University of Southern Queensland
Faculty of Engineering and Surveying

Investigation into the Impacts on 11kV feeder Operation as a Result of the Increasing use of Amorphous Core Transformers

A dissertation submitted by

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In fulfilment of the requirements of

Courses ENG4111 Research Project Part 1 and ENG4112 Research Project Part 2

Towards the degree of

Bachelor of Engineering (Power)

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I. ABSTRACT

The motivation for completing this specific project was because Ausgrid is currently conducting a small trial of four Amorphous Steel Core (ASC) 200kVA pole top transformers. This trial is part of a strategy to reduce operating costs of the distribution network, which would be specifically achieved by larger scale roll out of ASC transformers.

With this in mind two aspects of this trial deserved further investigation:

- A more meaningful economic comparison with specific attention to the performance of these transformers in comparison with existing cold rolled grain oriented (CRGO) legacy transformers across a range of load profiles.
- An investigation into the possible increased levels of inrush current in these 'new' transformers and what implications this increase level of inrush current might have on existing protection schemes used on Ausgrid's 11kV distribution system.

Both these investigations were carried out using Matlab applications and the results were as follows:

- The ASC transformers out performed economically the legacy CRGO transformers across all load profiles. This performance was due to the fact that these transformers exhibited reduced no load and load losses characteristics. What further influenced these results in the ASC favour was that the purchase price of these ACS transformers is only 10% higher than existing transformers.
- The ASC transformers developed inrush current levels well below those designed for in existing protection schemes and as such there is no implications if large scale roll out of these transformers was implimented.

With these results in mind there was 3 significant recommendation made before larger scale roll out of these transformers:

- Re-assess the manufactured quality of the transformers after a two year period.
- Assess the performance characteristics of other capacity transformers.
- Rectify an error within the inrush current simulator to ensure the validity of results presented in this report.

II. Limitations of Use

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III. Certification Page

CERTIFICATION

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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Signature

25/10/2012
Date

IV. Acknowledgements

I would like to take this opportunity to thank family and friends who have assisted me with the completion of this project and ultimately the conclusion in this stage of my education. Above all, thanks goes to my wife, who has provided many years of support, understanding and patience in completing numerous study programs culminating in the Bachelor of Engineering (Power).

I would like to acknowledge the flexibility and financial assistance provided by my employer and many colleagues in completion of this project and the Bachelor of Engineering.

Finally, I must highlight and acknowledge the professional and academic assistance provided by Dr Tony Ahfock on this project, especially in the final weeks before submission. Without his support and guidance on this topic it would not have been possible to complete.

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VII. Glossary of Terms

Ø_n: Total Mutual Flux
A: Transformer Core Cross Section Area
ASC: Amorphous Steel Transformer
Ausgrid: Electricity Distributor
B: Flux Density
C: Transformer Capital Purchase Cost
CRGO: Cold Rolled Grain Orientated
DC: Direct Current
EP: Wholesale Average Annual Spot Price
f: Supply Voltage Frequency
GUI: Graphical User Interface
I'_e: Excitation Current
L1: Primary Winding Series Inductance
L2: Secondary Winding Series Inductance
M: Transformer Life Span
mmf: Magnetomotive Force
N: Number of Winding Turns
N_n: Number of Turns per Winding
P: Load Factor Ratio
Q(t): Instantaneous Transformer Load
R'_c: Core Resistance
R1: Primary Winding Series Resistance
R2: Secondary Winding Series Resistance
S: Transformer Capacity
TOC: Total Owning Cost
v_n: Instantaneous Winding Voltage
V1: Primary Winding RMS Voltage
V2: Secondary Winding RMS Voltage
V_{RMS}: RMS Voltage
W_c: Fixed Transformer Core Loss
W_l: Variable Transformer Winding Loss
X'_m: Core Mutual Reactance
X_1: Winding 1 Series Reactance

1.0 INTRODUCTION

1.1 Project Aim

This project is an investigation into two performance aspects of transformers which have amorphous steel cores (ASC) These type of transformers are currently being trialled by Ausgrid; the two specific aspects of investigation are outlined in Appendix A and relate to;

a) What reduction in fixed core losses are achieved by these ASC transformers in comparison with legacy transformers which have cold rolled grain orientated (CRGO) silicon steel cores. This aspect of the project is extended to include a net present value analysis of both the transformers over the expected life spans and across a range of demand profiles.
b) The simulation of the maximum levels of inrush current developed in these ASC transformers and what impacts these levels of inrush current might have on the existing 11kV protection schemes used within the Ausgrid 11kV network.

1.2 Project Context

Ausgrid, one of three electricity distributors in NSW, has a distribution network ranging from 132kV sub transmission mains to 240V street services. This network is geographically centred around the Sydney Basin as shown in Figure 1. Ausgrid has a mixed asset base, ranging from a predominately underground network supplying the high density load of the central business district of Sydney, to a predominately overhead network servicing the low density rural areas of the Upper Hunter Valley.

Figure 1: Ausgrid Are Map & Trial Location (Ausgrid, 2012)

A major element of Ausgrid's asset base are the transformers used to step the supply voltages up and down across the network. These transformers have a resulting fixed power loss associated with this transformation and this power loss has an related financial cost[1]. The significance of this cost is illustrated by Table 1 which is a consideration of the number of 200kVA pole top transformers in Ausgrid's asset base and the associated costs of the fixed power loss associated with these transformers.

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[1] This project was commenced prior to the retail privatisation of State Owned NSW electricity distributors in March 2012 of which Ausgrid is one. As such, the assumption is made throughout this project that Ausgrid is still a supplier of electricity in the National Electricity Market and therefore has a large incentive to reduce power loss across its network.

No. of 200kVA Pole Top Transformers	~2000
Fixed core power loss of each transformer	~450W
Average spot price of electricity 2012/13	~$60 / MWh
Transformer Lifespan	~40 years
Cost of 200kVA Pole top transformers fixed Core Losses	**~$20M**

Table 1: Costs of Fixed Core Losses of 200kVA Pole Top TX Assets Base

Table 1 is highlighting that 200kVA pole top transformers alone cost Ausgrid approximately $500K per year in fixed core transformer power loss. The significance of this is even greater when we consider that 200kVA pole top transformers make up only a small portion of Ausgrid's transformer total fleet of distribution transformers which is ~13500.

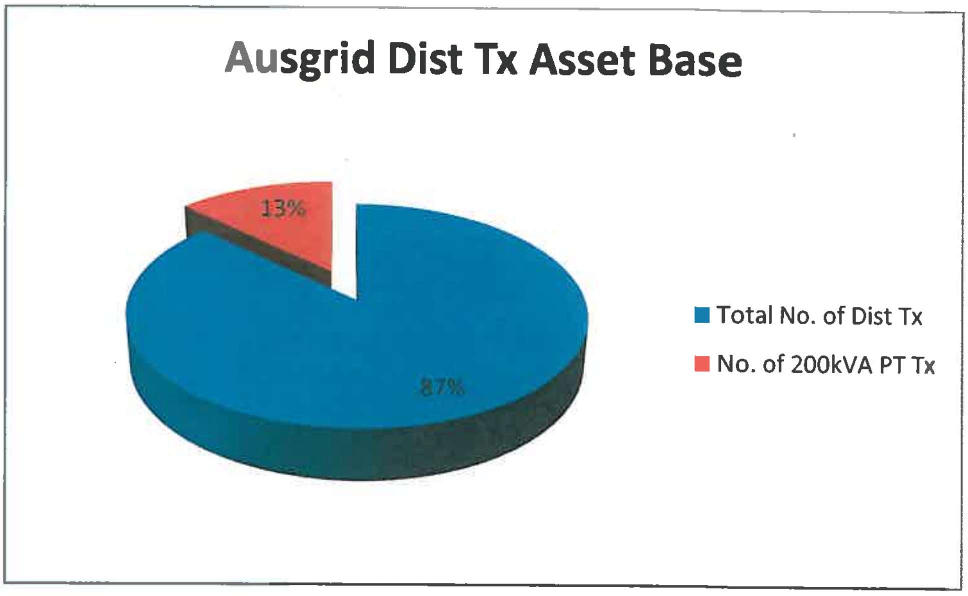

Figure 2: Ausgrid Distribution Tx Asset Base and the Preportion of 200kVA Pole Mounted Tx.

With the size of the Ausgrid distribution transformer base, the amount of losses per year as a result of fixed core distribution transformers is estimated at around $3.75M. Therefore, reducing fixed core transformer losses has large potential in reducing Ausgrid's cost base.

In an attempt to reduce these fixed transformer losses across the network, Ausgrid is currently conducting a small trial of four ASC 200kVA pole top transformers as shown in Figure 3. This trial is being carried out near Gosford on the Central Coast of NSW.

Figure 3: Photo of an in-service ASC Pole Top Transformer Currently on Trial

1.3 Properties of Amorphous Steel Cores

There are four relevant properties of ASC transformers with respect to this project, which are potentially;

- Lower fixed transformer core loss.
- Higher capital purchase costs.
- Higher load loss operating costs.
- Higher inrush current.

1.3.1 Lower Fixed Transformer Core Loss

ASC transformers have been available since the 1980's. The major advantage of ASC transformers is the beneficial property of a large reduction in fixed transformer core losses which is in the order of 80%. This core loss reduction is achieved as a result of the manufacturing process used to produce the steel which make up the laminations in the core of ASC transformers (Hitachi America, LTD, 2010).

With reference to Table 1 and Figure 2 this reduction in fixed core transformer losses would equate to an approximate cost reduction of $3M per year for Ausgrid.

1.3.2 Higher Capital Purchase Costs

Although ASC transformers have proven lower fixed loss operating characteristics, they have not had large scale penetration across the existing electricity distribution networks in Australia, this is due to historically higher capital purchase costs and higher load loss characteristics than equivalent CRGO silicon steel transformers. These undesirable characteristics are a specific result of ASC transformers having reduced flux density (*B*) values. If we consider the transformation formula (1).

$$V_{RMS} = 4.44\, N\emptyset\, f \tag{1}$$

We know that the total flux ($\emptyset$) is proportional to flux density (*B*) and the cross sectional area (*A*) of the transformer core, therefore.

$$V_{RMS} = 4.44\, N(BA)f \tag{2}$$

Reviewing equation (2) is it evident that to achieve the same voltage output (V_{RMS}) with a core exhibiting reduced flux density (*B*) properties the transformer designer must increase the cross sectional area (*A*) of the core or increase the number of winding turns (*N*) per phase. In reality to achieve the required voltage output both are increased to an optimal amount.

Therefore, the increase in capital purchase costs of ASC transformers consists of two factors. Firstly, the need to increase the core cross section area obviously results in more core material and a subsequent increases in core material costs. Secondly, both increasing the core cross section area and increasing the number of winding turns per phase results in an increase in winding material and a subsequent increase in winding material costs.

1.3.3 Higher Load Loss Operating Costs

Depending on the transformer winding design, if the number of winding turns per phase is increased considerably there could potentially be a significant increase in winding resistance per phase. This increase in winding resistance would result in an increase in load losses of the transformer and thereby increase the operating costs of the transformer.

1.3.4 Higher Inrush Current

The reduced flux density (*B*) magnetic property exhibited by ASC transformer cores not only results in the need to increase the core cross sectional area to achieve the desired outputs, but has the potential to cause undesirably higher values of transformer inrush current. This increased potential level of in inrush current may have implications for the existing protection schemes used on the distribution system.

1.4 Project Need

1.4.1 Net Present Value Comparison

Because it was envisaged that there was a possibility that ASC being trialled by Ausgrid may have the conflicting characteristics of having lower fixed core losses, higher capital purchase costs and higher load losses in comparison with legacy 200kVA pole top transformers, it was prudent to carry out a net present value simulation to determine the economic viability of larger scale implementation of these transformers across Ausgrid's overhead network.

This comparison also needed to be extended further to compare these two transformer types across a range of demand profiles to assess the viability of installing these transformers in different load areas of Ausgrid's network. It was also considered that, depending on the results obtained, this simulator may be used by designers to select the most cost effective transformer types for specific applications. For example, if the results proved highly sensitive to changes in load cycle, it would be beneficial for network designers to have discretion in the transformer core selection. Also a designer would be better equipped to assess specific location parameters such as shorter life span locations, high load areas and specific load profile locations.

1.4.2 Inrush Current Simulation

As suggested in Section 1.3.4, there is the possibility that the ASC transformers being trialled may experience higher values of inrush current than previously designed for on Ausgrid's network. Therefore, it was again thought prudent to carry out a simulated 'check' of the inrush current values expected to be developed in these transformers and what implications these levels of inrush current may have on existing 11kV protection schemes implemented across Ausgrid's distribution system.

2.0 BACKGROUND

The following section outlines in detail some of the fundamental principles which underpinned the rationale regarding;

- Why the project was carried out?
- What methodology was used to carry out the investigations?
- How will the results be analysed after investigation?

2.1 Physical Transformer Core Types

As this project investigates two performance aspects of the steel core used in a transformer. Specifically in the case of this project, the ASC transformers on trial and the existing legacy CRGO silicon steel core transformers. Therefore, it is important to highlight the fundamentals regarding the physical construction and the comparative magnetic performances of these transformer cores.

2.1.1 Contruction Process

2.1.1.1 CRGO Silicon Steel

Figure 4 illustrates the stages of production for CRGO steel laminations, which are:

- The strip steel lamination is produced by a continuous casting machine from molten metal into the preliminary dimensions required for the next stage of production.
- Some hot rolling is carried out by the continuous casting machine and prior to the cold rolling phase of production.
- The first phase of the cold rolled strip production involves surface de-scaling and the first cold rolling is carried out to obtain intermediate thickness.
- Decarburisation and re-crystallisation is then carried out.
- The second phase of cold rolling is then completed to produce the final thickness.
- Finally, some surface preparation is conducted before transportation to market. (NLMK, 2012, p. 5)

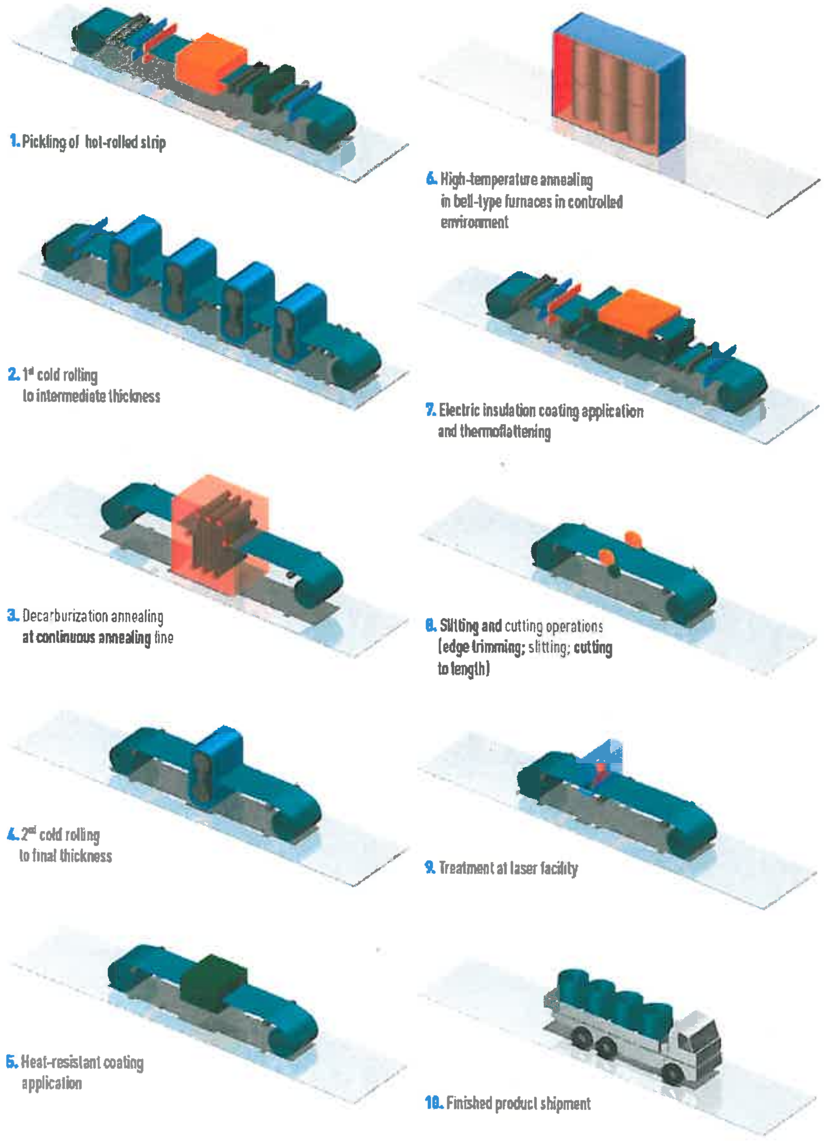

Figure 4: CRGO Steel Lamination Production Process (NLMK, 2012, p. 6)

2.1.1.2 ASC

Figure 5 illustrates the production method for ASC transformer core laminations, which is:

- Allowing the molten metal alloy to pour in a ribbon form onto a rotating drum.
- The rotating drum chills the molten metal at a rapid rate, thereby forming a ribbon of material with a thickness less than 1mm .

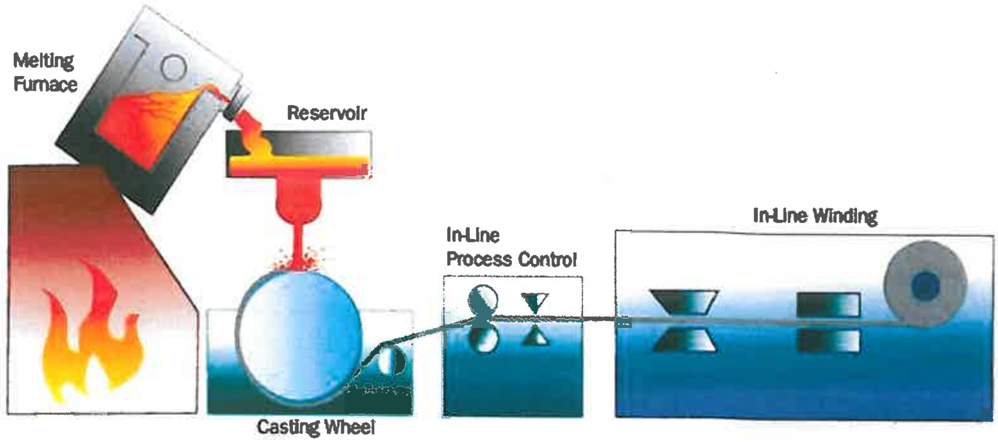

Figure 5: Amorphous Steel Core Lamination Production Process (BRG Energy Limited LTD, 2010)

2.1.2 Internal Atomic Structure & Magnetic Response

2.1.2.1 CRGO Silicon Steel

The production method used to produce CRGO steel laminations results in a systematic atomic structure, as represented in Figure 6. This orderly structure has a general characteristic of restricting magnetisation and demagnetisation of the internal magnetic domains of the atoms in comparison with amorphous steel. This magnetisation and demagnetisation is occurring at the rate of the supply frequency or 50 times per second.

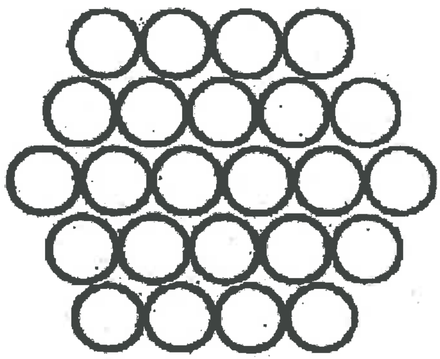

Figure 6: Crystalline Atomic Structure

2.1.2.2 ASC

Because amorphous core laminations metals are metal alloys made by rapidly cooling molten metal, the atoms are left stuck in a disorderly structure, as illustrated in Figure 7. This random, disorderly atomic structure allows for easier magnetisation and demagnetisation of the internal magnetic domains of the atoms, which (as stated above) is occurring at the supply voltage frequency rate.

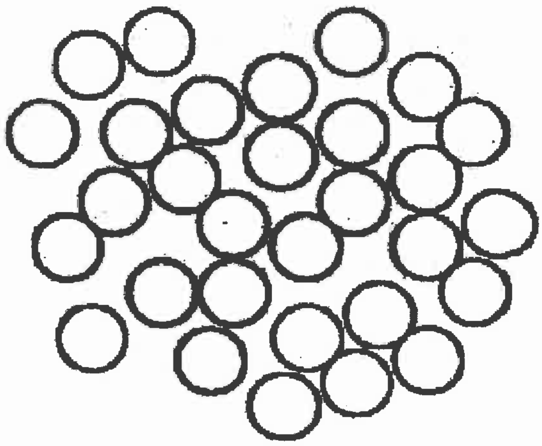

Figure 7: Amorphous Atomic Structure

2.2 Basic Transformer Theory

To understand the transformer performance characteristic investigated in this project it is essential to review some the first principles of transformer theory.

2.2.1 Ideal Transformer Model

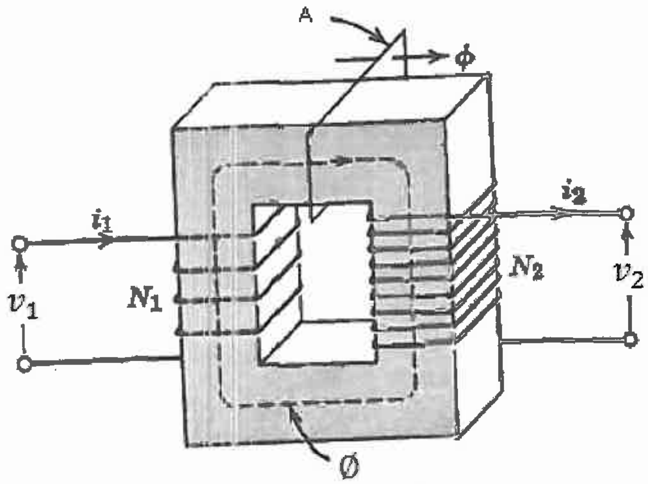

Figure 8: Ideal Transformer Model (Slemon G. R., 1966, p. 126)

Figure 8 is an illustration of the ideal transformer model, which is used for the prediction of transformer behaviour. From this model we can begin to derive the following relationships which will be applied throughout this project at different stages.

$$v_n = N_n \frac{d\emptyset_n}{d_t} \tag{3}$$

Equation (3) is illustrating that the instantaneous winding voltage (v_n) is proportional to the rate of change of total mutual flux ($\emptyset_n$) and the number of turns (N_n) of that winding.

$$\emptyset_n = \widehat{\emptyset_n} \sin(2\pi f)t \tag{4}$$

If the instantaneous value of total mutual flux is equal to equation (4), then the differential of equation (4) is equal to.

$$\frac{d\emptyset_n}{d_t} = \widehat{\emptyset_n}\, 2\pi f \cos 2\pi f t \tag{5}$$

The peak value of mutual flux instantaneous flux is equal to

$$\widehat{\emptyset_n} = BA \tag{6}$$

Therefore, we can re-write equation (3) to provide the peak value of voltage as

$$V_n = N_n BA\, 2\pi f \tag{7}$$

Finally, the RMS voltage can be determined, as shown in equation (8) & (9)

$$V_{n\_RMS} = N_n BA \frac{2\pi}{\sqrt{2}} f \tag{8}$$

$$V_{n\_RMS} = 4.44\, N_n BA\, f \tag{9}$$

Equation (9) highlights that the RMS winding voltage (V_{n_RMS}) is proportional to the number of winding turns (*N*), supply frequency (*f*), flux density (*B*) of the core material and cross sectional area (*A*) of the core. This relationship will be drawn on in further sections and it is important to highlight that these relationships can be applied to either winding by changing the necessary subscripts.

The ideal transformer model has limitations. Namely it does not account for winding losses or core losses and therefore we need to build on this model to develop the linear equivalent transformer model.

2.2.2 Linear Equivalent Transformer Model

With the inclusion of series winding resistance and reactance for both primary and secondary windings we obtain the equivalent circuit shown in Figure 9.

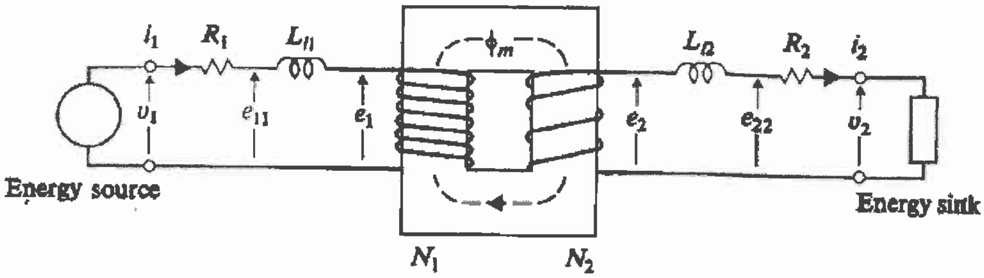

Figure 9: Linear Equivalent Transformer Model (Neglecting Core Loss) (Slemon & Straughen, 1980, p. 100)

Developing this transformer model further and with the addition of the parallel elements (R_c) and (X_m) which represent transformer core loss, we develop the complete equivalent transformer model. The majority of simulations within this project have the transformer parameters shown in the circuit of Figure 10 as core foundations.

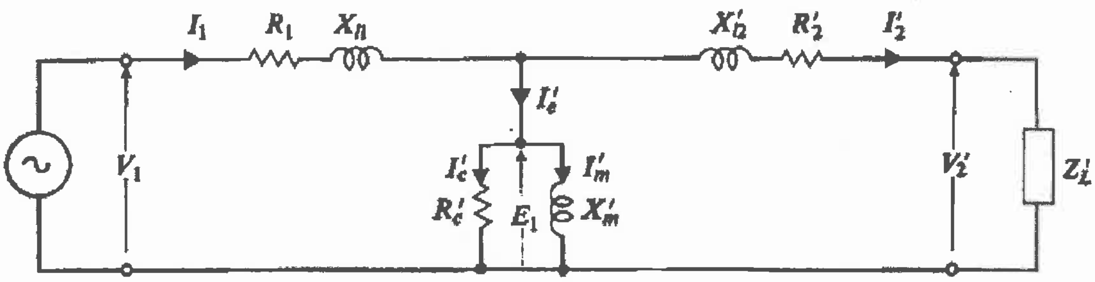

Figure 10: Complete Equivalent Transformer Model (Slemon & Straughen, 1980, p. 108)

Readers should be aware that the secondary winding elements and the transformer core elements have been referred to the primary side of the transformer.

2.3 Standard Transformer Tests

2.3.1 DC Resistance Tests

Because the transformers investigated as part of this trial have HV and LV winding connections as Delta /Star respectively, this section will only explain the DC resistance tests carried out on these type of transformers.

Figure 11 shows the connections made when carrying out the DC resistance tests for each individual phase on a three phase delta / star transformer.

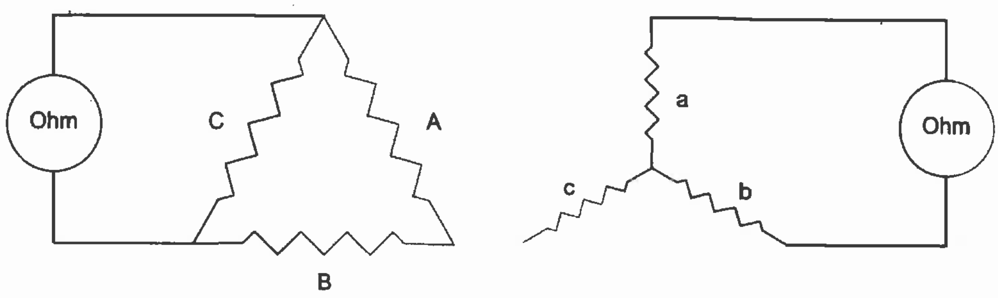

Figure 11: DC Resistance Test Connection Diagram

It becomes apparent that care needs to be taken when interpreting the results of these tests. With regard to the HV winding test, because it is a delta connected winding and the winding connections are internal to the transformer (thereby prohibiting isolation of the individual phases). It becomes evident that the results achieved are a parallel combination of 'C' phase and the series combination of 'A' and 'B' phase.

With regard to the LV winding, some care also needs to be applied to the results. The ohm reading obtained will be the series combination of 'a' and 'b' phase. It is reasonable to assume that the resistance of each LV winding phase will be close to equivalent, therefore the individual LV winding resistances can be determined by halving this measured value.

2.3.2 Open Circuit Test

The open circuit transformer test is carried out to determine the parallel parameters of the equivalent circuit and ultimately the no load power loss performance of the transformer.

The test is carried out by applying rated voltage to one side of the transformer, with the other winding open circuited. Commonly, the test voltage is applied to the lower voltage winding as this makes the test voltage more attainable without specialised test equipment. During test, the input current is measured.

With reference to Figure 10, because (R'_c) and (X'_m) are far greater in magnitude than (R_1) and (X_1), the current that results is overwhelmingly made up of the excitation current (I'_e) and the effective equivalent circuit is shown in Figure 12.

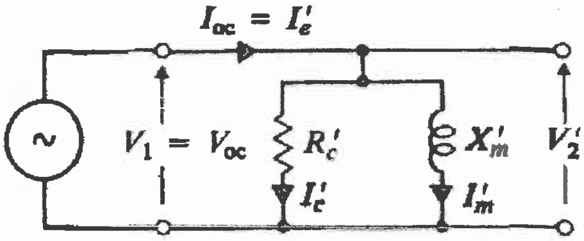

Figure 12: Open Circuit Test Equivalent Circuit (Slemon & Straughen, 1980, p. 110)

With the open circuit test (V_1), (I'_e) and (P_c) are measured, while (R'_c) and (X'_m) are calculated and the following relationship is evident.

$$No\ Load\ Loss = Pc = \frac{V_1^2}{R'_c}\ W \qquad (10)$$

2.3.3 Short Circuit Test

The short circuit test is carried out to determine the the series parameters of the equivalent circuit and hence the load power loss of the transformer windings.

To complete the short circuit test, the secondary terminals are short circuited and a voltage is applied to the primary winding to achieve rated current to flow in the primary winding. Input voltage ($V_{s/c}$), input current ($I_{s/c}$) and input power (P_w) are measured during test.

With reference to Figure 10, because (R'_c) and (X'_m) are far greater in magnitude than (R'_2) and (X'_2) the effective equivalent circuit can be developed as shown in Figure 13.

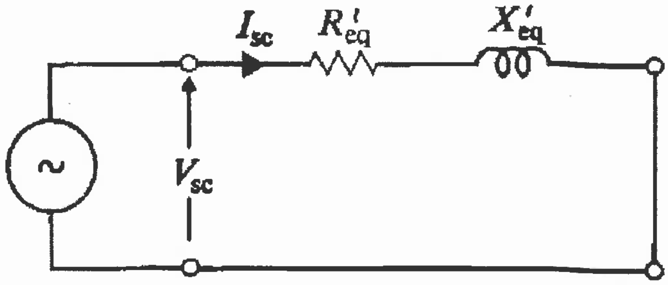

Figure 13: Short Circuit Test Equivalent Circuit (Slemon G. R., 1966)

With the short circuit test ($V_{s/c}$), ($I_{s/c}$) and (P_w) are measured and (R_{eq}) and (X_{eq}) are calculated. Where,

$$R_{eq} = R_1 + R'_2 \tag{11}$$

$$X_{eq} = X_1 + X'_2 \tag{12}$$

$$Load\ Loss = Pw = R_{eq} I_1^2\ W \tag{13}$$

2.4 Transformer Losses

Energy loss in distribution transformers consist of two (2) elements; no-load losses and load losses.

2.4.1 No Load Losses

No load losses are also described as:

- Fixed losses, as they are constant, continuous and independent of changes in load on the transformer while energised.
- Core losses, as the power loss occurs due to the effects of magnetisation and demagnetisation of the transformer core.

No-load losses are a result of excitation of the transformer. The two (2) largest components of no load losses result from hysteresis loss and eddy current loss in the transformer core.

Hysteresis losses are a result of the resistance of the core material to realignment of the magnetic domains in the material. This realignment is driven by the sinusoidal magnetic field intensity *(H)*.

This reluctance to magnetic alignment change results in a lagging response between changes in the magnetic field intensity *(H)* and the flux density *(B)*. It is from this relationship that the hysteresis loop is developed for individual transformers. The hysteresis loop represents the steady state magnetic response of a transformer and importantly the area enclosed by the hysteresis loop represents the hysteresis energy loss of the transformer per cycle. This energy loss is dissipated as heat in the magnetic material and represents the work done per unit volume in reorienting the magnetic moments of the material as it is carried through a cycle of magnetisation. (RFIC Technologies)

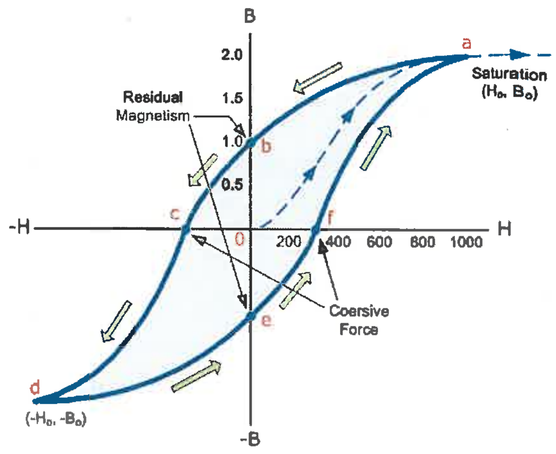

Figure 14: Typical Hysteresis Loop (Wayne , 2012)

Eddy currents are circulating currents induced within the transformer core. These circulating currents are induced during excitation due to the alternating flux. The power loss resulting from these circulating currents is because these eddy currents produce an Magnetomotive Force *(mmf)* opposing the increase in core flux. Therefore, in order to produce the required flux density, the excitation current needs to be greater. This has the effect of broadening the hysteresis loop and therefore increasing the energy loss. (Slemon & Straughen, 1980)

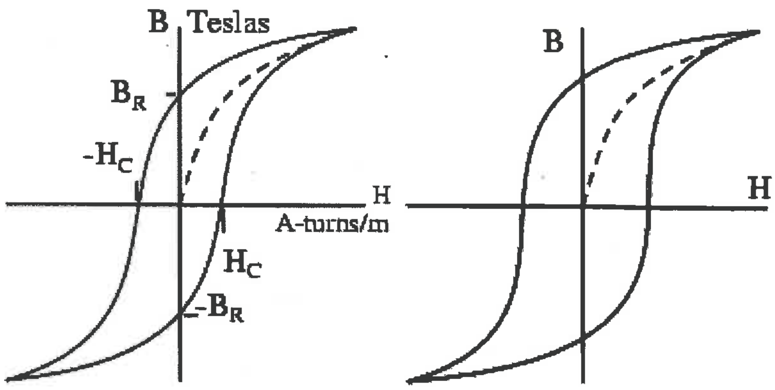

Figure 15: Hysteresis loop broadened by eddy current loss (Slemon G. R., 1966)

2.4.2 Load Losses

Load losses are also described as:

- Variable losses, because they are proportional to transformer load current.
- Copper losses, because they result from the (I^2R) power loss in the transformer windings which are commonly constructed of copper. This power loss is made up of the instantaneous load current supplied by the transformer (I_L) and the equivalent series resistance of the transformer windings (R_{eq})

Similar to no load losses, load losses are made up of various components, however the major component of it is the previously described (I^2R) losses in the windings.

2.4.3 ASC Transformers and Fixed Core Loss Reduction

ASC or amorphous metal transformers are reported as reducing no load losses by up to 80%.

These reductions are achieved because amorphous materials have good magnetic properties. This improved magnetic response is a result of the production methods used to produce the amorphous steel laminations.

2.4.3.1 Magnetic Properties

The random molecular structure of amorphous material results in less internal friction than compared with standard CRGO silicon steel transformer cores. Therefore, magnetisation and demagnetisation occurs easier; improving the hysteresis characteristics of the material.

Also, the method of producing the ASC laminations results in producing a steel with a high resistivity characteristic. The high resistivity of the material results in reducing the magnitude of eddy currents and hence the loss associated with them.

2.4.3.2 Thin Laminations

The production methods used to create the amorphous materials permits the laminations to be extremely thin, because of this eddy current loss is reduced.

2.5 The Cost of Transformer Losses

A net present value comparison know as 'Total Owing Cost' (TOC) is an industry accepted method used to compare the total life cost of transformers. It will be implemented in this project to compare currently used CRGO silicon steel transformers against the ASC transformers currently on trial in Ausgrid.

