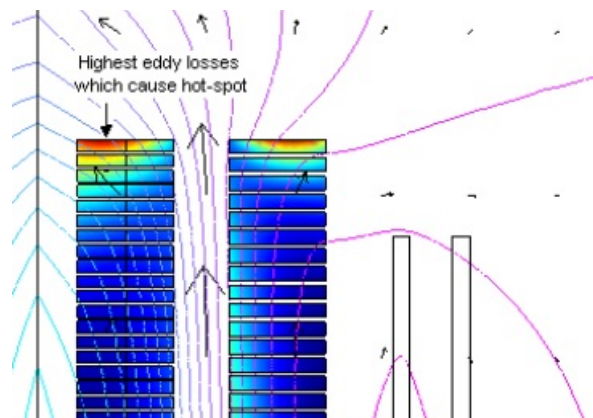


Figure 2.16: The leakage flux model obtained by finite element analysis, allowing precise prediction of the WHS (Elmoudi et al. 2006, p. 216).

Tan et al. (2012)

Tan et al. (2012) have attempted to improve on transformer thermal models by incorporating a *solar heat source* into the thermal circuit as shown in figure 2.17. Solar energy is highly variable throughout the loading cycle of an individual transformer, let alone for a fleet of geographically dispersed transformers. Additionally, the dimensions of a transformer, its colour and materials would all affect the amount of heat energy input to the transformer system from the sun. This raises the complexity of the model significantly. It may be for this reason that Tan et al. (2012) do not demonstrate or validate the solar portion of their model.

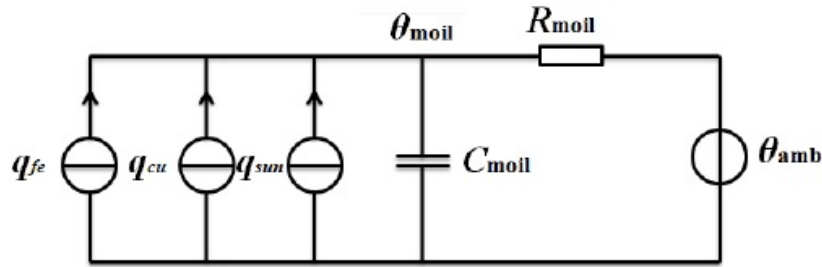


Figure 2.17: The model by Tan et al. (2012, p. 3) including a solar heat source.

Susa & Lehtonen (2006)

To improve on a previous model (Susa et al. 2005) (detailed earlier), Susa & Lehtonen (2006) considered the variation in transformer losses with temperature.

The **top oil thermal model** previously presented by Susa et al. (2005) is given as equation (2.50) which is repeated here:

$$\frac{1 + I_{pu}^2 \beta}{1 + \beta} \cdot \Delta\theta_{oil R} = \tau_{oil R} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil R}^n} \quad (2.50 \text{ repeated})$$

Susa & Lehtonen (2006, p. 1963) refine the top oil model as follows:

$$\boxed{\frac{1 + I_{pu}^2 \beta \cdot P_{l pu}}{1 + \beta} \cdot \Delta\theta_{oil R} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil R}^n}} \quad (2.55)$$

where: $P_{l pu}$ is the dependence of the load (copper) loss on temperature (i.e. is itself a function of temperature).

The dependence of the load loss on temperature $P_{l\ pu}$ is calculated using the following equation:

$$P_{l\ pu} = P_{dc\ pu} \cdot \left(\frac{\theta_e + \theta_k}{\theta_{e\ R} + \theta_k} \right) + P_{a\ pu} \cdot \left(\frac{\theta_{e\ R} + \theta_k}{\theta_e + \theta_k} \right) \quad (2.56)$$

- where:
- θ_e is the average of the high voltage and low voltage WHS temperatures [$^{\circ}C$];
 - $\theta_{e\ R}$ is the mean WHS temperature at *rated* load [$^{\circ}C$];
 - θ_k is equal to $225^{\circ}C$ for aluminium windings or $235^{\circ}C$ for copper windings;
 - $P_{dc\ pu}$ is the per unit value of DC loss at $\theta_{e\ R}$; &
 - $P_{a\ pu}$ is the per unit additional loss at $\theta_{e\ R}$ due to stray and eddy losses.

Susa & Lehtonen (2006, p. 1963) also extend the previous top oil model's application to transformers cooled by forced means. The exponent n in equation (2.55) takes on the values given in table 2.2 for ONAN, ONAF, OFAF and ODAF transformers. It can be seen that when oil flow is directed through the windings (ODAF), the model becomes linear.

Table 2.2: Values of the n exponent for different cooling modes in the Susa & Lehtonen (2006) top oil model.

Oil circulation	n			
	ONAN	ONAF	OFAF	ODAF
0 (cold start)	0.25	0.5	0.5	0
> 0 (on load)	0.25	0.2	0.2	0

The **WHS thermal model** previously presented by Susa et al. (2005) is given as equation (2.53) which is repeated here:

$$\Delta\theta_{hs\ R} \cdot I_{pu}^2 = \tau_{hs\ R} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{hs\ R}^n} \quad (2.53 \text{ repeated})$$

Through experiments, Susa & Lehtonen (2006, p. 1964) have also refined the WHS model as follows:

$$\Delta\theta_{hs\ R} \cdot I_{pu}^2 \cdot P_{w\ pu} = \tau_{hs\ R} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{n'+1}}{\mu_{pu}^n \cdot \Delta\theta_{hs\ R}^{n'}} \quad (2.57)$$

where: $P_{w pu}$ is the dependence of the load (copper) loss on temperature (i.e. is itself a function of temperature); &
 n' is a refined non-linearity exponent different from n .

The dependence of the load loss on temperature $P_{w pu}$ is calculated using the following equation:

$$P_{w pu} = P_{dc pu} \cdot \left(\frac{\theta_{hs} + \theta_k}{\theta_{hs R} + \theta_k} \right) + P_{eddy pu} \cdot \left(\frac{\theta_{hs R} + \theta_k}{\theta_{hs} + \theta_k} \right) \quad (2.58)$$

where: θ_{hs} is the WHS temperature [$^{\circ}C$];
 $\theta_{hs R}$ is the WHS temperature at *rated* load [$^{\circ}C$];
 θ_k is equal to $225^{\circ}C$ for Al windings or $235^{\circ}C$ for Cu windings;
 $P_{dc pu}$ is the per unit value of DC loss at $\theta_{hs R}$; &
 $P_{eddy pu}$ is the per unit winding eddy loss at $\theta_{hs R}$.

As for the top oil model, Susa & Lehtonen (2006, p. 1964) have also extended the previous WHS model's application to transformers cooled by forced means. The exponents n and n' in equation (2.57) take on the values given in table 2.3 for ONAN, ONAF and OFAF transformers.

Table 2.3: Values of the n and n' exponents for different cooling modes in the Susa & Lehtonen (2006) WHS model.

		Cooling modes		
Oil circulation	Exponent	ONAN	ONAF	OFAF
0 (cold start)	$n = n'$	0.25	2	2
> 0 (on load)	n	0.25	0.5	0.5
	n'	0.25	0.1	0.1

An equation for calculating the oil time constant (τ_{oil}) is also presented as part of this model. As the transformer heats and cools, its thermal capacitance (ability to store thermal energy) changes and so does the oil time constant. The oil time constant is calculated using the following equation (Susa & Lehtonen 2006, p. 1965-1966):

$$\tau_{oil} = \frac{C_{th oil} \Delta \theta_{oil R}}{q_{total R}} \quad (2.59)$$

where: $\Delta\theta_{oil R}$ is the top oil temperature rise at rated load [$^{\circ}C$];
 $q_{total R}$ is the total losses at rated load [W]; &
 $C_{th oil}$ is the thermal capacitance of the oil [$Ws/^{\circ}C$], which is itself
calculated using:

$$C_{th oil} = \frac{q_{wdg}}{q_{total}} \cdot m_{wdg} \cdot c_{wdg} + \frac{q_{fe}}{q_{total}} \cdot m_{fe} \cdot c_{fe} + \frac{q_{st}}{q_{total}} \cdot m_t \cdot c_t + O_{oil} \cdot m_{oil} \cdot c_{oil}$$

where: q_{wdg} is the winding DC & eddy losses at the current load [W];
 q_{st} is the stray losses at the current load [W];
 q_{fe} is the fixed core (iron) losses [W];
 q_{total} is the total losses at the current load [W];
 m_{wdg} is the mass of the winding [kg];
 m_{fe} is the mass of the core [kg];
 m_t is the mass of the tank & fittings [kg];
 m_{oil} is the mass of oil [kg];
 c_{wdg} is the specific heat capacity of winding (396 $Ws/kg/^{\circ}C$ for Copper
& 900 $Ws/kg/^{\circ}C$ for Aluminium);
 c_{fe} is the specific heat capacity of the core (468 $Ws/kg/^{\circ}C$);
 c_t is the specific heat capacity of the tank & fittings
(468 $Ws/kg/^{\circ}C$);
 c_{oil} is the specific heat capacity of oil (1836 $Ws/kg/^{\circ}C$); &
 O_{oil} is the correction factor for the oil (0.86 for ONXX or OFXX
cooling & 1.0 for ODXX cooling).

The winding time constant ($\tau_{hs R}$) is small and is taken as a constant. Susa et al. (2005) specify this constant value for a small number of transformers used to validate their model.

The Susa & Lehtonen (2006) model is more accurate than the previous version however some of the parameters are difficult to obtain. $P_{dc pu}$ and $P_a pu$ of equation (2.56) and $P_{dc pu}$ and $P_{eddy pu}$ of equation (2.57) are not known for many transformers of the Ergon Energy fleet (Susa et al. (2005) provide this data for a small number of transformers employed to validate their model). Additionally, the inability to apply the WHS model to ODXX cooled transformers restricts the application of the model universally to a fleet of transformers. By augmenting the Susa et al. (2005) model with parts of the Susa & Lehtonen (2006) model, the potential for a more accurate model exists.

Standards Australia (2013b)

This thermal transformer model is presented by Standards Australia (2013b) as part of *AS 60076.7 – Loading Guide for Oil-immersed Power Transformers*. The top oil and WHS models are presented in two forms:

1. Differential equations (claimed to be more accurate)
2. Exponential equations (more easily implemented)

Differential equations:

The differential equation model for **top oil temperature** is (Standards Australia 2013b, p. 42-43):

$$\left[\frac{1 + RK^2}{1 + R} \right]^x \cdot \Delta\theta_{or} = k_{11}\tau_o \cdot \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (2.60)$$

- where:
- K is the load factor ($\frac{\text{load current}}{\text{rated current}}$) (equivalent to I_{pu} in previous models);
 - R is the ratio of load to no-load losses at *rated* current (equivalent to β in previous models);
 - x is the oil exponent (refer to table 2.7);
 - θ_o is the top oil temperature;
 - $\Delta\theta_{or}$ is the top oil temperature rise above ambient at *rated* load;
 - τ_o is the oil time constant;
 - k_{11} is a constant (refer to table 2.7); &
 - θ_a is the ambient temperature.

The model for **WHS temperature** consists of two differential equations:

$$k_{21} \cdot K^y \cdot \Delta\theta_{hr} = k_{22}\tau_w \cdot \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \quad (2.61)$$

$$(k_{21} - 1) K^y \cdot \Delta\theta_{hr} = \frac{\tau_o}{k_{22}} \cdot \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \quad (2.62)$$

- where:
- y is the winding exponent (refer to table 2.7);
 - $\Delta\theta_{h1}$ is the first component of the WHS temperature rise above top oil temperature;
 - $\Delta\theta_{h2}$ is the second component of the WHS temperature rise above top oil temperature;
 - $\Delta\theta_{hr}$ is the WHS temperature rise above top oil temperature at *rated* load;
 - τ_w is the winding time constant; &
 - k_{21} & k_{22} are constants (refer to table 2.7).

The WHS temperature rise above top oil temperature ($\Delta\theta_h$) at a particular load is then calculated by subtracting the solution of equation (2.62) from the solution of equation (2.61). That is:

$$\boxed{\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2}} \quad (2.63)$$

Finally, the **WHS temperature** (θ_h) is calculated from:

$$\boxed{\theta_h = \theta_o + \Delta\theta_h} \quad (2.64)$$

Exponential equations:

The alternative model offered by Standards Australia (2013*b*, p. 28-29) is based on exponential equations. Two exponential equations are employed in the model – one for a step *increase* in load; one for a step *decrease* in load. Each equation yields the WHS temperature but by inspection can be easily divided into the following three components:

- Ambient temperature (θ_a);
- Top oil temperature rise above ambient temperature ($\Delta\theta_o$); &
- WHS temperature rise above top oil temperature ($\Delta\theta_h$).

That is, $\theta_h = \theta_a + \Delta\theta_o + \Delta\theta_h$.

For a step *increase* in load:

$$\theta_h(t) = \underbrace{\theta_a}_{\text{ambient}} + \underbrace{\Delta\theta_{oi} + \left\{ \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\}}_{\Delta\theta_o} f_1(t) + \underbrace{\Delta\theta_{hi} + \{Hg_r K^y - \Delta\theta_{hi}\}}_{\Delta\theta_h} f_2(t) \quad (2.65)$$

For a step *decrease* in load:

$$\theta_h(t) = \underbrace{\theta_a}_{\text{ambient}} + \underbrace{\Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x \right\}}_{\Delta\theta_o} f_3(t) + \underbrace{Hg_r K^y + \{\Delta\theta_{hi} - Hg_r K^y\} e^{-\frac{t}{\tau_w}}}_{\Delta\theta_h} \quad (2.66)$$

where: $\Delta\theta_{oi}$ is the initial top oil temperature rise above ambient temperature (i.e. before the load change);
 $\Delta\theta_{hi}$ is the initial WHS temperature rise above top oil temperature (i.e. before the load change);
 H is the hot spot factor (usually 1.3);
 g_r is the difference between the winding temperature gradient and the oil temperature gradient at *rated* load; &

$f_1(t)$, $f_2(t)$ & $f_3(t)$ are the following functions of time:

$$f_1(t) = \left(1 - e^{-\frac{t}{k_{11}\tau_o}} \right) \quad (2.67)$$

$$f_2(t) = \left[k_{21} \left(1 - e^{-\frac{t}{k_{22}\tau_w}} \right) - (k_{21} - 1) \left(1 - e^{-\frac{t}{\tau_o/k_{22}}} \right) \right] \quad (2.68)$$

$$f_3(t) = e^{-\frac{t}{k_{11}\tau_o}} \quad (2.69)$$

These equations provided in Standards Australia (2013b) have many similarities with the preceding models that have been introduced. A cursory glance at the bibliography of the loading guide reveals some names which by now are recognisable (Swift, Molinski, Lehn, Susa and Nordman) and this accounts for the similarities. The objective of the loading guide is to be relatively straight forward to apply, hence the lack of complexity in equations (2.60) to (2.66).

Summary of thermal models

As part of this project, AS 60076.7 will be employed to calculate cyclic ratings (refer to section 2.2.5). The Standards Australia (2013b) thermal models will therefore be employed as a matter of course. However objective (2) of the project requires demonstration of the creation of a thermal transformer model from heat transfer first principles (refer to section 1.4). In order to achieve this, it necessary to assess all of the models from the literature and select one as the basis for development of another thermal model to fulfill objective (5). This will be useful in terms of validating the cyclic rating calculator (based on AS 60076.7) which will be created.

Table 2.4 (on page 48) lists the different thermal models published, a description of their main features and their advantages and disadvantages relating to transformer modelling from the perspective of an electricity utility. Figure 2.18 displays the models on a spectrum from the simplest and least accurate but more universally applicable to the most complex and accurate but more specific. On page 46, the equations from all of the models analysed are repeated for ease of comparison.

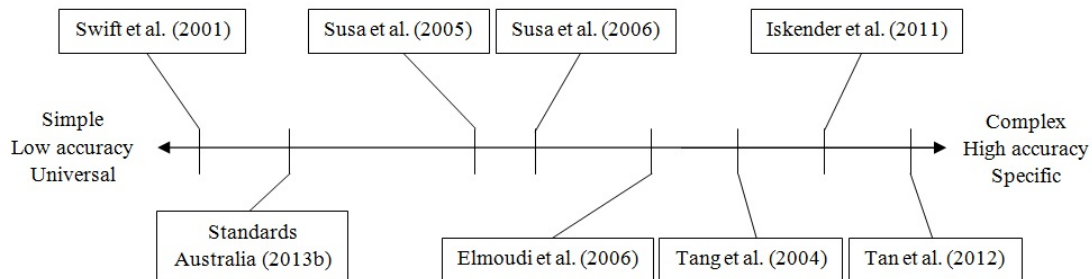


Figure 2.18: Comparison of thermal transformer models in terms of simplicity, accuracy and universality.

The models by Tang et al. (2004) and Elmoudi et al. (2006) are best applied to individual transformers and it would not be feasible for a utility to attempt application to an entire fleet. The models by Iskender & Mamizadeh (2011) and Tan et al. (2012) are novel, but the former is highly limited in its relevance to a fleet of predominantly outdoor transformers and the latter is prohibitively complex to implement due to variability of solar input. The model by Swift, Molinski & Lehn (2001), whilst highly useful in terms of forming an understanding of the heat transfer theory as applied to transformers, models non-linearity with a simplification and its accuracy therefore suffers.

This leaves the two models by Susa and colleagues which are intimately related since the Susa & Lehtonen (2006) model is a follow-on from the Susa et al. (2005) model. Application of the full Susa & Lehtonen (2006) model to a fleet of transformers would be difficult due to its division of the load loss parameter into DC, eddy and stray portions and the low probability of obtaining these values especially for older transformers with poor documentation. The model's specification of exponents for different cooling modes is however most useful. The Susa et al. (2005) model, though simplified in comparison, is well suited to implementation for a fleet of transformers as it is straightforward to implement yet complex enough in terms of its inclusion of non-linear effects to be very accurate and it is based on thermal parameters which can be readily obtained from nameplate data, manufacturer data or heat run tests. It is however restricted in its application to ONAN cooled transformers. Engineers of supply authorities such as Ergon Energy are more likely to apply the Australian Standard exponential equation model to their transformers. This is because it does not require expensive proprietary software (such as MATLAB) for solving differential equations and also because the use of Australian Standards enhances the confidence of engineers in their actions and decisions. With this in mind, the Susa & Lehtonen (2006) model, despite its dependence on some difficult to obtain parameters, can nevertheless be implemented to demonstrate a more complex model and to assist in validation of the AS 60076.7 versions since all the required parameters for a test transformer are provided by the authors.

Summary of thermal modelling equations:

Swift et al. (2001)

$$\frac{1 + I_{pu}^2 \beta}{1 + \beta} \cdot \Delta\theta_{oil R}^{1/n} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + [\theta_{oil} - \theta_{amb}]^{1/n} \quad (2.18 \text{ repeated})$$

$$\Delta\theta_{hs R}^{1/m} \cdot I_{pu}^2 = \tau_{hs} \cdot \frac{d\theta_{hs}}{dt} + [\theta_{hs} - \theta_{oil}]^{1/m} \quad (2.25 \text{ repeated})$$

Susa et al. (2005)

$$\frac{1 + I_{pu}^2 \beta}{1 + \beta} \cdot \Delta\theta_{oil R} = \tau_{oil R} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil R}^n} \quad (2.50 \text{ repeated})$$

$$\Delta\theta_{hs R} \cdot I_{pu}^2 = \tau_{hs R} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{hs R}^n} \quad (2.53 \text{ repeated})$$

Susa et al. (2006)

$$\frac{1 + I_{pu}^2 \beta \cdot P_{l\ pu}}{1 + \beta} \cdot \Delta\theta_{oil\ R} = \tau_{oil} \cdot \frac{d\theta_{oil}}{dt} + \frac{[\theta_{oil} - \theta_{amb}]^{n+1}}{\mu_{pu}^n \cdot \Delta\theta_{oil\ R}^n} \quad (2.55 \text{ repeated})$$

$$\Delta\theta_{hs\ R} \cdot I_{pu}^2 \cdot P_{w\ pu} = \tau_{hs\ R} \cdot \frac{d\theta_{hs}}{dt} + \frac{[\theta_{hs} - \theta_{oil}]^{n'+1}}{\mu_{pu}^n \cdot \Delta\theta_{hs\ R}^{n'}} \quad (2.57 \text{ repeated})$$

Standards Australia (2013b)

Differential equation models:

$$\left[\frac{1 + RK^2}{1 + R} \right]^x \cdot \Delta\theta_{or} = k_{11}\tau_o \cdot \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (2.60 \text{ repeated})$$

$$k_{21} \cdot K^y \cdot \Delta\theta_{hr} = k_{22}\tau_w \cdot \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \quad (2.61 \text{ repeated})$$

$$(k_{21} - 1) K^y \cdot \Delta\theta_{hr} = \frac{\tau_o}{k_{22}} \cdot \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \quad (2.62 \text{ repeated})$$

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \quad (2.63 \text{ repeated})$$

$$\theta_h = \theta_o + \Delta\theta_h \quad (2.64 \text{ repeated})$$

Exponential equation models:

For a step *increase* in load:

$$\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} f_1(t) + \Delta\theta_{hi} + \{HgrK^y - \Delta\theta_{hi}\} f_2(t) \quad (2.65 \text{ repeated})$$

For a step *decrease* in load:

$$\theta_h(t) = \theta_a + \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x \right\} f_3(t) + HgrK^y + \{ \Delta\theta_{hi} - HgrK^y \} e^{-\frac{t}{\tau_w}} \quad (2.66 \text{ repeated})$$

Table 2.4: Thermal models for power transformers presented in the literature.

Model	Description	Advantages	Disadvantages
Swift et al. (2001)	Top oil & WHS models with non-linearity	Very simple	Non-linearity applied using a simplification
Susa et al. (2005)	Top oil & WHS models with non-linearity & oil viscosity	Accurate; based on nameplate & HRT values	Applies only to ONAN transformers
Iskender et al. (2011)	Top oil model (indoor & outdoor) with non-linearity & oil viscosity	Validates the model by Susa et al. (2005);	No WHS model; model not in useable form; indoor application not useful
Tang et al. (2004)	Top oil & WHS models using GA optimisation	Very accurate due to GA optimisation	Specific to an individual transformer
Elmoudi et al. (2006)	Top oil & WHS models with non-linearity & FEA leakage flux	More accurately models losses and WHS	FEA requires knowledge of winding geometry (too specific)
Tan et al. (2012)	Top oil & WHS models with non-linearity & solar input	Potential for high accuracy	Solar portion very difficult to apply & quantify; unvalidated
Susa et al. (2006)	Top oil & WHS models with non-linearity, oil viscosity & losses	Very accurate; based on nameplate & HRT values	Some parameters unknown (e.g. winding eddy & stray losses)
SA (2013b)	Top oil & WHS models (diff & exp forms)	Simple; based on nameplate & HRT values	Lower accuracy than more complex models

2.2.5 Calculation of cyclic ratings

By now it is well understood that cyclic ratings are dependent upon transformer thermal limitations, both short term (flashover) and long term (insulation ageing). Methods to model and therefore predict the critical temperatures (top oil and WHS) have been investigated in-depth. The process of determining the cyclic rating for a transformer brings these concepts together and is outlined in *AS 60076.7 - Loading Guide for Oil-immersed Power Transformers* (Standards Australia 2013b). It is not compulsory to employ AS 60076.7 to determine cyclic ratings (other modelling techniques and limits can be used) however Australian Standard documents represent industry best practice and their use is therefore easily justified and defended. Ergon Energy Corporation (the project sponsor) utilises the AS 60076 suite of standards and for consistency in results, it was applied in this study to the concept of cyclic rating determination.

Before the process of determining cyclic ratings is described, it is necessary to define three types of cyclic rating (Standards Australia 2013b, p. 8):

1. Normal Cyclic (NC):

When operating at NC rating, a transformer may be loaded above nameplate and ambient temperature may vary throughout the loading cycle but the thermal ageing rate of the transformer is equivalent to that which occurs during continuous loading at nameplate rated value and normal ambient temperature. This implies that the overall thermal ageing rate of a transformer operating at its NC rating is unity. For this to be possible, periods of loading above nameplate rating (accelerated ageing) must always be compensated for by periods of loading below nameplate rating (retarded ageing). The risks of general loading above nameplate rating include (Standards Australia 2013b, p. 12):

- Temperatures of paper and oil can become excessive;
- Cyclic variations in temperature cause contraction and expansion of the winding which can result in loss of insulation packing blocks and loosening of clamping structures (Russell 2011);
- Leakage flux increases which in turn increases eddy current heating;
- Water and gas concentrations in the paper and oil change and may reduce the breakdown strength of the insulation;

- Tap changers, bushings etc. may have their thermal limits exceeded; &
- Saturation of the core is possible.

2. Long Term Emergency Cyclic (LTEC):

The LTEC rating permits the higher cyclic loading of a transformer for a prolonged period due to the outage of some other system component (e.g. another transformer). The steady-state transformer operating temperature is higher during loading at the LTEC rating than for NC which translates to a higher rate of ageing and loss of insulation life. This is considered preferable to a system outage however. In addition to the risks of general overloading noted for NC loading, the risks of operation at LTEC rating include (Standards Australia 2013*b*, p. 13):

- Accelerated ageing of insulation and reduction of transformer in-service life;
- Thermal runaway; &
- Brittle failure of gaskets.

3. Short Term Emergency Cyclic (STEC):

Operation at the STEC rating involves very high cyclic loading of a transformer (i.e. well above nameplate) for a short period (typically less than 30min) to maintain supply in the event of failure of other system components. Operation at the STEC rating involves high risks and rapid ageing. As such, this form of loading is *not* applied to Ergon Energy transformers. These risks include (Standards Australia 2013*b*, p. 12-13):

- Rapid gas generation, reducing dielectric strength, leading to flashover;
- Rapid expansion of oil causing overflow and pressure failures; &
- Temporary weakening of insulating paper reducing breakdown strength.

There are four limits which are used to determine each type of cyclic rating:

1. **Top oil temperature** – as previously described;
2. **WHS temperature** – as previously described;
3. **CRF** – a maximum overload level is set to protect components such as tap changers and bushings (Standards Australia 2013*b*, p. 19); &
4. **Cumulative ageing** (loss of insulation life) – as previously described.

The first three of these limits are specified in AS 60076.7 (Standards Australia 2013b, p. 18). The loss of life limits are not specified in AS 60076.7 but are left to be set by each utility based on a financial and risk analysis. Table 2.5 specifies the limits from the loading guide and those set by Ergon Energy for the purpose of determining cyclic ratings. It can be seen that in general, the Ergon Energy limits are more conservative.

Table 2.5: Limits used for the determination of cyclic ratings (*modified from: Standards Australia (2013b, p. 18)*).

Limits for types of loading	Transformer type			Ergon Energy
	Distribution	Medium power	Large power	
<i>NC loading</i>				
CRF (per unit)	1.5	1.5	1.3	1.5
WHS temp. (θ_h) [$^{\circ}C$]	120	120	120	120
Top oil temp. (θ_o) [$^{\circ}C$]	105	105	105	105
Ageing (L) [h/day]	–	–	–	24
<i>LTEC loading</i>				
CRF (per unit)	1.8	1.5	1.3	1.5
WHS temp. (θ_h) [$^{\circ}C$]	140	140	140	130
Top oil temp. (θ_o) [$^{\circ}C$]	115	115	115	115
Ageing (L) [h/day]	–	–	–	720
<i>STEC loading</i>				
CRF (per unit)	2.0	1.8	1.5	×
WHS temp. (θ_h) [$^{\circ}C$]	140	160	160	×
Top oil temp. (θ_o) [$^{\circ}C$]	115	115	115	×
Ageing (L) [h/day]	–	–	–	×
<p>– = <i>limit not specified</i></p> <p>× = <i>rating limit not applicable</i></p> <p><i>Distribution transformers: ≤ 2.5 MVA</i></p> <p><i>Medium power transformers: ≤ 100 MVA</i></p> <p><i>Large power transformers: > 100 MVA</i></p>				

The cyclic rating is then the set of particular load values at the discrete cycle times which result in one or more of the limits being reached but not exceeded. For example, if during the thermal modelling of a loading cycle, the top oil and WHS temperatures were below 105°C and 120°C respectively, the per unit load was less than 1.5 (medium power transformer) but the loss of insulation life was $\approx 24\text{ h}$, then the normal cyclic (NC) rating has been determined.

Calculation procedure

Determination of a cyclic rating for a particular transformer requires performing the following steps:

1. Obtain the per unit load profile applicable to the transformer. This is the per unit load at a number of discrete time steps during the loading cycle.
2. Multiply the per unit load profile by the nameplate rating of the transformer.
3. Select a CRF (1pu is usually a valid starting point).
4. Multiply the nameplate scaled load profile by the CRF.
5. Using either the differential equations (2.60) to (2.64) or the exponential equations (2.65) and (2.66) (these are repeated on page 54), calculate the top oil and WHS temperatures at each time step during the cycle.
6. Using either equation (2.1) or (2.2), calculate the ageing rate at each discrete time step throughout the cycle.
7. Determine the maximum top oil and WHS temperatures from the cycle.
8. Calculate the total amount of insulation ageing for the loading period using equation (2.4).
9. Compare maximum top oil temperature, maximum WHS temperature, maximum CRF and total insulation ageing against the limits for the relevant rating type in table 2.5. Three contingencies are then possible:
 - (a) If all parameters are below their respective limits, increase the CRF and repeat from step 4.

- (b) If any parameter exceeds its limit, decrease the CRF and repeat from step 4.
- (c) If any parameter is approximately equal to its limit, the load profile combined with the current CRF is the cyclic rating for the transformer. The process is complete.

Figure 2.19 outlines this procedure in the form of a flow chart.

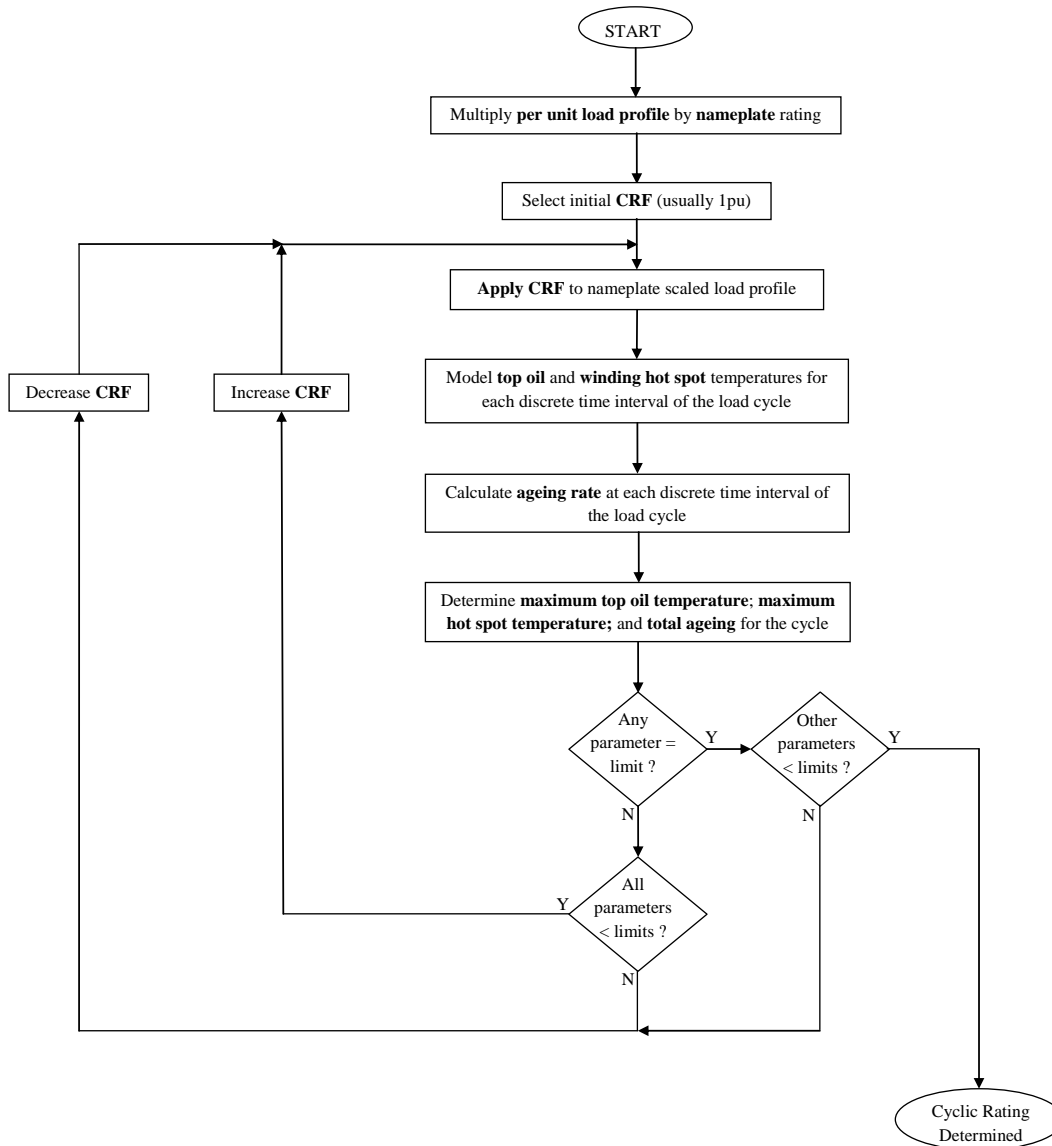


Figure 2.19: Flow chart for the process of determining the cyclic rating for a transformer.

For completeness, the thermal modelling equations for top oil and WHS temperature as well as the thermal ageing equations presented in the loading guide (Standards Australia 2013b) are repeated here. The reader is referred to either equations (2.60), (2.64), (2.65) and (2.66) or to table 2.6 for variable definitions.

Differential equation models:

Top oil temperature:

$$\left[\frac{1 + RK^2}{1 + R} \right]^x \cdot \Delta\theta_{or} = k_{11}\tau_o \cdot \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (2.60 \text{ repeated})$$

WHS temperature:

$$k_{21} \cdot K^y \cdot \Delta\theta_{hr} = k_{22}\tau_w \cdot \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \quad (2.61 \text{ repeated})$$

$$(k_{21} - 1) K^y \cdot \Delta\theta_{hr} = \frac{\tau_o}{k_{22}} \cdot \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \quad (2.62 \text{ repeated})$$

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \quad (2.63 \text{ repeated})$$

$$\theta_h = \theta_o + \Delta\theta_h \quad (2.64 \text{ repeated})$$

Exponential equation models:

For a step *increase* in load:

$$\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} f_1(t) + \Delta\theta_{hi} + \{ Hg_r K^y - \Delta\theta_{hi} \} f_2(t) \quad (2.65 \text{ repeated})$$

For a step *decrease* in load:

$$\theta_h(t) = \theta_a + \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x \right\} f_3(t) + Hg_r K^y + \{ \Delta\theta_{hi} - Hg_r K^y \} e^{-\frac{t}{\tau_w}} \quad (2.66 \text{ repeated})$$

Definitions of $f_1(t)$, $f_2(t)$ & $f_3(t)$:

$$f_1(t) = \left(1 - e^{-\frac{t}{k_{11}\tau_o}} \right) \quad (2.67 \text{ repeated})$$

$$f_2(t) = \left[k_{21} \left(1 - e^{-\frac{t}{k_{22}\tau_w}} \right) - (k_{21} - 1) \left(1 - e^{-\frac{t}{\tau_o/k_{22}}} \right) \right] \quad (2.68 \text{ repeated})$$

$$f_3(t) = e^{-\frac{t}{k_{11}\tau_o}} \quad (2.69 \text{ repeated})$$

Ageing models:

Ageing rate:

$$V = 2^{(\theta_n - 98)/6} \quad (2.1 \text{ repeated})$$

Total ageing:

$$L = \sum_{n=1}^N (V_n \cdot t_n) \quad (2.4 \text{ repeated})$$

Some particular aspects of the thermal modelling procedure as it relates to the calculation of cyclic ratings are now described:

1. Determination of ambient temperature, θ_a :

AS 60076.7 allows for the ambient temperature (θ_a) to be any one of the following (Standards Australia 2013b, p. 32):

- The actual temperature profile of a particular day;
- The monthly average temperature of the hottest month; or
- The yearly weighted ambient temperature.

The *actual temperature profile* is useful for on-load monitoring of a transformer, especially when being operated at an emergency cyclic rating.

The *monthly average temperature of the hottest month*, θ_{ma-max} , is used as θ_a in the calculation of WHS temperature. θ_{ma-max} is the average of the long-term mean of the daily maxima and the long-term mean of the daily minima for the hottest month of the year at the specified location.

The *yearly weighted ambient temperature*, θ_E , is used as θ_a in thermal ageing calculations. θ_E is determined using the following equation:

$$\theta_E = \theta_{ya} + 0.01 [2 (\theta_{ma-max} - \theta_{ya})]^{1.85} \quad (2.70)$$

where: θ_{ya} is the yearly average temperature (over many years).

2. Determination of time constants, τ_o and τ_w :

The oil and winding time constants can either be taken as constants from table 2.7 or can be calculated at each time step. Time constants are calculated using the

following equations (refer to table 2.6 for variable definitions):

$$\tau_w = \frac{m_w \cdot c \cdot g}{60P_w} \quad (2.71)$$

$$\tau_o = \frac{60C \cdot \Delta\theta_{om}}{P} \quad (2.72)$$

$$\text{where: } C = \begin{cases} 0.132m_a + 0.0882m_t + 0.4m_o, & \text{for ON.. cooling} \\ 0.132(m_a + m_t) + 0.580m_o, & \text{for OF.. \& OD.. cooling} \end{cases} \quad (2.73)$$

3. Determination of initial conditions for thermal modelling:

At the first time step of each thermal modelling iteration, the values of the initial parameters ($\Delta\theta_{oi}$ & $\Delta\theta_{hi}$) are unknown. If the transformer is to be placed on-load after a significant period of time off-load, then these initial temperature rises are 0 °C (i.e. all transformer components are at ambient temperature). However, if the cyclic rating is to be determined for a transformer already on-load (as is the normal situation), then appropriate initial values for $\Delta\theta_{oi}$ & $\Delta\theta_{hi}$ must be determined. This can be performed using the following procedure:

- (i.) Assume the initial temperature rises to be 0 °C and calculate the top oil and WHS temperatures for each time period in the cycle;
- (ii.) Take the temperature rises of the last time step as the initial temperature rises and reiterate the calculations for the load cycle;
- (iii.) Repeat steps (i.) and (ii.) until the initial and final temperatures in the one load cycle are suitably close.

4. Determination of other required parameters:

The remaining parameters required for solving the thermal modelling equations are the following:

- Those with subscripts: R which are *rated* load parameters;
- Those with subscripts: i which are *initial* values; &
- Constants.

Rated load parameters (e.g. $\Delta\theta_{or}$, $\Delta\theta_{hr}$, g_r & R) are specified in manufacturer HRT reports. For this project, these values have been supplied by Ergon Energy.

Initial values for parameters (e.g. $\Delta\theta_{oi}$ & $\Delta\theta_{hi}$) are the corresponding values calculated in the previous time step (i.e. $\Delta\theta_o$ & $\Delta\theta_h$ from previous time step).

Constants in the modelling equations (e.g. x , y , k_{11} , k_{21} & k_{22}) are obtained from table 2.7.

Table 2.6: Variables and symbols used in AS 60076.7 (Standards Australia 2013b).

Variable	Description	Units
C	Thermal capacity	Ws/K
c	Specific heat capacity (390 for Cu; 890 for Al)	$Ws/kg/K$
g_r	Difference between winding & oil gradients at rated load	$^{\circ}C$
g	Difference between winding & oil gradients at present load	$^{\circ}C$
m_t	Mass of tank	kg
m_a	Mass of core & coil assembly	kg
m_o	Mass of oil	kg
m_w	Mass of winding	kg
H	Hot spot factor (usually = 1.3)	–
k_{11}	Constant (refer to table 2.7)	–
k_{21}	Constant (refer to table 2.7)	–
k_{22}	Constant (refer to table 2.7)	–
K	Load factor $\frac{\text{load current}}{\text{rated current}}$	–
L	Use of life over a certain time period	h
P	Supplied losses (load and no-load losses)	W
P_w	Winding losses	W
R	Ratio of load to no-load losses at rated current	–
t	Time	min
x	Oil exponent (refer to table 2.7)	–
y	Winding exponent (refer to table 2.7)	–
θ_a	Ambient temperature	$^{\circ}C$
θ_h	WHS temperature at present load	$^{\circ}C$
θ_o	Top oil temperature at present load	$^{\circ}C$
$\Delta\theta_h$	WHS to top oil temperature rise at present load	$^{\circ}C$
$\Delta\theta_{hi}$	Initial WHS to top oil temperature rise at present load	$^{\circ}C$
$\Delta\theta_{hr}$	WHS to top oil temperature rise at rated load	$^{\circ}C$
$\Delta\theta_o$	Top oil to ambient temperature rise at present load	$^{\circ}C$
$\Delta\theta_{oi}$	Initial top oil to ambient temperature rise at present load	$^{\circ}C$
$\Delta\theta_{or}$	Top oil to ambient temperature rise at rated load	$^{\circ}C$
θ_{om}	Average oil temperature at present load	$^{\circ}C$
τ_o	Oil time constant (eqn (2.72) or table 2.7)	min
τ_w	Winding time constant (eqn (2.71) or table 2.7)	min

Table 2.7: Thermal modelling constants for different transformer cooling modes as specified in AS 60076.7 Loading Guide for Oil-immersed Power Transformers (Standards Australia 2013b).

Transformer class	Distribu- tion	Medium & Large			
Cooling mode	ONAN	ONAN	ONAF	OFXX	ODXX
Oil exponent (x)	0.8	0.8	0.8	1.0	1.0
Winding exponent (y)	1.6	1.3	1.3	1.3	2.0
Constant k_{11}	1.0	0.5	0.5	1.0	1.0
Constant k_{21}	1.0	2.0	2.0	1.3	1.0
Constant k_{22}	2.0	2.0	2.0	1.0	1.0
Oil time constant (τ_o) [min]	180	210	150	90	90
Winding time constant (τ_w) [min]	4	10	7	7	7

2.3 Demand side management

The second initiative being utilised by electricity supply utilities to reduce the cost of electricity to the consumer is *demand side management* (DSM).

Electricity networks are designed to be capable of supplying peak demand (Babu & Kumar 2013, p. 415). The daily peaks in load exist for only small durations (2-3 hours), yet the network must be capable of supplying these peaks. For the remainder of the day, the network is under-utilised and the *load factor*¹ is low (Babu & Kumar 2013, p. 415). Complicating this problem is the existence of very high peak loads which occur on only a few days each year (e.g. during very hot weather). This can be visualised by referring to figure 2.20 which displays the *load duration curve* for the Ergon Energy network in 2011. The load duration curve clearly demonstrates that the highest loads exist for only a very small proportion of the total time in the year. Ergon Energy Corporation (2013a, p. 3) estimates that 10% of total annual capital expenditure (CAPEX) is associated with network upgrades and augmentation merely to ensure that this peak demand can be supplied. Put simply, peaks in demand representing only 0.8% of the year, consume 10% of annual CAPEX. This historic approach of upgrading the network to solve peak demand problems decreases asset utilisation and raises the unit cost of electricity to the consumer (Ergon Energy Corporation 2013b, p. 9). Unaddressed, the issue will only become worse.

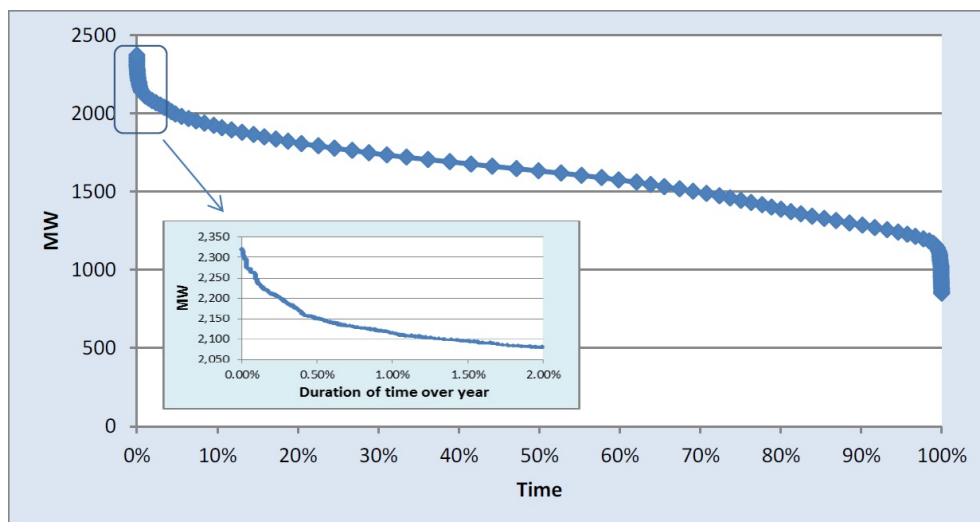


Figure 2.20: Load duration curve for the Ergon Energy network in 2011 (Ergon Energy Corporation 2013b, p. 8).

¹ The *load factor* metric is given by: $\frac{\text{average load}}{\text{peak load}}$

The solution is employing DSM techniques which reduce peak load, increase the load factor (i.e. flatten the load profile), increase asset utilisation and thus decrease the cost of electricity to the consumer (Lordan, Letizia & Gordon 2013, p. 3) (Huang & Billinton 2012, p. 336). DSM techniques require investment of capital to initiate and operate, however these costs are significantly lower than the costs of network upgrade (Palensky & Dietrich 2011, p. 381). Additionally, by flattening the load profile through peak reduction, DSM initiatives provide a capacity margin which frequently allows essential network upgrades to be deferred by a number of years (Lordan et al. 2013, p. 4). Deferral of CAPEX translates to significant savings for an electricity utility.

DSM is well covered in the literature. Yau, Smith, Huff, Vogt & Willis (1990, p. 506) and Babu & Kumar (2013, p. 416-417) identify three different types of DSM:

1. Peak clipping – removing peak demand from the profile;
2. Valley filling – increasing load during periods of very low demand and utilisation;
&
3. Load shifting – a combination of 1 & 2 whereby load removed from a peak period is supplied during an off-peak period (this technique aims to flatten the load profile from both directions).

Further DSM categories are explored by Yau et al. (1990) and Babu & Kumar (2013) but are essentially subcategories of those already mentioned.

In their article, Palensky & Dietrich (2011, p. 381-382) classify DSM initiatives into three different categories:

1. Energy efficiency – replacing loads with more efficient versions; this technique reduces demand generally, for all parts of the load cycle;
2. Time of use – incentivising customers through the use of tariffs to alter their consumption behaviour and utilise electricity during non-peak times; &
3. Demand response – network operators control certain consumer loads (e.g. hot water systems) and can therefore shed load in response to demand peaks and increase load during off-peak, under-utilised periods.

Time of use tariffs and demand response techniques are also investigated as DSM initiatives by Boshell & Veloza (2008, p. 2), Nair, Nayagam & Francis (2008, p. 3) and Lordan et al. (2013, p. 4).

Lordan et al. (2013, p. 14, 19-20) also list other DSM techniques which are available to network operators under the classification of *non-network alternatives* (NNA):

1. Call off load contracts – an agreement between a large consumer and the network operator whereby the consumer agrees to significantly reduce their load on the network within a specified time period after notification by the network operator; the network operator benefits from reduced peak load while the customer receives financial compensation;
2. Power factor correction – supply of capacitive or inductive reactive power closer to loads to reduce current in upstream parts of the network; may be installed by the network operator or may be a mandatory requirement for large consumers; &
3. Energy storage systems – battery storage of energy close to load centres can be called on line during peak periods to reduce demand on the upstream network.

While all of the techniques listed above by various authors are legitimate DSM options, not all are attractive to utilities. Through the use of DSM, a utility seeks to flatten the load profile by reducing peaks and increasing troughs, *not* by reducing demand in general. It would be undesirable from a utility perspective if the demand at all periods during the load cycle was to decrease because this would mean a reduction in the total energy being supplied, hence representing a loss of revenue for the utility (Nair et al. 2008, p. 2). Ergon Energy clearly states in its publicly available 2013/2014 Demand Management Plan that there exists the dual obligations for it to reduce electricity prices but also to be profitable (Ergon Energy Corporation 2013b, p. 31). For this reason, *load shifting* DSM techniques are the most common type pursued by utilities. Since the main objective of this project is to determine the effects on the cyclic ratings of power transformers due to DSM caused changes in load profile from a *utility* perspective, load shifting techniques will be focused on.

To summarise, the following DSM initiatives can all be classified as *load shifting* techniques since they all result in reduction of load during peak periods and an increase in load during off-peak periods:

- **Time of use tariffs;**
- **Demand response load control;**
- **Call off load contracts; &**
- **Energy storage systems.**

Huang & Billinton (2012, p. 336) present an algorithm which can be used to simulate the effects of load shifting demand management techniques:

$$\overline{L(t)} = \begin{cases} P, & \text{for } t = \text{peak hours} \\ L(t) + A, & \text{for } t = \text{off-peak hours} \end{cases} \quad (2.74)$$

Where: $\overline{L(t)}$ is modified load model;

$L(t)$ is the basic load model;

P is the pre-specified peak; &

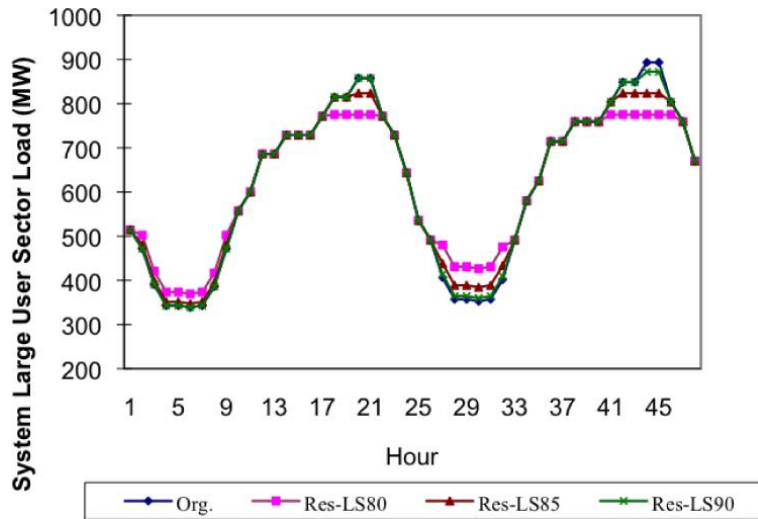
A is the MW load added to each off-peak hour and is given by:

$$A = a \left[\frac{\sum_t (L(t) - P)}{N} \right], \quad \text{for } t = \text{peak hours} \quad (2.75)$$

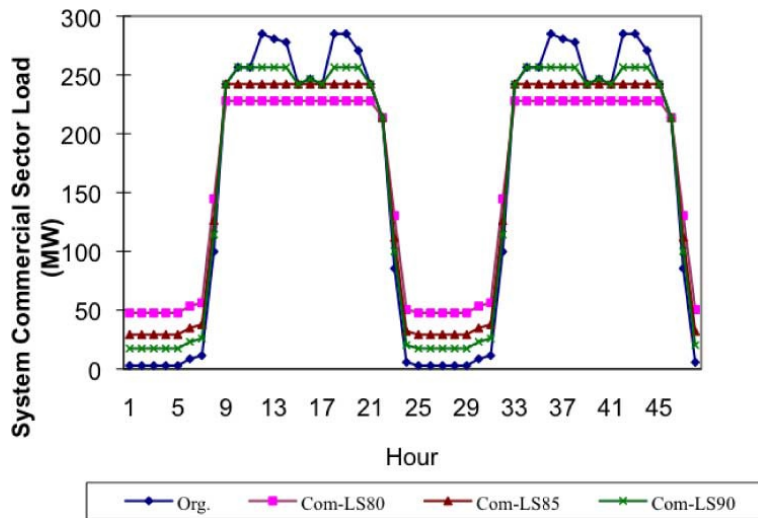
Where: a is the percentage of energy reduced during peak hours that is recovered during off-peak hours; &

N is the number of off-peak hours.

The algorithm functions by setting a new maximum value for loads during peak periods (P), reducing peak load values which are greater than this to the new maximum value and distributing a percentage of the reduction in peak load amongst the off-peak load values (A). Examples of the outputs of the algorithm are displayed in figure 2.21. Figure 2.21a is a residential 48 hour load profile while figure 2.21b is a commercial 48 hour load profile. The series of curves from blue to green to red to pink demonstrate the effect of setting the peak load limit (P in the algorithm) to 100%, 90%, 85% and 80% of its original value respectively. The effects of load shifting DSM are clear: reduced peak loads and increased off-peak loads. This algorithm was employed in the DSM modification of load profiles to be used in the sensitivity analysis of cyclic ratings (refer to chapter 7).



(a) Residential load profile.



(b) Commercial load profile.

Figure 2.21: Outputs of the load shifting DSM algorithm for a series of reducing peak load limits (100% [blue], 90% [green], 85% [red] & 80% [pink] of the original peak) (Huang & Billinton 2012, p. 338).

2.4 Knowledge Gap

While in-depth research revealed an extensive number of sources relating to transformer thermal modelling/cyclic ratings and DSM in isolation (the subject of the previous sections), it failed to yield any previous studies considering both together. This lack of existing information on any possible relationship between the two topics served to confirm the knowledge gap mentioned in section 1.3, reinforce the need for this study and set the scope of the project.

2.5 Chapter Summary

This chapter has presented the information obtained from diverse sources and relevant to this study in a single location which is easily referred to at any time. The literature review has facilitated successful completion of objectives (1), (2), (3) and (4): research into cyclic ratings; heat transfer theory for thermal modelling; DSM; and AS 60076.7 respectively (refer to section 1.4). Additionally, the information contained within this chapter was essential for the completion of remaining objectives. The lack of information sources relating to the effect of DSM on transformer cyclic ratings was noted. For these reasons, the literature review forms the critical foundation for the entire dissertation.

Chapter 3

Methodology

3.1 Chapter Overview

Methodology refers to the approaches which were adopted to successfully achieve the project objectives outlined in section 1.4. This chapter aims to outline the methodology in sufficient detail to place the remaining dissertation chapters in context, provide a preview of their content and note the objectives they target. Broadly, the tasks which were required to successfully complete the project were:

1. **Research**
2. **Model construction**
3. **Load profile modification**
4. **Sensitivity analysis**

The methodology for each of these tasks is discussed in the following sections. It should be noted however that these descriptions are not exhaustive. Full details of the processes and methods are located in the corresponding chapters.

3.2 Research

The outcomes of the research phase of the project have already been presented in the literature review of chapter 2. Discussion of research methodology remains valuable however. The main focus of the project relates to two topics which are areas of study in their own right – cyclic ratings and DSM. Success of the study depended on a thorough understanding of each topic. This need was identified early and embodied in objectives (1), (2), (3) and (4) of the project (refer to section 1.4). It was logical therefore to begin by conducting in-depth research into these topics in order to acquire the necessary knowledge. This would then act as a strong foundation from which to base the analytical work which was the principle aim of the project. The fundamental topics researched included:

- Definition of cyclic ratings for transformers and why they are employed;
- The role of transformer temperature rises and insulation ageing in determining a cyclic rating;
- Other factors limiting and influencing cyclic ratings;
- Principles of transformer thermal modelling using heat transfer theory;
- Existing transformer thermal models presented in the literature;
- Use of AS 60076.7 to calculate the cyclic rating of a transformer;
- Definition of DSM, why it is used and its various forms;
- The DSM technique most likely to be implemented by supply authorities; &
- The manner in which the above identified DSM technique alters load profiles.

The following points are worthy of further explanation:

- The extensive use of AS 60076.7 in the project is justified because Australian standards represent industry best practice in this country; it is already employed by Ergon Energy; and it incorporates amendments (to the IEC standard on which it is based) which account for unique climatic conditions in Australia (most other thermal models are from authors not of Australia).

- Even though the use of AS 60076.7 was planned during the project conception, it would have been inadequate to employ only the thermal modelling equations offered therein. A thorough analysis must derive these equations from first principles, identifying assumptions and simplifications, so that both author and reader may develop a stronger and more analytical understanding of transformer thermal behaviour and the factors affecting calculated ratings. To this end, the development of transformer thermal models using standard heat transfer theory was researched. A comparison of the many models studied permitted selection of three models to be implemented and further compared (two from AS 60076.7 and the model by Susa & Lehtonen (2006)).

3.3 Model Construction

3.3.1 Thermal models

Once research had been completed and the literature review compiled, all required knowledge was available to permit creation of the transformer thermal models using MATLAB as per objective (5) (refer to section 1.4). Three models were constructed:

1. **AS 60076.7 exponential equation thermal model:** The simplest of the three to implement, the exponential equation model is effectively a solution of the differential equation model also presented in AS 60076.7. This is because it does not require solving of any differential equations and as such can be implemented entirely within MATLAB (i.e. using no toolboxes or add-ons). The model allows calculation of top oil and WHS temperatures for each time step in a cycle, allows for changing time constants and incorporates the required non-linearity (albeit using a simplification which adversely affects its accuracy).
2. **AS 60076.7 differential equation thermal model:** The more complex of the two models offered in AS 60076.7, this version requires the use of a Simulink model called by the main MATLAB script to solve the differential equations. Like the exponential equation model, it permits calculation of top oil and WHS temperatures for each time step in a cycle, allows for changing time constants and incorporates the required non-linearity (albeit using the same simplification which

adversely affects its accuracy).

3. **Susa & Lehtonen (2006) thermal model:** The development of this model from heat transfer first principles was demonstrated in the literature review (2). This model is the most complex of the three since it correctly includes the non-linearity, allows for changing time constants, models changing oil viscosity with temperature and accounts for temperature variable transformer losses. Construction of this model also requires a Simulink model called by the main MATLAB script to solve the differential equations.

3.3.2 Model validation & comparison

Objective (6) of the project required validation and comparison of the three models (refer to section 1.4). Validation and comparison were carried out simultaneously by using the data presented in the paper by Susa et al. (2005). In this paper, a test transformer fitted with temperature sensors was loaded according to a particular profile and the top oil and WHS temperatures were recorded for the cycle. The temperatures were also predicted using the model proposed by Susa et al. (2005) and comparison against the measured data permitted validation of their model. Since all required data were provided by the authors, model validation and comparison in this project were similarly achieved. Comparison allowed selection of the most appropriate model to become the basis of a cyclic rating calculator. Selection was based upon the following factors:

- Accuracy (minimal error from the measured data);
- Ease of implementation both for this project and for a supply authority; &
- Execution time.