As it has been highlighted previously, the total loss of a transformer is made up of no load losses (W_c) and variable losses (W_l):

$$W_t = W_c + P^2 W_l \tag{14}$$

Where the load factor (P) is the ratio of instantaneous load to the rated capacity of the transformer.

$$P = \frac{Q(t)}{S} \tag{15}$$

To equate the load loss over a period of time the RMS method is used.

$$P_e = \sqrt{\frac{1}{T}\sum_{t=1}^{N}(\frac{Q(t)}{S})^2 \Delta t} \tag{16}$$

Therefore, the annual energy loss in watt hours for the transformer is calculated as.

$$W_{loss} = \{W_c + P_e^2 W_l\} \times 8760 \tag{17}$$

Finally, the complete Total Owning Cost (TOC) equation is shown below. This calculation is a net present value comparison.

$$C_{total} = \sum_{m=1}^{M} \frac{1}{(1+r)^m} \times \{W_c + P_e^2 W_l\} \times 8760 \times \frac{EP}{1000} + C \tag{18}$$

2.5.1 Load Cycles

Load cycles or load profiles are a graphical representation of the electrical load experienced or forecast on the system over time. Ausgrid uses (8) eight standard load cycles when designing the LV network; these load cycles are based on a 24 hour period.

The major characteristics which differentiate between the individual load cycles are:

- Does the load consist largely of residential, commercial or industrial loads?
- Is there is significant amount of electric hot water load present?
- What time of year is it, Summer or Winter?

Figure 16 is a graphical representation of the standard load cycles designed for within Ausgrid, it should be highlighted that the continuous load cycle is rarely experienced within a distribution system, it is more common in stand alone industrial applications.

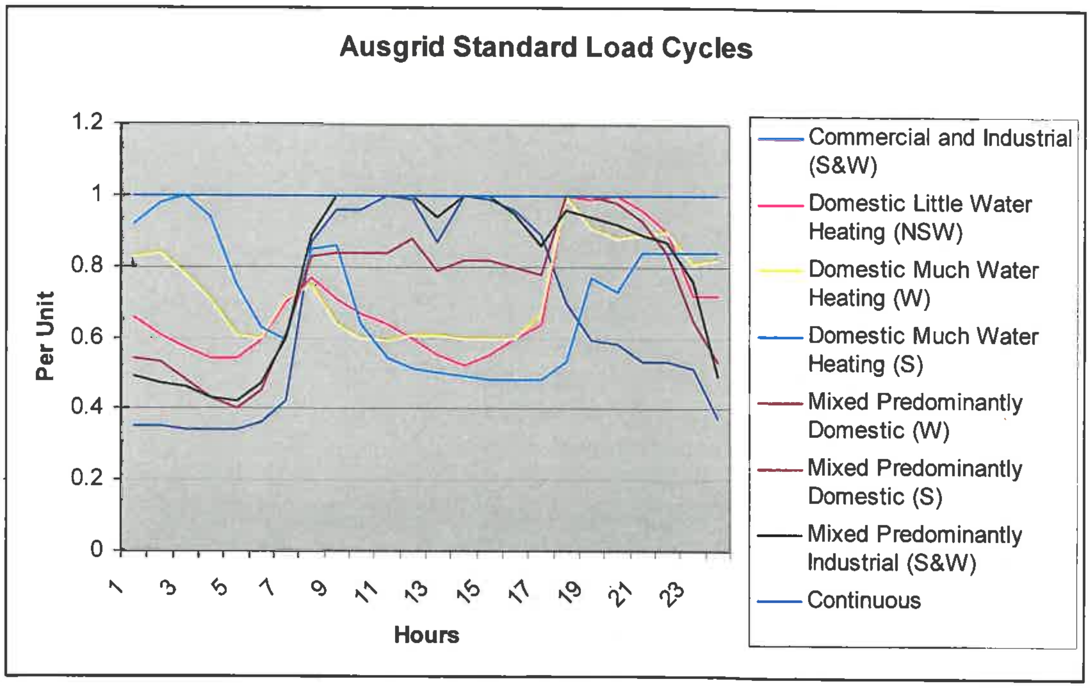

Figure 16: Ausgrid Standard Load Cycles

2.5.2 Effect of Load Profile on the Cost of Transformer Losses?

As depicted in the load cycle curves of Figure 16, the load on a transformer will vary throughout the day. Therefore, the value of ($Q(t)$ / S) will vary for individual TOC simulations.

To carry out the economic comparison for the multiple Ausgrid load cycles, the simulations documented in this project integrate the Ausgrid standard load cycles into the equation for (P_e). This will be illustrated in 4.1.1.4.

2.6 Transformer Inrush Current

2.6.1 How are Inrush Currents Developed?

Inrush current in transformers is best illustrated by considering the operation of transformers during different stages. For example steady state and initial energisation.

2.6.1.1 Steady State Transformer Operation

Under normal operating conditions transformer excitation current (I_e) is a fraction of full rated current. However very large magnitude currents can be experienced in transformers when initially connected (switched) to the network. This phenomenon is known as transformer inrush current.

We know from equation (3) that the instantaneous voltage drop across a transformer winding is proportional to the rate of change of flux in the transformer core.

$$v_n = N_n \frac{d\emptyset_n}{d_t} \tag{3}$$

It is observed in equation (5) that the voltage waveform is the derivative of the flux waveform and by definition the flux waveform is the integral of the voltage waveform. Therefore under normal operating conditions these two waveforms are 90° phase shifted. Also, it should be noted that since flux is proportional to magnemotive force (*mmf*) force (B-H curve) and (*mmf*) is proportional to winding current (lenz law), the current waveform will be in phase with the flux waveform.

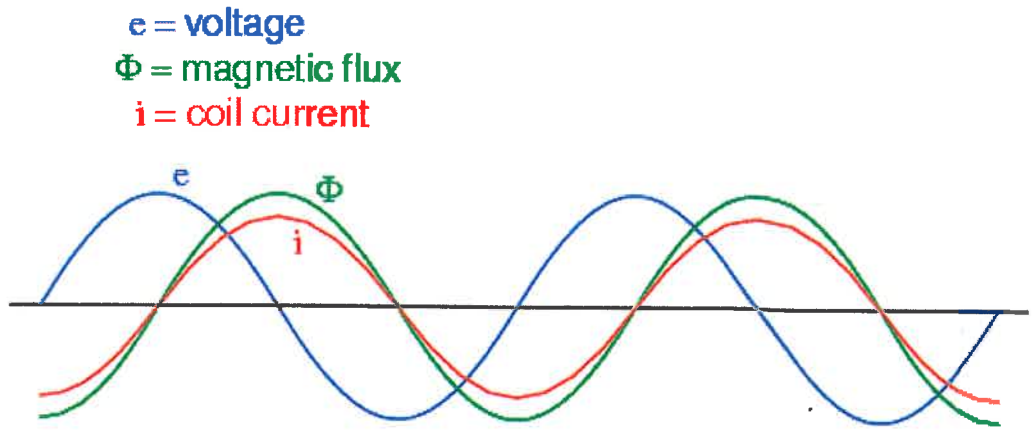

Figure 17: Voltage / Flux / Current Waveforms (Kuphaldt, 2000)

An important observation to make of Figure 17 is that during normal operating conditions the flux level is at negative peak when the voltage waveform is at zero.

2.6.1.2 Transformer Energisation (t=0, $V_1 = 0$)

To highlight inrush current, it will be assumed that the transformer is energised at an instant in time when the primary voltage is equal to zero and the transformer has been sitting idle for an extended period of time (ie residual flux is equal to zero).

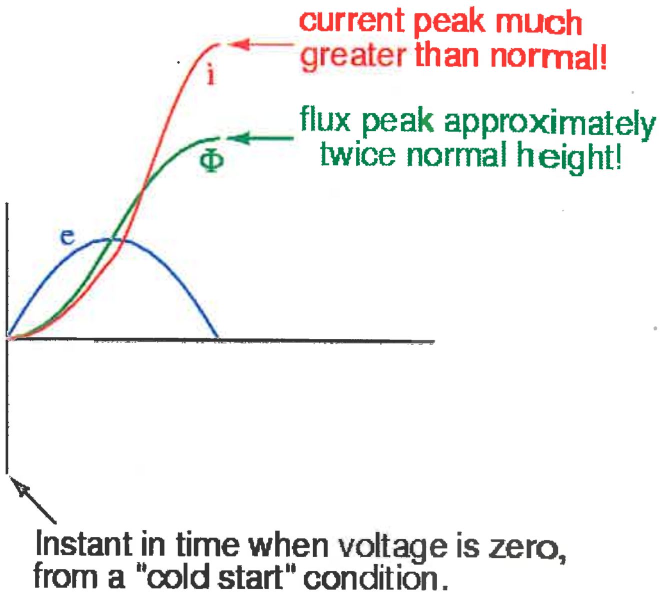

Figure 18: Voltage / Flux (Kuphaldt, 2000)

As shown in Figure 18, when energisation occurs, primary voltage commences to rise from zero to its peak value. The value of magnetic flux will rise in response to this positive change in voltage because of the integral relationship with the voltage waveform. Importantly though because the value of input voltage is rising from zero and not falling from a negative peak as was the case in Figure 17, the flux will continue to rise until it reaches approximately twice its steady state peak value, this causes saturation of the transformer.

Due to the non linear relationship between flux density and magnetic field strength of the transformer core, disproportionate amounts of *(mmf)* are needed to sustain these values of magnetic flux. This therefore means that the winding current, which creates the *(mmf)* will rise to values exceeding twice its normal peak, sometimes 10 times rated current of the transformer. (Kuphaldt, 2000)

2.6.2 What Effects do ASC Transformers have on Inrush Current?

Because saturation may occur at lower values of flux density in ASC transformers, it is reasonable to expect that inrush current values may be greater in ASC transformers than previously experienced with CRGO silicon steel transformers.

2.7 11kV Protection Systems Used in Ausgrid

2.7.1 Typical 11kV Schematic Diagram

Figure 19 is a schematic representation of a section of 11kV overhead network within Ausgrid's distribution network. It illustrates the electrical locations of standard protection devices used in the overhead network.

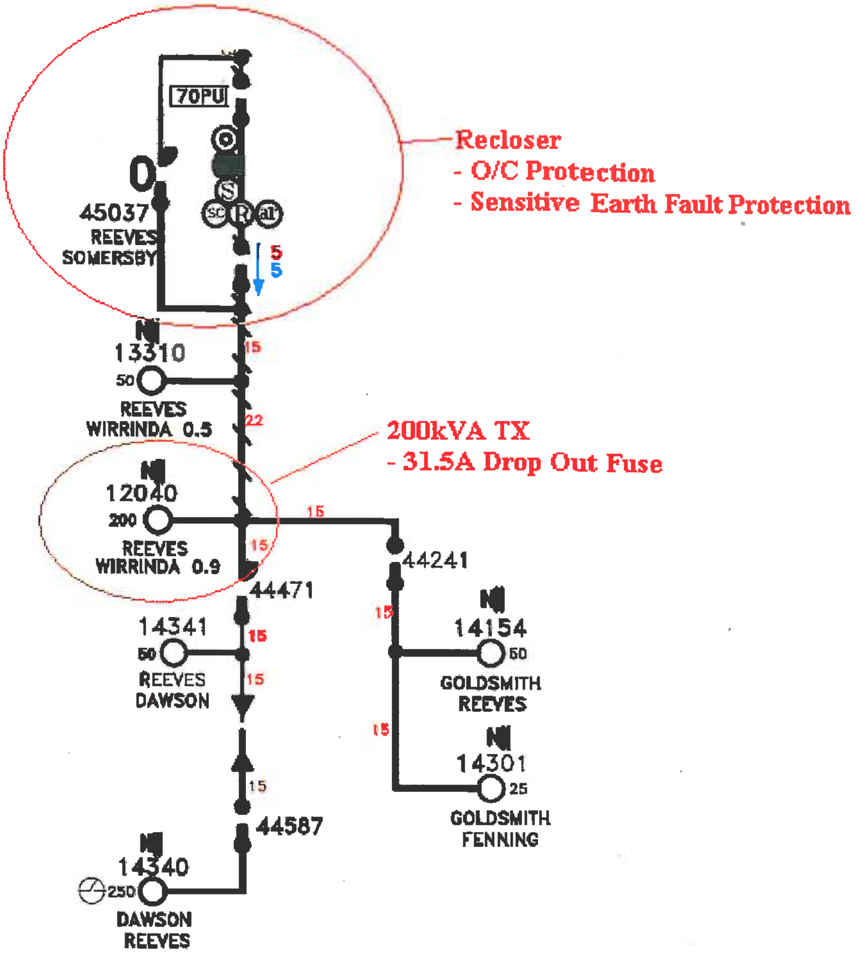

Figure 19: Typical 11kV Radial Feeder with Recloser and HV Fuse Protection

2.7.2 HV Fuses

High voltage fuses are positioned on the line side at every pole top transformer and as such are the first level of protection for individual pole mounted transformers within Ausgrid's 11kV overhead network. Fuses operate with the (I^2t) relationship. Therefore, to achieve appropriate inrush current discrimination, fuses are selected so that the fuse operating characteristic curve is outside possible inrush current values. As highlighted in Figure 20, the solid line representing the HV fuse characteristic needs to be outside the maximum level of inrush current for the maximum time duration.

It should be noted that protection issues may be experienced if HV fuses are selected with characteristic curves to discriminate inrush current and yet result in upstream protection devices operating for faults downstream of the HV fuses. That is, the fuse characteristic curve is to the right of dotted line representing the upstream protection device.

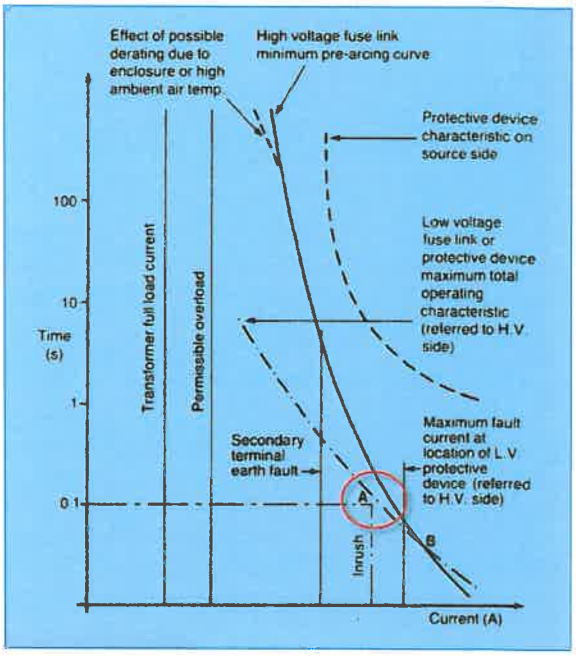

Figure 20: Generic HV Fuse Characteristic Curve (Overcurrent Protection for Phase and Earth Faults)

2.7.3 Overcurrrent Relay Protection

Overcurrent relay protection is the primary protection used on 11kV overhead and underground distribution feeders. These devices are located upstream of the HV transformer fuses, therefore acting as secondary protection for 11kV transformers. The operating characteristics of typical 11kV feeder overcurrent relays are similar to HV fuses in that they are dependent on the fault current level and fault current duration.

(4) Four standard characteristic curves are implemented as shown in Figure 21;

- Inverse
- Very Inverse
- Extremely Inverse
- Long Inverse

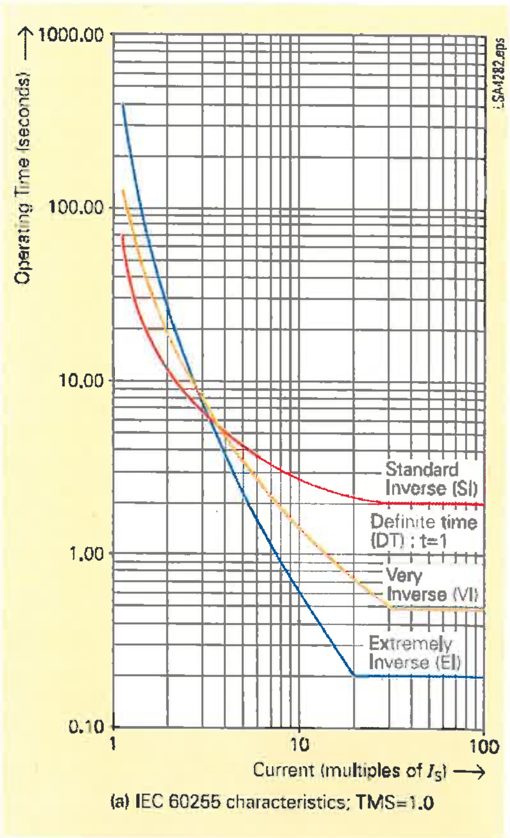

Figure 21: Inverse Relay Characteristic Curves (Overcurrent Protection for Phase and Earth Faults)

The characteristic curve of the relay is selected as per the philosophical reasons stated for HV fuses.

2.7.4 How are Inrush Currents Managed by Current 11kV Protection Systems?

In electricity network protection schemes, inrush current discrimination is managed in a number of different manners. Some more complex methods are second harmonic discrimination and waveform identification.

This project will focus on a typical 11kV distribution feeder within Ausgrid's Central Coast Region. The typical 11kV protection schemes employed on these feeders are HV fuses and over current protection relays. The primary method of discrimination of inrush currents within Ausgrid's protection schemes is the reliance on the fact that inrush currents are only sustained for a short time period in the order of <0.5s.

3.0 LITERATURE REVIEW

The literature review for this project focuses on journal articles; This is because the scope of the project, namely the cost benefit analysis of ASC transformers and the study of inrush currents are mostly industry orientated topics. Further to this, these topics have a relatively small scope and as such are more specialised studies suited to journal publication rather than scholarly textbooks.

3.1 Cost Benefits of Reduced Core Losses

The research of this aspect of the project focused on what previous economic comparisons had been completed before, how. these comparisons were completed and what results had been attained.

This research uncovered that the consistent approach reported by the majority of sources was that of the 'Total Owing Cost' method. This method is generally the method explained in the background notes in section 2.5 of this project, which will form the basis of this aspect of the project and was well reported by (Takagi, et al., 2009). Within this journal article the ratio of RMS load to rated capacity was obtained through manipulation of available data. For example, the following rationale was used to develop the model:

> Information provided by suppliers indicated that the average size ASC transformer supplied was between 20 – 30kVA. 30kVA was selected for the model.
>
> - A = Total capacity of transformers (kVA)
> - B = Total electricity demand (kWh)
> - C = B/A = Electricity demand per kVA of capacity (kWh/kVA)
> - D = C*30 = Electricity demand per transformer (kWh)

A variation of the method explained by (Takagi, et al., 2009) was outlined by (Fussell, 1989). The calculation outlined by (Fussell, 1989) was more comprehensive model for comparing the total owing costs of transformers. Fussell made the assumption that the user had more detailed information of the individual transformer costs. This is highlighted by the incorporation of the variable defined as 'fixed charge rate'. This variable incorporates not only the initial capital cost of the transformer; it extends this to include maintenance costs, taxes and insurance. Due to the need to have access to more detailed information, it seems Fussell's method suits a comparison of transformers on a smaller scale.

Takagi's method was selected to be the basis of this projects analysis because these additional maintenance costs are not known presently. This project varies from Takagi's method by comparing the transformers economic performance across generic Ausgrid load cycles rather than mean loads per transformer site.

3.2 11kV Protection System Problems Due to Increased Inrush Current

For the inrush current investigation of this project, the project literature was sought in previous studies which showed:

- How the implementation of ASC in transformers changed the possible value of transformer inrush current?
- What simulation models for transformers developed had been developed using Matlab, specifically SimPowerSystems?
- What affect, if any could these changes in inrush current levels have on traditional protection schemes implemented on 11kV distribution feeders.

The results of this literature review were able to find a considerable body of work for two elements:

- Analytical calculations of transformer inrush current.
- Studies into different protection schemes for mitigation of protection problems due to transformer inrush current.

Analysing these articles provided solid background knowledge on the phenomenon of inrush current for this project. What was evident, after obtaining this more detailed understanding of transformer inrush current and how protection schemes discriminate between inrush current and 'real' fault currents, was that there was not going to be a significant body of literature available on the implications of increased levels of inrush current resulting from ASC transformers. This was due to the follow reason.

As highlighted in Section 1.3, for ASC transformers to achieve the same levels of capacity as compared with legacy CRGO silicon steel transformers, the core cross sectional area needs to be greater. This then mitigates the suspected issue of inrush current as it pushes up the value of flux density (B) that the transformer saturates, thereby reducing the level of inrush current.

This issue did not negate the importance of carrying out the inrush current investigation as it would prove as confirmation of this theory and also a 'check' against the design principles of new supplier of transformers.

4.0 METHODOLOGY

Because there are two distinct areas of investigation within this project, the methodology for each investigation is presented separately within a dedicated section of this chapter. These two sections are;

- Cost benefits of reduced core losses.
- 11kV protection system problems due to possible increased inrush current.

4.1 Cost Benefits of Reduced Core Loss Investigation

4.1.1 Simulation Foundation Formula

To carry out the cost benefit analysis between the currently used CRGO silicon steel distribution transformers and the newly trialled ASC transformers I have applied the following Total Owning Cost (TOC) calculation.

$$C_{total} = \sum_{m=1}^{M} \frac{1}{(1+r)^m} \times \{W_c + P_e^2 W_l\} \times h \times \frac{EP}{1000} + C \qquad (19)$$

As highlighted within section 4.1, this cost calculation is implemented consistently within industry when comparing transformers for capital investment. It is worthwhile highlighting each variable of this formula and explaining what values were used within the Matlab simulation as part of this project.

4.1.1.1 Life of the Transformer (m)

The life of the transformer is regarded as the expected operational life of these transformers and therefore this value determines the number of years that the transformers economic performance can be compared for.

The value used in this project for the life of the transformer is 40 years. This value was selected as Ausgrid use 40 years as the financial depreciation life span of pole top transformers.

4.1.1.2 Discount Rate (r)

The discount rate represents the expected rate of return on capital investment if the purchase was not carried out, or the savings were reinvested.

The value used in this project for the discount rate is 5.65%. This value is the average value of the Australian 10 year bond yield between 1997 and 2012 as shown in Figure 22. This value was considered a conservative value as some literature suggested using values in excess of 7.5% as this was a typical rate of return from equities.

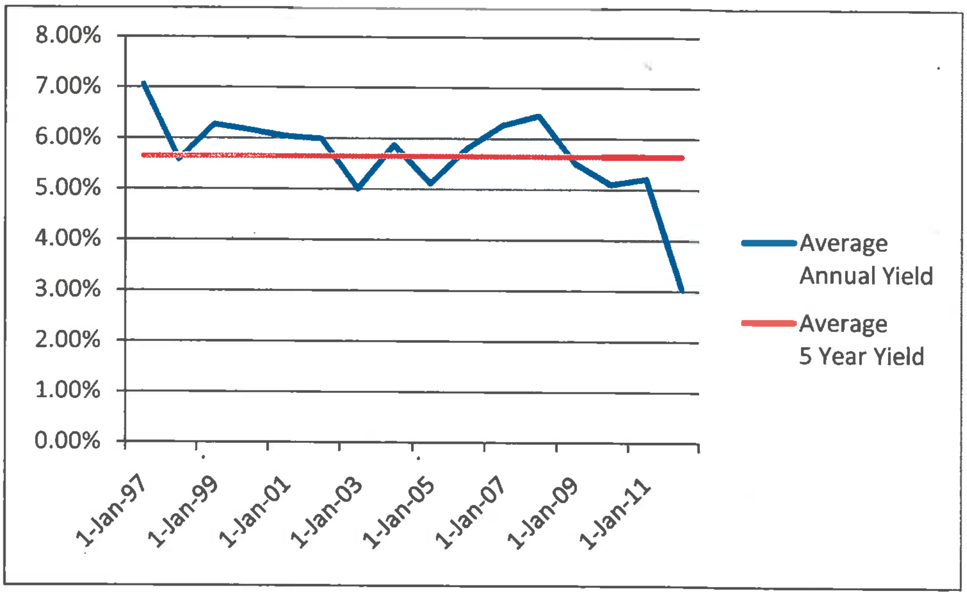

Figure 22: Average Annual Australian 10 Year Bond Yield (Australian Taxation Office)

4.1.1.3 Transformer No Load Losses (W_0)

The transformer no load loss values used in this project for the legacy and ASC transformers are 381W and 135W respectively.

These values have been obtained from within Ausgrid historical documentation for the legacy transformers (see Appendix B) and a NATA accredited transformer test report for the ASC transformers under trial (see Appendix C).

4.1.1.4 Load Factor (P_e)

The load factor variable within this calculation accounts for the instantaneous utilisation of transformer capacity. It is the RMS value of individual transformer load cycles over a defined timeframe.

$$P_e = \sqrt{\frac{1}{T}\sum_{t=1}^{N}\left(\frac{Q(t)}{S}\right)^2 \Delta t} \tag{20}$$

Where:

- $Q(t)$ = kVA load on the transformer at an instant in time (t)
- S = kVA rating of the transformer
- T = The averaging period in hours (h)
- Δt = Is the time interval by dividing T into N parts.

Within this project (P_e)is developed using the eight standard Ausgrid load cycles where Table 2 outlines the RMS values for each load cycle over a twenty four hour period. See Appendix D for hourly per unit utilisation values for each load cycle.

LOAD CYCLE	DESCRIPTION	RMS VALUE
A	Commercial and Industrial (S&W)	**0.7089**
B	Domestic Little Water Heating (NSW)	**0.7148**
CW	Domestic Much Water Heating (W)	**0.7425**
CS	Domestic Much Water Heating (S)	**0.7312**
DW	Mixed Predominently Domestic (W)	**0.7570**
DS	Mixed Predominently Domestic (S)	**0.8152**
E	Mixed Predominently Industrial (S&W)	**0.8152**
F	Continuous	**1.0**

Table 2: RMS Values of Standard Ausgrid Loads Cycles

4.1.1.5 Transformer Load Loss (W_l)

The transformer load loss values used in this project for the legacy and ASC transformers are 2200W and 1900W respectively.

These values have been obtained from within Ausgrid historical documentation for the legacy transformers (see Appendix B) and a NATA accredited transformer test report for the ASC transformers under trial (see Appendix C).

4.1.1.6 Annual Energisation Time (h)

It has been assumed for this project that planned and unplanned interruption to electricity supply to these transformers would be neglected. Therefore the transformer is energised continuously all year round and as such the annual energisation time is 8760 hours.

4.1.1.7 Price of Electricity (EP)

The value for the price of electricity is the average annual price of electricity for the period 2012/13 as quoted on the AEMO website on 05/10/2012, which was 0.061/kWh (Australian Energy Market Operator).

This period of time was selected in favour of a lower average annual price of electricity which would be calculated if a larger timeframe was assessed as the introduction of the Carbon Price in July 1st 2012 resulted in a step change in the price of electricity and therefore made the previous average values erroneous. This is shown in Figure 23.

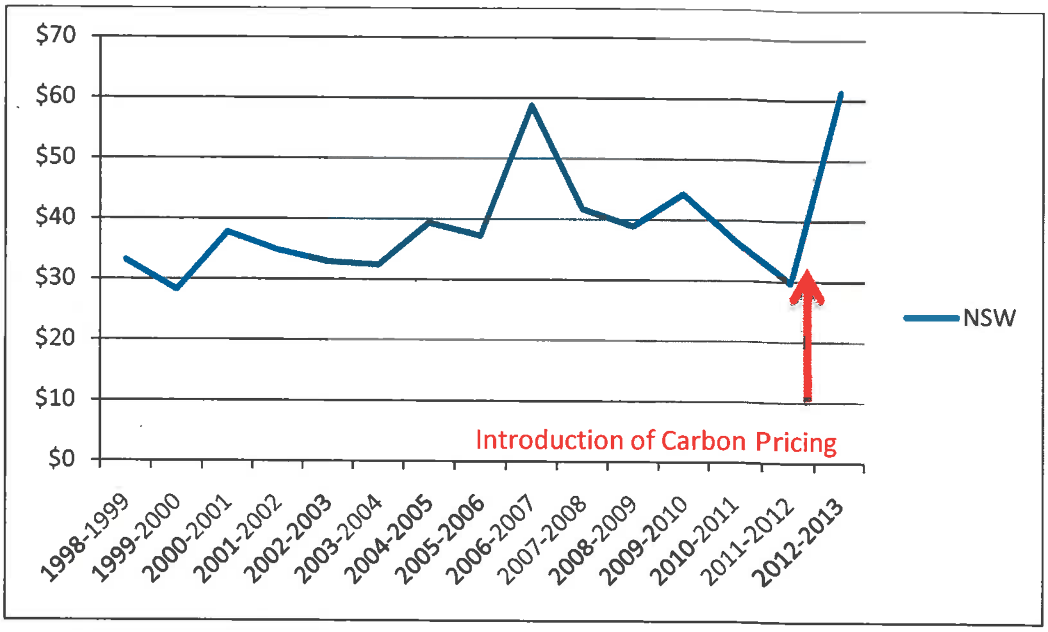

Figure 23: Average Annual price of Electricity (NSW) (Australian Energy Market Operator)

4.1.1.8 Capital Cost of the Transformers (C)

The capital cost values used in this project for the legacy and ASC transformers are $9760 and $10773 respectively.

These values have been provided by the Procurement Section within Ausgrid (see Appendix B).

4.1.1.9 TOC Input Information

Table 3 is a summarised table showing the necessary input values for the TOC calculation.

Item	Value		Source
	Si Steel	**AMC**	
Transformer Life Time (M)	40	40	Asset Management Section Ausgrid
Discount Rate (r)	5.65	5.65	10Y Average Australian bond yield
Fixed Losses (W_c)	381W	135W	Ausgrid Personnel & NATA tests
Variable Losses (W_l)	2200W	1900W	Ausgrid Personnel & NATA tests
Load Factor (Q)	See Figure 2	See Figure 2	Ausgrid Network Engineering Guideline NEG-PD01
EP	0.06124	0.06124	AEMO – NSW Annual Average MWh = 61.24 (2012/2013_Viewed 05/10/2012)
C	$9,760	$10,773	Procurement Section Ausgrid

Table 3: TOC Input Data

4.1.2 Total Owning Cost Simulation Explanation

Consideration was given to using either Matlab or Microsoft Excel to carry out this simulation. Matlab was selected as it provided the most versatile platform for user interaction, simulation functions and graphical representations of the results.

The specific Matlab simulation uses a basic graphical user interface (GUI) for user inputs and result outputs.

On start up of the GUI file, the input parameters are set to those outlined in Table 3, however the user does have the option of changing these parameters if site specific conditions warrant such changes, or variations on the comparisons are necessary. Figure 24 depicts what the user witnesses on start up.

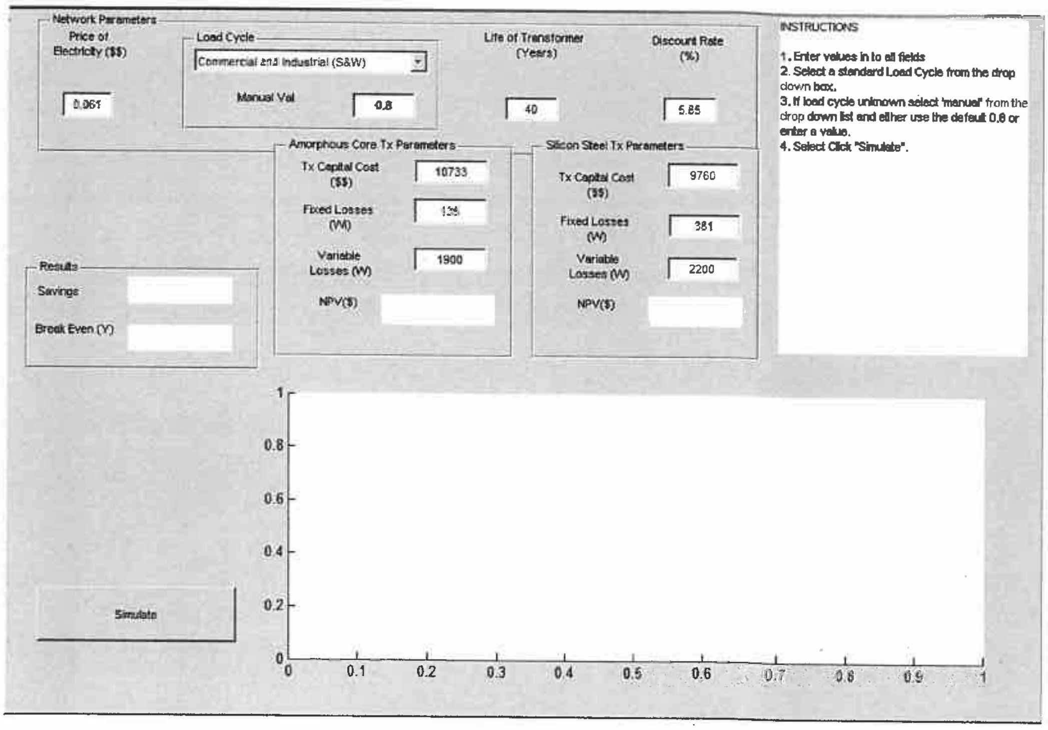

Figure 24: Total Owning Cost Simulation on Start Up

As shown above, the input variables are segregated into three toolbars:

- Network Parameters.
- ASC Parameters.
- Silicon Steel Tx Parameters.

Figure 25 is an example illustrating the numerical and graphical outputs shown to the user when the simulate button is executed.

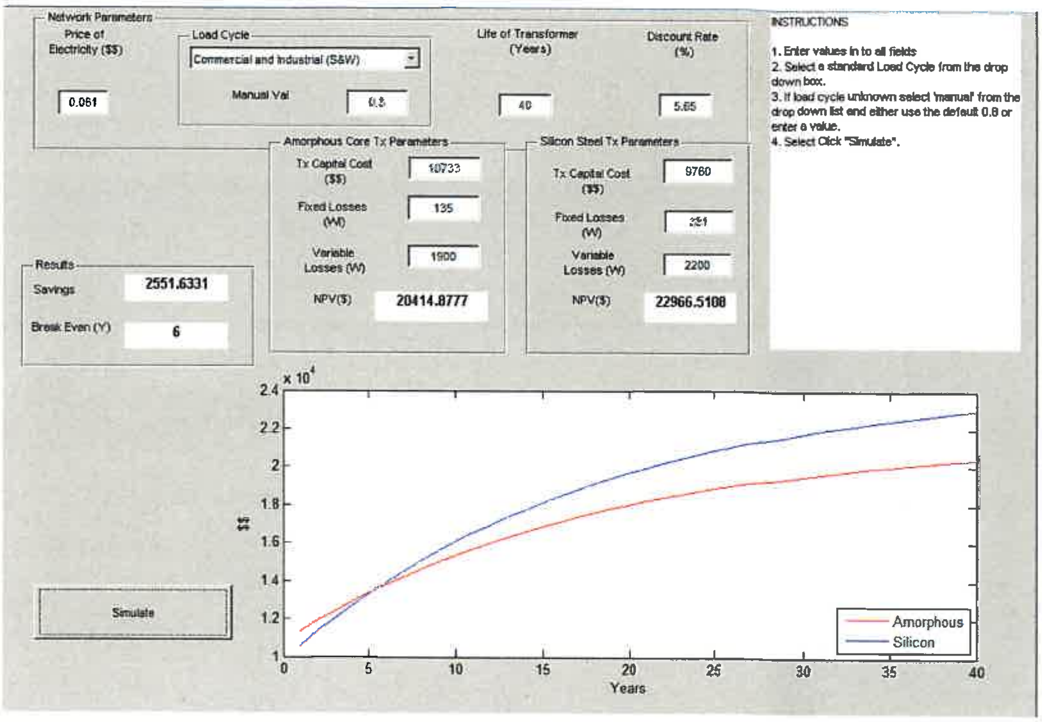

Figure 25: Total Owning Cost Simulation with Outputs

4.1.2.1 Structure of the Program

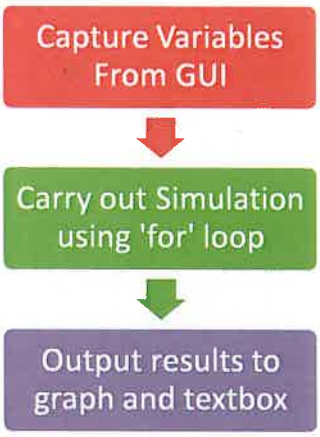

Figure 26: Total Owning Cost General Program Structure

4.1.2.2 Capturing Variables

On start up of the GUI, all necessary input variables are populated with those shown in Figure 24. To carry out a simulation the user must select the required Load Cycle from the drop down box and then click on the '*Simulate*' button. If the load cycle is unknown, or a specific load cycle is not available in the drop down box, the user should select '*manual*' in the load cycle drop down box and then type in the desired RMS daily load cycle value.

4.1.2.3 'For' Loop Simulation

Using the variables input into the GUI, the simulator implements the TOC formula shown above in a '*For*' loop for the number of years stipulated as the life of the transformer. The net present value for each year for each transformer is stored in a Matlab vector ready for display when the loop is complete.

4.1.2.4 Results Output

As shown in Figure 25, the results of the simulation are displayed graphically in the form of a line chart and numerically. The graphical representation depicts the economic performance of each transformer over the life span selected. The numerical representation shows the net present value of each transformer after the life span selected; the savings are highlighted, along with the break even year.

4.1.3 Interpretation of Results

By using this simulator within this project, it will be attempted to show what possible savings are achieved by these ASC transformers for a single transformer across multiple load cycles. Also, these savings will be extrapolated to show potential cost reductions that could be achieved if these ASC transformers were rolled out for the entire Ausgrid pole top transformer asset base.

4.2 11kV Protection System Problems Due to Increased Inrush Current

To assess the level of inrush current developed in the ASC transformers and if there are any possible subsequent impacts to current 11kV protection schemes, this project uses a Simulink model within Matlab, specifically implementing blocks from the SimPowerSystems library.

Specifically, I have built a single transformer model using the 'Saturable Single Phase Transformer' block within this toolbox. Within this block, users are able to customise the transformer parameters to ensure accurate modelling of the magnetic properties of the transformer.

4.2.1 Inrush Simulation Model

Figure 8 shows the model that was used to simulate the level of inrush current that could be expected to be experienced in the ASC transformers on trial. It consists of the following SimPowerSystemsBlocks:

- Three Phase Source
- Three Phase Breaker
- ASC Saturable Transformer
- Continuous powergui.
- Multimeter

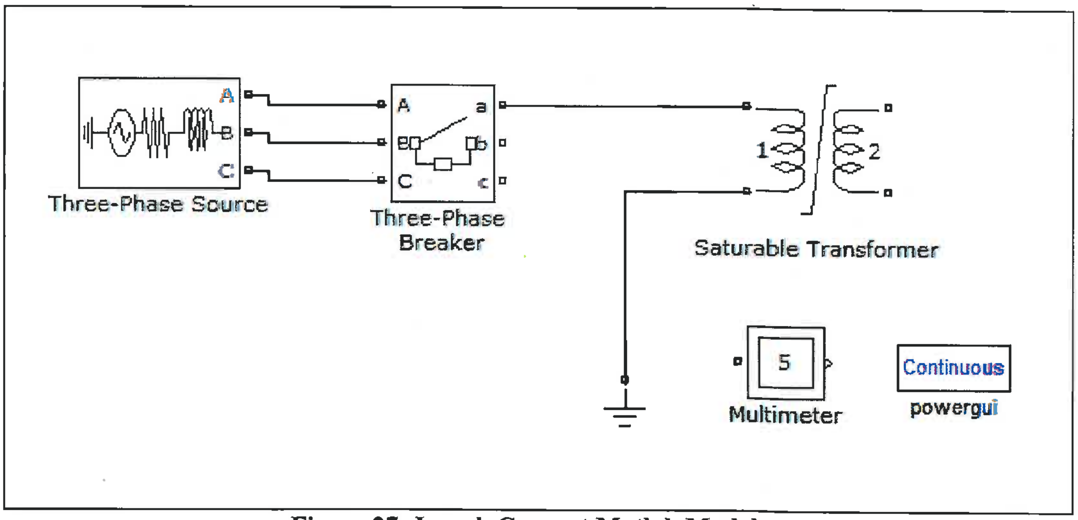

Figure 27: Inrush Current Matlab Model

4.2.2 Three Phase Source

The three phase source block had the following parameter settings as shown in Table 4 and Figure 28.

Parameter	Setting
Phase to Phase RMS Voltage	11000V
Phase Angle	0
Frequency	50hz
Internal Connection	Star
Source Resistance & Inductance	Default

Table 4: Three Phase Source Parameter Settings

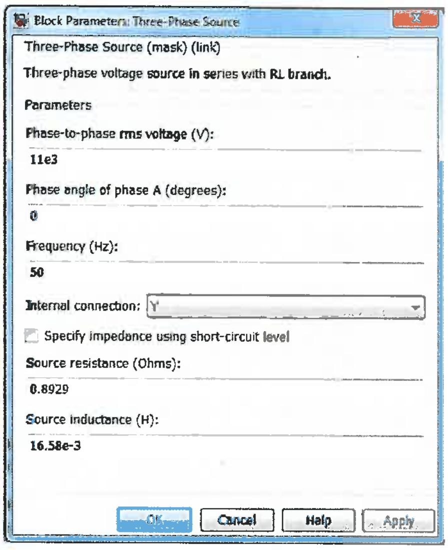

Figure 28: Three Phase Source Parameters

4.2.3 Three Phase Breaker

The three phase source block had the following important parameter settings as shown in Table 5 and Figure 29. It is important to highlight that the breaker needs to be set to 'close' when the input voltage is at a zero crossing to achieve maximum inrush current. The value selected is after 10 cycles so the results are not obstructed by the axis thereby causing them to be difficult to interpret.

Parameter	Setting
Initial Status	Open
Closes after	10/50s

Table 5: Three Phase Breaker Paramcter Settings

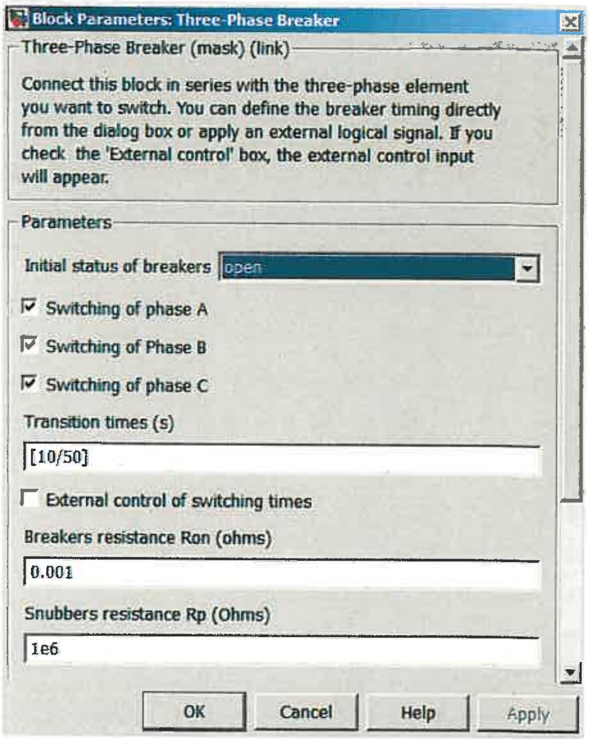

Figure 29: Three Phase Breaker Parameter Settings

4.2.4 Single Phase Saturable Transformer Matlab Block

The input data required for the 'Saturable Single Phase Transformer' block are split over 3 tabs:

- Configuration.
- Parameters.
- Advanced (The advanced tab is not required for this project)

The determination of the parameters used within this block will be explained in Section 4.2.8.

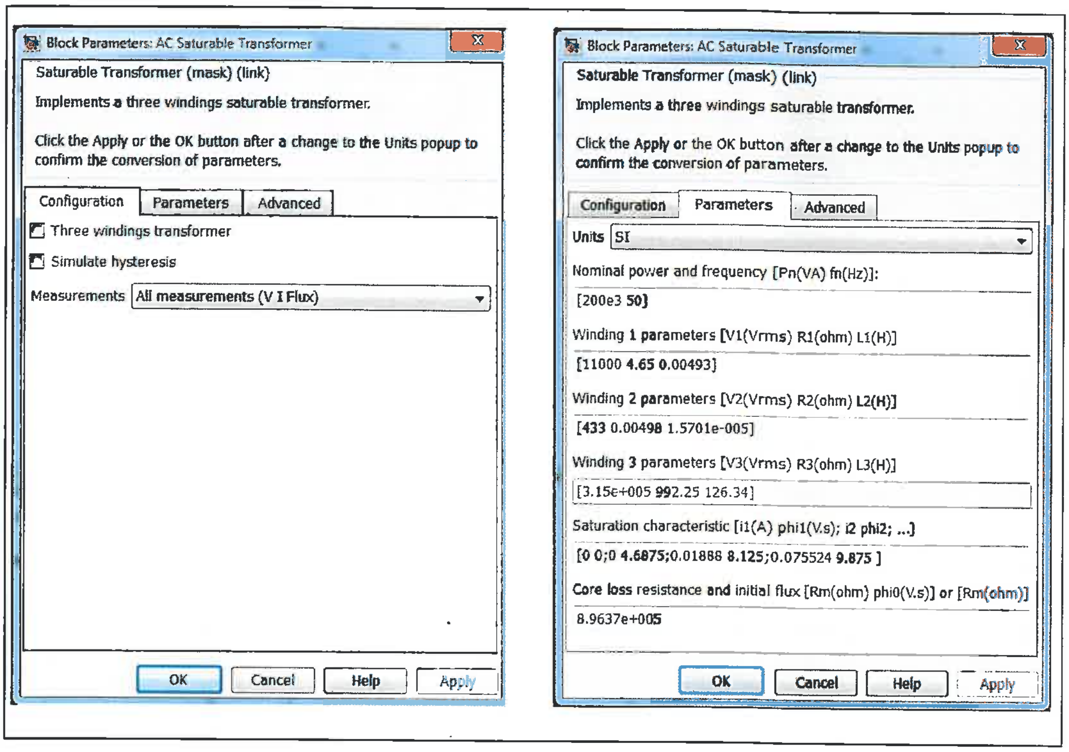

Figure 30: Single Phase Transformer Block Configuration Tabs

4.2.5 Determination of Single Phase Transformer Block Parameters

A series of standard tests were carried out by Ausgrid's internal NATA Accredited Testing Section on the ASC transformers under trial. Results of these tests are attached in Appendix C

4.2.6 Equivalent Transformer Circuit

Figure 31 illustrates the equivalent circuit of the single phase saturable transformer block (third winding omitted for clarity). This equivalent circuit will be used to assist the explanation of some of the ASC transformer parameters.

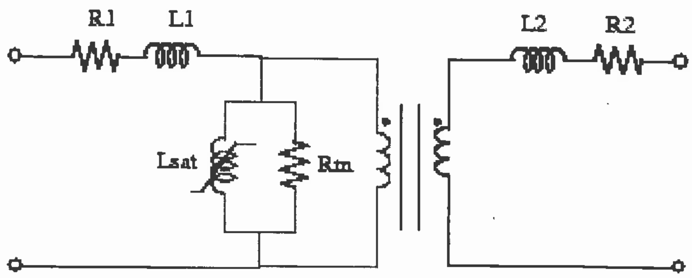

Figure 31: Matlab Saturable Transformer Equivalent Circuit (Matlab)

4.2.7 Interpretation of DC Resistance & Short Circuit Test Results

4.2.7.1 DC Resistance Test Results

DC Resistance tests were carried out on nominal tap setting four.

A-B ($R_{1(DC)}$)	4.5Ω
a-b ($R_{2(DC)}$)	6.4mΩ
∴ a-n (by inspection)	3.2 mΩ

Table 6: DC Resistance Test Results (Testing & Certification Australia, 2011)

4.2.7.2 Short Circuit Test Results

Short circuit test was carried out on nominal tap setting four.

Average Line Voltage (V_l)	432V
Average Line Current (I_{in})	10.5A
Total Power (P_{in})	1559W
Equivalent Total Impedance (Z_{EQ})	23.83Ω

Table 7: Short Circuit Test Results (Testing & Certification Australia, 2011)

Firstly we determine the equivalent total series resistance of the transformer.

$$R_{eq} = R_1 + R_2' \tag{21}$$

$$P_{in\_\emptyset} = I_{in}^2 R_{eq} \tag{22}$$

$$R_{eq} = \frac{P_{in\_\emptyset}}{I_{in}^2}$$

$$R_{eq} = \frac{(\frac{1559}{3})}{10.5^2}$$

$$R_{eq} = 4.714\Omega$$

Because we know the equivalent total impedance (Z_{EQ}) and we have just determined the equivalent total resistance (R_{eq}), we can now calculate the total equivalent series reactance (X_{eq}) of the transformer.

$$X_{eq} = \sqrt{(Z_{eq})^2 - (R_{eq})^2} \tag{23}$$

$$X_{eq} = \sqrt{(23.83)^2 - (4.714)^2}$$

$$X_{eq} = 23.35\Omega$$

To implement the 'saturable transformer' Matlab block we need to provide the individual resistance and leakage inductance for each winding of the transformer.

To split the equivalent resistance into winding components we remove one of the DC measured resistance values to reveal the other winding resistance and, because this transformer is a Delta/Star connection, it is easier to remove the LV winding DC measure resistance. However to do this I need to refer the LV DC resistance value to the primary side first.

$$a = \frac{N_1}{N_2} \tag{24}$$

It should be highlighted that the equivalent values we have determined are the star equivalent parameters and therefore we need to use the star equivalent phase voltage when determining the turns ratio.

$$a = \frac{(\frac{11000}{\sqrt{3}})}{250}$$

$$a = 25.40$$

$$R'_2 = R_{2(DC)} \times a^2 \tag{25}$$

$$R'_2 = 0.0032 \times 25.40^2$$

$$R'_2 = 2.0651\Omega$$

Now we can calculate the primary series resistance

$$R_1 = R_{eq} - R'_2 \tag{26}$$

$$R_1 = 4.714 - 2.0651$$

$$R_1 = 2.649\Omega$$

To split the leakage reactance across the two windings it is acceptable to half the total value. (Slemon & Straughen, 1980)

$$X_1 = \frac{X_{eq}}{2} = X_2' \quad (27)$$

$$X_1 = \frac{23.35}{2}$$

$$X_1 = 11.675\Omega$$

$$X_2' = 11.675\Omega$$

Now I need to convert the referred leakage reactance value of winding two to its actual value.

$$X_2 = \frac{X_2'}{a^2} \quad (28)$$

$$X_2 = \frac{11.675}{25.40^2}$$

$$X_2 = 18.10\text{m}\Omega$$

These leakage reactance values are not in the correct format for the Matlab block; they need to be converted to inductances.

$$X_L = 2\pi f L \quad (29)$$

$$L_1 = \frac{X_1}{2\pi f}$$

$$L_1 = \frac{11.675}{2 \times \pi \times 50}$$

$$L_1 = 37.163\text{mH}$$

$$L_2 = \frac{0.0181}{2 \times \pi \times 50}$$

$$L_2 = 57.61\mu\text{H}$$

4.2.8 Interpretation of Open Circuit Test Results

4.2.8.1 Open Circuit Test Results

Phase Voltage (V_i)	250V
Phase current (I_{in})	0.36 A
Total Power (P_{in})	135W

Table 8: Open Circuit Test Results (Testing & Certification Australia, 2011)

With the results of the open circuit test we can determine the magnetising resistance (Rm) on the LV side of the transformer

$$R_M = \frac{V_L^2}{P_L} \tag{30}$$

$$R_M = \frac{250^2}{135}$$

$$R_M = 463\Omega$$

Referring to the HV side of the transformer we have:

$$R'_M = R_M \times a^2 \tag{31}$$

$$R'_M = 436 \times 44^2$$

$$R'_M = 896.368\ k\Omega$$

4.2.9 Interpretations of Saturation Characteristics

To implement the saturation characteristic within the Matlab block, the user must define the magnetisation response of the transformer. This requires the user to provide coordinates of the magnetic response (Ø vs i) of the transformer in Webers and Amperes.

4.2.9.1 Amorphous Core Magnetisation Characteristic

To model the magnetic response of the ASC transformers this project utilised supplier-provided hysteresis curves, as shown in Figure 32.

To convert this into a usable single line response I plotted the average of the two lines of the amorphous metal and used the coordinates of this average curve to input into Matlab.

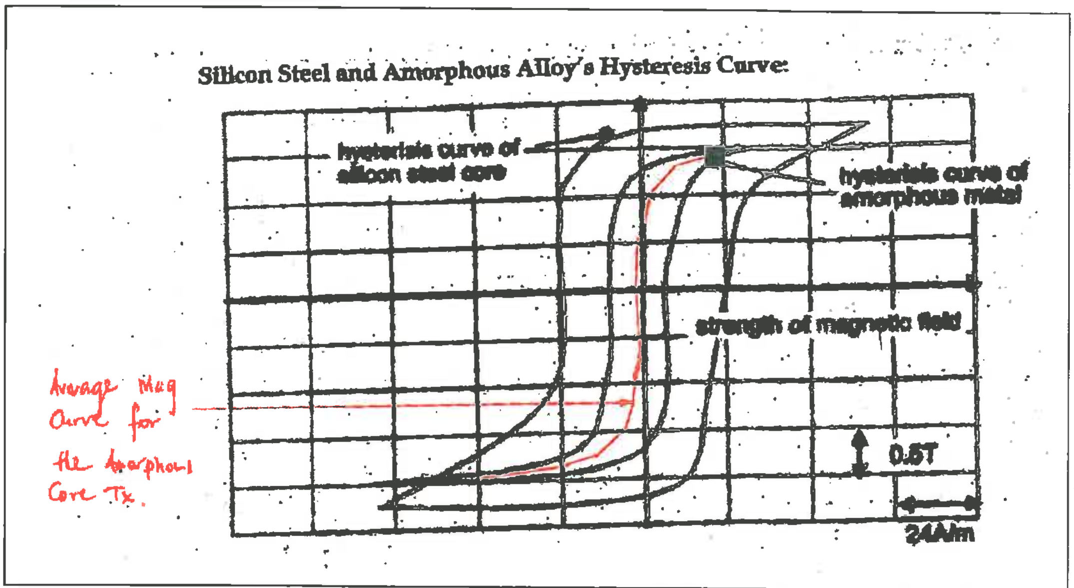

Figure 32: Hysteresis Curves of ASC transformers on trial and typical CRGO transformers

The red line indicates this average line and is a representation of the magnetising characteristic for the amorphous core transformer. From this red line curve I have formulated the values shown in Table 8 for the saturation characteristic.

Magnetising Current (A/m)	Flux (T)
0.0	0.0
4	0.75
12	1.3
48	1.4

Table 9: Magentic Response of ASC Transformer Provided by Supplier

A further complication is that this hysteresis illustration is provided in units which are incompatible with the Matlab block. It depicts the flux values as flux density and is therefore in units of Tesla. The magnetising current is represented as magnetic field strength (A/m). Therefore I need to convert these values into the values required for Matlab, which are Webers and Amperes respectively.

4.2.9.2 Conversion of Hysteresis Values

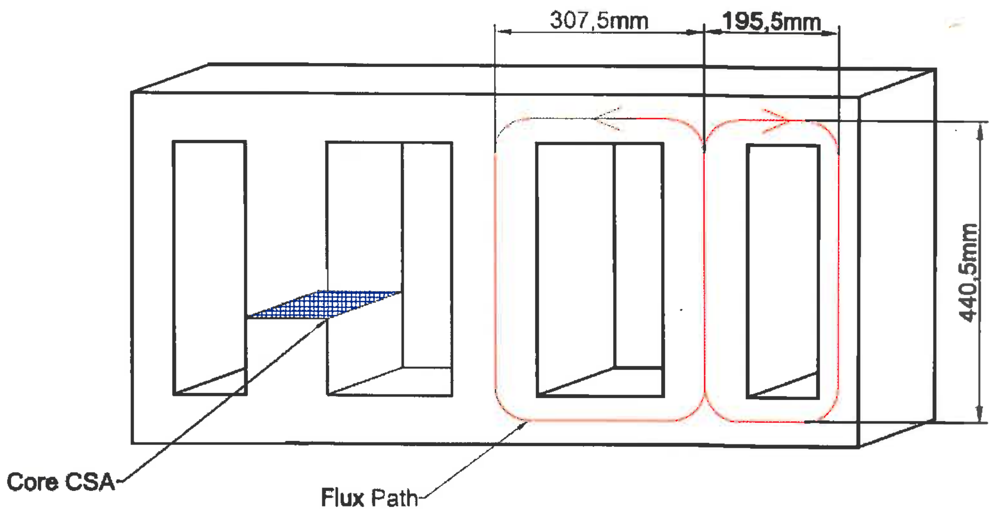

Figure 33: Amorphous Core Transformer Core showing CSA and mean flux path Approx Dimensions

We can estimate the cross sectional area of the core using the two following formula for mutual flux (Φ) and flux density (B) as we have been provided the volts per turn of the transformer in Appendix E.

$$\emptyset = \frac{E_i}{4.44\ \times f} = \frac{Volts\ per\ turn}{4.44\ \times frequency} \tag{32}$$

$$A = \frac{\emptyset}{B} = \frac{Flux}{Flux\ Density} = \frac{Webers}{T} \tag{33}$$

So if we first determine the mutual flux produced by the transformer core

$$\emptyset = \frac{6.4101}{4.44\ \times 50}$$

$$\emptyset = \ 0.028874\, Wb$$

Now we can determine the cross sectional area as we know the max flux density in Tesla, as shown in Figure 32.

$$A = \frac{0.028874}{1.5}$$

$$A = \ 0.019249\, m^2$$

Using this value of core cross sectional area we are able to convert the flux density values shown in the hysteresis response of Figure 32 into total flux values required for the Matlab block.

$$\emptyset = \ BA \tag{34}$$

Now we need to convert the magnetic field strength values of figure 19 into the required magnetic current values for the Matlab block. To achieve this we require the mean flux field path length and the number of turns.

Firstly if we look at the number of turns for the primary winding, we are provided with the volts per turn performance of the core as 6.4101 V/turn. We also know that the star equivalent voltage of the primary delta winding is 6351V.

This allows one to determine the star equivalent number of turns for the HV winding as.

$$N = \frac{Equivalent\ Star\ Voltage}{Volts\ per\ turn} \tag{35}$$

$$N = \frac{6351}{6.4101}$$

$$N = 990.78$$

Now if we consider the mean flux field path, to determine this value we need the physical dimensions of the transformer core, which are provided in Figure 33. If we consider the 'A' phase leg of the transformer and assume that the flux is split evenly between loops 1 and 2, we can determine the mean flux field path as approximately equal to average length of the summation of loop 1 and 2.

$$l_{LOOP\ 1} = (307.5\ \times 2) + (440.5\ \times 2) = 1.496m \tag{36}$$

$$l_{LOOP\ 2} = (195.5\ \times 2) + (440.5\ \times 2) = 1.272m \tag{37}$$

Therefore the mean flux path is equal to.

$$l = \frac{(l_{LOOP\ 1}) + (l_{LOOP\ 2})}{2} \tag{38}$$

$$l = \frac{(1.496) + (1.272)}{2} = 1.384m$$

Therefore we can convert the magnetic field strength values provided in Figure 32 to magnetic field current required for the Matlab block by using the following formula.

$$H = \frac{Ni}{l} = \frac{Tx\ Turns\ \times Mag\ Current}{Field\ Length} \tag{39}$$

$$i = \frac{l \times H}{N} \tag{40}$$

Point	Magnetising Current	Turns	Mean Flux Path Length	Magnetising Current	Flux Density	Core CSA	Total Flux
	H	N	*l*	I = (lxH) / N	B	A	Ø = BA
1	0	990.78	1.384	0	0	0.019249	0
2	6	990.78	1.384	0.00838128	1	0.019249	0.01925
3	12	990.78	1.384	0.01676255	1.3	0.019249	0.02502
4	24	990.78	1.384	0.0335251	1.4	0.019249	0.02695
5	48	990.78	1.384	0.0670502	1.5	0.019249	0.02887

Table 10: Magentic Response of ASC Transformer with Appropriate Units

4.2.10 Matlab Block Input Values

Tab	Input	Value	Determination Method
Configuration	Measurements	All Measurements	By Inspection
Parameters	Units	SI	By Inspection
	Nominal power (S)	200kVA	By Inspection
	Frequency (f)	50Hz	By Inspection
	Winding 1 - RMS Volts (V1)	6351V	By Inspection
	Winding 1 - Resistance (R1)	2.649Ω	Short Circuit Test
	Winding 1 – Inductance (L1)	37.163mH	Short Circuit Test
	Winding 2 - RMS Volts (V2)	250V	By Inspection
	Winding 2 – Resistance (R2)	3.2 mΩ	Short Circuit Test
	Winding 2 - Inductance (L2)	57.61µH	Short Circuit Test
	Magnetising Resistance LV Side (Rm)	463Ω	Open Circuit Test
	Magnetising Resistance HV Side (R'm)	896.368 *kΩ*	Open Circuit Test
	No. of turns HV winding	990.78	Data Sheet
	No. of Turns LV winding	39	Data Sheet
	Saturation Characteristic (I1,phi1....etc)	[00;0.00838 0.01925;0.01676 0.02502;0.03353 0.027;0.0671 0.029]	Interpretation of Data sheet

Table 11: Summary of Parameters used in Inrush Simulation

4.2.11 Explaination of How the Results will be Obtained

Using the parameters shown in Table 11, the level of inrush current will be assessed in two ways.

Firstly a single transformer will be modelled and the resultant inrush current levels recorded. This will allow one to determine if there are going to be any protection implications for the HV drop out fuses used to protect each individual transformer.

Secondly after obtaining the results for a single transformer we can extrapolate these results to model a specific radial feeder as shown in Figure 19. The specific example under consideration will be when there has been a planned interruption on the feeder and the network operators are restoring the line. When restoring the line, the transformers would typically have the secondaries open circuited as this would have been a requirement of the Ausgrid Safety Rules and the feeder would be energised via a recloser and then individual transformers would have the secondaries closed, thereby restoring supply to the residents. By analysing this situation we will be able to ascertain if there are any implications for the over current protection settings at the recloser.

5.0 RESULTS & DISCUSSION

5.1 Cost Benefits of Reduced Core Loss Investigation

The results for the economic comparison between the two types of transformers will be presented in the following sections:

- General Overview
- Results for parameters as determined in Section 4.1.1.9
- Effect of Wholesale Electricity Price Changes
- Effect of change in life span

5.1.1 Results General Overview

The parameters in Table 12 show the important characteristics which influence the TOC results.

Item	Value	
	Si Steel	**ASC**
Fixed Losses	381W	135W
Variable Losses	2200W	1900W
Capital Costs	$9,760	$10,773

Table 12: Important TOC Input Data

It should be highlighted that the following earlier expectations are confirmed with the results obtained;

- ASC have reduced fixed core transformer losses
- ASC transformer have a higher capital purchase cost.

However an interesting characteristic which influenced the results was that the following expectation was contradicted;

- ASC transformer have higher load losses.

Generally the results confirmed expectations of the cost effectiveness of ASC transformers which is that over the first few years of the simulation the ASC transformers have a higher net present value and are therefore more costly than the legacy transformers. However after four to six years, depending on the load cycle simulated, the ASC transformers proved to be more cost effective than the CRGO legacy transformers. An example of this economic performance is shown in Figure 34. On the left hand side of the orange line the CRGO transformer is more cost effective than the ASC transformer and on the right hand side of the orange line the ASC transformer is more cost effective than the CRGO transformer. It should be also highlighted that the total savings of $2681.00 over the 40 year life span on the selected load cycle is illustrated by the green line.

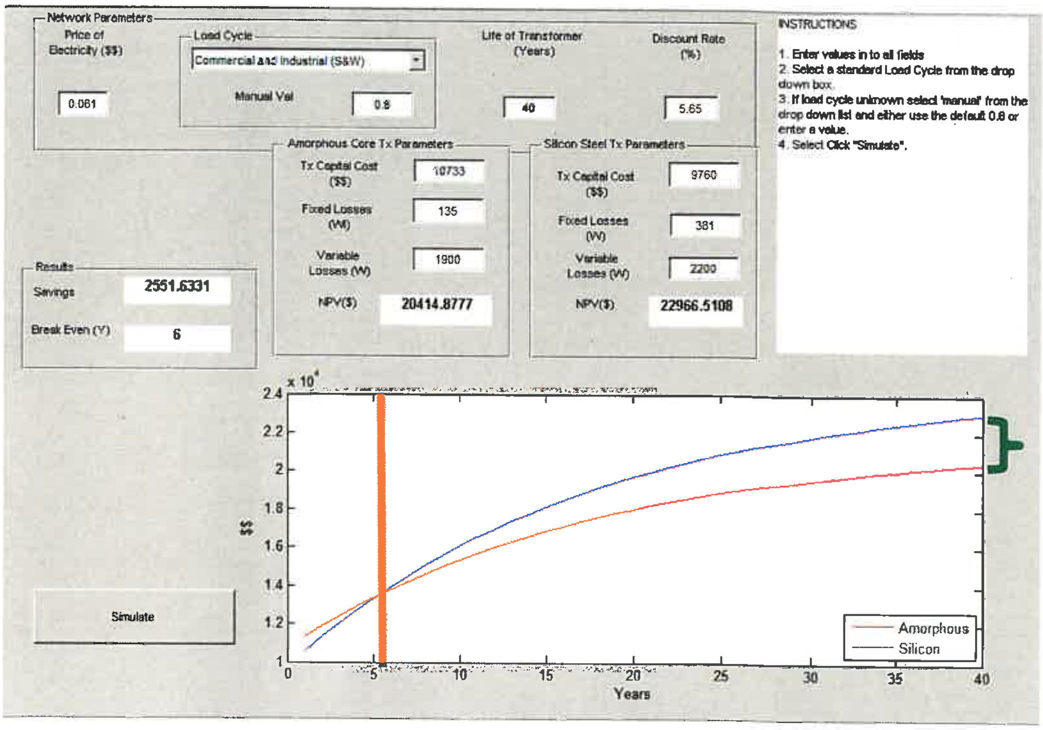

Figure 34: Economic Comparison of Transformers on Load Cycle (A)

5.1.2 Results for Parameters as Determined in Section 4.1.1.9

Carrying out the simulation using the parameters determined in Section 4.1.1.9 the results obtained are shown within Table 13 and Figure 35.

Description	Load Cycle	NPV AC ($$)	NPV CRGO ($$)	SAVINGS ($$)	Ausgrid Potential Savings ($$)	BREAKEVEN (YR)	EP ($$/kWh)
Commercial and Industrial (S&W)	A	$20,414.88	$22,966.51	$2,551.63	$5,103,264.60	6	0.061
Domestic Little Water Heating (NSW)	B	$20,556.16	$23,130.10	$2,573.94	$5,147,880.00	6	0.061
Domestic Much Water Heating (W)	CW	$21,236.00	$23,917.28	$2,681.28	$5,362,568.00	5	0.061
Domestic Much Water Heating (S)	CS	$20,956.17	$23,593.27	$2,637.10	$5,274,196.00	5	0.061
Mixed Predominantly Domestic (W)	DW	$21,604.85	$24,344.38	$2,739.53	$5,479,054.00	5	0.061
Mixed Predominantly Domestic (S)	DS	$20,202.50	$22,720.59	$2,518.10	$5,036,190.00	6	0.061
Mixed Predominantly Industrial (S&W)	E	$23,149.76	$26,133.22	$2,983.46	$5,966,913.00	5	0.061
Continuous	F	$28,810.32	$32,687.55	$3,877.23	$7,754,458.40	4	0.061

Table 13: Results for Parameters Determined in Section 4.1.1.9

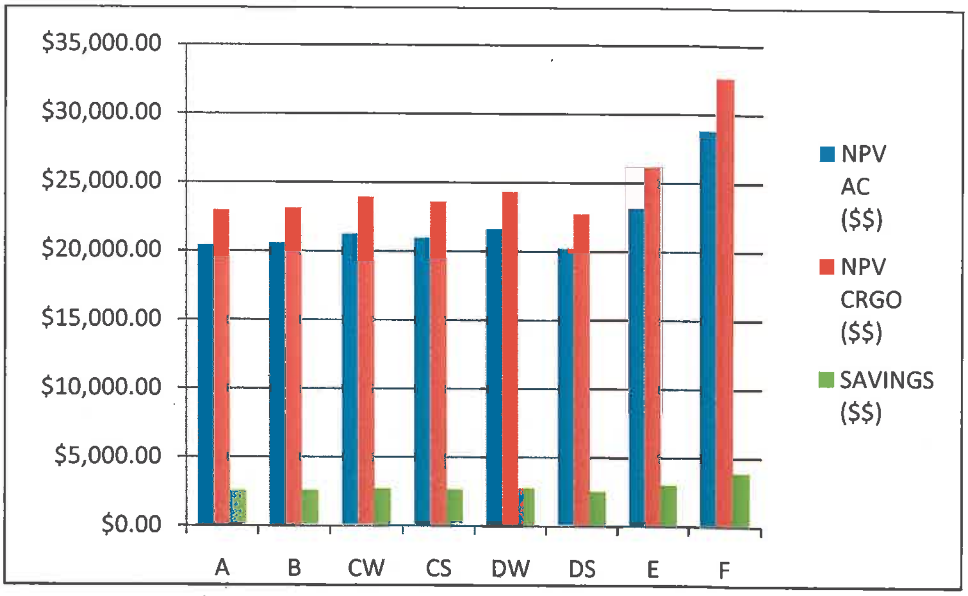

Figure 35: Results for Parameters Determined in Section 4.1.1.9

It can be seen that for all load cycles the ASC transformers economically outperform the legacy CRGO transformers. With the savings ranging from approximately $2,500.00 through to $3,800.00, the potential savings for each load cycle is highlighted in Figure 35.

5.1.2.1 Implications for Ausgrid

The implication for Ausgrid becomes apparent when the total asset base is considered. Ausgrid has an asset base of approximately 2000, 200kVA pole top transformers. The continuous load cycle (F) is disregarded as this is an extremely rare load cycle for a distribution network, therefore the potential savings are in the order of $5 - 6M across the 200kVA pole top transformer asset base across the 40 year financial life of these transformers.

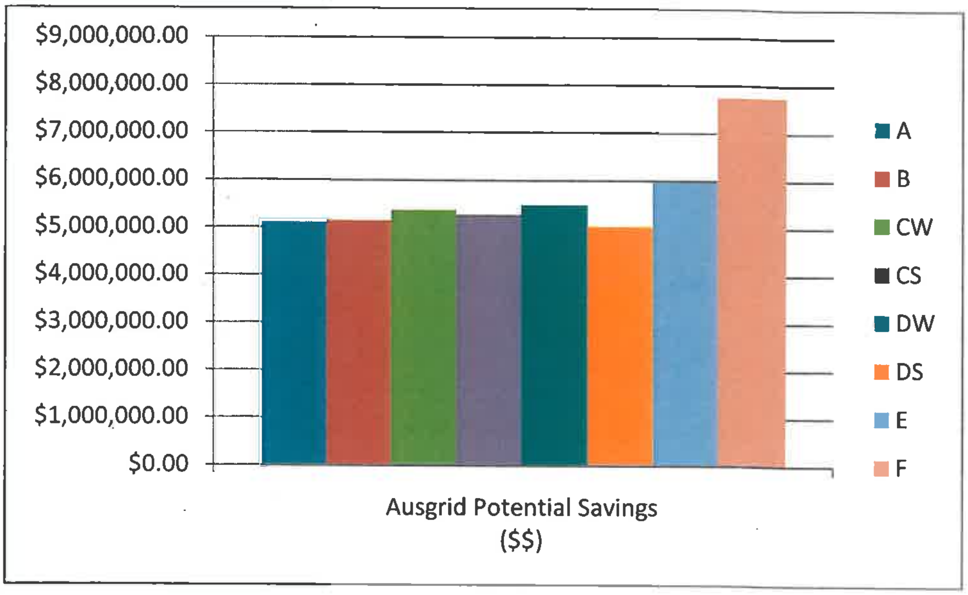

Figure 36: Savings for Ausgrid Asset Base for Each Load Cycle

5.1.3 Effect of Wholesale Electricity Price Changes

To investigate the effect of electricity price increases on the cost effectiveness of the ASC transformers on trial, this section reports on the economic comparison between the two transformers across a range of strategic price changes.

In the NSW Electricity Network and Price Enquir Report conducted by the NSW State Government in 2010, wholesale electricity prices are expected to increase over the next 15 years. This price increase is forecast to occur at different rates largely dependent on the effect of changes in the Carbon Price. Figure 37 illustrates the average annual National Electricity Market spot price over the next 15 years as a result of three different carbon price scenarios, high carbon price, medium carbon price and no carbon price (NSW State Government, 2010).