3.3.3 Cyclic rating calculator

The cyclic rating calculator has, at its centre, the chosen thermal model which calculates the top oil and WHS temperatures throughout a cycle. It also possesses additional components which determine the maximum temperatures, calculate the insulation ageing and compare these against limits to determine whether the particular loading cycle

can be permitted. To calculate the actual cyclic rating, the above actions must be iterated with successively scaled-up versions of the load profile shape until one of the limits is reached. This limiting profile then becomes the cyclic rating for the transformer. The cyclic rating calculator was therefore constructed in MATLAB around the chosen thermal model code and features the additional components mentioned. This resulted in achievement of objective (7) (refer to section 1.4). The cyclic rating calculator was employed in the sensitivity analysis which was the final stage of the project.

3.4 Load Profile Modification

Also required for the sensitivity analysis was a set of load profiles which had been modified to simulate load shifting DSM. This requirement was formalised in objective (8) (refer to section 1.4). These profiles were then inputs for the cyclic rating calculator previously described. A DSM simulation algorithm published by Huang & Billinton (2012) was located during the research phase, presented in the literature review (refer to section 2.3) and employed to modify a set of load curves. Three different types of load profile were modified using the DSM algorithm:

1. **Square wave load profile**

Simplest type of load profile with step changes in load; a useful starting point.

2. **Industry standard load profiles**

Standard residential, industrial and mixed residential-industrial shapes.

3. **Actual load profiles**

Measured load profiles from a selection of 12 Ergon Energy transformers.

In a similar manner to that carried out by Huang & Billinton (2012) (refer to figure 2.21), the peaks of the square wave, industry standard and Ergon Energy load profiles were successively reduced to 95%, 90%, 85% and 80% of their original values. As it was load shifting DSM which was simulated, the load amounts removed from the peaks were distributed across the troughs in load. Therefore, the profiles became progressively flatter with each successive level of DSM with the total energy supplied in one cycle (proportional to the area under the load curve) remaining constant. The

final set of load profiles provided as inputs to the cyclic rating calculator consisted of 80 curves made up of the following:

- 5 × square load profiles (100% (unmodified), 95%, 90%, 85% and 80%);
- 5 × standard residential load profiles (100%, 95%, 90%, 85% and 80%);
- 5 × standard industrial load profiles (100%, 95%, 90%, 85% and 80%);
- 5 × standard mixed load profiles (100%, 95%, 90%, 85% and 80%); &
- 60 × actual profiles (100%, 95%, 90%, 85% and 80% for each of 12 transformers);

3.5 Sensitivity Analysis

After the transformer rating calculator had been produced and the set of DSM modified load curves generated, the analysis of the impact of DSM on cyclic ratings (objective (9)) could be commenced. This involved executing the cyclic rating calculator for every combination of transformer (one of the selected 12), cooling mode and load profile. This generated a large number of cyclic ratings which were then compared and analysed to determine the relationship between cyclic ratings and DSM.

Knowledge gained in the literature review (chapter 2) permitted prediction that there would be a change in the cyclic ratings caused by DSM, however the variations required quantification. A range of metrics were used to describe the manner in which the load profiles changed and permit prediction of the variations. It is this ability to predict the effect on cyclic ratings of variations in load profile which is useful to the plant rating engineer. The metrics employed were:

- Minimum load;
- Maximum load;
- Average load; &
- Load factor.

3.6 Chapter Summary

This chapter has described the processes, techniques and methods employed to successfully complete the objectives of the project. This enabled division of the project into the broad tasks of: research; model construction; load profile modification; and sensitivity analysis. Table 3.1 lists each broad task, the chapter/s in which full details are provided and the corresponding project objectives.

Table 3.1: Linkages between the project methodology, dissertation chapters and objectives.

Task	Relevant chapters	Objectives achieved
Research	2. Literature Review	(1), (2), (3), (4)
Model construction	4. Thermal Model Design & Construction	(5)
	5. Model Validation	(6)
	6. Cyclic Rating Calculator	(7)
Profile modification	7. Demand Side Management Simulation	(8)
Sensitivity analysis	8. Sensitivity Analysis	(9)

Chapter 4

Thermal Model Design & Construction

4.1 Chapter Overview

The aim of this chapter is to describe the design and construction of three transformer thermal models which were tested and compared for the purpose of selecting one which became the basis of the cyclic rating calculator. The three models constructed were:

1. **AS 60076.7 Exponential Equation Model**
2. **AS 60076.7 Differential Equation Model**
3. **Susa & Lehtonen (2006) Model**

These models were presented in section 2.2.4 and their selection justified on page 45. It is convenient to reiterate here however that the AS 60076.7 models were selected since they represent industry best practice and are in use by Ergon Energy; while the Susa & Lehtonen (2006) model was selected because it was the most complex which could be derived from first principles and implemented.

The three models were implemented in MATLAB and the resulting scripts are contained within Appendix B. Table 4.1 displays a list of the variables employed in the three models as written in this dissertation and as used in MATLAB.

Table 4.1: Thermal modelling variables and their MATLAB equivalents.

Variable	Description	Matlab notation
<i>Variables common to all three models:</i>		
C	Thermal capacity	C
m_t	Mass of tank	m_t
m_a	Mass of core & coil assembly	m_a
m_o	Mass of oil	m_o
m_w	Mass of winding	m_w
m_c	Mass of core	m_c
H	Hot spot factor	H
S_r	Nameplate rating	S_r
S_{pu}	Per unit load profile	profile
S	Actual load profile	S
K	Load factor (S/S_r)	K
P_{lr}	Load losses at rated load	P_l_r
P_l	Load losses at present load	P_l
P_{nl}	No-load losses	P_nl
R	Ratio of load to no-load losses at rated current	R
t	Time	t_steps
g_r	Winding to oil gradient at rated load	g_r
g	Winding to oil gradient at present load	g
θ_a	Ambient temp	ambient
θ_h	WHS temp at present load	theta_h
θ_o	Top oil temp at present load	theta_o
θ_{oi}	Top oil temp from previous time step	theta_o_i
$\Delta\theta_{hr}$	WHS to top oil temp rise at rated load	D_theta_h_r
$\Delta\theta_{or}$	Top oil to ambient temp rise at rated load	D_theta_o_r
τ_o	Oil time constant	tau_o
τ_w	Winding time constant	tau_w
<i>AS 60076.7 variables:</i>		
c	Specific heat capacity	c
x	Oil exponent	x

y	Winding exponent	<code>y</code>
k_{11}	Constant	<code>k_11</code>
k_{21}	Constant	<code>k_21</code>
k_{22}	Constant	<code>k_22</code>
k_{22}	Constant	<code>k_22</code>
$\Delta\theta_o$	Top oil to ambient temp rise at present load	<code>D_theta_o</code>
$\Delta\theta_{oi}$	Top oil to ambient temp rise from previous time step	<code>D_theta_o_i</code>
$\Delta\theta_h$	WHS to top oil temp rise at present load	<code>D_theta_h</code>
$\Delta\theta_{hi}$	WHS to top oil temp rise from previous time step	<code>D_theta_h_i</code>
$\Delta\theta_{h1}$	WHS1 to top oil temp rise	<code>D_theta_h1</code>
$\Delta\theta_{h2}$	WHS2 to top oil temp rise	<code>D_theta_h2</code>
$\Delta\theta_{h1i}$	WHS1 to top oil temp rise from previous time step	<code>D_theta_h1_i</code>
$\Delta\theta_{h2i}$	WHS2 to top oil temp rise from previous time step	<code>D_theta_h2_i</code>
$\Delta\theta_{obr}$	Bottom oil to ambient temp rise at rated load	<code>D_theta_o_b_r</code>
$\Delta\theta_{omr}$	Average oil to ambient temp rise at rated load	<code>D_theta_o_m_r</code>
$\Delta\theta_{om}$	Average oil to ambient temp rise at present load	<code>D_theta_o_m</code>
R_{mo-to}	Ratio of mean oil to top oil temp rise at rated load	<code>mo_to_ratio</code>
<i>Susa & Lehtonen (2006) variables:</i>		
c_w	Specific heat capacity of Copper winding	<code>c_w</code>
c_c	Specific heat capacity of iron core	<code>c_c</code>
c_t	Specific heat capacity of tank	<code>c_t</code>
c_o	Specific heat capacity of oil	<code>c_o</code>
n_o	Top oil model exponent	<code>n_o</code>
n_h	WHS model exponent 1	<code>n_h</code>
n_h'	WHS model exponent 2	<code>n_h_</code>
O_o	Oil correction factor	<code>O_o</code>
P_{dc}	DC losses at present load	<code>P_dc</code>
$P_{dc r}$	DC losses at rated load	<code>P_dc_r</code>
$P_{dc pu r}$	Per unit DC losses at rated load	<code>P_dc_pu_r</code>
P_e	Winding eddy losses at present load	<code>P_e</code>
$P_e r$	Winding eddy losses at rated load	<code>P_e_r</code>
$P_e pu r$	Per unit winding eddy losses at rated load	<code>P_e_pu_r</code>
P_s	Stray losses at present load	<code>P_s</code>
$P_s r$	Stray losses at rated load	<code>P_s_r</code>

$P_{a\ r}$	Stray & eddy losses at rated load	P_a_r
$P_{a\ pu\ r}$	Per unit stray & eddy losses at rated load	P_a_pu_r
$P_{l\ pu}$	Temp variable per unit load losses (top oil model)	P_l_pu
$P_{w\ pu}$	Temp variable per unit load losses (WHS model)	P_w_pu
θ_{hi}	WHS temp from previous time step	theta_h_i
θ_{μ}	Average of top oil & WHS temps for calculation of viscosity	theta_u
μ_r	Oil viscosity at rated load	u_r
μ_{pu}	Per unit oil viscosity at present load	u_pu

4.2 AS 60076.7 Exponential Equation Model Script

The exponential equations employed to predict top oil and WHS temperatures by this model have been presented in section 2.2.4 as equations (2.65) to (2.69). These equations have been divided into their component parts which is more conducive to implementation:

For a step *increase* in load:

$$\Delta\theta_o(t) = \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} \left(1 - e^{-\frac{t}{k_{11}\tau_o}} \right)$$

$$\Delta\theta_h(t) = \Delta\theta_{hi} + \{HgrK^y - \Delta\theta_{hi}\} \left[k_{21} \left(1 - e^{-\frac{t}{k_{22}\tau_w}} \right) - (k_{21} - 1) \left(1 - e^{-\frac{t}{\tau_o/k_{22}}} \right) \right]$$

(2.65, 2.67 & 2.68 modified)

For a step *decrease* in load:

$$\Delta\theta_o(t) = \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x \right\} e^{-\frac{t}{k_{11}\tau_o}}$$

$$\Delta\theta_h(t) = HgrK^y + \{ \Delta\theta_{hi} - HgrK^y \} e^{-\frac{t}{\tau_w}}$$

(2.66 & 2.69 modified)

Finally:

$$\theta_o(t) = \theta_a + \Delta\theta_o(t)$$

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h(t)$$

Additional equations required for this model are equations (2.71) & (2.72) for the winding and oil time constants respectively, the latter requiring equation (2.73) for calculation of thermal capacity. As presented in AS 60076.7, these equations calculate the time constants in minutes but have been modified here to calculate the time constants in seconds:

Time constants & thermal capacity:

$$\tau_w = \frac{m_w \cdot c \cdot g}{P_l} \quad (2.71 \text{ modified})$$

$$\tau_o = \frac{3600C \cdot \Delta\theta_{om}}{P_l + P_{nl}} \quad (2.72 \text{ modified})$$

$$\text{where: } C = \begin{cases} 0.132m_a + 0.0882m_t + 0.4m_o, & \text{for ON.. cooling} \\ 0.132(m_a + m_t) + 0.580m_o, & \text{for OF.. \& OD.. cooling} \end{cases} \quad (2.73 \text{ repeated})$$

Selection of modelling constants for the exponential equation model is carried out in accordance with table 2.7 specified in section 2.2.5. Part of this table is repeated below for convenience as table 4.2.

Table 4.2: AS 60076.7 thermal modelling constants (Standards Australia 2013b).

Transformer class	Distribution	Medium & Large			
Cooling mode	ONAN	ONAN	ONAF	OFXX	ODXX
Oil exponent (x)	0.8	0.8	0.8	1.0	1.0
Winding exponent (y)	1.6	1.3	1.3	1.3	2.0
Constant k_{11}	1.0	0.5	0.5	1.0	1.0
Constant k_{21}	1.0	2.0	2.0	1.3	1.0
Constant k_{22}	2.0	2.0	2.0	1.0	1.0

A flowchart describing the structure and function of the AS 60076.7 exponential equation thermal model is displayed as figure 4.1. The MATLAB script for the exponential equation model was written in accordance with this flowchart and is located in Appendix B. A series of notes following the flowchart assist in explanation of the model operation.

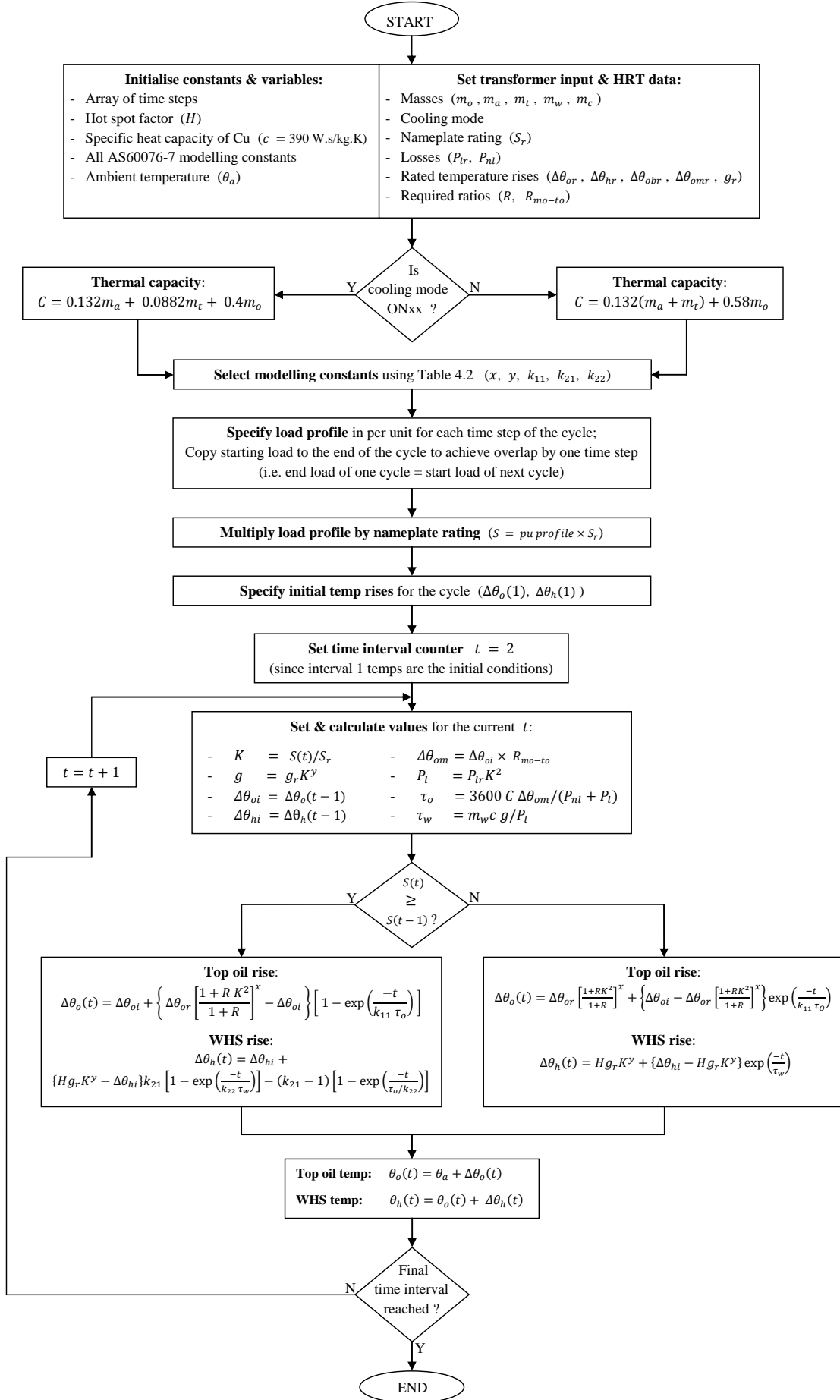


Figure 4.1: Flowchart for the AS 60076.7 exponential equation thermal model.

Explanatory notes for the exponential equation model script & flowchart:

- A numerical code is used to specify the cooling mode of the transformer (`cool_mode`):
ONAN = 1; ONAF = 2; OFAN = 3; OFAF = 4; ODAN = 5; & ODAF = 6.
- The load profile is assumed to be a regular cycle and consequently, if the modelling period begins at $t = 0$ and ends at $t = t_{max}$, then the load at $t = t_{max} + 1$ is made equal to that at $t = 0$ (i.e. $S(0) = S(t_{max} + 1)$).
- Arrays for the top oil and WHS temperature rises of lengths equal to the number of discrete time steps in the cycle are created and the first element of each array is set as the specified initial temperature rise. Consequently, the time interval counter need only begin at interval 2 (where the first interval is 1, not 0).
- Load losses at the current time step (P_l) are calculated from the rated load losses (P_{lr}) and the ratio of the current load to the nameplate rating ($K = S/S_r$) (Stapleton et al. 2011, p. 64): $P_l = P_{lr} \times K^2$
- The winding and oil time constant calculations in the flowchart and MATLAB script are the equivalent of equations (2.71) & (2.72) multiplied by 60 in order to convert the outputs from minutes to seconds.
- Equation (2.72) for the oil time constant requires the mean oil temperature rise for the current time step ($\Delta\theta_{om}$). However the calculation of current time step temperature rises requires the top oil time constant for equations (2.65) & (2.66). This mutual dependency was circumvented by calculating and utilising the mean oil temperature rise from the previous time step. This is justifiable if the time steps are small enough such that the change in temperature rise between adjacent time steps is not large. The calculation uses the top oil temperature rise from the previous time step ($\Delta\theta_{oi}$) and the ratio of mean oil ($\Delta\theta_{omr}$) to top oil ($\Delta\theta_{or}$) temperature rise at rated load (thus assuming a linear relationship):

$$\Delta\theta_{om} = \Delta\theta_{oi} \times \frac{\Delta\theta_{omr}}{\Delta\theta_{or}} = \Delta\theta_{oi} \times R_{mo-to}$$

- Equations (2.65) & (2.66) have been separated into their component parts in order to calculate the top oil rise and WHS rise separately. These components were identified when the equations were first presented in section 2.2.4. Top oil temperature is calculated by adding the top oil rise to the ambient temperature. WHS temperature is calculated by adding the WHS rise to the top oil temperature.

4.3 AS 60076.7 Differential Equation Model Script

The differential equations employed to predict top oil and WHS temperatures by this model have been presented in section 2.2.4 as equations (2.60) to (2.64). Additional equations required for this model are equations (2.71) to (2.73) for calculation of the winding and oil time constants, which are identical to those used by the exponential equation model (modified for seconds not minutes). The set of differential equations is repeated here for easy reference:

For top oil temperature:

$$\left[\frac{1 + RK^2}{1 + R} \right]^x \cdot \Delta\theta_{or} = k_{11}\tau_o \cdot \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (2.60 \text{ repeated})$$

For WHS temperature:

$$k_{21} \cdot K^y \cdot \Delta\theta_{hr} = k_{22}\tau_w \cdot \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \quad (2.61 \text{ repeated})$$

$$(k_{21} - 1) K^y \cdot \Delta\theta_{hr} = \frac{\tau_o}{k_{22}} \cdot \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \quad (2.62 \text{ repeated})$$

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \quad (2.63 \text{ repeated})$$

$$\theta_h = \theta_o + \Delta\theta_h \quad (2.64 \text{ repeated})$$

The selection of modelling constants (x , y , k_{11} , k_{21} , k_{22}) for the differential equation model is performed in exactly the same manner as for the exponential equation model – that is, using table 4.2.

As for the exponential equation model, a flowchart was prepared to describe the operation of the differential equation thermal model and the MATLAB script was written accordingly. The flowchart is displayed as figure 4.2 and the script is contained within Appendix B. It can be seen from figure 4.2 that the initial portions of both the exponential and differential equation models, which mainly involve initialisation of variables and calculation of required parameters, are identical apart from the initial conditions which must be specified. The difference is of course in the equations utilised, which for the differential equation model, are solved using Simulink (since it provides for the

simple solution of differential equations). Details of the Simulink model are presented following the main script in Appendix B. The Simulink model is called by the main script and calculates the top oil and WHS temperatures in parallel over the loading cycle. Specifically, the main script calculates and sets the required constants and variables before passing control to the Simulink model which then calculates and returns the oil time constant (τ_o); winding time constant (τ_w); top oil temperature (θ_o); WHS temperature rises ($\Delta\theta_{h1}$, $\Delta\theta_{h2}$ & $\Delta\theta_h$); and WHS temperature (θ_h) for *each time step*.

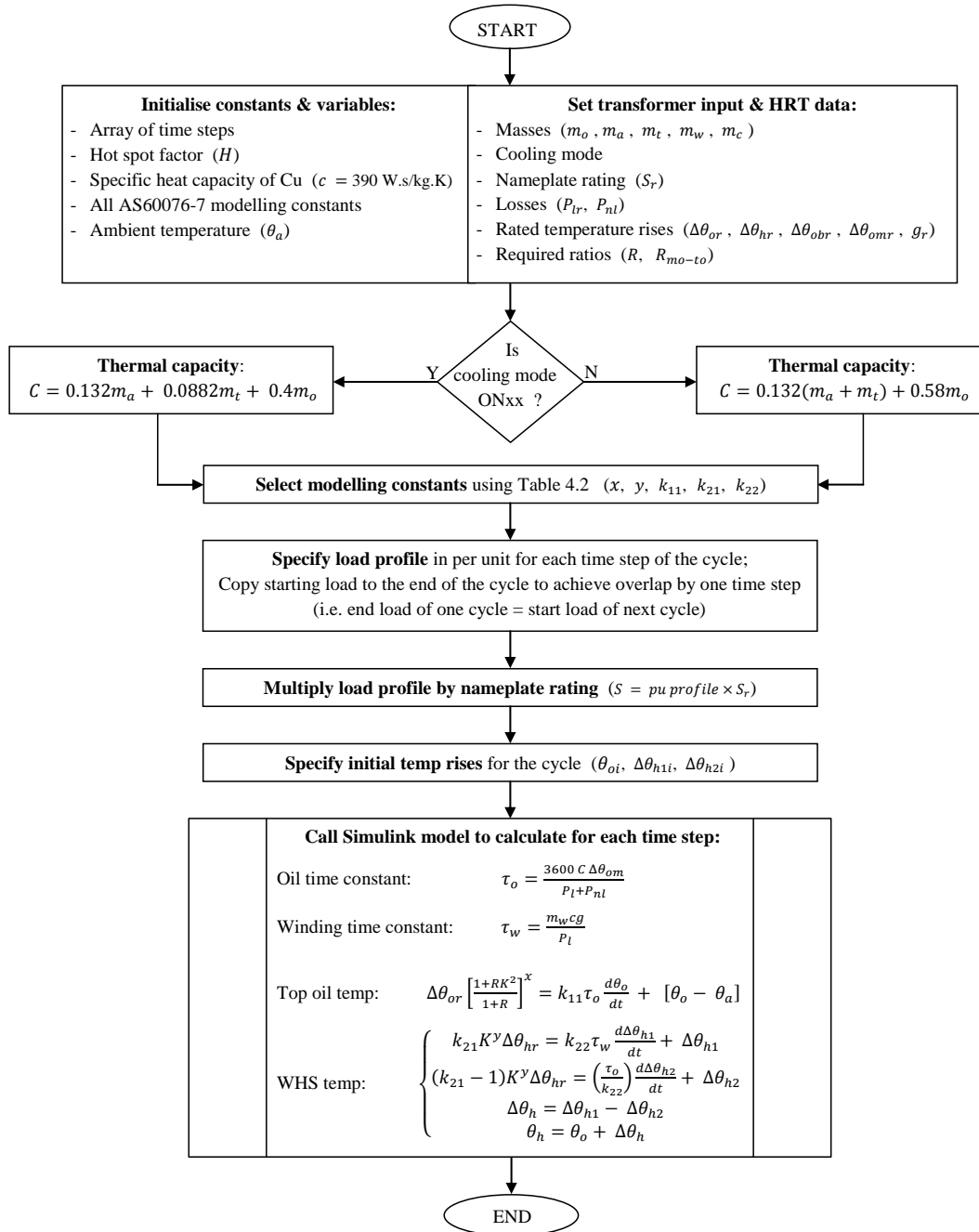


Figure 4.2: Flowchart for the AS 60076.7 differential equation thermal model.

4.4 Susa & Lehtonen (2006) Model Script

This model was presented in detail in section 2.2.4 and defining it are equations (2.55) & (2.57). These equations are repeated here but have been modified such that their variables are consistent with those of the AS 60076.7 models and table 4.1:

For top oil temperature:

$$\frac{1 + RK^2 \cdot P_{l\ pu}}{1 + R} \cdot \Delta\theta_{or} = \tau_o \cdot \frac{d\theta_o}{dt} + \frac{[\theta_o - \theta_a]^{n_o+1}}{\mu_{pu}^{n_o} \cdot \Delta\theta_{or}^{n_o}} \quad (2.55 \text{ modified})$$

For WHS temperature:

$$\Delta\theta_{hr} \cdot K^2 \cdot P_{w\ pu} = \tau_w \cdot \frac{d\theta_h}{dt} + \frac{[\theta_h - \theta_o]^{n_h'+1}}{\mu_{pu}^{n_h} \cdot \Delta\theta_{hr}^{n_h'}} \quad (2.57 \text{ modified})$$

Recall that the Susa & Lehtonen (2006) model accounts for variations in load loss with temperature ($P_{l\ pu}$ & $P_{w\ pu}$) and variations in oil viscosity with temperature (μ_{pu}). Equations (2.56), (2.58) & (2.54) define these parts of the model and are rewritten here for ease of implementation and variable consistency:

Variable load loss for top oil model:

$$P_{l\ pu} = P_{dc\ pu\ r} \cdot \left(\frac{\theta_h + 235}{\theta_a + \Delta\theta_{or} + \Delta\theta_{hr} + 235} \right) + P_{a\ pu\ r} \cdot \left(\frac{\theta_a + \Delta\theta_{or} + \Delta\theta_{hr} + 235}{\theta_h + 235} \right) \quad (2.56 \text{ modified})$$

Variable load loss for WHS model:

$$P_{w\ pu} = P_{dc\ pu\ r} \cdot \left(\frac{\theta_h + 235}{\theta_a + \Delta\theta_{or} + \Delta\theta_{hr} + 235} \right) + P_{e\ pu\ r} \cdot \left(\frac{\theta_a + \Delta\theta_{or} + \Delta\theta_{hr} + 235}{\theta_h + 235} \right) \quad (2.58 \text{ modified})$$

Oil viscosity:

$$\begin{aligned} \mu &= 1.36 \times 10^{-3} \cdot \exp \left[\frac{2797.3}{\frac{1}{2}(\theta_a + \theta_h) + 273} \right] \\ \mu_r &= 1.36 \times 10^{-3} \cdot \exp \left[\frac{2797.3}{\frac{1}{2}(2\theta_a + \Delta\theta_{or} + \Delta\theta_{hr}) + 273} \right] \\ \mu_{pu} &= \frac{\mu}{\mu_r} \end{aligned}$$

(2.54 modified)

The Susa & Lehtonen (2006) model does not specify a manner in which the winding time constant is calculated but the oil time constant and its required thermal capacity are also rewritten here for ease of implementation and variable consistency:

$$\begin{aligned}\tau_o &= \frac{C\Delta\theta_{or}}{P_{dc} + P_e + P_s + P_{nl}} \\ C &= \frac{(P_{dc} + P_e)m_w c_w + P_{nl}m_c c_c + P_s m_t c_t}{P_{dc} + P_e + P_s + P_{nl}} + O_o m_o c_o \\ O_o &= \begin{cases} 0.86, & \text{for ON.. or OF.. cooling} \\ 1.0, & \text{for OD.. cooling} \end{cases}\end{aligned}\tag{2.59 modified}$$

Finally, tables 2.2 & 2.3 specifying the n & n' exponents were modified and are repeated here as table 4.3 which excludes exponents for the cold start case which does not apply to this project.

Table 4.3: n exponents for the Susa & Lehtonen (2006) model.

Exponent	ONAN	ONAF	OF AF	ODAF
n_o	0.25	0.2	0.2	0
n_h	0.25	0.5	0.5	0
n_h'	0.25	0.1	0.1	0

The MATLAB implementation of the Susa & Lehtonen (2006) model employs a script and Simulink model (similar to the AS 60076.7 differential equation model). The script initialises and calculates constants and variables before calling the Simulink model which then employs the summarised equations above to calculate the top oil and WHS temperatures for each time step. Again, Simulink was used because it facilitates the very straightforward solution of differential equations. The MATLAB script as well as the Simulink model systems and subsystems are contained within Appendix B. Figure 4.3 displays a flowchart of the Susa & Lehtonen (2006) thermal model program. It can be seen that the initial portion of the process (setting and calculation of parameters) and specification of the load profile are very similar to that of the AS 60076.7 models with some differences in the types of parameters used. Specifically, the Susa & Lehtonen (2006) model employs four specific heat capacity values compared with the AS 60076.7 model's one; it does not utilise the AS 60076.7 constants; it requires more specific loss

data such as DC, eddy and stray losses; and the winding time constant is fixed for the entire cycle. Other than this, the Susa & Lehtonen (2006) model is significantly different in its implementation since different modelling constants (n_o , n_h , n_h' & O_o), initial conditions and modelling equations are employed.

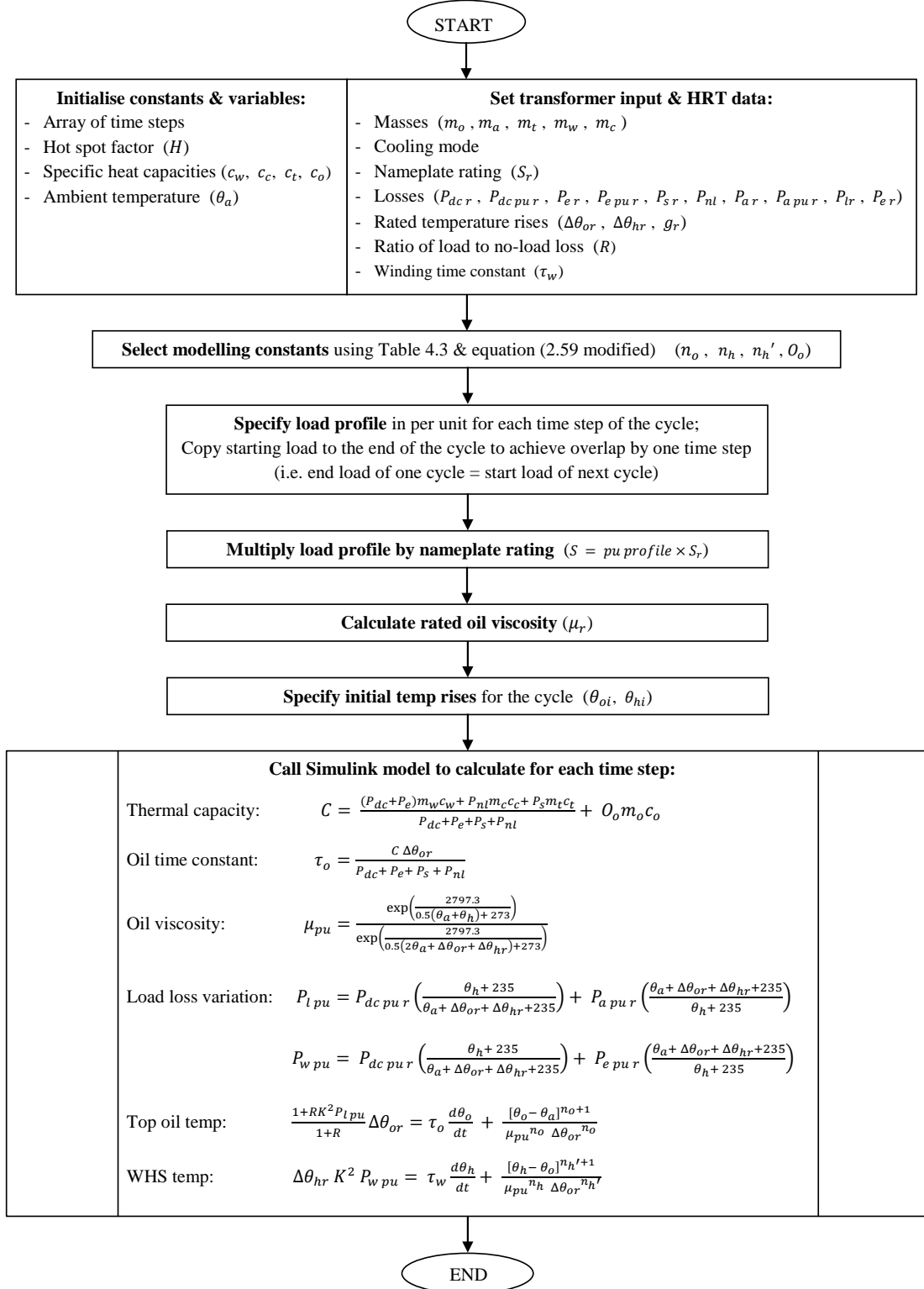


Figure 4.3: Flowchart for the Susa & Lehtonen (2006) thermal model.

4.5 Chapter Summary

The following list summarises the outcomes of this chapter:

- The equations for each of the three thermal models were re-introduced to permit simple referral for the reader when studying the model scripts.
- The variables used in the modelling equations were altered from those initially presented in section 2.2.4 to a standard set displayed in table 4.1.
- Flowcharts were presented to describe the design and construction process of the MATLAB program for each model; to display the structure and function of each program; and to permit simple comparison between the three models.
- The MATLAB scripts and Simulink systems for the three models were included in Appendix B and referenced from this chapter.

As a result, objective (5) (refer to section 1.4) has been achieved. The construction of each thermal model has been discussed in sufficient detail to enable the reader to create the same or similar models for the purposes of validation or further study. In this case, the reader is referred to the dissertation disclaimer (Limitations of Use).

As stated in the project methodology (section 3.3), after thermal models were implemented in MATLAB, the next phase was validation and comparison of these models with a view towards selecting one as the basis of a cyclic rating calculator. This is the subject of the next chapter.

Chapter 5

Thermal Model Validation

5.1 Chapter Overview

The purpose of this chapter is to present the input data for and the results of validation and comparison of the three transformer thermal models selected from the literature review (section 2.2.4) and implemented in MATLAB (chapter 4): the AS exponential equation model, the AS differential equation model and the Susa & Lehtonen (2006) model. Confirming the accuracy of the models was critical but the main outcome of the work presented in this chapter was the selection of a single model which was employed as the foundation for the cyclic rating calculator.

5.2 Model Input Data

To successfully validate and compare the three thermal model programs, it was necessary to execute them using common input data for which the real-world output data was known. As such, nameplate, loading and temperature data for a 400 MVA, ONAF cooled test transformer was located in the research paper by Susa et al. (2005). These authors used this data for much the same purpose – validating the transformer thermal model which was the subject of the paper. Nameplate and loading data for transformers is very common, however it was only in the Susa et al. (2005) paper that *actual measured top oil and WHS temperatures* were also provided. This measured data was used as a benchmark for validation and accuracy assessment of the three models.

5.2.1 Input load profile

The load profile supplied by the 400 MVA test transformer was obtained from Table VII in the paper by Susa et al. (2005). This load profile was provided as an input to the three thermal models (as the variable `profile`) and is numerically described in table 5.1 and graphically displayed in figure 5.1.

Table 5.1: Load profile input for validation of the three thermal models (Susa et al. 2005).

Time period (s)	Load (pu)
0 – 18000	1.00
18000 – 36000	0.65
36000 – 46800	1.60

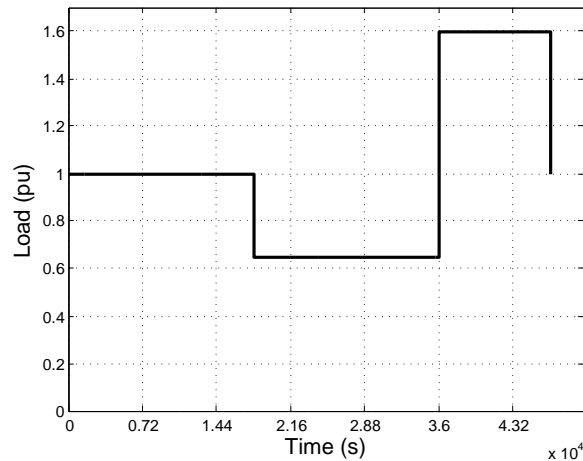


Figure 5.1: Load profile input for validation of the three thermal models.

5.2.2 Nameplate, HRT & other data inputs

The model input data relating to the test transformer rated load, rated losses, component masses, HRT temperature rises and other required variables such as specific heat capacities was also obtained from Susa et al. (2005) and is displayed in table 5.2. Note the differences in the input data requirements for each model. It should be noted that for the AS 60076.7 exponential equation model, all of the variables are set in the MATLAB script, however for the AS 60076.7 differential equation model and the Susa & Lehtonen (2006) model, which both utilise Simulink in addition to a MATLAB script, some variables must be set in the Simulink system blocks themselves. These include the simulation time and the initial conditions of integrator blocks. The notes which follow

table 5.2 explain the derivation of some of the model inputs and the values assigned to variables for which no data was available.

Table 5.2: Input data for validation of the three thermal models (Susa et al. 2005).

Input variable	Units	Thermal model		
		AS exponential	AS differential	Susa & Lehtonen
t	s	0:46800	0:46800	0:46800
H	–	1.2	1.2	1.2
c	$J/kg.K$	390	390	–
c_w	$J/kg.K$	–	–	396
c_c	$J/kg.K$	–	–	468
c_t	$J/kg.K$	–	–	468
c_o	$J/kg.K$	–	–	1836
θ_a	$^{\circ}C$	25	25	25
m_o	kg	91397	91397	91397
m_a	kg	215200	215200	215200
m_t	kg	67252	67252	67252
cool_mode	–	2	2	2
S_r	MVA	400	400	400
P_{lr}	W	762650	762650	–
$P_{dc\ r}$	W	–	–	637100
$P_{e\ r}$	W	–	–	59778
$P_{s\ r}$	W	–	–	65772
τ_w	s	–	–	492
$\Delta\theta_{or}$	$^{\circ}C$	38	38	38
$\Delta\theta_{obr}$	$^{\circ}C$	24.8	24.8	–
$\Delta\theta_{hr}$	$^{\circ}C$	18.6	18.6	18.6
g_r	$^{\circ}C$	15.5	15.5	15.5
θ_{oi}	$^{\circ}C$	–	30.9	30.9
θ_{hi}	$^{\circ}C$	–	–	31.6
$\Delta\theta_{oi}$	$^{\circ}C$	5.9	–	–
$\Delta\theta_{hi}$	$^{\circ}C$	0.7	–	–
$\Delta\theta_{h1i}$	$^{\circ}C$	–	0.7	–
$\Delta\theta_{h2i}$	$^{\circ}C$	–	0	–

Explanatory notes for table 5.2:

- Winding and core masses (m_w & m_c) were not provided by Susa et al. (2005). Therefore, m_w and m_c were each assumed to be half the assembly mass (m_a).
- The ambient temperature (θ_a) during the tests performed in the Susa et al. (2005) paper was not explicitly stated but could be estimated from figures 8 & 9 to be $25^\circ C$.
- No-load losses (P_{nl}) for the test transformer were not stated in the Susa et al. (2005) paper. An analysis of a selection of Ergon Energy transformers revealed the average ratio of no-load to rated load losses to be approximately 10%. Hence for the validation of the thermal models, the no-load loss input was:

$$\begin{aligned}
 P_{nl} &= 0.1 \times P_{lr} \\
 &= 0.1 \times 762650 \\
 &= 76265W
 \end{aligned}$$

- Susa et al. (2005, p. 204) provide the rated WHS rise *above ambient temperature* ($\Delta\theta_{hr/a}$) not above top oil temperature ($\Delta\theta_{hr}$) as is required for the models of this project. The following simple calculation corrects this:

$$\begin{aligned}
 \Delta\theta_{hr} &= \Delta\theta_{hr/a} - \Delta\theta_{or} \\
 &= 56.6 - 38.0 \\
 &= 18.6^\circ C
 \end{aligned}$$

- Rated DC losses ($P_{dc r}$), winding eddy losses ($P_{e r}$) and stray load losses ($P_{s r}$) are provided by Susa et al. (2005, p. 204) which are used explicitly in the Susa & Lehtonen (2006) thermal model. These losses are simply summed to obtain the total rated load losses ($P_{lr} = 762650 W$) for the AS 60076.7 models.
- Susa et al. (2005, p. 204) specify the initial top oil temperature (θ_{oi}) and initial WHS temperature (θ_{hi}) for the cycle as $30.9^\circ C$ and $31.6^\circ C$ respectively. These are used explicitly in the Susa & Lehtonen (2006) thermal model.

For the AS 60076.7 exponential equation model, it is the initial top oil and WHS temperature *rises* which are required ($\Delta\theta_{oi}$ & $\Delta\theta_{hi}$ respectively). These are

calculated from the data provided as follows:

$$\begin{aligned}\Delta\theta_{oi} &= \theta_{oi} - \theta_a \\ &= 30.9 - 25 \\ &= 5.9^\circ C\end{aligned}$$

$$\begin{aligned}\Delta\theta_{hi} &= \theta_{hi} - \theta_{oi} \\ &= 31.6 - 30.9 \\ &= 0.7^\circ C\end{aligned}$$

For the AS 60076.7 differential equation model, θ_{oi} is used explicitly however due to the separation of the WHS temperature rise into two components, $\Delta\theta_{h1}$ & $\Delta\theta_{h2}$ (refer to equation (2.63)), two WHS initial conditions must be specified which are calculated as follows:

$$\Delta\theta_{hi} = \Delta\theta_{h1i} - \Delta\theta_{h2i} \quad (\text{from 2.63})$$

$$0.7 = \Delta\theta_{h1i} - \Delta\theta_{h2i}$$

Therefore let $\Delta\theta_{h1i} = 0.7^\circ C$ and $\Delta\theta_{h2i} = 0^\circ C$.

5.2.3 Measured temperature data

As mentioned previously, the paper by Susa et al. (2005) provides actual top oil and WHS temperatures measured using temperature probes installed within the 400 MVA test transformer on ONAF cooling supplying the load described in figure 5.1. These data are not explicitly provided but must be read from the graphs of figures 8 & 9 on page 203 of the paper. Consequently, the possibility of error was introduced and the results of validation were analysed with this in mind. The measured top oil and WHS temperatures are presented in tables C.1 & C.2 of Appendix C.

5.3 Results & Analysis

After entering the input data for the test transformer into each of the three models (as shown in the MATLAB scripts of Appendix B), they were executed to generate output arrays of top oil and WHS temperatures for the loading cycle. These were plotted along

with the measured temperature profiles from Appendix C. Figure 5.2 displays the top oil plot and figure 5.3 displays the WHS plot.

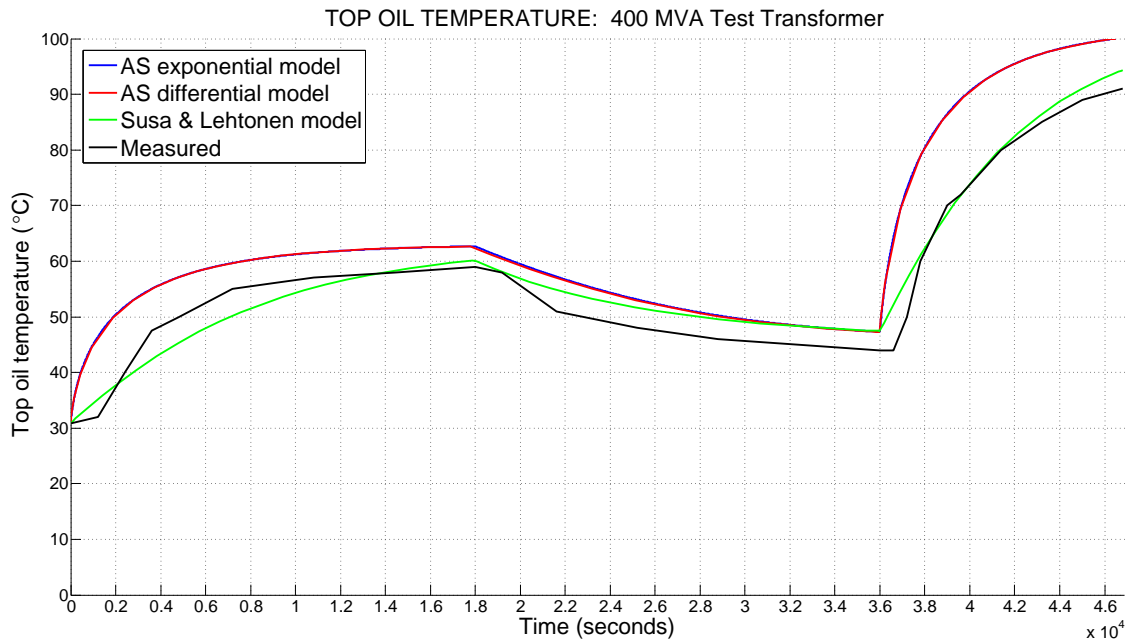


Figure 5.2: Top oil temperature profile predicted by each thermal model.

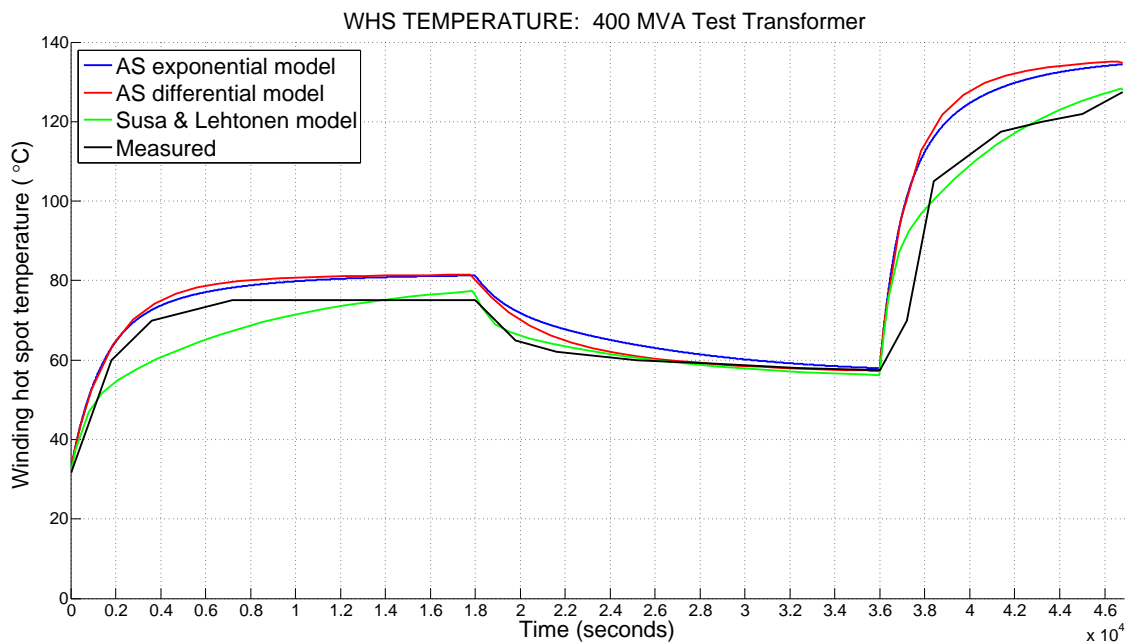


Figure 5.3: WHS temperature profile predicted by each thermal model.

By simple inspection of figures 5.2 & 5.3 it can be seen that in general, the top oil and WHS temperatures predicted by the Susa & Lehtonen (2006) model follow the actual measured profiles more closely than the AS 60076.7 models. To determine whether this is in fact the case, it was necessary to calculate the *mean square error (MSE)* for the

temperature profile of each model (top oil and WHS). This is essentially an indicator of how close each predicted temperature profile is to the actual measured profile. The MSE was calculated using the following equation:

$$MSE = \frac{1}{N} \sum_n [\theta_m(n) - \theta_p(n)]^2 \quad (5.1)$$

where: N is the total number of data points;
 n is an individual data point from 1 to N ;
 $\theta_m(n)$ is the n^{th} actual measured temperature data point; &
 $\theta_p(n)$ is the n^{th} temperature data point predicted by the model.

It is easy to focus on the maxima and minima of the temperature profiles predicted by the models, believing that they are the critical points, however it must be recalled that the ageing of the transformer insulation is proportional to the area under the temperature profile (refer to equations (2.3) & (2.1)) and so the MSE over the entire cycle is the most important metric.

Table 5.3 displays the results of the MSE calculations for the top oil and WHS temperature predictions by each thermal model. The temperature profiles predicted by the Susa & Lehtonen (2006) thermal model clearly possess the lowest MSE or divergence from the actual values.

Table 5.3: Mean Square Error (MSE) for top oil & WHS temperature profiles predicted by the thermal models.

Thermal model	MSE ($^{\circ}C^2$)	
	Top oil profile	WHS profile
AS exponential	122.48	96.28
AS differential	122.35	112.51
Susa & Lehtonen	11.73	37.07

The greater complexity of the Susa & Lehtonen (2006) model was discussed in section 2.2.4 and it is likely that its incorporation of variable load losses and oil viscosity with changing temperature are the enablers of its higher accuracy.

Figure 5.4 is a graph of the load losses for the 400 MVA test transformer over the loading cycle as calculated by the thermal models. The load losses calculated by the AS 60076.7 exponential and differential equation models are identical and so it was

only necessary to plot one load loss curve to represent both models in figure 5.4. It can be seen that the load losses calculated by the AS 60076.7 models are constant over each constant loading portion of the cycle, abruptly changing to a different value with the step changes in load. The Susa & Lehtonen (2006) model calculated losses follow the same general trend but gradually change over each constant portion of the loading cycle. Equations (2.56) & (2.58) for the Susa & Lehtonen (2006) model show that the DC losses are directly proportional to the WHS temperature and the eddy and stray losses are inversely proportional to the WHS temperature. Since the DC losses are significantly greater than the combined eddy and stray losses, it could be expected that the overall change in load loss will be in direct proportion to the temperature change. From figure 5.4, this is indeed the case with the load losses increasing as the transformer heats and decreasing as it cools.

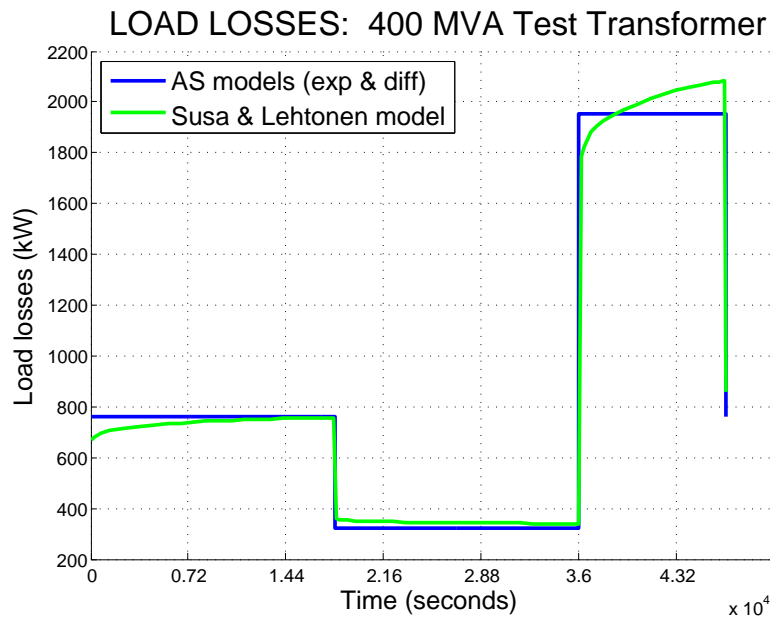


Figure 5.4: Variation in load losses over the test cycle as predicted by the thermal models.

Figure 5.5 displays the variation in oil viscosity over the loading cycle as predicted by the Susa & Lehtonen (2006) model. Intuitively, it would be expected for mineral oil to become less viscous (i.e. thinner) and flow more easily as it is heated. Figure 5.5 shows this to be the case with the oil viscosity reducing after the step increases in load and increasing after the step decrease in load.

As the transformer heats, the load losses increase which contribute further to heating. However, the viscosity of the oil reduces, thereby improving its flow and effectiveness as a cooling fluid. The two effects therefore counteract one another to an extent which

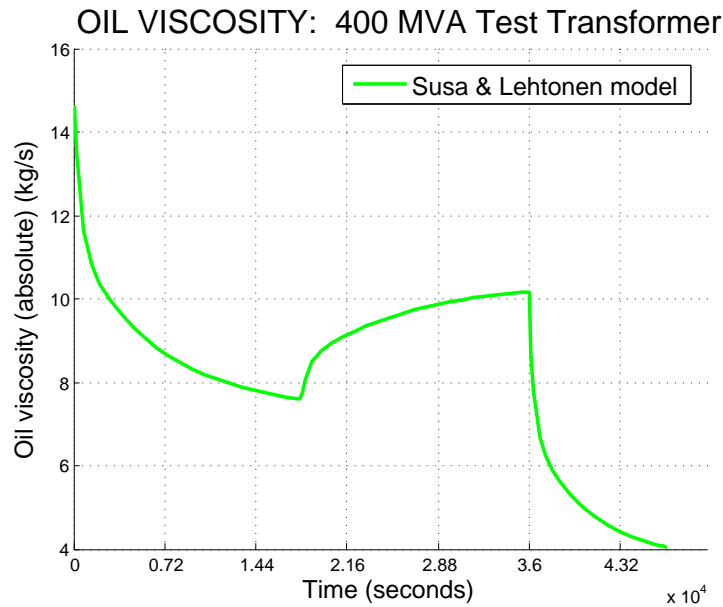


Figure 5.5: Variation in oil viscosity over the test cycle as predicted by the Susa & Lehtonen (2006) model.

explains why it is possible for the AS 60076.7 models to neglect both whilst producing acceptably accurate results. Of course, the effects do not completely cancel one another but interact in a complex manner resulting in an overall greater accuracy for the Susa & Lehtonen (2006) model. As discussed in section 2.2.4, the inclusion of the non-linearity exponent in the correct location also contributes to its greater accuracy.

Finally, referring again to figures 5.2 & 5.3, it is easily observed that the top oil and WHS temperature profile outputs of the AS 60076.7 models are almost coincident. This is more pronounced for the top oil profile than for the WHS profile, as is reflected in the MSE values of table 5.3. The explanation for this is that the exponential equation model is merely a solution of the differential equation model. The differences between the two AS 60076.7 models are most likely due to the simplifications which have been made to ensure that the equations are relatively simple to understand and implement (refer to section 2.2.4).

5.4 Model Selection

The purpose of appraising a number of models, selecting three, implementing the selection and comparing their outputs was to determine which model was most suitable for use as the basis for the cyclic rating calculator. It was important to make this decision in the context of both the requirements of this project and those of Ergon Energy. As a result, the following criteria were set to select the most appropriate of the three models:

1. **Accuracy:** Minimum deviation of predicted temperatures from the actual.
2. **Execution time:** Time for the MATLAB program to run and generate results.
3. **Simplicity:** Ease of understanding, implementation & modification.

Table 5.4 displays the results of assessment of each model against these three rating criteria. The Susa & Lehtonen (2006) model is the most accurate of the three models, however the accuracy of the AS 60076.7 models is not unacceptable. Due to their use of Simulink, the Susa & Lehtonen (2006) and the AS 60076.7 differential equation models are more than twice as slow as the AS 60076.7 exponential equation model. This is not a problem when the models are stand-alone, however as part of a cyclic rating calculator which must iterate many times for an individual transformer, let alone a large number of transformers in a fleet, this additional latency could accumulate to a prohibitive level. Finally, due to the absence of differential equations to solve, the AS 60076.7 exponential equation model is the most simple to understand and therefore program and modify.

Table 5.4: Assessment of the three thermal models.

	Thermal Model		
Criterion	AS exponential	AS differential	Susa & Lehtonen
Accuracy	Acceptable	Acceptable	High
Execution time	≤ 1 second	≈ 3 seconds	≈ 3 seconds
Simplicity	High	Moderate	Low-moderate

At Ergon Energy, expensive proprietary modelling software (such as MATLAB) is rarely used. Instead, Microsoft Excel coupled with VBA programming is common. Whilst it is not impossible to solve a differential equation in VBA, it would be very difficult to

justify the time expenditure to do so when a much simpler, effectively equivalent model based on exponential equations is available. For all of these reasons, the AS 60076.7 exponential equation model was selected to become the basis of the cyclic rating calculator developed in chapter 6.

5.5 Chapter Summary

This chapter has presented the results of validation and comparison of the three transformer thermal models selected from literature. The following conclusions were made:

- The Susa & Lehtonen (2006) model is the most accurate.
- Accuracy of the AS 60076.7 models is acceptable.
- Variations in load losses and oil viscosity with temperature as predicted by the Susa & Lehtonen (2006) model are reasonable and appear to contribute to its greater accuracy.
- For the Susa & Lehtonen (2006) model, load losses increase and oil viscosity decreases with increasing temperature.
- The AS 60076.7 exponential equation model is a simplified solution of the AS 60076.7 differential equation model.
- The AS 60076.7 exponential equation model is the fastest to execute and the simplest to implement.

The outcome of this chapter was the selection of the AS 60076.7 exponential equation model as the most appropriate to become the basis of the cyclic rating calculator, thereby resulting in achievement of project objective (6) (refer to section 1.4). The development of the cyclic rating calculator is discussed in the following chapter (chapter 6).

Chapter 6

Cyclic Rating Calculator

6.1 Chapter Overview

At this point in the project, the concepts of power transformer thermal modelling and cyclic ratings had been thoroughly investigated; three thermal models had been developed and tested; and one had been selected as being the most appropriate for further use.

This chapter focuses on the construction of a MATLAB program, incorporating the selected AS 60076.7 exponential equation thermal model at its core, which calculates cyclic ratings of specified power transformers. Specifically, the cyclic rating calculator was created to compute a large number of cyclic ratings for a range of transformers, cooling modes and load profiles such that the effect of variations in load profiles on cyclic ratings could be determined. In other words, the cyclic rating calculator was developed to generate the data on which the analysis of chapter 8 is based. The MATLAB script listing for the cyclic rating calculator is located in Appendix D.

Additionally, this chapter introduces the input data for the cyclic rating calculator – nameplate, HRT, ambient temperature and load profile data from a set of Ergon Energy power transformers. These transformers were selected for this project to represent a diverse range of manufacturers, sizes, cooling modes, geographical locations and load profile shapes.

6.2 Cyclic Rating Calculator Design & Construction

The calculation of cyclic ratings for power transformers in accordance with AS 60076.7 was discussed in detail in section 2.2.5 which also provided a flowchart to describe the process (figure 2.19). Briefly summarised, the determination of a cyclic rating for a given power transformer involves scaling the relevant load profile with an adjustable CRF until one or more of the parameters calculated using a thermal model reach their respective limits outlined in AS 60076.7 (table 2.5). The limiting parameters are: top oil temperature, WHS temperature, insulation ageing and CRF.

Figure 6.1 displays the flowchart created for the design and development of the cyclic rating calculator for this project. The MATLAB code listing is contained in Appendix D. Table 6.1 lists all of the variables employed in the cyclic rating calculator and their MATLAB equivalents. For conciseness, figure 6.1 contains references to tables and equations which have been presented in previous chapters. To simplify the task for the reader, these have been repeated following table 6.1 without further explanation (refer to section 2.2.5 for detail). A series of explanatory notes detailing important parts of the cyclic rating calculator are provided following figure 6.1.

Table 6.1: Cyclic rating calculator variables and their MATLAB equivalents.

Variable	Description	Matlab notation
c	Specific heat capacity	<code>c</code>
C	Thermal capacity	<code>C</code>
H	Hot spot factor	<code>H</code>
m_t	Mass of tank	<code>m_t</code>
m_a	Mass of core & coil assembly	<code>m_a</code>
m_o	Mass of oil	<code>m_o</code>
m_w	Mass of winding	<code>m_w</code>
θ_{ma-max}	Monthly average temperature of hottest month	<code>theta_ma_max</code>
θ_E	Yearly weighted ambient temperature	<code>theta_E</code>
x	Oil exponent	<code>x</code>
y	Winding exponent	<code>y</code>
k_{11}	Constant	<code>k_11</code>

k_{21}	Constant	k_21
k_{22}	Constant	k_22
k_{22}	Constant	k_22
τ_o	Oil time constant	tau_o
τ_w	Winding time constant	tau_w
S_r	Nameplate rating	S_r
P_{lr}	Load losses at rated load	P_l_r
P_l	Load losses at present load ($P_{lr}K^2$)	P_l
P_{nl}	No-load losses	P_nl
R	Ratio of load to no-load losses at rated current	R
S_{pu}	Per unit load profile	profile
CRF	Cyclic Rating Factor	CRF
M	Multiplier ($CRF \times S_r$)	M
S	Load profile ($S_{pu} \times M$)	S
K	Load factor (S/S_r)	K
$\Delta\theta_{or}$	Top oil to ambient temp rise at rated load	D.theta_o_r
$\Delta\theta_{omr}$	Average oil to ambient temp rise at rated load	D.theta_o_m_r
R_{mo-to}	Ratio of mean oil to top oil temp rise at rated load	mo_to_ratio
$\Delta\theta_{om}$	Average oil to ambient temp rise at present load ($\Delta\theta_{oi} \times R_{mo-to}$)	D.theta_o_m
$\Delta\theta_{hr}$	WHS to top oil temp rise at rated load	D.theta_h_r
g_r	Winding to oil temp gradient at rated load	g_r
g	Winding to oil temp gradient at present load (g_rK^y)	g
$\Delta\theta_o$	Array of top oil to ambient temp rises for current load	D.theta_o
$\Delta\theta_h$	Array of WHS to top oil temp rises for current load	D.theta_h
$\Delta\theta_{oi}$	Top oil to ambient temp rise from previous time step	D.theta_o_i
$\Delta\theta_{hi}$	WHS to top oil temp rise from previous time step	D.theta_h_i
θ_o	Array of top oil temps for current load profile	theta_o
θ_h	Array of WHS temps for current load profile	theta_h
θ_h'	Array of WHS temps for thermal ageing calculation	theta_h_ageing
$\theta_o \max$	Maximum top oil temp in current cycle	theta_o_max
$\theta_h \max$	Maximum WHS temp in current cycle	theta_o_max

L	Array of insulation ageing times for each cycle interval	L
L_{total}	Total insulation ageing over current cycle	L_total
$\theta_o \text{ lim}$	AS 60076.7 top oil temp limit	theta_o_lim
$\theta_h \text{ lim}$	AS 60076.7 WHS temp limit	theta_o_lim
CRF_{lim}	AS 60076.7 CRF load limit	load_lim
L_{lim}	Thermal ageing limit	L_lim
t	Time step (1/2 h)	t
–	Array of time steps (0:24 h in 1/2 h steps)	t_steps
–	Transformer number/counter	TX_no
–	Cooling mode counter	cool_count
–	Cooling mode	cool_mode
–	Profile number/counter	profile_no

Table 6.2: AS 60076.7 thermal modelling constants (from table 2.7).

Transformer class	Distribution	Medium & Large			
Cooling mode	ONAN	ONAN	ONAF	OFXX	ODXX
Oil exponent (x)	0.8	0.8	0.8	1.0	1.0
Winding exponent (y)	1.6	1.3	1.3	1.3	2.0
Constant k_{11}	1.0	0.5	0.5	1.0	1.0
Constant k_{21}	1.0	2.0	2.0	1.3	1.0
Constant k_{22}	2.0	2.0	2.0	1.0	1.0

Table 6.3: AS 60076.7 cyclic rating limits (NC) (from table 2.5).

NC Limits	Transformer type		
	Distribution	Medium power	Large power
CRF (per unit)	1.5	1.5	1.3
WHS temp. (θ_h) [$^{\circ}C$]	120	120	120
Top oil temp. (θ_o) [$^{\circ}C$]	105	105	105
Ageing (L) [h/day]	24	24	24

For a step *increase* in load:

$$\begin{aligned}\Delta\theta_o(t) &= \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} \left(1 - e^{-\frac{t}{k_{11}\tau_o}} \right) \\ \Delta\theta_h(t) &= \Delta\theta_{hi} + \{ Hg_r K^y - \Delta\theta_{hi} \} \left[k_{21} \left(1 - e^{-\frac{t}{k_{22}\tau_w}} \right) - (k_{21} - 1) \left(1 - e^{-\frac{t}{\tau_o/k_{22}}} \right) \right]\end{aligned}$$

(2.65, 2.67 & 2.68 modified)

For a step *decrease* in load:

$$\begin{aligned}\Delta\theta_o(t) &= \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \left[\frac{1 + RK^2}{1 + R} \right]^x \right\} e^{-\frac{t}{k_{11}\tau_o}} \\ \Delta\theta_h(t) &= Hg_r K^y + \{ \Delta\theta_{hi} - Hg_r K^y \} e^{-\frac{t}{\tau_w}}\end{aligned}$$

(2.66 & 2.69 modified)

Finally:

$$\theta_o(t) = \theta_{ma-max} + \Delta\theta_o(t) \quad (6.1)$$

$$\theta_h(t) = \theta_{ma-max} + \Delta\theta_o(t) + \Delta\theta_h(t) \quad (6.2)$$

$$\theta_h(t)' = \theta_E + \Delta\theta_o(t) + \Delta\theta_h(t) \quad (6.3)$$

Time constants & thermal capacity:

$$\tau_w = \frac{m_w \cdot c \cdot g}{60P_l} \quad (2.71 \text{ repeated})$$

$$\tau_o = \frac{60C \cdot \Delta\theta_{om}}{P_l + P_{nl}} \quad (2.72 \text{ repeated})$$

$$\text{where: } C = \begin{cases} 0.132m_a + 0.0882m_t + 0.4m_o, & \text{for ON.. cooling} \\ 0.132(m_a + m_t) + 0.580m_o, & \text{for OF.. \& OD.. cooling} \end{cases} \quad (2.73 \text{ repeated})$$

Thermal ageing of insulation:

$$L(t) = V(t) \times t = t \cdot 2^{(\theta_h(t)' - 98)/6} \quad (2.1 \text{ modified})$$

$$L_{total} = \sum_{t=1}^{48} L(t) \quad (2.4 \text{ modified})$$

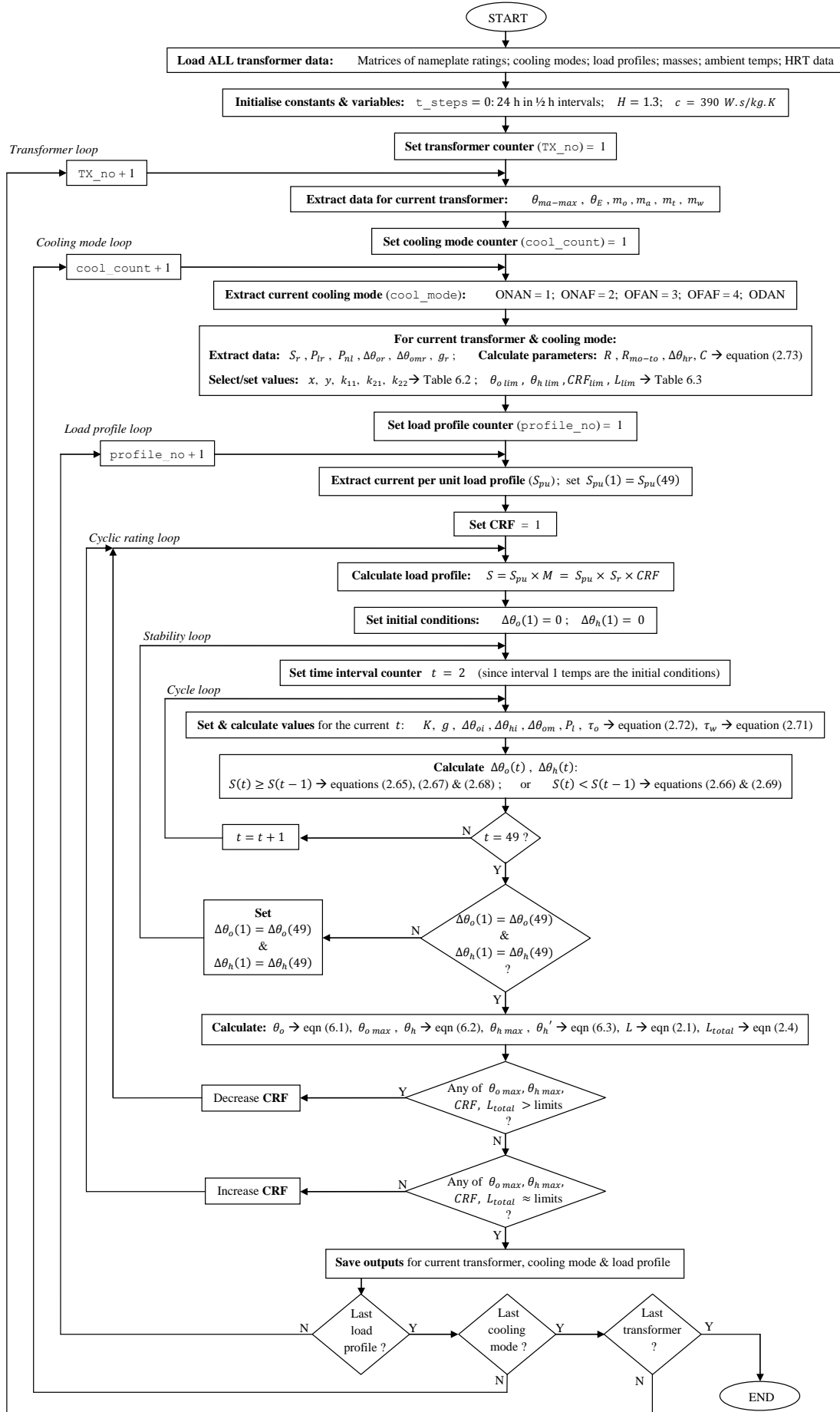


Figure 6.1: Flowchart for the AS 60076.7 based transformer cyclic rating calculator.

Explanatory notes for the cyclic rating calculator script & flowchart:

- The cyclic rating calculator contains six nested loops:
 1. **Cycle loop** – the innermost loop; AS 60076.7 exponential equation thermal model which calculates top oil and WHS temperatures over a 24 hour cycle
 2. **Stability loop** – iterates the cycle loop, updating the initial cycle temperatures, until the final temperatures of the cycle equal the corresponding initial temperatures (necessary because the final temperatures of the cycle are the initial temperatures for the next day’s cycle; i.e. there is one half hour period overlap or 49 half hour periods)
 3. **Cyclic rating loop** – iterates the lower two loops indefinitely, updating the CRF, until at least one cyclic rating limit is reached
 4. **Load profile loop** – iterates the cyclic rating loop for every load profile (i.e. calculates a cyclic rating for each load profile)
 5. **Cooling mode loop** – iterates the load profile loop for every cooling mode
 6. **Transformer loop** – the outermost loop; iterates the cooling mode loop for each transformer
- Transformer data referred to in the flowchart is described in detail in section 6.3.
- By using different limits from AS 60076.7 (refer to table 2.5), NC or LTEC ratings can be calculated. The MATLAB script for the calculator (in Appendix D) contains a selector (1 or 0) such that the user can set the type of rating to be calculated (note: NC limits only were calculated for this project).
- Two ambient temperature parameters are necessary for cyclic rating calculation: the monthly average temperature of the hottest month (θ_{ma-max}) for modelling top oil and WHS temperatures (equations (6.1) & (6.2)); and the yearly weighted ambient temperature (θ_E) for calculating insulation ageing (equation (6.3)). Determination of these ambient temperature parameters is detailed in section 6.3.
- The cooling mode counter (`cool_count`) of the cooling mode loop steps through up to three (3) cooling modes for each transformer. If a selected transformer possesses fewer than three, the remainder are stored as zeros (0) in the data. When the cooling mode is read by the program, if it is a zero, the cooling mode loop is exited and the next iteration of the transformer loop commences.

- Since the cyclic rating calculator is based on the AS 60076.7 exponential equation model, many features of the flowchart (figure 6.1) and MATLAB script (Appendix D) are recognisable from section 4.2 in which this thermal model was initially implemented. Such features include calculation of ratios R & R_{mo-to} , selection of modelling constants (x , y , k_{11} , k_{21} & k_{22}) and calculation of thermal capacity (C). The portion of the calculator within the cycle loop is almost an exact copy of the corresponding part of the exponential equation thermal model.
- In the MATLAB listing, per unit load profiles are extracted from the `DSM_profiles` matrix. This refers to demand side management (DSM) modified load profiles derived for the project. Chapter 7 is devoted to an explanation of this process.
- Updating of the CRF with each iteration of the cyclic rating loop occurs using the following algorithm:
 1. Calculate the difference between each cyclic parameter and its limit (i.e. $[\theta_o \text{ lim} - \theta_o \text{ max}]$; $[\theta_h \text{ lim} - \theta_h \text{ max}]$; $[CRF_{lim} - CRF]$; & $[L_{lim} - L_{total}]$);
 2. Find the minimum difference; the aim being to find the negative difference if it exists (i.e. the parameter which exceeds its corresponding limit); if it does not exist, the minimum difference will be positive
 3. Normalise this minimum difference to ± 1 and multiply it by an increment which is made smaller with each iteration of the cyclic rating loop
 4. Add this product to the previous CRF

By this process, the CRF is increased whenever all of the cyclic parameters are less than their corresponding limits (thereby allowing higher loading) and is decreased whenever any one of the cyclic parameters exceeds its corresponding limit (thereby reducing the loading). Additionally, the amount by which the CRF is adjusted becomes smaller with each iteration. In this way, the final value can be approached in ever decreasing steps thereby ensuring convergence and preventing oscillation. The amount by which the increment is reduced on each iteration is critical. Choice of an inappropriate value causes an early and undesirable exit from the cyclic rating loop. For example, if the CRF and the increment are initially set as 1 and the increment is reduced by a factor of 2 on each iteration, the CRF often increases to 1.5 on the second iteration which breaks the cyclic rating loop because this is equal to the CRF limit. For this reason, 1.1 was selected as the divisor.

- Due to computer rounding, it is highly improbable that the calculated cyclic parameters ($\theta_{o \ max}$, $\theta_{h \ max}$, CRF & L_{total}) will ever exactly equal their corresponding limits. Hence, in the portion of the MATLAB code which performs the comparison, a limit is deemed to have been reached if the corresponding parameter lies in the range between the limit and the limit minus a small user definable tolerance (set as 0.01 in the current form of the script).
- The output of the cyclic rating calculator program is a large matrix named **results** which contains the following data for *every combination of transformer, cooling mode and load profile*:
 - Transformer number
 - Cooling mode
 - Load profile number
 - Characteristics of the load profile (max, min, average, load factor)
 - Minimum & maximum ($\theta_{o \ max}$) top oil temperatures for the cycle
 - Minimum & maximum ($\theta_{h \ max}$) WHS temperatures for the cycle
 - CRF defining the calculated cyclic rating
 - Total insulation ageing for the cycle (L_{total})
 - The cyclic rating limit which was reached (top oil, WHS, CRF or ageing)
 - Top oil temperatures for the cycle (θ_o) (for graphing)
 - WHS temperatures for the cycle (θ_h) (for graphing)
 - Insulation ageing values for each time step of the cycle (L) (for graphing)

6.3 Input Data

As was eluded to in section 6.2, the cyclic rating calculator functions to compute the cyclic ratings of a number of transformers, each with up to three cooling modes, supplying a range of load profiles. The purpose of this was to create sufficient data to determine the influence of load profile changes on cyclic ratings. This section introduces the transformers selected for this study and their associated data.

6.3.1 Transformers

Twelve (12) transformers were selected from the Ergon Energy fleet representing a diverse range of manufacturers, sizes, cooling modes, geographical locations and load profile types. Table 6.4 lists the selected transformers and their important characteristics. Figure 6.2 displays the locations in which the selected transformers are installed.

Table 6.4: The 12 selected Ergon Energy transformers (*Source: G.Caldwell, Ergon Energy*).

Location	Region	Manufacturer & year	Cooling modes	Ratings (MVA)	Voltages (kV)
Cairns	Northern	GEC Alstom (1992)	ONAN/ODAN	64/80	132/22
Cloncurry	Northern	Tyree (1976)	ONAN/ONAF	2/2.3	66/11
Croydon	Northern	GEC Alstom (1991)	ONAN	2	66/22
Dalby	Southern	ABB (2008)	ONAN/ONAF	50/63	110/33
Gladstone	Central	Fortune (2005)	ONAN/ONAF	35/40	66/11
Howard	Southern	EE (1955)	ONAN	7.2	62/11
Mackay	Central	Tyree (1975)	ONAN/ONAF	5/7.5	33/11
Maryborough	Southern	Wilson (2006)	ONAN/ODAN	80/100	132/66
Rockhampton	Central	Wilson (1980)	ONAN/ONAF	5/6.25	66/11
Toowoomba	Southern	Areva (2006)	ONAN/ONAF	30/40	110/11
Townsville Central	Northern	EE (1970)	ONAN/ODAN/ ODAF	15/20/25	66/11
Townsville North	Northern	Areva (1977)	ONAN/ODAN/ ODAF	15/20/25	66/11

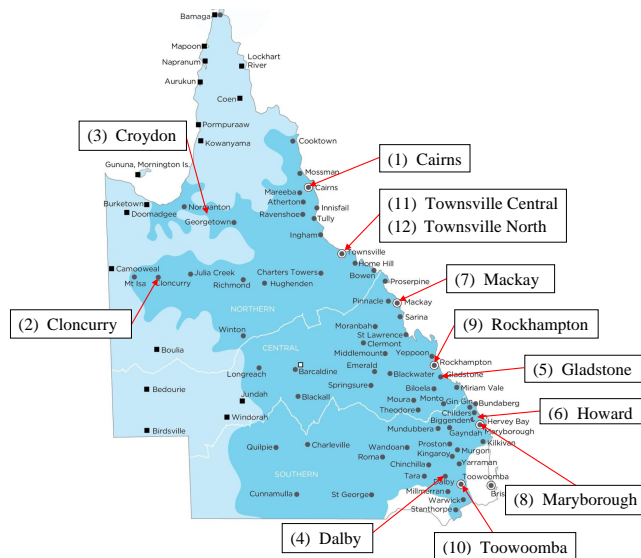


Figure 6.2: Selected transformer locations (*Source: G.Caldwell, Ergon Energy*).

As previously displayed in the flowchart for the cyclic rating calculator (figure 6.1), a data matrix of transformer parameters is loaded as the first step in the program. This matrix (`TX_data`) contains the following data for *each transformer*:

- **Ambient temperatures:**
 - Monthly average temperature of the hottest month (θ_{ma-max}) [$^{\circ}C$]
 - Yearly weighted ambient temperature (θ_E) [$^{\circ}C$]
- **Masses:**
 - Transformer tank (m_t) [kg]
 - Core & winding assembly (m_a) [kg]
 - Mineral oil (m_o) [kg]
- **Heat Run Test (HRT) data** for up to three cooling modes:
 - Cooling mode (ONAN = 1; ONAF = 2; OFAN = 3; OFAF = 4; ODAN = 5; ODAF = 6)
 - Nameplate rating (S_r) [MVA]
 - No-load losses (P_{nl}) [W]
 - Load losses for nameplate loading (P_{lr}) [W]
 - Top oil temperature rise for nameplate loading ($\Delta\theta_{or}$) [$^{\circ}C$]
 - Average oil temperature rise for nameplate loading ($\Delta\theta_{omr}$) [$^{\circ}C$]
 - Winding to top oil temperature differential for nameplate loading (g_r) [$^{\circ}C$]

It was necessary to calculate the ambient temperature parameters for each transformer location. The procedure for achieving this was previously described on page 55 of section 2.2.5. The basis data for each transformer location on which the ambient temperature calculations were performed was obtained from the Bureau of Meteorology (BOM) website. The calculation procedure is demonstrated in Appendix E.

The remaining data were supplied by Ergon Energy for each of the 12 selected transformers and were entered into a spreadsheet along with the ambient temperature parameters. The MATLAB function `xlsread()` was then employed to extract the transformer data from the `.xls` spreadsheet file into the MATLAB workspace. Following this, the

data was saved as a MATLAB `.mat` file which could then be accessed by the cyclic rating calculator using the `load()` function (refer to Appendix D). To facilitate independent verification of results, the data for the 12 selected power transformers has been included in Appendix F.

6.3.2 Load profiles

Also obtained courtesy of Ergon Energy were the load profile curves for each of the 12 selected transformers. These load profiles had been derived by averaging the past five years of metered load data for each transformer. The next chapter (chapter 7) is devoted to the load profiles employed with the cyclic rating calculator and so the selected transformer load curves are presented there.

6.4 Chapter Summary

This chapter has focused on the design and construction of the cyclic rating calculator in MATLAB. It has also presented the data for the 12 selected Ergon Energy transformers which became the input data for the calculator. The completion of the cyclic rating calculator marked the achievement of project objective (7) (refer to section 1.4) however a final component of preparation prior to its use in generating cyclic ratings required the modification of a set of load profiles to simulate demand side management (DSM). This is the subject of the following chapter.

Chapter 7

Demand Side Management Simulation

7.1 Chapter Overview

The main objective of this project was to determine the impact of changes in load profiles on cyclic ratings. At this stage, a calculator had been constructed to determine the cyclic ratings of 12 selected Ergon Energy transformers but a critical final development was necessary: a set of load profiles, modified to simulate demand side management (DSM), was required as the final input to the cyclic rating calculator.

DSM was introduced in section 2.3 where it was stated that *load shifting* DSM is the most attractive method for utilities, such as Ergon Energy, seeking to flatten load profiles. Fundamentally, this is because load shifting DSM does not reduce the overall energy supplied during the loading cycle, thereby not reducing revenue. It is achieved primarily through the utility actively transferring load from peak to off-peak times and/or by incentivising customers to consume less during peak times.

This chapter first discusses the selection of an original set of unmodified load profiles. Secondly, the development of a load shifting DSM simulator is described. Finally, the results of application of the DSM simulator to the original set of load profiles are presented.

7.2 Original Load Profiles

A load profile for each of the 12 selected Ergon Energy transformers (discussed in section 6.3) was obtained, however it was considered valuable to also include a number of simpler, generic profiles which could be applied to every transformer. The original set of load profiles therefore consisted of the following which are discussed in turn:

1. **Square wave load profile**
2. **Industry standard load profiles**
3. **Actual Ergon Energy load profiles**

7.2.1 Square wave load profile

The hypothetical square wave load profile (with DC offset) was simple to create and modify, serving as a useful starting point. An example of such a square wave load profile is displayed in figure 7.1. Note that the rising and falling edges are not vertical due to the half hour time resolution employed in the cyclic rating calculator (refer to section 6.2).

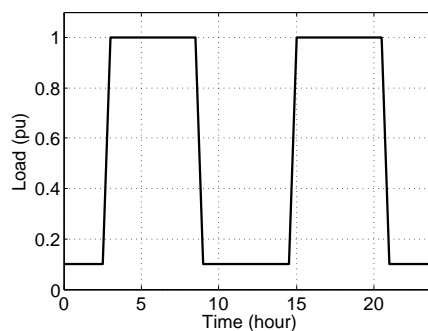


Figure 7.1: Square wave load profile with DC offset.

Although the square profile was intended to be hypothetical, an actual version was located for an Ergon Energy transformer. In a unique arrangement, this transformer supplies a large industrial induction furnace almost exclusively. The load profile over a 30 hour period is displayed in figure 7.2. It can be seen that the load supplied by this transformer is similar to a square profile with abrupt step-like changes in load corresponding to operation of the furnace. As a result, the square wave load profile input to the cyclic rating calculator was more useful than originally planned.

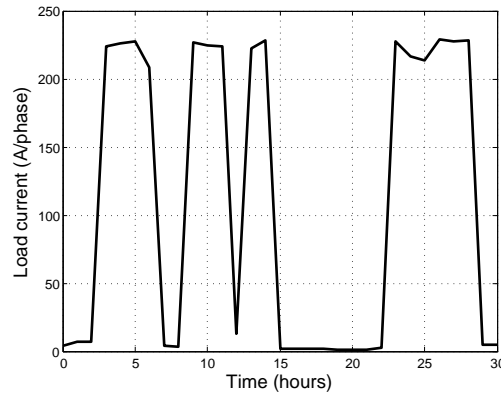
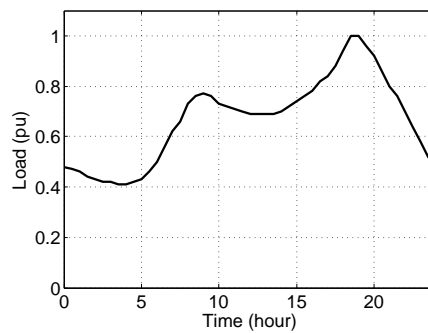


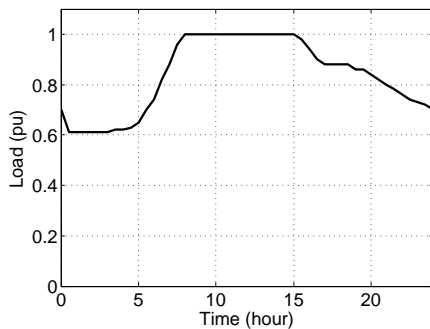
Figure 7.2: Actual square-like load profile (*Source: G. Caldwell, Ergon Energy*).

7.2.2 Industry standard load profiles

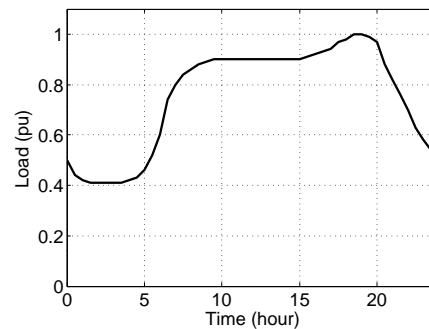
From analysis and averaging of much data, standard load profiles have been developed by the utilities. These include standard residential, industrial and mixed residential-industrial load profiles which are displayed in figures 7.3a, 7.3b and 7.3c respectively. The standard profiles were useful since they are ideal representations of actual profiles, lying mid-way between the hypothetical square profile and real, measured data.



(a) Standard residential load profile.



(b) Standard industrial load profile.



(c) Standard mixed load profile.

Figure 7.3: Industry standard load profiles (*Source: G. Caldwell, Ergon Energy*).

7.2.3 Ergon Energy load profiles

Ergon Energy Corporation measures and stores various types of data from their network. Metered power data is therefore readily available for power transformers. Ideally, it would be desirable to calculate a cyclic rating before a specific loading period occurs however the load profile from that period is not yet known. A historical load profile could therefore be used, however diversity exists from day to day. To address this issue, Ergon Energy creates load profiles from an average of the previous five years of weekday data. It could be argued that for conservativeness, the profile from the day of peak load should be employed however there may be aspects of a normal day's loading absent in the peak day which significantly affect the rating. In any case, it can be seen in figure 7.4 that the five year average load profile has much the same shape as the peak day load profile without the transient fluctuations. Absolute values of load are unimportant with respect to cyclic rating calculation since load profiles are normalised for this purpose (refer to section 6.2). Therefore, the five year average load profiles for the 12 selected Ergon Energy transformers (refer to section 6.3) were obtained.

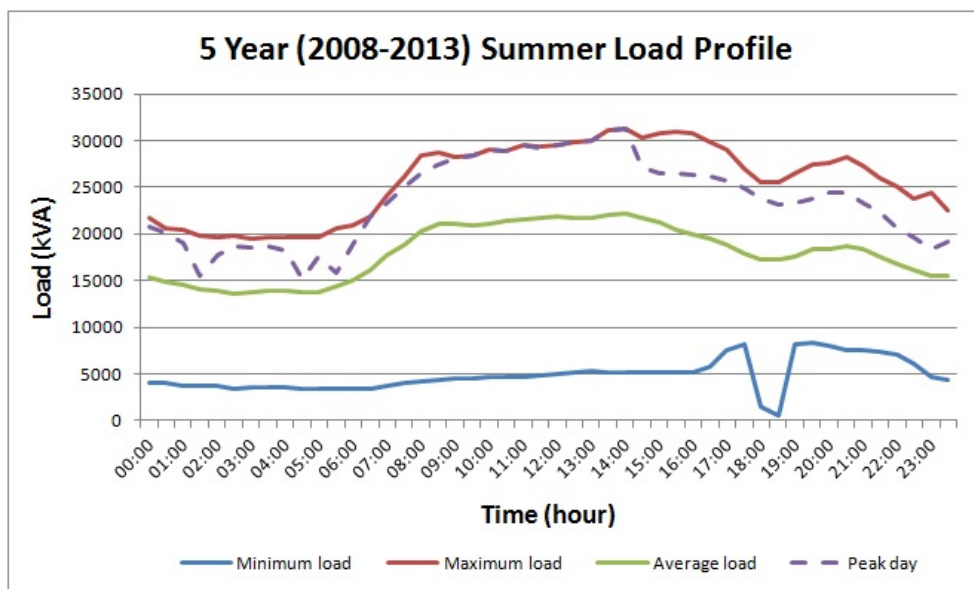


Figure 7.4: Ergon Energy five year maximum, average and minimum load profile with peak day load (summer) for a Townsville transformer (*Source: G.Caldwell, Ergon Energy*).

7.3 Load Shifting DSM Simulator

Once the set of original load profiles had been selected, a means of simulating load shifting DSM was required. This was achieved by implementing an algorithm similar to that published by Huang & Billinton (2012, p. 336) in MATLAB. The Huang & Billinton (2012) load shifting DSM algorithm was presented on page 62 of section 2.3 and essentially involves the following steps:

1. Set the maximum value for the load in the cycle;
2. Reduce the load peaks to this maximum value;
3. Distribute the load removed from the peaks evenly across the troughs.

Application of this algorithm causes a load profile to become flatter (less peaky) but retain the same average value or area under the curve (refer to figure 2.21). That is, the algorithm simulates ideal load shifting DSM because the energy associated with each of the original and the DSM modified load profiles is the same.

This algorithm was implemented in MATLAB and follows the flowchart presented in figure 7.5. The MATLAB script for the load shifting DSM simulator is located in Appendix G. The following explanatory notes accompany the flowchart and MATLAB code.

Explanatory notes for the DSM simulator script & flowchart:

- The specified maximum load peaks represent the percentage of the unmodified load profile peak which will become the new peak load. That is, 100%, 95% , 90%, 85% & 80% result in reductions in peak load of 0%, 5%, 10%, 15% & 20% respectively compared with the original, unmodified load profile. The 100% load peak of course represents no DSM.
- All original load profiles were obtained from Ergon Energy in per unit form (apart from the square profile which was created). These were imported from a spreadsheet into MATLAB before being saved as part of the `TX_data.mat` file. The profiles are extracted from this file using the `load()` function in the script and concatenated into one matrix (`old_profiles`).

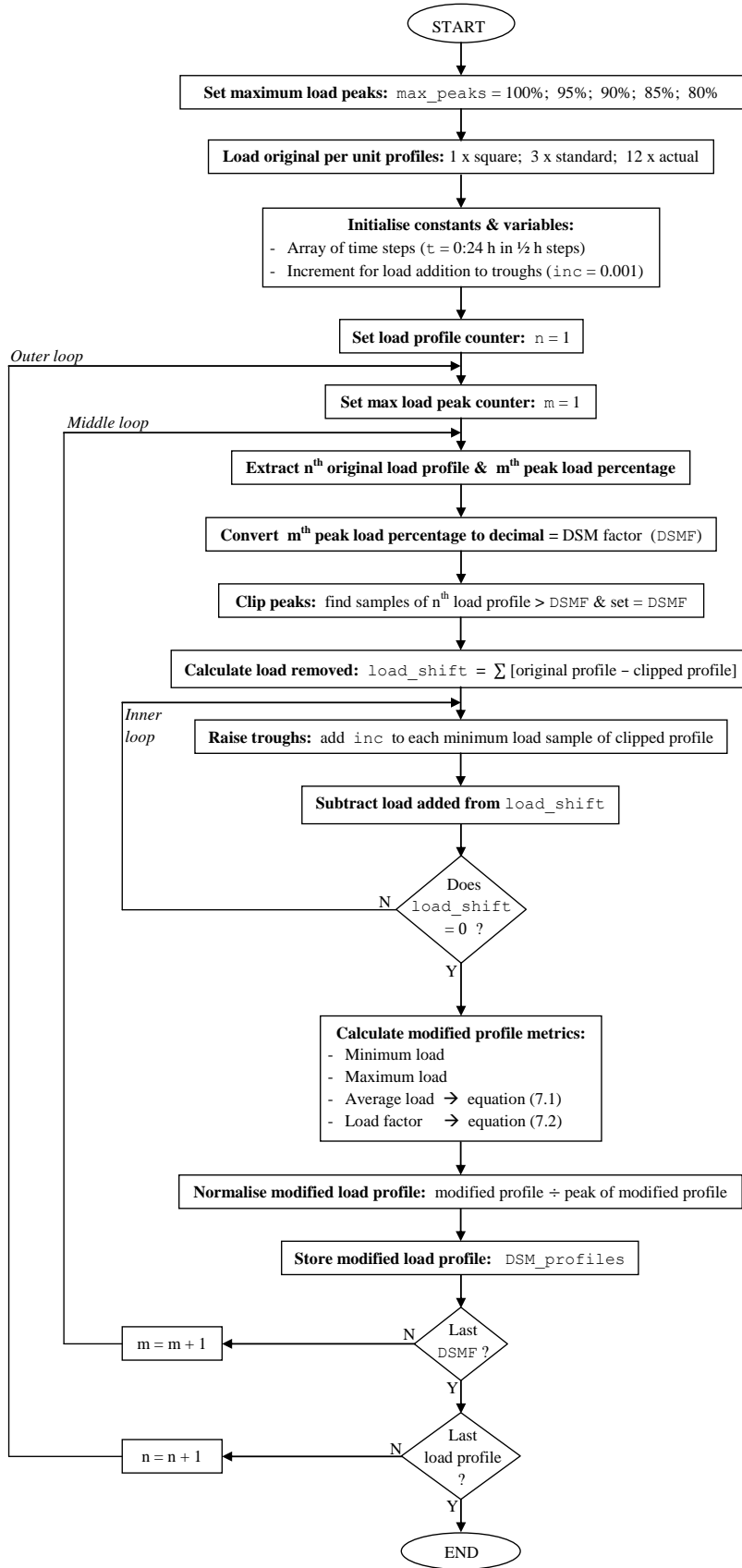


Figure 7.5: Flowchart for the load shifting DSM simulator.

- Three nested loops exist in the DSM simulation program:
 1. The **outer** loop steps through each original load profile in turn:
1 square + 3 standard + 12 actual = 16 original profiles
 2. The **middle** loop steps through each specified peak load percentage for each original profile:
5 peak load reductions \times 16 original profiles = 80 DSM modified profiles (including the unmodified versions)
 3. The **inner** loop performs the load shifting function by distributing the load removed from the peaks amongst the troughs for each reduction in peak load of each original profile.
- Peak reduction is a straightforward task accomplished by locating the load samples equal to the decimal version of the current peak load percentage and setting them to this value. The simplicity is by virtue of the fact that the load profiles are in per unit form. Thus, when the peak load percentage for DSM is 80% for example, all load samples in the selected original profile greater than 0.8 are set to 0.8.
- After peak clipping had been performed, the amount of load removed is obtained by subtracting the clipped profile from the original unmodified profile and summing the samples.
- Trough or valley filling is then performed incrementally. That is, the minimum/minima of the clipped profile are located and a very small amount of load is added to each. This small increment is named **inc** in the flowchart and script and was set to 0.001. The combined load added is then subtracted from the total load removed from the peaks and the process repeated until all removed load has been added to the troughs (obviously there exists some error due to the additions of discrete amounts).
- Through the addition of load to the troughs, it is possible for the profile to become flat at a higher value of load than the specified peak percentage. This was found to be the case for the low peak percentages in combination with those original profiles which did not feature large fluctuations in load. The effect is a manifestation of the theoretical requirement of load shifting DSM to maintain a fixed average value. Due to the fact that all curves were normalised prior to

use in the cyclic rating calculator (see below), no negative consequences resulted because the profile merely became flat at 1 per unit.

- The cyclic rating calculator functions by multiplying an input per unit load profile by the transformer nameplate rating and by a continuously refined CRF until thermal limits are reached. In this way, the CRF need not be calculated because since it is equal to the maximum peak which can be supplied divided by the nameplate rating, it is already explicitly available. However, this technique relies on the *peak of the input load profile being 1 per unit* such that the profile can then be scaled to the transformer nameplate rating, thereby allowing the updated multiplying factor to be the CRF. It is for this reason that the DSM modified load profiles generated by the simulator are normalised. Further, this is the reason why the occurrence of some flattened profiles at values higher than the specified peak load (previous note) were not problematic.
- The following characteristic metrics were determined/calculated for each modified load profile:

- Maximum per unit load (S_{max})

- Minimum per unit load (S_{min})

- Average load:

$$S_{avg} = \frac{1}{t_{max}} \int_0^{t_{max}} S(t) dt \quad (7.1)$$

- Load factor:

$$LF = \frac{S_{avg}}{S_{max}} \quad (7.2)$$

7.4 DSM Modified Load Profiles

Application of the load shifting DSM simulator to the set of original load curves generated a matrix (`DSM_profiles`) of 80 profiles which was provided to the cyclic rating calculator as the load profile input (refer to section 6.2). This set of 80 original and DSM modified load profiles is presented in table H.1 of Appendix H to permit third party verification of results and/or further study.

To demonstrate the function of the load shifting DSM simulator, each original load profile was graphed along with its DSM modified versions. These plots are displayed as figures 7.6 to 7.8. When viewing these plots, the following points are noteworthy:

- The DSM modified profiles have been plotted *before* being normalised to permit visualisation of the process. As stated previously in section 7.3, all profiles are normalised before input to the cyclic rating calculator.
- As the peaks reduce the curves approach (& in some cases reach) a flat profile.
- The average values of each original profile and its DSM modified versions are equal as per the definition of load shifting DSM.
- For some of the original profiles at the lower values of peak load percentage, the profile becomes flat at a higher load than the specified peak. As mentioned in section 7.3, normalisation of the profile negates any effect this might have had.

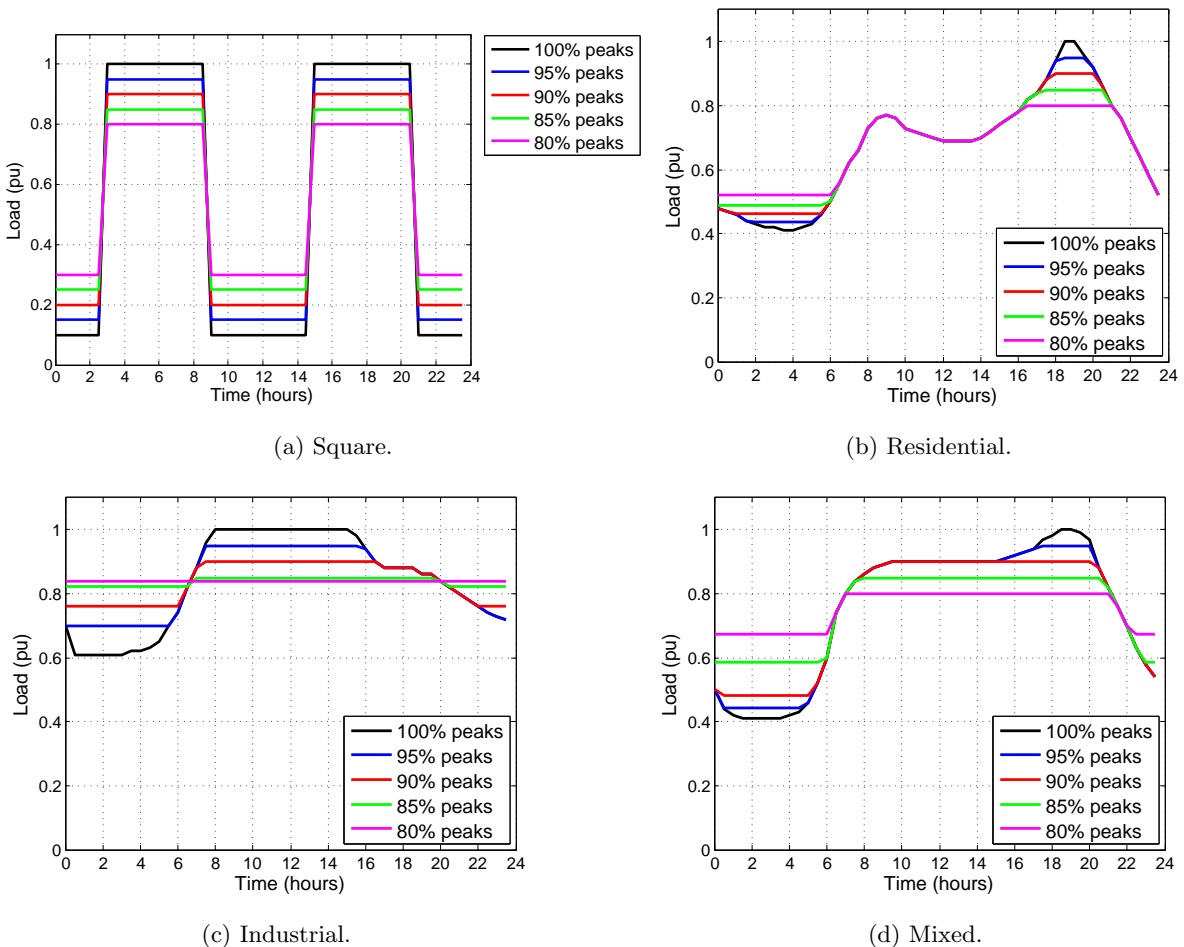
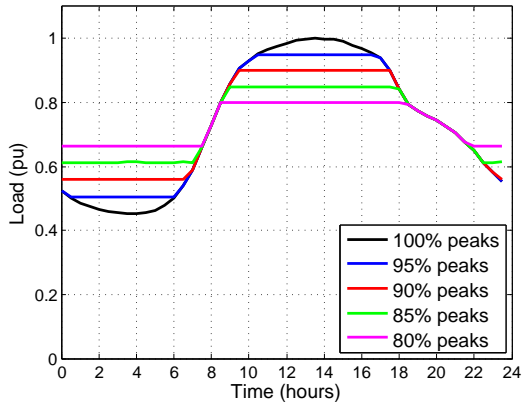
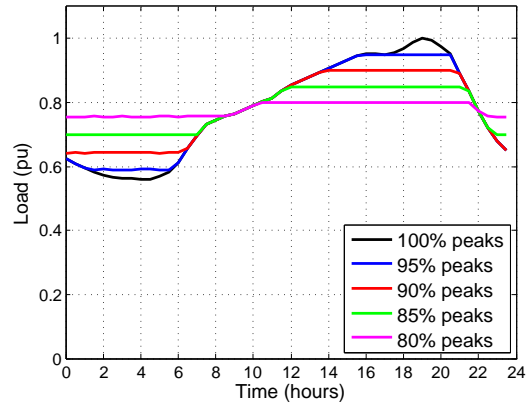


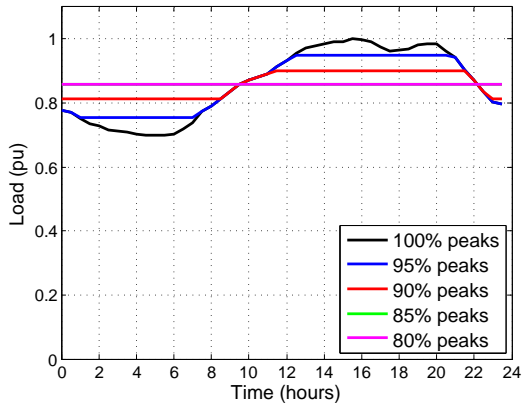
Figure 7.6: Results of application of the DSM simulator to **square** & **standard** profiles.



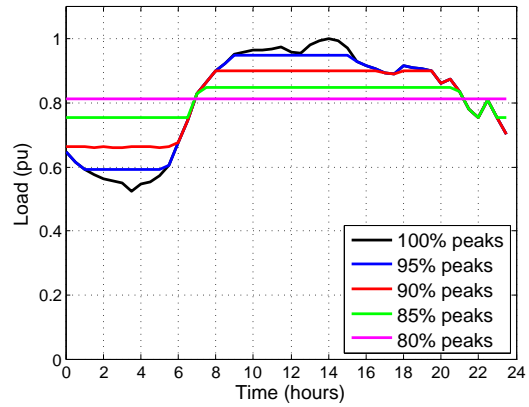
(a) Cairns.



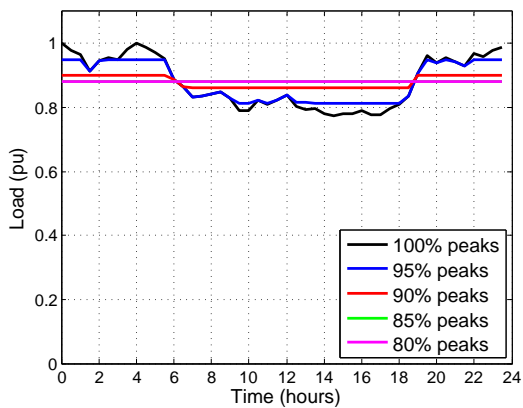
(b) Cloncurry.



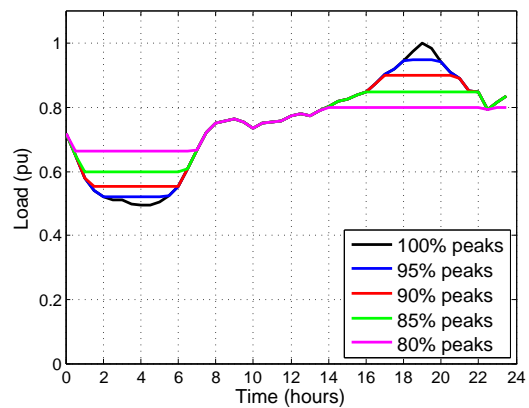
(c) Croydon.



(d) Dalby.

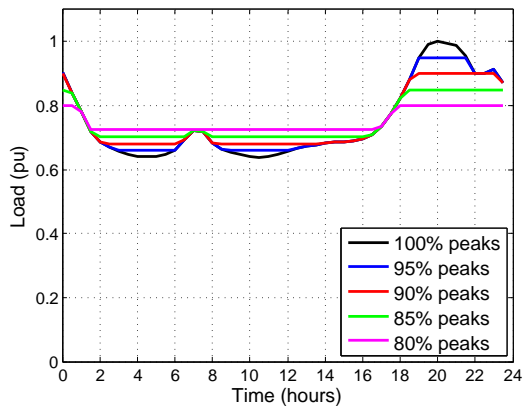


(e) Gladstone.

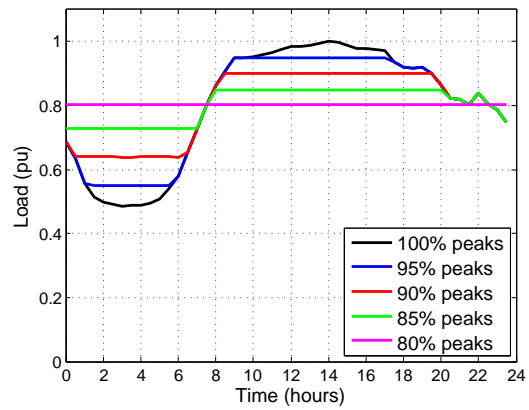


(f) Howard.

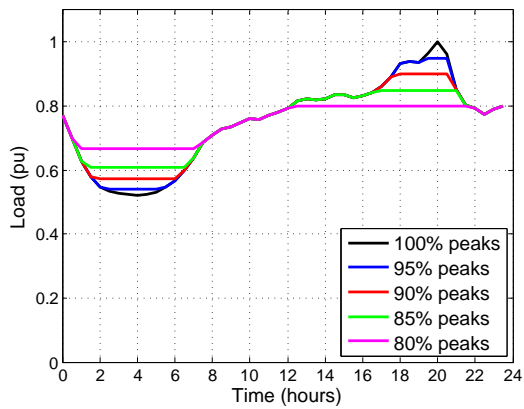
Figure 7.7: Results of application of the DSM simulator to **actual** load profiles (first six).



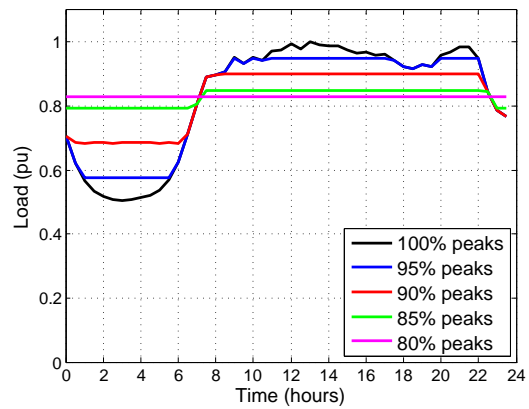
(a) Mackay.



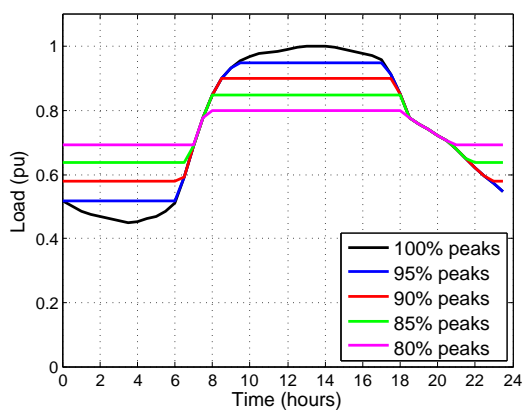
(b) Maryborough.



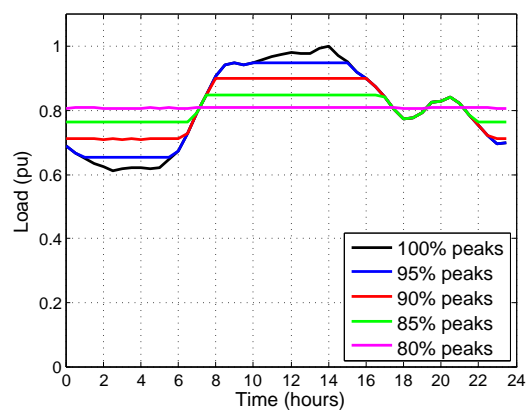
(c) Rockhampton.



(d) Toowoomba.



(e) Townsville Central.



(f) Townsville North.

Figure 7.8: Results of application of the DSM simulator to **actual** load profiles (second six).

7.5 Chapter Summary

This chapter has described the formation of a set of load profiles to be provided as inputs to the cyclic rating calculator. The project achievements discussed in this chapter were:

- Specification of an original load profile set containing a square wave profile, three industry standard profiles & 12 actual Ergon Energy profiles from the transformers selected in section 6.3.
- Design & construction of a load shifting DSM simulation program using MATLAB.
- Application of the DSM simulator to the original load profile set to generate five DSM modified versions of each load profile type (including the unmodified profile) thereby creating a set of 80 profiles for use in the sensitivity analysis.

These achievements were sufficient to meet objective (8) of the project (refer to section 1.4). At the conclusion of this chapter, the foundation from which the sensitivity analysis could be launched was complete.

Chapter 8

Sensitivity Analysis

8.1 Chapter Overview

This penultimate chapter aims to answer the question underpinning the entire project: *what is the effect of DSM variations in load profile on the cyclic ratings of power transformers ?* Previous chapters have detailed the foundations prepared for this purpose. Chapter 2 presented the essential theory of transformer thermal modelling and cyclic rating calculation. Chapters 4 & 5 detailed the implementation of thermal models in MATLAB, their subsequent evaluation and the selection of the AS 60076.7 exponential equation model for further use. Chapter 6 focused on the design and construction of a full AS 60076.7 compliant transformer cyclic rating calculator based on the chosen thermal model and the selection of 12 transformers from the Ergon Energy fleet as inputs to the calculator. Finally, chapter 7 was devoted to the selection of a set of load profiles and their modification to simulate load shifting DSM using a MATLAB implemented algorithm. These profiles were the final required input for the cyclic rating calculator.

In this chapter, a simplified analytical solution to the AS 60076.7 top oil differential equation is initially presented. This was performed in order to formulate a hypothesis regarding the effect of DSM variations in load profiles on cyclic ratings. Following this, the results of execution of the cyclic rating calculator for every input combination of transformer, cooling mode and load profile (600 different cyclic ratings) are illustrated and analysed.

8.2 Analytical solution of simplified model

Before the cyclic rating calculator was employed to generate ratings based on DSM modified input load profiles, it was essential to formulate a hypothesis predicting the influence of a flattening load profile on a given cyclic rating. To support this prediction, a simplified solution to the AS 60076.7 top oil differential equation (2.60) was derived and its response to a series of progressively flattening load profile inputs was determined. By analysing the output top oil temperature profiles, it was possible to predict the impact on the cyclic rating calculation process.

8.2.1 Derivation

The differential equation describing the top oil temperature as defined by Standards Australia (2013b) is:

$$\left[\frac{1 + RK^2}{1 + R} \right]^x \cdot \Delta\theta_{or} = k_{11}\tau_o \cdot \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (2.60 \text{ repeated})$$

To permit simple solution by hand, this equation can be linearised by assuming that the transformer cooling mode is OFXX or ODXX since in any of these cases, $x = 1$ and $k_{11} = 1$ (refer to table 2.7). Thus equation (2.60) becomes:

$$\left[\frac{1 + RK^2}{1 + R} \right] \cdot \Delta\theta_{or} = \tau_o \cdot \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (8.1)$$

Rearranged, equation (8.1) becomes:

$$\frac{d\theta_o}{dt} + \frac{\theta_o}{\tau_o} = \frac{1}{\tau_o} \left(\theta_a + \frac{1 + RK^2}{1 + R} \Delta\theta_{or} \right) \quad (8.2)$$

Now let the load profile $S(t)$ supplied by the transformer be a periodic function consisting of two loading periods (1 & 2) with step transitions and repeated every T seconds according to:

$$S(t) = \begin{cases} 2 - s, & \text{for } 0 \leq t \leq t_{12} \\ s, & \text{for } t_{12} \leq t \leq T \end{cases} \quad (8.3)$$

where: $S(t)$ is the per unit load;

T is the period; &

s is a smoothing factor, where $0 \leq s \leq 1$.

This load profile is displayed in figure 8.1. If the smoothing factor s in equation (8.3) is equal to zero, then the peak of S is 2 pu and the trough is 0 pu. However, if s is increased to its maximum value of 1, then the load profile is perfectly flat at 1 pu. In this way, load shifting DSM can be easily simulated by changing s .

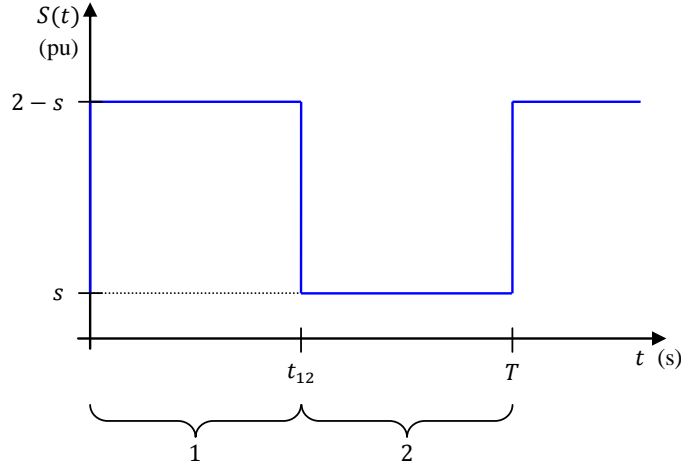


Figure 8.1: Simple periodic load profile used in the analytical solution.

Let the period from $0 \leq t \leq t_{12}$ be denoted by subscript $_1$ and the period from $t_{12} \leq t \leq T$ be denoted by subscript $_2$.