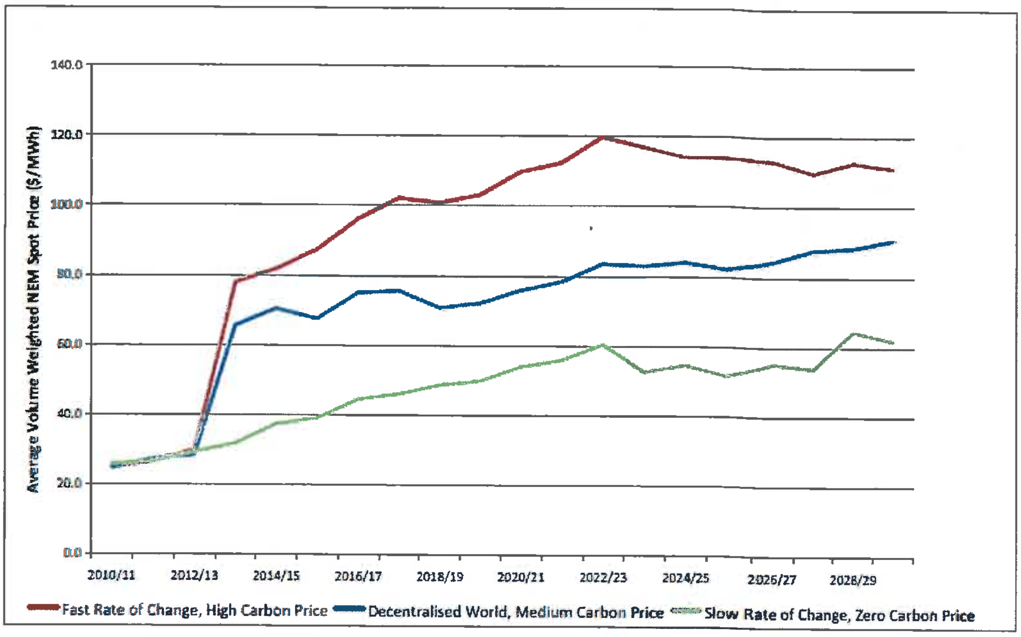

Figure 37: Forecast NEM Spot Price for Different Carbon Price Scenarios (NSW State Government, 2010)

To review the effect that changes in wholesale electricity prices and the cost effectiveness of these ASC transformers, this section reports on the results of simulations with the wholesale electricity price set to $90/MWh and $110/MWh as forecast to occur in 2028/29 for the different expected carbon price scenarios. Further to this, because the policy of the current federal political Opposition Party is to rescind the Carbon Price as soon as elected, this section will analyse a price of $35/MWh. This price was selected as it is the expected spot price which coincides with the next federal election in November 2013. (Liberal Party of Australia, 2012)

The results achieved for each of these price scenarios are as shown in the following tables and figures;

Description	Load Cycle	NPV AC ($$)	NPV CRGO ($$)	SAVINGS ($$)	Ausgrid Potential Savings ($$)	BREAKEVEN (YR)	EP ($$/kWh)
Commercial and Industrial (S&W)	A	$25,017.73	$29,245.02	$4,227.29	$8,454,572.00	4	0.09
Domestic Little Water Heating (NSW)	B	$25,226.19	$29,486.38	$4,260.19	$8,520,380.00	4	0.09
Domestic Much Water Heating (W)	CW	$26,229.22	$30,647.79	$4,418.57	$8,837,140.00	4	0.09
Domestic Much Water Heating (S)	CS	$25,816.37	$30,169.75	$4,353.38	$8,706,760.00	4	0.09
Mixed Predominantly Domestic (W)	DW	$26,773.44	$31,277.93	$4,504.49	$9,008,980.00	4	0.09
Mixed Predominantly Domestic (S)	DS	$24,704.38	$28,882.19	$4,177.81	$8,355,620.00	4	0.09
Mixed Predominantly Industrial (S&W)	E	$29,052.81	$33,917.21	$4,864.40	$9,728,800.00	3	0.09
Continuous	F	$37,404.45	$43,587.53	$6,183.08	$12,366,160.00	3	0.09

Table 14: Results for EP = $90/MWh

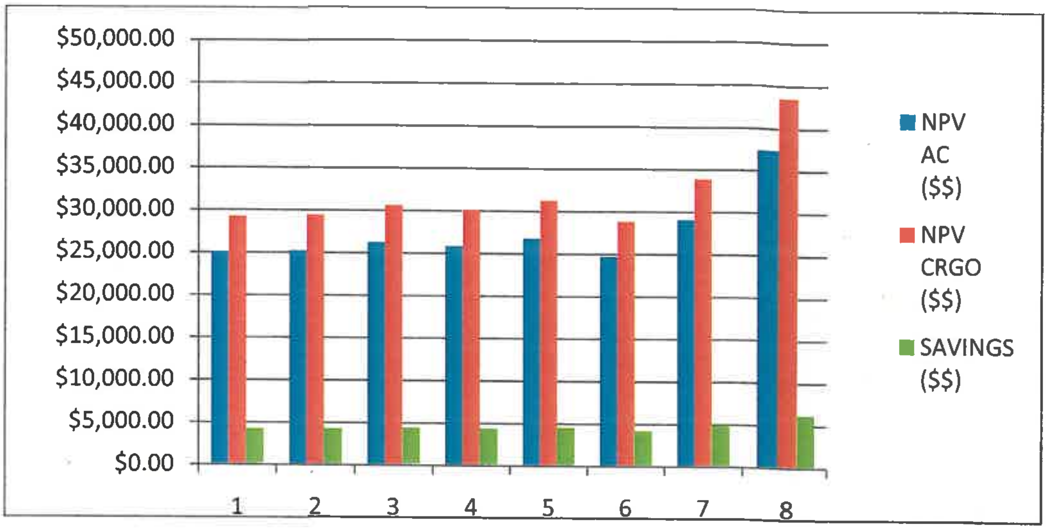

Figure 38: Results for EP = $90/MWh

Description	Load Cycle	NPV AC ($$)	NPV CRGO ($$)	SAVINGS ($$)	Ausgrid Potential Savings ($$)	BREAKEVEN (YR)	EP ($$/kWh)
Commercial and Industrial (S&W)	A	$28,192.12	$33,575.02	$5,382.90	$10,765,800.00	3	0.11
Domestic Little Water Heating (NSW)	B	$28,446.90	$33,870.02	$5,423.12	$10,846,240.00	3	0.11
Domestic Much Water Heating (W)	CW	$29,672.83	$35,289.52	$5,616.69	$11,233,380.00	3	0.11
Domestic Much Water Heating (S)	CS	$29,168.23	$34,705.25	$5,537.02	$11,074,040.00	3	0.11
Mixed Predominantly Domestic (W)	DW	$30,337.98	$36,059.70	$5,721.72	$11,443,440.00	3	0.11
Mixed Predominantly Domestic (S)	DS	$27,809.14	$33,131.56	$5,322.42	$10,644,840.00	3	0.11
Mixed Predominantly Industrial (S&W)	E	$33,123.88	$39,285.47	$6,161.59	$12,323,180.00	3	0.11
Continuous	F	$43,331.44	$51,104.76	$7,773.32	$15,546,640.00	2	0.11

Table 15: Results for EP = $110/MWh

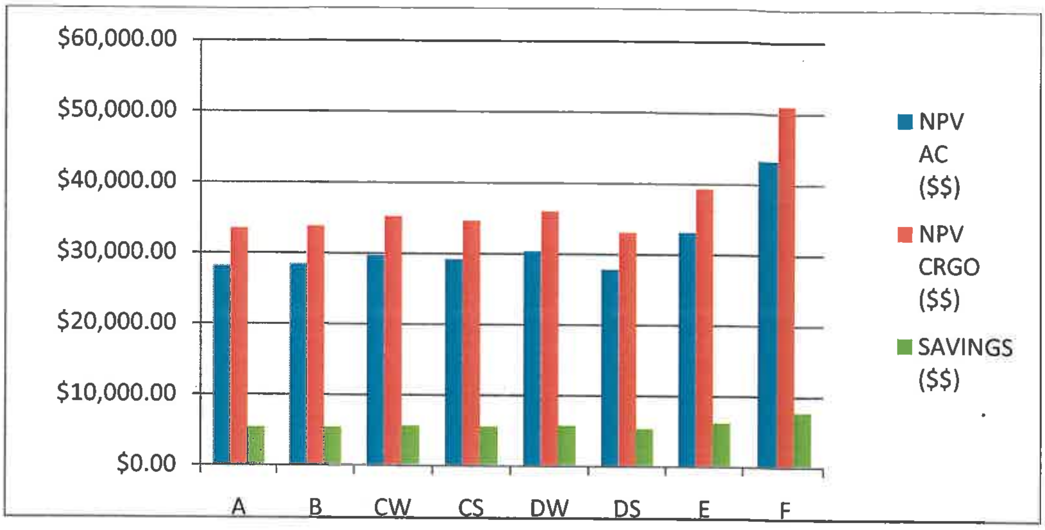

Figure 39: Results for EP = $110/MWh

Description	Load Cycle	NPV AC ($$)	NPV CRGO ($$)	SAVINGS ($$)	Ausgrid Potential Savings ($$)	BREAKEVEN (YR)	EP ($$/kWh)
Commercial and Industrial (S&W)	A	$16,288.18	$17,337.51	$1,049.33	$2,098,660.00	11	0.035
Domestic Little Water Heating (NSW)	B	$16,369.24	$17,431.37	$1,062.13	$2,124,260.00	11	0.035
Domestic Much Water Heating (W)	CW	$16,759.31	$17,883.03	$1,123.72	$2,247,440.00	10	0.035
Domestic Much Water Heating (S)	CS	$16,598.75	$17,697.12	$1,098.37	$2,196,740.00	10	0.035
Mixed Predominantly Domestic (W)	DW	$16,970.94	$18,128.09	$1,157.15	$2,314,300.00	10	0.035
Mixed Predominantly Domestic (S)	DS	$16,166.32	$17,196.41	$1,030.09	$2,060,180.00	11	0.035
Mixed Predominantly Industrial (S&W)	E	$17,857.37	$19,154.47	$1,297.10	$2,594,200.00	9	0.035
Continuous	F	$21,105.23	$22,915.15	$1,809.92	$3,619,840.00	7	0.035

Table 16: Results for EP = $35/MWh

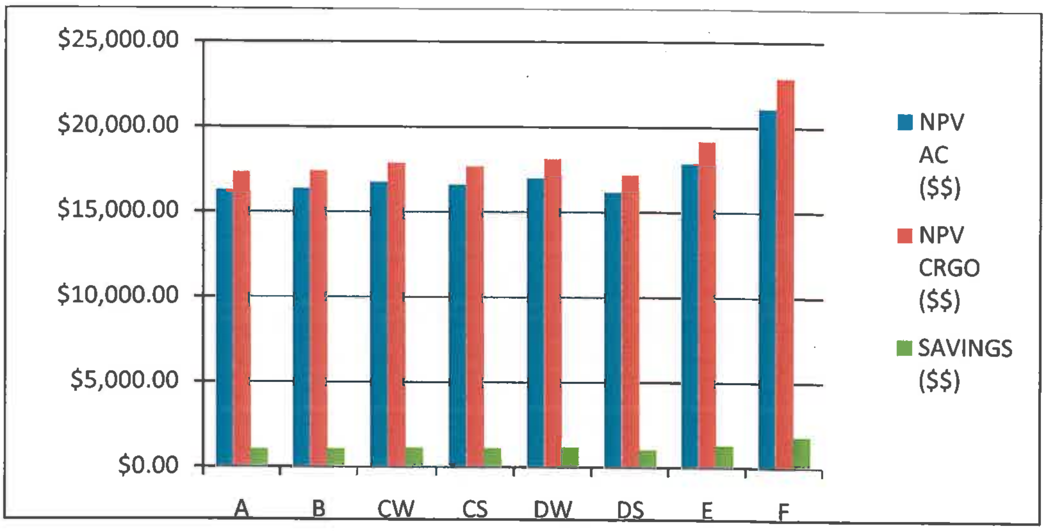

Figure 40: Results for EP = $35/MWh

5.1.3.1 Implications for Ausgrid as a Result of Changes in Price

The implications for Ausgrid with changes in the price of wholesale electricity are as expected. Increases in electricity prices above the current average of $61/MWh results in greater potential savings and if the carbon price was abolished and the wholesale electricity price was able to be returned to previous averages the potential savings would be eroded.

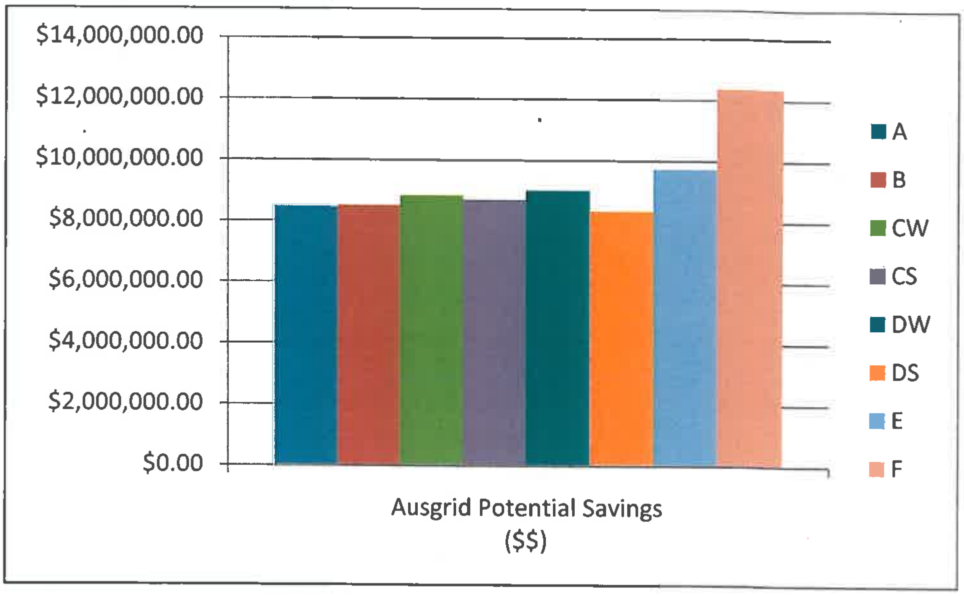

Figure 41: Results for EP = $90/MWh

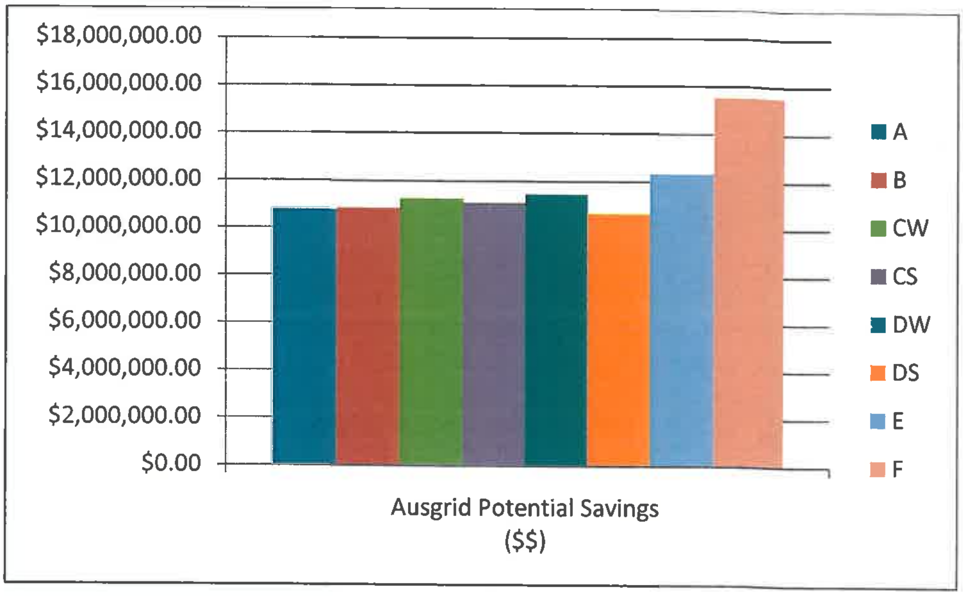

Figure 42: Results for EP = $110/MWh

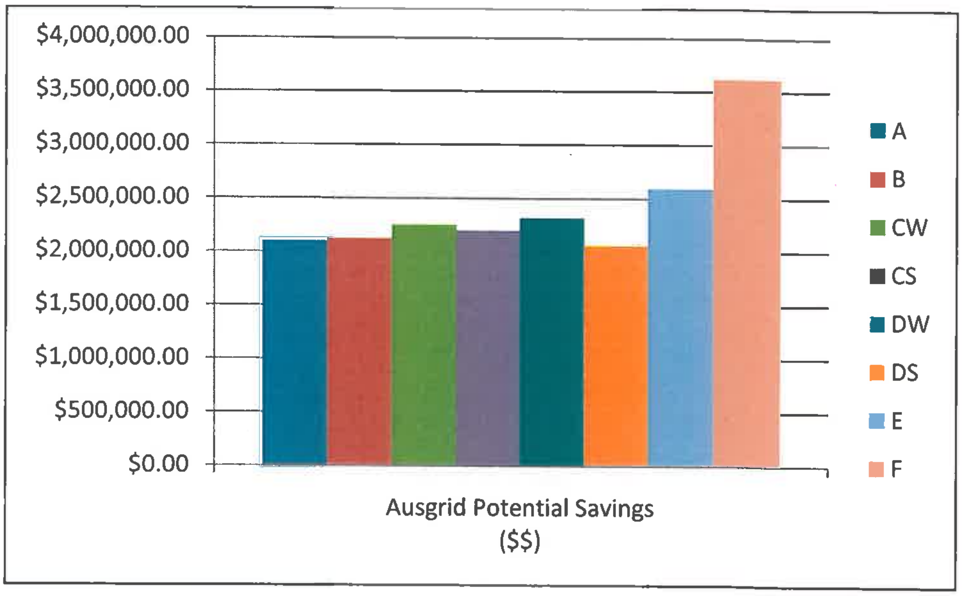

Figure 43: Results for EP = $35/MWh

Once again if the continuous load cycle is ignored, Figure 41 and Figure 42 illustrate that the potential savings achieved by Ausgrid corresponding to increases of the average spot price to $90/MWh and $110/MWh would be in the order of ($8M – $10M) and ($10M – $12M) respectively.

Figure 43 shows that the potential savings would be in the order of ($2M – $2.5M) for a price reduction to $35/MWh.

5.1.4 Effect of change in life span

As highlighted in Section 4.1.1.8 the capital cost of the ASC transformers are ~10% more expensive than the existing legacy transformers. What makes this value more significant is that the ASC transformers have both lower load loss and fixed loss values. This price equivalency could be because the manufacturer quality is not comparable to the legacy CRGO transformer. This reduction in manufacturer quality would result in a reduced life span of the ASC transformer when compared to the legacy CRGO transformers and as such reduce the potential savings achieved by the ASC transformers. It is for this reason that this section will report on the possible savings achieved by the ASC transformers for reduced life spans. The values analysed will be 30 and 20 years, as it was assumed that the reduction in life span would not exceed 50% of the expected life span. These simulations will also be carried out with a projected minimum price of electricity of $35/MWh as this will be the most conservative analysis and will provide a good basis for larger scale decision making.

Description	Load Cycle	NPV ASC ($$)	NPV CRGO ($$)	SAVINGS ($$)	Ausgrid Potential Savings ($$)	BREAKEVEN (YR)	Tx Life (Year)
Commercial and Industrial (S&W)	A	$15,780.18	$16,644.57	$864.39	$1,728,784.00	11	30
Domestic Little Water Heating (NSW)	B	$15,853.83	$16,729.85	$876.02	$1,752,040.00	11	30
Domestic Much Water Heating (W)	CW	$16,208.23	$17,140.21	$931.98	$1,863,962.00	10	30
Domestic Much Water Heating (S)	CS	$16,062.36	$16,971.31	$908.95	$1,817,900.00	10	30
Mixed Predominantly Domestic (W)	DW	$16,400.51	$17,362.86	$962.35	$1,924,700.00	10	30
Mixed Predominantly Domestic (S)	DS	$15,669.46	$16,516.38	$846.92	$1,693,840.00	11	30
Mixed Predominantly Industrial (S&W)	E	$17,205.88	$18,295.38	$1,089.50	$2,179,000.00	9	30
Continuous	F	$20,156.74	$21,712.17	$1,555.43	$3,110,860.00	7	30

Table 17: Results for M = 30 Years

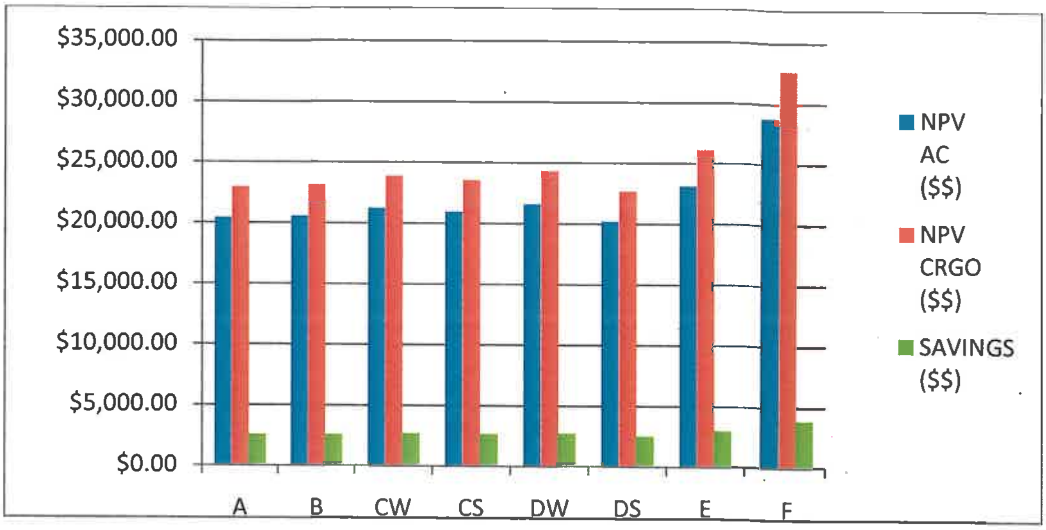

Figure 44: Results for M = 30 Years

Description	Load Cycle	NPV ASC ($$)	NPV CRGO ($$)	SAVINGS ($$)	Ausgrid Potential Savings ($$)	BREAKEVEN (YR)	Tx Life (Year)
Commercial and Industrial (S&W)	A	$14,900.03	$15,444.01	$543.98	$1,087,960.00	11	20
Domestic Little Water Heating (NSW)	B	$14,960.83	$15,514.42	$553.59	$1,107,180.00	11	20
Domestic Much Water Heating (W)	CW	$15,253.43	$15,853.21	$599.78	$1,199,560.00	10	20
Domestic Much Water Heating (S)	CS	$15,132.99	$15,713.76	$580.77	$1,161,540.00	10	20
Mixed Predominantly Domestic (W)	DW	$15,412.19	$16,037.03	$624.84	$1,249,680.00	10	20
Mixed Predominantly Domestic (S)	DS	$14,808.62	$15,338.17	$529.55	$1,059,100.00	11	20
Mixed Predominantly Industrial (S&W)	E	$16,077.10	$16,806.94	$729.84	$1,459,680.00	9	20
Continuous	F	$18,513.38	$19,627.89	$1,114.51	$2,229,020.00	7	20

Table 18: Results for M = 20 Years

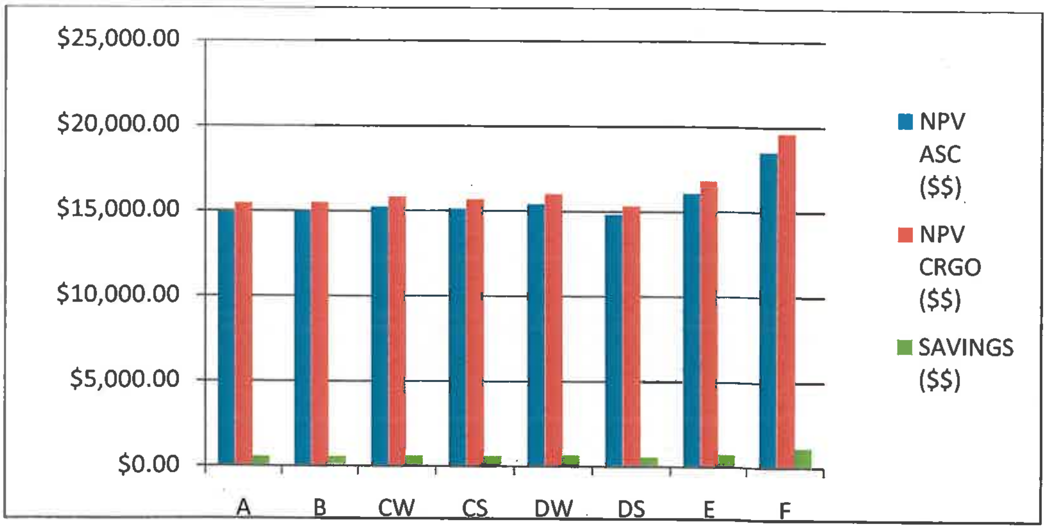

Figure 45: Results for M = 20 Years

5.1.4.1 Implications for Ausgrid

Once again as expected, if the expected lifespan was reduced this would result in a corresponding reduction in potential savings. Specifically if the expected lifespan is reduced to a total of 30 years, the equivalent potential savings to below $2M over the entire 200kVA pole top transformer asset base as illustrated by Figure 46.

A further reduction to a 20 year lifespan, reduces this potential savings to approximately $1M as shown by Figure 47.

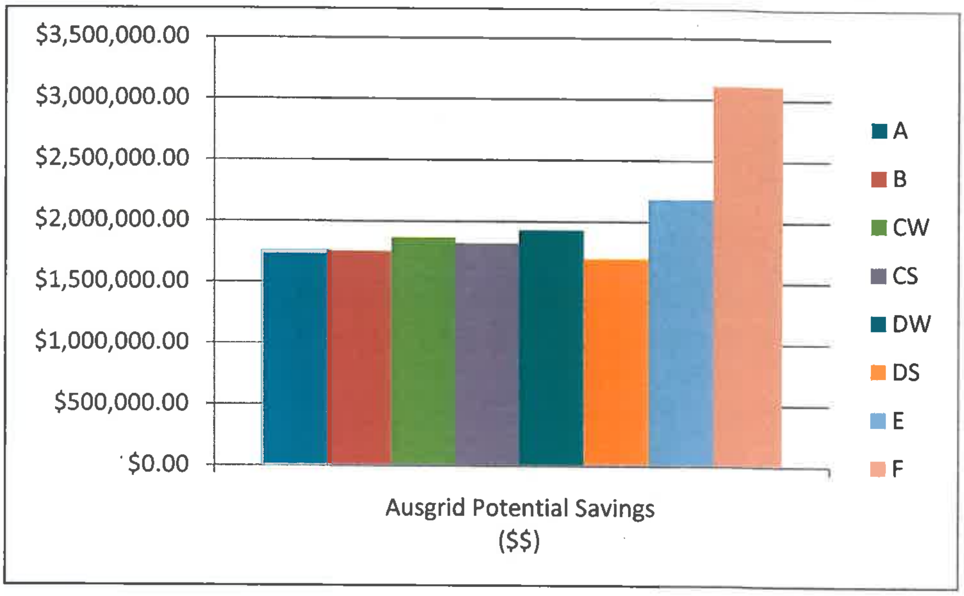

Figure 46: Results for M = 30 Years

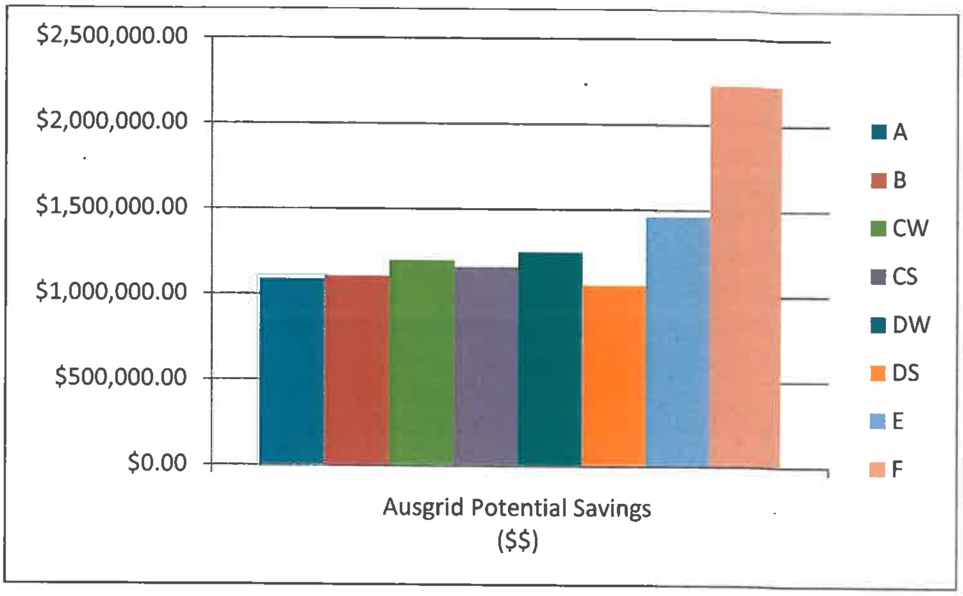

Figure 47: Results for M = 20 Years

5.2 11kV Protection System Problems Due to Increased Inrush Current

In trying to complete the inrush modelling using the single transformer model with the parameters outlined in Table 11, an issue with current oscillation was encountered as shown in Figure 48. This issue was unable to be resolved and therefore casts doubt over the results achieved for this aspect of the project.

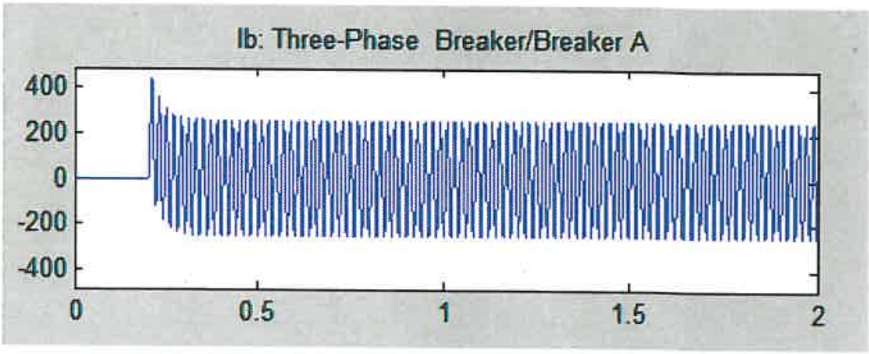

Figure 48: Simulated Inrush Current Waveform with Erroneous Oscillation

Therefore the presentation of the results for this section will be in a 'step by step' manner, showing individual results for minor changes in the default parameters of the Matlab saturable transformer block to the parameters outlined in Table 11.

5.2.1 Single Transformer Results

5.2.2 Test No. 1 - Default Parameters (No Inrush)

The first test that will be reported is used as a control to ascertain that the correct switching time is being used for the remaining tests completed. The simulation will be run with all the default parameters of the saturable transformer unchanged and the switching time set to 10.25/50. Which corresponds to a switching time when the supply voltage should be at a positive peak, thereby resulting in zero inrush current.

The essential parameters of the simulation are shown in Table 19

Input	Value
Switching Time	10.25/50s
Nominal power (S)	200kVA
Frequency (f)	50Hz
Winding 1 - RMS Volts (V1)	6351V
Winding 1 - Resistance (R1)	Default
Winding 1 – Inductance (L1)	Default
Winding 2 - RMS Volts (V2)	250V
Winding 2 – Resistance (R2)	Default
Winding 2 - Inductance (L2)	Default
Magnetising Resistance HV Side (R'm)	Default
Saturation Characteristic (I1,phi1….etc)	Default

Table 19: Test No. 1 Default Parameters (No Inrush)

As expected because the secondaries are open circuited and the switching time was selected so the transformer was energised at the peak of the supply voltage, the primary current was approximately equal to zero. Figure 49 illustrated this performance, where (*Ub*) is the supply voltage and shows that the switching time coincided with a positive supply peak and (I_{W1}), is the primary winding current which is equal to zero.

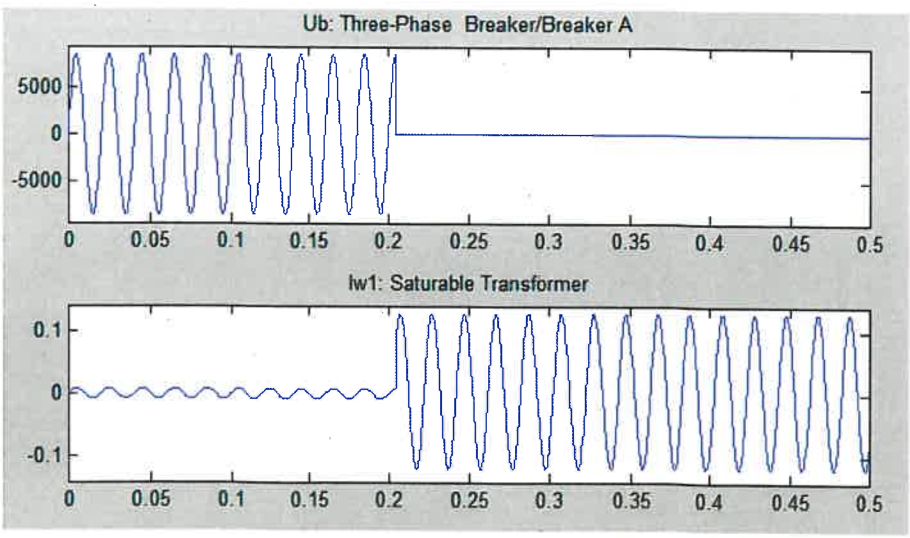

Figure 49: Test No. 1 Default Parameters (No Inrush) – Voltage / Current Waves

5.2.3 Test No. 2 - Default Parameters (Inrush)

The second test attempts to cause maximum inrush current to flow in the default transformer. This will be achieved by changing the switching time so that it coincides with a zero crossing of the supply voltage.

Input	Value
Switching Time	10/50
Nominal power (S)	200kVA
Frequency (f)	50Hz
Winding 1 - RMS Volts (V1)	6351V
Winding 1 - Resistance (R1)	Default
Winding 1 – Inductance (L1)	Default
Winding 2 - RMS Volts (V2)	250V
Winding 2 – Resistance (R2)	Default
Winding 2 - Inductance (L2)	Default
Magnetising Resistance HV Side (R'm)	Default
Saturation Characteristic (I1,phi1….etc)	Default

Table 20: Test No. 2 Default Parameters (Inrush)

Once again the expected result is achieved and more importantly inrush is achieved. This can be witnessed in Figure 50, where we see initial values of primary current is in excess of 75A, which is approximately 2.4 times the rated current of the transformer. It is also relevant to highlight that this primary winding current consists only of positive pulses and decays gradually. Both properties are consistent with inrush current as explained in section 2.6.

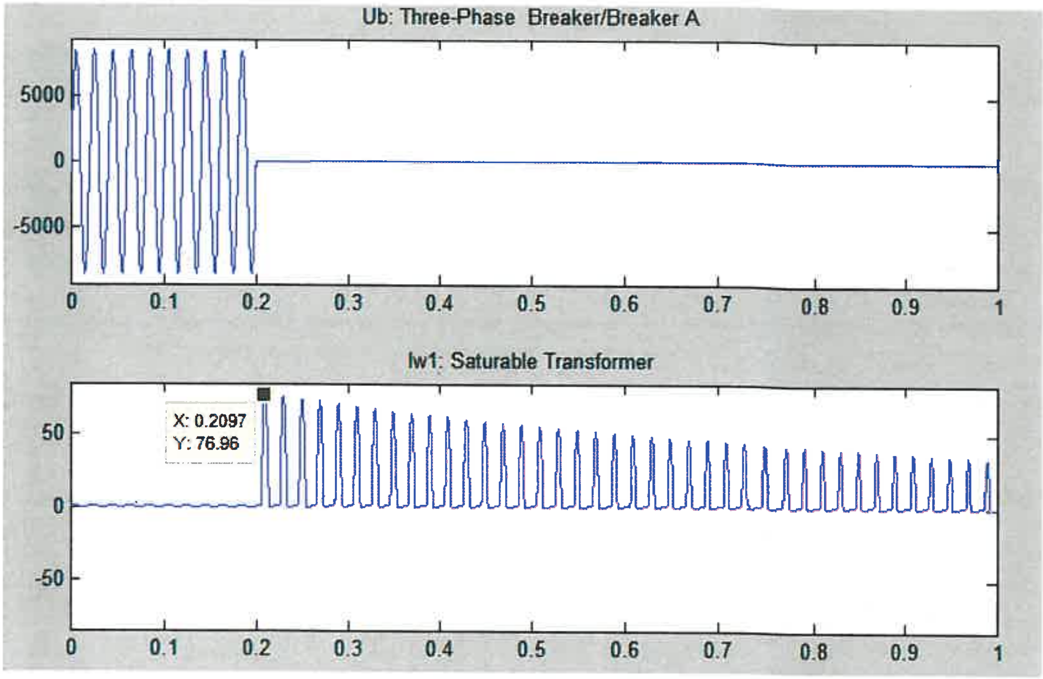

Figure 50: Test No. 2 Default Parameters (Inrush) – Voltage / Current Waves

Since we have confirmed that the simulation model is switching at the correct time so as to produce transformer saturation and hence inrush to occur. We will now begin to change the parameters of the default block to those of Table 11 and record the results. Also the following tests will neglect to show the supply voltage waveform.