Now simplify part of equation (8.2) as follows:

$$\theta_a + \frac{1 + RK^2}{1 + R} \Delta\theta_{or} = I(t) \quad (8.4)$$

where: $I(t)$ is an input function defined as follows:

For $0 \leq t \leq t_{12}$:

$$I(t) = I_1 = \theta_a + \frac{1 + R(2-s)^2}{1 + R} \Delta\theta_{or} \quad (8.5)$$

For $t_{12} \leq t \leq T$:

$$I(t) = I_2 = \theta_a + \frac{1 + Rs^2}{1 + R} \Delta\theta_{or} \quad (8.6)$$

Equation (8.2) can then be rewritten as two equations – one for each loading period – using equations (8.5) & (8.6):

$$\frac{d\theta_{o1}}{dt} + \frac{\theta_{o1}}{\tau_o} = \frac{I_1}{\tau_o} \quad (8.7)$$

$$\frac{d\theta_{o2}}{dt} + \frac{\theta_{o2}}{\tau_o} = \frac{I_2}{\tau_o} \quad (8.8)$$

Equations (8.7) & (8.8) are in the general form of standard first order linear ordinary differential equations. The solution of this type of equation consists of the sum of **transient** and **steady-state** parts.

For loading period 1, the solution of equation (8.7) by inspection is:

$$\theta_{o1}(t) = \underbrace{\theta_o(0)e^{-t/\tau_o}}_{\text{transient}} + \underbrace{I_1 \left(1 - e^{-t/\tau_o}\right)}_{\text{steady-state}} \quad (8.9)$$

For loading period 2, the solution of equation (8.8) by inspection is:

$$\theta_{o2}(t) = \underbrace{\theta_o(t_{12})e^{-(t-t_{12})/\tau_o}}_{\text{transient}} + \underbrace{I_2 \left(1 - e^{-(t-t_{12})/\tau_o}\right)}_{\text{steady-state}} \quad (8.10)$$

Now, $\theta_{o1}(0)$ must be equal to $\theta_{o2}(T)$ since the loading of the transformer is cyclic and the final temperature of one cycle equals the initial temperature of the next. Therefore, substituting $t = 0$ into equation (8.9) and $t = T$ into equation (8.10) and equating the results yields:

$$\begin{aligned} \theta_o(0)e^{-0/\tau_o} + I_1 \left(1 - e^{-0/\tau_o}\right) &= \theta_o(t_{12})e^{-(T-t_{12})/\tau_o} + I_2 \left(1 - e^{-(T-t_{12})/\tau_o}\right) \\ \therefore \theta_o(0) &= \theta_o(t_{12})e^{-(T-t_{12})/\tau_o} + I_2 \left(1 - e^{-(T-t_{12})/\tau_o}\right) \end{aligned} \quad (8.11)$$

Also, $\theta_{o1}(t_{12})$ must be equal to $\theta_{o2}(t_{12})$ since they are the same top oil temperature merely represented in different equations. Substituting $t = t_{12}$ into both equations (8.9) & (8.10) yields:

$$\begin{aligned} \theta_o(0)e^{-t_{12}/\tau_o} + I_1 \left(1 - e^{-t_{12}/\tau_o}\right) &= \theta_o(t_{12})e^{-(t_{12}-t_{12})/\tau_o} + I_2 \left(1 - e^{-(t_{12}-t_{12})/\tau_o}\right) \\ \therefore \theta_o(t_{12}) &= \theta_o(0)e^{-t_{12}/\tau_o} + I_1 \left(1 - e^{-t_{12}/\tau_o}\right) \end{aligned} \quad (8.12)$$

Now substitute equation (8.12) into equation (8.11):

$$\begin{aligned} \theta_o(0) &= \left[\theta_o(0)e^{-t_{12}/\tau_o} + I_1 \left(1 - e^{-t_{12}/\tau_o}\right) \right] e^{-(T-t_{12})/\tau_o} + I_2 \left(1 - e^{-(T-t_{12})/\tau_o}\right) \\ \theta_o(0) &= \theta_o(0)e^{-T/\tau_o} + I_1 \left(1 - e^{-t_{12}/\tau_o}\right) e^{-(T-t_{12})/\tau_o} + I_2 - I_2 e^{-(T-t_{12})/\tau_o} \\ \theta_o(0) \left(1 - e^{-T/\tau_o}\right) &= e^{-(T-t_{12})/\tau_o} \left[I_1 \left(1 - e^{-t_{12}/\tau_o}\right) - I_2 \right] + I_2 \end{aligned}$$

$$\therefore \theta_o(0) = \frac{I_2 + [I_1 (1 - e^{-t_{12}/\tau_o}) - I_2] e^{-(T-t_{12})/\tau_o}}{1 - e^{-T/\tau_o}} \quad (8.13)$$

Now substitute equation (8.13) into equation (8.12):

$$\theta_o(t_{12}) = \left[\frac{I_2 + [I_1 (1 - e^{-t_{12}/\tau_o}) - I_2] e^{-(T-t_{12})/\tau_o}}{1 - e^{-T/\tau_o}} \right] e^{-t_{12}/\tau_o} + I_1 (1 - e^{-t_{12}/\tau_o})$$

$$\therefore \theta_o(t_{12}) = \frac{I_2 e^{-t_{12}/\tau_o} + [I_1 (1 - e^{-t_{12}/\tau_o}) - I_2] e^{-T/\tau_o}}{1 - e^{-T/\tau_o}} + I_1 (1 - e^{-t_{12}/\tau_o}) \quad (8.14)$$

Finally, substituting equations (8.13) & (8.14) into equations (8.9) & (8.10) respectively, yields the explicit solutions to the top oil differential equation for the two loading periods:

$$\theta_{o1}(t) = \left[\frac{I_2 + [I_1 (1 - e^{-t_{12}/\tau_o}) - I_2] e^{-(T-t_{12})/\tau_o}}{1 - e^{-T/\tau_o}} \right] e^{-t/\tau_o} + I_1 (1 - e^{-t/\tau_o})$$

for $0 \leq t \leq t_{12}$ (8.15)

$$\theta_{o2}(t) = \left[\frac{I_2 e^{-t_{12}/\tau_o} + [I_1 (1 - e^{-t_{12}/\tau_o}) - I_2] e^{-T/\tau_o}}{1 - e^{-T/\tau_o}} + I_1 (1 - e^{-t_{12}/\tau_o}) \right] e^{-(t-t_{12})/\tau_o}$$

+ $I_2 (1 - e^{-(t-t_{12})/\tau_o})$ for $t_{12} \leq t \leq T$ (8.16)

8.2.2 Response to flattening load profiles

Equations (8.15) & (8.16) were implemented in MATLAB to enable calculation and graphing of the top oil temperature over the loading cycle for a number of different smoothing factors (s) and with variables set arbitrarily as per table 8.1. Figure 8.2 displays the load profiles provided as inputs. Note that the profiles are the result of smoothing factor s set to the values 0, 0.25, 0.5, 0.75 & 1 in equation (8.3). Figure 8.3 displays the top oil temperatures calculated for each of the load profiles. It can be seen from figure 8.3 that as the load profile flattens (i.e. as s increases to 1), the top oil

Table 8.1: Variables for the MATLAB implementation of the simplified analytical solution.

Variable	Value
t	0:86400 s (0:24 h)
T	86400 s (24 h)
t_{12}	43200 s (12 h)
τ_o	9000 s (150 min)
θ_a	25 °C
$\Delta\theta_{or}$	38 °C
R	6.67
s	0; 0.25; 0.5; 0.75 & 1

temperature profile also flattens. That is, the maximum temperature reduces and the minimum temperature increases until in the limit, when the load profile is flat ($s = 1$), the temperature profile also becomes flat. When $s = 1$, the load is a constant 1 pu and the top oil temperature is a constant 63 °C. At constant 1 pu loading, the transformer is supplying its nameplate rating and therefore it is not surprising that the 63 °C top oil temperature is the sum of the rated top oil temperature rise from the HRT data ($\Delta\theta_{or} = 38^\circ\text{C}$) and the ambient temperature ($\theta_a = 25^\circ\text{C}$). This result suggests that in the limit, as a load profile flattens, the cyclic rating approaches the nameplate rating. In other words, CRFs decrease as load profiles flatten. This conclusion depends however on the WHS temperatures and insulation ageing rates following a similar trend.

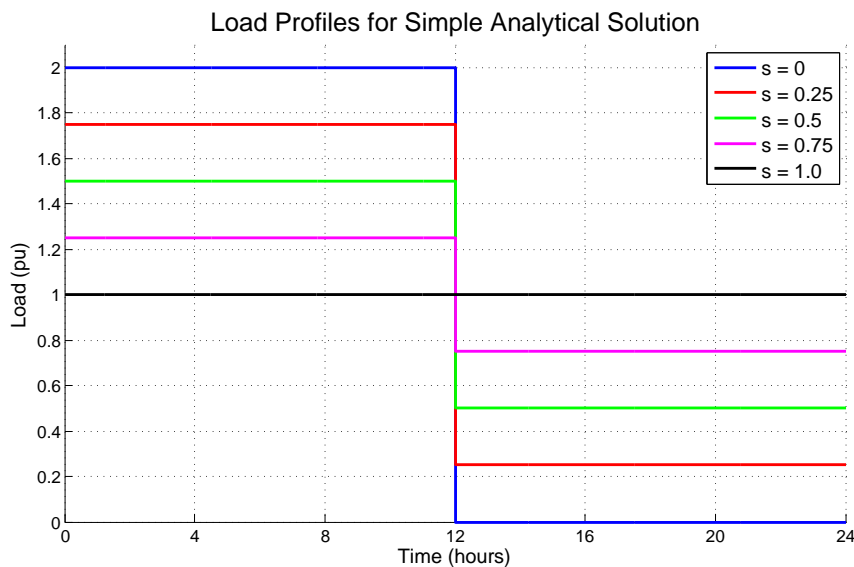


Figure 8.2: The five load profiles employed in the simplified analytical solution.

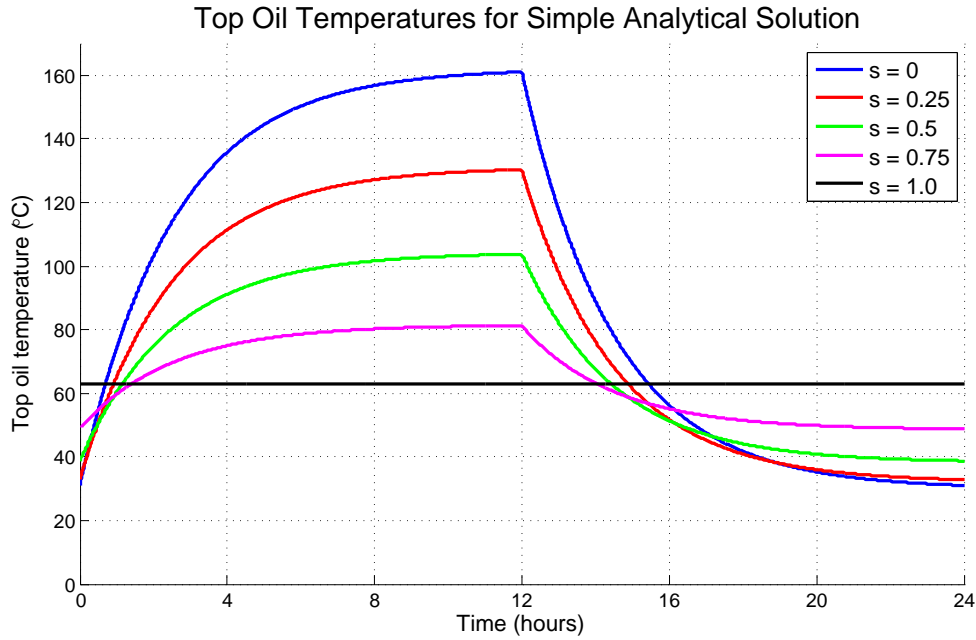


Figure 8.3: Top oil temperatures for each load profile of the simplified analytical solution.

8.3 Generation of Cyclic Ratings

The analytical solution of the simplified AS 60076.7 top oil thermal model justified formulation of the following hypothesis: **the cyclic ratings of power transformers decrease as load shifting DSM causes load profiles to flatten.**

To test this hypothesis, the cyclic rating calculator was executed to generate a large number of cyclic ratings for the 12 selected transformers supplying load profiles which exhibited a range of levels of DSM modification. The 12 selected transformers and their associated cooling modes are displayed in table F.1. Some transformers possess three different cooling modes while others possess only one. A cyclic rating was calculated for every combination of transformer, available cooling mode and relevant load profile (for detail, refer to section 6.2). The load profiles used with every transformer-cooling mode combination were as follows:

1. Square \times 5 – original (100%) plus four DSM versions (95%, 90%, 85% & 80%);
2. Standard residential \times 5 (100%, 95%, 90%, 85% & 80%);
3. Standard industrial \times 5 (100%, 95%, 90%, 85% & 80%);

4. Standard mixed $\times 5$ (100%, 95%, 90%, 85% & 80%); &
5. Actual profile relevant to the transformer $\times 5$ (100%, 95%, 90%, 85% & 80%).

This is a total of 25 profiles (and thus 25 cyclic ratings) for each combination of transformer and cooling mode. As an example, 50 cyclic ratings were calculated for the Toowoomba transformer: 25 for ONAN cooling; 25 for ONAF cooling with each set of 25 consisting of five each of square, residential, industrial, mixed and actual Toowoomba profiles. Following this pattern, the cyclic rating calculator generated 600 different cyclic ratings which were then analysed.

8.4 Results & Analysis

The output from the cyclic rating calculator was a matrix of 600 cyclic ratings and associated quantities which is displayed as table I.1 in Appendix I. This section presents the results of an extensive analysis of the output data which was undertaken with a view towards establishing and quantifying the relationship between load profile changes and cyclic ratings.

8.4.1 Example output

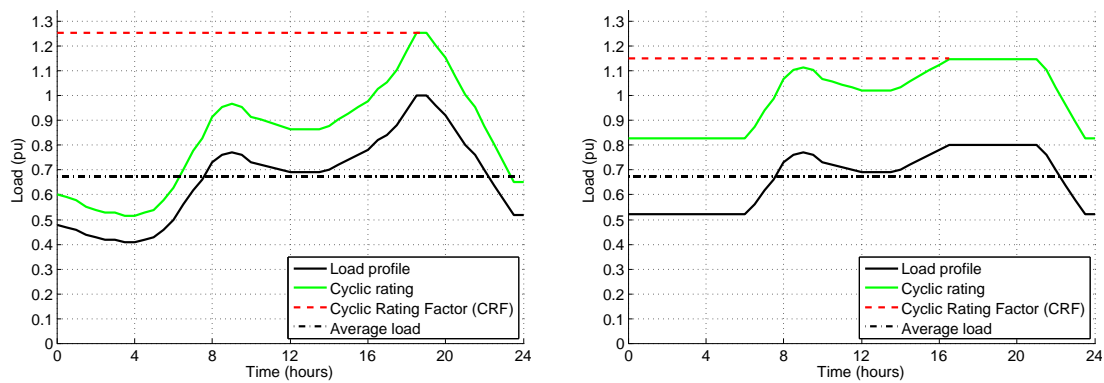
An example of the output from the cyclic rating calculator is initially analysed. Table 8.2 displays the results for the Toowoomba transformer on ONAN cooling, supplying the standard residential load profile. Each row of table 8.2 corresponds to one of the peak percentages associated with the different levels of DSM (i.e. 100%, 95%, 90%, 85% & 80%). This is reflected in the “peak load” column which displays the peak loads decreasing from 1.0 pu to 0.8 pu. In other words, the standard residential load profile progressively flattens from row one to five. The averages of the five DSM modified profiles are equal at 0.67 pu which was expected since the definition of load shifting DSM specifies that the average load is not changed (refer to section 2.3). Importantly, these results are in agreement with those of the analytical solution displayed in figure 8.3. That is, as the load profile progressively flattens, the minimum top oil temperature increases and the maximum top oil temperature decreases (apart from a minor increase from the 100% to the 95% profile). The minimum and maximum WHS temperatures

follow the same trend. As predicted using the analytical solution of section 8.2.2, progressive flattening of the load profile causes a decrease in CRF. The hypothesis based on the analytical solution therefore appears valid at least for the Toowoomba transformer.

Table 8.2: Example output from the cyclic rating calculator.

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Toow	ONAN	Res_100	1.00	0.67	0.67	45.26	89.21	55.66	119.99	1.257	19.41	WHS
Toow	ONAN	Res_95	0.95	0.67	0.71	46.63	89.65	57.74	119.99	1.232	22.90	WHS
Toow	ONAN	Res_90	0.90	0.67	0.75	48.68	88.71	61.09	118.24	1.206	24.00	Age
Toow	ONAN	Res_85	0.85	0.67	0.79	51.69	86.87	65.64	115.49	1.178	24.00	Age
Toow	ONAN	Res_80	0.80	0.67	0.84	55.68	84.75	71.56	112.49	1.150	24.00	Age

Figure 8.4 displays the cyclic ratings calculated for the Toowoomba transformer graphically. Figure 8.4a shows the rating calculated for the original unmodified load profile while figure 8.4b shows the rating calculated for the DSM modified profile where the peak has been reduced to 80%. It can be seen that the average values of the two profiles are the same and yet the cyclic ratings are significantly different. For the unmodified profile, the CRF is 1.257 pu while for the 80% peak profile, this has reduced to 1.150 pu. The nameplate rating of the Toowoomba transformer on ONAN cooling is 30 MVA. Thus for the unmodified profile, the peak cyclic capacity of the transformer is 37.71 MVA while for the 80% peak profile, the peak cyclic capacity is 34.50 MVA. A loss of 3.21 MVA in peak cyclic capacity has therefore been caused by flattening of the load profile. Alternatively, a reduction in peak load of 20% (with a fixed average) has caused an 8.51% reduction in CRF.



(a) Rating for original profile.

(b) Rating for 80% peak DSM profile.

Figure 8.4: Cyclic ratings calculated for the Toowoomba transformer on ONAN cooling, supplying the standard residential load profile.

8.4.2 Percentage change analysis

The foregoing analysis applied only to a single combination of transformer, cooling mode and load profile. A more structured and extensive analysis of the 600 calculated ratings was required to confirm the trend revealed and to quantify the relationship. It was decided that the most appropriate manner in which to accomplish this was by computing *percentage changes* in a range of input and output variables for the progressive DSM flattening of each load profile (from 100% peaks to 80% peaks) such that the outputs for all transformers could be compared on a common basis. Percentage changes were calculated for the following variables:

- CRF
- Peak load
- Load factor
- Average load
- Minimum top oil temperature
- Maximum top oil temperature
- Minimum WHS temperature
- Maximum WHS temperature
- Insulation ageing

Percentage changes were calculated such that a positive value indicates an increase and a negative value indicates a decrease. For example a -5% change in CRF means that it was reduced by 5%. Change in CRF is the variable of greatest interest since it describes a cyclic rating. As such, percentage changes in CRF were compared against percentage changes in the other variables. These comparisons are plotted and discussed in the following sections. It is important to note that each data point on the plots which follow represents one cyclic rating determined by the cyclic rating calculator for a single combination of transformer, cooling mode and load profile.

Change in CRF with change in peak load

Figure 8.5 is a scatter plot of the percentage changes in CRF with percentage changes in peak load as a result of load shifting DSM. It can be seen there are five main groups of data points aligned at changes in peak load of 0%, -5%, -10%, -15% & -20%, corresponding to the original load profiles (100% peaks) and the DSM profiles with peak loads reduced to 95%, 90%, 85% & 80%. The data points between these groups are the result of the DSM simulator increasing the relevant profile above the specified DSM peak in order to maintain a constant average (refer to section 7.3). There are no positive changes in CRF; that is, as load profiles flattened, cyclic ratings decreased *without exception*. This is in agreement with the stated hypothesis of section 8.2.2. CRF changes range from 0% to -13.5%. Given this wide range, it was beneficial to classify the data points according to transformer **location**; **size**; & **cooling mode**.

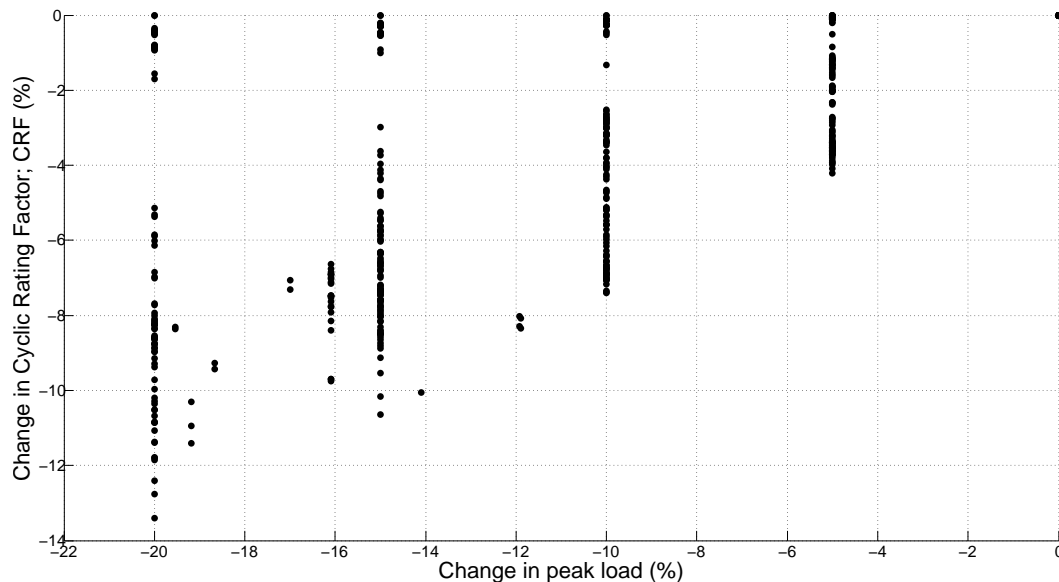


Figure 8.5: Changes in CRF with changes in peak load.

Location: Figure 8.6 displays the changes in CRF against changes in peak load with the data points coloured according to the transformer location: Northern, Central or Southern. Table 6.4 provides the locations for the 12 selected transformers. At the lower values of peak load reduction, there is an even representation of locations across the data points. At the higher values of peak load reduction, the Northern and Central transformers experience the largest decreases in CRF. This can be explained by the higher ambient temperatures in these locations (refer to table F.1) which result in smaller permissible temperature rises and greater insulation ageing for the same temperature rises.

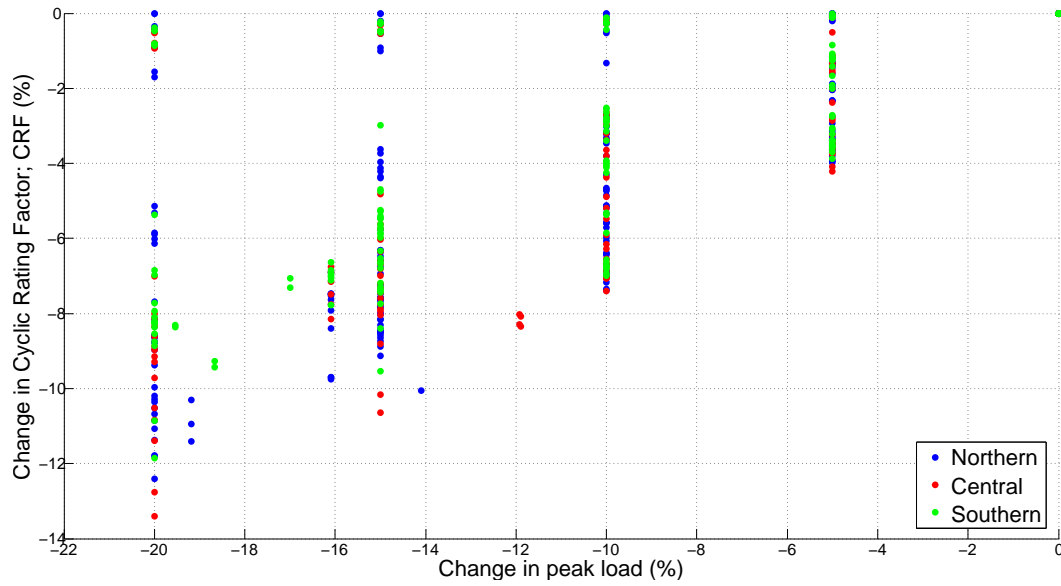


Figure 8.6: Changes in CRF with changes in peak load by transformer location.

Size: Figure 8.7 displays the same scatter plot but with the data points coloured according to transformer size or nameplate rating. The classifications are: small (up to 10 MVA); medium (from 10 MVA up to 50 MVA); & large (above 50 MVA). Nameplate ratings for the selected transformers are given in table 6.4. At the lower values of peak load reduction, there exists an even distribution of sizes across the range of CRF changes. At the higher values of peak load reduction, the greatest decreases in CRF correspond to the smaller transformers. This is due to the fact that smaller transformers have less mass and hence lower thermal inertia. This causes greater sensitivity to changes in loading compared to a large transformer which can simply absorb the change.

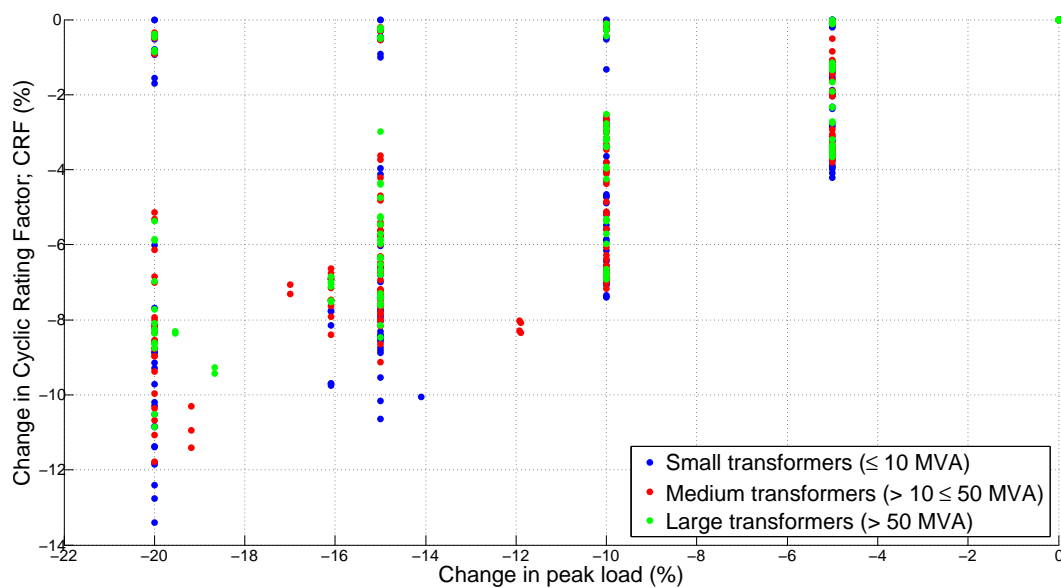


Figure 8.7: Changes in CRF with changes in peak load by transformer size.

Cooling mode: In figure 8.8, the data points are organised by transformer cooling mode (ONAN, ONAF, ODAN & ODAF). Again, there exists an even distribution of the classes across the range of CRF changes for lower values of peak load reduction. At higher values of peak load reduction, transformers using less effective cooling modes (ONAN & ONAF) experience the greatest decreases in CRF. This is because transformers using more effective cooling (ODAN & ODAF), where the oil is pumped through and/or air is forced across the radiators, are less sensitive to changes in loading because they are capable of dissipating heat more readily and operating further from cyclic rating limits. The opposite is true for the less effective cooling modes.

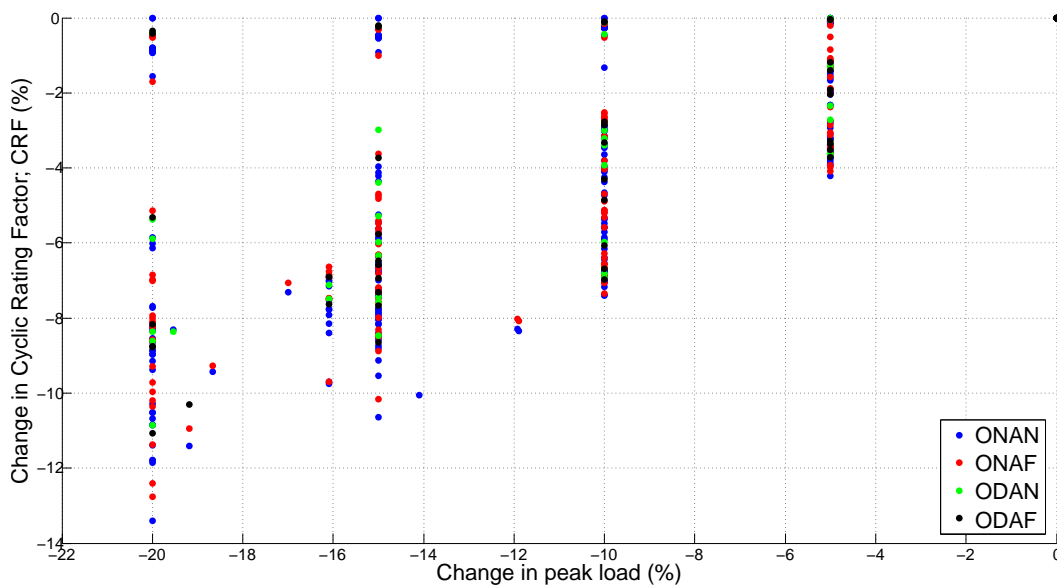


Figure 8.8: Changes in CRF with changes in peak load by transformer cooling mode.

Change in CRF with change in load factor

Load factor is defined as the ratio of the average to the peak load. By definition (refer to section 2.3), load shifting DSM flattens load profiles without altering the average load and therefore causes the load factor to increase towards a maximum value of unity.

Figure 8.9 displays a plot of the percentage changes in CRF with percentage change in load factor. Note that the positive percentage changes in load factor represent flattening of the load profile as peak load approaches average load. Figure 8.9 reveals a consistent trend: as load profiles flatten, cyclic ratings decrease. Figure 8.9 also confirms that the percentage change in CRF ranges from 0% to 13.5% with changes in load factor from 0% to 25.5%.

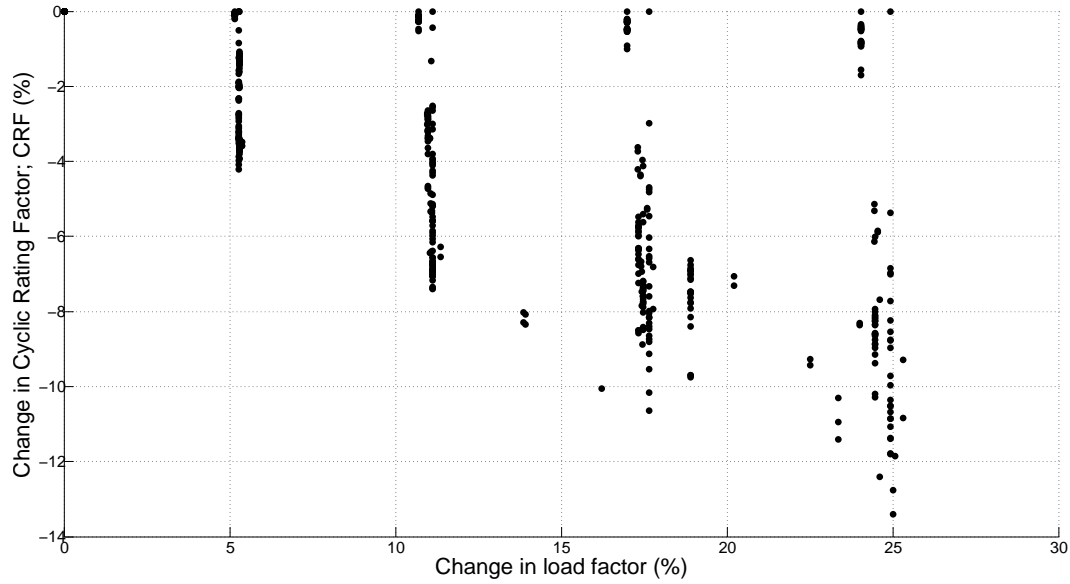


Figure 8.9: Changes in CRF with changes in load factor.

It was again of interest to identify the data points of figure 8.9 in order to reveal any underlying trends. Figures 8.10, 8.11 & 8.12 display change in CRF against change in load factor with data points classified according to transformer **location**, **size** and **cooling mode** respectively. These plots confirm that at greater values of load profile flattening (here indicated by an increasing percentage change in load factor) it is the more Northern transformers &/or the smaller transformers &/or the transformers with less effective cooling modes which experience the greatest reductions in CRF and hence cyclic rating. The reasons for this were explained in section 8.4.2.

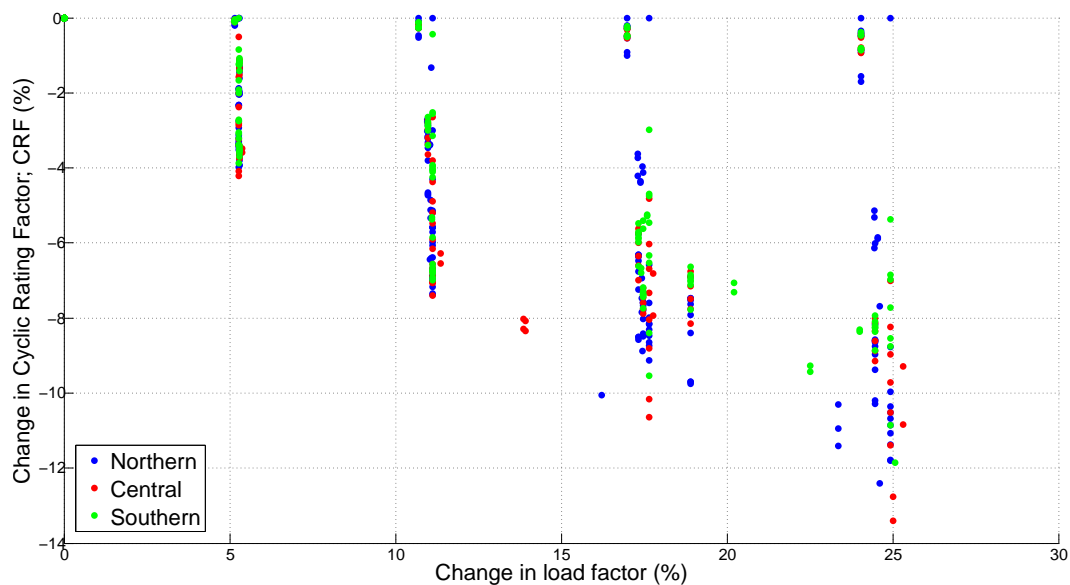


Figure 8.10: Changes in CRF with changes in load factor by transformer location.

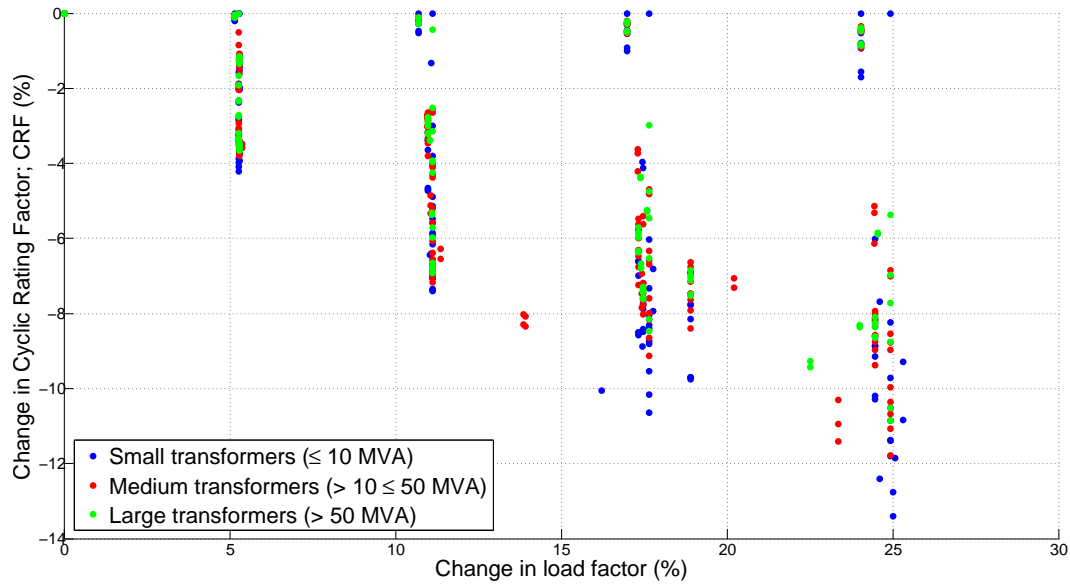


Figure 8.11: Changes in CRF with changes in load factor by transformer size.

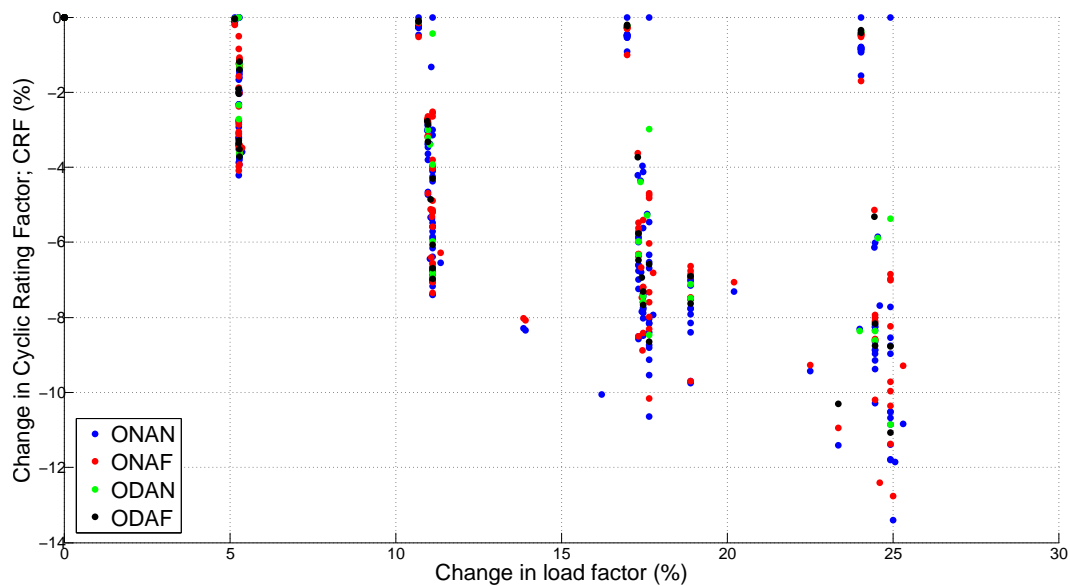


Figure 8.12: Changes in CRF with changes in load factor by transformer cooling mode.

Change in CRF with change in average load

Figure 8.13 displays a scatter plot of percentage change in CRF with percentage change in average load. It can be seen that the changes in average load are centred around 0% with no changes above 0.4% or below -0.8% . This was expected because the load shifting DSM algorithm ensured that all peak load removed from a profile was added to the troughs, thereby maintaining the average value (refer to section 7.3). The large range of CRF changes despite relatively constant averages suggests that the average of

a load profile has no influence on a cyclic rating. The non-zero percentage changes in average load which exist are due to the removed peak load being added to the troughs in discrete increments. This error could be reduced by using a smaller load addition increment however this could only occur at the expense of computation time which was already significant for the current increment value.

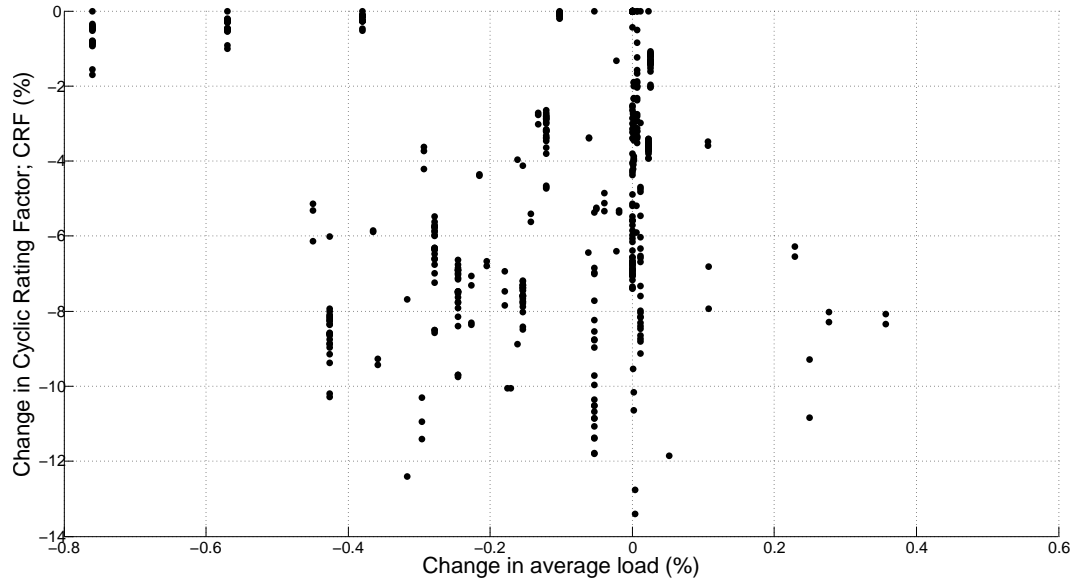


Figure 8.13: Changes in CRF with changes in average load.

Change in CRF with change in top oil & WHS temperature

Figures 8.14 & 8.15 display plots of the percentage change in CRF with percentage change in maximum and minimum top oil temperatures respectively. It has already been demonstrated that as load profiles flatten, CRFs decrease. Thus it can be seen that in general, as load profiles flatten (as CRFs reduce), the maximum top oil temperature reduces while the minimum top oil temperature increases. These trends are in agreement with the analytical solution of section 8.2.2, where in figure 8.3 it was shown that the top oil temperature profile flattened with a lowering maximum and an increasing minimum as the load profile flattened.

Figures 8.16 & 8.17 display plots of the percentage change in CRF with percentage change in maximum and minimum WHS temperatures. The results are consistent with those of the top oil temperature changes (figures 8.14 & 8.15) with maximum WHS temperatures reducing and minimum WHS temperatures increasing as load profiles flatten and cause reductions in CRF.

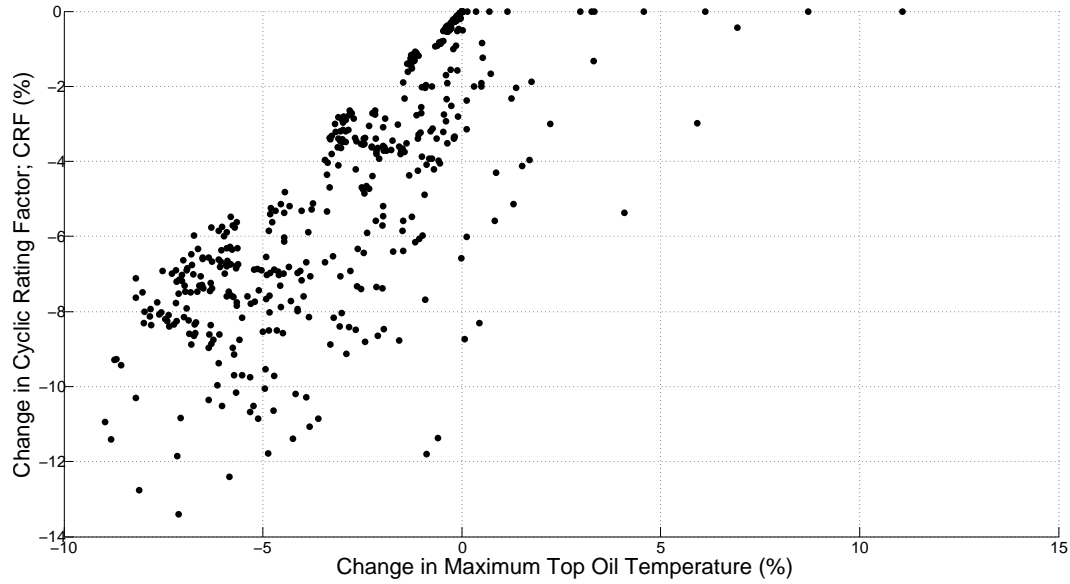


Figure 8.14: Changes in CRF with changes in maximum top oil temperature.

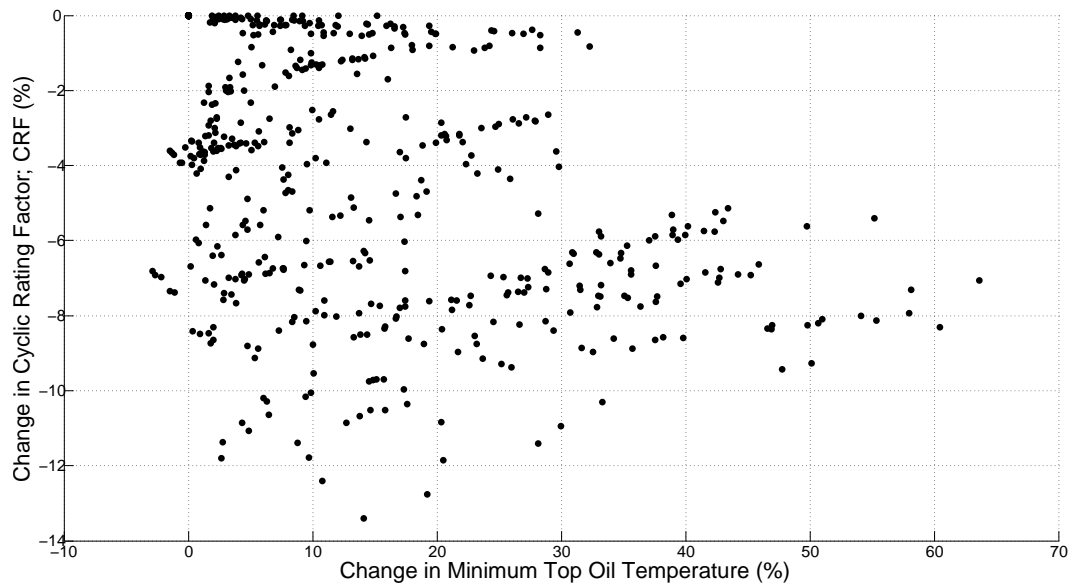


Figure 8.15: Changes in CRF with changes in minimum top oil temperature.

It is also observable for both sets of temperature plots that the changes in minimum temperature are more widely distributed over a larger range of percentages than the changes in maximum temperature. Therefore, load shifting DSM appears to have a greater impact on the lower temperatures in a cycle than on the higher temperatures. This effect most likely contributes to the CRF reductions with flattening load profiles by limiting the transformer cooling which can occur during load troughs and which is significant for highly peaky (i.e. low load factor) profiles.

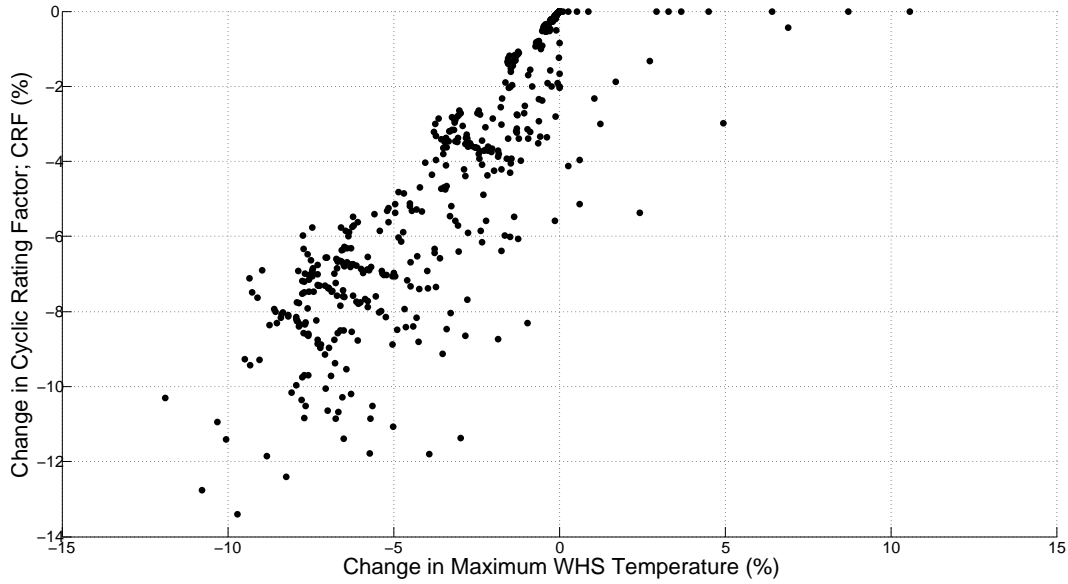


Figure 8.16: Changes in CRF with changes in maximum WHS temperature.

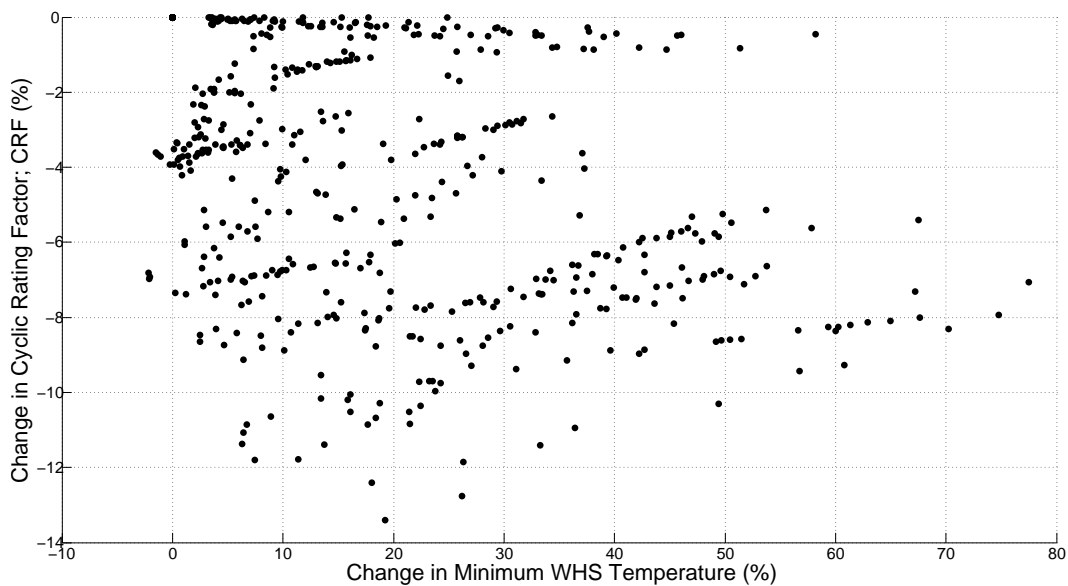


Figure 8.17: Changes in CRF with changes in minimum WHS temperature.

Change in CRF with change in insulation ageing

The percentage changes in CRF are plotted against the percentage changes in total insulation ageing in figure 8.18. It can be seen that despite the changes in load profile, there are very few changes in insulation ageing. This is reflected in the results contained within Appendix I where it can be seen that the majority of insulation ageing values are approximately 24 h/day (hence the reason why the ageing limit is the most common limit reached). Where changes in ageing occur, they are always increases and are

therefore not desirable. Some very significant insulation ageing increases in excess of 100% exist. These results suggest that load shifting DSM can cause significantly increased ageing and therefore reduced transformer life. Consequently, it is important to assess this risk when applying cyclic ratings.

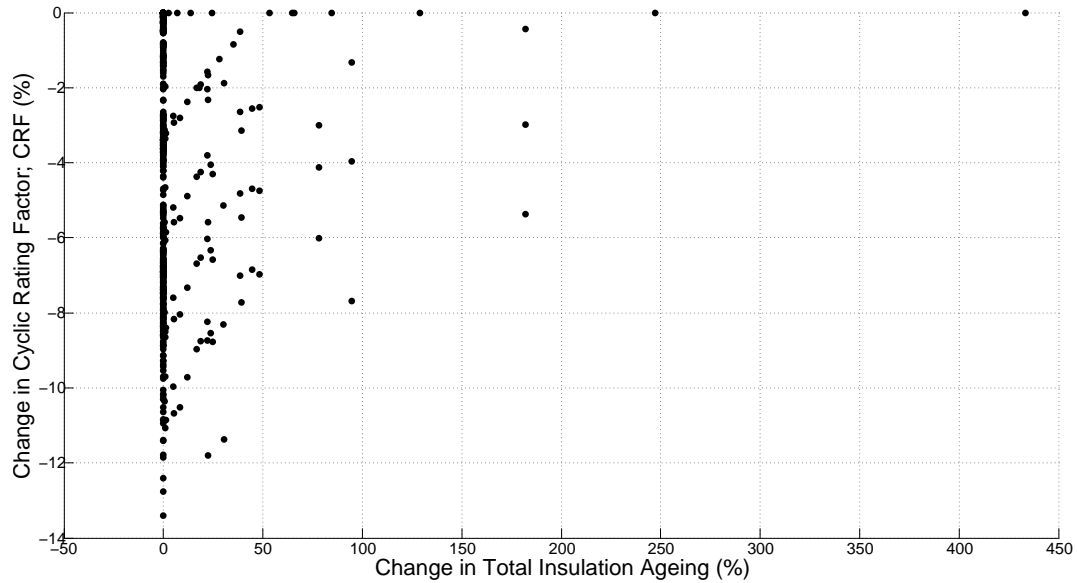


Figure 8.18: Changes in CRF with changes in insulation ageing.

8.5 Predicting Changes in Cyclic Ratings

From the results of section 8.4, it is clear that cyclic ratings are negatively affected by load shifting DSM. It is therefore of great value to a utility plant rating engineer to be capable of predicting the impact on the cyclic capacity of transformers given an actual or targeted change in load profile. Within a utility, different workgroups are usually responsible for plant ratings and DSM programs. Enabling plant rating engineers to predict changes in cyclic capacity will enhance communication between these groups and contribute to the prevention of deleterious operational or financial events.

8.5.1 Regression models

The prediction of cyclic rating changes is best carried out on the basis of a given change in peak load or load factor (assuming load shifting DSM). To achieve this, regression models for the presented data were developed. Prior to this, some preparation of the data was required.

Data preparation

In figures 8.5 to 8.8, which simply contain different representations of the same data, there exists a band of data points diverging from the origin to a range of CRF changes from approximately 5% to 13.5% at a peak load change of -20% . This band is marked on figure 8.19. A corresponding band also exists on the CRF change with change in load factor plots (figures 8.9 to 8.12). Above the band (on either set of plots) is a number of data points which correspond to only small changes in CRF with flattening load profile. An investigation to locate the source of these data points revealed that they correspond to all cyclic ratings calculated using square profiles and the ratings calculated for the Cloncurry transformer on ONAN cooling, supplying the standard residential load profile.

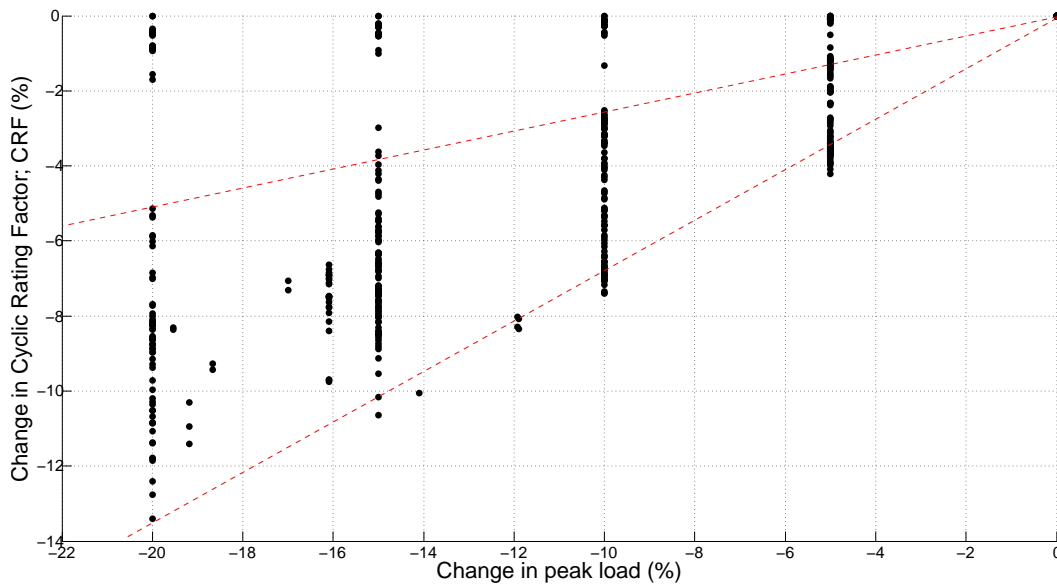


Figure 8.19: Plot of change in CRF against change in peak load with useful band of data points marked (dashed lines).

While it was shown in section 7.2.1 that a square-like load profile exists for a transformer of the Ergon Energy fleet, this type of load profile is extremely rare and therefore should not contribute to the regression models for prediction of cyclic rating changes.

Table 8.3 displays the output from the cyclic rating calculator for the Cloncurry transformer on ONAN cooling, supplying the standard residential load profile. Unusually, it can be seen that despite flattening of the load profile, the CRF remains unchanged at approximately 1.5 pu (the limit for the CRF). As would be expected, the minimum

top oil and WHS temperatures increase as the load profile flattens, however the maximum top oil and WHS temperatures also increase. For the original load profile, the insulation ageing is very low (only 4 h/day) which suggests that if supplying this profile, the Cloncurry transformer would be operating very much below capacity. As the load profile flattens, the ageing increases significantly but remains below the 24 h/day limit. This anomaly was originally thought to be due to input data errors, however the remainder of the Cloncurry ratings appear to follow the normal trend. The most likely explanation is that the Cloncurry transformer is particularly suited to the standard residential profile and could be loaded above 1.5 pu before any other rating limit would be reached. Regardless, this data is an exception to the trend and so was not considered in the derivation of the regression models.

Table 8.3: Portion of cyclic rating calculator output for Cloncurry.

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Clon	ONAN	Res_100	1.00	0.67	0.67	64.82	77.41	73.02	100.81	1.497	4.05	CRF
Clon	ONAN	Res_95	0.95	0.67	0.71	66.68	79.99	75.64	104.51	1.497	6.20	CRF
Clon	ONAN	Res_90	0.90	0.67	0.75	68.43	82.16	78.42	107.28	1.497	9.26	CRF
Clon	ONAN	Res_85	0.85	0.67	0.79	70.33	84.15	81.63	109.60	1.497	14.05	CRF
Clon	ONAN	Res_80	0.80	0.67	0.84	72.64	85.99	85.97	111.47	1.497	21.59	CRF

Regression models based on transformer location

Figures 8.20 & 8.21 display plots of percentage change in CRF against percentage changes in peak load and load factor respectively by transformer location without inclusion of the square profile and Cloncurry-ONAN-residential profile data. These plots have been fitted with regression curves to enable prediction of CRF change given a change in load profile (peak or load factor) based on location. The regression line equations are displayed in the plot legends. These lines do not pass through the origin and so are not valid for a 0% change in peak load or load factor since a 0% change in CRF is certain under those conditions. The regression lines confirm that the Northern and Central transformers experience the greatest reductions in CRF as load profiles flatten, however, Central Queensland transformers are marginally more sensitive than those from North Queensland. Although unexpected, this difference is very small. Sensitivity is proportional to the magnitude of the gradient of each regression line.

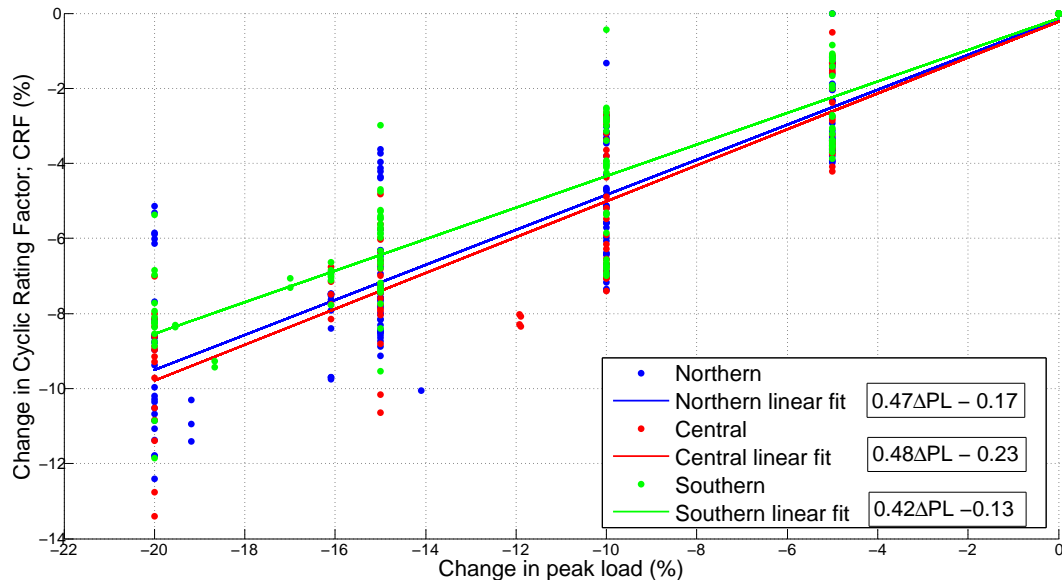


Figure 8.20: Changes in CRF with changes in peak load with by transformer location with regression models.

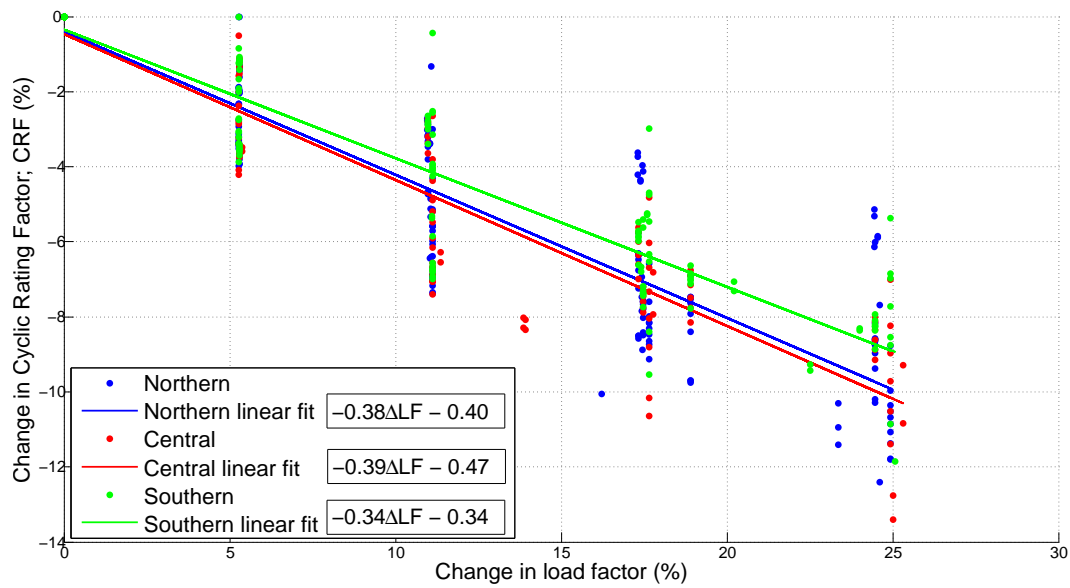


Figure 8.21: Changes in CRF with changes in load factor by transformer location with regression models.

Regression models based on transformer size

Figures 8.22 & 8.23 display plots of percentage change in CRF against percentage changes in peak load and load factor respectively by transformer size without inclusion of the square profile and Cloncurry-ONAN-residential profile data. The plots have again been fitted with linear regression models, confirming that as load profiles flatten (more negative peak load change or more positive load factor change), it is the smaller

transformers which suffer the greatest reductions in CRF. As expected, the next most sensitive are the medium transformers, with the larger transformers the least sensitive.

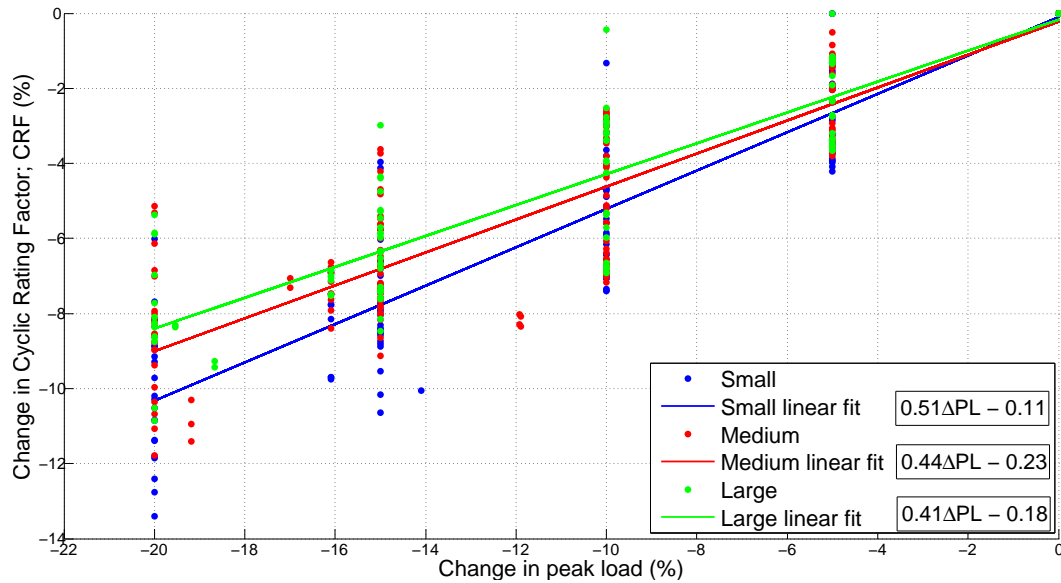


Figure 8.22: Changes in CRF with changes in peak load by transformer size with regression models.

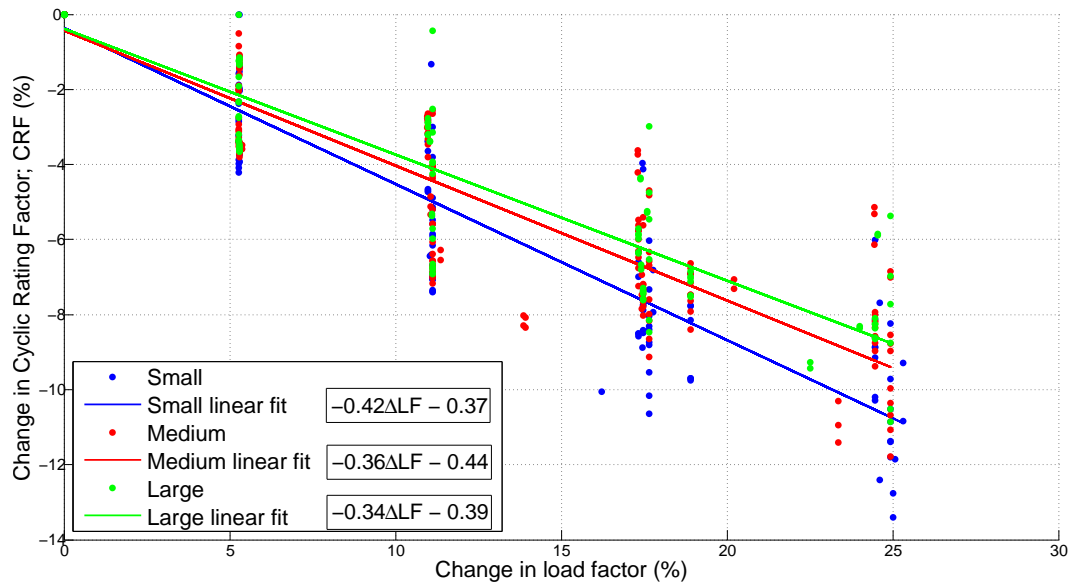


Figure 8.23: Changes in CRF with changes in load factor by transformer size with regression models.

Regression models based on transformer cooling mode

Figures 8.24 & 8.25 display plots of percentage change in CRF against percentage changes in peak load and load factor respectively by transformer cooling mode without

inclusion of the square profile and Cloncurry-ONAN-residential profile data. A final set of regression curves fitted to these plots confirms that the less effective cooling modes (ONAN & ONAF) experience the greatest reductions in CRF due to flattening of load profiles. Unexpectedly however, the most effective cooling mode – ODAF – is not the least sensitive to load profile changes. This is most likely due to the small number of transformers employing ODAF cooling in the sample and hence the relatively small number of data points.

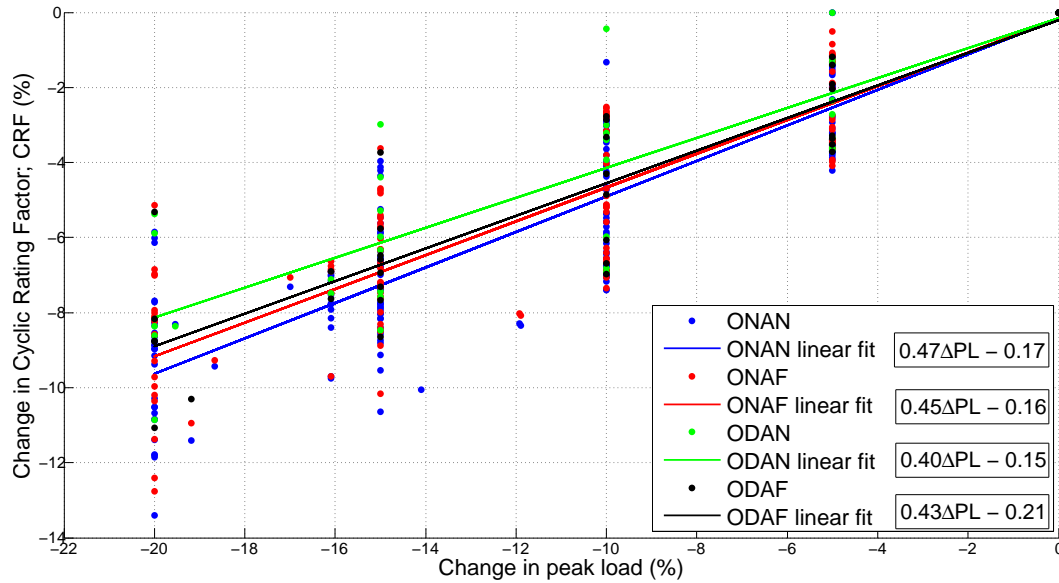


Figure 8.24: Changes in CRF with changes in peak load by transformer cooling mode with regression models.

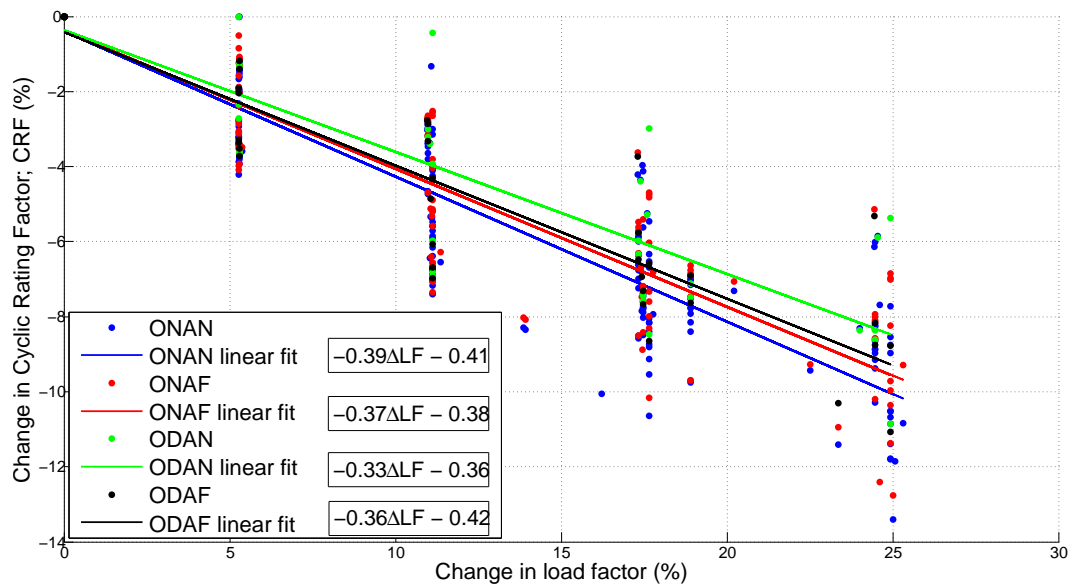


Figure 8.25: Changes in CRF with changes in load factor by transformer cooling mode with regression models.

8.5.2 Influencing factors

It has been shown during this analysis that cyclic ratings are indeed negatively affected by load profiles. It has also been shown that the amount by which a cyclic rating changes, given a particular change in load profile, is not simple to predict. A multitude of factors interact to influence the change in a cyclic rating. These include:

1. Transformer characteristics:

- (a) Size/nameplate rating
- (b) Volume of oil; mass of steel & copper
- (c) Surface area
- (d) Load & no-load losses
- (e) Leakage flux
- (f) Impedance
- (g) Age & condition

2. Installation location:

- (a) Ambient temperature
- (b) Solar radiation
- (c) Wind
- (d) Humidity

3. Cooling mode/s employed

4. Load profile characteristics:

- (a) Load factor
- (b) Average
- (c) Maximum & minimum
- (d) Changes caused by DSM

5. Cyclic rating limits:

- (a) Thermal, ageing & loading limits permitted
- (b) The limit reached during calculation of the rating

The complexity of the prediction is not surprising when it is recalled that at the heart of the cyclic rating calculator is a non-linear thermal model selected from a large number of models for which numerous papers have been written and much intellectual effort expended in pursuit of improvement. Additionally, the discrete nature of the cyclic rating calculation algorithm adds to the complexity. That is, as a load profile flattens, the CRF may decrease linearly but only while the rating limit reached is unchanged. If a different limit is reached, a step change in CRF may result. Given the four limits (top oil, WHS, CRF & ageing) it is difficult to predict which will be reached first and therefore what the calculated cyclic rating will be. Table 8.4 displays this effect occurring for the Maryborough transformer on ODAN cooling, supplying the standard residential profile. It can be seen that the CRF remains unchanged from the original profile to the 95% peak DSM profile with the CRF limit being reached (recall the CRF limit for large transformers is 1.3 pu; refer to table 2.5). The insulation ageing increases rapidly with these changes in load profile and for the 90% DSM profile, the ageing limit is reached. With further load flattening, the CRF reduces approximately linearly.

Table 8.4: Portion of cyclic rating calculator output for Maryborough.

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Mary	ODAN	Res_100	1.00	0.67	0.67	54.93	86.86	62.22	111.43	1.293	8.51	CRF
Mary	ODAN	Res_95	0.95	0.67	0.71	57.02	90.83	64.99	116.46	1.293	15.69	CRF
Mary	ODAN	Res_90	0.90	0.67	0.75	58.67	92.87	67.24	119.12	1.287	24.00	Age
Mary	ODAN	Res_85	0.85	0.67	0.79	59.42	92.00	68.41	116.94	1.254	24.00	Age
Mary	ODAN	Res_80	0.80	0.67	0.84	61.30	90.41	71.69	114.14	1.223	23.99	Age

8.5.3 Prediction expressions

Due to the multitude of influencing factors, the most appropriate and accurate manner in which to predict a change in cyclic rating for a given change in load profile is to alter the load profile input to the cyclic rating calculator to reflect the expected change and then re-calculate the rating for the transformer of interest. However, general rules of thumb are useful for plant rating engineers to develop a “feel” for the relationship and to provide approximate or informal predictions without needing to access the calculator. General expressions were derived from the equations to the regression lines in figures 8.20 to 8.25 by making some simplifying approximations to fit with the trends

revealed. These expressions are displayed in table 8.5. Note that the negative signs of the regression equations have been omitted because the expression now calculates percentage **decrease** in CRF explicitly given a percentage **decrease** in peak load (ΔPL_d) or a percentage **increase** in load factor (ΔLF_i).

Table 8.5: General expressions for prediction of percentage decrease in CRF.

Characteristic	Dependent variable	
	Peak load	Load factor
Location:		
Northern & central	$0.48\Delta PL_d + 0.20$	$0.39\Delta LF_i + 0.44$
Southern	$0.42\Delta PL_d + 0.13$	$0.34\Delta LF_i + 0.34$
Size:		
Small (≤ 10 MVA)	$0.51\Delta PL_d + 0.11$	$0.42\Delta LF_i + 0.37$
Medium ($> 10 \leq 50$ MVA)	$0.44\Delta PL_d + 0.23$	$0.36\Delta LF_i + 0.44$
Large (> 50 MVA)	$0.41\Delta PL_d + 0.18$	$0.34\Delta LF_i + 0.39$
Cooling mode:		
ONXX	$0.46\Delta PL_d + 0.17$	$0.38\Delta LF_i + 0.40$
ODXX	$0.42\Delta PL_d + 0.18$	$0.34\Delta LF_i + 0.40$
<p>Notes:</p> <p><i>These expressions allow approximation of the percentage decrease in CRF</i></p> <p><i>ΔPL_d is the percentage decrease in peak load</i></p> <p><i>ΔLF_i is the percentage increase in load factor</i></p>		

Averaging all of the coefficients of the regression equations and neglecting the constant terms yields two very approximate but simple to remember expressions for predicting change in CRF with change in load profile (assuming load shifting DSM):

$$\Delta CRF_d = 0.45 \times \Delta PL_d \quad (8.17)$$

$$\Delta CRF_d = 0.37 \times \Delta LF_i \quad (8.18)$$

where: ΔCRF_d is the percentage decrease in CRF;
 ΔPL_d is the percentage decrease in peak load; &
 ΔLF_i is the percentage increase in load factor.

8.6 Consequences for a Utility

The reduction in cyclic ratings caused by load shifting DSM may have significant negative impacts for a utility in the contexts of transformer operational management; peak capacity; transformer lifespan and maintenance; planning and budgeting for network augmentation; reduction of capital expenditure; and the valuation of DSM programs. The following hypothetical scenarios are possible following significant load profile flattening and CRF reduction:

- If the total peak cyclic capacity of the transformers for a utility was (say) 1000 MVA and the peaks of the load profiles for all transformers were reduced by 5% (assuming a constant average), then by equation (8.17), the reduction in overall CRF would be approximately 2.25%. This equates to a loss in peak cyclic capacity of 23 MVA which is comparable to the rating of a medium sized transformer.
- As a result of load shifting DSM, a transformer may begin to operate much closer to its now reduced cyclic rating. Firstly, this has the effect of increasing the ageing rate of the transformer insulation thereby reducing the expected lifespan of the transformer. Secondly, the margin between present demand and planning thresholds may be reduced such that augmentation (transformer replacement or installation of another) is now required earlier (say in three years rather than five). Since the purpose of the load shifting DSM program was to defer expenditure (and it will have been financially justified on this basis), the validity of the program may be brought into question.
- In a worst case scenario, if the cyclic rating of a transformer was reduced below the load being supplied, a significantly greater risk of transformer failure would exist. The consequences of transformer failure could include: outages and related penalties from the regulator; further outages due to overload of remaining plant; fire and damage to other substation plant; and injury to people.

The above points serve to highlight the risks associated with both loss in cyclic capacity due to load profile changes and incorrect calculation &/or application of cyclic ratings. In this light, the results and insights presented in this chapter are particularly important.

8.7 Chapter Summary

This chapter has presented the results of an analysis conducted to determine and quantify the changes in cyclic ratings which occur due to load shifting DSM alteration of load profiles.

The chapter commenced with derivation of a solution to a simplified version of the AS 60076.7 top oil differential equation. Evaluating the solution for a series of flattening load profile inputs demonstrated that the top oil temperature profile also flattened and approached the rated value. It was therefore predicted that in the limit, as a load profile becomes a horizontal line, the cyclic rating would approach the nameplate rating (i.e. decrease with flattening of the load profile).

The cyclic rating calculator was then employed to generate 600 different cyclic ratings for combinations of the 12 selected transformers, their available cooling modes and a series of flattening load profiles from the DSM simulator. Analysis of these ratings confirmed the prediction that cyclic ratings decrease with flattening of load profiles. Additionally, it was demonstrated that the amount by which a CRF changes depends on location, size and cooling mode of the transformer.

Prediction of cyclic ratings by means other than use of the cyclic rating calculator was shown to be complex due to a multiplicity of variables interacting with one another. Despite this, it was deemed valuable to determine a number of regression models allowing prediction of a CRF change given a change in peak load or load factor using a simple linear equation. These prediction models should only be used where an indication of change in CRF, not an exact change is required. Whenever an accurate cyclic rating is required, the cyclic rating calculator should be employed.

Finally, in light of the presented results, insights and conclusions, the possible impact on a utility of the identified negative relationship between cyclic ratings and load shifting DSM was postulated.

The ultimate objective of this project (objective (9), section 1.4) was to determine and quantify the impact of changes in load profile on power transformer cyclic ratings. Objective (9), while contributed to by all previous chapters, was fully achieved in this chapter.

Chapter 9

Conclusions & Further Work

9.1 Conclusions

The main objective of the project presented in this dissertation was to determine and quantify the relationship between changes in load profile and changes in power transformer cyclic ratings. It was revealed that the cyclic ratings of power transformers are negatively affected by load shifting DSM. That is, flattening of load profiles causes reduction in cyclic ratings. Additionally, it was demonstrated that the amount by which cyclic ratings change given a change in load profile varies according to several factors including: location, size and cooling mode of the transformer. Finally, regression models for simple but approximate prediction of cyclic rating changes were developed.

In addition to achievement of the main project objective, a range of other objectives were set and achieved via the project outcomes. These include: a thorough investigation of the techniques and theory involved in transformer thermal modelling, insulation ageing, cyclic rating calculation and DSM; development of a program which automatically calculates cyclic ratings for power transformers; and creation of a load shifting DSM simulation program, useful for generating altered load profiles for use with the cyclic rating calculator. This collection of knowledge and programs is of significant value along with the results of the main analysis.

The impact of load shifting DSM on cyclic ratings, as identified in this dissertation, may negatively influence factors including: peak capacity; transformer lifespan and

maintenance; planning and budgeting for network augmentation; reduction in capital expenditure; and the valuation of DSM programs. The results, insights and conclusions of this project have the potential to assist plant rating engineers in their understanding and application of cyclic ratings in the context of changing load profiles such that they may anticipate and therefore prevent many of the negative side-effects identified. Additionally, the project outcomes will contribute to the operational and life management of power transformers in an environment where DSM altered load profiles, deferral of expenditure and reduction in electricity pricing are important drivers.

9.2 Further Work

Due to time constraints, it was not possible to investigate all avenues identified at the commencement and during the course of the project. As such, these ideas become sources of further or future work for other students or for the author. A list of these topics is presented below. Some of these concepts involve simply developments or improvements for the current project; others could become projects in their own right.

1. **Investigation of the effect on cyclic ratings of thermal fluids and insulation paper with higher temperature ratings:**

In this project, standard mineral oil and Kraft paper were assumed (as this is the norm). Synthetic dielectric/cooling fluids and thermally upgraded insulating paper with significantly higher temperature ratings are increasingly being used. These insulating media may become standard in the future and it will be important for plant rating engineers to understand their influences on the transformer cyclic rating process.

2. **Assessment of the impact of cyclic loading on the maintenance of power transformers:**

High cyclic loading causes particular stresses on structures within the transformer other than the insulating oil and paper. For example, the expansion and contraction of the winding and core with load cycling can cause dislodgement of insulation packing blocks, thereby loosening the compression on the winding by the clamping structures. An assessment of the negative consequences of cyclic loading could therefore be valuable.

3. Study of IEEE C57.91:

IEEE C57.91 is a loading guide for mineral oil immersed power transformers and is therefore the American equivalent of AS 60076.7. Unsurprisingly, there are some distinct correlations between the two standards, however there are also some significant differences. A thorough study of IEEE C57.91 and a formal comparison with AS 60076.7 would be valuable.

4. Modification of the cyclic rating calculator for Ergon Energy use:

The cyclic rating calculator is currently implemented only in MATLAB. This modelling software is not available within Ergon Energy. It is therefore necessary to re-write the program in VBA to operate within Microsoft Excel, a program widely available throughout Ergon (recall this is one of the reasons why the AS 60076.7 exponential equation model was selected; refer to section 5.4). The present version of the cyclic rating calculator operates with only 12 input transformers and calculates the ratings for all combinations of the inputs. For use within Ergon Energy it would be more convenient for the user to be able to specify one or more transformers, cooling modes and load profiles for the calculation of cyclic ratings. A more user friendly and perhaps graphical output from the program is also desirable. Finally, the code may require optimisation for speed of execution if ratings for hundreds of transformers are calculated at once.

5. Confirm or refine regression models:

It would be interesting and valuable to expand the cyclic rating calculator to accept more transformers (in particular more ODAF transformers) to permit either confirmation or refinement of the regression models developed in section 8.5.1.

6. LTEC cyclic ratings:

Recall from section 2.2.5 that cyclic ratings can be classified as either normal cyclic (NC) or long term emergency cyclic (LTEC). Both are employed within Ergon Energy but there was insufficient time to analyse a second set of results in detail to determine the effect of load profile changes on LTEC cyclic ratings. This analysis would also be valuable.

References

- Allan, D. (2011), ‘Transformer Life’. Transformer Technology Design and Operation Course (ELEC 7051), University of Queensland, Australia, courtesy of Ergon Energy Corporation.
- Babu, P. & Kumar, K. (2013), Application of Novel DSM Techniques for Industrial Peak Load Management, *in* ‘2013 International Conference on Power, Energy and Control (ICPEC)’, pp. 415–419.
- Boshell, F. & Veloza, O. P. (2008), Review of Developed Demand Side Management Programs Including Different Concepts and their Results, *in* ‘Transmission and Distribution Conference and Exposition: Latin America, 2008 IEEE/PES’, pp. 1–7.
- Bureau of Meteorology (2014), ‘Climate Data Online’. Australian Government, viewed 16 October 2014, <http://www.bom.gov.au/climate/data/>.
- Çengel, Y. (2008), *Introduction to Thermodynamics and Heat Transfer*, 2nd edn, McGraw Hill, New York.
- Cigré (2009), ‘Thermal Performance of Transformers’. Cigré working group A2.24.
- Ekanayake, C. (2011*a*), ‘Introduction’. Transformer Technology Design and Operation Course (ELEC 7051), University of Queensland, Australia, courtesy of Ergon Energy Corporation.
- Ekanayake, C. (2011*b*), ‘Transformer Condition Monitoring’. Transformer Technology Design and Operation Course (ELEC 7051), University of Queensland, Australia, courtesy of Ergon Energy Corporation.
- Elmoudi, A., Lehtonen, M. & Nordman, H. (2006), Thermal Model for Power Trans-

- formers Dynamic Loading, *in* 'Conference Record of the 2006 IEEE International Symposium on Electrical Insulation', pp. 214–217.
- Ergon Energy Corporation (2013a), 'Demand Side Engagement Strategy 2013'. Viewed 6 May 2014, <https://www.ergon.com.au/energy-conservation/demand-management>.
- Ergon Energy Corporation (2013b), 'Ergon Energy Demand Management Plan 2013/14'. Viewed 6 May 2014, <https://www.ergon.com.au/energy-conservation/demand-management>.
- Ergon Energy Corporation (2013c), 'Plant Rating Guidelines'. ver. 1, Ref: NA000000R100.
- Feng, D. Y., Wang, Z. D. & Jarman, P. (2012), Modeling Thermal Life Expectancy of the UK Transmission Power Transformers, *in* '2012 International Conference on High Voltage Engineering and Application (ICHVE)', pp. 540–543.
- Huang, D. & Billinton, R. (2012), 'Effects of Load Sector Demand Side Management Applications in Generating Capacity Adequacy Assessment', *IEEE Transactions on Power Systems* **27**(1), 335–343.
- IEEE (2010), IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers, Standard IEEE Std C57.12.00-2010 (Revision of IEEE Std C57.12.00-2006), Institute of Electrical and Electronic Engineers.
- Iskender, I. & Mamizadeh, A. (2011), 'An Improved Nonlinear Thermal Model for MV/LV Prefabricated Oil-Immersed Power Transformer Substations', *Electrical Engineering* **93**(1), 9–22. <http://dx.doi.org/10.1007/s00202-010-0186-y>.
- Lordan, C., Letizia, D. & Gordon, I. (2013), 'Ergon Energy Pty. Ltd. Demand Side Shaping - System Business Requirements'. Study completed for Ergon Energy by Gravelroad Consulting, West End, Queensland.
- Nair, N., Nayagam, R. & Francis, R. (2008), New Zealand Utility Experiences with Demand Side Management, *in* '2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century', pp. 1–5.

- Nordman, H., Rafsback, N. & Susa, D. (2003), ‘Temperature Responses to Step Changes in the Load Current of Power Transformers’, *IEEE Transactions on Power Delivery* **18**(4), 1110–1117.
- Palensky, P. & Dietrich, D. (2011), ‘Demand Side Management: Demand Response, Intelligent Energy Systems, and Smart Loads’, *IEEE Transactions on Industrial Informatics* **7**(3), 381–388.
- Russell, G. (2011), ‘Insulating Oil Diagnostics: Theory & Case Studies’. Transformer Technology Design and Operation Course (ELEC 7051), University of Queensland, Australia, courtesy of Ergon Energy Corporation.
- Saha, T. (2011), ‘Transformer Failure Modes and Ageing’. Transformer Technology Design and Operation Course (ELEC 7051), University of Queensland, Australia, courtesy of Ergon Energy Corporation.
- Standards Australia (2005), Power transformers: Part 1: General, Standard AS/NZS 60076.1:2005 (IEC 60076-1, Ed. 2.1 (2000) MOD), Standards Australia.
- Standards Australia (2013a), Power transformers: Part 2: Temperature rise for liquid-immersed transformers, Standard AS/NZS 60076.2:2013 (IEC 60076-2, Ed. 3.0 (2011) MOD), Standards Australia.
- Standards Australia (2013b), Power transformers: Part 7: Loading guide for oil-immersed power transformers, Standard AS/NZS 60076-7:2013 (IEC 60076.7, Ed. 1.0 (2005) MOD), Standards Australia.
- Stapleton, G., Miller, T., Pearce, D. & Castillo, M. (2011), *Thermal Ratings and Heat Transfer*. EEP202, Postgraduate Electricity Supply Training Course, Queensland University of Technology, Australia, courtesy of Ergon Energy Corporation.
- Susa, D. & Lehtonen, M. (2006), ‘Dynamic Thermal Modeling of Power Transformers: Further Development — Part I’, *IEEE Transactions on Power Delivery* **21**(4), 1961–1970.
- Susa, D., Lehtonen, M. & Nordman, H. (2005), ‘Dynamic Thermal Modelling of Power Transformers’, *IEEE Transactions on Power Delivery* **20**(1), 197–204.
- Susa, D. & Nordman, H. (2009), ‘A Simple Model for Calculating Transformer Hot-Spot Temperature’, *IEEE Transactions on Power Delivery* **24**(3), 1257–1265.

- Swift, G., Molinski, T., Bray, R. & Menzies, R. (2001), 'A Fundamental Approach to Transformer Thermal Modeling. II. Field Verification', *IEEE Transactions on Power Delivery* **16**(2), 176–180.
- Swift, G., Molinski, T. & Lehn, W. (2001), 'A Fundamental Approach to Transformer Thermal Modeling. I. Theory and Equivalent Circuit', *IEEE Transactions on Power Delivery* **16**(2), 171–175.
- Tan, L., Li, H., Yan, X., Tian, J. & Li, J. (2012), An Improved Thermal Model for Power Transformers with Dynamic Loading, *in* 'Power and Energy Engineering Conference (APPEEC), 2012 Asia-Pacific', pp. 1–4.
- Tang, W. H., Wu, Q. & Richardson, Z. (2004), 'A Simplified Transformer Thermal Model Based on Thermal-Electric Analogy', *IEEE Transactions on Power Delivery* **19**(3), 1112–1119.
- Yau, T., Smith, W. M., Huff, R., Vogt, L. & Willis, H. (1990), 'Demand-Side Management Impact on the Transmission and Distribution system', *IEEE Transactions on Power Systems* **5**(2), 506–512.

Appendix A

Project Specification

University of Southern Queensland
Faculty of Health, Engineering & Sciences

ENG 4111/2 Research Project

Project Specification

For: **Andrew Atkinson**

Topic: EFFECT OF VARIATIONS IN LOAD PROFILE ON POWER
TRANSFORMER CYCLIC RATINGS

Supervisors: Dr. Tony Ahfock (USQ)
Mr. Greg Caldwell (Ergon Energy)

Sponsorship: Ergon Energy Corporation Ltd.

Project Aim: To model and analyse the impact that changes in load profile caused by demand side management initiatives have on the cyclic ratings calculated for power transformers.

Program:

1. Identify, analyse and compare the standard methods of calculating power transformer cyclic ratings.
2. Research approaches to the modelling of transformer heating and construct a simplified analytical model.
3. Investigate the various forms of demand side management initiatives and the impact they have on load profiles.
4. Construct a cyclic rating calculator compliant with AS 60076.7.
5. Employ modifiable square wave and realistic standard load profiles as calculator inputs to simulate the effects of demand side management and thus analyse the sensitivity of cyclic ratings to load profile changes.
6. Validate the findings from (5.) using data from Ergon Energy transformers representing a diverse range of manufacturers, cooling modes, nameplate ratings and geographic locations.

7. Prepare an academic dissertation communicating the activities, approaches, methodologies and results of the project.

As time and resources permit:

1. Construct models which employ the identified alternate methods of cyclic rating calculation and compare the results obtained from all of the approaches in order to identify differences and inaccuracies.

Appendix B

MATLAB Scripts for the Transformer Thermal Models

B.1 AS 60076.7 Exponential Equation Model Script

```

=====
%
%           AS60076.7 - Exponential Equation Transformer Thermal Model
%
%           Andrew Atkinson
%
%           August 2014
%
=====

% This program models the top oil and winding hot spot temperatures of power
% transformers employing the exponential equations method outlined in AS60076.7, with
% variable oil and winding time constants, given a particular load profile.

%
=====

clear all; close all; clc; % prepare Matlab workspace

%
% INITIALISE CONSTANTS & VARIABLES:

t_steps = (0:46800)'; % array of time steps (0 to 680 min) in seconds
H = 1.2; % hot spot factor
c = 390; % specific heat capacity of Copper (W.s/kg.K)

% AS 60076.7 constants:
AS_constants = [0.8 0.8 0.8 1.0 1.0 % oil exponent, x
                1.6 1.3 1.3 1.3 2.0 % winding exponent, y
                1.0 0.5 0.5 1.0 1.0 % constant k_11
                1.0 2.0 2.0 1.3 1.0 % constant k_21
                2.0 2.0 2.0 1.0 1.0]; % constant k_22

% Ambient temperature in transformer location:
ambient = 25; % 'C'

%
%
% TRANSFORMER DATA:

% Transformer masses:
m_o = 91397; % mass of oil in transformer (kg)
m_a = 215200; % mass of transformer core and winding assembly (kg)
m_t = 67252; % mass of transformer tank (kg)
m_w = m_a/2; % mass of winding (kg) (assume half of assembly)
m_c = m_a - m_w; % mass of core (kg) (assume remainder of assembly)

% Cooling mode:

% Cooling mode | Code
% -----|-----
%          ONAN | 1
%          ONAF | 2
%          OFAN | 3
%          OFAF | 4
%          ODAN | 5
%          ODAF | 6
cool_mode = 2;

% HRT data:
S_r = 400; % nameplate rating (MVA)
P_l_r = 637100 + 59778 + 65772; % load losses at rated load (W)
P_nl = 0.1*P_l_r; % no-load losses (W)
R = P_l_r/P_nl; % ratio of rated load losses to no-load losses
D_theta_o_r = 38; % top oil temp rise above ambient at rated load
D_theta_h_r = 18.6; % WHS temp rise above top oil at rated load
g_r = 15.5; % oil to winding thermal gradient at rated load
D_theta_o_b_r = 24.8; % bottom oil temp rise at rated load
D_theta_o_m_r = (D_theta_o_r + D_theta_o_b_r)/2; % mean oil temp rise at rated load
mo_to_ratio = D_theta_o_m_r/D_theta_o_r; % ratio of mean oil rise to top oil rise

```



```

% Thermal modelling parameters:
if S_r <= 2.5 % transformer is a distribution transformer
    column = 1;
elseif cool_mode == 1 % cooling mode is ONAN
    column = 2;
elseif cool_mode == 2 % cooling mode is ONAF
    column = 3;
elseif cool_mode == 3 || cool_mode == 4 % cooling mode is OFAN or OFAF
    column = 4;
elseif cool_mode == 5 || cool_mode == 6 % cooling mode is ODAN or ODAF
    column = 5;
end

x = AS_constants(1, column); % oil exponent
y = AS_constants(2, column); % winding exponent
k_11 = AS_constants(3, column); % constant k_11
k_21 = AS_constants(4, column); % constant k_21
k_22 = AS_constants(5, column); % constant k_22

% Thermal capacity calculation (C):
if cool_mode == 1 || cool_mode == 2 % cooling mode is ONAN or ONAF
    C = 0.132*m_a + 0.0882*m_t + 0.4*m_o;
else % cooling mode is OFAN, OFAF, ODAN or ODAF
    C = 0.132*(m_a + m_t) + 0.580*m_o;
end

%
%
%
% LOAD PROFILE:

profile = zeros(length(t_steps)-1,1); % initialise load profile array
profile(1:18000) = 1; % 1 pu for first 5 hours
profile(18001:36000) = 0.65; % 0.65 pu for next 5 hours
profile(36001:46800) = 1.6; % 1.6 pu for next 3 hours

% Force load at last time to be equal to that at first time:
profile = [profile; profile(1)];
%
%
%*****
% ***** THERMAL MODELLING *****
%*****

%
% CALCULATE PARAMETERS FOR THE CYCLE:

S = profile * S_r; % multiply per unit load profile by nameplate rating

% prepare arrays for top oil & WHS temp rise values for the cycle intervals:
D_theta_o = zeros(length(t_steps),1);
D_theta_h = zeros(length(t_steps),1);

% set initial temp rises:
D_theta_o(1) = 5.9;
D_theta_h(1) = 0.7;

for t = 2:length(t_steps) % iterate for each time step (not including 1st step)

    K = S(t)/S_r; % ratio of current load to nameplate rating
    g = g_r*K^y; % winding to oil thermal gradient at current load

    % initial top oil rise = top oil rise from previous time step:
    D_theta_o_i = D_theta_o(t-1);
    % mean oil rise = initial top oil rise * mean oil to top oil rise ratio:
    D_theta_o_m = D_theta_o_i * mo_to_ratio;
    % initial WHS rise = WHS rise from previous time step:
    D_theta_h_i = D_theta_h(t-1);

```

```

% previous load = load from previous time step:
S_prev = S(t-1);
% load losses at current load:
P_l = P_l_r * K^2;

% Update time constants:
tau_o = 3600*C*D_theta_o_m/(P_nl + P_l);    % top oil time constant (s)
tau_w = m_w*c*g/P_l;                       % winding time constant (s)

if (S(t) - S_prev) >= 0    % if load has stayed the same or increased:
% Top oil rise:
D_theta_o(t) = D_theta_o_i + ...
(D_theta_o_r*((1+R*K^2)/(1+R))^x - D_theta_o_i)* ...
(1-exp(-1/(k_11*tau_o)));

% WHS rise:
D_theta_h(t) = D_theta_h_i + ...
(H*g_r*K^y - D_theta_h_i)* ...
(k_21*(1-exp(-1/(k_22*tau_w))) - ...
(k_21-1)*(1-exp(-1/(tau_o/k_22))));

else    % otherwise, load must have decreased:
% Top oil rise:
D_theta_o(t) = D_theta_o_r*((1+R*K^2)/(1+R))^x + ...
(D_theta_o_i - D_theta_o_r*((1+R*K^2)/(1+R))^x)* ...
exp(-1/(k_11*tau_o));

% WHS rise:
D_theta_h(t) = H*g_r*K^y + (D_theta_h_i - H*g_r*K^y)*exp(-1/tau_w);
end

end

% Top oil & WHS temperatures:
theta_o_exp = ambient + D_theta_o;    % top oil temps = ambient + top oil rises
theta_h_exp = theta_o_exp + D_theta_h; % WHS temps = top oil temps + WHS rises
%
%
% SAVE RESULTS FOR ANALYSIS OR PLOTTING:
%
save('exp_results','theta_o_exp','theta_h_exp','profile','t_steps');
%

```

B.2 AS 60076.7 Differential Equation Model Script

B.2.1 MATLAB Script

```

=====
%
%           AS60076.7 - Differential Equation Transformer Thermal Model
%
%           Andrew Atkinson
%
%           August 2014
%
=====

% This program models the top oil and winding hot spot temperatures of power
% transformers employing the differential equations method outlined in AS60076.7 with
% variable oil and winding time constants.

=====

clear all; clc; % prepare Matlab workspace

%
%-----
% INITIALISE CONSTANTS & VARIABLES:

t_steps = (0:46800)'; % array of time steps (0 to 680 min) in seconds
H = 1.2; % hot spot factor
c = 390; % specific heat capacity of Copper (J/kg.K)

% AS 60076.7 constants:
AS_constants = [0.8 0.8 0.8 1.0 1.0 % oil exponent, x
                1.6 1.3 1.3 1.3 2.0 % winding exponent, y
                1.0 0.5 0.5 1.0 1.0 % constant k_11
                1.0 2.0 2.0 1.3 1.0 % constant k_21
                2.0 2.0 2.0 1.0 1.0]; % constant k_22

% Ambient temperature in transformer location:
ambient = 25; % 'C'
%
%-----

%
%-----
% TRANSFORMER DATA:

% Transformer masses:
m_o = 91397; % mass of oil in transformer (kg)
m_a = 215200; % mass of transformer core and winding assembly (kg)
m_t = 67252; % mass of transformer tank (kg)
m_w = m_a/2; % mass of winding (kg) (assume half of assembly)
m_c = m_a - m_w; % mass of core (kg) (assume remainder of assembly)

% Cooling mode:

%Cooling mode | Code
%-----|-----
%          ONAN | 1
%          ONAF | 2
%          OFAN | 3
%          OFAF | 4
%          ODAN | 5
%          ODAF | 6
cool_mode = 2;

% HRT data:
S_r = 400; % nameplate rating (MVA)
P_l_r = 637100 + 59778 + 65772; % load losses at rated load (W)
P_nl = 0.1*P_l_r; % no-load losses (W)
R = P_l_r/P_nl; % ratio of rated load losses to no-load losses
D_theta_o_r = 38; % top oil temp rise above ambient at rated load
D_theta_h_r = 18.6; % WHS temp rise above top oil at rated load
g_r = 15.5; % oil to winding thermal gradient at rated load
D_theta_o_b_r = 24.8; % bottom oil temp rise at rated load
D_theta_o_m_r = (D_theta_o_r + D_theta_o_b_r)/2; % mean oil temp rise at rated load
mo_to_ratio = D_theta_o_m_r/D_theta_o_r; % ratio of mean oil rise to top oil rise

```

```

% Thermal modelling parameters:
if S_r <= 2.5 % transformer is a distribution transformer
    column = 1;
elseif cool_mode == 1 % cooling mode is ONAN
    column = 2;
elseif cool_mode == 2 % cooling mode is ONAF
    column = 3;
elseif cool_mode == 3 || cool_mode == 4 % cooling mode is OFAN or OFAF
    column = 4;
elseif cool_mode == 5 || cool_mode == 6 % cooling mode is ODAN or ODAF
    column = 5;
end

x = AS_constants(1, column); % oil exponent
y = AS_constants(2, column); % winding exponent
k_11 = AS_constants(3, column); % constant k_11
k_21 = AS_constants(4, column); % constant k_21
k_22 = AS_constants(5, column); % constant k_22

% Thermal capacity calculation (C):
if cool_mode == 1 || cool_mode == 2 % cooling mode is ONAN or ONAF
    C = 0.132*m_a + 0.0882*m_t + 0.4*m_o;
else % cooling mode is OFAN, OFAF, ODAN or ODAF
    C = 0.132*(m_a + m_t) + 0.580*m_o;
end

%
%
%
% LOAD PROFILE:

profile = zeros(length(t_steps)-1,1); % initialise load profile array
profile(1:18000) = 1; % 1 pu for first 5 hours
profile(18001:36000) = 0.65; % 0.65 pu for next 5 hours
profile(36001:46800) = 1.6; % 1.6 pu for next 3 hours

% Force load at last time to be equal to that at first time:
profile = [profile; profile(1)];
%
%
%*****
% ***** THERMAL MODELLING *****
%*****
%
% CALCULATE PARAMETERS FOR THE CYCLE:

S = profile * S_r; % multiply per unit load profile by nameplate

theta_o_i = 30.9; % set initial top oil temp (will be updated)
D_theta_h1_i = 0.7; % set initial WHS1 temp rise (this will be updated)
D_theta_h2_i = 0; % set initial WHS2 temp rise (this will be updated)

% solve top oil diff eqn using Simulink model:
sim('AS_diff_Simulink_model') % run Simulink model
theta_o = theta_o_sim; % save output as top oil temps
theta_h = theta_h_sim; % save output as WHS temps
%
%
%
% GENERATE RESULTS:
t_diff = t_sim;
theta_o_diff = theta_o;
theta_h_diff = theta_h;

save('diff_results', 'theta_o_diff', 'theta_h_diff', 't_diff');
%

```

B.2.2 Simulink Model

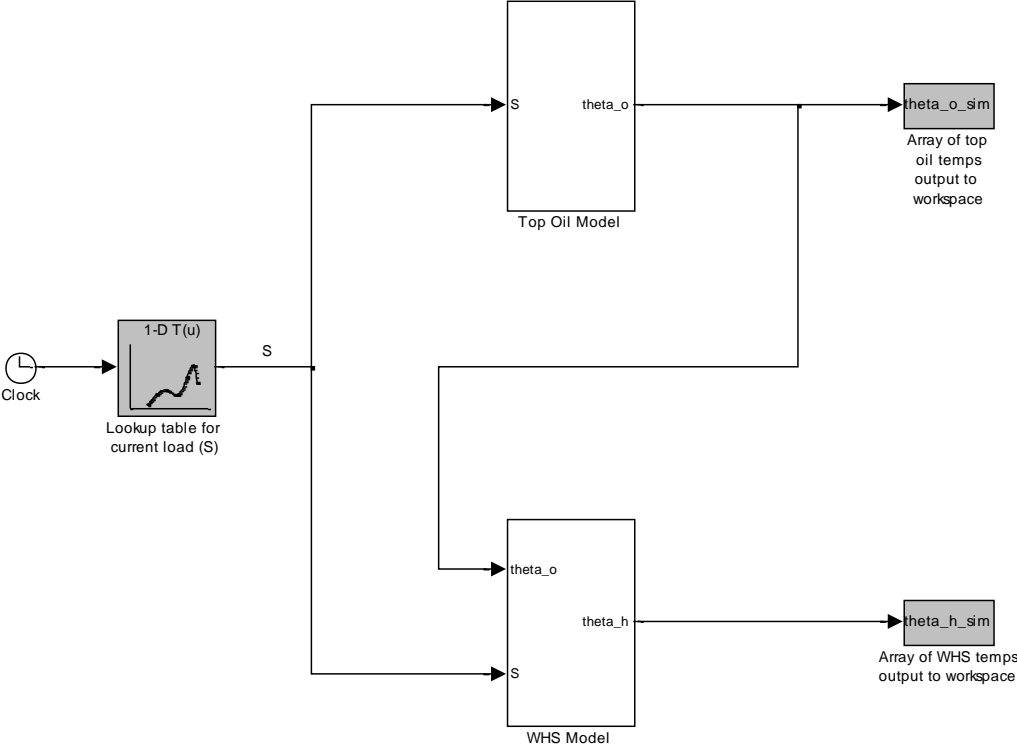


Figure B.1: Main Simulink system for the AS 60076.7 differential equation model.

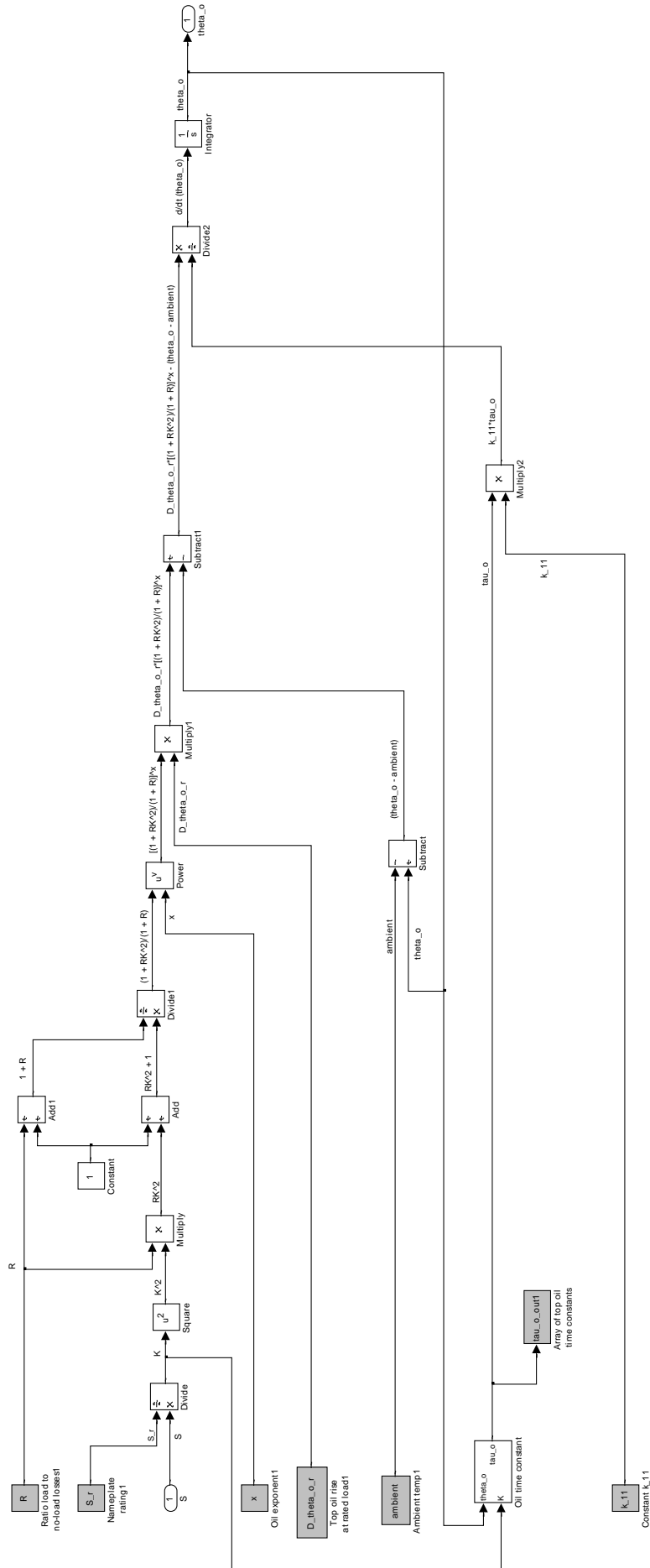


Figure B.2: Simulink subsystem for calculation of the top oil temperature.

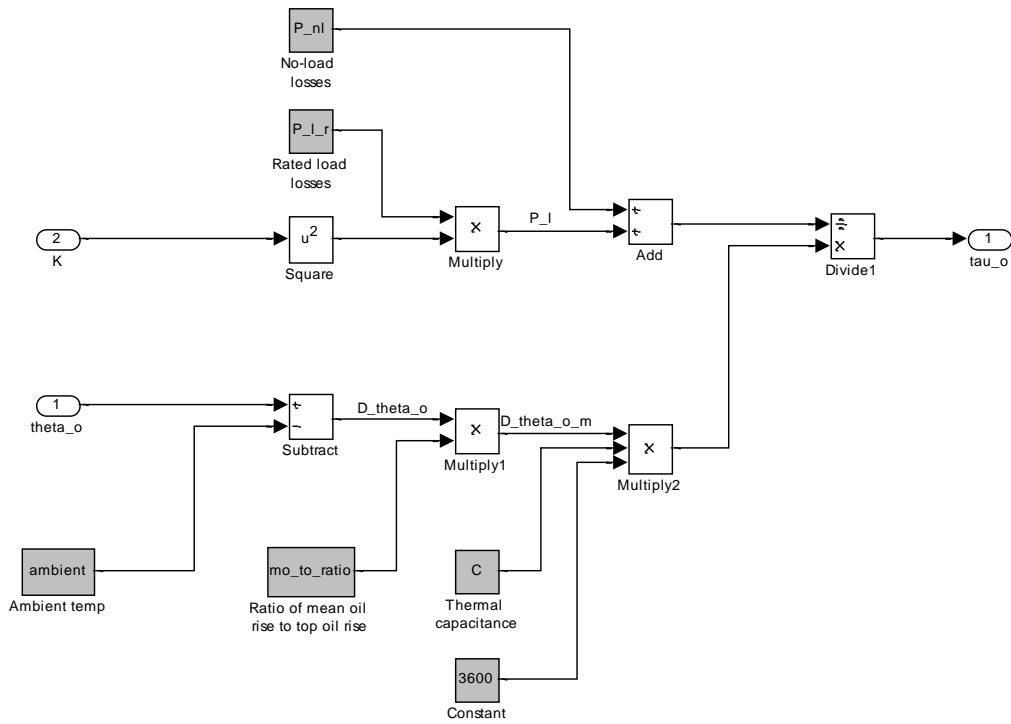


Figure B.4: Simulink subsystem for calculation of the **oil time constant**.

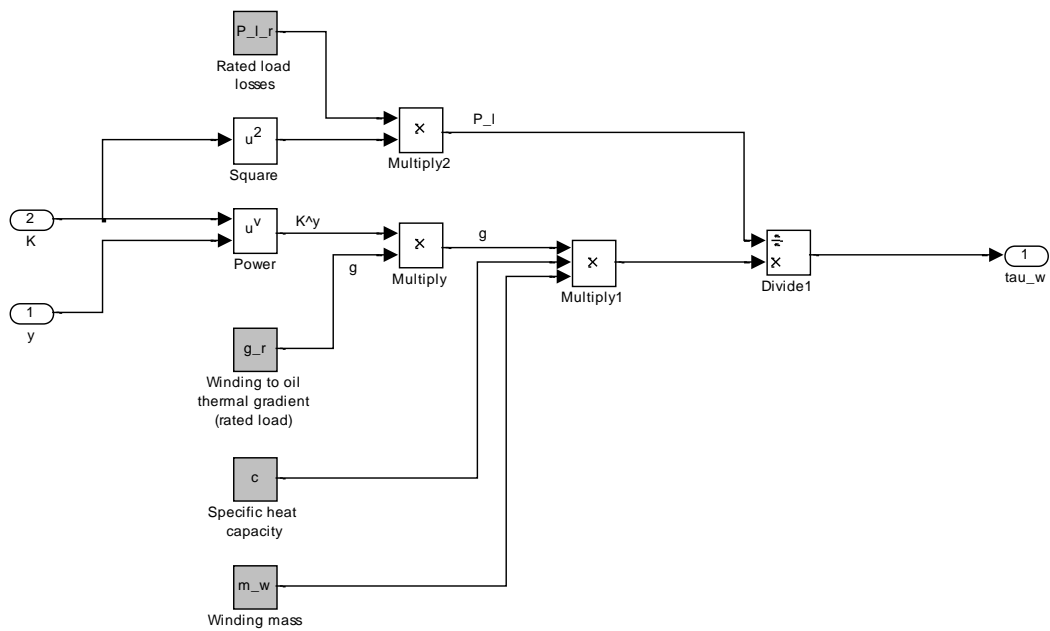


Figure B.5: Simulink subsystem for calculation of the **winding time constant**.