5.2.4 Test No. 3 – Change Series Equivalent Parameters (Inrush)

Input	Value
Switching Time	10/50s
Nominal power (S)	200kVA
Frequency (f)	50Hz
Winding 1 - RMS Volts (V1)	6351V
Winding 1 - Resistance (R1)	2.649Ω
Winding 1 – Inductance (L1)	37.163mH
Winding 2 - RMS Volts (V2)	250V
Winding 2 – Resistance (R2)	3.2 mΩ
Winding 2 - Inductance (L2)	57.61μH
Magnetising Resistance HV Side (R'm)	Default
Saturation Characteristic (I1,phi1….etc)	Default

Table 21: Test No. 3 Change Equivalent Series Parameters (Inrush)

As is shown in Figure 51, changing the equivalent series parameter this resulted in a corresponding slight increase in inrush current initial levels, however there is a significant change in the decay time. This was due to the fact that the default primary series resistance is 10X less than the value of the ASC under trial.

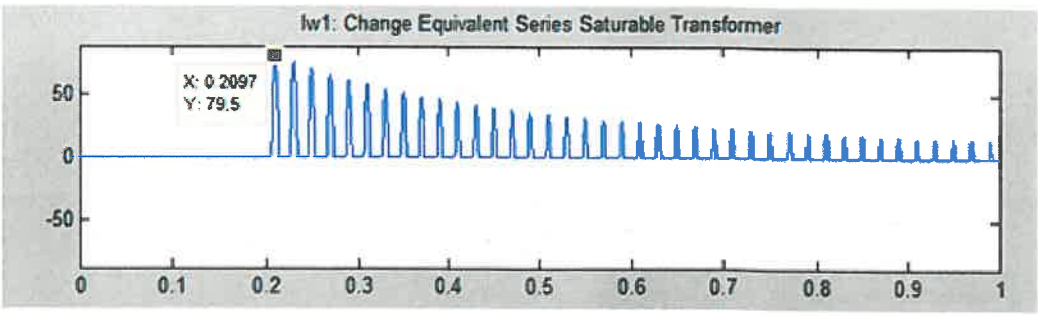

Figure 51: Test No. 3 Change Equivalent Series Parameters (Inrush) – Current Waves

5.2.5 Test No. 4 – Change Magnetic Resistance Parameter (Inrush)

As shown in Table 22 the only parameter change made for this simulation was the magnetic resistance parameter

Input	Value
Switching Time	10/50s
Nominal power (S)	200kVA
Frequency (f)	50Hz
Winding 1 - RMS Volts (V1)	6351V
Winding 1 - Resistance (R1)	2.649Ω
Winding 1 – Inductance (L1)	37.163mH
Winding 2 - RMS Volts (V2)	250V
Winding 2 – Resistance (R2)	3.2 mΩ
Winding 2 - Inductance (L2)	57.61μH
Magnetising Resistance HV Side (R'm)	896.368 kΩ
Saturation Characteristic (I1,phi1….etc)	Default

Table 22: Test No. 4 Change Magnetic Resistance Parameters (Inrush)

The results for Test No. 4 show that changing the value of magnetising resistance this results in a slight increase in the level of inrush current. This is because the value of the ASC transformer magnetising resistance is less than the default block.

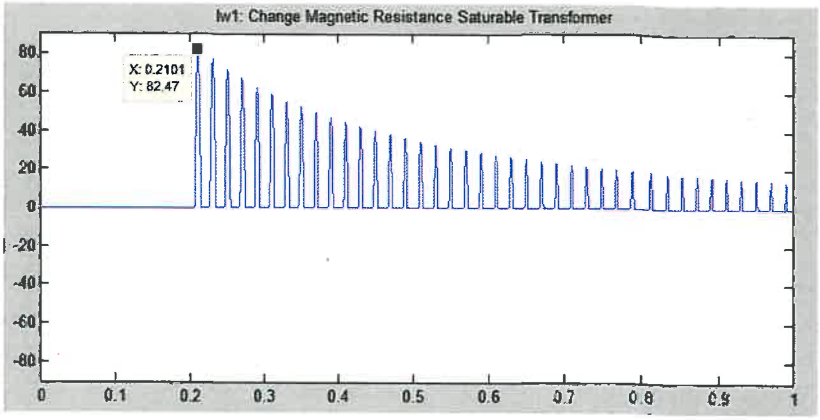

Figure 52: Test No. 4 Change Magnetic Resistance Parameter (Inrush) – Current Waves

5.2.6 Test No. 5 – Change Saturation Parameter (Inrush)

Test No. 5 is the final test. All parameters have been changed so that the transformer should have similar performance characteristics as the ASC transformers on trial. As shown in Table 23 the only parameter change made for this simulation was the saturation parameters.

Input	Value
Switching Time	10/50s
Nominal power (S)	200kVA
Frequency (f)	50Hz
Winding 1 - RMS Volts (V1)	6351V
Winding 1 - Resistance (R1)	2.649Ω
Winding 1 – Inductance (L1)	37.163mH
Winding 2 - RMS Volts (V2)	250V
Winding 2 – Resistance (R2)	3.2 mΩ
Winding 2 - Inductance (L2)	57.61μH
Magnetising Resistance HV Side (R'm)	896.368 *kΩ*
Saturation Characteristic (I1,phi1....etc)	**[00;0.00838 0.01925;0.01676 0.02502;0.03353 0.027;0.0671 0.029]**

Table 23: Test No. 5 Change Saturation Parameters (Inrush)

There is a significant change in the inrush current results with this final change in the transformer block parameters. The transformer now has a general response as follows:

- On energisation a peak inrush current value of 435A is experienced.
- The inrush current level appears to quickly decay after approximately 0.2s the current value has stabilised to a value of 250A.
- The current level then oscillates at the value of 250A indefinitely.

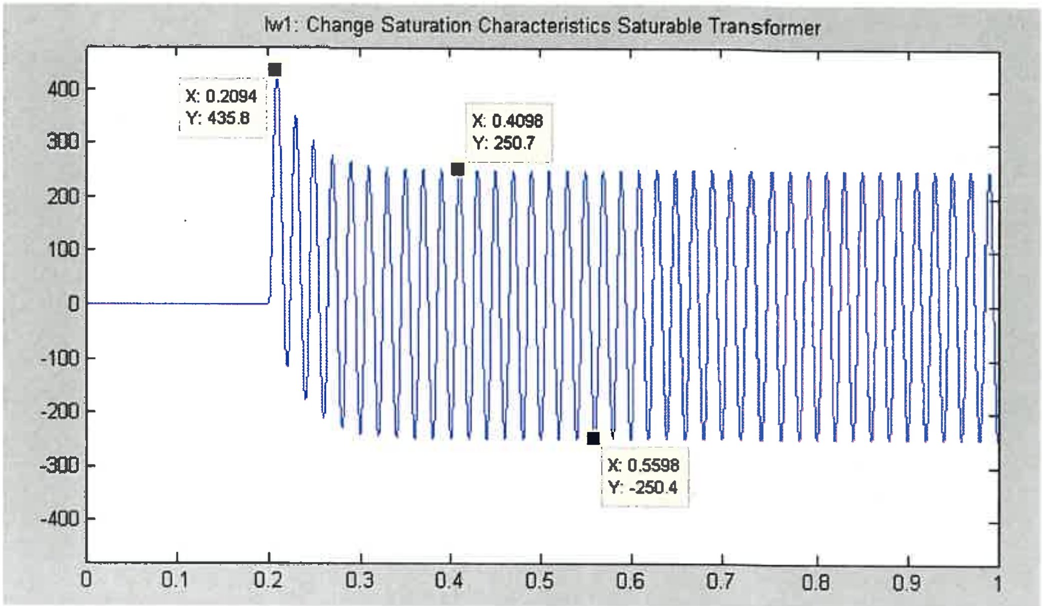

Figure 53: Test No. 5 Saturation Parameter (Inrush) – Current Wave

The evidence shows that there is now a large oscillatory response from the transformer. This suggests that the transformer saturable parameters are incorrect. This casts doubt over the validity of this aspect of the report, however to extend this investigation to look at the possible implications for the 11kV protection schemes used on Ausgrid's network the following assumption will be made.

It will be assumed that the transformer exhibits an inrush current response similar to that shown in Figure 53 but the oscillatory response will be ignored. The assumed response is highlighted in Figure 54.

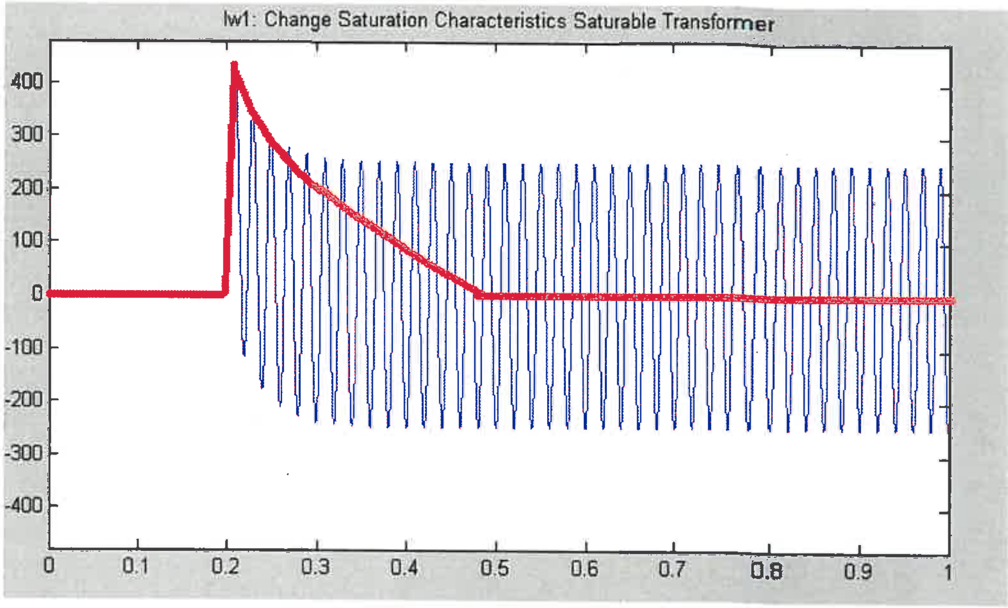

Figure 54: Assumed Inrush Current Response of the ASC transformer

This single line assumed response is based on the fact that the peak value would be the worst case scenario from the results shown above and if one removes the oscillation it does appear that the level of inrush current follows this decay rate.

5.2.7 Implications for Transformer Fuse Protection Due to Inrush Current

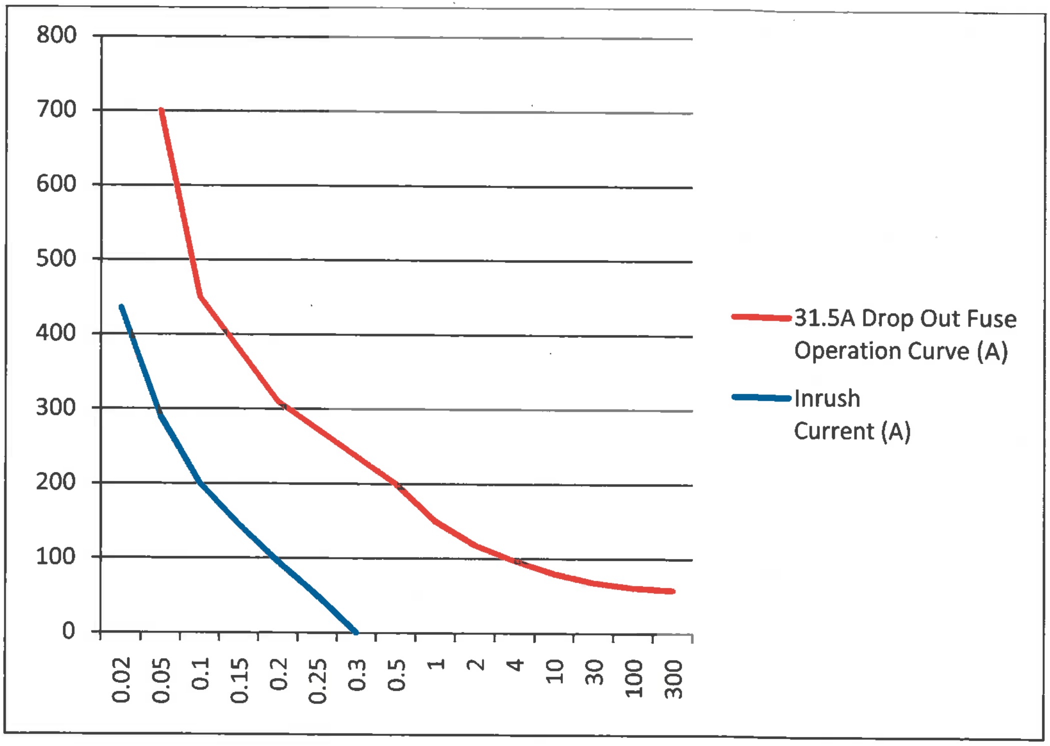

Figure 55 is a chart showing two time vs current characteristic curves. The curve shown in blue is an approximation of the inrush current response of the ASC transformers as depicted in Figure 54. The red curve is the time vs current fuse characteristic curve of a 31.5A drop out fuse. This fuse is the standard drop out fuse used on Ausgrid's network for 200kVA pole top transformers.

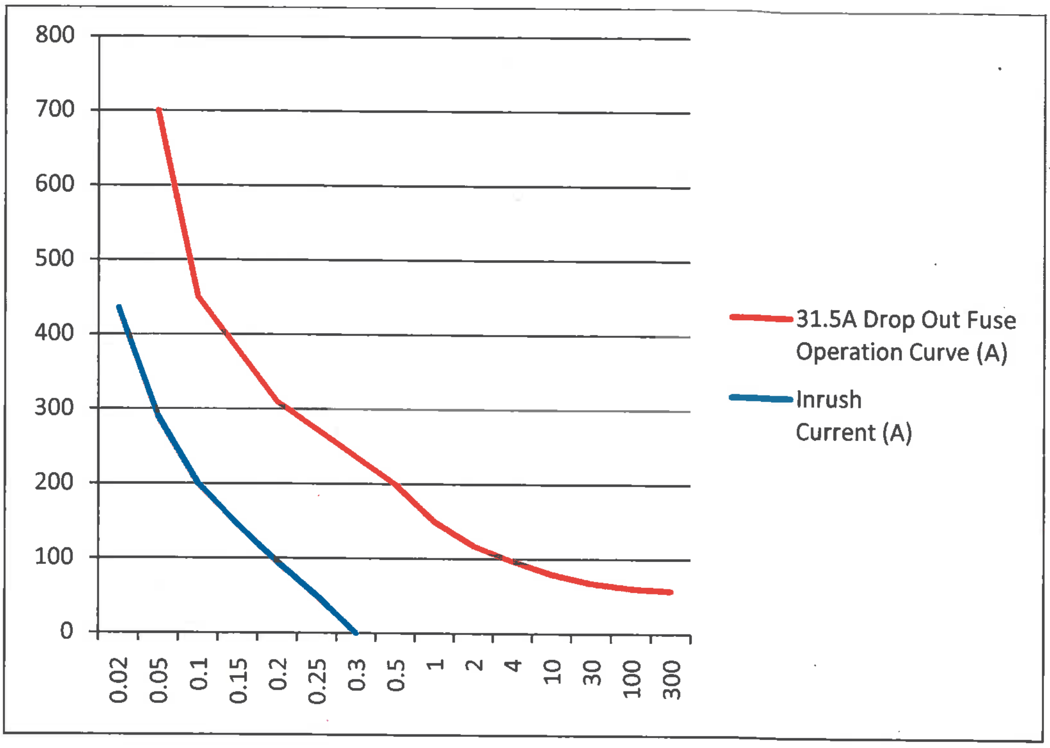

Figure 55: 31.5A Drop Out Fuse Characteristic Curve vs Inrush Current

The important aspect to highlight in

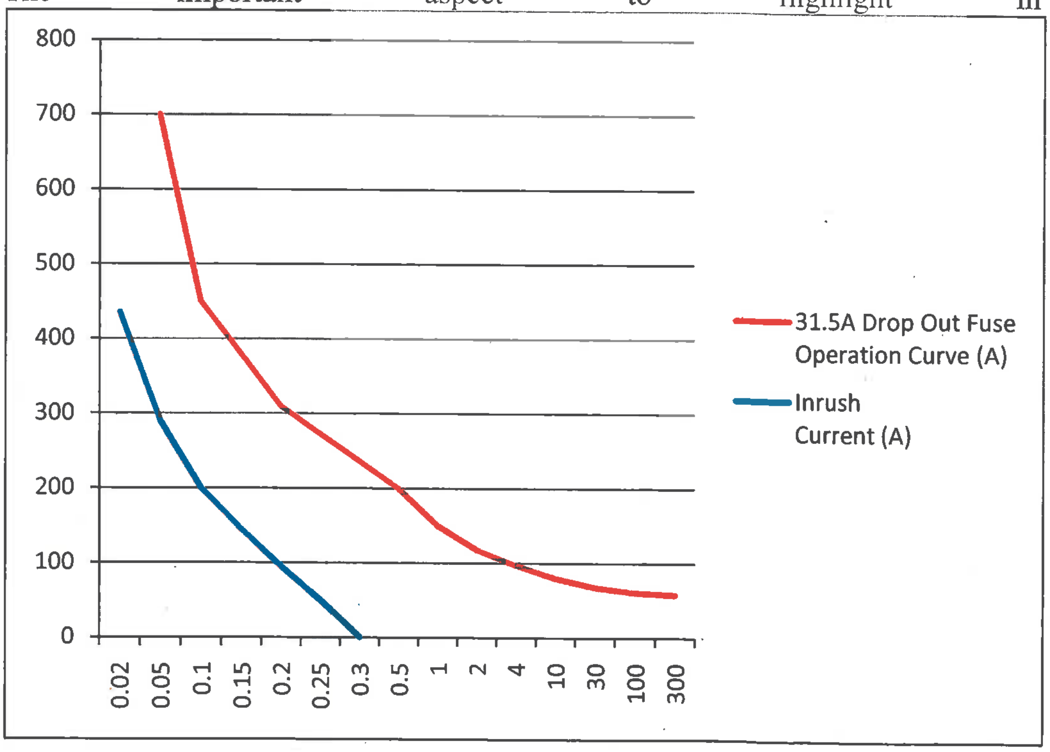

Figure 55 is that there is appropriate discrimination between the expected inrush current levels and the operating characteristic curve of the protecting fuse. This is evident as the operating curve is to the right hand side of the inrush current curve and there is no intersection of these curves.

5.2.8 Radial Feeder Results Transformer Results

The review into possible implications for a radial feeder with greater penetration of ASC transformers is redundant to some extent for the following reasons:

- Because the results obtained for a single transformer are overshadowed by some level of uncertainty due to the oscillatory response of the primary current. This uncertainty would be exacerbated in an investigation of a larger 11kV feeder with greater penetration of ASC transformers, thereby making the results further problematic.
- If one considers the results in Section 5.2.7 as being accurate. Then an investigation into the possible implications for the upstream protection devices (eg O/C relay) is not required. This is because of two reasons:
    - The simulated inrush current levels do not exceed the individual fuse characteristic curves which is the primary protection device for these pole top transformers.
    - The secondary protect device (eg O/C relays) should be set up with the general protection philosophy of grading (as per Section 2.7.3). This suggests that the upstream protection device would be set with greater tolerances than the down stream device, in this case the fuse characteristics.

6.0 FURTHER WORK

Within this section further areas of investigations are highlighted for each aspect of the project.

6.1 Cost Benefits of Reduced Core Loss Investigation

6.1.1 Monitoring the Quality of Manufacture

As suggested earlier, due to the higher amount of core and winding material required in the ASC transformers, there was expected to be a significant difference between the capital purchase costs of each transformer. In the case of this two transformer trial, the difference however is only approximately $1000 or 10% of the purchase price.

This factor is given more significance when one considers that both the load and fixed loss characteristics of the ASC transformers are lower than the CRGO transformer. Given these physical characteristics and electrical performance characteristics one would expect that the cost difference would be higher if the transformers are constructed with similar quality.

Two factors which may assist in the explanation with regard to the fact that the capital costs of each transformers are comparable, are:

- The labour costs of production of the ASC transformers are lower, this could be because they are produced in an offshore marketplace.
- The production quality is not comparable between the two suppliers of transformers.

Therefore a suggestion for further work would be to carry out half yearly physical inspections of the transformers specifically with the intention of reviewing the integrity of the galvanising.

6.1.2 Reassessment of the Load and Fixed Losses of the Transformers

Because the majority of potential savings occur over a large timeframe and there wasn't much available literature on the electrical performance of ASC transformers over an extended time frame. This project suggests that the transformer electrical characteristics should be re-measured after 2 years of continuous operation to confirm the electrical performance over the medium term.

6.1.3 Investigate other capacities eg 63kVA – 400kVA

Because this project only investigated the potential savings available to Ausgrid with large scale roll out of 200kVA pole top transformers, this project will suggest as further work, that similar investigations be carried out other standard distribution capacity transformers in Ausgrid's network.

Ausgrid's standard available transformers are:

- (25kVA – 63kVA) Single Phase
- (60kVA – 1000kVA) Three Phase

6.2 11kV Protection System Problems Due to Increased Inrush Current

6.2.1 Rectifying the Oscillation of the Model.

As the results of the inrush current simulations are not reliable, this project recommends a further review of the saturable parameters used, in the attempt to obtain a true inrush current response and thereby allow the appropriate 11kV protection checks to be carried out.

6.2.2 Simulate Inrush Current with Remnant Magnetisation

If the issue of current oscillation is resolved then the study can be extended by specifically addressing the inrush current response of the transformer with values of remnant flux not equal to zero. An example of this scenario could be when a fault is experienced on a radial feeder, therefore causing a reclose to occur.

7.0 CONCLUSIONS

When this project was conceived, it was assumed that the ASC transformers on trial would have the following characteristics:

- Significant reduced no load transformer core losses.
- Higher capital purchase costs.
- Higher load loss characteristics.
- Potentially problematic levels of inrush current.

The first three points regarding the economic performance of these transformers, fuelled the idea that it would be an interesting investigation to carry out an economic comparison between the existing transformers and these 'new' type transformers on trial. Specifically, it was thought that these transformers would obviously be more costly in the short term, however at some point in time they would be more cost effective than the existing legacy transformers. This medium to long term cost effectiveness, presented an opportunity for Ausgrid to reduce operating costs, the extent of these potential savings was unknown. Further to this, this study could be extended to investigate what affect would the different load profiles have on this potential savings.

The aspect of the project regarding the possible problematic levels of inrush current, was developed after further research into these ASC type transformers raised it as a potential issue, further to this, this topic was not well documented within internal Ausgrid guidelines. Because of these two issues, it proved worthy of further investigation.

The following sections present a summary of the results and recommendations provided by this project. Once again due to the fact that there are two distinct aspects to the project these results will be presented in two separate sections:

- Cost benefits of reduced core loss investigation.
- 11kV protection system problems due to increased inrush current.

7.1 Cost Benefits of Reduced Core Loss Investigation

7.1.1 Summary of results

The general results developed in this aspect of the project highlighted that two of the three assumed characteristics of these ASC transformers are correct, they are:

- Significant reduced no load transformer core losses, which are in the order of 2.8 times lower.
- Higher capital purchase costs, by approximately 10%.

An interesting and unexpected result from these investigations was that the variable losses, that is, the load loss characteristics of the ASC transformers are lower than the CRGO legacy transformers.

Due to these three factors the ASC transformers outperformed the CRGO transformers in all aspects of the simulations carried out within this aspect of the project. Specifically:

- 40 year life time cost savings when comparing individual transformers were in the range of $20K - $25K over the standard Ausgrid load cycles.
- This individual cost savings expanded to $5M - $6M when considering roll out of these ASC transformers for all of Ausgrid's 200kVA pole top transformers.

With consideration to changes in wholesale electricity prices, as forecasted by the NSW State Government. The results showed that the following savings could be achieved:

- At the high end ($10M - $12M) savings across Ausgrid's 200kVA pole top transformer asset base when projecting high growth in the carbon price.
- At the low end ($2 - $2.5M) across Ausgrid's 200kVA pole top transformer asset base when projecting removal of the carbon price.

When considering the ASC purchase price was only 10% higher than the legacy transformers and these ASC transformers out performed in both electrical aspects of load and no load losses. It was thought prudent to assess what changes in life span had on the economic comparison. This was motivated because of the thought that, a way to reduce purchase costs was to reduce manufacture quality. The following results were achieved:

- For a life span of 30 years the potential savings ranged between $1.5M - $2M.
- For a life span of 20 years the potential savings ranged between
- $1M – $1.5M.

7.1.2 Recommendations

1) Because these ASC transformers out performed the legacy transformers in all simulated aspects and the fact that the purchase price was comparable. There was some uncertainty regarding the manufactured quality of these ASC. Therefore it was thought prudent that:

- A visual inspection of the transformers manufacture quality be carried out at 6 monthly intervals. Giving specific focus to the integrity of the galvanising and bushing connections.
- A review of the electrical performance be carried after two years.
- Carry out the simulations again with these revised results.

2) On consideration of these revised results if all simulations present similar results then it should be made policy that gradual change over from the existing legacy CRGO transformers be carried. This could be achieved by the natural replacement program of these 200kVA pole top transformers.

3) In addition to recommendations (1) and (2), investigations should be carried out on other capacity transformers. This would assess the viability of expanding the roll to all pole top transformers.

4) Finally, with regard to the need for designers to have access to this simulator, this was deemed unnecessary. Because the results proved that the potential savings achieved were not sensitive to changes in load cycle, it has been determined that a general policy change towards ASC transformers is warranted.

7.2 11kV Protection System Problems Due to Increased Inrush Current

7.2.1 Summary of results

The inrush simulation results achieved in this report proved to have some uncertainty. This was due to an oscillatory current response which was unexpected and attributable to the saturation characteristics determined for the ASC transformers. If this uncertainty was neglected, it was shown that the peak level of inrush current was 485A and this inrush current decayed at a rapid rate where zero primary current was achieved after 0.3 sec. These results are consistent with the presented theory in Section 2.0. Specifically highlighting that by increasing the cross sectional area of the transformer core to achieve the desired transformer capacity, the issues of inrush current are negated.

There were no implications for the primary 11kV protection system which are drop out fuses located on the line side of the pole top transformers. Therefore, and as a result of the general protection philosophy of grading, there is no implication for upstream protection devices for larger scale ASC transformer roll out.

7.2.2 Recommendations

1) This project recommends that the inrush current simulation model be interrogated further with the ambition of determining the specific cause of the oscillatory response.

2) Once a more accurate response is achieved, the simulation should be completed to determine a more accurate inrush current level.

3) With this improved model, implications for 11kV protection schemes should be assessed and recommendations made.

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9.0 Appendix

A. Project Specification

FOR:	**MICHAEL DUFFY (50053990)**
TOPIC:	**Investigation into the impact on 11kV feeder operation as a result of the increasing use of Amorphous Core Transformers**
SUPERVISOR:	**Tony Ahfock**
ENROLMENT:	**ENG4111 – S1, D, 2012**
	ENG4112 – S2, D, 2012
PROJECT AIM:	**Investigate the performance of amorphous core transformers being trial on the Ausgrid distribution system, specifically with regard to reduction of losses and any modifications that would have to be made to 11kV protection systems.**
PROGRAMME:	**Issue 1.0, 21st March 2012**

The program I have constructed is split between two distinct tasks identified within the topic proposal document.

1) **Carry out present value analysis to determine economic impact of increased use of Amorphous Core Transformers. The method of analysis would allow for different daily/weekly/seasonal demand profiles. A question that the investigation will seek to answer would be the sensitivity of the economic benefit on demand profile.**

i) Investigate Present Value analysis, understand how it is calculated and identify what input values are required to calculate for this project. Specifically with regard to fix loss reduction and changes to load profile.

ii) Investigate and obtain all required inputs, this could be through direct measurements, information provided by manufacturers, information provided by employer and information obtained from external parties.

iii) Carry out calculation and assess economic benefit sensitivity to changes in load profile.

2) **Construct realistic model of a typical feeder. The model should allow for simulation inrush in the worst case scenario which may be during "cold load pick-up. A question that the simulation will seek to answer would be whether or not redesign of the protection system will be necessary. Would the HV fuses normally used to protect the standard distribution transformer still be appropriate? Would the overcurrent relay characteristics have to be different?**

i) Obtain, investigate and understand how the Simpowersystems toolbox (MATLAB) works.

ii) Determine what inputs are required to build feeder model.

iii) Build typical feeder model.

iv) Simulate inrush current and determine worst case scenario.

v) Investigate currently employed 11kV protection schemes for 11kV feeders.

vi) Investigate the impacts of previously simulated inrush current on the employed protection schemes and determine if changes be required.

___________________(Student) ____________________(Supervisor)

_____/_____/ 2012 _____/_____/ 2012

B. Legacy Transformers Information

Information provided by internal Ausgrid Staff Member Mark Andrews						
Transformer Type	NLL (W)	LL (W)	Total Loss (W)	Purchase price (Excl. GST) $	Weight kg	Oil (l)
CRGO	381	2200	2581	9760	1190	363
AC	135	1900	2035	10773	1400	405

C. NATA Test Report

Provided by George

Test Report

Number 102896

Testing & Certification Australia

Apparatus	A three phase, 11000 / 433 V, 50 Hz, Category 1 oil immersed, transformer rated at 200 kVA. The high voltage winding of the transformer has 9 tap positions ranging from 11495 V to 10175 V. The manufacturer nominated tap 4 (11000 / 433 V) as principal tap
Client	Distribution Automation and Substation Engineering Ausgrid 25 - 27 Pomeroy Street, Homebush NSW 2140
Date of Tests	31 January to 18 February 2011

The apparatus, constructed in accordance with the description and photographs incorporated in this Test Report has been tested in accordance with:

AS 60076.1-2005, AS 2374.2-1997, AS 60076.3:2008, AS 2374.5-1982, AS 2374.6-1994 with Amendment 1, ENA DOC 007-2006, Tender No EA.1540/10 and client's instructions.

Tests

Routine tests	AS 60076.1-2005	Clause 10.1.1
Temperature-rise tests	AS 2374.2-1997	Clause 5
Short-circuit tests	AS 2374.5-1982	-
Rated Insulation Level LI95/AC28/AC15	AS 60076.3:2008	Clauses 11, 12 and 14
Partial Discharge	Tender No EA.1540/10	Clause C14.6.3
Sound level	AS 2374.6-1994 Tender No EA.1540/10	Clauses 5 and 6 Clause C25.3
Transformer tank pressure test	ENA DOC 007-2006	Clause 6.4

Conclusion

The transformer complied with the requirements of the above standards for all tests except for the sound level test which complied with the reduced limit of 56 dB(A) when energised at rated voltage but exceeded the reduced limit when energised at 105% rated voltage as specified in Clause C25.3 of Tender No EA.1540/10 (Refer to the test record pages for details.)

This Test Report comprises 25 pages, 3 diagrams, 27 oscillograms, 16 photographs and 1drawing

J. Child
NATA Signatory

Manager - Testing

18/11/2011
Date of Issue

NATA

Test Record

Laboratory Reference No: 102896

Testing & Certification Australia

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APPARATUS TESTED

A three phase, 11000 / 433 V, 50 Hz, Category 1 oil immersed, transformer rated at 200 kVA.

The high voltage winding of the transformer has 9 tap positions ranging from 11495 V to 10175 V. The manufacturer nominated tap 4 (11000 / 433 V) as principal tap.

TRANSFORMER DETAILS

Manufacturer	:	Vijai Electricals Ltd
Rating	:	200 kVA
Nominal Voltage Ratio	:	11000 V / 433 V
Nominal Current ratio	:	10.5 A / 266.674 A
Manufacturer's Serial No.	:	T0082213
Vector Symbol	:	Dyn11
Rating Plate Impedance	:	3.97 %
Cooling	:	ONAN
Mass	:	1550 kg
Final user	:	Ausgrid
Windings	:	Non-circular
HV	:	Wire (Al)
LV	:	Sheet (Al)

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Test Record

Laboratory Reference No: 102896

Testing & Certification Australia

CLIENT

Distribution Automation and Substation Engineering
Ausgrid
25 – 27 Pomeroy Street,
Homebush NSW 2140

DATE OF RECEIPT OF TEST ITEMS

31 January 2011

ORDER NUMBER

Email 29 October 2010

MANUFACTURER

The manufacturer has declared that the apparatus was manufactured at the following location :

WITNESSES TO TESTS

Name	**Organisation**
M. Andrews	Distribution Automation and Substation Engineering, Ausgrid
D. Ozgur	Distribution Automation and Substation Engineering, Ausgrid
B. Bird	Distribution Automation and Substation Engineering, Ausgrid

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Test Record

Laboratory Reference No: 102896

LABORATORY

The apparatus was tested at:

Testing & Certification Australia
Lane Cove Testing Station
18 Mars Road
Lane Cove West NSW 2066 Australia
Telephone 61 (0)2 9424 3600, Facsimile 61 (0)2 9428 2645
www.tcaust.com

The laboratory accreditation details are:

NATA Accredited Laboratory to ISO / IEC 17025. Accreditation Number 62.

ASTA recognized Laboratory to ISO / IEC 17025 and
Regulations for ASTA recognized laboratories,
Certificate Number 5118.

NCS International Certified Quality Management System to
AS/NZS ISO 9001:2008, Certification No. 14785

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SCHEDULE OF TESTS

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Short-circuit tests	AS 2374.5	-	17
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Transformer tank pressure test	ENA DOC 007 - 2006	Clause 6.4	24

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TEST CONDITIONS

General

1. The routine and type tests were performed on transformer Serial No. T0082213.

Routine tests

2. For all routine tests except the dielectric tests the transformer was supplied from a sinusoidal 50 Hz three phase supply. For the separate source withstand test the transformer was supplied from a sinusoidal 50 Hz single phase supply. For the Short-duration induced AC withstand voltage test the transformer was supplied from a sinusoidal 200 Hz three phase supply.
3. The HV and LV winding resistances were measured using a Tettex high current resistance meter type 2291.
4. The voltage ratio and check of phase displacement were measured using a Norma Wide Band Power Analyser Model No. D6100.
5. For the load loss and no-load loss tests, power, voltages and currents were measured using a Norma Wide Band Power Analyser Model No. D6100.
6. For the load loss test the transformer's HV winding was energised with the LV winding short-circuited such that at least 50 % of rated current flowed in the HV winding.
7. For the no-load loss test the transformer's LV winding was energised at rated voltage with the HV winding open circuited in accordance with Clause 10.5 of AS 60076.1.

TEST CONDITIONS (Continued)

Temperature-rise Test

8. In accordance with Clause 4.2 as the transformer has a tapping range exceeding ±5 % the temperature-rise test was performed on the maximum current tapping, Tap 9 (10175 / 433 V).

9. Load loss, no-load loss and dc resistance measurements were used to calculate the total power required for the temperature-rise test.

10. The HV (B-C) and LV (b-c) winding resistances were measured with the HV and LV windings connected in series before and after the temperature rise test. The HV and LV winding resistances were measured using a Tettex high current resistance meter type 2291.

11. The transformer was tested using the short-circuit method described in Clause 5.2.2 a) and b) of AS 2374.2. The test was performed in two parts as follows:

    a) Total loss injection -
    The transformer HV winding was subjected to a test voltage sufficient to supply total losses with the LV winding short-circuited. The test power was maintained until the increase in top oil temperature-rise had fallen below 1 K per hour for a period of 3 hours.

    b) Rated current injection -
    At the completion of part a) the test current was reduced to rated current for 1 hour followed by rapid disconnection of the test supply and the dc resistance of the windings measured to determine their maximum temperatures using the change of resistance method.

12. The top oil temperature was measured with a thermocouple inserted through the filling hole in the transformer lid and resting in the top layer of oil. The bottom radiator return temperatures were also measured with thermocouples to determine the average oil temperature during the test.

13. All thermocouple temperature measurements were made using an Agilent Technologies Data Logger Model No. 34980A.

14. The ambient temperature was the average of three thermocouples in oil cups with a 2 hour time constant. The oil cups were located at approximately half the transformer's height and one to two metres from the transformer.

15. At the client's request an additional overload temperature-rise test was performed at 150 % rated current for 2 hours. In accordance with the client's test requirements the transformer was supplied at 60 % of rated current on tap 9 plus an allowance for the no-load loss until stable temperature-rises were achieved. The test supply current was then increased to 150 % of rated current for 2 hours followed by rapid disconnection of the test supply and resistance measurements to determine the winding temperatures.

TEST CONDITIONS (Continued)

Special tests

Short-circuit Tests

16. The impedance of the transformer was measured using a Norma wide band power analyser Model No. D6100 as follows :
    In a single-phase circuit before and after the short-circuit tests to determine change in reactance.
    In a three-phase circuit before the short-circuit tests to determine short-circuit impedance and X/R ratio used in the calculation of short-circuit currents.
17. The transformer HV winding was energised from a three-phase 50 Hz test supply. Three consecutive short-circuit tests of nominal 0.5 s duration were performed by short-circuiting the LV winding in accordance with Clause 3.2.5 of AS 2374-5. See Figure 1.
18. For the short-circuit tests, an earth fault detection device comprising a 0.1 mm diameter, 50 mm long tinned copper fuse wire was connected between the tank of the transformer and test station earth.

    Note: The earth fault detection device did not operate during any test.

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TEST CONDITIONS (Continued)

Lightning impulse test

19. The lightning impulse test chopped on the tail (LIC) was conducted after the short-circuit test. At the client's request the peak value of the chopped wave was adjusted to the same value as the full wave test.

20. The transformer was tested at 95 kV with a single stage Marx type impulse generator see Figure 2.

21. The test circuit was calibrated correcting for atmospheric conditions with the transformer connected.

22. The impulses were applied to one HV line terminal at a time with the other two HV line terminals connected together and to earth via a current shunt.

23. For all tests the LV neutral terminal was solidly earthed and the LV phase terminals were earthed via 215 Ohm resistors.

24. For all tests the transformer frame and core were solidly earthed.

25. A full sequence of tests in accordance with Clause 14 of AS 60076.3 was conducted on each phase with the transformer under test on principle tap.

26. Fault detection was by comparison of oscillographic voltage and current traces between the 50 % and 100 % tests.

27. Corrections for atmospheric conditions were applied during voltage calibration.
Atmospheric conditions :

Test Parameter		Value
Temperature	°C	24.0
Pressure	mb	1010
Humidity	% RH	73
Nominal calibration voltage	kV	60
Correction factor	kd	0.9836
Actual calibration voltage	kV	59.0
Date of tests		12 February 2011

Partial discharge test

28. The partial discharge test was performed in accordance with Tender No. EA.1540/10, which uses Clause 12.4 of AS 60076.3 as a reference.

Note: AS 60076.3 - 2008 does not require partial discharge to be measured on transformers' with $U_m \leq 72.5$ kV

29. The partial discharge test was performed after the lightning impulse test in accordance with client's test sequence as detailed on page 20.

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TEST CONDITIONS (Continued)

Inspection

30. The transformer core and windings were inspected after the completion of all tests.

Sound Level Test

31. The sound pressure was measured in accordance with Clause 5 of AS 2374.6
32. The sound pressure level tests were performed with the transformer in the middle of a 5.5 m wide x 5.95 m deep x 6.1 m high sound attenuated room. The room was empty except for the test item, test equipment and two testing officers.
33. Measurements were made using a Type 1 sound level meter complying with IEC 60651 and calibrated in accordance with AS 1259.1 as follows:
    Brüel & Kjoer sound level meter, Type 2209, Serial No. 569047
    Brüel & Kjoer microphone, Type 4165, Serial No. 675305
    Brüel & Kjoer sound level calibrator, Type 4230, Serial No. 724522.
34. Before and after the sound pressure level tests, the A-weighted sound pressure level of the background was measured.
35. The transformer sound pressure level was measured under no load conditions with the LV winding supplied at rated volts from a sinusoidal 50 Hz three phase supply with the HV windings open circuit in accordance with AS 2374.6. In accordance with the client's tender document No. EA 1540/10 the sound pressure level was remeasured with the transformer energised at 105% of rated volts.
36. The sound pressure level was measured at 6 positions around the prescribed contour at a distance of 0.3 metres from the transformer's principal radiating surface at half transformer height.
37. The average sound pressure level and power level were calculated from the measured sound pressure levels in accordance with Clause 6 of AS 2374.6.

Transformer Tank Pressure Test

38. The pressure test was performed in accordance with Clause 6.4 of ENA DOC 007 – 2006.
39. The pressure applied to the tank was measured with a 100 / 0 / 150 kPa 100 mm compound pressure gauge with accuracy of ±1%, Instrument No. 105845.
40. Positive pressure was applied to the transformer tank using regulated compressed air.

Test Record

Laboratory Reference No: 102896

Testing & Certification Australia

TEST RESULTS

Measurement of Winding Resistance

	Phase	Before short-circuit	After short-circuit
HV winding	A-B	4.687 Ω	4.606 Ω
(Tap 1)	B-C	4.684 Ω	4.617 Ω
	C-A	4.697 Ω	4.619 Ω
HV winding	A-B	4.478 Ω	4.410 Ω
(Tap 4)	B-C	4.485 Ω	4.418 Ω
	C-A	4.482 Ω	4.411 Ω
HV winding	A-B	4.144 Ω	4.081 Ω
(Tap 9)	B-C	4.148 Ω	4.088 Ω
	C-A	4.140 Ω	4.082 Ω
Temperature		28.5 °C	24.9 °C
LV winding	a-b	6.364 mΩ	6.272 mΩ
	b-c	6.400 mΩ	6.316 mΩ
	c-a	6.378 mΩ	6.283 mΩ
Temperature		28.5 °C	24.9 °C
Dates of Tests :		1 February 2011	17 February 2011

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TEST RESULTS (Continued)

Measurement of voltage ratio and check of phase displacement

Tap No.	Rated Voltage	Nominal Ratio	Measured ratio before short-circuit tests			Measured ratio after short-circuit tests		
			AB-an	BC-bn	CA-cn	AB-an	BC-bn	CA-cn
1	11495	45.98	45.96	45.95	46.00	45.96	45.96	46.00
2	11330	45.32	45.30	45.30	45.34	45.31	45.31	45.34
3	11165	44.66	44.65	44.65	44.68	44.65	44.64	44.69
4	11000	44.00	43.99	43.99	44.03	43.99	43.99	44.03
5	10835	43.34	43.34	43.34	43.37	43.34	43.34	43.38
6	10670	42.68	42.68	42.68	42.72	42.69	42.69	42.72
7	10505	42.02	42.03	42.02	42.06	42.03	42.03	42.06
8	10340	41.36	41.37	41.38	41.41	41.37	41.38	41.41
9	10175	40.70	40.72	40.72	40.75	40.72	40.72	40.76
Dates of Tests :			1 February 2011			17 February 2011		

Transformer was verified to be connected as Dyn11.

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TEST RESULTS (Continued)

Measurement of short-circuit impedance and load loss

	Before short-circuit	After short-circuit
Tap 1		
Average line voltage	447 V	461 V
Average line current	10.1 A	10.0 A
Total power	1512 W	1487 W
Temperature	29.6 °C	26.2 °C
Load loss corrected to 75 °C	1740 W	1736 W
Impedance corrected to 75 °C	25.84 Ω	26.65 Ω
Percent Impedance corrected to 75 °C	3.91 %	4.03 %
Tap 4		
Average line voltage	432 V	433 V
Average line current	10.5 A	10.5 A
Total power	1559 W	1514 W
Temperature	29.6 °C	26.2 °C
Load loss corrected to 75 °C	1783 W	1805 W
Impedance corrected to 75 °C	23.83 Ω	25.62 Ω
Percent Impedance corrected to 75 °C	3.94 %	4.24 %
Tap 9		
Average line voltage	396 V	408 V
Average line current	11.4 A	11.3 A
Total power	1610 W	1582 W
Temperature	29.6 °C	26.2 °C
Load loss corrected to 75 °C	1854 W	1853 W
Impedance corrected to 75 °C	20.27 Ω	23.62 Ω
Percent Impedance corrected to 75 °C	3.92 %	4.56 %
Dates of Tests :	1 February 2011	17 February 2011

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TEST RESULTS (Continued)

Measurement of no-load loss and current

		Before short-circuit		After short-circuit	
		U' mean scaled rms	U rms	U' mean scaled rms	U rms
Phase voltage	a-n	251 V	252 V	251 V	251 V
	b-n	250 V	250 V	250 V	251 V
	c-n	250 V	251 V	250 V	251 V
Phase current	a	0.36 A		0.38 A	
	b	0.23 A		0.24 A	
	c	0.33 A		0.34 A	
Total power	P_m	134 W		135 W	
Total power	P_0	134 W		135 W	
Dates of Tests :		1 February 2011		17 February 2011	

Maximum rated losses for the temperature-rise test

= Load loss (Tap 9) at 75 °C + No-load loss

= 1854 W + 134 W

= 1988 W

TEST RESULTS (Continued)

Separate source voltage withstand

Satisfactorily withstood 28 kV applied for 60 s to the HV terminals with the LV terminals and frame earthed before the short-circuit tests.

Satisfactorily withstood 21 kV applied for 60 s to the HV terminals with the LV terminals and frame earthed after the short-circuit and lightning impulse tests.

Satisfactorily withstood 15 kV applied for 60 s to the LV terminals with the HV terminals and frame earthed before the short-circuit tests.

Satisfactorily withstood 11.3 kV applied for 60 s to the LV terminals with the HV terminals and frame earthed after the lightning impulse tests.

Date of Tests Before Short-circuit : 2 February 2011
Date of Tests After Lightning Impulse : 17 February 2011

Induced over voltage withstand

Satisfactorily withstood 866 V at 200 Hz applied phase to phase for 30 s to the LV winding with the HV winding open-circuited and the frame earthed before short-circuit tests.

Satisfactorily withstood 650 V at 200 Hz applied phase to phase for 30 s to the LV winding with the HV winding open-circuited and the frame earthed after the short-circuit and lightning impulse tests.

Date of Tests Before Short-circuit : 2 February 2011
Date of Tests After Lightning Impulse : 17 February 2011

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TEST RESULTS (Continued)

Temperature-rise Test at 100% rated current on Tap 9

a) Oil Temperature Rise

Average injected power during last hour of test	= 2022 W
Total rated losses	= 1988 W
Average ambient temperature during last hour of test	= 32.1 °C
Average top oil temperature-rise measured during last hour of test	= 41.0 °C
Guaranteed limit : 60 K	
Average oil temperature-rise measured during last hour of test	= 31.9 °C

Corrected top oil temperature-rise

$$\Delta\theta = 41.0 \left(\frac{1988}{2022}\right)^{0.8} = \mathbf{40.4\ K}$$

Corrected average oil temperature-rise

$$\Delta\theta = 31.9 \left(\frac{1988}{2022}\right)^{0.8} = 31.5\ K$$

b) Winding Temperature Rises

Average HV current during last hour of test	= 11.37 A
Rated HV current	= 11.35 A

Temperatures extrapolated back to time of switch off,
HV winding temperature = 80.8 °C
LV winding temperature = 78.4 °C

Average oil temperature-rise at switch off	= 31.9 K
Ambient temperature at switch off	= 32.7 °C
Average oil temperature	= 64.6 °C

Winding temperature-rises above average oil temperature at switch off
HV winding = 80.8 - 64.6 = 16.1 K
LV winding = 78.4 - 64.6 = 13.8 K

Corrected winding temperature-rises above average oil temperature:

$$\Delta\theta_w HV = 16.1\left(\frac{11.35}{11.37}\right)^{1.6} = 16.1\ K \qquad \Delta\theta_w LV = 13.8\left(\frac{11.35}{11.37}\right)^{1.6} = 13.8\ K$$

Corrected average oil temperature-rise during last hour of test to part a) = 31.5 K

HV winding temperature-rise = 16.1 + 31.5 = **47.6 K**

LV winding temperature-rise = 13.8 + 31.5 = **45.3 K**

Guaranteed limit: 65 K

Dates of Test : 3 and 4 February 2011

See Photographs No. 25039 - 1619 and 1620.

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TEST RESULTS (Continued)

Overload Temperature-rise Test at 150% rated current for 2 hours

Temperature-rise tests at 60% and 150% of rated current were performed at the client's request and to the client's instructions.
Measured and uncorrected results are shown for the tests at 60% and 150% rated current.

Stable Temperature-rises at 60% rated current

Average injected power during last hour of test	= 760 W
Average HV current during last hour of test	= 7.51 [1] A
Average ambient temperature during last hour of test	= 25.6 °C
Average top oil temperature-rise measured during last hour of test	= 22.2 °C
Average oil temperature-rise measured during last hour of test	= 16.2 °C

Dates of Test : 7 and 8 February 2011

Temperature-rise Test at 150% rated current for 2 hours

Average HV current during test	= 17.44 A
Rated HV current	= 11.35 A

Winding temperatures extrapolated back to time of switch off,

HV winding temperature = 83.0 °C
LV winding temperature = 78.9 °C

Top oil temperature-rise at switch off	= 38.1 °C
Average oil temperature-rise at switch off	= 30.9 °C
Average ambient temperature at switch off	= 26.2 °C

HV winding temperature-rise = 83.0 - 26.2 = **56.8 K**

LV winding temperature-rise = 78.9 - 26.2 = **52.7 K**

Date of Test : 8 February 2011

[1] Note: Test supply current equal to 60% of rated current plus additional current sufficient to supply the no-load loss of 134 W.

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Test Record

Laboratory Reference No: 102896

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TEST RESULTS (Continued)

Short-circuit Tests

Tap		1	4	9
Rated Voltage	- V	11495	11000	10175
Transformer Impedance	- Ω/Phase	25.68	23.68	20.13
X/R Ratio		5.06	4.96	4.74
Theoretical Short-circuit Winding Currents				
Average Symmetrical	- A	149	155	168
Maximum Asymmetrical Peak	- A	328	339	365
Test No.	8751.	008	009	010
Applied HV Line Voltage	- V	12.3	12.1	11.4
HV Line Voltage During Short-circuit Tests	- V	12.1	11.9	11.1
Duration	- s	0.52	0.51	0.52
Symmetrical HV Winding Current *	- A	141	148	162
	- A	145	152	166
	- A	143	150	164
Average Symmetrical HV Winding Current	- A	143	150	164
Asymmetrical Peak HV Winding Current *	- A	320	276	286
	- A	275	341	307
	- A	263	278	359
Percent change in reactance	- A phase	3.0	3.1	3.2
	- B phase	3.4	3.6	3.8
	- C phase	3.7	3.9	4.0
Date of Tests : 9 February 2011				

*Note: Phase values recorded in order A, B and C.

Note: Maximum allowable percentage change in reactance for transformers with non circular concentric coils in accordance with Clause 3.2.6.4 a) of AS 2374.5 is 4.0 %.

The transformer passed the short-circuit tests.

See Photographs No. 25039 - 1634 and 1636

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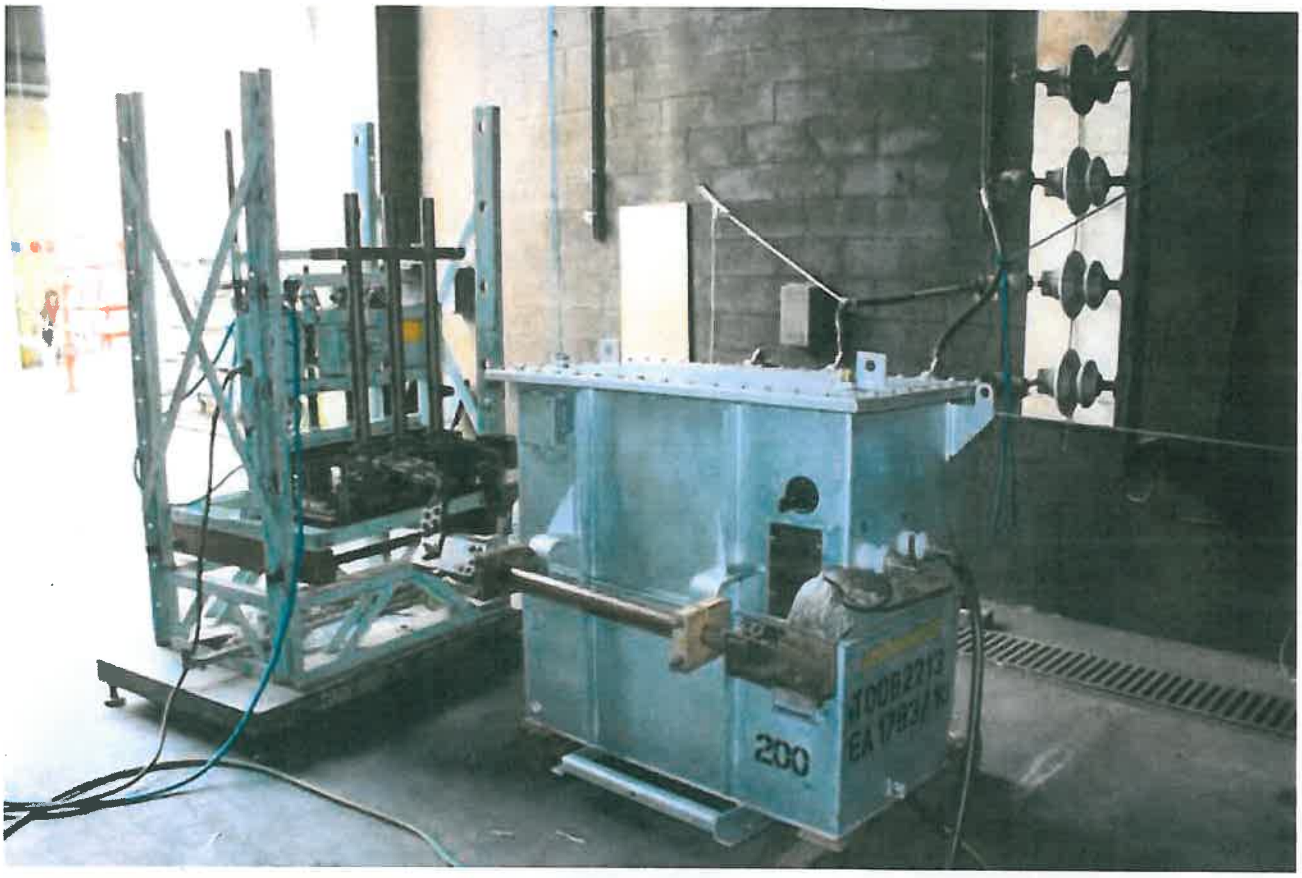
25039-1261

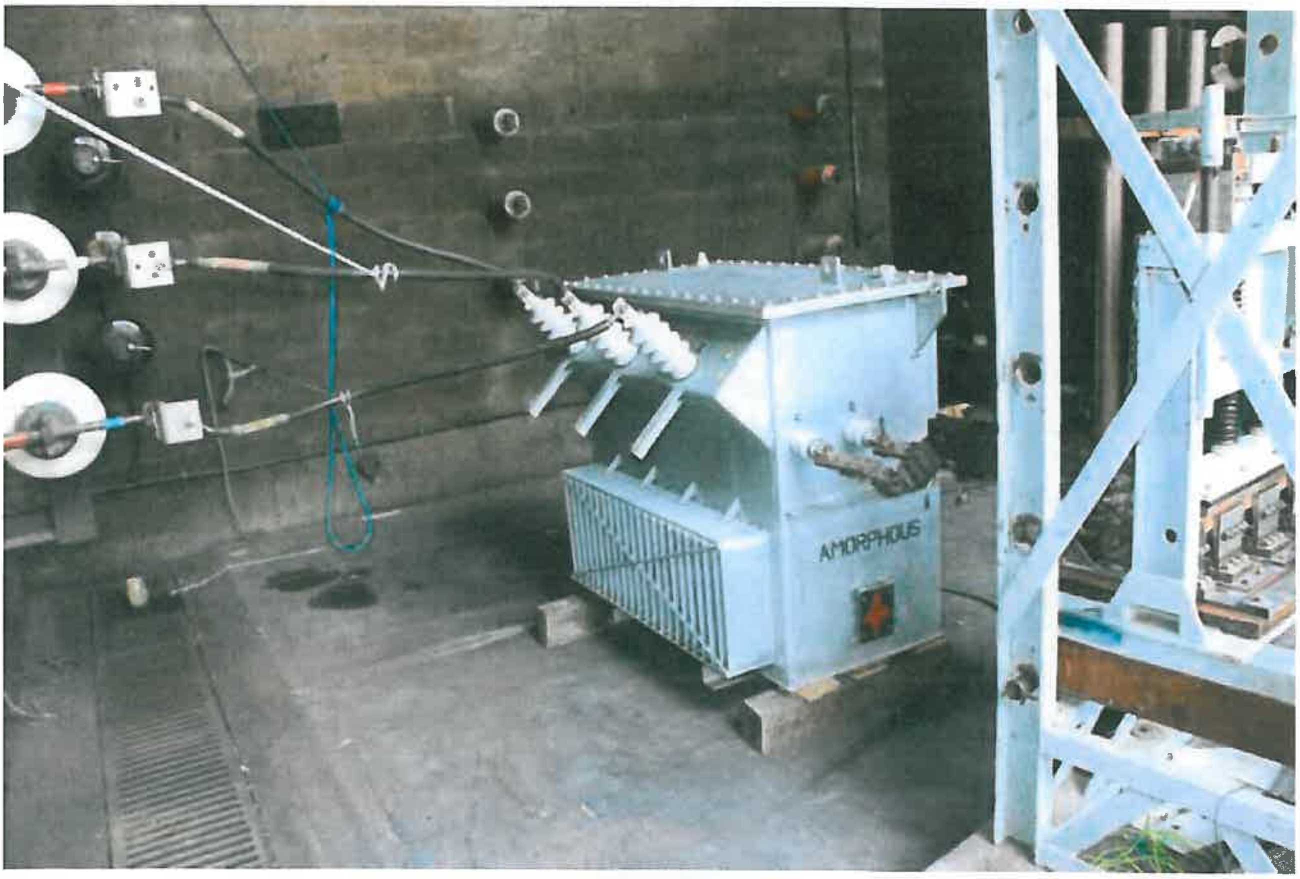
25039-1273

25039-1274

25039-1619



25039-1634



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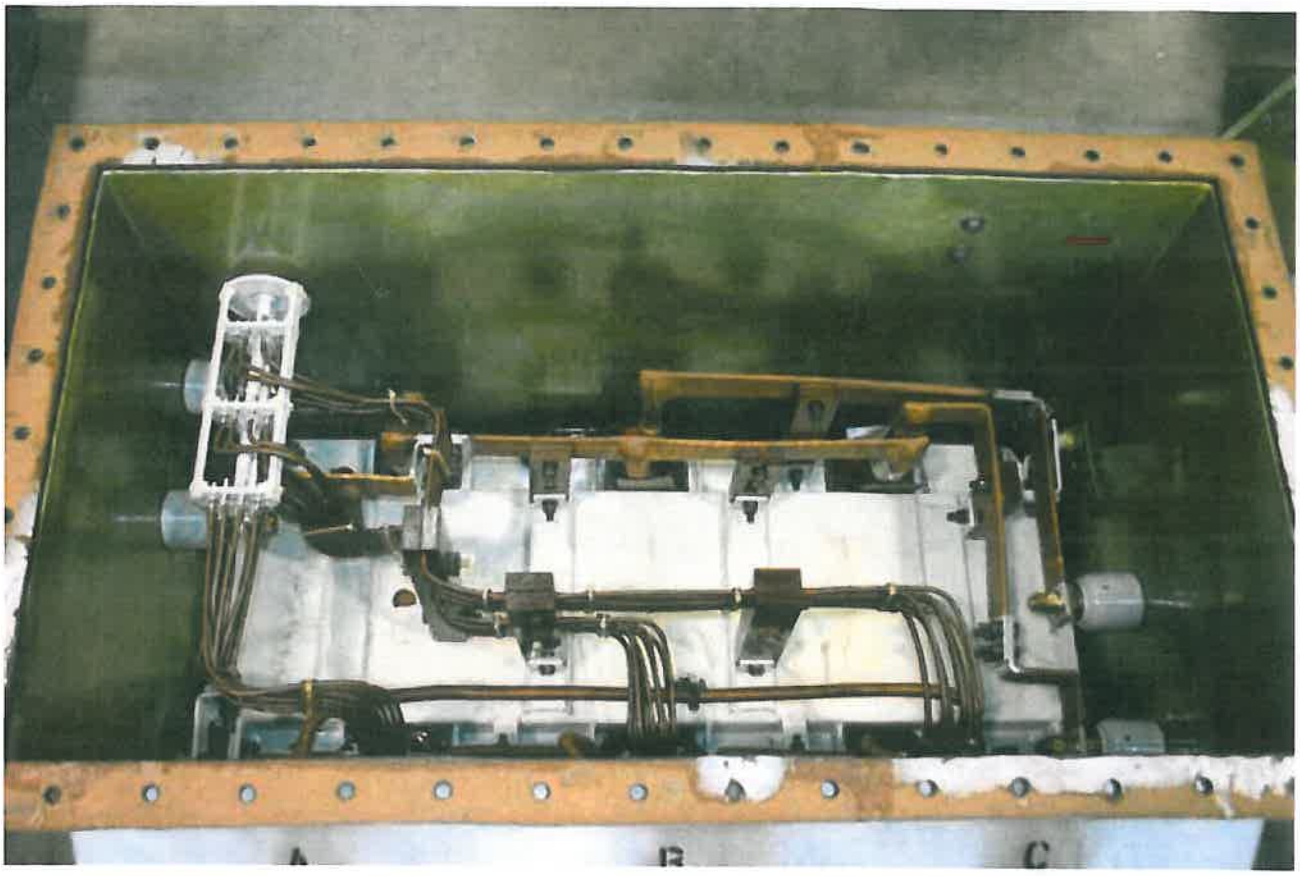
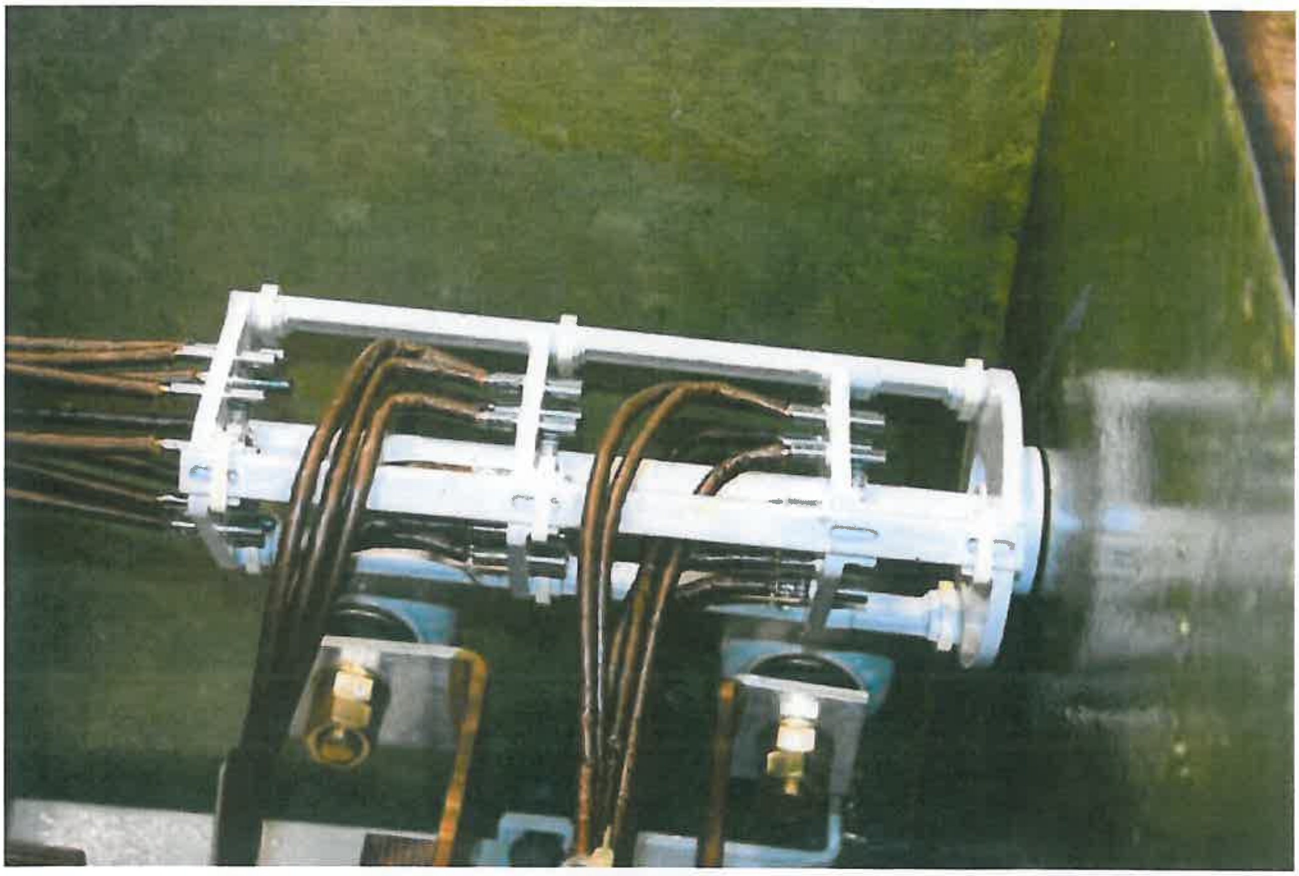
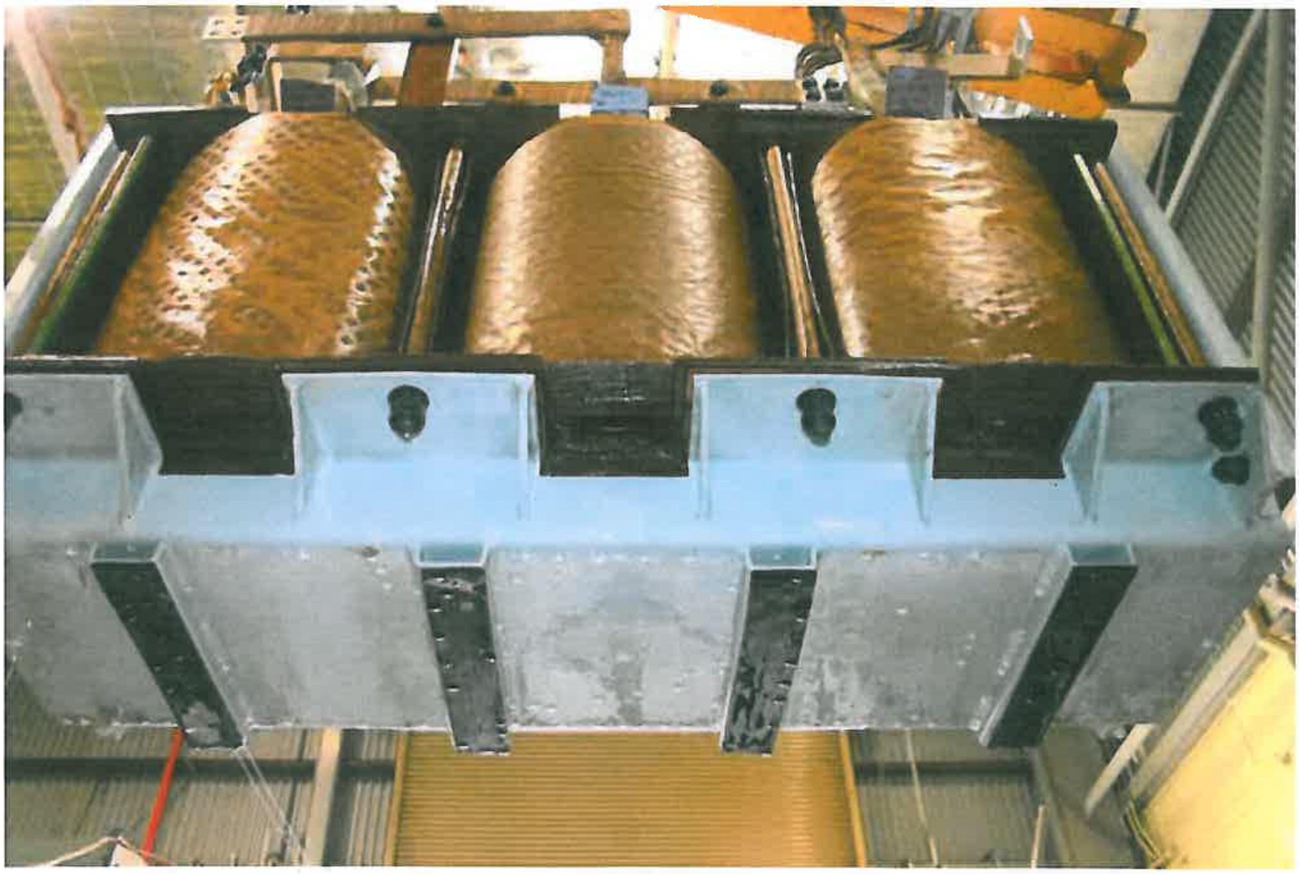


25039-1712



25039-1714

25039-1715



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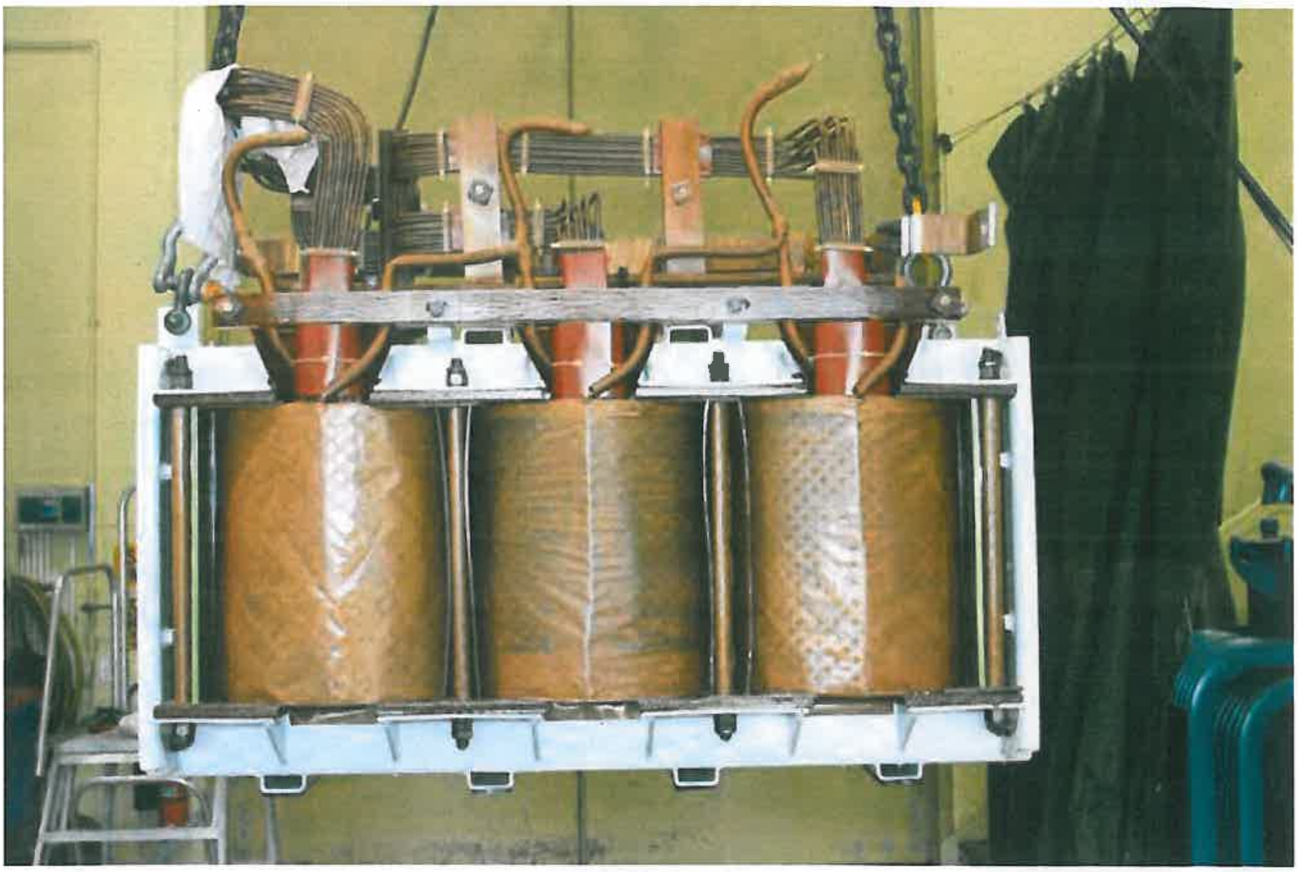