B.3 Susa & Lehtonen (2006) Model Script

B.3.1 MATLAB Script

```

=====
%
%                               Transformer Thermal Model Based on Susa & Lehtonen 2006
%
%                               Andrew Atkinson
%
%                               August 2014
%
=====

% This program models the top oil and winding hot spot temperatures of power
% transformers employing the differential equations outlined by Susa and Lehtonen
% (2006), with variable oil time constant, given a particular load profile

=====

clear all; clc; % prepare Matlab workspace

%
%-----
% INITIALISE CONSTANTS & VARIABLES:
%-----

t_steps = (0:46800)'; % array of time steps (0 to 680 min) in seconds
H = 1.2; % hot spot factor
c_w = 396; % specific heat capacity of copper winding (J/kg.K)
c_c = 468; % specific heat capacity of iron core (J/kg.K)
c_t = 468; % specific heat capacity of tank (J/kg.K)
c_o = 1836; % specific heat capacity of oil (J/kg.K)
ambient = 25; % Ambient temperature in transformer location ('C)
%
%-----

%
%-----
% TRANSFORMER DATA:
%-----

% Transformer masses:
m_o = 91397; % mass of oil in transformer (kg)
m_a = 215200; % mass of transformer core and winding assembly (kg)
m_t = 67252; % mass of transformer tank (kg)
m_w = m_a/2; % mass of winding (kg) (assume half of assembly)
m_c = m_a - m_w; % mass of core (kg) (assume remainder of assembly)

% Cooling mode:
%-----
% Cooling mode | Code
%-----|-----
% ONAN | 1
% ONAF | 2
% OFAN | 3
% OFAF | 4
% ODAN | 5
% ODAF | 6
cool_mode = 2;

% HRT data:
S_r = 400; % nameplate rating (MVA)
P_dc_r = 637100; % DC loss at rated load (W)
P_e_r = 59778; % Winding eddy loss at rated load (W)
P_s_r = 65772; % Stray loss at rated load (W)
P_a_r = P_e_r + P_s_r; % stray & eddy losses at rated load (W)
P_l_r = P_dc_r + P_a_r; % load losses at rated load (W)
P_nl = 0.1*P_l_r; % no-load losses (W) (assume 10% of load losses)
P_dc_pu_r = P_dc_r/P_l_r; % pu DC loss at rated load
P_e_pu_r = P_e_r/P_l_r; % pu eddy loss at rated load
P_a_pu_r = P_a_r/P_l_r; % pu stray & eddy loss at rated load
R = P_l_r/P_nl; % ratio of rated load losses to no-load losses
D_theta_o_r = 38; % top oil temp rise above ambient at rated load
D_theta_h_r = 18.6; % WHS temp rise above top oil at rated load
g_r = 15.5; % oil to winding thermal gradient at rated load

% Winding time constant:
tau_w = 8.2*60; % seconds

```

```

% Thermal modelling exponents:
if cool_mode == 1 % cooling mode is ONAN
    n_o = 0.25;
    n_h = 0.25;
    n_h_ = 0.25;
elseif cool_mode == 2 || cool_mode == 3 || cool_mode == 4 % cooling mode is ONAF,
    n_o = 0.2; % OFAN or OFAF
    n_h = 0.5;
    n_h_ = 0.1;
elseif cool_mode == 5 || cool_mode == 6 % cooling mode is ODAN or ODAF
    n_o = 0;
    n_h = 0;
    n_h_ = 0;
end

% Oil correction factor for thermal capacity calculation (C):
if cool_mode == 5 || cool_mode == 6 % cooling mode is ODAN or ODAF
    O_o = 1; % correction factor for oil
else % cooling mode is ONAN, ONAF, OFAN, OFAF
    O_o = 0.86;
end

%
%
%
% LOAD PROFILE:

profile = zeros(length(t_steps)-1,1); % initialise load profile array
profile(1:18000) = 1; % 1 pu for first 5 hours
profile(18001:36000) = 0.65; % 0.65 pu for next 5 hours
profile(36001:46800) = 1.6; % 1.6 pu for next 3 hours

% Force load at last time to be equal to that at first time:
profile = [profile; profile(1)];
%
%
%*****
% ***** THERMAL MODELLING *****
%*****
%
% CALCULATE PARAMETERS FOR THE CYCLE:

S = profile * S_r; % multiply per unit load profile by nameplate

theta_u = (ambient + D_theta_o_r + D_theta_h_r + ambient)/2;
u_r = (1.36e-3)*exp(2797.3/(theta_u + 273)); % rated oil viscosity

theta_o_i = 30.9; % set initial top oil temp (will be updated)
theta_h_i = 31.6; % set initial WHS temp (will be updated)

% solve top oil & WHS differential equations using Simulink model:
sim('Susa_Simulink_model') % run Simulink model
theta_o = theta_o_sim; % save output as top oil temps
theta_h = theta_h_sim; % save output as WHS temps
%
%
% GENERATE RESULTS:
t_Susa = t_sim;
theta_o_Susa = theta_o;
theta_h_Susa = theta_h;

save('Susa_results', 'theta_o_Susa', 'theta_h_Susa', 't_Susa');
%

```

B.3.2 Simulink Model

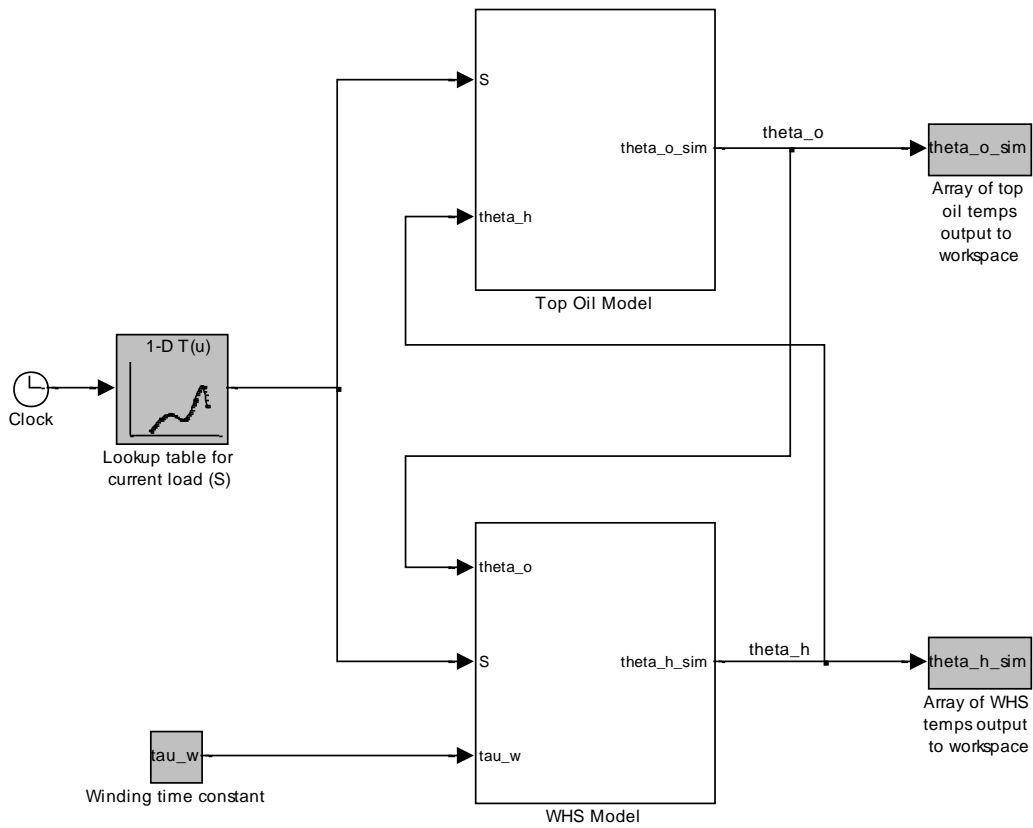


Figure B.6: Main Simulink system for the **Susa & Lehtonen (2006)** model.

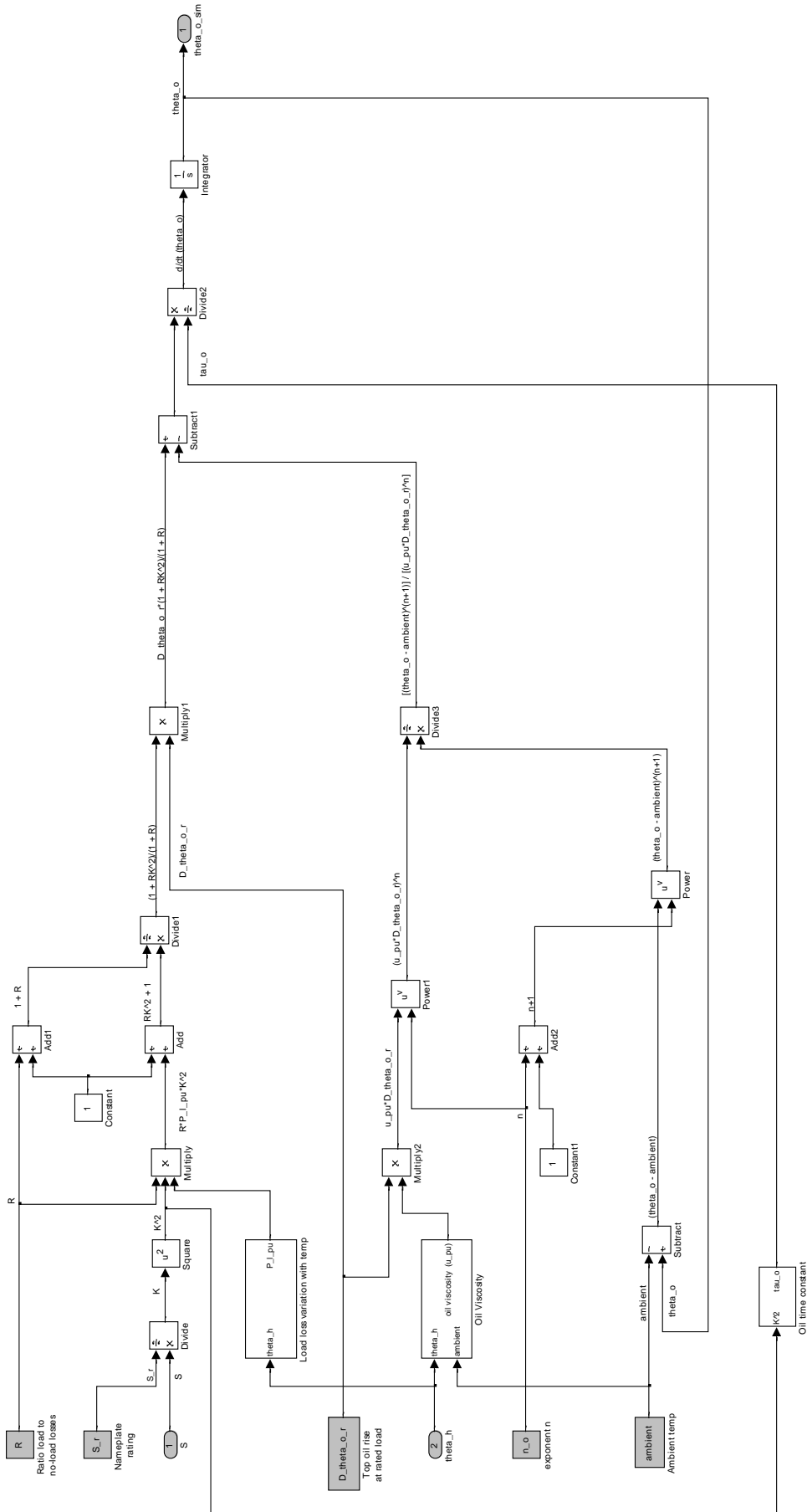


Figure B.7: Simulink subsystem for calculation of the top oil temperature.

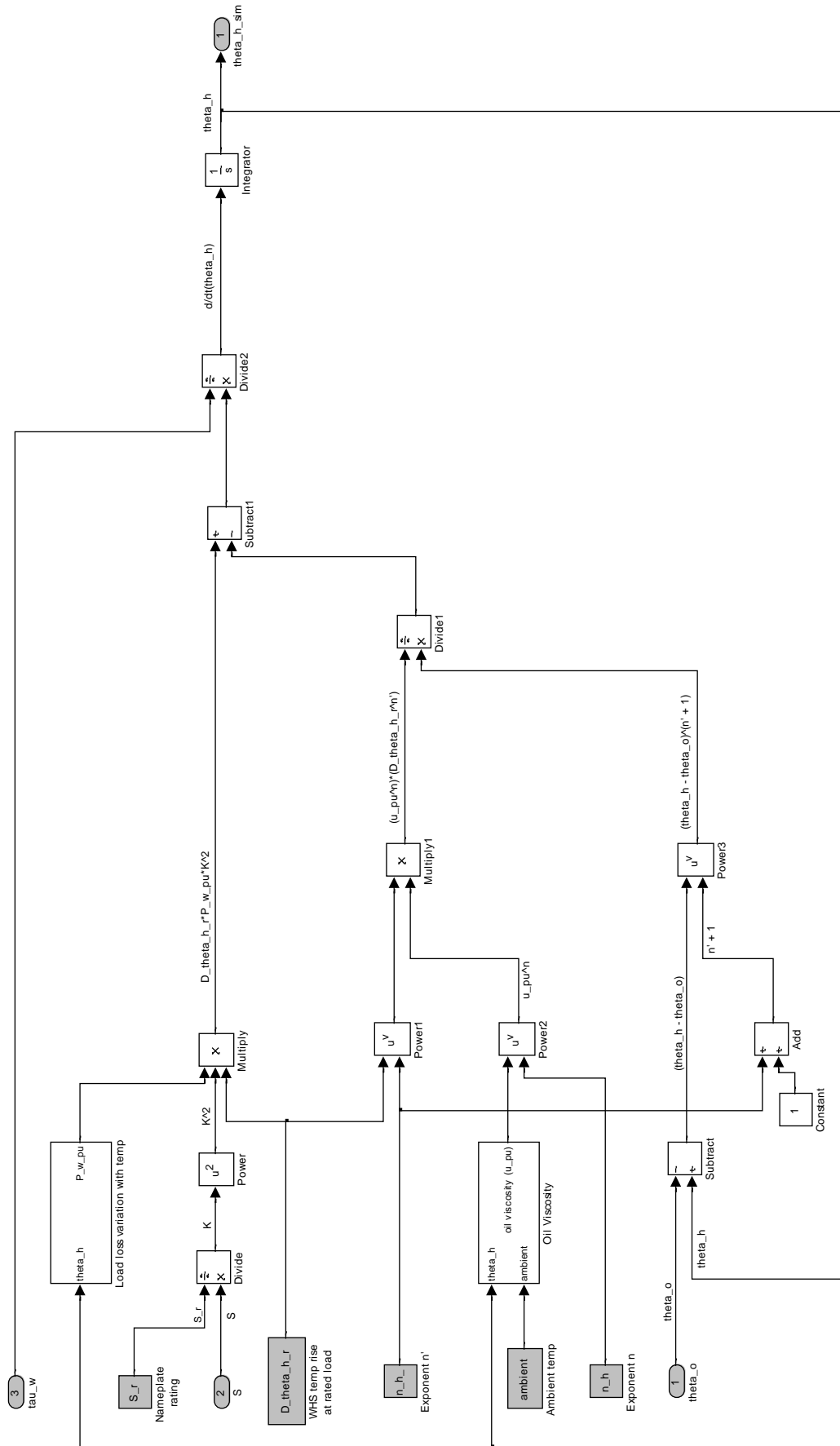


Figure B.8: Simulink subsystem for calculation of the WHS temperature.

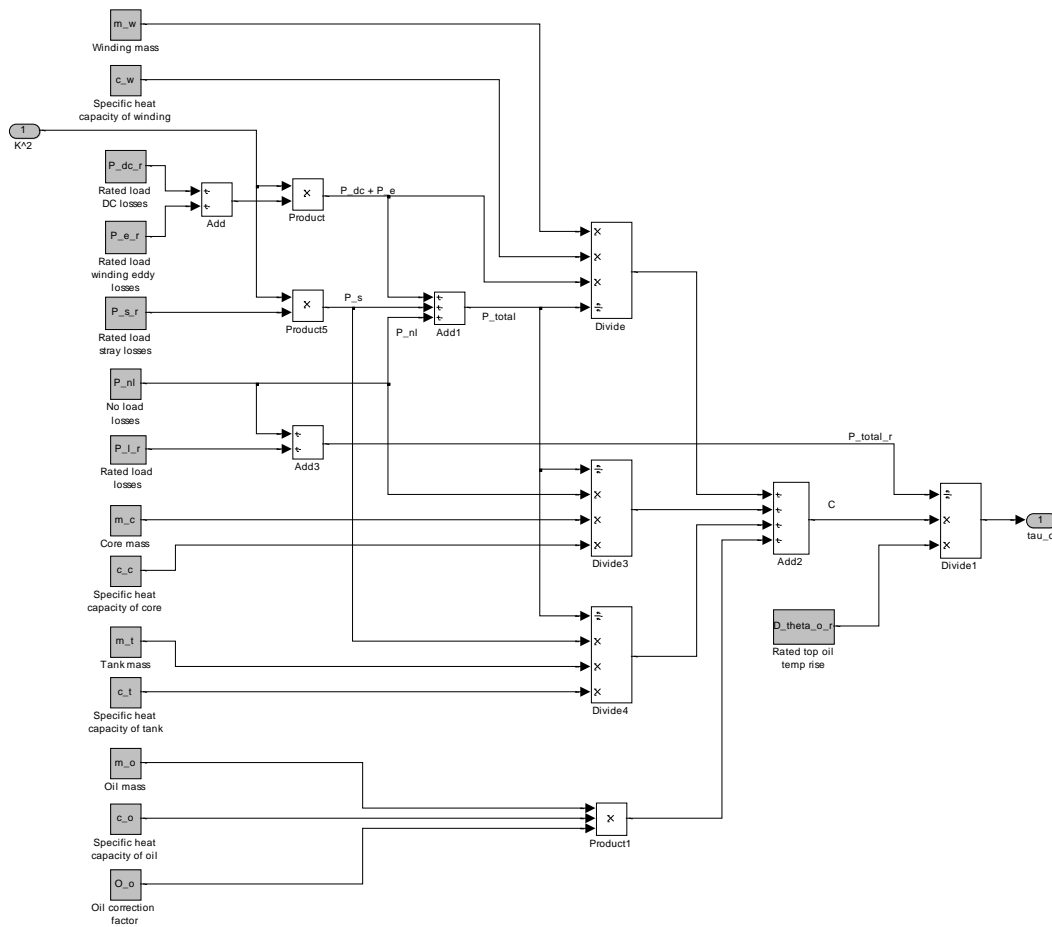


Figure B.9: Simulink subsystem for calculation of the **oil time constant**.

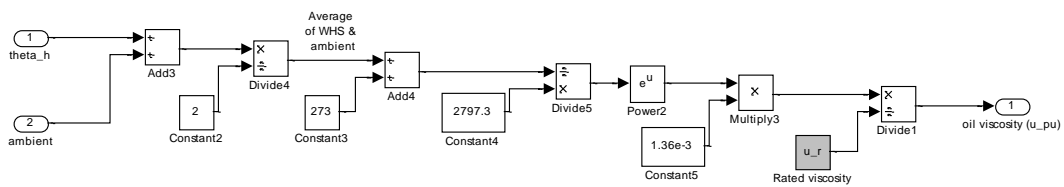


Figure B.10: Simulink subsystem for calculation of the **oil viscosity**.

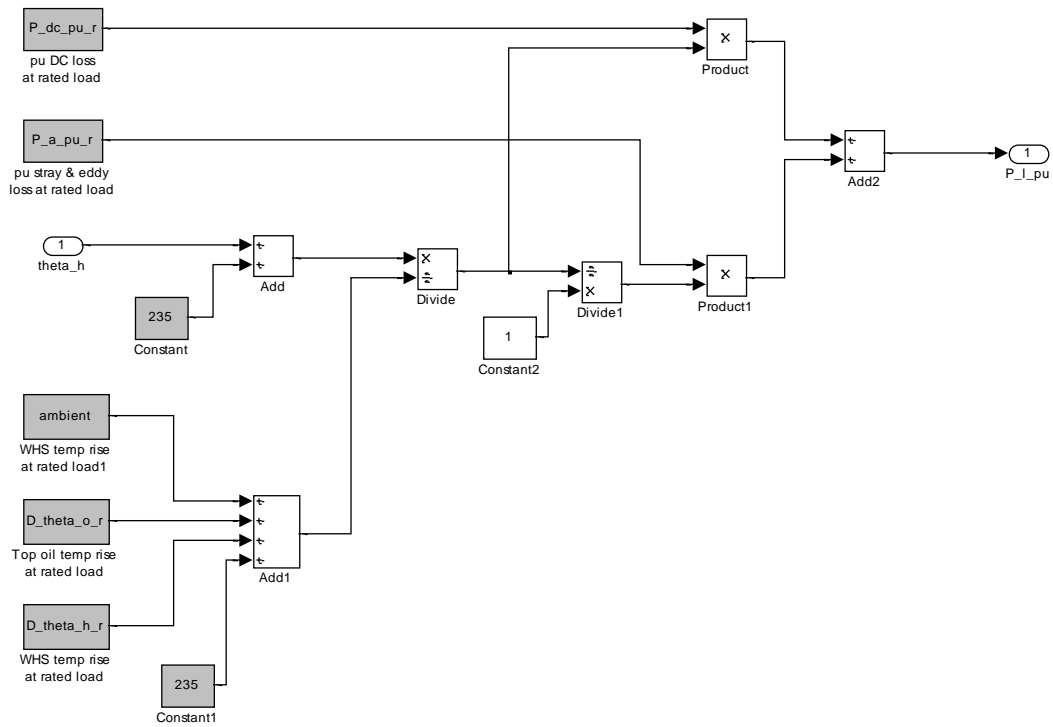


Figure B.11: Simulink subsystem for calculation of the **variable load loss for the top oil model**.

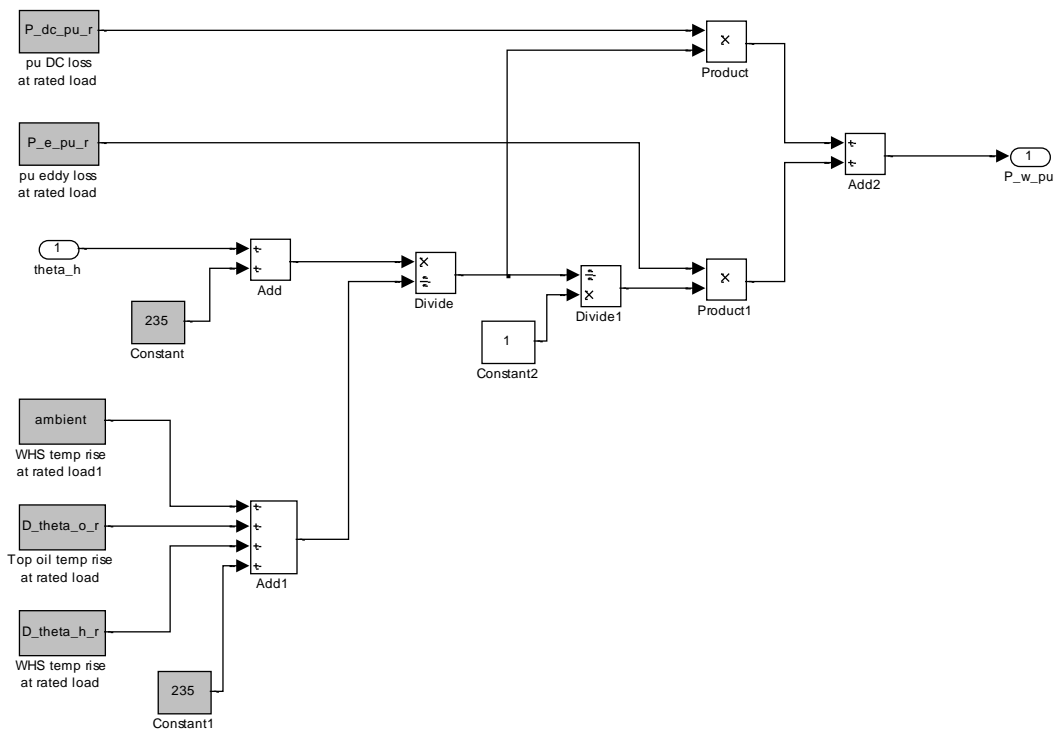


Figure B.12: Simulink subsystem for calculation of the **variable load loss for the WHS model**.

Appendix C

Measured Temperature Data For Thermal Model Validation

Tables C.1 & C.2 display the top oil and WHS temperatures respectively, measured for the 400 MVA test transformer on ONAF cooling supplying the load specified in figure 5.1. These data are presented in graphical form in the paper by Susa et al. (2005) and values were interpolated to create the tables. The outputs of the three thermal models were compared against these temperature data in chapter 5.

Table C.1: Measured **top oil temperatures**.

Time (s)	Top oil temp ($^{\circ}C$)	Time (s)	Top oil temp ($^{\circ}C$)
0	30.9	28800	46.0
1200	32.0	32400	45.0
2400	40.0	36000	44.0
3600	47.5	36600	44.0
4800	50.0	37200	50.0
7200	55.0	37800	60.0
9000	56.0	39000	70.0
10800	57.0	39600	72.0
14400	58.0	41400	80.0
18000	59.0	43200	85.0
19200	58.0	45000	89.0
21600	51.0	46800	91.0
25200	48.0		

Table C.2: Measured **WHS temperatures**.

Time (s)	WHS temp ($^{\circ}C$)	Time (s)	WHS temp ($^{\circ}C$)
0	31.6	28800	59.0
1800	60.0	32400	58.0
3600	70.0	36000	57.5
7200	75.0	37200	70.0
10800	75.0	38400	105.0
14400	75.0	39600	110.0
18000	75.0	41400	117.5
19800	65.0	43200	120.0
21600	62.0	45000	122.0
25200	60.0	46800	127.5

Appendix D

MATLAB Script for the Cyclic Rating Calculator

```

=====
%
%
%       AS60076.7 Based Transformer Thermal Model & Cyclic Rating Calculator:
%       Exponential Equations Method
%
%
%               Andrew Atkinson
%
%               August 2014
%
=====
%
% This program models the top oil and winding hot spot temperatures of power
% transformers for a range of 24 hour load cycles employing the exponential equations
% method outlined in AS60076.7 with variable oil and winding time constants.
% Using the temperature profiles, the cyclic ratings of the transformers for the
% different load profiles are then determined according to the limits specified in
% AS60076.7.
%
%
% *** TRANSFORMERS ***
% The transformers employed in the program are listed in the table below along with the
% column number which is consistent across all data tables:
%
%
%       Transformer location | Column Number
%       -----|-----
%       Cairns              | 1
%       Cloncurry           | 2
%       Croydon             | 3
%       Dalby               | 4
%       Gladstone          | 5
%       Howard              | 6
%       Mackay              | 7
%       Maryborough        | 8
%       Rockhampton        | 9
%       Toowoomba          | 10
%       Townsville Central | 11
%       Townsville North  | 12
%
%
% *** COOLING MODES ***
% Some transformers possess multiple cooling modes which for ease of programming have
% been assigned a number code according to the following table:
%
%
%       Cooling mode | Code
%       -----|-----
%       ONAN          | 1
%       ONAF          | 2
%       OFAN          | 3
%       OFAF          | 4
%       ODAN          | 5
%       ODAF          | 6
%
=====
clear all; close all; clc; % prepare Matlab workspace

%
% SELECT TYPE OF RATING TO BE CALCULATED:
%
% Select ONE ONLY of the following (1 = selected):
NC = 1; % Normal cyclic ratings
LTEC = 0; % Long term emergency cyclic ratings
%
%
% LOAD DATA & INITIALISE CONSTANTS & VARIABLES:
%
load TX_data % ambient temperature, mass & heat run test (HRT) data; per unit standard
% load profiles and per unit load profiles for each transformer

% AS 60076.7 constants:
AS_constants = [0.8 0.8 0.8 1.0 1.0 % oil exponent, x
1.6 1.3 1.3 1.3 2.0 % winding exponent, y
1.0 0.5 0.5 1.0 1.0 % constant k_11
1.0 2.0 2.0 1.3 1.0 % constant k_21
2.0 2.0 2.0 1.0 1.0]; % constant k_22

% Normal Cyclic (NC) & Long Term Emergency Cyclic (LTEC) Limits:
%
% Distribution | Medium | Large
% <= 2.5 MVA | <= 100 MVA | > 100 MVA
NC_limits = [ 105 105 105 ; % top oil temp limit ('C)
120 120 120 ; % WHS temp limit ('C)
1.5 1.5 1.3 ; % per unit load limit
24 24 24 ]; % thermal ageing limit (h/day)

```

```

LTEC_limits = [      115          115          115 ;      % top oil temp limit ('C)
                130          130          130 ;      % WHS temp limit ('C)
                1.5          1.5          1.3 ;      % per unit load limit
                720          720          720 ];      % thermal ageing limit (h/day)

% Other constants & variables:
t_steps = (0:0.5:24)';      % array of time steps (0 to 23.5 h; steps of 0.5 h)
c = 390;      % specific heat capacity of Copper (J/kg/K)
H = 1.3;      % hot spot factor
results = [];      % initialise results matrix
%
%
% SELECT TRANSFORMER & EXTRACT RELEVANT DATA:
for TX_no = 1:12      % Transformer loop: consider each transformer individually

    % Ambient temperatures:
    theta_ma_max = ambient_temp_data(1, TX_no); % monthly avg temp of hottest month ('C)
    theta_E      = ambient_temp_data(2, TX_no); % yearly weighted ambient temp ('C)

    % Transformer masses:
    m_o = mass_data(1, TX_no);      % mass of oil in transformer (kg)
    m_a = mass_data(2, TX_no);      % mass of transformer core and winding assembly (kg)
    m_t = mass_data(3, TX_no);      % mass of transformer tank (kg)
    m_w = m_a/2;      % mass of winding (kg) (assume half of assembly)
%
%
% SELECT COOLING MODE & EXTRACT RELEVANT DATA:

    cool_codes = [ HRT_1_data(1, TX_no) ;
                  HRT_2_data(1, TX_no) ;
                  HRT_3_data(1, TX_no) ];      % extract cooling mode codes

    for cool_count = 1:3      % Cooling mode loop: step through each cooling mode for each TX

        cool_mode = cool_codes(cool_count);      % extract current cooling mode

        if cool_mode == 0      % cooling mode of 0 means no HRT data available
            continue      % if cooling mode is 0, move to next cooling mode
        end

        % Heat Run Test (HRT) data:
        if cool_count == 1      % Select the appropriate HRT data set according to
            HRT_data = HRT_1_data; % the counter (1, 2 or 3)
        elseif cool_count == 2
            HRT_data = HRT_2_data;
        elseif cool_count == 3
            HRT_data = HRT_3_data;
        end

        S_r      = HRT_data(2, TX_no);      % nameplate rating of current TX cooling mode
        P_nl      = HRT_data(3, TX_no);      % no-load losses
        P_l_r     = HRT_data(4, TX_no);      % load losses at rated load
        R         = P_l_r/P_nl;      % ratio of rated load losses to no-load losses
        D_theta_o_r = HRT_data(5, TX_no);      % top oil temp rise above ambient at rated load
        D_theta_o_m_r = HRT_data(6, TX_no);      % mean oil temp rise at rated load
        mo_to_ratio = D_theta_o_m_r/D_theta_o_r; % ratio of mean oil rise to top oil rise
        g_r       = HRT_data(7, TX_no);      % winding to oil thermal gradient at rated load
        D_theta_h_r = H*g_r;      % WHS temp rise above top oil at rated load

        % AS60076.7 Cyclic Rating Limits:
        if NC == 1 && LTEC == 0      % normal cyclic rating to be calculated
            if S_r <= 2.5      % transformer is a distribution transformer
                theta_o_lim = NC_limits(1,1);      % top oil temp limit
                theta_h_lim = NC_limits(2,1);      % WHS temp limit
                load_lim    = NC_limits(3,1);      % per unit load or current limit
                L_lim       = NC_limits(4,1);      % thermal ageing limit
            elseif S_r < 100      % transformer is a medium power transformer
                theta_o_lim = NC_limits(1,2);      % top oil temp limit
                theta_h_lim = NC_limits(2,2);      % WHS temp limit
                load_lim    = NC_limits(3,2);      % per unit load or current limit
                L_lim       = NC_limits(4,2);      % thermal ageing limit
            else      % transformer is a large power transformer
                theta_o_lim = NC_limits(1,3);      % top oil temp limit
                theta_h_lim = NC_limits(2,3);      % WHS temp limit
                load_lim    = NC_limits(3,3);      % per unit load or current limit
                L_lim       = NC_limits(4,3);      % thermal ageing limit
            end
        end
    end
end

```

```

elseif NC == 0 && LTEC == 1 % long term emergency cyclic rating to be calculated
  if S_r <= 2.5 % transformer is a distribution transformer
    theta_o_lim = LTEC_limits(1,1); % top oil temp limit
    theta_h_lim = LTEC_limits(2,1); % WHS temp limit
    load_lim = LTEC_limits(3,1); % per unit load or current limit
    L_lim = LTEC_limits(4,1); % thermal ageing limit
  elseif S_r < 100 % transformer is a medium power transformer
    theta_o_lim = LTEC_limits(1,2); % top oil temp limit
    theta_h_lim = LTEC_limits(2,2); % WHS temp limit
    load_lim = LTEC_limits(3,2); % per unit load or current limit
    L_lim = LTEC_limits(4,2); % thermal ageing limit
  else % transformer is a large power transformer
    theta_o_lim = LTEC_limits(1,3); % top oil temp limit
    theta_h_lim = LTEC_limits(2,3); % WHS temp limit
    load_lim = LTEC_limits(3,3); % per unit load or current limit
    L_lim = LTEC_limits(4,3); % thermal ageing limit
  end
else error('Must select one and only one of NC or LTEC')
end

% AS60076.7 specified constants:
if S_r <= 2.5 % transformer is a distribution transformer
  column = 1;
elseif cool_mode == 1 % cooling mode is ONAN
  column = 2;
elseif cool_mode == 2 % cooling mode is ONAF
  column = 3;
elseif cool_mode == 3 || cool_mode == 4 % cooling mode is OFAN or OFAF
  column = 4;
elseif cool_mode == 5 || cool_mode == 6 % cooling mode is ODAN or ODAF
  column = 5;
end

x = AS_constants(1, column); % oil exponent
y = AS_constants(2, column); % winding exponent
k_11 = AS_constants(3, column); % constant k_11
k_21 = AS_constants(4, column); % constant k_21
k_22 = AS_constants(5, column); % constant k_22

% Thermal capacity calculation (C):
if cool_mode == 1 || cool_mode == 2 % cooling mode is ONAN or ONAF
  C = 0.132*m_a + 0.0882*m_t + 0.4*m_o;
else % cooling mode is OFAN, OFAF, ODAN or ODAF
  C = 0.132*(m_a + m_t) + 0.580*m_o;
end

%
%
% SELECT LOAD PROFILE & EXTRACT DATA:
for profile_no = 1:25 % Load profile loop:

  % step through all load profiles for each transformer (25 in total):
  % - square wave (+ 4 x DSM modified versions)
  % - standard domestic (+ 4 x DSM modified versions)
  % - standard industrial (+ 4 x DSM modified versions)
  % - standard mixed (+ 4 x DSM modified versions)
  % - unique actual profile for the transformer (+ 4 x DSM modified versions)

  if profile_no <= 20 % profile is square or standard
    profile = DSM_profiles(:, profile_no); % extract profile data
    metrics = profile_metrics(:, profile_no); % extract profile metrics
  else % profile is an actual profile
    profile = DSM_profiles(:, profile_no + (TX_no-1)*5); % extract profile data
    % for particular TX
    metrics = profile_metrics(:, profile_no + (TX_no-1)*5); % profile metrics
  end

  % Force load at time 2400 hours to be equal to that at time 0000 hours:
  profile = [profile; profile(1)];
end

%
%*****
% **** THERMAL MODELLING ****
%*****
%
limit_reached = 0; % 0 = no limit reached; 1 = limit reached
itr = 0; % iteration counter

```

```

while limit_reached == 0 % Cyclic rating loop:
    % program will continue looping, recalculating temperatures
    % with a different Cyclic Rating Factor (CRF) until any or
    % all of the thermal, load and ageing limits are reached but
    % not exceeded.

%
% UPDATE LOAD PROFILE MULTIPLIER:

if itr == 0 % first pass
    inc = 1; % increment to be used in CRF updating in future iterations
    CRF = inc; % CRF = 1 initially for each load profile
else % second or higher pass
    % difference between top oil temp limit and highest top oil temp in the cycle:
    theta_o_diff = theta_o_lim - theta_o_max;
    % difference between WHS temp limit and highest WHS temp in the cycle:
    theta_h_diff = theta_h_lim - theta_h_max;
    % difference between ageing limit and total ageing in the cycle:
    L_diff = L_lim - L_total;
    % difference between the load limit and the CRF used:
    CRF_diff = load_lim - CRF;

    % find the -ve difference if it exists:
    min_diff = min([theta_o_diff, theta_h_diff, L_diff, CRF_diff]);

    inc = inc/1.1; % increment made progressively smaller with each iteration to
    % more precisely approach limits

    CRF = CRF + (min_diff/abs(min_diff))*inc; % i.e. CRF = CRF +/- increment
end

M = S_r * CRF; % load profile multiplier is nameplate rating multiplied by CRF
S = profile.*M; % multiply per unit load profile by multiplier

%
%
% CALCULATE PARAMETERS FOR THE CYCLE:

% prepare arrays for top oil & WHS temp rise values for the cycle
% (49 x half hour intervals):
D_theta_o = zeros(49,1);
D_theta_h = zeros(49,1);

diff_o = 1; % ensures 'while' loop is entered into the first time
diff_h = 1; % ensures 'while' loop is entered into the first time
count = 0; % initialise a loop counter

% Stability loop: iterate while loop until difference between first and last
% temperatures is small enough:
while (diff_o > 0.1 || diff_h > 0.1) && (count < 1000)

    count = count + 1; % increment counter

    % set first step temp rises equal to the last step temp rises of previous cycle:
    D_theta_o(1) = D_theta_o(49);
    D_theta_h(1) = D_theta_h(49);

    % Cycle loop:
    for t = 2:49 % iterate for each half hour time step (not including 1st step)

        K = S(t)/S_r; % ratio of current load to nameplate rating
        g = g_r*K^y; % winding to oil thermal gradient at current load

        % initial top oil rise = top oil rise from previous time step:
        D_theta_o_i = D_theta_o(t-1);
        % mean oil rise = initial top oil rise * mean oil to top oil rise ratio:
        D_theta_o_m = D_theta_o_i * mo_to_ratio;
        % initial WHS rise = WHS rise from previous time step:
        D_theta_h_i = D_theta_h(t-1);
        % previous load = load from previous time step:
        S_prev = S(t-1);
        % load losses at current load:
        P_l = P_l_r * K^2;

        % Update time constants:
        if profile_no <= 5; % if profile is square, use AS60076.7 time constants
            tau_o = AS_constants(6, column); % oil time constant (minutes)
            tau_w = AS_constants(7, column); % winding time constant (minutes)
        else
            tau_o = 60*C*D_theta_o_m/(P_nl + P_l); % calculate top oil time constant
            tau_w = m_w*c*g/(60*P_l); % calculate winding time constant
        end
        % (both in minutes)
    end
end

```

```

if (S(t) >= S_prev)           % if load has stayed the same or increased:
% Top oil rise:
D_theta_o(t) = D_theta_o_i + ...
              (D_theta_o_r*((1+R*K^2)/(1+R))^x - D_theta_o_i)* ...
              (1-exp(-30/(k_11*tau_o)));

% WHS rise:
D_theta_h(t) = D_theta_h_i + ...
              (H*g_r*K^y - D_theta_h_i)* ...
              (k_21*(1-exp(-30/(k_22*tau_w))) - ...
              (k_21-1)*(1-exp(-30/(tau_o/k_22))));

else                           % otherwise, load must have decreased:
% Top oil rise:
D_theta_o(t) = D_theta_o_r*((1+R*K^2)/(1+R))^x + ...
              (D_theta_o_i - D_theta_o_r*((1+R*K^2)/(1+R))^x)* ...
              exp(-30/(k_11*tau_o));

% WHS rise:
D_theta_h(t) = H*g_r*K^y + (D_theta_h_i - H*g_r*K^y)*exp(-30/tau_w);
end

end % cycle loop

% find magnitude of difference between first and last top oil rise temps:
diff_o = abs( D_theta_o(1) - D_theta_o(49) );

% find magnitude of difference between first and last WHS rise temps:
diff_h = abs( D_theta_h(1) - D_theta_h(49) );

end % stability loop

% Top oil & WHS temperatures:
theta_o = theta_ma_max + D_theta_o;    % top oil temps = ambient + top oil rises
theta_h = theta_o + D_theta_h;        % WHS temps = top oil temps + WHS rises
theta_o_max = max(theta_o);           % maximum top oil temperature in the cycle
theta_h_max = max(theta_h);           % maximum WHS temperature in the cycle
theta_o_min = min(theta_o);           % minimum top oil temperature in the cycle
theta_h_min = min(theta_h);           % minimum WHS temperature in the cycle

% Insulation ageing:
theta_h_ageing = theta_E + D_theta_o + D_theta_h; % WHS temps for ageing calcs
L = 0.5 * 2.^((theta_h_ageing - 98)/6); % ageing times for each interval
L_total = sum(L(1:end-1)); % total insulation ageing over cycle
% not including overlapping half hour

%
%
% COMPARE PARAMETERS WITH LIMITS:

temp_tol = 0.01; % tolerances for reaching the cyclic rating limits
CRF_tol = 0.01;
L_tol = 0.01;

if (theta_o_max <= theta_o_lim) && (theta_o_max > (theta_o_lim - temp_tol)) &&...
(theta_h_max <= theta_h_lim) && (CRF <= load_lim) && (L_total <= L_lim)
% top oil limit has been reached & other parameters are <= their limits:
limit_reached = 1; % ends the iterations
limit_code = 1; % top oil limit code = 1

elseif (theta_h_max <= theta_h_lim) && (theta_h_max > (theta_h_lim - temp_tol)) &&...
(theta_o_max <= theta_o_lim) && (CRF <= load_lim) && (L_total <= L_lim)
% WHS limit has been reached & other parameters are <= their limits:
limit_reached = 1;
limit_code = 2; % WHS limit code = 2

elseif (CRF <= load_lim) && (CRF > (load_lim - CRF_tol)) && ...
(theta_o_max <= theta_o_lim) && (theta_h_max <= theta_h_lim) && ...
(L_total <= L_lim)
% load limit has been reached & other parameters are <= their limits:
limit_reached = 1;
limit_code = 3; % load limit code = 3

elseif (L_total <= L_lim) && (L_total > (L_lim - L_tol)) && ...
(theta_o_max <= theta_o_lim) && (theta_h_max <= theta_h_lim) && ...
(CRF <= load_lim)
% ageing limit has been reached & other parameters are <= their limits:
limit_reached = 1;
limit_code = 4; % ageing limit code = 4

end

```

```
%  
  
itr = itr + 1;  
end % cyclic rating loop  
%  
  
%  
% GENERATE RESULTS:  
  
results = [results; [TX_no, cool_mode, profile_no, metrics', theta_o_min, theta_o_max, ...  
                    theta_h_min, theta_h_max, CRF, L_total, limit_code, theta_o', theta_h', L']];  
%  
  
end % next load profile  
end % next cooling mode  
end % next transformer  
%  
  
% OUTPUTS:  
  
xlswrite('results_NC',results,'all_data','A2'); % write results to spreadsheet  
save results_NC; % save all variables to eliminate need to re-execute program  
%
```

Appendix E

Calculation of Ambient Temperature Parameters for Selected Transformer Locations

E.1 Overview

This appendix describes the procedure for calculating the two ambient temperature parameters required for each transformer input to the cyclic rating calculator program. The monthly average temperature of the hottest month and the yearly weighted ambient temperature are specified in AS 60076.7 and were introduced on page 55 of section 2.2.5. Here, the procedure is demonstrated for the **Toowoomba transformer**. The process was repeated for the remaining 11 transformers. Basis temperature data was obtained from the Bureau of Meteorology (BOM).

E.2 Monthly Average Temperature of the Hottest Month

The monthly average temperature of the hottest month (θ_{ma-max}) is used to calculate WHS temperatures for a loading cycle as shown in equations (6.1) & (6.2). It is defined as the average of the long-term mean of the daily maxima and the long-term mean of the daily minima for the hottest month of the year at the specified location (Standards Australia 2013*b*, p. 32).

The procedure for calculation of the monthly average temperature of the hottest month is demonstrated below for the Toowoomba transformer:

1. Access the BOM *Climate Data Online* resource at <http://www.bom.gov.au/climate/data/>
2. Click the “*Select using Text*” tab
3. Change the “*Data about*” drop down box to *Temperature* and the “*Type of data*” radio field and drop down box to “*Monthly*” and “*Mean maximum temperature*” respectively
4. Enter *Toowoomba* in the “*Enter a location*” drop down box and click “Find”
5. Select the matching town from the list which appears then select the desired BOM station (for this example, *Toowoomba Airport* was selected)
6. Click “*Get Data*”

These steps are displayed in figure E.1.

7. Scroll down to the table “*Summary statistics for all years*” and copy the top row which are the long-term means of the monthly mean maximum temperatures (which are in turn the means of the daily maximum temperatures in that month) This is displayed in figure E.2.
8. Repeat from step 1 but for “*Mean minimum temperature*”.
9. Calculate the average of the long-term mean maximum temperature and the long-term mean minimum temperature for each month
10. The largest of these averages is the monthly average temperature of the hottest month

Following this procedure resulted in the generation of table E.1 which clearly shows that the monthly average temperature of the hottest month for the Toowoomba transformer is **22.75 °C** which corresponds to the month of January.

Table E.1: Calculation of the monthly average temperature of the hottest month for the Toowoomba transformer.

Month	Means (°C)		Average (°C)
	Maxima	Minima	
Jan	28.0	17.5	22.75
Feb	27.1	17.5	22.30
Mar	26.0	16.2	21.10
Apr	23.2	13.4	18.30
May	19.8	9.8	14.80
Jun	16.8	7.5	12.15
Jul	16.5	6.3	11.40
Aug	18.5	7.5	13.00
Sep	22.2	10.5	16.35
Oct	24.3	12.7	18.50
Nov	25.7	14.6	20.15
Dec	27.3	16.6	21.95
Annual	23.0	12.6	17.80

The screenshot shows a web interface for selecting weather data. It has two tabs: 'Select using Text' (active) and 'Select using Map'. The interface is divided into three main sections:

- 1: Selected: Monthly mean maximum temperature**: This section allows users to choose the data type. Under 'Data about', 'Temperature' is selected. Under 'Type of data', 'Monthly' is selected. A dropdown menu shows 'Mean maximum temperature'.
- 2: Select a weather station in the area of Interest**: A search box contains 'Toowoomba' and a 'Find' button. Below, there are two lists: 'Matching towns' (listing Toowoomba, Toowoomba City, East Toowoomba, and North Toowoomba) and 'Nearest Bureau stations' (listing 041529 Toowoomba Airport QLD (4.1km away), 041011 Cambooya Post Office QLD (18.3km away), 041359 Oakey Aero QLD (26.8km away), 041082 Pittsworth QLD (35.5km away), and 040436 Gatton Daff Research Stn QLD (37.2km away)). A checkbox 'Only show open stations' is checked.
- 3: Get the data**: A 'Station number' field contains '041529' and a 'Get Data' button.

At the bottom, there is a 'Data available for the selected station' bar chart showing data availability from 1850 to 2000, with a 100% availability mark.

Figure E.1: Selecting Toowoomba temperature data (Bureau of Meteorology 2014).

Summary statistics for all years Information about climate statistics

Statistic	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	28.1	27.2	25.9	23.2	19.7	16.8	16.5	18.6	22.4	24.4	25.8	27.4	23.0
Lowest	26.0	24.5	23.9	21.4	18.2	14.6	15.3	16.7	20.2	21.0	22.2	23.6	21.5
5th %ile	26.2	24.6	23.9	21.4	18.4	15.4	15.6	16.8	20.2	21.7	23.0	24.0	21.6
10th %ile	26.3	25.2	24.0	21.8	18.5	15.7	15.6	17.1	20.5	22.3	23.7	24.2	21.8
Median	28.8	27.1	25.0	22.1	18.5	17.0	16.6	18.5	22.3	24.1	26.0	27.0	23.1

Figure E.2: Monthly mean maximum temperatures (Bureau of Meteorology 2014)

E.3 Yearly Weighted Ambient Temperature

The yearly weighted ambient temperature (θ_E) is used in thermal ageing calculations as shown in equation (6.3). It is calculated using the following equation:

$$\theta_E = \theta_{ya} + 0.01 [2 (\theta_{ma-max} - \theta_{ya})]^{1.85} \quad (2.70 \text{ repeated})$$

where: θ_{ya} is the yearly average temperature (over many years).

During the process of calculating the monthly average temperature of the hottest month, the long-term yearly average temperature (θ_{ya}) was also calculated; this is the last row of table E.1. That is, for the Toowoomba transformer, $\theta_{ya} = 17.80^\circ\text{C}$. Thus, the yearly weighted ambient temperature for the Toowoomba transformer is:

$$\theta_E = 17.80 + 0.01 [2 (22.75 - 17.80)]^{1.85} = 18.49^\circ\text{C}$$

Appendix F

Selected Transformer Data

Table F.1 contains the relevant data for each of the 12 selected Ergon Energy transformers. These data were imported from a spreadsheet into MATLAB from where loading into the cyclic rating calculator was possible (refer to section 6.3).

Table F.1: Data for the 12 selected transformers (*Source: G.Caldwell, Ergon Energy*).

Parameter	Transformer location											
	Cairns	Cloncurry	Croydon	Dalby	Gladstone	Howard	Mackay	Maryborough	Rockhampton	Toowoomba	Townsville Central	Townsville North
Ambient temperatures:												
θ_{ma-max} ($^{\circ}C$)	27.55	31.60	31.20	25.60	27.00	25.65	26.60	25.65	27.00	22.75	27.85	27.85
θ_E ($^{\circ}C$)	25.12	26.84	27.55	20.39	23.04	21.69	22.95	21.69	23.04	18.49	24.72	24.72
Masses:												
m_o (kg)	32956	6512	4145	25402	11176	928	4928	35200	8492	17389	14002	12047
m_a (kg)	49000	7200	5000	41300	26300	1600	7500	41500	8350	30200	19780	20000
m_t (kg)	20000	3000	1000	16000	15000	1200	4000	22950	5000	12000	15000	8000
Heat Run Test 1:												
Cooling mode	1	1	1	1	1	1	1	1	1	1	1	1
S_r (MVA)	55	2	2	50	35	10	5	80	5	30	15	15
P_{nl} (W)	23110	3145	2624	23870	16310	1217	6600	18494	5962	9900	17000	19700
P_{lr} (W)	88990	14341	11320	209700	162220	6597	31390	253836	31710	175940	54500	57440
$\Delta\theta_{or}$ ($^{\circ}C$)	42.90	32.91	37.10	43.00	50.30	49.90	52.20	43.70	43.80	50.20	48.00	41.50
$\Delta\theta_{omr}$ ($^{\circ}C$)	29.60	29.30	34.50	31.70	42.50	42.70	43.40	29.80	36.90	40.60	36.34	31.90
g_r ($^{\circ}C$)	16.70	10.28	14.30	17.40	15.90	17.70	6.77	15.00	19.00	17.80	8.50	12.10
Heat Run Test 2:												
Cooling mode	5	2	0	2	2	0	2	5	2	2	2	2
S_r (MVA)	80	2.3	-	63	40	-	7.5	100	6.25	40	20	20
P_{nl} (W)	23110	3145	-	23870	16310	-	6600	18494	5962	9900	17000	19700
P_{lr} (W)	396900	18966	-	332920	212160	-	70620	396618	49547	312790	91000	102100
$\Delta\theta_{or}$ ($^{\circ}C$)	51.50	39.54	-	48.70	34.50	-	52.00	45.20	42.90	52.60	43.50	45.00
$\Delta\theta_{omr}$ ($^{\circ}C$)	49.00	34.18	-	35.90	24.40	-	37.00	44.10	34.60	36.80	28.97	33.00
g_r ($^{\circ}C$)	13.10	12.27	-	21.30	15.00	-	10.97	12.20	23.30	28.00	14.40	18.60
Heat Run Test 3:												
Cooling mode	0	0	0	0	0	0	0	0	0	0	6	6
S_r (MVA)	-	-	-	-	-	-	-	-	-	-	25	25
P_{nl} (W)	-	-	-	-	-	-	-	-	-	-	17000	19700
P_{lr} (W)	-	-	-	-	-	-	-	-	-	-	143000	159570
$\Delta\theta_{or}$ ($^{\circ}C$)	-	-	-	-	-	-	-	-	-	-	42.50	44.30
$\Delta\theta_{omr}$ ($^{\circ}C$)	-	-	-	-	-	-	-	-	-	-	41.82	43.30
g_r ($^{\circ}C$)	-	-	-	-	-	-	-	-	-	-	7.00	24.50
Notes:												
Cooling mode codes: ONAN = 1; ONAF = 2; OFAN = 3; OFAF = 4; ODAN = 5; ODAF = 6												
Refer to section 2.2.3, page 17 for definitions of the cooling modes.												
Up to three cooling modes for each transformer are handled by the cyclic rating calculator; where a transformer possesses fewer than three, the remaining cooling modes are stored as zeros; the cyclic rating calculator recognises the zeros and shifts execution to the next transformer (refer to section 6.2).												

Appendix G

MATLAB Script for the Load Shifting DSM Simulator

```

=====
%
%                               Demand Side Management (DSM) Simulator
%
%                               Andrew Atkinson
%
%                               August 2014
%
=====

% This program simulates the load shifting DSM effect on load profiles by decreasing
% peaks of load profiles and increasing troughs by the amount removed from the peaks
% such that the total energy for the load cycle remains the same.
% The algorithm is based on the work of Huang & Billinton (2012).

=====

clear all; close all; clc;

%*****
% USER INPUT:

max_peaks = [100, 95, 90, 85, 80];
% array of load peak limits in percent of unmodified peak; program will simulate DSM by
% reducing the peaks of each load profile to the percentages specified; the load removed
% from the peaks is added to the troughs such that the total energy remains the same for
% each profile
%*****

%
%-----
% LOAD DATA & INITIALISE VARIABLES:

load TX_data;           % loads data from Excel file containing all load profiles

inc = 1e-3;             % increment by which troughs will be increased gradually
t = (0:0.5:23.5)';     % array of 30 min time intervals for one 24 hour cycle

% Form one large matrix of all load profiles:
old_profiles = [standard_load_profiles, actual_load_profiles];

% Initialise matrix to contain all original and new DSM modified profiles:
num_profiles = (length(max_peaks))*size(old_profiles,2); % total number of profiles
DSM_profiles = zeros(length(t), num_profiles);

% Initialise matrix to contain load profile metrics:
profile_metrics = zeros(5, num_profiles);
%
%-----

%
%-----
% DSM SIMULATION:

p = 0; % initialise pointer

% Loop through each original profile in turn and reduce peak values to new DSM peak:
for n = 1:size(old_profiles,2)
    profile_100 = old_profiles(:,n); % extract original load profile (peak = 100%)

    % Loop through each DSM factor in turn:
    for m = 1:length(max_peaks)
        DSMF = max_peaks(m)/100; % extract max peak percentage & convert to fraction = DSMF
                                % (Demand Side Management Factor)
        peaks = find(profile_100 > DSMF); % indices of loads greater than DSMF
        profile_DSM = profile_100; % copy original load profile
        profile_DSM(peaks) = DSMF; % set loads greater than DSMF to DSMF
        load_shift = sum(profile_100 - profile_DSM); % calculate load removed from peaks

        % Add the load removed from the peaks to the troughs until it is reduced to zero:
        while load_shift > 0;
            troughs = find(profile_DSM == min(profile_DSM)); % find min loads
            profile_DSM(troughs) = profile_DSM(troughs) + inc; % increase troughs by increment
            load_shift = load_shift - length(troughs)*inc; % remaining load to shift
        end
    end
end

```

```
% Calculate metrics for the profile and store in metrics matrix:
min_load = min(profile_DSM);           % load minimum
max_load = max(profile_DSM);           % load maximum
avg_load  = trapz(t,profile_DSM)/t(end); % average load
load_factor = avg_load/max_load;       % load factor
RMS_load  = sqrt(trapz(t,(profile_DSM.^2))/t(end)); % load RMS

p = p + 1; % increment pointer
profile_metrics(:,p) = [min_load; max_load; avg_load; load_factor; RMS_load];

% normalise profile; *** ESSENTIAL FOR INPUT TO CYCLIC RATING CALCULATOR ***
% (if generating plots, comment out the following line)
profile_DSM = profile_DSM/max_load;

DSM_profiles(:,p) = profile_DSM; % store modified profile in output matrix

end % next DSM factor

end % next profile

save('TX_data','mass_data','AS_constants','ambient_temp_data','HRT_1_data', ...
     'HRT_2_data','HRT_3_data', 'standard_load_profiles', 'actual_load_profiles', ...
     'DSM_profiles','profile_metrics');
%
```

Appendix H

Load Profile Data

The load profile data presented in table H.1 over the following pages is **NOT NORMALISED** as the flowchart of figure 7.5 describes. This is because once normalised, the absolute values of the load profile samples are lost. Normalising these data is a straightforward process involving the division of each load profile by its maximum value. For each profile type, five sets of data are presented: one for each level of load shifting DSM carried out (100%, 95%, 90%, 85% & 80%).

Table H.1: Load profile data for input to the cyclic rating calculator.