25039-1720

25039-1721

25039-1723

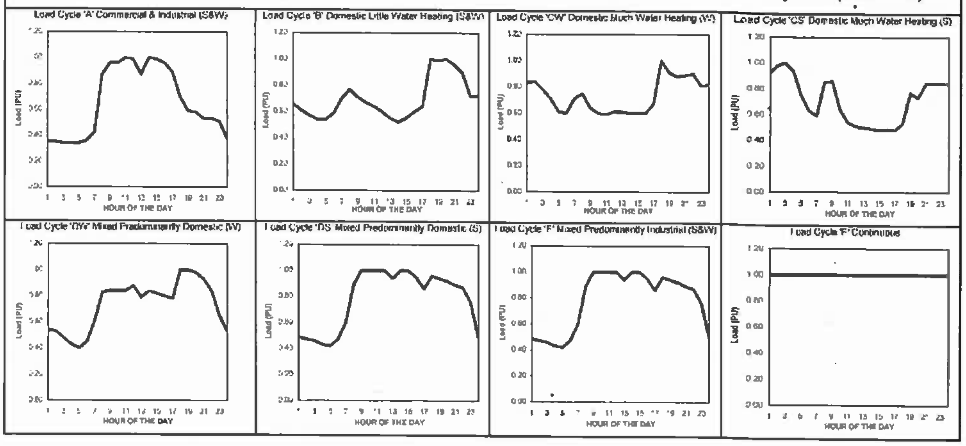
25039-1727

D. Load Cycle Data from Ausgrid Engineering Guideline

PU VALUES OF MAXIMUM DEMAND FOR EACH HOUR OF THE DAY

Load Cycle	Description	HOUR OF THE DAY																							
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A	Commercial & Industrial (S&W)	0.35	0.35	0.34	0.34	0.34	0.36	0.42	0.87	0.96	0.98	1.00	0.99	0.87	1.00	0.99	0.96	0.89	0.70	0.59	0.58	0.55	0.53	0.51	0.37
B	Domestic Little Water Heating (S&W)	0.66	0.61	0.57	0.54	0.54	0.59	0.70	0.77	0.71	0.67	0.64	0.60	0.55	0.52	0.55	0.60	0.64	1.00	0.99	1.00	0.96	0.90	0.72	0.72
CW	Domestic Much Water Heating (W)	0.83	0.84	0.78	0.71	0.61	0.60	0.71	0.75	0.64	0.60	0.59	0.61	0.61	0.60	0.60	0.60	0.67	1.00	0.91	0.88	0.89	0.90	0.81	0.82
CS	Domestic Much Water Heating (S)	0.92	0.98	1.00	0.94	0.75	0.63	0.59	0.85	0.86	0.64	0.54	0.51	0.50	0.49	0.48	0.48	0.48	0.53	0.77	0.73	0.84	0.84	0.84	0.84
DW	Mixed Predominantly Domestic (W)	0.54	0.53	0.48	0.43	0.40	0.45	0.61	0.83	0.84	0.84	0.84	0.88	0.79	0.84	0.82	0.80	0.78	1.00	1.00	0.98	0.93	0.84	0.65	0.53
DS	Mixed Predominantly Domestic (S)	0.49	0.47	0.46	0.43	0.42	0.47	0.60	0.89	1.00	1.00	1.00	1.00	0.94	1.00	1.00	0.95	0.86	0.96	0.94	0.92	0.89	0.87	0.76	0.49
E	Mixed Predominantly Industrial (S&W)	0.49	0.47	0.46	0.43	0.42	0.47	0.60	0.89	1.00	1.00	1.00	1.00	0.94	1.00	1.00	0.95	0.86	0.96	0.94	0.92	0.89	0.87	0.75	0.49
F	Continuous	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Graph of Individual Loadcycles for each of the Standard Energy Australia Loadcycles (Per Unit)



File Name: STANDCYC.xls
Sheet Name: Data & Individual LC Graphs

Page 1 of 1

14/04/2011

E. Plant Details of the Amorphous Core Transformers

Provided by George

PLANT DETAILS

REF	PARTICULARS	UNITS	200KVA, 11/0.433KV RESPONSE MAY BE REQUIRED(ref cl.8.2.2) FOR ANY ITEM DURING ADJUDICATION OR ON AWARDS
1	Overall dimensions		
1.1	Length(Pole mounting side)	mm	1385
1.2	Width	mm	950
1.3	Height	mm	1215
2	Mass		
2.1	Total(complte with all fittings filled with oil and ready for service)	kg	1345(Max)
2.2	core and winding	kg	615
3	Insulating oil(required to fill to correct level of 15°c		
3.1	Mass	kg	281
3.2	Volume	litre	345
4	HV bushings		
4.1	Make		ZEP OR EQUIVALENT
4.2	Type		PORCELAIN
4.3	Referance to TX-4 drw		
4.4	Current rating	A	30
5	LV bushings		
5.1	Make		ZEP OR EQUIVALENT
5.2	Type		PORCELAIN
5.3	Referance to TX-4 drw		
5.4	Current rating	A	300
6	HV winding		
6.1	Type		LAYER
6.2	Conductor material		ALUMINIUM
6.3	Total mass of conductor	kg	103
6.4	Shape of cross-section of Conductor		ROUND
6.5	cross-sectional area of conductor	sq mm	6.2016
6.6	Number of effective turns:		
	On principal tapping		1716
	On maximum tapping		1888
6.7	Conductor insulation material		SUPER ENAMEL
6.8	Current density	A/ sq mm	1.8(MAX)
6.9	Rated volts per turn		6.4101
7	LV winding		
7.1	Type		SPIRAL
7.2	Conductor material		ALUMINIUM
7.3	Total mass of conductor	kg	60
7.4	Shape of cross-section of Conductor		STRIP
7.5	cross-sectional area of conductor	sq mm	239.6
7.6	Number of turns:		39
7.7	Conductor insulation material		SUPER ENAMEL
7.8	Current density	A/ sq mm	1.8(MAX)

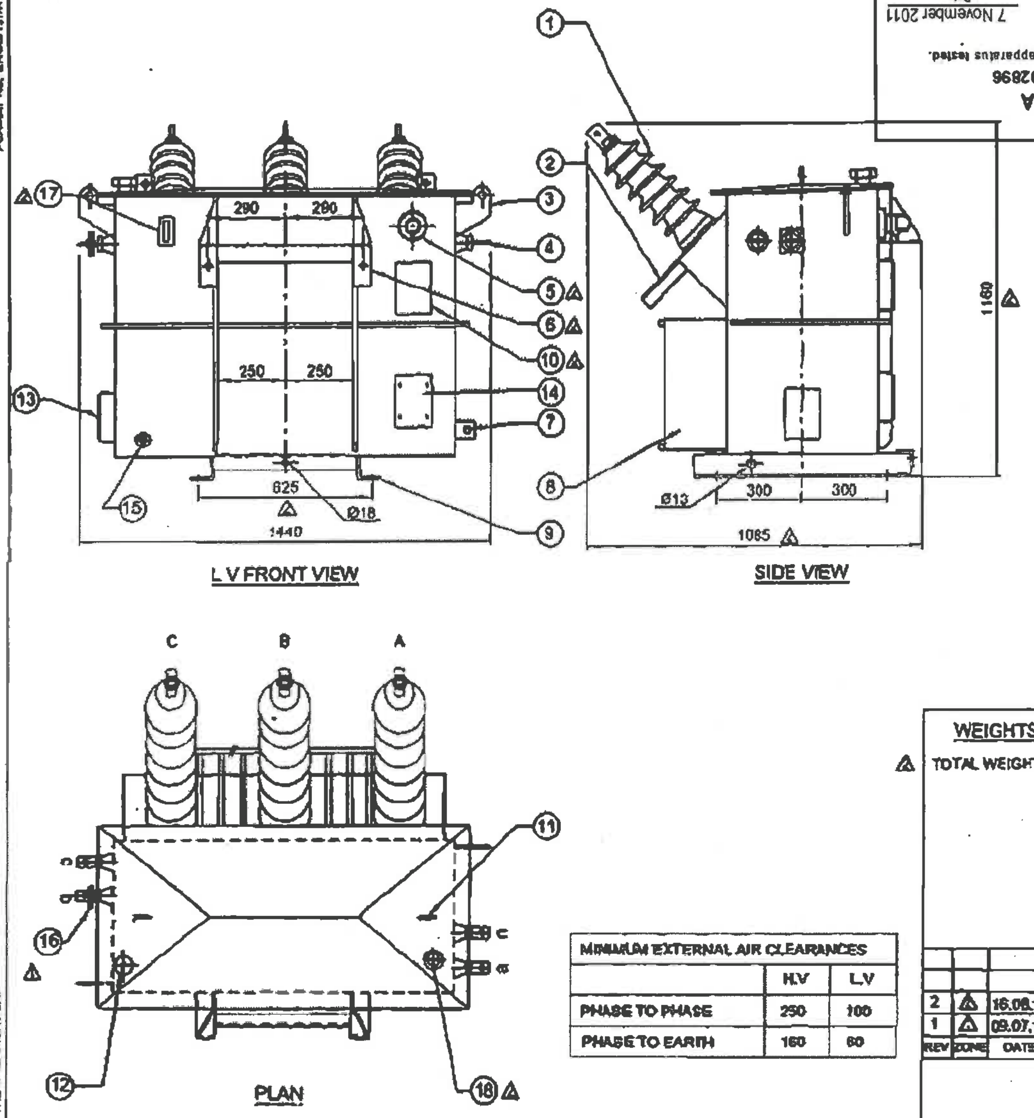
REF	PARTICULARS	UNITS	200KVA, 11/0.433KV RESPONSE MAY BE REQUIRED(ref cl.8.2.2) FOR ANY ITEM [redacted] DURING ADJUDICATION OR ON AWARDS
8	Core		
8.1	Type		WOUND
8.2	Brand or trade name and grade electrical steel		AMORPHOUS METAL & HITACHI(OR)EQUIVALENT
8.3	Country of supply		US &JAPAN OR EQUIVALENT
8.4	Total mass of electrical steel	kg	452
8.5	Flux density based on net croos-sectional area with rated voltage applied at rated frequency		1.4(MAX)
	Limbs	T	
	Yokes	T	
9	Impedence voltage components at rated current on principal tapping		4.0+IEC TOL
9.1	Resistance voltage	%rared voltage	1.117(Approx)
9.2	Reactance voltage	%rared voltage	3.824
10	Regulation		
10.1	Unity p.f.	%	1.23
10.2	0.8 p.f.	%	3.25
11	Degree of dryness expressed as dielectric loss angle at 20°c	%	LESS THAN 1.14 DEG C
12	Maximum operating pressure of the sealing system at max. permi-ssible overload	kpa absolute	25
13	Design withstand pressure of tank	Mpa	0.0225
14	vacuum withstand capacity		
14.1	Tank	Kpa	20
14.2	Corrugation	Kpa	20
15	Pemissible angle of tilt to the vertical during erection		
15.1	parallel to the length	Degrees	2.5(AS PER SPEC)
15.2	paralle to the width	Degrees	2.5(AS PER SPEC)

NOTE:

1) SOUND LEVELS ARE MAINTAINED ACCORDING TO AS 2374.6 OF REDUCED LIMIT
2) %REGULATION VALUES ARE CALUCULATED BASED ON NOMINAL VALUES OF %IMPEDENCE , NOLOAD & LOAD LOSSES AT 75°C.
3) ALL DIMENSIONS AND WEIGHTS (EXCEPT OVERALL WEIGHT) ARE SUBJECTED TO +/- 10 TOL

GUARANTEED PERFORMANCE FOR STANDARD DISTRIBUTION TRANSFORMER

REF	PARTICULARS	UNITS	200KVA, 11/0.433KV
1	Losses on principal tap at 75 ° c		
1.1	Load	W	2310(MAX)
1.2	No load	W	124(MAX)
2	Temperature rise limts during overload condition cl.6.3.5		
2.1	Top oil	°C	60(AT RATED LOAD)
2.2	Winding(by resisstance)	°C	65(AT RATED LOAD)
3	Minimum insulation resistance at 20°c(1kv test after 1 minute) for		
3.1	HV winding	M ohms	1000
3.2	SWER Winding	M ohms	————————
3.3	LV winding	M ohms	1000
3.4	Core	M ohms	NOT APPLICABLE
4	Continuous permissible over voltage at any tap	%	10(combined effect of voltage and frequency)



TESTING CERTIFICATION AUSTRALIA
LABORATORY REFERENCE No. 102896
This drawing / schedule applies to the apparatus tested.

Signature on behalf of the Testing Authority — 7 November 2011 (Date)

1. ALL DIMENSIONS ARE SUBJECT TO ±10% TOLERANCE.
2. THE POSITION AND LOCATIONS OF ACCESSORIES AND FITTINGS MAY SLIGHTLY VARY DURING MANUFACTURING.
3. TOP COVER IS SLIGHTLY SLOPED TOWARDS H.V SIDE.
4. OIL LEVEL INDICATION WILL BE PROVIDED INSIDE THE TANK.

CUSTOMER: M/s. ENERGY AUSTRALIA

P.O No. & DATE: PO No.P077324 DATED:24.06.2010

NO	DESCRIPTION	QTY
18	PRD	1
17	OIL LEVEL GAUGE	1
16	MEASURING CT	1
15	DRAIN PLUG (FRO HDG COATING)	1
14	IDENTIFICATION PLATE	1
13	VE MONOGRAM	1
12	FILLER CAP	1
11	TOP COVER LIFTING LUGS	2
10	RATING AND TERMINAL MARKING PLATE	1
9	BASE CHANNELS	2
8	CORRUGATION PANNEL	-
7	EARTHING TERMINAL	1
6	POLE MOUNTING BRACKET	2
5	TAP SWITCH	1
4	LV BUSHING	4
3	TRANSFORMER LIFTING LUG	2
2	SURGE ARRESTER MOUNTING BRACKET	3
1	HV BUSHING	3

WEIGHTS

TOTAL WEIGHT (MAX): 1550 Kg

RATING		: 200	KVA
VOLTAGE	HV	: 11000	V
	-7.5% To +4.5% IN STEPS OF 1.5%		
	LV	: 433	V
CURRENT	HV	: 10.5	A
	LV	: 266.674	A
FREQUENCY		: 50	Hz

NO OF PHASES	: 3
COOLING	: ONAN
TEMP.RISE O/W	: 60/65°c
VECTOR GROUP	: Dyn 11
TYPE	: OUT DOOR SEALED
SPECIFICATION	: AS 2374

MINIMUM EXTERNAL AIR CLEARANCES	HV	LV
PHASE TO PHASE	290	100
PHASE TO EARTH	160	60

REV	ZONE	DATE	MODIFICATION	MODIFIED	CHECKED	APPRD.
2	△	16.08.10	MODIFIED AS PER CUSTOMER REQUIREMENT			
1	△	09.07.10	CT TERMINAL BOX & CTS (EXCEPT 'b' PHASE) REMOVED	RAMANA	K.R.K	K.V.K.R

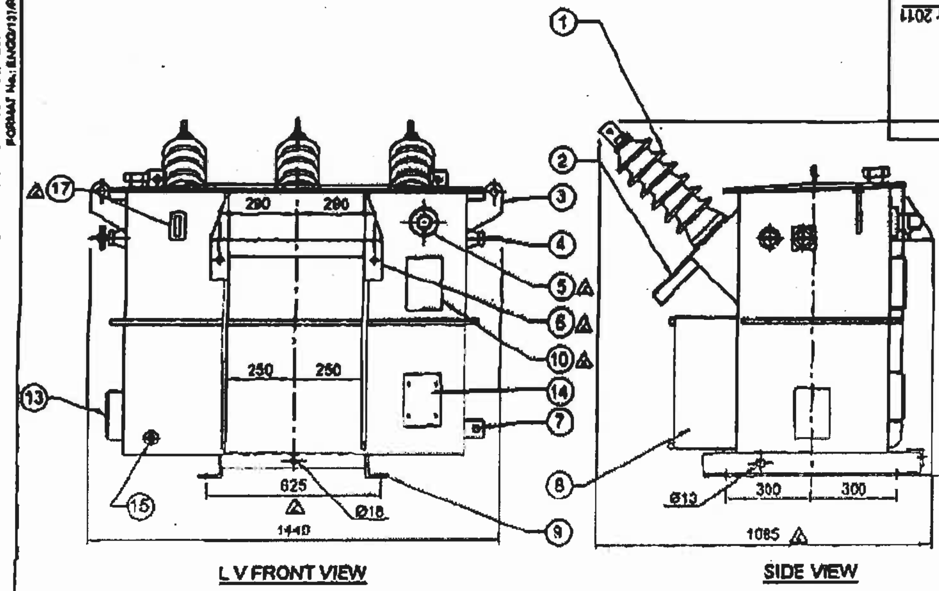
	NAME	DATE
DESIGNED	KOTI	06.07.10
DRAWN	RAMANA	06.07.10
CHECKED	K.R.K	06.07.10
APPROVED	JACOB	06.07.10
W. O. No	4754 A	
DRG NO.	3 OG 30740	

SCALE: NTS

OUTLINE GENERAL ARRANGEMENT FOR 200 kVA,3Ø AMORPHOUS METAL DISTRIBUTION TRANSFORMER

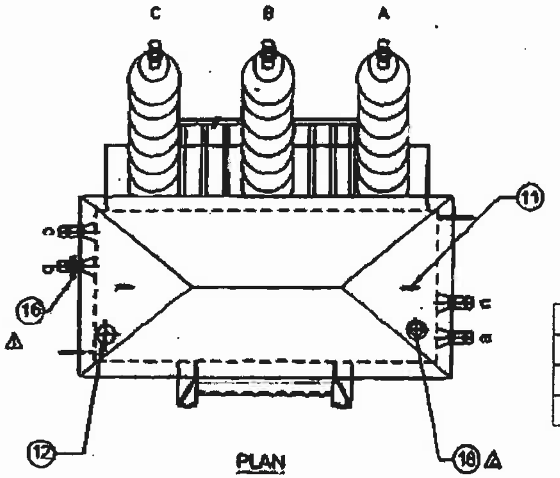
ALL DIMENSIONS ARE IN mm & WEIGHTS ARE IN kg UNLESS OTHER WISE SPECIFIED.
FORMAT No.: ENGG/131/R1

ALL DIMENSIONS ARE IN mm & WEIGHTS ARE IN kg UNLESS OTHER WISE SPECIFIED.
FORMAT No.: ENGG/131/R1



L V FRONT VIEW

SIDE VIEW



PLAN

TESTING ... CERTIFICATION AUSTRALIA
LABORATORY REFERENCE No. 102896
This drawing / schedule applies to the apparatus tested.
Signature on behalf of the Testing Authority
7 November 2011
Date

1. ALL DIMENSIONS ARE SUBJECT TO ±10% TOLERANCE.
2. THE POSITION AND LOCATIONS OF ACCESSORIES AND FITTINGS MAY SLIGHTLY VARY DURING MANUFACTURING.
3. TOP COVER IS SLIGHTLY SLOPED TOWARDS H.V SIDE.
4. OIL LEVEL INDICATION WILL BE PROVIDED INSIDE THE TANK.

CUSTOMER: M/s. ENERGY AUSTRALIA

P.O No. & DATE: PO No.P077324 DATED:24.06.2010

NO	DESCRIPTION	QTY
18 △	PRD	1
17 △	OIL LEVEL GAUGE	1
16 △	MEASURING CT	1
15	DRAIN PLUG (FRO HDG COATING)	1
14	IDENTIFICATION PLATE	1
13	VE MONOGRAM	1
12	FILLER CAP	1
11	TOP COVER LIFTING LUGS	2
10	RATING AND TERMINAL MARKING PLATE	1
9	BASE CHANNELS	2
8	CORRUGATION PANNEL	-
7	EARTHING TERMINAL	1
6	POLE MOUNTING BRACKET	2
5	TAP SWITCH	1
4	LV BUSHING	4
3	TRANSFORMER LIFTING LUG	2
2	SURGE ARRESTER MOUNTING BRACKET	3
1	HV BUSHING	3

WEIGHTS

△ TOTAL WEIGHT (MAX): 1550 Kg

RATING		: 200 kVA
VOLTAGE	HV	: 11000 V
		-7.5% To +4.5% IN STEPS OF 1.5%
	LV	: 433 V
CURRENT	HV	: 10.5 A
	LV	: 266.674 A
FREQUENCY		: 50 Hz

NO OF PHASES	: 3
COOLING	: ONAN
TEMP.RISE O/W	: 60/65°c
VECTOR GROUP	: Dyn 11
TYPE	: OUT DOOR SEALED
SPECIFICATION	: AS 2374

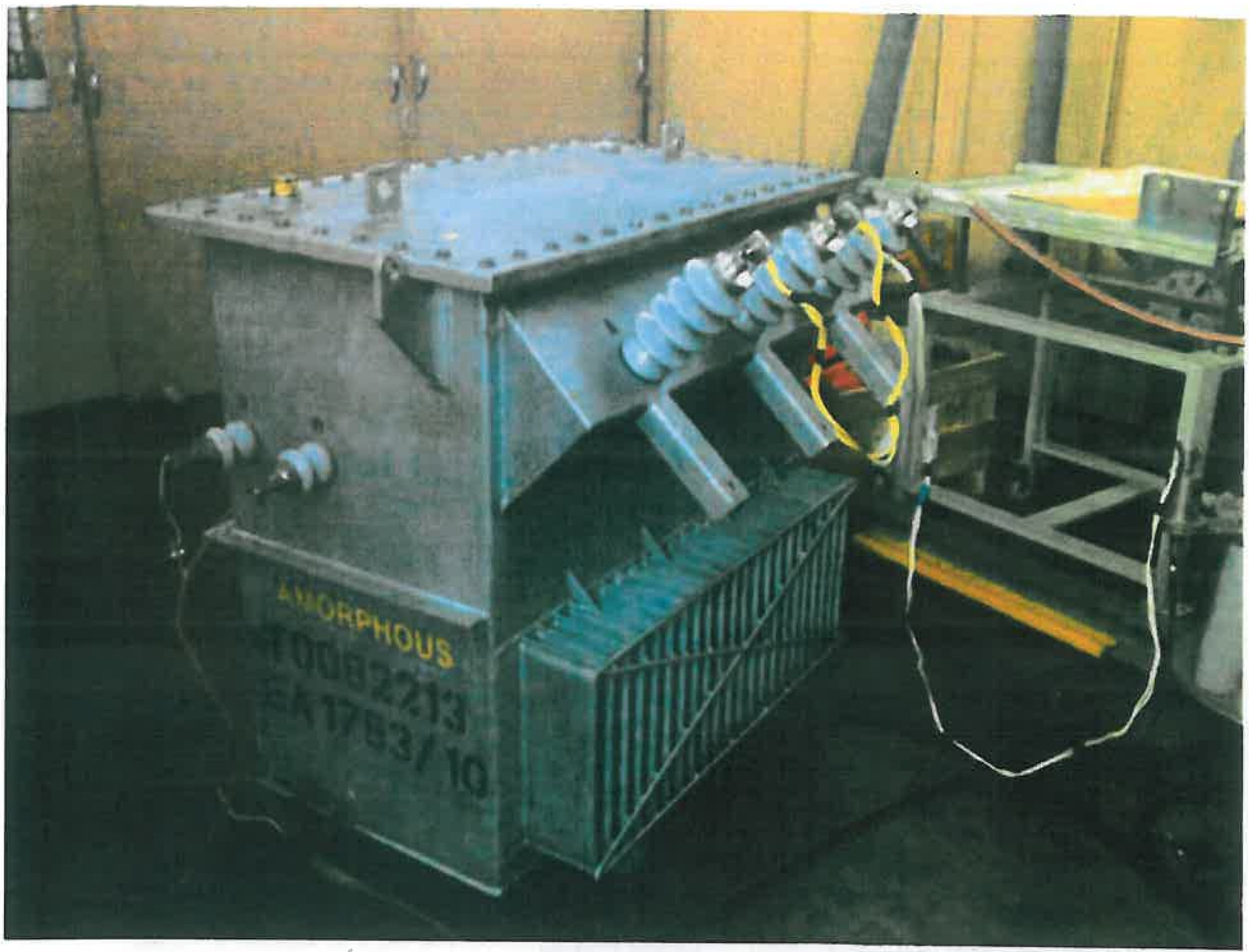
MINIMUM EXTERNAL AIR CLEARANCES	HV	LV
PHASE TO PHASE	250	100
PHASE TO EARTH	160	80

REV	ZONE	DATE	MODIFICATION	MODIFIED	CHECKED	APPRD.
2	△	16.09.10	MODIFIED AS PER CUSTOMER REQUIREMENT	RAMANA	K.R.K	K.V.K.R
1	△	09.07.10	CT TERMINAL BOX & CT'S (EXCEPT 'B' PHASE) REMOVED			

	NAME	DATE
DESIGNED	KOTI	06.07.10
DRAWN	RAMANA	06.07.10
CHECKED	K.R.K	06.07.10
APPROVED	JACOB	06.07.10
W. O. No	4754 A	
DRG.NO.:	3 OG 30740	

SCALE: NTS

OUTLINE GENERAL ARRANGEMENT FOR 200 kVA,3Ø AMORPHOUS METAL DISTRIBUTION TRANSFORMER



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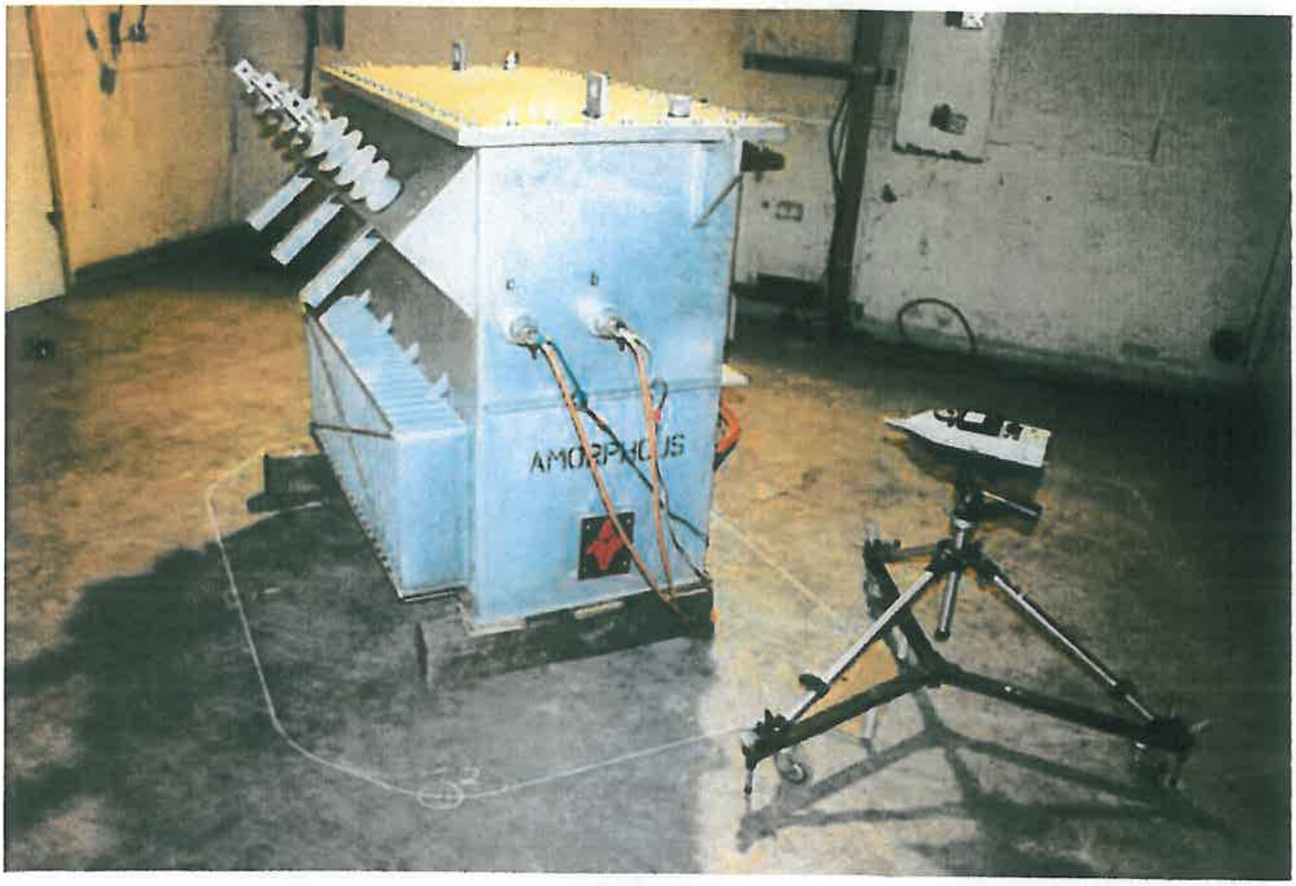

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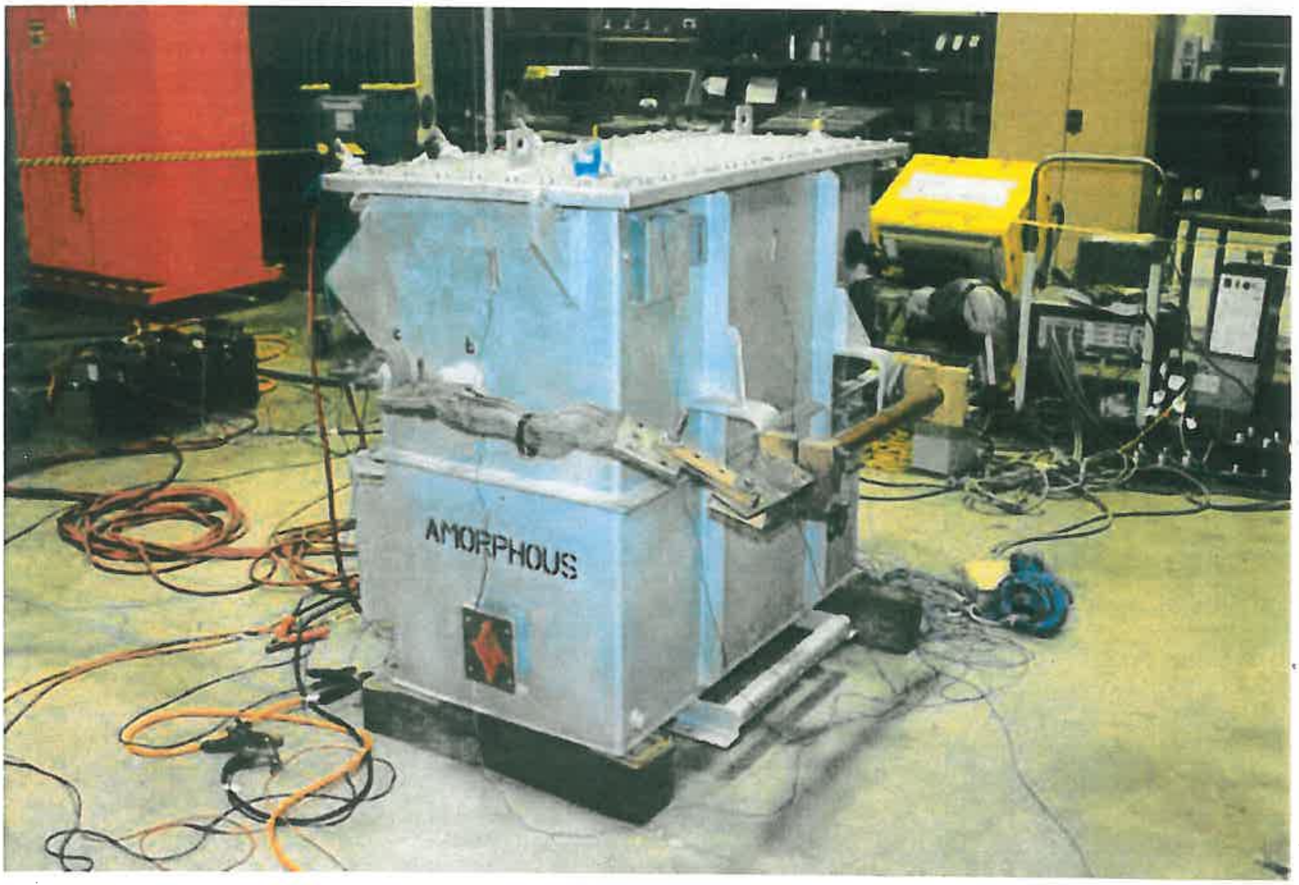

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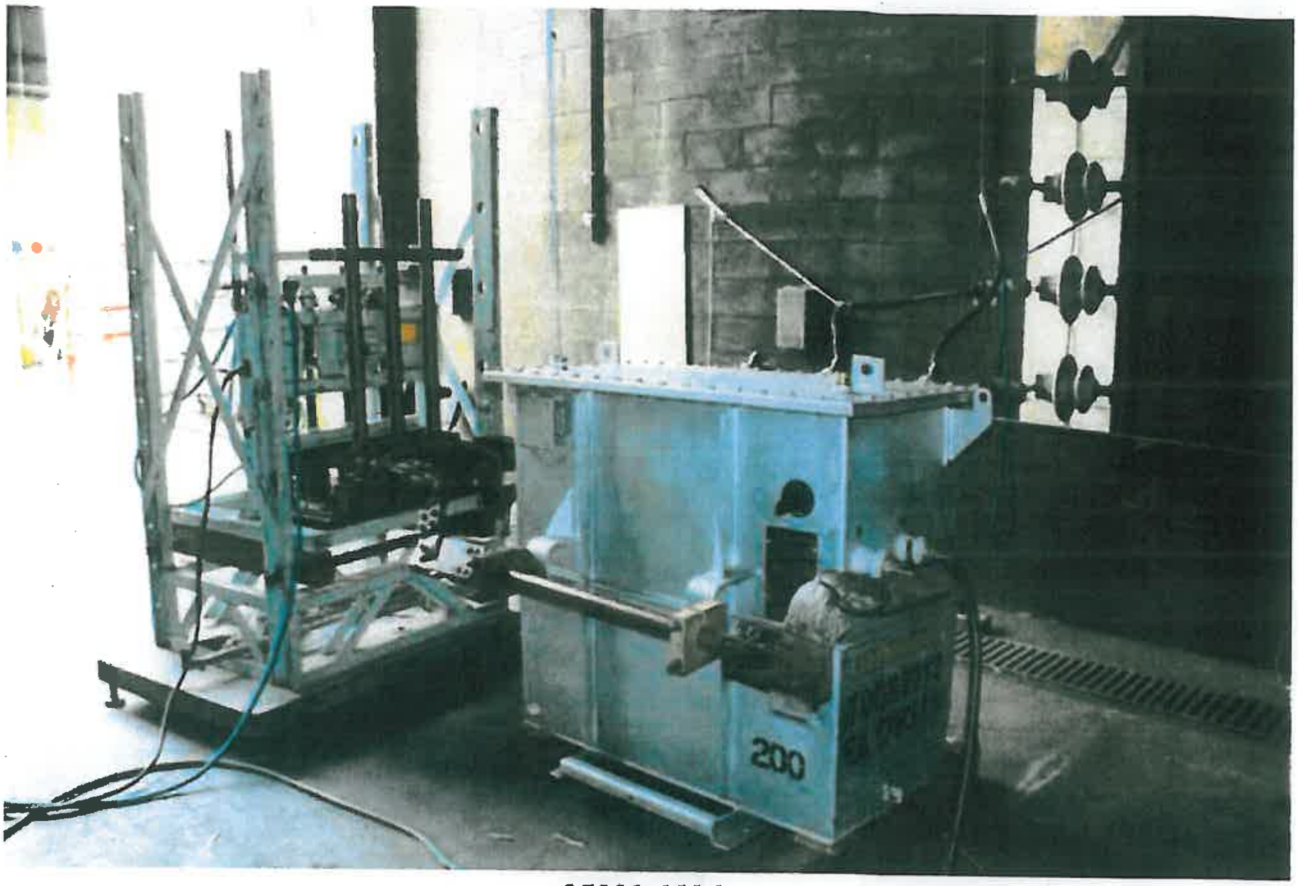

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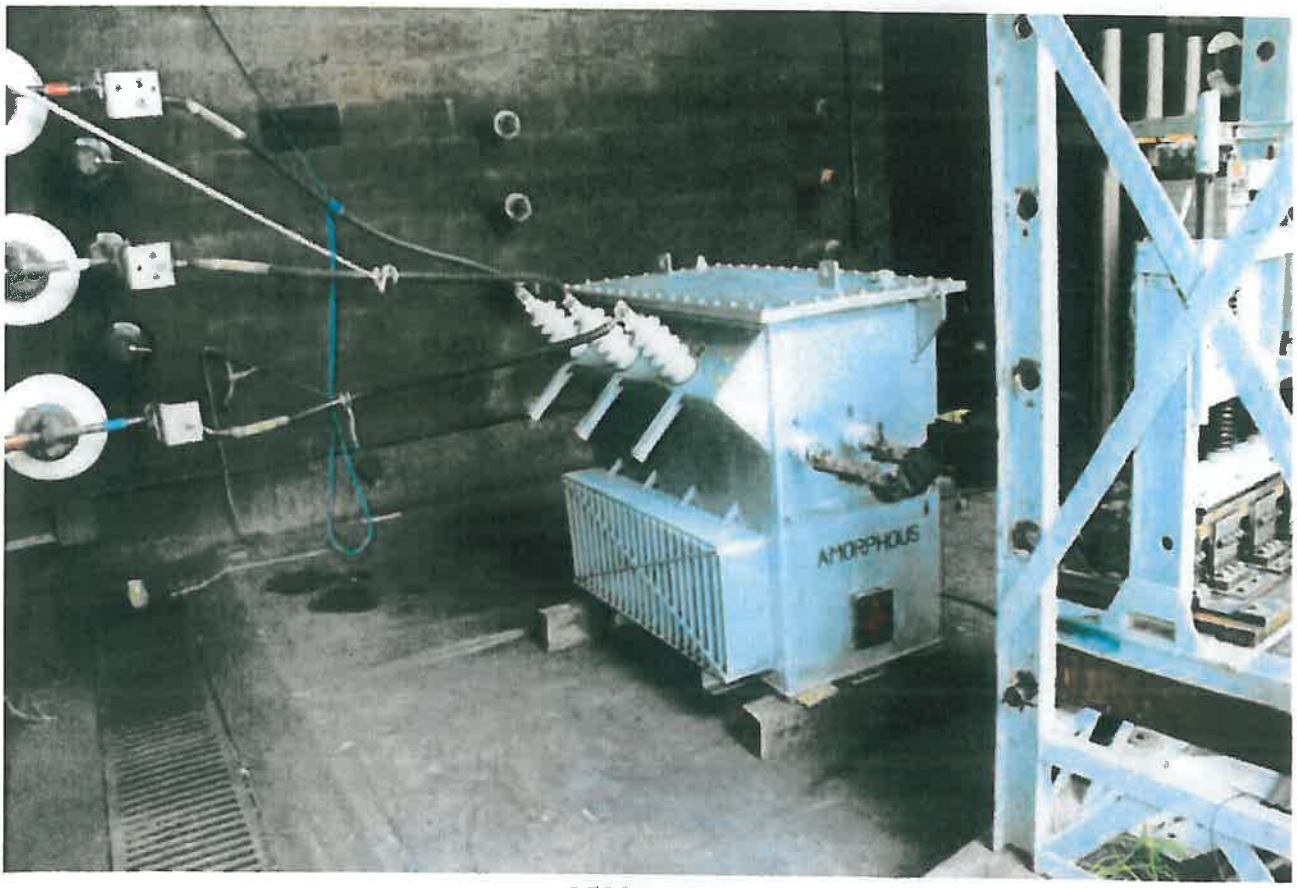

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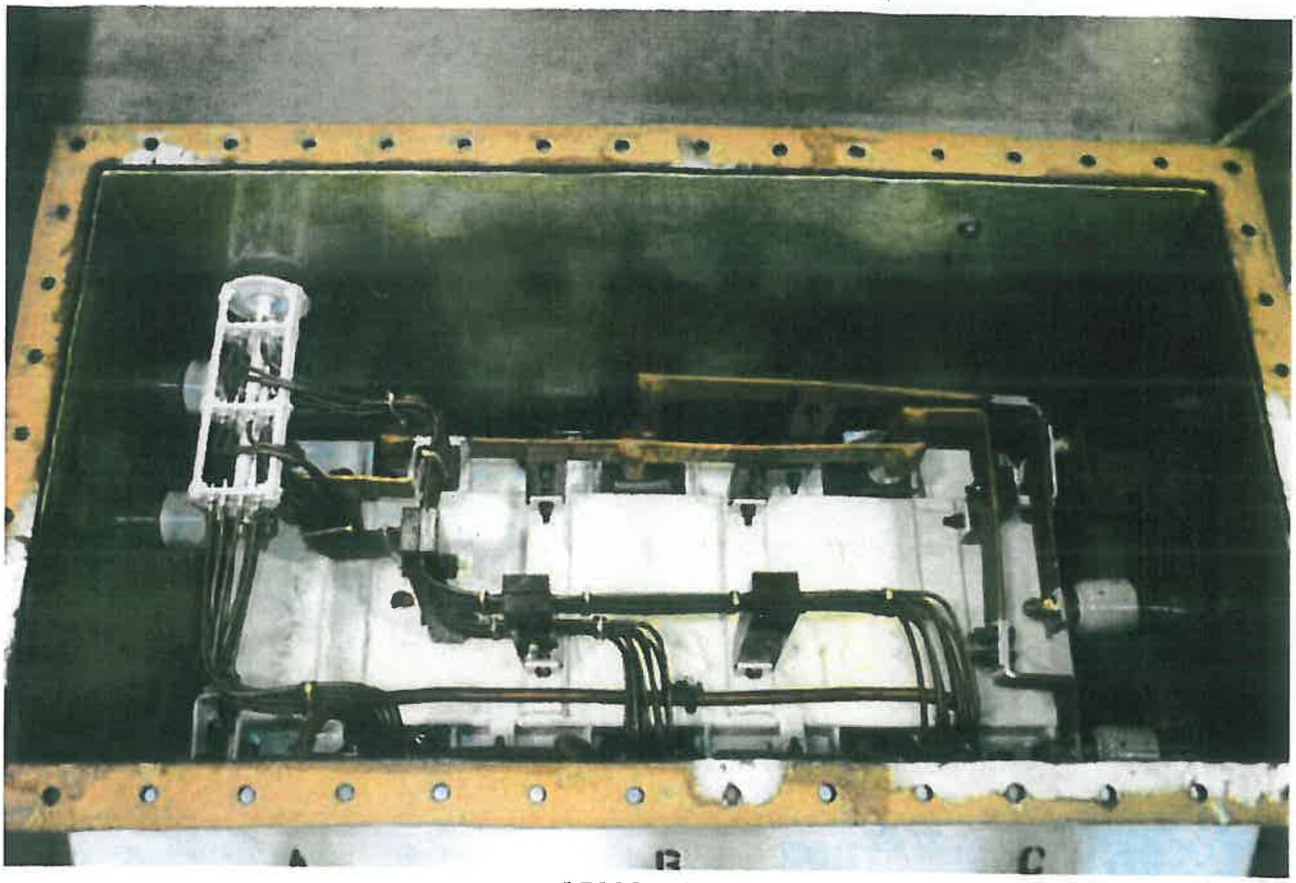

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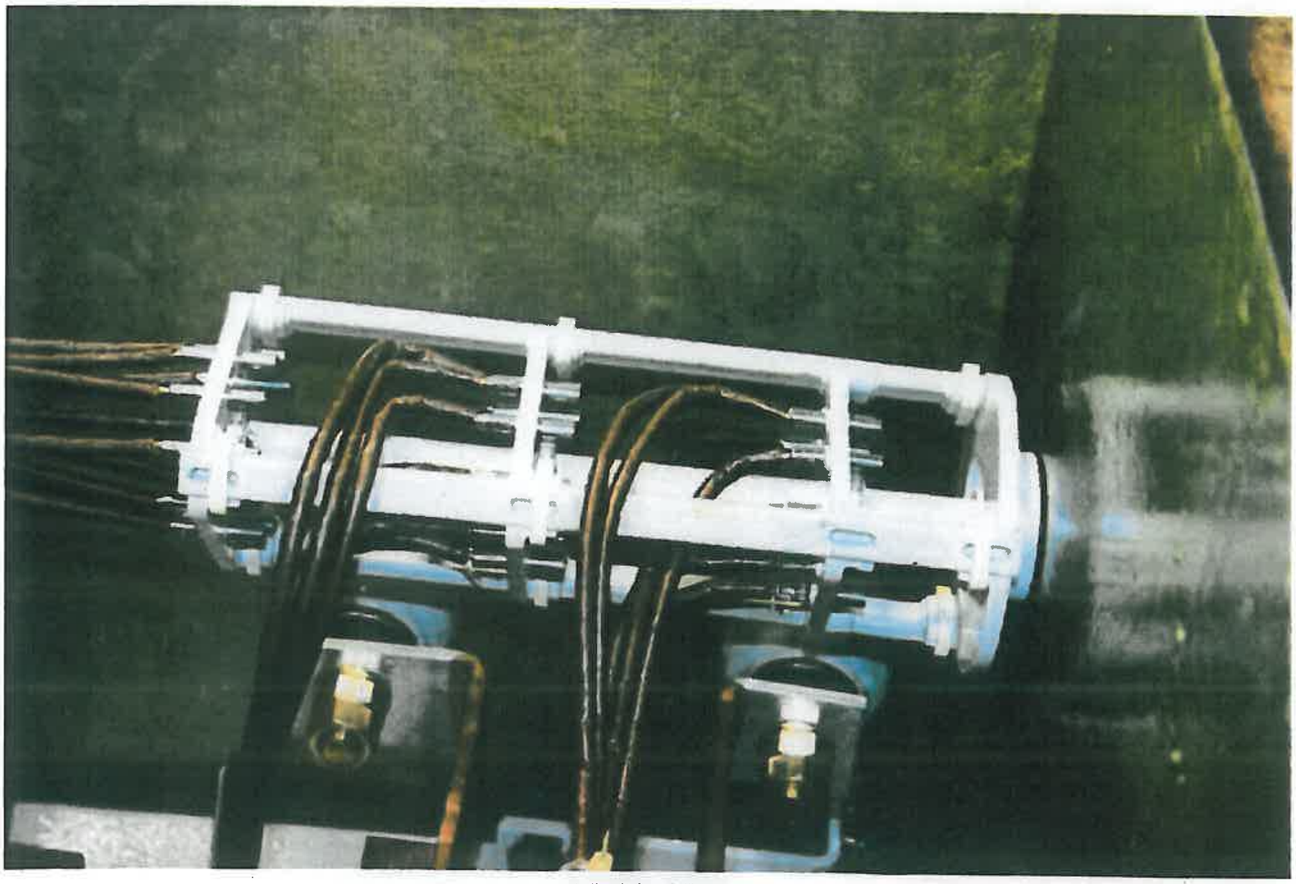

25039-1714

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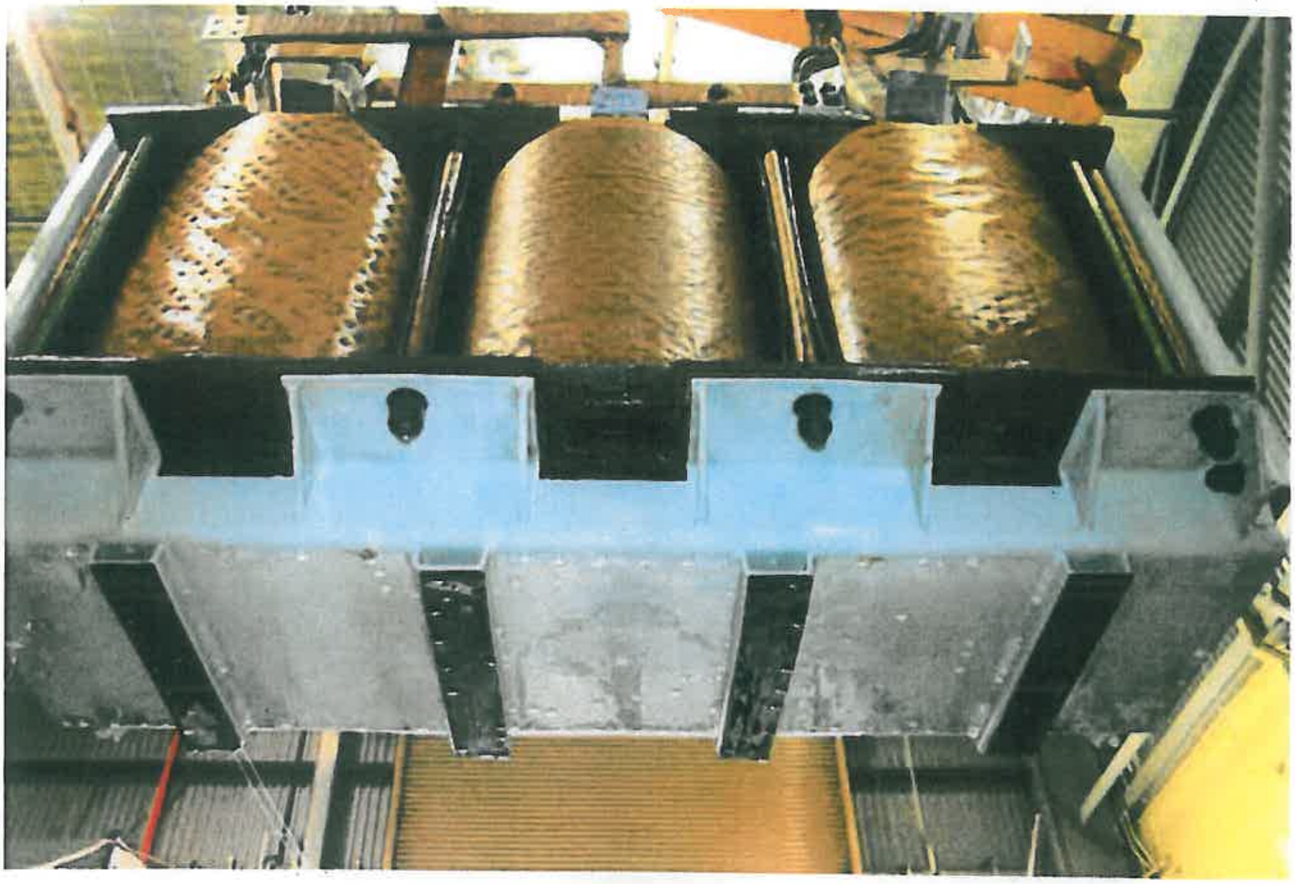

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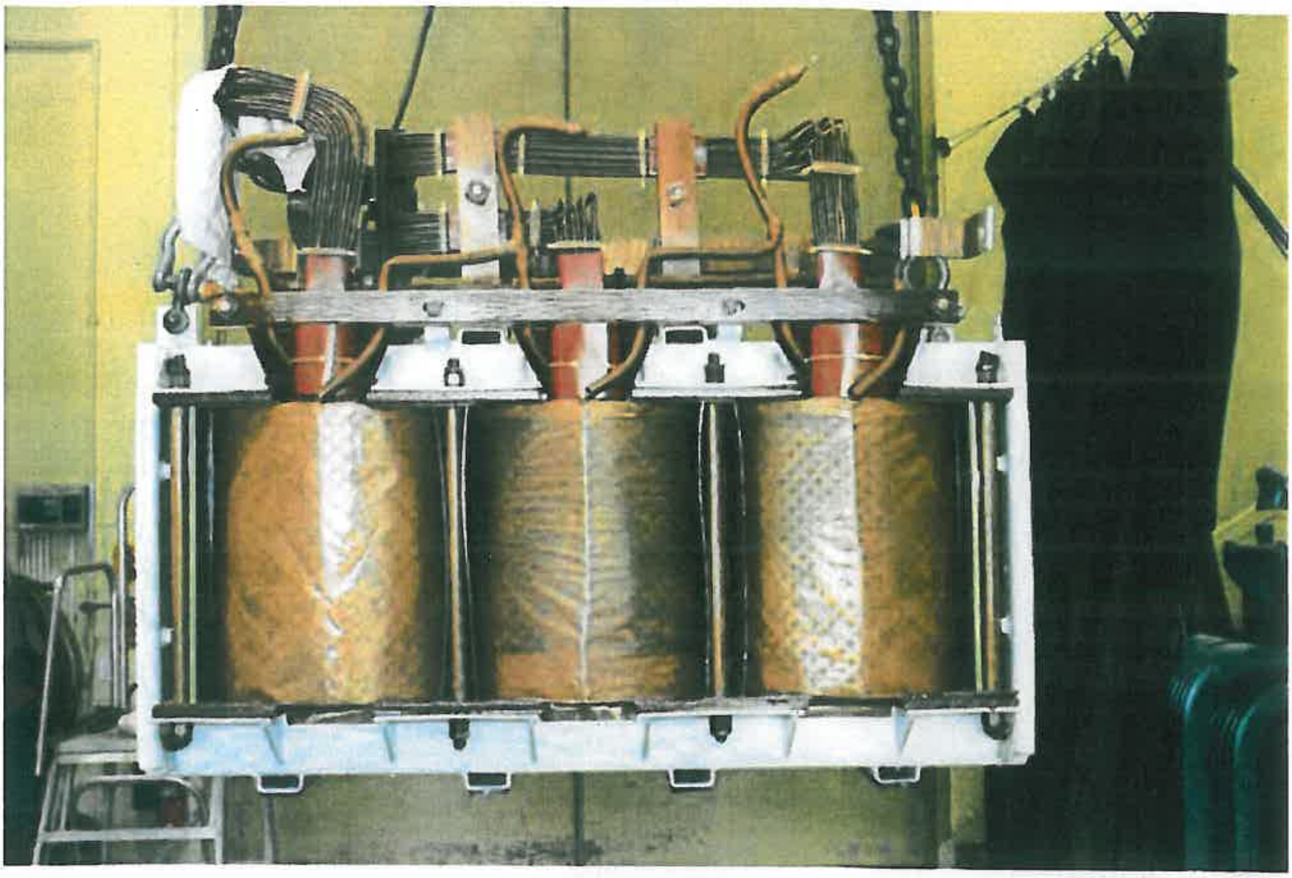

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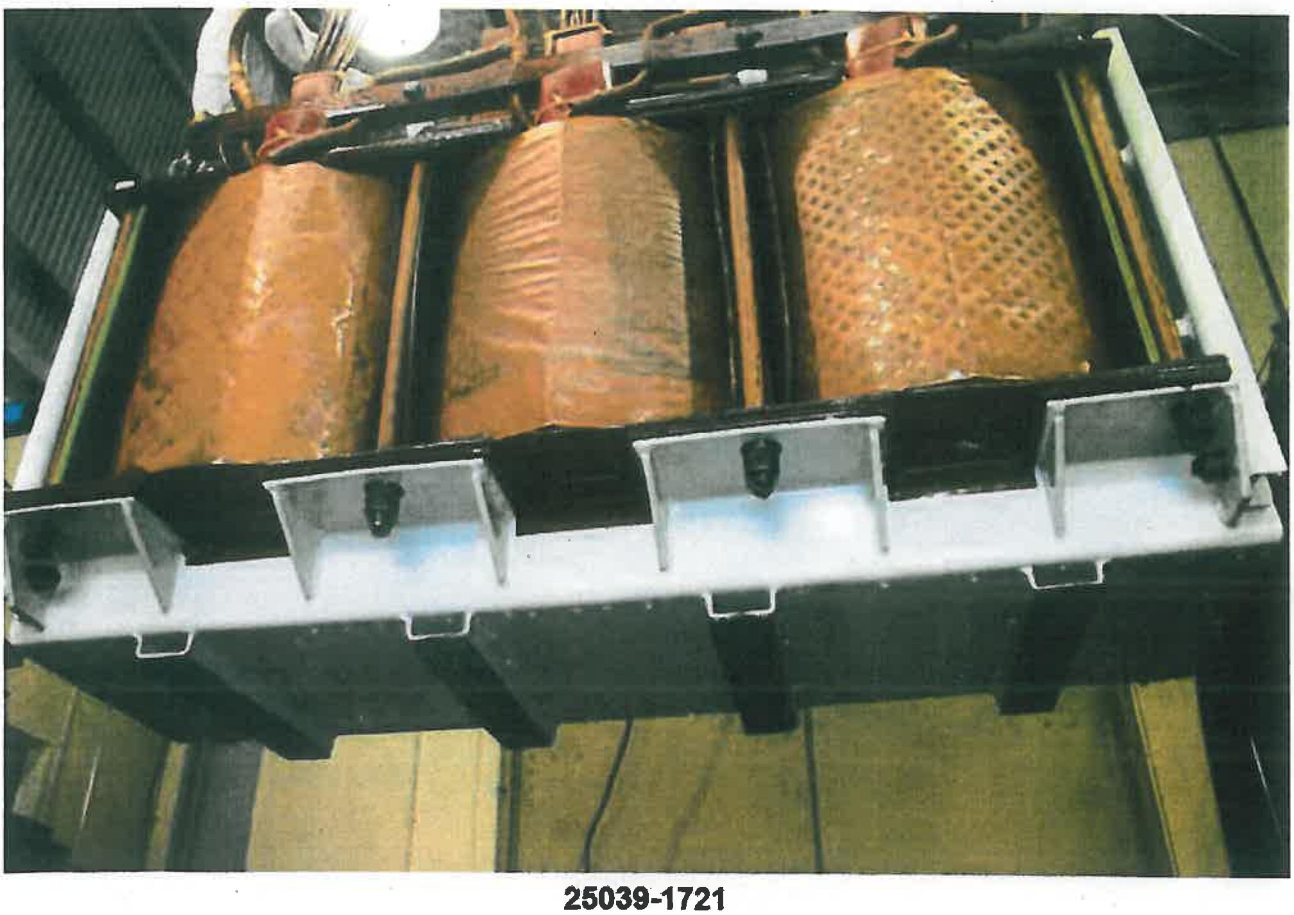

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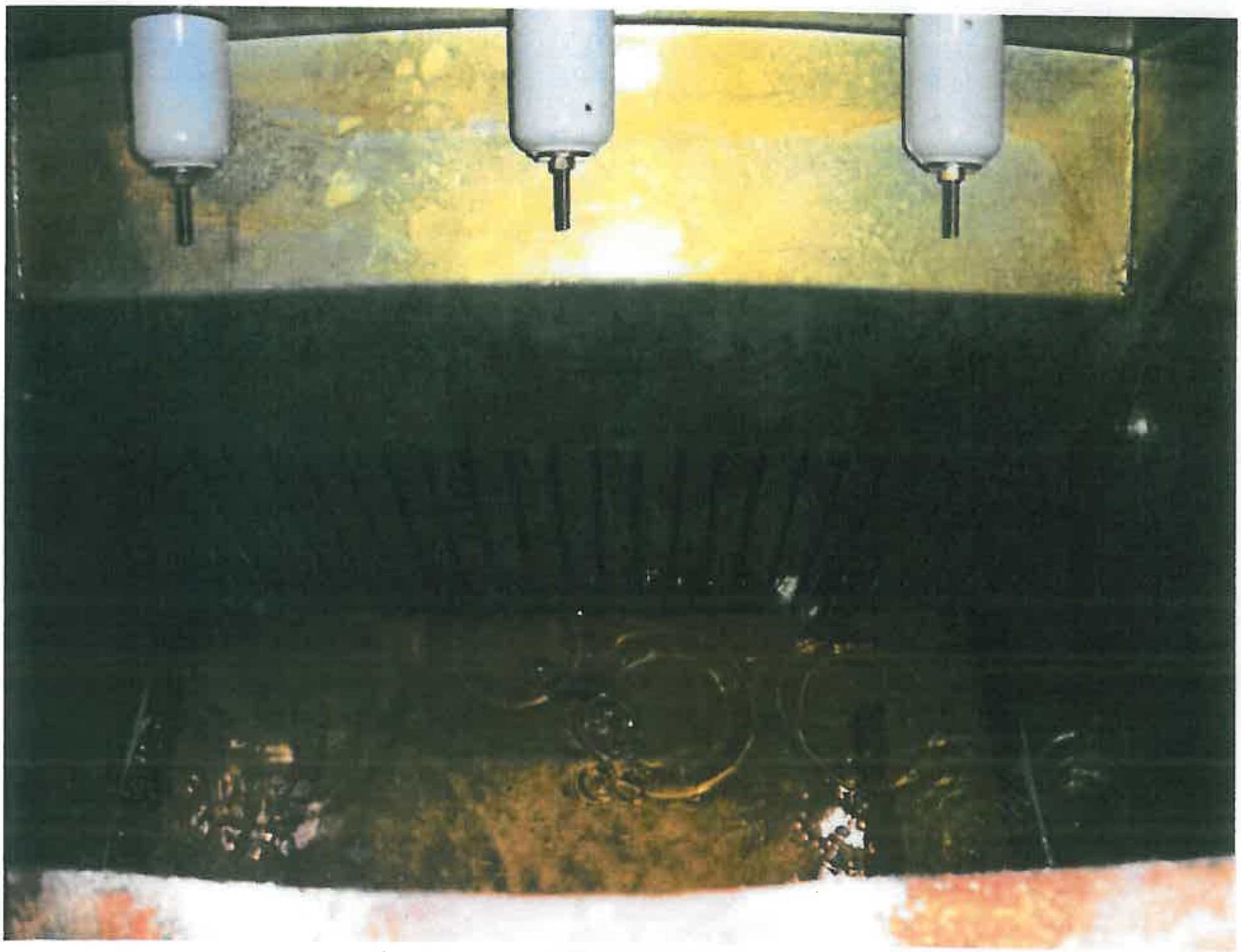
25039-1723



25039-1727

F. Matlab Script for TOC Simulator

```
function varargout = TOC_Simulator0_10(varargin)
% TOC_SIMULATOR0_10 M-file for TOC_Simulator0_10.fig
%      TOC_SIMULATOR0_10, by itself, creates a new TOC_SIMULATOR0_10 or raises the
existing
%      singleton*.
%
%      H = TOC_SIMULATOR0_10 returns the handle to a new TOC_SIMULATOR0_10 or the
handle to
%      the existing singleton*.
%
%      TOC_SIMULATOR0_10('CALLBACK',hObject,eventData,handles,...) calls the local
%      function named CALLBACK in TOC_SIMULATOR0_10.M with the given input arguments.
%
%      TOC_SIMULATOR0_10('Property','Value',...) creates a new TOC_SIMULATOR0_10 or
raises the
%      existing singleton*.  Starting from the left, property value pairs are
%      applied to the GUI before TOC_Simulator0_10_OpeningFcn gets called.  An
%      unrecognized property name or invalid value makes property application
%      stop.  All inputs are passed to TOC_Simulator0_10_OpeningFcn via varargin.
%
%      *See GUI Options on GUIDE's Tools menu.  Choose "GUI allows only one
%      instance to run (singleton)".
%
% See also: GUIDE, GUIDATA, GUIHANDLES

% Edit the above text to modify the response to help TOC_Simulator0_10

% Last Modified by GUIDE v2.5 21-Oct-2012 12:30:59

% Begin initialization code - DO NOT EDIT
gui_Singleton = 1;
gui_State = struct('gui_Name',       mfilename, ...
                   'gui_Singleton',  gui_Singleton, ...
                   'gui_OpeningFcn', @TOC_Simulator0_10_OpeningFcn, ...
                   'gui_OutputFcn',  @TOC_Simulator0_10_OutputFcn, ...
                   'gui_LayoutFcn',  [] , ...
                   'gui_Callback',   []);
if nargin && ischar(varargin{1})
    gui_State.gui_Callback = str2func(varargin{1});
end

if nargout
    [varargout{1:nargout}] = gui_mainfcn(gui_State, varargin{:});
else
    gui_mainfcn(gui_State, varargin{:});
end
% End initialization code - DO NOT EDIT


% --- Executes just before TOC_Simulator0_10 is made visible.
function TOC_Simulator0_10_OpeningFcn(hObject, eventdata, handles, varargin)
% This function has no output args, see OutputFcn.
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
```

```
% varargin   command line arguments to TOC_Simulator0_10 (see VARARGIN)

% Choose default command line output for TOC_Simulator0_10
handles.output = hObject;

% Update handles structure
guidata(hObject, handles);

% UIWAIT makes TOC_Simulator0_10 wait for user response (see UIRESUME)
% uiwait(handles.figure1);


% --- Outputs from this function are returned to the command line.
function varargout = TOC_Simulator0_10_OutputFcn(hObject, eventdata, handles)
% varargout  cell array for returning output args (see VARARGOUT);
% hObject    handle to figure
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Get default command line output from handles structure
varargout{1} = handles.output;


% --- Executes on button press in factorial.
function factorial_Callback(hObject, eventdata, handles)
% hObject    handle to factorial (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)
clc

%Amorphous Core Transformer Information
Wi = str2num(get(handles.Wi_AMCT,'String'))
Wc = str2num(get(handles.Wc_AMCT,'String'))
Ctr = str2num(get(handles.Ctr_AMCT,'String'))

%Silicon Steel Core Transformer Information
Wi1 = str2num(get(handles.Wi_Si,'String'))
Wc1 = str2num(get(handles.Wc_Si,'String'))
Ctr1 = str2num(get(handles.Ctr_Si,'String'))

%Determine the Load Cycle Selected

str = get(handles.LoadCycle,'String')
val = get(handles.LoadCycle,'Value')

%%%%%%%%%%%%% Initialise Variables %%%%%%%%%%%%%%%%

switch str{val};
case 'Commercial and Industrial (S&W)' % User DMW
    Pe = 0.70893112;
case 'Domestic Little Water Heating (NSW)' % User DMW
    Pe = 0.714810581;
case 'Domestic Much Water Heating (W)' % User DMW
    Pe = 0.742450896;
case 'Domestic Much Water Heating (S)' % User DMW
```

```
    Pe = 0.731200497;
case 'Mixed Predominantly Domestic (W)' % User DMW
    Pe = 0.757025429;
case 'Mixed Predominantly Domestic (S)' % User DMW
    Pe = 0.7;
case 'Mixed Predominantly Industrial (S&W)' % User DMW
    Pe = 0.815242806;
case 'Continuous' % User DMW
    Pe = 1.0;
case 'Manual' % User selects Manual
    Pe = str2num(get(handles.Manual_Pe,'String'))
end

M = str2num(get(handles.M,'String'))
r_decimal = str2num(get(handles.Rate,'String'))
r = r_decimal/100

EP = str2num(get(handles.EP,'String'))

f=0;
f1=0;
y=0;
x=1;
f_inter=-1;

%%%%%%%%%%%%%%%%% Carry out Simulation using For loop %%%%%%%%%%%%%%%%%%%%

for i=1:M

    g=[1/(1+r)^y]*[[Wi+(Pe^2*Wc)]*8760*(EP/1000)+Ctr]; %amorphous core TOC↙
calculation
    f=f+g
    fa(x)=f;

    g1=[1/(1+r)^y]*[[Wi1+(Pe^2*Wc1)]*8760*(EP/1000)+Ctr1]; %CRGO TOC calculation
    f1=f1+g1
    fb(x)=f1;

    if ((f1>f) && (f_inter<1))
        f_inter=x
    end

    Ctr=0;
    Ctr1=0;
    y=y+1;
    years(x)=x;
    x=x+1;
end

%%%%%%%%%%%%%%%%% Output Results %%%%%%%%%%%%%%%%%%%%

ff = num2str(f)
ff1 = num2str(f1)
set(handles.NPV_AMCT,'string',ff)
set(handles.NPV_Si,'string',ff1)
```

```
s = f1-f;
ss = num2str(s)
ff_inter = num2str(f_inter)

set(handles.Savings,'string',ss)
set(handles.Breakeven,'string',ff_inter)

plot(years,fa,'r',years,fb,'b')
xlabel('Years')
ylabel('$$')
legend ('Amorphous','Silicon','Location','SouthEast')


function Wi_AMCT_Callback(hObject, eventdata, handles)
% hObject    handle to Wi_AMCT (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Wi_AMCT as text
%        str2double(get(hObject,'String')) returns contents of Wi_AMCT as a double


% --- Executes during object creation, after setting all properties.
function Wi_AMCT_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Wi_AMCT (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function Wc_AMCT_Callback(hObject, eventdata, handles)
% hObject    handle to Wc_AMCT (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Wc_AMCT as text
%        str2double(get(hObject,'String')) returns contents of Wc_AMCT as a double


% --- Executes during object creation, after setting all properties.
function Wc_AMCT_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Wc_AMCT (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
```

```
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function Manual_Pe_Callback(hObject, eventdata, handles)
% hObject    handle to Manual_Pe (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Manual_Pe as text
%        str2double(get(hObject,'String')) returns contents of Manual_Pe as a double


% --- Executes during object creation, after setting all properties.
function Manual_Pe_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Manual_Pe (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function M_Callback(hObject, eventdata, handles)
% hObject    handle to M (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of M as text
%        str2double(get(hObject,'String')) returns contents of M as a double


% --- Executes during object creation, after setting all properties.
function M_CreateFcn(hObject, eventdata, handles)
% hObject    handle to M (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end
```

```
function Rate_Callback(hObject, eventdata, handles)
% hObject    handle to Rate (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Rate as text
%        str2double(get(hObject,'String')) returns contents of Rate as a double


% --- Executes during object creation, after setting all properties.
function Rate_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Rate (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function Ctr_AMCT_Callback(hObject, eventdata, handles)
% hObject    handle to Ctr_AMCT (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Ctr_AMCT as text
%        str2double(get(hObject,'String')) returns contents of Ctr_AMCT as a double


% --- Executes during object creation, after setting all properties.
function Ctr_AMCT_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Ctr_AMCT (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function EP_Callback(hObject, eventdata, handles)
% hObject    handle to EP (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of EP as text
%        str2double(get(hObject,'String')) returns contents of EP as a double
```

```
% --- Executes during object creation, after setting all properties.
function EP_CreateFcn(hObject, eventdata, handles)
% hObject    handle to EP (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function Ctr_Si_Callback(hObject, eventdata, handles)
% hObject    handle to Ctr_Si (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Ctr_Si as text
%        str2double(get(hObject,'String')) returns contents of Ctr_Si as a double


% --- Executes during object creation, after setting all properties.
function Ctr_Si_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Ctr_Si (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function Wi_Si_Callback(hObject, eventdata, handles)
% hObject    handle to Wi_Si (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Wi_Si as text
%        str2double(get(hObject,'String')) returns contents of Wi_Si as a double


% --- Executes during object creation, after setting all properties.
function Wi_Si_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Wi_Si (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called
```

```
% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end



function number21_Callback(hObject, eventdata, handles)
% hObject    handle to Wc_Si (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Wc_Si as text
%        str2double(get(hObject,'String')) returns contents of Wc_Si as a double


% --- Executes during object creation, after setting all properties.
function Wc_Si_CreateFcn(hObject, eventdata, handles)
% hObject    handle to Wc_Si (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: edit controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
end


% --- Executes on selection change in LoadCycle.
function LoadCycle_Callback(hObject, eventdata, handles)
% hObject    handle to LoadCycle (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: contents = cellstr(get(hObject,'String')) returns LoadCycle contents as cell↙
array
%        contents{get(hObject,'Value')} returns selected item from LoadCycle


% --- Executes during object creation, after setting all properties.
function LoadCycle_CreateFcn(hObject, eventdata, handles)
% hObject    handle to LoadCycle (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    empty - handles not created until after all CreateFcns called

% Hint: popupmenu controls usually have a white background on Windows.
%       See ISPC and COMPUTER.
if ispc && isequal(get(hObject,'BackgroundColor'), get↙
(0,'defaultUicontrolBackgroundColor'))
    set(hObject,'BackgroundColor','white');
```

```
end



function Wc_Si_Callback(hObject, eventdata, handles)
% hObject    handle to Wc_Si (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hints: get(hObject,'String') returns contents of Wc_Si as text
%        str2double(get(hObject,'String')) returns contents of Wc_Si as a double


% --- Executes when user attempts to close figure1.
function figure1_CloseRequestFcn(hObject, eventdata, handles)
% hObject    handle to figure1 (see GCBO)
% eventdata  reserved - to be defined in a future version of MATLAB
% handles    structure with handles and user data (see GUIDATA)

% Hint: delete(hObject) closes the figure
delete(hObject);
```