Time (h)	Load profiles									
	Square					Residential				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.100	0.151	0.200	0.250	0.300	0.480	0.480	0.480	0.489	0.521
0030	0.100	0.151	0.200	0.250	0.300	0.470	0.470	0.470	0.489	0.521
0100	0.100	0.151	0.200	0.250	0.300	0.460	0.460	0.462	0.489	0.521
0130	0.100	0.151	0.200	0.250	0.300	0.440	0.440	0.462	0.489	0.521
0200	0.100	0.151	0.200	0.250	0.300	0.430	0.436	0.462	0.489	0.521
0230	0.100	0.151	0.200	0.250	0.300	0.420	0.436	0.462	0.489	0.521
0300	1.000	0.950	0.900	0.850	0.800	0.420	0.436	0.462	0.489	0.521
0330	1.000	0.950	0.900	0.850	0.800	0.410	0.436	0.462	0.489	0.521
0400	1.000	0.950	0.900	0.850	0.800	0.410	0.436	0.462	0.489	0.521
0430	1.000	0.950	0.900	0.850	0.800	0.420	0.436	0.462	0.489	0.521
0500	1.000	0.950	0.900	0.850	0.800	0.430	0.436	0.462	0.489	0.521
0530	1.000	0.950	0.900	0.850	0.800	0.460	0.460	0.462	0.489	0.521
0600	1.000	0.950	0.900	0.850	0.800	0.500	0.500	0.500	0.500	0.521
0630	1.000	0.950	0.900	0.850	0.800	0.560	0.560	0.560	0.560	0.560
0700	1.000	0.950	0.900	0.850	0.800	0.620	0.620	0.620	0.620	0.620
0730	1.000	0.950	0.900	0.850	0.800	0.660	0.660	0.660	0.660	0.660
0800	1.000	0.950	0.900	0.850	0.800	0.730	0.730	0.730	0.730	0.730
0830	1.000	0.950	0.900	0.850	0.800	0.760	0.760	0.760	0.760	0.760
0900	0.100	0.151	0.200	0.250	0.300	0.770	0.770	0.770	0.770	0.770
0930	0.100	0.151	0.200	0.250	0.300	0.760	0.760	0.760	0.760	0.760
1000	0.100	0.151	0.200	0.250	0.300	0.730	0.730	0.730	0.730	0.730
1030	0.100	0.151	0.200	0.250	0.300	0.720	0.720	0.720	0.720	0.720
1100	0.100	0.151	0.200	0.250	0.300	0.710	0.710	0.710	0.710	0.710
1130	0.100	0.151	0.200	0.250	0.300	0.700	0.700	0.700	0.700	0.700
1200	0.100	0.151	0.200	0.250	0.300	0.690	0.690	0.690	0.690	0.690
1230	0.100	0.151	0.200	0.250	0.300	0.690	0.690	0.690	0.690	0.690
1300	0.100	0.151	0.200	0.250	0.300	0.690	0.690	0.690	0.690	0.690
1330	0.100	0.151	0.200	0.250	0.300	0.690	0.690	0.690	0.690	0.690
1400	0.100	0.151	0.200	0.250	0.300	0.700	0.700	0.700	0.700	0.700
1430	0.100	0.151	0.200	0.250	0.300	0.720	0.720	0.720	0.720	0.720
1500	1.000	0.950	0.900	0.850	0.800	0.740	0.740	0.740	0.740	0.740
1530	1.000	0.950	0.900	0.850	0.800	0.760	0.760	0.760	0.760	0.760
1600	1.000	0.950	0.900	0.850	0.800	0.780	0.780	0.780	0.780	0.780
1630	1.000	0.950	0.900	0.850	0.800	0.820	0.820	0.820	0.820	0.800
1700	1.000	0.950	0.900	0.850	0.800	0.840	0.840	0.840	0.840	0.800
1730	1.000	0.950	0.900	0.850	0.800	0.880	0.880	0.880	0.850	0.800
1800	1.000	0.950	0.900	0.850	0.800	0.940	0.940	0.900	0.850	0.800
1830	1.000	0.950	0.900	0.850	0.800	1.000	0.950	0.900	0.850	0.800
1900	1.000	0.950	0.900	0.850	0.800	1.000	0.950	0.900	0.850	0.800
1930	1.000	0.950	0.900	0.850	0.800	0.960	0.950	0.900	0.850	0.800
2000	1.000	0.950	0.900	0.850	0.800	0.920	0.920	0.900	0.850	0.800
2030	1.000	0.950	0.900	0.850	0.800	0.860	0.860	0.860	0.850	0.800
2100	0.100	0.151	0.200	0.250	0.300	0.800	0.800	0.800	0.800	0.800
2130	0.100	0.151	0.200	0.250	0.300	0.760	0.760	0.760	0.760	0.760
2200	0.100	0.151	0.200	0.250	0.300	0.700	0.700	0.700	0.700	0.700
2230	0.100	0.151	0.200	0.250	0.300	0.640	0.640	0.640	0.640	0.640
2300	0.100	0.151	0.200	0.250	0.300	0.580	0.580	0.580	0.580	0.580
2330	0.100	0.151	0.200	0.250	0.300	0.520	0.520	0.520	0.520	0.521

Time (h)	Load profiles									
	Industrial					Mixed				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.700	0.700	0.762	0.824	0.839	0.500	0.500	0.500	0.585	0.673
0030	0.610	0.698	0.762	0.823	0.838	0.440	0.442	0.483	0.585	0.673
0100	0.610	0.698	0.762	0.823	0.838	0.420	0.442	0.483	0.585	0.673
0130	0.610	0.698	0.762	0.823	0.838	0.410	0.442	0.483	0.585	0.673
0200	0.610	0.698	0.762	0.823	0.838	0.410	0.442	0.483	0.585	0.673
0230	0.610	0.698	0.762	0.823	0.838	0.410	0.442	0.483	0.585	0.673
0300	0.610	0.698	0.762	0.823	0.838	0.410	0.442	0.483	0.585	0.673
0330	0.620	0.698	0.762	0.823	0.838	0.410	0.442	0.483	0.585	0.673
0400	0.620	0.698	0.762	0.823	0.838	0.420	0.442	0.483	0.585	0.673
0430	0.630	0.698	0.762	0.823	0.838	0.430	0.442	0.483	0.585	0.673
0500	0.650	0.698	0.762	0.823	0.838	0.460	0.460	0.483	0.585	0.673
0530	0.700	0.700	0.762	0.824	0.839	0.520	0.520	0.520	0.585	0.673
0600	0.740	0.740	0.762	0.824	0.839	0.600	0.600	0.600	0.600	0.674
0630	0.820	0.820	0.820	0.824	0.839	0.740	0.740	0.740	0.740	0.740
0700	0.880	0.880	0.880	0.850	0.839	0.800	0.800	0.800	0.800	0.800
0730	0.960	0.950	0.900	0.850	0.839	0.840	0.840	0.840	0.840	0.800
0800	1.000	0.950	0.900	0.850	0.839	0.860	0.860	0.860	0.850	0.800
0830	1.000	0.950	0.900	0.850	0.839	0.880	0.880	0.880	0.850	0.800
0900	1.000	0.950	0.900	0.850	0.839	0.890	0.890	0.890	0.850	0.800
0930	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1000	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1030	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1100	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1130	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1200	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1230	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1300	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1330	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1400	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1430	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1500	1.000	0.950	0.900	0.850	0.839	0.900	0.900	0.900	0.850	0.800
1530	0.980	0.950	0.900	0.850	0.839	0.910	0.910	0.900	0.850	0.800
1600	0.940	0.940	0.900	0.850	0.839	0.920	0.920	0.900	0.850	0.800
1630	0.900	0.900	0.900	0.850	0.839	0.930	0.930	0.900	0.850	0.800
1700	0.880	0.880	0.880	0.850	0.839	0.940	0.940	0.900	0.850	0.800
1730	0.880	0.880	0.880	0.850	0.839	0.970	0.950	0.900	0.850	0.800
1800	0.880	0.880	0.880	0.850	0.839	0.980	0.950	0.900	0.850	0.800
1830	0.880	0.880	0.880	0.850	0.839	1.000	0.950	0.900	0.850	0.800
1900	0.860	0.860	0.860	0.850	0.839	1.000	0.950	0.900	0.850	0.800
1930	0.860	0.860	0.860	0.850	0.839	0.990	0.950	0.900	0.850	0.800
2000	0.840	0.840	0.840	0.840	0.839	0.970	0.950	0.900	0.850	0.800
2030	0.820	0.820	0.820	0.824	0.839	0.880	0.880	0.880	0.850	0.800
2100	0.800	0.800	0.800	0.824	0.839	0.820	0.820	0.820	0.820	0.800
2130	0.780	0.780	0.780	0.824	0.839	0.760	0.760	0.760	0.760	0.760
2200	0.760	0.760	0.762	0.824	0.839	0.700	0.700	0.700	0.700	0.700
2230	0.740	0.740	0.762	0.824	0.839	0.630	0.630	0.630	0.630	0.674
2300	0.730	0.730	0.762	0.824	0.839	0.580	0.580	0.580	0.585	0.674
2330	0.720	0.720	0.762	0.824	0.839	0.540	0.540	0.540	0.585	0.673

Time (h)	Load profiles									
	Cairns					Cloncurry				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.523	0.523	0.559	0.613	0.665	0.625	0.625	0.642	0.698	0.755
0030	0.502	0.504	0.560	0.613	0.665	0.609	0.609	0.643	0.699	0.756
0100	0.486	0.504	0.559	0.613	0.664	0.594	0.594	0.642	0.698	0.755
0130	0.474	0.504	0.559	0.613	0.664	0.582	0.590	0.643	0.699	0.756
0200	0.466	0.504	0.560	0.613	0.665	0.573	0.591	0.643	0.699	0.756
0230	0.459	0.504	0.559	0.613	0.664	0.567	0.590	0.642	0.698	0.755
0300	0.455	0.504	0.560	0.613	0.665	0.563	0.590	0.643	0.699	0.756
0330	0.452	0.504	0.559	0.613	0.664	0.562	0.590	0.643	0.699	0.756
0400	0.452	0.504	0.560	0.614	0.665	0.561	0.591	0.643	0.699	0.756
0430	0.455	0.504	0.560	0.613	0.665	0.559	0.591	0.643	0.699	0.756
0500	0.462	0.504	0.560	0.613	0.665	0.570	0.590	0.642	0.698	0.756
0530	0.479	0.504	0.559	0.613	0.664	0.583	0.590	0.643	0.699	0.756
0600	0.501	0.504	0.559	0.613	0.664	0.612	0.612	0.643	0.699	0.756
0630	0.541	0.541	0.559	0.613	0.664	0.656	0.656	0.656	0.699	0.756
0700	0.588	0.588	0.588	0.613	0.665	0.696	0.696	0.696	0.699	0.756
0730	0.662	0.662	0.662	0.662	0.665	0.733	0.733	0.733	0.733	0.756
0800	0.729	0.729	0.729	0.729	0.729	0.746	0.746	0.746	0.746	0.756
0830	0.800	0.800	0.800	0.800	0.800	0.758	0.758	0.758	0.758	0.758
0900	0.859	0.859	0.859	0.850	0.800	0.765	0.765	0.765	0.765	0.765
0930	0.907	0.907	0.900	0.850	0.800	0.777	0.777	0.777	0.777	0.777
1000	0.930	0.930	0.900	0.850	0.800	0.790	0.790	0.790	0.790	0.790
1030	0.953	0.950	0.900	0.850	0.800	0.803	0.803	0.803	0.803	0.800
1100	0.965	0.950	0.900	0.850	0.800	0.814	0.814	0.814	0.814	0.800
1130	0.975	0.950	0.900	0.850	0.800	0.836	0.836	0.836	0.836	0.800
1200	0.986	0.950	0.900	0.850	0.800	0.853	0.853	0.853	0.850	0.800
1230	0.993	0.950	0.900	0.850	0.800	0.869	0.869	0.869	0.850	0.800
1300	0.997	0.950	0.900	0.850	0.800	0.882	0.882	0.882	0.850	0.800
1330	1.000	0.950	0.900	0.850	0.800	0.894	0.894	0.894	0.850	0.800
1400	0.999	0.950	0.900	0.850	0.800	0.906	0.906	0.900	0.850	0.800
1430	0.996	0.950	0.900	0.850	0.800	0.920	0.920	0.900	0.850	0.800
1500	0.990	0.950	0.900	0.850	0.800	0.933	0.933	0.900	0.850	0.800
1530	0.978	0.950	0.900	0.850	0.800	0.945	0.945	0.900	0.850	0.800
1600	0.967	0.950	0.900	0.850	0.800	0.952	0.950	0.900	0.850	0.800
1630	0.954	0.950	0.900	0.850	0.800	0.954	0.950	0.900	0.850	0.800
1700	0.940	0.940	0.900	0.850	0.800	0.948	0.948	0.900	0.850	0.800
1730	0.900	0.900	0.900	0.850	0.800	0.956	0.950	0.900	0.850	0.800
1800	0.842	0.842	0.842	0.842	0.800	0.970	0.950	0.900	0.850	0.800
1830	0.795	0.795	0.795	0.795	0.795	0.988	0.950	0.900	0.850	0.800
1900	0.773	0.773	0.773	0.773	0.773	1.000	0.950	0.900	0.850	0.800
1930	0.756	0.756	0.756	0.756	0.756	0.994	0.950	0.900	0.850	0.800
2000	0.744	0.744	0.744	0.744	0.744	0.976	0.950	0.900	0.850	0.800
2030	0.725	0.725	0.725	0.725	0.725	0.951	0.950	0.900	0.850	0.800
2100	0.706	0.706	0.706	0.706	0.706	0.891	0.891	0.891	0.850	0.800
2130	0.677	0.677	0.677	0.677	0.677	0.835	0.835	0.835	0.835	0.800
2200	0.652	0.652	0.652	0.652	0.665	0.774	0.774	0.774	0.774	0.774
2230	0.613	0.613	0.613	0.613	0.664	0.721	0.721	0.721	0.721	0.756
2300	0.583	0.583	0.583	0.613	0.665	0.680	0.680	0.680	0.699	0.756
2330	0.552	0.552	0.559	0.613	0.664	0.651	0.651	0.651	0.698	0.755

Time (h)	Load profiles									
	Croydon					Dalby				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.778	0.778	0.813	0.858	0.858	0.647	0.647	0.662	0.754	0.813
0030	0.770	0.770	0.813	0.858	0.858	0.613	0.613	0.662	0.753	0.812
0100	0.750	0.754	0.814	0.858	0.858	0.591	0.592	0.662	0.754	0.813
0130	0.736	0.754	0.814	0.858	0.858	0.575	0.592	0.662	0.754	0.813
0200	0.729	0.755	0.814	0.859	0.859	0.564	0.591	0.662	0.753	0.812
0230	0.717	0.754	0.814	0.858	0.858	0.557	0.592	0.662	0.754	0.813
0300	0.711	0.754	0.813	0.858	0.858	0.550	0.592	0.662	0.754	0.813
0330	0.708	0.755	0.814	0.859	0.859	0.524	0.591	0.662	0.754	0.813
0400	0.703	0.755	0.814	0.859	0.859	0.545	0.591	0.662	0.753	0.813
0430	0.698	0.754	0.814	0.858	0.858	0.553	0.592	0.662	0.754	0.813
0500	0.698	0.754	0.814	0.858	0.858	0.573	0.592	0.662	0.754	0.813
0530	0.699	0.754	0.814	0.859	0.859	0.604	0.604	0.662	0.754	0.813
0600	0.704	0.754	0.814	0.859	0.859	0.677	0.677	0.677	0.754	0.813
0630	0.719	0.754	0.813	0.858	0.858	0.745	0.745	0.745	0.754	0.813
0700	0.737	0.754	0.813	0.858	0.858	0.828	0.828	0.828	0.828	0.813
0730	0.774	0.774	0.814	0.859	0.859	0.866	0.866	0.866	0.850	0.813
0800	0.792	0.792	0.814	0.859	0.859	0.899	0.899	0.899	0.850	0.813
0830	0.814	0.814	0.814	0.859	0.859	0.922	0.922	0.900	0.850	0.813
0900	0.836	0.836	0.836	0.859	0.859	0.952	0.950	0.900	0.850	0.813
0930	0.858	0.858	0.858	0.859	0.859	0.958	0.950	0.900	0.850	0.813
1000	0.871	0.871	0.871	0.859	0.859	0.966	0.950	0.900	0.850	0.813
1030	0.882	0.882	0.882	0.859	0.859	0.965	0.950	0.900	0.850	0.813
1100	0.891	0.891	0.891	0.859	0.859	0.969	0.950	0.900	0.850	0.813
1130	0.913	0.913	0.900	0.859	0.859	0.976	0.950	0.900	0.850	0.813
1200	0.934	0.934	0.900	0.859	0.859	0.957	0.950	0.900	0.850	0.813
1230	0.957	0.950	0.900	0.859	0.859	0.955	0.950	0.900	0.850	0.813
1300	0.970	0.950	0.900	0.859	0.859	0.983	0.950	0.900	0.850	0.813
1330	0.978	0.950	0.900	0.859	0.859	0.995	0.950	0.900	0.850	0.813
1400	0.983	0.950	0.900	0.859	0.859	1.000	0.950	0.900	0.850	0.813
1430	0.990	0.950	0.900	0.859	0.859	0.994	0.950	0.900	0.850	0.813
1500	0.992	0.950	0.900	0.859	0.859	0.972	0.950	0.900	0.850	0.813
1530	1.000	0.950	0.900	0.859	0.859	0.928	0.928	0.900	0.850	0.813
1600	0.997	0.950	0.900	0.859	0.859	0.915	0.915	0.900	0.850	0.813
1630	0.991	0.950	0.900	0.859	0.859	0.908	0.908	0.900	0.850	0.813
1700	0.976	0.950	0.900	0.859	0.859	0.896	0.896	0.896	0.850	0.813
1730	0.963	0.950	0.900	0.859	0.859	0.892	0.892	0.892	0.850	0.813
1800	0.966	0.950	0.900	0.859	0.859	0.916	0.916	0.900	0.850	0.813
1830	0.969	0.950	0.900	0.859	0.859	0.909	0.909	0.900	0.850	0.813
1900	0.980	0.950	0.900	0.859	0.859	0.906	0.906	0.900	0.850	0.813
1930	0.986	0.950	0.900	0.859	0.859	0.899	0.899	0.899	0.850	0.813
2000	0.984	0.950	0.900	0.859	0.859	0.862	0.862	0.862	0.850	0.813
2030	0.961	0.950	0.900	0.859	0.859	0.873	0.873	0.873	0.850	0.813
2100	0.942	0.942	0.900	0.859	0.859	0.836	0.836	0.836	0.836	0.813
2130	0.903	0.903	0.900	0.859	0.859	0.779	0.779	0.779	0.779	0.813
2200	0.872	0.872	0.872	0.859	0.859	0.755	0.755	0.755	0.755	0.812
2230	0.836	0.836	0.836	0.858	0.859	0.811	0.811	0.811	0.811	0.813
2300	0.802	0.802	0.813	0.858	0.859	0.755	0.755	0.755	0.755	0.813
2330	0.797	0.797	0.814	0.859	0.859	0.704	0.704	0.704	0.754	0.813

Time (h)	Load profiles									
	Gladstone					Howard				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.999	0.950	0.900	0.880	0.881	0.720	0.720	0.720	0.720	0.720
0030	0.978	0.950	0.900	0.880	0.881	0.651	0.651	0.651	0.651	0.664
0100	0.967	0.950	0.900	0.880	0.881	0.579	0.579	0.579	0.598	0.663
0130	0.913	0.913	0.900	0.880	0.881	0.541	0.541	0.553	0.598	0.663
0200	0.946	0.946	0.900	0.880	0.881	0.520	0.521	0.553	0.598	0.663
0230	0.957	0.950	0.900	0.880	0.881	0.511	0.520	0.553	0.598	0.663
0300	0.950	0.950	0.900	0.880	0.881	0.510	0.521	0.554	0.598	0.664
0330	0.981	0.950	0.900	0.880	0.881	0.500	0.521	0.553	0.598	0.664
0400	1.000	0.950	0.900	0.880	0.881	0.494	0.521	0.553	0.598	0.663
0430	0.987	0.950	0.900	0.880	0.881	0.495	0.520	0.553	0.597	0.663
0500	0.973	0.950	0.900	0.880	0.881	0.504	0.521	0.553	0.598	0.663
0530	0.954	0.950	0.900	0.880	0.881	0.523	0.523	0.553	0.598	0.663
0600	0.889	0.889	0.889	0.880	0.881	0.553	0.553	0.553	0.598	0.663
0630	0.864	0.864	0.864	0.880	0.881	0.608	0.608	0.608	0.608	0.663
0700	0.832	0.832	0.862	0.880	0.881	0.668	0.668	0.668	0.668	0.668
0730	0.837	0.837	0.862	0.880	0.881	0.721	0.721	0.721	0.721	0.721
0800	0.844	0.844	0.863	0.881	0.881	0.750	0.750	0.750	0.750	0.750
0830	0.847	0.847	0.862	0.880	0.881	0.758	0.758	0.758	0.758	0.758
0900	0.828	0.828	0.862	0.880	0.881	0.765	0.765	0.765	0.765	0.765
0930	0.790	0.814	0.862	0.880	0.880	0.754	0.754	0.754	0.754	0.754
1000	0.791	0.814	0.862	0.880	0.880	0.736	0.736	0.736	0.736	0.736
1030	0.823	0.823	0.863	0.881	0.881	0.750	0.750	0.750	0.750	0.750
1100	0.808	0.814	0.862	0.880	0.881	0.753	0.753	0.753	0.753	0.753
1130	0.824	0.824	0.863	0.881	0.881	0.759	0.759	0.759	0.759	0.759
1200	0.840	0.840	0.863	0.881	0.881	0.773	0.773	0.773	0.773	0.773
1230	0.804	0.815	0.863	0.881	0.881	0.781	0.781	0.781	0.781	0.781
1300	0.794	0.814	0.862	0.880	0.880	0.775	0.775	0.775	0.775	0.775
1330	0.798	0.814	0.863	0.881	0.881	0.789	0.789	0.789	0.789	0.789
1400	0.779	0.814	0.862	0.880	0.880	0.802	0.802	0.802	0.802	0.800
1430	0.775	0.814	0.863	0.881	0.881	0.819	0.819	0.819	0.819	0.800
1500	0.782	0.814	0.862	0.881	0.881	0.826	0.826	0.826	0.826	0.800
1530	0.781	0.814	0.862	0.880	0.880	0.839	0.839	0.839	0.839	0.800
1600	0.791	0.814	0.862	0.880	0.880	0.849	0.849	0.849	0.849	0.800
1630	0.777	0.814	0.862	0.880	0.881	0.876	0.876	0.876	0.850	0.800
1700	0.776	0.814	0.862	0.880	0.881	0.904	0.904	0.900	0.850	0.800
1730	0.798	0.814	0.863	0.881	0.881	0.919	0.919	0.900	0.850	0.800
1800	0.811	0.814	0.862	0.880	0.881	0.946	0.946	0.900	0.850	0.800
1830	0.835	0.835	0.863	0.881	0.881	0.974	0.950	0.900	0.850	0.800
1900	0.906	0.906	0.900	0.880	0.881	1.000	0.950	0.900	0.850	0.800
1930	0.962	0.950	0.900	0.880	0.881	0.986	0.950	0.900	0.850	0.800
2000	0.939	0.939	0.900	0.880	0.881	0.943	0.943	0.900	0.850	0.800
2030	0.955	0.950	0.900	0.880	0.881	0.909	0.909	0.900	0.850	0.800
2100	0.941	0.941	0.900	0.880	0.881	0.891	0.891	0.891	0.850	0.800
2130	0.931	0.931	0.900	0.880	0.881	0.850	0.850	0.850	0.850	0.800
2200	0.968	0.950	0.900	0.880	0.881	0.848	0.848	0.848	0.848	0.800
2230	0.959	0.950	0.900	0.880	0.881	0.793	0.793	0.793	0.793	0.793
2300	0.980	0.950	0.900	0.880	0.881	0.817	0.817	0.817	0.817	0.800
2330	0.988	0.950	0.900	0.880	0.881	0.836	0.836	0.836	0.836	0.800

Time (h)	Load profiles									
	Mackay					Maryborough				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.903	0.903	0.900	0.850	0.800	0.687	0.687	0.687	0.727	0.804
0030	0.839	0.839	0.839	0.839	0.800	0.633	0.633	0.640	0.728	0.804
0100	0.779	0.779	0.779	0.779	0.779	0.558	0.558	0.640	0.728	0.805
0130	0.717	0.717	0.717	0.717	0.725	0.516	0.551	0.640	0.728	0.805
0200	0.685	0.685	0.685	0.702	0.725	0.498	0.551	0.640	0.728	0.805
0230	0.670	0.670	0.679	0.702	0.725	0.490	0.550	0.639	0.727	0.804
0300	0.657	0.660	0.680	0.703	0.726	0.486	0.550	0.639	0.728	0.804
0330	0.648	0.660	0.680	0.703	0.726	0.487	0.550	0.639	0.728	0.804
0400	0.640	0.659	0.679	0.702	0.725	0.488	0.550	0.640	0.728	0.804
0430	0.642	0.660	0.680	0.703	0.726	0.495	0.550	0.639	0.728	0.804
0500	0.642	0.660	0.680	0.703	0.726	0.509	0.551	0.640	0.728	0.805
0530	0.648	0.660	0.680	0.703	0.726	0.541	0.550	0.640	0.728	0.804
0600	0.661	0.661	0.679	0.702	0.726	0.579	0.579	0.639	0.728	0.804
0630	0.694	0.694	0.694	0.702	0.726	0.655	0.655	0.655	0.728	0.805
0700	0.722	0.722	0.722	0.722	0.725	0.725	0.725	0.725	0.728	0.804
0730	0.719	0.719	0.719	0.719	0.725	0.801	0.801	0.801	0.801	0.804
0800	0.682	0.682	0.682	0.702	0.726	0.861	0.861	0.861	0.850	0.804
0830	0.663	0.663	0.679	0.702	0.725	0.908	0.908	0.900	0.850	0.804
0900	0.654	0.660	0.679	0.702	0.725	0.949	0.949	0.900	0.850	0.804
0930	0.646	0.660	0.679	0.702	0.725	0.950	0.950	0.900	0.850	0.804
1000	0.640	0.660	0.680	0.703	0.726	0.953	0.950	0.900	0.850	0.804
1030	0.637	0.660	0.679	0.702	0.725	0.958	0.950	0.900	0.850	0.804
1100	0.640	0.660	0.679	0.702	0.726	0.967	0.950	0.900	0.850	0.804
1130	0.649	0.660	0.680	0.703	0.726	0.974	0.950	0.900	0.850	0.804
1200	0.658	0.660	0.680	0.702	0.726	0.984	0.950	0.900	0.850	0.804
1230	0.668	0.668	0.680	0.703	0.726	0.986	0.950	0.900	0.850	0.804
1300	0.673	0.673	0.679	0.702	0.725	0.988	0.950	0.900	0.850	0.804
1330	0.677	0.677	0.680	0.703	0.726	0.993	0.950	0.900	0.850	0.804
1400	0.684	0.684	0.684	0.702	0.726	1.000	0.950	0.900	0.850	0.804
1430	0.686	0.686	0.686	0.703	0.726	0.996	0.950	0.900	0.850	0.804
1500	0.685	0.685	0.685	0.702	0.725	0.987	0.950	0.900	0.850	0.804
1530	0.689	0.689	0.689	0.703	0.726	0.980	0.950	0.900	0.850	0.804
1600	0.696	0.696	0.696	0.702	0.725	0.978	0.950	0.900	0.850	0.804
1630	0.710	0.710	0.710	0.710	0.726	0.977	0.950	0.900	0.850	0.804
1700	0.734	0.734	0.734	0.734	0.734	0.972	0.950	0.900	0.850	0.804
1730	0.774	0.774	0.774	0.774	0.774	0.936	0.936	0.900	0.850	0.804
1800	0.821	0.821	0.821	0.821	0.800	0.921	0.921	0.900	0.850	0.804
1830	0.881	0.881	0.881	0.850	0.800	0.917	0.917	0.900	0.850	0.804
1900	0.950	0.950	0.900	0.850	0.800	0.920	0.920	0.900	0.850	0.804
1930	0.990	0.950	0.900	0.850	0.800	0.900	0.900	0.900	0.850	0.804
2000	1.000	0.950	0.900	0.850	0.800	0.865	0.865	0.865	0.850	0.804
2030	0.994	0.950	0.900	0.850	0.800	0.824	0.824	0.824	0.824	0.804
2100	0.989	0.950	0.900	0.850	0.800	0.819	0.819	0.819	0.819	0.804
2130	0.955	0.950	0.900	0.850	0.800	0.805	0.805	0.805	0.805	0.804
2200	0.901	0.901	0.900	0.850	0.800	0.837	0.837	0.837	0.837	0.804
2230	0.901	0.901	0.900	0.850	0.800	0.808	0.808	0.808	0.808	0.804
2300	0.915	0.915	0.900	0.850	0.800	0.788	0.788	0.788	0.788	0.804
2330	0.872	0.872	0.872	0.850	0.800	0.749	0.749	0.749	0.749	0.805

Time (h)	Load profiles									
	Rockhampton					Toowoomba				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.771	0.771	0.771	0.771	0.771	0.705	0.705	0.705	0.792	0.829
0030	0.701	0.701	0.701	0.701	0.701	0.623	0.623	0.685	0.792	0.830
0100	0.629	0.629	0.629	0.629	0.667	0.568	0.576	0.685	0.793	0.830
0130	0.579	0.579	0.579	0.608	0.666	0.535	0.575	0.685	0.792	0.829
0200	0.548	0.548	0.573	0.608	0.666	0.517	0.575	0.685	0.792	0.830
0230	0.534	0.540	0.573	0.608	0.666	0.509	0.576	0.685	0.793	0.830
0300	0.527	0.539	0.573	0.608	0.666	0.505	0.575	0.685	0.792	0.829
0330	0.523	0.540	0.573	0.608	0.666	0.508	0.575	0.685	0.792	0.829
0400	0.522	0.540	0.573	0.608	0.666	0.513	0.575	0.685	0.792	0.830
0430	0.526	0.540	0.573	0.608	0.667	0.520	0.575	0.685	0.792	0.829
0500	0.529	0.539	0.573	0.608	0.666	0.535	0.575	0.684	0.792	0.829
0530	0.547	0.547	0.573	0.608	0.666	0.571	0.576	0.685	0.793	0.830
0600	0.567	0.567	0.572	0.608	0.666	0.626	0.626	0.685	0.793	0.830
0630	0.600	0.600	0.600	0.608	0.666	0.714	0.714	0.714	0.792	0.830
0700	0.638	0.638	0.638	0.638	0.667	0.806	0.806	0.806	0.806	0.830
0730	0.685	0.685	0.685	0.685	0.685	0.889	0.889	0.889	0.850	0.830
0800	0.710	0.710	0.710	0.710	0.710	0.897	0.897	0.897	0.850	0.830
0830	0.728	0.728	0.728	0.728	0.728	0.908	0.908	0.900	0.850	0.830
0900	0.736	0.736	0.736	0.736	0.736	0.951	0.950	0.900	0.850	0.830
0930	0.749	0.749	0.749	0.749	0.749	0.933	0.933	0.900	0.850	0.830
1000	0.760	0.760	0.760	0.760	0.760	0.953	0.950	0.900	0.850	0.830
1030	0.759	0.759	0.759	0.759	0.759	0.943	0.943	0.900	0.850	0.830
1100	0.771	0.771	0.771	0.771	0.771	0.973	0.950	0.900	0.850	0.830
1130	0.781	0.781	0.781	0.781	0.781	0.975	0.950	0.900	0.850	0.830
1200	0.793	0.793	0.793	0.793	0.793	0.994	0.950	0.900	0.850	0.830
1230	0.816	0.816	0.816	0.816	0.800	0.978	0.950	0.900	0.850	0.830
1300	0.821	0.821	0.821	0.821	0.800	1.000	0.950	0.900	0.850	0.830
1330	0.819	0.819	0.819	0.819	0.800	0.992	0.950	0.900	0.850	0.830
1400	0.822	0.822	0.822	0.822	0.800	0.989	0.950	0.900	0.850	0.830
1430	0.836	0.836	0.836	0.836	0.800	0.987	0.950	0.900	0.850	0.830
1500	0.836	0.836	0.836	0.836	0.800	0.976	0.950	0.900	0.850	0.830
1530	0.827	0.827	0.827	0.827	0.800	0.965	0.950	0.900	0.850	0.830
1600	0.831	0.831	0.831	0.831	0.800	0.968	0.950	0.900	0.850	0.830
1630	0.843	0.843	0.843	0.843	0.800	0.959	0.950	0.900	0.850	0.830
1700	0.861	0.861	0.861	0.850	0.800	0.961	0.950	0.900	0.850	0.830
1730	0.889	0.889	0.889	0.850	0.800	0.941	0.941	0.900	0.850	0.830
1800	0.933	0.933	0.900	0.850	0.800	0.924	0.924	0.900	0.850	0.830
1830	0.938	0.938	0.900	0.850	0.800	0.915	0.915	0.900	0.850	0.830
1900	0.935	0.935	0.900	0.850	0.800	0.930	0.930	0.900	0.850	0.830
1930	0.966	0.950	0.900	0.850	0.800	0.924	0.924	0.900	0.850	0.830
2000	1.000	0.950	0.900	0.850	0.800	0.959	0.950	0.900	0.850	0.830
2030	0.961	0.950	0.900	0.850	0.800	0.970	0.950	0.900	0.850	0.830
2100	0.852	0.852	0.852	0.850	0.800	0.985	0.950	0.900	0.850	0.830
2130	0.803	0.803	0.803	0.803	0.800	0.985	0.950	0.900	0.850	0.830
2200	0.793	0.793	0.793	0.793	0.793	0.949	0.949	0.900	0.850	0.830
2230	0.774	0.774	0.774	0.774	0.774	0.847	0.847	0.847	0.847	0.830
2300	0.790	0.790	0.790	0.790	0.790	0.785	0.785	0.785	0.792	0.829
2330	0.801	0.801	0.801	0.801	0.800	0.767	0.767	0.767	0.792	0.830

Time (h)	Load profiles									
	Townsville Central					Townsville North				
	100%	95%	90%	85%	80%	100%	95%	90%	85%	80%
0000	0.518	0.518	0.580	0.637	0.692	0.691	0.691	0.711	0.764	0.808
0030	0.500	0.518	0.580	0.637	0.692	0.668	0.668	0.711	0.763	0.808
0100	0.486	0.518	0.581	0.637	0.692	0.651	0.653	0.711	0.763	0.808
0130	0.476	0.518	0.581	0.637	0.692	0.634	0.653	0.711	0.763	0.808
0200	0.468	0.518	0.580	0.637	0.692	0.624	0.653	0.711	0.764	0.808
0230	0.462	0.518	0.580	0.637	0.692	0.613	0.653	0.711	0.763	0.808
0300	0.456	0.518	0.580	0.637	0.692	0.619	0.653	0.711	0.764	0.808
0330	0.451	0.518	0.580	0.637	0.692	0.622	0.653	0.711	0.764	0.808
0400	0.452	0.518	0.580	0.637	0.692	0.621	0.652	0.710	0.763	0.807
0430	0.462	0.518	0.580	0.637	0.692	0.617	0.653	0.711	0.763	0.808
0500	0.467	0.518	0.580	0.636	0.692	0.620	0.652	0.711	0.763	0.807
0530	0.484	0.518	0.580	0.636	0.691	0.647	0.653	0.711	0.763	0.808
0600	0.511	0.518	0.580	0.636	0.692	0.672	0.672	0.711	0.763	0.807
0630	0.593	0.593	0.593	0.637	0.692	0.727	0.727	0.727	0.764	0.808
0700	0.690	0.690	0.690	0.690	0.692	0.794	0.794	0.794	0.794	0.808
0730	0.777	0.777	0.777	0.777	0.777	0.850	0.850	0.850	0.850	0.808
0800	0.849	0.849	0.849	0.849	0.800	0.908	0.908	0.900	0.850	0.808
0830	0.899	0.899	0.899	0.850	0.800	0.944	0.944	0.900	0.850	0.808
0900	0.933	0.933	0.900	0.850	0.800	0.948	0.948	0.900	0.850	0.808
0930	0.956	0.950	0.900	0.850	0.800	0.942	0.942	0.900	0.850	0.808
1000	0.969	0.950	0.900	0.850	0.800	0.948	0.948	0.900	0.850	0.808
1030	0.979	0.950	0.900	0.850	0.800	0.959	0.950	0.900	0.850	0.808
1100	0.981	0.950	0.900	0.850	0.800	0.970	0.950	0.900	0.850	0.808
1130	0.985	0.950	0.900	0.850	0.800	0.976	0.950	0.900	0.850	0.808
1200	0.992	0.950	0.900	0.850	0.800	0.980	0.950	0.900	0.850	0.808
1230	0.998	0.950	0.900	0.850	0.800	0.979	0.950	0.900	0.850	0.808
1300	1.000	0.950	0.900	0.850	0.800	0.978	0.950	0.900	0.850	0.808
1330	1.000	0.950	0.900	0.850	0.800	0.993	0.950	0.900	0.850	0.808
1400	1.000	0.950	0.900	0.850	0.800	1.000	0.950	0.900	0.850	0.808
1430	0.998	0.950	0.900	0.850	0.800	0.972	0.950	0.900	0.850	0.808
1500	0.990	0.950	0.900	0.850	0.800	0.952	0.950	0.900	0.850	0.808
1530	0.985	0.950	0.900	0.850	0.800	0.921	0.921	0.900	0.850	0.808
1600	0.978	0.950	0.900	0.850	0.800	0.900	0.900	0.900	0.850	0.808
1630	0.972	0.950	0.900	0.850	0.800	0.876	0.876	0.876	0.850	0.808
1700	0.958	0.950	0.900	0.850	0.800	0.844	0.844	0.844	0.844	0.808
1730	0.915	0.915	0.900	0.850	0.800	0.802	0.802	0.802	0.802	0.808
1800	0.852	0.852	0.852	0.850	0.800	0.773	0.773	0.773	0.773	0.807
1830	0.776	0.776	0.776	0.776	0.776	0.777	0.777	0.777	0.777	0.807
1900	0.758	0.758	0.758	0.758	0.758	0.793	0.793	0.793	0.793	0.808
1930	0.742	0.742	0.742	0.742	0.742	0.824	0.824	0.824	0.824	0.808
2000	0.722	0.722	0.722	0.722	0.722	0.828	0.828	0.828	0.828	0.808
2030	0.705	0.705	0.705	0.705	0.705	0.843	0.843	0.843	0.843	0.808
2100	0.681	0.681	0.681	0.681	0.692	0.824	0.824	0.824	0.824	0.808
2130	0.649	0.649	0.649	0.649	0.692	0.787	0.787	0.787	0.787	0.808
2200	0.621	0.621	0.621	0.637	0.692	0.753	0.753	0.753	0.763	0.808
2230	0.594	0.594	0.594	0.636	0.691	0.722	0.722	0.722	0.763	0.808
2300	0.573	0.573	0.580	0.637	0.692	0.695	0.695	0.711	0.764	0.808
2330	0.547	0.547	0.580	0.636	0.692	0.699	0.699	0.711	0.764	0.808

Appendix I

Cyclic Rating Calculator Output

The data presented in table I.1 is from the output of the cyclic rating calculator. It is from this data that the percentage changes were calculated. For conciseness, the percentage change data is not included as it is possible to calculate it from table I.1.

Table I.1: Selected output data from the cyclic rating calculator output.

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Cair	ONAN	Sq_100	1.00	0.56	0.56	37.12	83.99	38.54	112.41	1.230	24.00	Age
Cair	ONAN	Sq_95	0.95	0.56	0.59	38.14	83.93	40.73	112.32	1.229	23.99	Age
Cair	ONAN	Sq_90	0.90	0.56	0.62	39.68	83.85	43.69	112.19	1.227	24.00	Age
Cair	ONAN	Sq_85	0.85	0.56	0.65	41.94	83.73	47.69	111.97	1.224	24.00	Age
Cair	ONAN	Sq_80	0.80	0.56	0.69	45.02	83.54	52.87	111.66	1.220	23.99	Age
Cair	ONAN	Res_100	1.00	0.67	0.67	50.27	88.16	60.84	119.29	1.334	24.00	Age
Cair	ONAN	Res_95	0.95	0.67	0.71	51.10	87.48	62.29	117.73	1.291	23.99	Age
Cair	ONAN	Res_90	0.90	0.67	0.75	52.67	86.41	64.96	115.65	1.257	24.00	Age
Cair	ONAN	Res_85	0.85	0.67	0.79	55.04	84.78	68.84	113.04	1.225	23.99	Age
Cair	ONAN	Res_80	0.80	0.67	0.84	58.23	82.85	73.87	110.17	1.193	24.00	Age
Cair	ONAN	Ind_100	1.00	0.84	0.84	56.20	81.99	70.69	108.89	1.179	23.99	Age
Cair	ONAN	Ind_95	0.95	0.84	0.89	62.16	80.95	79.88	107.39	1.164	24.00	Age
Cair	ONAN	Ind_90	0.90	0.84	0.93	68.44	79.49	89.21	105.27	1.142	24.00	Age
Cair	ONAN	Ind_85	0.85	0.84	0.99	74.78	77.04	98.46	101.74	1.104	24.00	Age
Cair	ONAN	Ind_80	0.84	0.84	1.00	76.07	76.15	100.33	100.45	1.091	23.99	Age
Cair	ONAN	Mix_100	1.00	0.76	0.76	49.06	84.32	58.84	112.57	1.236	23.99	Age
Cair	ONAN	Mix_95	0.95	0.76	0.80	49.72	82.54	60.19	109.78	1.191	23.99	Age
Cair	ONAN	Mix_90	0.90	0.76	0.84	51.46	80.07	63.06	106.11	1.150	23.99	Age
Cair	ONAN	Mix_85	0.85	0.76	0.89	58.57	79.48	74.44	105.26	1.141	24.00	Age
Cair	ONAN	Mix_80	0.80	0.76	0.94	67.49	78.64	87.79	104.05	1.129	24.00	Age
Cair	ONAN	Cair_100	1.00	0.74	0.74	48.73	84.08	58.99	112.10	1.221	24.00	Age
Cair	ONAN	Cair_95	0.95	0.74	0.78	51.18	82.87	63.16	110.17	1.193	24.00	Age
Cair	ONAN	Cair_90	0.90	0.74	0.82	55.73	82.04	70.23	108.95	1.180	23.99	Age
Cair	ONAN	Cair_85	0.85	0.74	0.87	61.34	81.23	78.71	107.79	1.168	24.00	Age
Cair	ONAN	Cair_80	0.80	0.73	0.92	67.73	80.01	88.16	106.03	1.149	23.99	Age
Cair	ODAN	Sq_100	1.00	0.56	0.56	32.10	90.87	32.31	112.42	1.125	23.99	Age
Cair	ODAN	Sq_95	0.95	0.56	0.59	33.02	90.83	33.56	112.36	1.124	24.00	Age
Cair	ODAN	Sq_90	0.90	0.56	0.62	34.47	90.77	35.53	112.27	1.124	23.99	Age
Cair	ODAN	Sq_85	0.85	0.56	0.65	36.69	90.67	38.55	112.12	1.122	23.99	Age
Cair	ODAN	Sq_80	0.80	0.56	0.69	39.92	90.53	42.92	111.91	1.120	24.00	Age
Cair	ODAN	Res_100	1.00	0.67	0.67	60.77	93.88	68.42	119.02	1.268	23.99	Age
Cair	ODAN	Res_95	0.95	0.67	0.71	60.93	93.71	68.70	118.34	1.225	24.00	Age
Cair	ODAN	Res_90	0.90	0.67	0.75	61.15	92.95	69.18	117.06	1.192	23.99	Age
Cair	ODAN	Res_85	0.85	0.67	0.79	61.78	92.04	70.14	114.97	1.160	24.00	Age
Cair	ODAN	Res_80	0.80	0.67	0.84	63.41	90.50	73.02	112.25	1.130	23.99	Age
Cair	ODAN	Ind_100	1.00	0.84	0.84	59.70	89.49	68.64	110.71	1.116	23.99	Age
Cair	ODAN	Ind_95	0.95	0.84	0.89	64.86	88.33	76.08	108.99	1.101	24.00	Age
Cair	ODAN	Ind_90	0.90	0.84	0.93	72.08	86.65	86.33	106.53	1.080	24.00	Age
Cair	ODAN	Ind_85	0.85	0.84	0.99	80.47	83.54	97.97	102.17	1.046	24.00	Age
Cair	ODAN	Ind_80	0.84	0.84	1.00	82.20	82.30	100.32	100.46	1.033	23.99	Age
Cair	ODAN	Mix_100	1.00	0.76	0.76	60.67	91.41	67.64	113.97	1.169	23.99	Age
Cair	ODAN	Mix_95	0.95	0.76	0.80	59.87	90.05	66.75	111.66	1.127	24.00	Age
Cair	ODAN	Mix_90	0.90	0.76	0.84	59.06	87.70	66.24	107.88	1.089	24.00	Age
Cair	ODAN	Mix_85	0.85	0.76	0.89	62.40	87.00	72.31	106.89	1.081	24.00	Age
Cair	ODAN	Mix_80	0.80	0.76	0.94	71.43	85.84	85.23	105.29	1.069	23.99	Age
Cair	ODAN	Cair_100	1.00	0.74	0.74	53.21	90.89	59.49	112.85	1.156	23.99	Age
Cair	ODAN	Cair_95	0.95	0.74	0.78	54.38	90.54	61.06	112.15	1.129	23.99	Age
Cair	ODAN	Cair_90	0.90	0.74	0.82	57.54	89.88	65.93	111.11	1.116	23.99	Age
Cair	ODAN	Cair_85	0.85	0.74	0.87	63.18	88.85	73.99	109.64	1.105	23.99	Age
Cair	ODAN	Cair_80	0.80	0.73	0.92	70.87	87.38	84.79	107.53	1.088	23.99	Age
Clon	ONAN	Sq_100	1.00	0.56	0.56	46.42	83.49	47.06	108.97	1.497	10.63	CRF

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Clon	ONAN	Sq_95	0.95	0.56	0.59	47.30	83.61	48.65	109.09	1.497	10.92	CRF
Clon	ONAN	Sq_90	0.90	0.56	0.62	48.66	83.79	50.96	109.27	1.497	11.37	CRF
Clon	ONAN	Sq_85	0.85	0.56	0.65	50.67	84.06	54.26	109.54	1.497	12.10	CRF
Clon	ONAN	Sq_80	0.80	0.56	0.69	53.45	84.44	58.76	109.92	1.497	13.23	CRF
Clon	ONAN	Res_100	1.00	0.67	0.67	64.82	77.41	73.02	100.81	1.497	4.05	CRF
Clon	ONAN	Res_95	0.95	0.67	0.71	66.68	79.99	75.64	104.51	1.497	6.20	CRF
Clon	ONAN	Res_90	0.90	0.67	0.75	68.43	82.16	78.42	107.28	1.497	9.26	CRF
Clon	ONAN	Res_85	0.85	0.67	0.79	70.33	84.15	81.63	109.60	1.497	14.05	CRF
Clon	ONAN	Res_80	0.80	0.67	0.84	72.64	85.99	85.97	111.47	1.497	21.59	CRF
Clon	ONAN	Ind_100	1.00	0.84	0.84	70.50	85.97	83.32	111.21	1.493	23.77	CRF
Clon	ONAN	Ind_95	0.95	0.84	0.89	72.82	85.19	88.03	109.64	1.464	24.00	Age
Clon	ONAN	Ind_90	0.90	0.84	0.93	76.17	83.91	94.19	107.42	1.424	24.00	Age
Clon	ONAN	Ind_85	0.85	0.84	0.99	80.26	81.97	101.20	103.98	1.366	23.99	Age
Clon	ONAN	Ind_80	0.84	0.84	1.00	81.18	81.22	102.69	102.78	1.348	23.99	Age
Clon	ONAN	Mix_100	1.00	0.76	0.76	69.50	83.68	77.63	108.48	1.497	13.46	CRF
Clon	ONAN	Mix_95	0.95	0.76	0.80	71.20	86.18	80.19	111.65	1.497	22.20	CRF
Clon	ONAN	Mix_90	0.90	0.76	0.84	70.96	85.54	81.06	109.81	1.452	23.99	Age
Clon	ONAN	Mix_85	0.85	0.76	0.89	72.18	84.95	85.61	108.77	1.435	24.00	Age
Clon	ONAN	Mix_80	0.80	0.76	0.94	76.10	83.79	93.62	106.86	1.407	23.99	Age
Clon	ONAN	Clon_100	1.00	0.78	0.78	69.41	83.36	81.16	108.01	1.497	12.32	CRF
Clon	ONAN	Clon_95	0.95	0.78	0.82	71.71	86.08	84.67	111.56	1.497	20.42	CRF
Clon	ONAN	Clon_90	0.90	0.78	0.87	73.55	86.13	88.61	110.96	1.477	24.00	Age
Clon	ONAN	Clon_85	0.85	0.78	0.92	76.04	84.78	93.54	108.67	1.437	24.00	Age
Clon	ONAN	Clon_80	0.80	0.78	0.97	79.61	82.60	100.13	105.01	1.382	23.99	Age
Clon	ONAF	Sq_100	1.00	0.56	0.56	47.25	89.20	47.94	116.63	1.403	23.99	Age
Clon	ONAF	Sq_95	0.95	0.56	0.59	48.24	89.16	49.68	116.51	1.400	24.00	Age
Clon	ONAF	Sq_90	0.90	0.56	0.62	49.74	89.10	52.19	116.30	1.396	23.99	Age
Clon	ONAF	Sq_85	0.85	0.56	0.65	51.90	89.00	55.71	115.99	1.389	24.00	Age
Clon	ONAF	Sq_80	0.80	0.56	0.69	54.84	88.85	60.39	115.54	1.380	24.00	Age
Clon	ONAF	Res_100	1.00	0.67	0.67	71.34	87.97	81.31	115.96	1.497	18.41	CRF
Clon	ONAF	Res_95	0.95	0.67	0.71	72.50	89.52	83.01	117.94	1.469	24.00	Age
Clon	ONAF	Res_90	0.90	0.67	0.75	72.58	89.11	83.63	116.67	1.420	23.99	Age
Clon	ONAF	Res_85	0.85	0.67	0.79	72.76	88.37	84.53	114.83	1.372	24.00	Age
Clon	ONAF	Res_80	0.80	0.67	0.84	73.30	87.44	86.42	112.52	1.327	24.00	Age
Clon	ONAF	Ind_100	1.00	0.84	0.84	70.66	86.80	83.14	111.34	1.313	23.99	Age
Clon	ONAF	Ind_95	0.95	0.84	0.89	73.06	85.94	87.83	109.68	1.287	23.99	Age
Clon	ONAF	Ind_90	0.90	0.84	0.93	76.57	84.61	94.08	107.46	1.252	24.00	Age
Clon	ONAF	Ind_85	0.85	0.84	0.99	80.82	82.60	101.18	103.99	1.201	23.99	Age
Clon	ONAF	Ind_80	0.84	0.84	1.00	81.78	81.83	102.70	102.79	1.186	23.99	Age
Clon	ONAF	Mix_100	1.00	0.76	0.76	72.09	88.15	80.69	114.06	1.378	24.00	Age
Clon	ONAF	Mix_95	0.95	0.76	0.80	71.61	87.43	80.50	112.41	1.324	24.00	Age
Clon	ONAF	Mix_90	0.90	0.76	0.84	71.03	86.26	80.87	109.82	1.276	24.00	Age
Clon	ONAF	Mix_85	0.85	0.76	0.89	72.35	85.65	85.39	108.78	1.262	24.00	Age
Clon	ONAF	Mix_80	0.80	0.76	0.94	76.44	84.47	93.47	106.89	1.237	24.00	Age
Clon	ONAF	Clon_100	1.00	0.78	0.78	72.36	88.41	84.82	114.46	1.387	23.99	Age
Clon	ONAF	Clon_95	0.95	0.78	0.82	72.55	87.89	85.40	113.13	1.332	24.00	Age
Clon	ONAF	Clon_90	0.90	0.78	0.87	73.78	86.88	88.41	110.99	1.298	24.00	Age
Clon	ONAF	Clon_85	0.85	0.78	0.92	76.41	85.49	93.40	108.70	1.264	23.99	Age
Clon	ONAF	Clon_80	0.80	0.78	0.97	80.15	83.24	100.10	105.03	1.215	24.00	Age
Croy	ONAN	Sq_100	1.00	0.56	0.56	47.26	83.51	48.05	114.85	1.386	24.00	Age
Croy	ONAN	Sq_95	0.95	0.56	0.59	48.08	83.49	49.73	114.73	1.383	24.00	Age
Croy	ONAN	Sq_90	0.90	0.56	0.62	49.34	83.45	52.14	114.55	1.379	24.00	Age
Croy	ONAN	Sq_85	0.85	0.56	0.65	51.17	83.38	55.53	114.26	1.373	23.99	Age
Croy	ONAN	Sq_80	0.80	0.56	0.69	53.68	83.27	60.04	113.84	1.364	23.99	Age
Croy	ONAN	Res_100	1.00	0.67	0.67	68.07	83.13	78.98	115.92	1.497	19.63	CRF
Croy	ONAN	Res_95	0.95	0.67	0.71	68.91	84.16	80.47	117.15	1.462	24.00	Age
Croy	ONAN	Res_90	0.90	0.67	0.75	69.04	83.81	81.39	115.76	1.413	24.00	Age
Croy	ONAN	Res_85	0.85	0.67	0.79	69.29	83.19	82.66	113.78	1.366	23.99	Age
Croy	ONAN	Res_80	0.80	0.67	0.84	69.87	82.39	84.88	111.38	1.320	24.00	Age
Croy	ONAN	Ind_100	1.00	0.84	0.84	67.58	81.81	81.74	110.22	1.307	23.99	Age
Croy	ONAN	Ind_95	0.95	0.84	0.89	69.75	81.06	86.78	108.55	1.280	24.00	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Croy	ONAN	Ind_90	0.90	0.84	0.93	72.85	79.90	93.08	106.30	1.245	23.99	Age
Croy	ONAN	Ind_85	0.85	0.84	0.99	76.58	78.13	100.10	102.86	1.195	23.99	Age
Croy	ONAN	Ind_80	0.84	0.84	1.00	77.42	77.46	101.58	101.67	1.180	24.00	Age
Croy	ONAN	Mix_100	1.00	0.76	0.76	68.40	83.04	77.83	113.11	1.372	23.99	Age
Croy	ONAN	Mix_95	0.95	0.76	0.80	68.05	82.41	77.92	111.31	1.318	24.00	Age
Croy	ONAN	Mix_90	0.90	0.76	0.84	67.66	81.37	78.76	108.64	1.270	23.99	Age
Croy	ONAN	Mix_85	0.85	0.76	0.89	69.04	80.83	84.06	107.58	1.255	24.00	Age
Croy	ONAN	Mix_80	0.80	0.76	0.94	72.73	79.79	92.41	105.71	1.231	24.00	Age
Croy	ONAN	Croy_100	1.00	0.86	0.86	70.46	81.49	87.51	109.38	1.312	24.00	Age
Croy	ONAN	Croy_95	0.95	0.86	0.91	71.90	80.97	90.92	108.05	1.267	23.99	Age
Croy	ONAN	Croy_90	0.90	0.86	0.96	74.79	79.48	96.74	105.28	1.227	23.99	Age
Croy	ONAN	Croy_85	0.86	0.86	1.00	77.43	77.46	101.60	101.67	1.180	24.00	Age
Croy	ONAN	Croy_80	0.86	0.86	1.00	77.43	77.46	101.60	101.67	1.180	24.00	Age
Dalb	ONAN	Sq_100	1.00	0.56	0.56	34.97	84.69	36.51	115.42	1.266	24.00	Age
Dalb	ONAN	Sq_95	0.95	0.56	0.59	36.07	84.64	38.88	115.33	1.265	23.99	Age
Dalb	ONAN	Sq_90	0.90	0.56	0.62	37.73	84.56	42.06	115.19	1.263	24.00	Age
Dalb	ONAN	Sq_85	0.85	0.56	0.65	40.14	84.44	46.37	114.98	1.260	23.99	Age
Dalb	ONAN	Sq_80	0.80	0.56	0.69	43.43	84.26	51.93	114.67	1.256	23.99	Age
Dalb	ONAN	Res_100	1.00	0.67	0.67	46.57	87.31	57.35	119.99	1.330	17.22	WHS
Dalb	ONAN	Res_95	0.95	0.67	0.71	48.12	87.94	59.76	119.99	1.307	21.10	WHS
Dalb	ONAN	Res_90	0.90	0.67	0.75	50.46	87.41	63.67	118.84	1.288	23.99	Age
Dalb	ONAN	Res_85	0.85	0.67	0.79	53.34	85.58	68.19	116.03	1.257	24.00	Age
Dalb	ONAN	Res_80	0.80	0.67	0.84	57.11	83.55	74.01	113.06	1.227	24.00	Age
Dalb	ONAN	Ind_100	1.00	0.84	0.84	54.76	82.61	70.29	111.67	1.213	24.00	Age
Dalb	ONAN	Ind_95	0.95	0.84	0.89	61.55	81.61	80.72	110.22	1.198	23.99	Age
Dalb	ONAN	Ind_90	0.90	0.84	0.93	68.43	80.19	90.97	108.17	1.178	23.99	Age
Dalb	ONAN	Ind_85	0.85	0.84	0.99	75.32	77.73	101.08	104.60	1.142	23.99	Age
Dalb	ONAN	Ind_80	0.84	0.84	1.00	76.71	76.80	103.11	103.24	1.128	24.00	Age
Dalb	ONAN	Mix_100	1.00	0.76	0.76	45.85	85.41	56.10	116.04	1.269	23.99	Age
Dalb	ONAN	Mix_95	0.95	0.76	0.80	47.04	83.32	57.94	112.76	1.225	23.99	Age
Dalb	ONAN	Mix_90	0.90	0.76	0.84	49.33	80.61	61.88	108.78	1.184	23.99	Age
Dalb	ONAN	Mix_85	0.85	0.76	0.89	57.63	80.05	74.81	107.96	1.176	23.99	Age
Dalb	ONAN	Mix_80	0.80	0.76	0.94	67.37	79.29	89.40	106.87	1.165	23.99	Age
Dalb	ONAN	Dalb_100	1.00	0.82	0.82	51.93	83.98	65.81	113.86	1.245	23.99	Age
Dalb	ONAN	Dalb_95	0.95	0.82	0.86	54.72	81.91	70.26	110.68	1.203	24.00	Age
Dalb	ONAN	Dalb_90	0.90	0.82	0.91	60.80	80.23	79.59	108.23	1.178	23.99	Age
Dalb	ONAN	Dalb_85	0.85	0.81	0.96	70.43	79.02	93.91	106.48	1.161	24.00	Age
Dalb	ONAN	Dalb_80	0.81	0.81	1.00	76.75	76.79	103.17	103.24	1.128	23.99	Age
Dalb	ONAF	Sq_100	1.00	0.56	0.56	32.36	82.01	33.95	113.66	1.108	24.00	Age
Dalb	ONAF	Sq_95	0.95	0.56	0.59	33.46	81.98	36.36	113.60	1.108	23.99	Age
Dalb	ONAF	Sq_90	0.90	0.56	0.62	35.12	81.92	39.59	113.50	1.107	24.00	Age
Dalb	ONAF	Sq_85	0.85	0.56	0.65	37.52	81.82	43.94	113.35	1.105	23.99	Age
Dalb	ONAF	Sq_80	0.80	0.56	0.69	40.79	81.69	49.57	113.14	1.103	24.00	Age
Dalb	ONAF	Res_100	1.00	0.67	0.67	44.30	85.75	55.25	120.00	1.180	16.19	WHS
Dalb	ONAF	Res_95	0.95	0.67	0.71	46.07	86.20	58.35	119.99	1.166	20.76	WHS
Dalb	ONAF	Res_90	0.90	0.67	0.75	48.72	85.53	62.69	118.76	1.150	23.99	Age
Dalb	ONAF	Res_85	0.85	0.67	0.79	51.69	83.62	67.40	115.86	1.124	23.99	Age
Dalb	ONAF	Res_80	0.80	0.67	0.84	55.54	81.62	73.44	112.89	1.098	24.00	Age
Dalb	ONAF	Ind_100	1.00	0.84	0.84	53.00	80.70	69.21	111.52	1.086	24.00	Age
Dalb	ONAF	Ind_95	0.95	0.84	0.89	60.00	79.76	80.33	110.12	1.073	23.99	Age
Dalb	ONAF	Ind_90	0.90	0.84	0.93	66.84	78.42	90.77	108.13	1.056	23.99	Age
Dalb	ONAF	Ind_85	0.85	0.84	0.99	73.68	76.05	101.06	104.60	1.024	24.00	Age
Dalb	ONAF	Ind_80	0.84	0.84	1.00	75.05	75.14	103.11	103.24	1.011	23.99	Age
Dalb	ONAF	Mix_100	1.00	0.76	0.76	43.57	83.69	54.05	116.33	1.136	23.99	Age
Dalb	ONAF	Mix_95	0.95	0.76	0.80	44.98	81.47	56.52	112.68	1.096	23.99	Age
Dalb	ONAF	Mix_90	0.90	0.76	0.84	47.64	78.77	60.95	108.65	1.060	24.00	Age
Dalb	ONAF	Mix_85	0.85	0.76	0.89	56.11	78.22	74.33	107.84	1.053	24.00	Age
Dalb	ONAF	Mix_80	0.80	0.76	0.94	65.79	77.53	89.17	106.81	1.044	24.00	Age
Dalb	ONAF	Dalb_100	1.00	0.82	0.82	50.01	82.27	64.16	114.07	1.115	24.00	Age
Dalb	ONAF	Dalb_95	0.95	0.82	0.86	53.07	80.06	69.55	110.57	1.077	23.99	Age
Dalb	ONAF	Dalb_90	0.90	0.82	0.91	59.24	78.42	79.16	108.14	1.056	24.00	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Dalb	ONAF	Dalb_85	0.85	0.81	0.96	68.81	77.29	93.73	106.45	1.041	23.99	Age
Dalb	ONAF	Dalb_80	0.81	0.81	1.00	75.09	75.13	103.16	103.24	1.012	23.99	Age
Glad	ONAN	Sq_100	1.00	0.56	0.56	36.96	88.89	38.23	114.32	1.173	23.99	Age
Glad	ONAN	Sq_95	0.95	0.56	0.59	38.10	88.83	40.43	114.23	1.172	23.99	Age
Glad	ONAN	Sq_90	0.90	0.56	0.62	39.83	88.74	43.42	114.08	1.170	24.00	Age
Glad	ONAN	Sq_85	0.85	0.56	0.65	42.34	88.60	47.49	113.86	1.167	23.99	Age
Glad	ONAN	Sq_80	0.80	0.56	0.69	45.77	88.39	52.80	113.54	1.163	24.00	Age
Glad	ONAN	Res_100	1.00	0.67	0.67	49.21	92.70	58.31	120.00	1.244	20.54	WHS
Glad	ONAN	Res_95	0.95	0.67	0.71	50.77	92.98	60.49	119.72	1.219	24.00	Age
Glad	ONAN	Res_90	0.90	0.67	0.75	52.98	91.48	63.87	117.39	1.190	24.00	Age
Glad	ONAN	Res_85	0.85	0.67	0.79	55.97	89.51	68.21	114.61	1.161	24.00	Age
Glad	ONAN	Res_80	0.80	0.67	0.84	59.88	87.36	73.80	111.66	1.133	24.00	Age
Glad	ONAN	Ind_100	1.00	0.84	0.84	57.42	86.37	70.24	110.32	1.120	23.99	Age
Glad	ONAN	Ind_95	0.95	0.84	0.89	64.49	85.31	80.27	108.87	1.106	23.99	Age
Glad	ONAN	Ind_90	0.90	0.84	0.93	71.60	83.80	90.14	106.83	1.087	24.00	Age
Glad	ONAN	Ind_85	0.85	0.84	0.99	78.71	81.21	99.89	103.30	1.053	24.00	Age
Glad	ONAN	Ind_80	0.84	0.84	1.00	80.14	80.24	101.85	101.98	1.040	23.99	Age
Glad	ONAN	Mix_100	1.00	0.76	0.76	48.09	89.33	56.58	114.49	1.172	24.00	Age
Glad	ONAN	Mix_95	0.95	0.76	0.80	49.36	87.12	58.33	111.36	1.131	24.00	Age
Glad	ONAN	Mix_90	0.90	0.76	0.84	51.77	84.28	62.10	107.48	1.093	23.99	Age
Glad	ONAN	Mix_85	0.85	0.76	0.89	60.41	83.68	74.54	106.66	1.085	23.99	Age
Glad	ONAN	Mix_80	0.80	0.76	0.94	70.50	82.86	88.62	105.55	1.074	23.99	Age
Glad	ONAN	Glad_100	1.00	0.88	0.88	69.25	86.01	86.76	110.45	1.134	23.99	Age
Glad	ONAN	Glad_95	0.95	0.88	0.92	72.78	84.31	91.76	107.52	1.094	24.00	Age
Glad	ONAN	Glad_90	0.90	0.88	0.98	78.42	81.77	99.50	104.07	1.060	23.99	Age
Glad	ONAN	Glad_85	0.88	0.88	1.00	80.20	80.25	101.92	102.01	1.040	23.99	Age
Glad	ONAN	Glad_80	0.88	0.88	1.00	80.17	80.23	101.88	101.97	1.040	23.99	Age
Glad	ONAF	Sq_100	1.00	0.56	0.56	32.40	82.80	33.89	112.45	1.381	24.00	Age
Glad	ONAF	Sq_95	0.95	0.56	0.59	33.57	82.76	36.28	112.39	1.380	23.99	Age
Glad	ONAF	Sq_90	0.90	0.56	0.62	35.30	82.69	39.49	112.29	1.378	24.00	Age
Glad	ONAF	Sq_85	0.85	0.56	0.65	37.78	82.59	43.80	112.13	1.376	24.00	Age
Glad	ONAF	Sq_80	0.80	0.56	0.69	41.13	82.45	49.36	111.91	1.374	23.99	Age
Glad	ONAF	Res_100	1.00	0.67	0.67	43.95	88.04	54.00	120.00	1.465	17.31	WHS
Glad	ONAF	Res_95	0.95	0.67	0.71	46.41	88.06	57.97	119.89	1.458	24.00	Age
Glad	ONAF	Res_90	0.90	0.67	0.75	48.99	86.12	61.99	117.07	1.427	23.99	Age
Glad	ONAF	Res_85	0.85	0.67	0.79	52.02	84.12	66.67	114.17	1.395	24.00	Age
Glad	ONAF	Res_80	0.80	0.67	0.84	55.93	82.10	72.63	111.25	1.363	23.99	Age
Glad	ONAF	Ind_100	1.00	0.84	0.84	52.96	81.23	68.09	110.00	1.349	23.99	Age
Glad	ONAF	Ind_95	0.95	0.84	0.89	60.47	80.30	79.45	108.65	1.333	23.99	Age
Glad	ONAF	Ind_90	0.90	0.84	0.93	67.37	78.98	89.72	106.73	1.312	23.99	Age
Glad	ONAF	Ind_85	0.85	0.84	0.99	74.25	76.63	99.83	103.31	1.273	24.00	Age
Glad	ONAF	Ind_80	0.84	0.84	1.00	75.63	75.72	101.85	101.98	1.257	24.00	Age
Glad	ONAF	Mix_100	1.00	0.76	0.76	43.01	84.84	52.57	115.27	1.410	24.00	Age
Glad	ONAF	Mix_95	0.95	0.76	0.80	45.02	82.04	55.80	111.16	1.362	23.99	Age
Glad	ONAF	Mix_90	0.90	0.76	0.84	47.93	79.31	60.35	107.20	1.317	24.00	Age
Glad	ONAF	Mix_85	0.85	0.76	0.89	56.55	78.75	73.55	106.39	1.308	24.00	Age
Glad	ONAF	Mix_80	0.80	0.76	0.94	66.29	78.08	88.13	105.41	1.297	23.99	Age
Glad	ONAF	Glad_100	1.00	0.88	0.88	64.82	81.94	85.88	111.30	1.368	24.00	Age
Glad	ONAF	Glad_95	0.95	0.88	0.92	68.46	79.47	91.33	107.45	1.320	23.99	Age
Glad	ONAF	Glad_90	0.90	0.88	0.98	73.96	77.16	99.41	104.09	1.282	23.99	Age
Glad	ONAF	Glad_85	0.88	0.88	1.00	75.68	75.74	101.92	102.02	1.258	24.00	Age
Glad	ONAF	Glad_80	0.88	0.88	1.00	75.64	75.71	101.87	101.97	1.257	23.99	Age
Howa	ONAN	Sq_100	1.00	0.56	0.56	39.15	85.81	40.56	113.92	1.166	24.00	Age
Howa	ONAN	Sq_95	0.95	0.56	0.59	40.10	85.76	42.67	113.84	1.165	23.99	Age
Howa	ONAN	Sq_90	0.90	0.56	0.62	41.57	85.68	45.53	113.70	1.164	24.00	Age
Howa	ONAN	Sq_85	0.85	0.56	0.65	43.73	85.56	49.42	113.50	1.161	23.99	Age
Howa	ONAN	Sq_80	0.80	0.56	0.69	46.73	85.38	54.51	113.19	1.157	24.00	Age
Howa	ONAN	Res_100	1.00	0.67	0.67	53.79	89.33	64.71	119.99	1.274	23.67	WHS
Howa	ONAN	Res_95	0.95	0.67	0.71	54.53	88.92	66.01	118.95	1.233	23.99	Age
Howa	ONAN	Res_90	0.90	0.67	0.75	55.83	88.00	68.11	117.14	1.199	23.99	Age
Howa	ONAN	Res_85	0.85	0.67	0.79	57.69	86.59	71.64	114.72	1.167	24.00	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Howa	ONAN	Res_80	0.80	0.67	0.84	60.62	84.76	76.17	111.91	1.136	23.99	Age
Howa	ONAN	Ind_100	1.00	0.84	0.84	58.59	83.95	73.15	110.68	1.122	23.99	Age
Howa	ONAN	Ind_95	0.95	0.84	0.89	64.11	82.87	81.75	109.11	1.106	24.00	Age
Howa	ONAN	Ind_90	0.90	0.84	0.93	70.25	81.34	90.83	106.90	1.084	23.99	Age
Howa	ONAN	Ind_85	0.85	0.84	0.99	76.56	78.82	100.00	103.27	1.048	23.99	Age
Howa	ONAN	Ind_80	0.84	0.84	1.00	77.84	77.92	101.86	101.98	1.035	24.00	Age
Howa	ONAN	Mix_100	1.00	0.76	0.76	52.68	85.92	62.72	114.01	1.176	23.99	Age
Howa	ONAN	Mix_95	0.95	0.76	0.80	53.15	84.40	63.60	111.46	1.133	23.99	Age
Howa	ONAN	Mix_90	0.90	0.76	0.84	54.41	82.07	66.03	107.93	1.094	23.99	Age
Howa	ONAN	Mix_85	0.85	0.76	0.89	60.79	81.45	76.53	107.04	1.085	23.99	Age
Howa	ONAN	Mix_80	0.80	0.76	0.94	69.35	80.52	89.51	105.70	1.072	24.00	Age
Howa	ONAN	Howa_100	1.00	0.75	0.75	57.49	87.41	70.65	116.95	1.227	24.00	Age
Howa	ONAN	Howa_95	0.95	0.75	0.79	58.22	86.54	71.71	114.79	1.179	24.00	Age
Howa	ONAN	Howa_90	0.90	0.75	0.83	59.96	84.96	74.47	112.30	1.142	23.99	Age
Howa	ONAN	Howa_85	0.85	0.75	0.88	63.30	83.09	80.15	109.44	1.110	23.99	Age
Howa	ONAN	Howa_80	0.80	0.75	0.93	69.28	81.15	89.27	106.62	1.081	23.99	Age
Mack	ONAN	Sq_100	1.00	0.56	0.56	42.32	101.74	42.95	114.46	1.327	23.99	Age
Mack	ONAN	Sq_95	0.95	0.56	0.59	43.55	101.67	44.71	114.36	1.326	23.99	Age
Mack	ONAN	Sq_90	0.90	0.56	0.62	45.44	101.54	47.23	114.21	1.323	23.99	Age
Mack	ONAN	Sq_85	0.85	0.56	0.65	48.21	101.35	50.79	113.98	1.320	23.99	Age
Mack	ONAN	Sq_80	0.80	0.56	0.69	52.04	101.07	55.55	113.64	1.315	24.00	Age
Mack	ONAN	Res_100	1.00	0.67	0.67	60.32	105.00	65.57	118.30	1.431	22.16	TO
Mack	ONAN	Res_95	0.95	0.67	0.71	61.41	104.89	66.87	118.18	1.391	24.00	Age
Mack	ONAN	Res_90	0.90	0.67	0.75	63.09	103.68	68.57	116.69	1.352	24.00	Age
Mack	ONAN	Res_85	0.85	0.67	0.79	65.45	101.84	71.85	114.42	1.316	24.00	Age
Mack	ONAN	Res_80	0.80	0.67	0.84	69.16	99.51	76.11	111.64	1.280	23.99	Age
Mack	ONAN	Ind_100	1.00	0.84	0.84	66.60	98.45	73.19	110.40	1.265	23.99	Age
Mack	ONAN	Ind_95	0.95	0.84	0.89	73.59	97.10	81.49	108.83	1.247	23.99	Age
Mack	ONAN	Ind_90	0.90	0.84	0.93	81.31	95.19	90.51	106.62	1.222	23.99	Age
Mack	ONAN	Ind_85	0.85	0.84	0.99	89.21	92.04	99.69	102.97	1.181	23.99	Age
Mack	ONAN	Ind_80	0.84	0.84	1.00	90.82	90.92	101.55	101.67	1.167	23.99	Age
Mack	ONAN	Mix_100	1.00	0.76	0.76	59.07	101.03	63.90	113.57	1.326	23.99	Age
Mack	ONAN	Mix_95	0.95	0.76	0.80	59.65	99.05	64.50	111.13	1.277	23.99	Age
Mack	ONAN	Mix_90	0.90	0.76	0.84	61.31	96.09	66.54	107.64	1.233	23.99	Age
Mack	ONAN	Mix_85	0.85	0.76	0.89	69.38	95.32	76.42	106.75	1.223	24.00	Age
Mack	ONAN	Mix_80	0.80	0.76	0.94	80.18	94.16	89.20	105.42	1.209	24.00	Age
Mack	ONAN	Mack_100	1.00	0.75	0.75	72.39	103.09	80.06	116.29	1.381	24.00	Age
Mack	ONAN	Mack_95	0.95	0.75	0.79	74.46	102.03	82.45	114.79	1.336	23.99	Age
Mack	ONAN	Mack_90	0.90	0.75	0.83	77.62	100.64	86.20	113.08	1.299	24.00	Age
Mack	ONAN	Mack_85	0.85	0.75	0.88	82.34	98.84	91.72	110.85	1.271	23.99	Age
Mack	ONAN	Mack_80	0.80	0.75	0.94	87.13	95.80	97.28	107.33	1.231	23.99	Age
Mack	ONAF	Sq_100	1.00	0.56	0.56	35.25	94.50	36.16	112.63	1.203	24.00	Age
Mack	ONAF	Sq_95	0.95	0.56	0.59	36.54	94.45	38.20	112.57	1.202	24.00	Age
Mack	ONAF	Sq_90	0.90	0.56	0.62	38.50	94.37	41.06	112.46	1.201	24.00	Age
Mack	ONAF	Sq_85	0.85	0.56	0.65	41.34	94.24	45.02	112.30	1.199	23.99	Age
Mack	ONAF	Sq_80	0.80	0.56	0.69	45.23	94.06	50.26	112.06	1.197	24.00	Age
Mack	ONAF	Res_100	1.00	0.67	0.67	49.38	100.32	55.69	119.99	1.291	19.64	WHS
Mack	ONAF	Res_95	0.95	0.67	0.71	51.54	100.22	58.62	119.66	1.271	23.99	Age
Mack	ONAF	Res_90	0.90	0.67	0.75	54.44	98.18	62.38	117.08	1.242	24.00	Age
Mack	ONAF	Res_85	0.85	0.67	0.79	57.96	95.84	66.89	114.18	1.213	24.00	Age
Mack	ONAF	Res_80	0.80	0.67	0.84	62.53	93.43	72.70	111.21	1.185	23.99	Age
Mack	ONAF	Ind_100	1.00	0.84	0.84	59.36	92.35	68.58	109.87	1.172	23.99	Age
Mack	ONAF	Ind_95	0.95	0.84	0.89	67.81	91.22	79.37	108.48	1.158	24.00	Age
Mack	ONAF	Ind_90	0.90	0.84	0.93	75.90	89.61	89.50	106.50	1.139	23.99	Age
Mack	ONAF	Ind_85	0.85	0.84	0.99	83.98	86.79	99.53	103.01	1.104	23.99	Age
Mack	ONAF	Ind_80	0.84	0.84	1.00	85.60	85.71	101.55	101.67	1.091	24.00	Age
Mack	ONAF	Mix_100	1.00	0.76	0.76	48.05	96.08	53.98	114.55	1.226	24.00	Age
Mack	ONAF	Mix_95	0.95	0.76	0.80	49.89	93.28	56.45	111.02	1.183	23.99	Age
Mack	ONAF	Mix_90	0.90	0.76	0.84	53.14	90.05	60.71	107.03	1.144	24.00	Age
Mack	ONAF	Mix_85	0.85	0.76	0.89	63.20	89.39	73.56	106.22	1.136	23.99	Age
Mack	ONAF	Mix_80	0.80	0.76	0.94	74.65	88.56	87.94	105.20	1.126	24.00	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Mack	ONAF	Mack_100	1.00	0.75	0.75	65.30	99.04	76.17	118.14	1.266	24.00	Age
Mack	ONAF	Mack_95	0.95	0.75	0.79	68.06	97.13	79.68	115.78	1.230	24.00	Age
Mack	ONAF	Mack_90	0.90	0.75	0.83	71.68	94.74	84.22	112.82	1.200	24.00	Age
Mack	ONAF	Mack_85	0.85	0.75	0.88	76.68	93.02	90.46	110.69	1.180	24.00	Age
Mack	ONAF	Mack_80	0.80	0.75	0.94	81.75	90.39	96.77	107.45	1.148	24.00	Age
Mary	ONAN	Sq_100	1.00	0.56	0.56	33.44	87.53	34.79	114.48	1.283	24.00	Age
Mary	ONAN	Sq_95	0.95	0.56	0.59	34.71	87.47	37.17	114.38	1.281	23.99	Age
Mary	ONAN	Sq_90	0.90	0.56	0.62	36.58	87.38	40.39	114.23	1.279	23.99	Age
Mary	ONAN	Sq_85	0.85	0.56	0.65	39.28	87.24	44.73	114.01	1.276	24.00	Age
Mary	ONAN	Sq_80	0.80	0.56	0.69	42.91	87.03	50.35	113.68	1.272	23.99	Age
Mary	ONAN	Res_100	1.00	0.67	0.67	46.84	91.18	56.58	119.99	1.359	20.22	WHS
Mary	ONAN	Res_95	0.95	0.67	0.71	48.42	91.62	58.72	119.94	1.333	24.00	Age
Mary	ONAN	Res_90	0.90	0.67	0.75	50.60	90.17	62.15	117.64	1.301	24.00	Age
Mary	ONAN	Res_85	0.85	0.67	0.79	53.68	88.23	66.65	114.84	1.270	23.99	Age
Mary	ONAN	Res_80	0.80	0.67	0.84	57.71	86.07	72.48	111.86	1.240	24.00	Age
Mary	ONAN	Ind_100	1.00	0.84	0.84	55.20	85.05	68.83	110.46	1.226	23.99	Age
Mary	ONAN	Ind_95	0.95	0.84	0.89	62.48	83.99	79.24	109.01	1.211	23.99	Age
Mary	ONAN	Ind_90	0.90	0.84	0.93	69.87	82.48	89.57	106.95	1.190	23.99	Age
Mary	ONAN	Ind_85	0.85	0.84	0.99	77.27	79.86	99.80	103.35	1.154	24.00	Age
Mary	ONAN	Ind_80	0.84	0.84	1.00	78.77	78.86	101.85	101.98	1.140	23.99	Age
Mary	ONAN	Mix_100	1.00	0.76	0.76	45.88	88.05	54.92	114.69	1.283	24.00	Age
Mary	ONAN	Mix_95	0.95	0.76	0.80	46.99	85.82	56.60	111.55	1.238	24.00	Age
Mary	ONAN	Mix_90	0.90	0.76	0.84	49.39	82.93	60.36	107.55	1.197	23.99	Age
Mary	ONAN	Mix_85	0.85	0.76	0.89	58.27	82.33	73.28	106.73	1.188	23.99	Age
Mary	ONAN	Mix_80	0.80	0.76	0.94	68.74	81.52	88.00	105.63	1.177	24.00	Age
Mary	ONAN	Mary_100	1.00	0.81	0.81	49.12	85.74	59.87	111.51	1.244	24.00	Age
Mary	ONAN	Mary_95	0.95	0.81	0.85	52.33	83.87	64.59	108.84	1.209	23.99	Age
Mary	ONAN	Mary_90	0.90	0.81	0.90	60.09	82.78	75.83	107.35	1.195	24.00	Age
Mary	ONAN	Mary_85	0.85	0.81	0.95	69.95	81.61	89.68	105.75	1.178	24.00	Age
Mary	ONAN	Mary_80	0.80	0.80	1.00	78.83	78.88	101.93	102.02	1.140	24.00	Age
Mary	ODAN	Sq_100	1.00	0.56	0.56	29.44	90.56	29.68	114.08	1.218	24.00	Age
Mary	ODAN	Sq_95	0.95	0.56	0.59	30.40	90.52	31.00	114.02	1.217	23.99	Age
Mary	ODAN	Sq_90	0.90	0.56	0.62	31.91	90.47	33.07	113.93	1.216	24.00	Age
Mary	ODAN	Sq_85	0.85	0.56	0.65	34.23	90.37	36.25	113.79	1.215	24.00	Age
Mary	ODAN	Sq_80	0.80	0.56	0.69	37.58	90.23	40.86	113.57	1.213	23.99	Age
Mary	ODAN	Res_100	1.00	0.67	0.67	54.93	86.86	62.22	111.43	1.293	8.51	CRF
Mary	ODAN	Res_95	0.95	0.67	0.71	57.02	90.83	64.99	116.46	1.293	15.69	CRF
Mary	ODAN	Res_90	0.90	0.67	0.75	58.67	92.87	67.24	119.12	1.287	24.00	Age
Mary	ODAN	Res_85	0.85	0.67	0.79	59.42	92.00	68.41	116.94	1.254	24.00	Age
Mary	ODAN	Res_80	0.80	0.67	0.84	61.30	90.41	71.69	114.14	1.223	23.99	Age
Mary	ODAN	Ind_100	1.00	0.84	0.84	57.45	89.35	67.13	112.49	1.208	24.00	Age
Mary	ODAN	Ind_95	0.95	0.84	0.89	63.15	88.20	75.40	110.77	1.193	24.00	Age
Mary	ODAN	Ind_90	0.90	0.84	0.93	71.00	86.50	86.61	108.28	1.172	23.99	Age
Mary	ODAN	Ind_85	0.85	0.84	0.99	80.07	83.33	99.28	103.79	1.136	24.00	Age
Mary	ODAN	Ind_80	0.84	0.84	1.00	81.92	82.03	101.84	101.99	1.122	24.00	Age
Mary	ODAN	Mix_100	1.00	0.76	0.76	58.36	91.37	65.84	116.01	1.265	23.99	Age
Mary	ODAN	Mix_95	0.95	0.76	0.80	57.50	89.93	64.87	113.51	1.219	23.99	Age
Mary	ODAN	Mix_90	0.90	0.76	0.84	56.67	87.39	64.40	109.43	1.179	23.99	Age
Mary	ODAN	Mix_85	0.85	0.76	0.89	60.37	86.70	71.18	108.45	1.171	24.00	Age
Mary	ODAN	Mix_80	0.80	0.76	0.94	70.25	85.60	85.38	106.92	1.159	24.00	Age
Mary	ODAN	Mary_100	1.00	0.81	0.81	55.81	88.98	63.70	111.78	1.225	24.00	Age
Mary	ODAN	Mary_95	0.95	0.81	0.85	57.09	88.07	65.51	110.59	1.192	23.99	Age
Mary	ODAN	Mary_90	0.90	0.81	0.90	61.99	87.14	73.50	109.10	1.177	24.00	Age
Mary	ODAN	Mary_85	0.85	0.81	0.95	71.52	85.63	87.18	106.98	1.160	23.99	Age
Mary	ODAN	Mary_80	0.80	0.80	1.00	81.99	82.03	101.93	102.01	1.122	24.00	Age
Rock	ONAN	Sq_100	1.00	0.56	0.56	39.08	82.18	40.66	113.62	1.204	23.99	Age
Rock	ONAN	Sq_95	0.95	0.56	0.59	39.97	82.14	42.84	113.54	1.203	23.99	Age
Rock	ONAN	Sq_90	0.90	0.56	0.62	41.33	82.07	45.76	113.42	1.201	24.00	Age
Rock	ONAN	Sq_85	0.85	0.56	0.65	43.33	81.96	49.70	113.22	1.198	24.00	Age
Rock	ONAN	Sq_80	0.80	0.56	0.69	46.11	81.80	54.81	112.92	1.195	23.99	Age
Rock	ONAN	Res_100	1.00	0.67	0.67	55.42	84.93	68.39	119.69	1.330	23.99	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Rock	ONAN	Res_95	0.95	0.67	0.71	55.88	84.76	69.42	118.56	1.285	23.99	Age
Rock	ONAN	Res_90	0.90	0.67	0.75	56.72	83.94	70.95	116.89	1.248	23.99	Age
Rock	ONAN	Res_85	0.85	0.67	0.79	58.06	82.87	73.93	114.61	1.213	24.00	Age
Rock	ONAN	Res_80	0.80	0.67	0.84	60.29	81.32	77.80	111.90	1.179	24.00	Age
Rock	ONAN	Ind_100	1.00	0.84	0.84	58.22	80.65	74.81	110.77	1.165	23.99	Age
Rock	ONAN	Ind_95	0.95	0.84	0.89	62.76	79.64	82.61	109.15	1.147	23.99	Age
Rock	ONAN	Ind_90	0.90	0.84	0.93	68.13	78.20	91.25	106.90	1.122	24.00	Age
Rock	ONAN	Ind_85	0.85	0.84	0.99	73.79	75.84	100.07	103.25	1.083	24.00	Age
Rock	ONAN	Ind_80	0.84	0.84	1.00	74.95	75.01	101.87	101.98	1.070	24.00	Age
Rock	ONAN	Mix_100	1.00	0.76	0.76	54.50	82.19	66.36	113.82	1.221	23.99	Age
Rock	ONAN	Mix_95	0.95	0.76	0.80	54.61	81.01	66.75	111.49	1.176	23.99	Age
Rock	ONAN	Mix_90	0.90	0.76	0.84	55.24	79.06	68.61	108.18	1.135	24.00	Age
Rock	ONAN	Mix_85	0.85	0.76	0.89	60.07	78.45	77.89	107.24	1.125	23.99	Age
Rock	ONAN	Mix_80	0.80	0.76	0.94	67.41	77.49	90.05	105.77	1.110	23.99	Age
Rock	ONAN	Rock_100	1.00	0.75	0.75	59.23	83.84	75.53	117.78	1.289	23.99	Age
Rock	ONAN	Rock_95	0.95	0.75	0.79	59.62	83.25	76.16	115.74	1.235	24.00	Age
Rock	ONAN	Rock_90	0.90	0.75	0.83	60.94	81.72	78.47	112.81	1.194	23.99	Age
Rock	ONAN	Rock_85	0.85	0.75	0.88	63.06	79.86	82.27	109.54	1.152	23.99	Age
Rock	ONAN	Rock_80	0.80	0.75	0.94	67.58	77.86	90.06	106.36	1.116	24.00	Age
Rock	ONAF	Sq_100	1.00	0.56	0.56	35.14	76.92	36.89	111.85	1.116	23.99	Age
Rock	ONAF	Sq_95	0.95	0.56	0.59	36.01	76.89	39.20	111.80	1.115	24.00	Age
Rock	ONAF	Sq_90	0.90	0.56	0.62	37.34	76.85	42.27	111.72	1.115	24.00	Age
Rock	ONAF	Sq_85	0.85	0.56	0.65	39.29	76.77	46.39	111.59	1.113	24.00	Age
Rock	ONAF	Sq_80	0.80	0.56	0.69	42.00	76.66	51.70	111.39	1.111	23.99	Age
Rock	ONAF	Res_100	1.00	0.67	0.67	47.94	80.74	61.32	119.99	1.233	21.42	WHS
Rock	ONAF	Res_95	0.95	0.67	0.71	48.86	80.83	63.11	119.37	1.204	23.99	Age
Rock	ONAF	Res_90	0.90	0.67	0.75	50.22	79.99	65.88	117.24	1.173	23.99	Age
Rock	ONAF	Res_85	0.85	0.67	0.79	52.25	78.60	69.87	114.62	1.142	23.99	Age
Rock	ONAF	Res_80	0.80	0.67	0.84	55.06	76.92	74.99	111.74	1.113	24.00	Age
Rock	ONAF	Ind_100	1.00	0.84	0.84	53.26	76.18	71.75	110.47	1.100	24.00	Age
Rock	ONAF	Ind_95	0.95	0.84	0.89	58.50	75.26	81.09	108.96	1.086	24.00	Age
Rock	ONAF	Ind_90	0.90	0.84	0.93	64.10	73.96	90.58	106.84	1.065	24.00	Age
Rock	ONAF	Ind_85	0.85	0.84	0.99	69.76	71.78	99.96	103.27	1.030	23.99	Age
Rock	ONAF	Ind_80	0.84	0.84	1.00	70.92	70.99	101.86	101.98	1.018	23.99	Age
Rock	ONAF	Mix_100	1.00	0.76	0.76	47.12	78.16	59.55	114.25	1.152	23.99	Age
Rock	ONAF	Mix_95	0.95	0.76	0.80	47.67	76.64	60.92	111.36	1.111	23.99	Age
Rock	ONAF	Mix_90	0.90	0.76	0.84	49.16	74.48	63.94	107.67	1.073	24.00	Age
Rock	ONAF	Mix_85	0.85	0.76	0.89	55.35	73.95	75.57	106.82	1.065	23.99	Age
Rock	ONAF	Mix_80	0.80	0.76	0.94	63.26	73.20	89.13	105.60	1.053	23.99	Age
Rock	ONAF	Rock_100	1.00	0.75	0.75	52.97	80.10	70.44	119.09	1.214	23.99	Age
Rock	ONAF	Rock_95	0.95	0.75	0.79	53.51	79.40	71.62	116.33	1.165	23.99	Age
Rock	ONAF	Rock_90	0.90	0.75	0.83	55.35	77.66	75.03	113.11	1.129	23.99	Age
Rock	ONAF	Rock_85	0.85	0.75	0.88	57.97	75.56	79.93	109.49	1.091	24.00	Age
Rock	ONAF	Rock_80	0.80	0.75	0.94	63.15	73.61	88.91	106.26	1.059	24.00	Age
Toow	ONAN	Sq_100	1.00	0.56	0.56	30.36	86.01	31.81	114.89	1.186	24.00	Age
Toow	ONAN	Sq_95	0.95	0.56	0.59	31.68	85.95	34.32	114.79	1.185	24.00	Age
Toow	ONAN	Sq_90	0.90	0.56	0.62	33.62	85.86	37.70	114.64	1.183	23.99	Age
Toow	ONAN	Sq_85	0.85	0.56	0.65	36.41	85.73	42.26	114.42	1.180	24.00	Age
Toow	ONAN	Sq_80	0.80	0.56	0.69	40.16	85.52	48.14	114.09	1.176	23.99	Age
Toow	ONAN	Res_100	1.00	0.67	0.67	45.26	89.21	55.66	119.99	1.257	19.41	WHS
Toow	ONAN	Res_95	0.95	0.67	0.71	46.63	89.65	57.74	119.99	1.232	22.90	WHS
Toow	ONAN	Res_90	0.90	0.67	0.75	48.68	88.71	61.09	118.24	1.206	24.00	Age
Toow	ONAN	Res_85	0.85	0.67	0.79	51.69	86.87	65.64	115.49	1.178	24.00	Age
Toow	ONAN	Res_80	0.80	0.67	0.84	55.68	84.75	71.56	112.49	1.150	24.00	Age
Toow	ONAN	Ind_100	1.00	0.84	0.84	53.22	83.70	67.89	111.01	1.136	23.99	Age
Toow	ONAN	Ind_95	0.95	0.84	0.89	60.50	82.63	78.52	109.53	1.123	24.00	Age
Toow	ONAN	Ind_90	0.90	0.84	0.93	68.10	81.10	89.29	107.42	1.104	24.00	Age
Toow	ONAN	Ind_85	0.85	0.84	0.99	75.76	78.43	100.00	103.71	1.071	24.00	Age
Toow	ONAN	Ind_80	0.84	0.84	1.00	77.30	77.40	102.15	102.28	1.057	24.00	Age
Toow	ONAN	Mix_100	1.00	0.76	0.76	44.44	86.58	54.34	115.21	1.189	24.00	Age
Toow	ONAN	Mix_95	0.95	0.76	0.80	45.26	84.44	55.84	112.11	1.147	23.99	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
Toow	ONAN	Mix_90	0.90	0.76	0.84	47.46	81.54	59.25	108.02	1.109	23.99	Age
Toow	ONAN	Mix_85	0.85	0.76	0.89	56.22	80.93	72.37	107.18	1.102	24.00	Age
Toow	ONAN	Mix_80	0.80	0.76	0.94	66.96	80.12	87.67	106.06	1.092	24.00	Age
Toow	ONAN	Toow_100	1.00	0.83	0.83	48.90	82.86	61.11	110.05	1.141	23.99	Age
Toow	ONAN	Toow_95	0.95	0.83	0.88	51.66	81.23	65.41	107.59	1.106	24.00	Age
Toow	ONAN	Toow_90	0.90	0.83	0.92	61.07	80.29	79.30	106.30	1.094	23.99	Age
Toow	ONAN	Toow_85	0.85	0.83	0.98	73.23	78.92	96.46	104.39	1.077	24.00	Age
Toow	ONAN	Toow_80	0.83	0.83	1.00	77.33	77.39	102.18	102.27	1.057	23.99	Age
Toow	ONAF	Sq_100	1.00	0.56	0.56	27.20	75.74	29.05	112.59	1.010	23.99	Age
Toow	ONAF	Sq_95	0.95	0.56	0.59	28.36	75.70	31.73	112.53	1.009	23.99	Age
Toow	ONAF	Sq_90	0.90	0.56	0.62	30.06	75.65	35.26	112.43	1.008	24.00	Age
Toow	ONAF	Sq_85	0.85	0.56	0.65	32.48	75.56	39.96	112.29	1.007	24.00	Age
Toow	ONAF	Sq_80	0.80	0.56	0.69	35.73	75.43	45.96	112.07	1.005	24.00	Age
Toow	ONAF	Res_100	1.00	0.67	0.67	38.92	80.02	51.50	119.99	1.075	16.58	WHS
Toow	ONAF	Res_95	0.95	0.67	0.71	40.88	80.44	55.26	120.00	1.066	22.42	WHS
Toow	ONAF	Res_90	0.90	0.67	0.75	43.44	79.21	59.70	117.89	1.048	23.99	Age
Toow	ONAF	Res_85	0.85	0.67	0.79	46.38	77.37	64.69	114.94	1.025	23.99	Age
Toow	ONAF	Res_80	0.80	0.67	0.84	50.18	75.48	71.07	111.95	1.002	23.99	Age
Toow	ONAF	Ind_100	1.00	0.84	0.84	47.51	74.60	66.42	110.57	0.991	24.00	Age
Toow	ONAF	Ind_95	0.95	0.84	0.89	54.56	73.73	78.31	109.19	0.980	24.00	Age
Toow	ONAF	Ind_90	0.90	0.84	0.93	61.26	72.50	89.24	107.24	0.965	24.00	Age
Toow	ONAF	Ind_85	0.85	0.84	0.99	67.96	70.27	100.01	103.69	0.936	24.00	Age
Toow	ONAF	Ind_80	0.84	0.84	1.00	69.30	69.38	102.14	102.28	0.925	23.99	Age
Toow	ONAF	Mix_100	1.00	0.76	0.76	38.13	77.72	50.12	115.81	1.036	24.00	Age
Toow	ONAF	Mix_95	0.95	0.76	0.80	39.70	75.38	53.18	111.81	1.001	23.99	Age
Toow	ONAF	Mix_90	0.90	0.76	0.84	42.44	72.77	57.98	107.66	0.968	23.99	Age
Toow	ONAF	Mix_85	0.85	0.76	0.89	50.78	72.25	72.06	106.85	0.962	23.99	Age
Toow	ONAF	Mix_80	0.80	0.76	0.94	60.23	71.64	87.57	105.86	0.954	23.99	Age
Toow	ONAF	Toow_100	1.00	0.83	0.83	42.36	74.25	57.57	110.49	0.995	24.00	Age
Toow	ONAF	Toow_95	0.95	0.83	0.88	46.12	72.52	64.24	107.27	0.965	24.00	Age
Toow	ONAF	Toow_90	0.90	0.83	0.92	55.00	71.74	79.03	106.04	0.955	24.00	Age
Toow	ONAF	Toow_85	0.85	0.83	0.98	65.73	70.67	96.44	104.33	0.942	24.00	Age
Toow	ONAF	Toow_80	0.83	0.83	1.00	69.32	69.38	102.17	102.27	0.925	23.99	Age
T Cen	ONAN	Sq_100	1.00	0.56	0.56	45.50	97.08	46.32	113.42	1.351	24.00	Age
T Cen	ONAN	Sq_95	0.95	0.56	0.59	46.52	97.01	48.02	113.33	1.350	23.99	Age
T Cen	ONAN	Sq_90	0.90	0.56	0.62	48.11	96.90	50.41	113.19	1.348	24.00	Age
T Cen	ONAN	Sq_85	0.85	0.56	0.65	50.45	96.74	53.76	112.97	1.344	23.99	Age
T Cen	ONAN	Sq_80	0.80	0.56	0.69	53.72	96.48	58.23	112.63	1.339	23.99	Age
T Cen	ONAN	Res_100	1.00	0.67	0.67	63.65	100.02	70.79	117.55	1.485	23.99	Age
T Cen	ONAN	Res_95	0.95	0.67	0.71	64.24	99.66	71.51	116.80	1.432	24.00	Age
T Cen	ONAN	Res_90	0.90	0.67	0.75	65.36	98.54	72.83	115.50	1.390	23.99	Age
T Cen	ONAN	Res_85	0.85	0.67	0.79	67.07	97.11	75.31	113.42	1.349	23.99	Age
T Cen	ONAN	Res_80	0.80	0.67	0.84	69.84	95.14	78.82	110.83	1.310	24.00	Age
T Cen	ONAN	Ind_100	1.00	0.84	0.84	67.47	94.32	76.08	109.76	1.294	23.99	Age
T Cen	ONAN	Ind_95	0.95	0.84	0.89	72.94	93.03	83.12	108.16	1.273	23.99	Age
T Cen	ONAN	Ind_90	0.90	0.84	0.93	79.28	91.24	91.11	105.92	1.245	23.99	Age
T Cen	ONAN	Ind_85	0.85	0.84	0.99	85.92	88.36	99.36	102.37	1.200	23.99	Age
T Cen	ONAN	Ind_80	0.84	0.84	1.00	87.29	87.37	101.05	101.16	1.185	23.99	Age
T Cen	ONAN	Mix_100	1.00	0.76	0.76	62.23	96.26	68.65	112.47	1.358	24.00	Age
T Cen	ONAN	Mix_95	0.95	0.76	0.80	62.53	94.77	69.00	110.41	1.306	24.00	Age
T Cen	ONAN	Mix_90	0.90	0.76	0.84	63.52	92.38	70.56	107.31	1.261	23.99	Age
T Cen	ONAN	Mix_85	0.85	0.76	0.89	69.64	91.61	78.82	106.36	1.249	24.00	Age
T Cen	ONAN	Mix_80	0.80	0.76	0.94	78.41	90.39	90.00	104.86	1.231	23.99	Age
T Cen	ONAN	T Cen_100	1.00	0.75	0.75	59.57	95.61	65.90	111.36	1.327	23.99	Age
T Cen	ONAN	T Cen_95	0.95	0.75	0.79	62.24	94.89	69.31	110.44	1.300	23.99	Age
T Cen	ONAN	T Cen_90	0.90	0.75	0.83	67.33	94.07	76.00	109.41	1.287	24.00	Age
T Cen	ONAN	T Cen_85	0.85	0.75	0.88	73.42	93.05	83.79	108.15	1.271	24.00	Age
T Cen	ONAN	T Cen_80	0.80	0.75	0.93	80.59	91.35	92.76	106.05	1.246	24.00	Age
T Cen	ONAF	Sq_100	1.00	0.56	0.56	38.81	86.56	40.06	111.49	1.247	23.99	Age
T Cen	ONAF	Sq_95	0.95	0.56	0.59	39.78	86.52	42.06	111.43	1.246	23.99	Age
T Cen	ONAF	Sq_90	0.90	0.56	0.62	41.27	86.46	44.79	111.34	1.245	24.00	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
T Cen	ONAF	Sq_85	0.85	0.56	0.65	43.47	86.36	48.53	111.20	1.243	23.99	Age
T Cen	ONAF	Sq_80	0.80	0.56	0.69	46.52	86.21	53.44	110.98	1.240	23.99	Age
T Cen	ONAF	Res_100	1.00	0.67	0.67	51.67	91.90	61.14	120.00	1.377	23.86	WHS
T Cen	ONAF	Res_95	0.95	0.67	0.71	52.80	91.23	62.69	118.45	1.334	23.99	Age
T Cen	ONAF	Res_90	0.90	0.67	0.75	54.66	89.92	65.73	116.25	1.300	23.99	Age
T Cen	ONAF	Res_85	0.85	0.67	0.79	57.31	88.10	69.72	113.56	1.267	23.99	Age
T Cen	ONAF	Res_80	0.80	0.67	0.84	60.78	86.05	74.87	110.67	1.234	23.99	Age
T Cen	ONAF	Ind_100	1.00	0.84	0.84	58.61	85.16	71.63	109.41	1.220	24.00	Age
T Cen	ONAF	Ind_95	0.95	0.84	0.89	64.93	84.10	80.90	107.94	1.204	23.99	Age
T Cen	ONAF	Ind_90	0.90	0.84	0.93	71.38	82.62	90.11	105.87	1.182	23.99	Age
T Cen	ONAF	Ind_85	0.85	0.84	0.99	77.84	80.14	99.20	102.41	1.143	24.00	Age
T Cen	ONAF	Ind_80	0.84	0.84	1.00	79.15	79.24	101.04	101.16	1.129	24.00	Age
T Cen	ONAF	Mix_100	1.00	0.76	0.76	50.34	87.77	58.94	113.22	1.278	23.99	Age
T Cen	ONAF	Mix_95	0.95	0.76	0.80	51.35	85.79	60.53	110.34	1.232	24.00	Age
T Cen	ONAF	Mix_90	0.90	0.76	0.84	53.47	83.19	63.92	106.66	1.190	23.99	Age
T Cen	ONAF	Mix_85	0.85	0.76	0.89	61.20	82.59	75.50	105.83	1.181	23.99	Age
T Cen	ONAF	Mix_80	0.80	0.76	0.94	70.37	81.75	88.68	104.66	1.168	23.99	Age
T Cen	ONAF	T Cen_100	1.00	0.75	0.75	50.69	86.63	59.81	111.48	1.247	23.99	Age
T Cen	ONAF	T Cen_95	0.95	0.75	0.79	54.22	85.35	65.28	109.67	1.223	23.99	Age
T Cen	ONAF	T Cen_90	0.90	0.75	0.83	59.55	84.67	73.15	108.73	1.213	23.99	Age
T Cen	ONAF	T Cen_85	0.85	0.75	0.88	65.68	83.93	82.00	107.69	1.201	24.00	Age
T Cen	ONAF	T Cen_80	0.80	0.75	0.93	72.69	82.69	91.95	105.97	1.183	24.00	Age
T Cen	ODAF	Sq_100	1.00	0.56	0.56	34.21	97.47	34.37	113.35	1.321	23.99	Age
T Cen	ODAF	Sq_95	0.95	0.56	0.59	35.20	97.43	35.60	113.29	1.320	23.99	Age
T Cen	ODAF	Sq_90	0.90	0.56	0.62	36.76	97.36	37.54	113.20	1.319	23.99	Age
T Cen	ODAF	Sq_85	0.85	0.56	0.65	39.16	97.25	40.52	113.05	1.318	24.00	Age
T Cen	ODAF	Sq_80	0.80	0.56	0.69	42.62	97.07	44.84	112.82	1.315	24.00	Age
T Cen	ODAF	Res_100	1.00	0.67	0.67	64.57	100.67	70.38	118.76	1.490	23.79	CRF
T Cen	ODAF	Res_95	0.95	0.67	0.71	64.76	100.47	70.67	118.31	1.440	24.00	Age
T Cen	ODAF	Res_90	0.90	0.67	0.75	65.10	99.59	71.16	117.30	1.400	23.99	Age
T Cen	ODAF	Res_85	0.85	0.67	0.79	65.87	98.54	72.14	115.40	1.361	23.99	Age
T Cen	ODAF	Res_80	0.80	0.67	0.84	67.72	96.82	74.89	112.80	1.325	24.00	Age
T Cen	ODAF	Ind_100	1.00	0.84	0.84	63.77	95.71	70.35	111.30	1.309	23.99	Age
T Cen	ODAF	Ind_95	0.95	0.84	0.89	69.33	94.43	77.56	109.59	1.291	23.99	Age
T Cen	ODAF	Ind_90	0.90	0.84	0.93	77.02	92.57	87.46	107.15	1.265	24.00	Age
T Cen	ODAF	Ind_85	0.85	0.84	0.99	85.92	89.21	98.73	102.84	1.224	24.00	Age
T Cen	ODAF	Ind_80	0.84	0.84	1.00	87.77	87.87	101.03	101.16	1.209	23.99	Age
T Cen	ODAF	Mix_100	1.00	0.76	0.76	64.15	97.83	69.57	114.31	1.372	24.00	Age
T Cen	ODAF	Mix_95	0.95	0.76	0.80	63.42	96.33	68.81	112.21	1.321	24.00	Age
T Cen	ODAF	Mix_90	0.90	0.76	0.84	62.76	93.80	68.13	108.61	1.276	24.00	Age
T Cen	ODAF	Mix_85	0.85	0.76	0.89	66.63	93.02	73.90	107.61	1.266	24.00	Age
T Cen	ODAF	Mix_80	0.80	0.76	0.94	76.32	91.72	86.44	105.97	1.252	23.99	Age
T Cen	ODAF	T Cen_100	1.00	0.75	0.75	56.51	96.73	60.81	112.44	1.337	24.00	Age
T Cen	ODAF	T Cen_95	0.95	0.75	0.79	58.20	96.38	62.93	112.04	1.312	23.99	Age
T Cen	ODAF	T Cen_90	0.90	0.75	0.83	62.43	95.63	69.10	111.02	1.300	23.99	Age
T Cen	ODAF	T Cen_85	0.85	0.75	0.88	69.37	94.66	77.83	109.75	1.288	24.00	Age
T Cen	ODAF	T Cen_80	0.80	0.75	0.93	78.49	92.84	89.39	107.43	1.266	23.99	Age
T Nor	ONAN	Sq_100	1.00	0.56	0.56	43.90	89.04	45.10	112.96	1.381	23.99	Age
T Nor	ONAN	Sq_95	0.95	0.56	0.59	44.80	88.98	46.98	112.88	1.379	24.00	Age
T Nor	ONAN	Sq_90	0.90	0.56	0.62	46.17	88.90	49.55	112.75	1.377	24.00	Age
T Nor	ONAN	Sq_85	0.85	0.56	0.65	48.22	88.77	53.07	112.54	1.374	24.00	Age
T Nor	ONAN	Sq_80	0.80	0.56	0.69	51.08	88.57	57.69	112.23	1.369	23.99	Age
T Nor	ONAN	Res_100	1.00	0.67	0.67	56.03	92.62	64.96	118.53	1.497	22.77	CRF
T Nor	ONAN	Res_95	0.95	0.67	0.71	56.95	92.25	66.44	117.81	1.453	23.99	Age
T Nor	ONAN	Res_90	0.90	0.67	0.75	58.48	91.25	68.84	115.91	1.413	24.00	Age
T Nor	ONAN	Res_85	0.85	0.67	0.79	60.72	89.64	72.37	113.43	1.375	23.99	Age
T Nor	ONAN	Res_80	0.80	0.67	0.84	63.75	87.69	76.89	110.64	1.337	24.00	Age
T Nor	ONAN	Ind_100	1.00	0.84	0.84	61.79	86.87	74.00	109.47	1.321	23.99	Age
T Nor	ONAN	Ind_95	0.95	0.84	0.89	67.44	85.77	82.32	107.94	1.302	23.99	Age
T Nor	ONAN	Ind_90	0.90	0.84	0.93	73.45	84.22	90.83	105.81	1.276	23.99	Age
T Nor	ONAN	Ind_85	0.85	0.84	0.99	79.53	81.73	99.31	102.36	1.232	24.00	Age

Transformer	Cooling mode	Load profile	Peak load	Average load	Load factor	Min top oil temp	Max top oil temp	Min WHS temp	Max WHS temp	CRF	Ageing	Limit reached
T Nor	ONAN	Ind_80	0.84	0.84	1.00	80.78	80.85	101.04	101.15	1.217	23.99	Age
T Nor	ONAN	Mix_100	1.00	0.76	0.76	54.71	89.06	62.94	112.79	1.385	23.99	Age
T Nor	ONAN	Mix_95	0.95	0.76	0.80	55.44	87.37	64.26	110.25	1.334	23.99	Age
T Nor	ONAN	Mix_90	0.90	0.76	0.84	57.20	84.97	66.94	106.83	1.288	24.00	Age
T Nor	ONAN	Mix_85	0.85	0.76	0.89	64.01	84.34	77.32	105.96	1.277	24.00	Age
T Nor	ONAN	Mix_80	0.80	0.76	0.94	72.53	83.40	89.53	104.66	1.261	23.99	Age
T Nor	ONAN	T Nor_100	1.00	0.81	0.81	63.08	88.66	75.86	112.45	1.374	23.99	Age
T Nor	ONAN	T Nor_95	0.95	0.81	0.85	65.40	87.12	79.34	109.83	1.326	24.00	Age
T Nor	ONAN	T Nor_90	0.90	0.81	0.90	70.79	85.66	87.09	107.79	1.300	23.99	Age
T Nor	ONAN	T Nor_85	0.85	0.81	0.95	76.45	83.65	95.03	105.02	1.266	23.99	Age
T Nor	ONAN	T Nor_80	0.81	0.81	1.00	80.82	80.85	101.10	101.15	1.217	23.99	Age
T Nor	ONAF	Sq_100	1.00	0.56	0.56	39.26	82.10	40.71	111.16	1.152	23.99	Age
T Nor	ONAF	Sq_95	0.95	0.56	0.59	40.11	82.07	42.76	111.11	1.151	24.00	Age
T Nor	ONAF	Sq_90	0.90	0.56	0.62	41.42	82.02	45.52	111.02	1.150	24.00	Age
T Nor	ONAF	Sq_85	0.85	0.56	0.65	43.37	81.93	49.26	110.89	1.149	23.99	Age
T Nor	ONAF	Sq_80	0.80	0.56	0.69	46.08	81.80	54.15	110.68	1.146	24.00	Age
T Nor	ONAF	Res_100	1.00	0.67	0.67	50.12	87.11	60.80	120.00	1.268	22.84	WHS
T Nor	ONAF	Res_95	0.95	0.67	0.71	51.27	86.71	62.80	118.46	1.233	23.99	Age
T Nor	ONAF	Res_90	0.90	0.67	0.75	53.14	85.39	66.05	116.10	1.202	23.99	Age
T Nor	ONAF	Res_85	0.85	0.67	0.79	55.60	83.65	70.08	113.36	1.172	23.99	Age
T Nor	ONAF	Res_80	0.80	0.67	0.84	58.82	81.75	75.26	110.47	1.142	23.99	Age
T Nor	ONAF	Ind_100	1.00	0.84	0.84	56.77	80.95	71.81	109.25	1.129	23.99	Age
T Nor	ONAF	Ind_95	0.95	0.84	0.89	62.61	79.99	81.25	107.81	1.114	24.00	Age
T Nor	ONAF	Ind_90	0.90	0.84	0.93	68.47	78.64	90.33	105.78	1.093	24.00	Age
T Nor	ONAF	Ind_85	0.85	0.84	0.99	74.30	76.38	99.24	102.39	1.057	24.00	Age
T Nor	ONAF	Ind_80	0.84	0.84	1.00	75.49	75.57	101.04	101.16	1.044	23.99	Age
T Nor	ONAF	Mix_100	1.00	0.76	0.76	48.88	83.44	58.69	113.32	1.182	24.00	Age
T Nor	ONAF	Mix_95	0.95	0.76	0.80	49.99	81.55	60.59	110.20	1.139	24.00	Age
T Nor	ONAF	Mix_90	0.90	0.76	0.84	52.07	79.15	64.27	106.55	1.101	24.00	Age
T Nor	ONAF	Mix_85	0.85	0.76	0.89	59.22	78.60	75.91	105.73	1.093	23.99	Age
T Nor	ONAF	Mix_80	0.80	0.76	0.94	67.54	77.84	88.90	104.59	1.081	23.99	Age
T Nor	ONAF	T Nor_100	1.00	0.81	0.81	58.12	83.01	74.10	112.78	1.173	23.99	Age
T Nor	ONAF	T Nor_95	0.95	0.81	0.85	60.57	81.22	78.04	109.66	1.133	24.00	Age
T Nor	ONAF	T Nor_90	0.90	0.81	0.90	65.87	79.91	86.31	107.69	1.113	23.99	Age
T Nor	ONAF	T Nor_85	0.85	0.81	0.95	71.33	78.14	94.71	105.04	1.085	24.00	Age
T Nor	ONAF	T Nor_80	0.81	0.81	1.00	75.53	75.56	101.08	101.15	1.045	23.99	Age
T Nor	ODAF	Sq_100	1.00	0.56	0.56	33.95	76.27	34.31	112.09	1.060	23.99	Age
T Nor	ODAF	Sq_95	0.95	0.56	0.59	34.61	76.25	35.52	112.04	1.060	23.99	Age
T Nor	ODAF	Sq_90	0.90	0.56	0.62	35.66	76.22	37.43	111.96	1.059	24.00	Age
T Nor	ODAF	Sq_85	0.85	0.56	0.65	37.26	76.16	40.35	111.83	1.058	24.00	Age
T Nor	ODAF	Sq_80	0.80	0.56	0.69	39.59	76.07	44.59	111.64	1.057	23.99	Age
T Nor	ODAF	Res_100	1.00	0.67	0.67	49.44	77.78	58.89	119.99	1.168	19.25	WHS
T Nor	ODAF	Res_95	0.95	0.67	0.71	50.26	78.84	60.50	120.00	1.144	23.48	WHS
T Nor	ODAF	Res_90	0.90	0.67	0.75	51.04	78.45	62.08	118.22	1.117	24.00	Age
T Nor	ODAF	Res_85	0.85	0.67	0.79	52.24	77.77	65.32	115.66	1.091	24.00	Age
T Nor	ODAF	Res_80	0.80	0.67	0.84	54.39	76.55	69.72	112.69	1.065	24.00	Age
T Nor	ODAF	Ind_100	1.00	0.84	0.84	51.99	75.83	66.12	111.12	1.053	24.00	Age
T Nor	ODAF	Ind_95	0.95	0.84	0.89	56.68	75.00	75.38	109.46	1.040	24.00	Age
T Nor	ODAF	Ind_90	0.90	0.84	0.93	62.58	73.77	86.45	107.08	1.023	23.99	Age
T Nor	ODAF	Ind_85	0.85	0.84	0.99	69.18	71.51	98.56	102.85	0.992	24.00	Age
T Nor	ODAF	Ind_80	0.84	0.84	1.00	70.51	70.58	101.02	101.17	0.980	24.00	Age
T Nor	ODAF	Mix_100	1.00	0.76	0.76	49.69	77.31	58.47	115.31	1.102	23.99	Age
T Nor	ODAF	Mix_95	0.95	0.76	0.80	49.56	76.24	58.57	112.22	1.063	24.00	Age
T Nor	ODAF	Mix_90	0.90	0.76	0.84	49.79	74.29	60.03	107.94	1.028	24.00	Age
T Nor	ODAF	Mix_85	0.85	0.76	0.89	54.10	73.78	70.02	106.99	1.021	24.00	Age
T Nor	ODAF	Mix_80	0.80	0.76	0.94	61.89	73.04	85.02	105.63	1.012	24.00	Age
T Nor	ODAF	T Nor_100	1.00	0.81	0.81	52.91	76.88	67.64	114.80	1.093	24.00	Age
T Nor	ODAF	T Nor_95	0.95	0.81	0.85	54.79	76.04	71.60	111.60	1.057	23.99	Age
T Nor	ODAF	T Nor_90	0.90	0.81	0.90	59.83	75.00	81.34	109.41	1.040	23.99	Age
T Nor	ODAF	T Nor_85	0.85	0.81	0.95	65.78	73.33	92.36	106.26	1.017	23.99	Age
T Nor	ODAF	T Nor_80	0.81	0.81	1.00	70.55	70.57	101.08	101.16	0.980	23.99	Age