EVALUATION OF AN EFFICIENCENT TRANSFORMER CORE DESIGN

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Declaration

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

Signed: P Lutchman

Date: 7 September 2012

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Nomenclature

The term "Hexaformer" and "Hexa-transformer" are used interchangeably in this document. Both refer to the three phase triangular core transformer produced by Hexaformer AB in Sweden.

A - Ampere
AC - Alternating Current
CSIR - Council for Scientific and Industrial Research
DC – Direct Current
Dx - Distribution System
EPRI - Electric Power Research Institute
ESEERCO - Empire State Electric Energy Corporation
EU - European Union
h - Hour
HTS - High Temperature Superconducting
HV - High Voltage
IEEE - Institute of Electrical and Electronics Engineers
K - Kelvin
kVA – kilovolt-ampere
kW - kilowatt
kWHr – kilowatt-hour
LTS - Low Temperature Superconducting
LV - Low Voltage
MEPS - Minimum Energy Producing Standards
OHL - Over Head Line
P - Power
PCB - Polychlorinated Biphenyl
PS - Power Station
PTFE - Polytetrafluoroethylene
TOC - Total Ownership Cost
TW - Terawatt
TWhr – Terawatt-hour
Tx - Transmission system
V - Volt
W - Watt

Abstract

Distribution transformers have inherently high efficiencies of up to 99%, however they are in continuous operation and have a long lifespan, hence their power loss cost is still significant. A small efficiency improvement can lead to a considerable amount of energy savings over the lifetime of the transformer.

Symmetric core design has the potential to improve transformer efficiency. The aim of this dissertation is to evaluate a relatively new symmetrical triangular core transformer for use in the Eskom Distribution network in South Africa. The transformer is called the hexa-transformer.

A three phase 100 kVA hexa-transformer unit has been purchased from Hexaformer AB in Sweden. The unit has been routinely tested. A 50% no-load loss reduction has been achieved. The transformer was also opened and examined. The results indicated sound manufacturing quality. The economic analysis indicated a life cycle saving of R 2 727.41 per transformer over a 25 year period when compared to a conventional E-core transformer of the same rating. It is recommended that Eskom consider these units for future implementation in their Distribution network.

1. CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

This chapter provides an introduction to the rest of the dissertation. The key objectives of this research are discussed and a brief summary of each chapter is presented.

Transformers form an integral part of the electricity grid. They however do not generate any electrical power; they are voltage changers used to step-up or step-down voltages in the electrical grid [1].

Transformers are not 100% efficient. There are electrical losses associated with them. Distribution transformers have inherently high efficiencies compared to other electrical devices; however they are in continuous operation and have a relatively long lifespan. As a result a small efficiency increase can add up to significant savings over the lifespan of the transformer [2]. Distribution transformers play a large role in the electrical grid. They are used in large numbers to facilitate the distribution of electricity to the end user.

1.1.1 The need for an efficient transformer in Eskom

South Africa is currently experiencing a shortage of electricity throughout the country. Due to insufficient electricity available, the country is looking at methods to decrease its power consumption [3]. There exists the potential for Eskom to reduce its grid losses by installing new efficient equipment in their grid, thus making more power available for consumption. The following dissertation evaluates the possible use of a new low loss transformer, the hexa-transformer in the Eskom electricity distribution grid [3].

A 100 kVA transformer used by Eskom has no-load losses of 300 W. This results in 300 kW of losses per fleet of 1000 transformers. The hexa-transformer is claimed to have no-load losses of 145 W. This may result in saving of half the power lost if implemented in the Eskom distribution network [4, 5].

1.2 RESEARCH OBJECTIVES

The objective of this dissertation is to analyse the hexa-transformer for electricity distribution applications in South Africa. The first phase of this research is to gain information on the hexa-transformer, what is it and where is it produced. The next step is to validate its core design from a scientific evaluation, how does its core design cause a reduction in the core losses. Once the design has been proven, it is necessary to test the transformer practically. For this a 100 kVA unit has been purchased and tested in order to validate its efficiency claims. Evaluating the manufacturing quality of the transformer also forms part of this research.

1.3 THESIS LAYOUT

Chapter 1 is an introduction to the dissertation. A brief summary and the dissertation objectives are presented.

Chapter 2 reviews the existing literature of the research that is proposed. A background on electricity production and transmission is presented. The electrical grid is analysed and a potential for the reduction of losses is suggested.

Chapter 3 of this thesis provides information on the hexa-transformer. An overview of its manufacturing process is given. The transformer core is analysed and compared to a conventional E-core design.

Chapter 4 presents an account of testing the transformer. The manufacturing quality of the transformer is presented in Chapter 5. The transformer is opened and inspected. Detailed accounts of both the interior and exterior observations are presented in Chapter 6.

Chapter 7 draws conclusions from the research and provides recommendations for further studies.

2. CHAPTER 2 – LITERATURE REVIEW

This chapter provides background information on the subsequent thesis. It provides the reader with information on electric power. The generation, transmission, and distribution of electricity are briefly explained. The electric power grid is analysed and loss sources are identified. The focus of this chapter is to present various methods on reducing distribution transformer losses. This chapter concludes with a suggested approach to reduce electric grid losses in South Africa.

South Africa is currently facing a shortage of power in the country. This problem is currently been rectified through the construction of two new coal-fired power stations by Eskom, namely Medupi and Kusile. Medupi and Kusile are both made up of 6 X 800 MW units with a total individual capacity of 4800 MW, they are due for completion in 2015 and 2018 respectively [6]. In the interim Eskom is currently looking at methods to decrease energy consumption in South Africa by promoting many energy efficient incentives.

2.1 ELECTRICITY PRODUCTION AND TRANSMISSION

2.1.1 Background

The basic structure of a power station (PS) is as follows: Primary energy is converted to mechanical energy which in turn is used to drive a turbine generator that converts this energy into electricity using Faraday's principle of electro-magnetic induction. The construction of an electricity power station is dependent on various elements. The primary resource for a South African PS is the availability of coal. In South Africa coal is the primary source of energy. Coal is naturally abundant and hence provides an economic means of producing electricity at a large scale. However according to a study conducted by the Council for Scientific and Industrial Research (CSIR), it is expected that the coal resources in South Africa would be depleted within the next century [7].

Electricity is not always used in the same place that it is produced. Long distance transmission lines and distribution systems are necessary to transfer the electricity produced to its end user. Electricity transmission and distribution refers to the process of delivering electric energy from the high voltage (HV) transmission grid to separate locations such as residential locations. The distribution grid encompasses the substations and feeder lines that take power from HV grid and progressively step down the voltage to 220 V via the use of transformers. Transmission (Tx) and Distribution (Dx) system losses together consist of overhead power line (OHL) losses and transformer losses [8]. Refer to Figure 1 below.

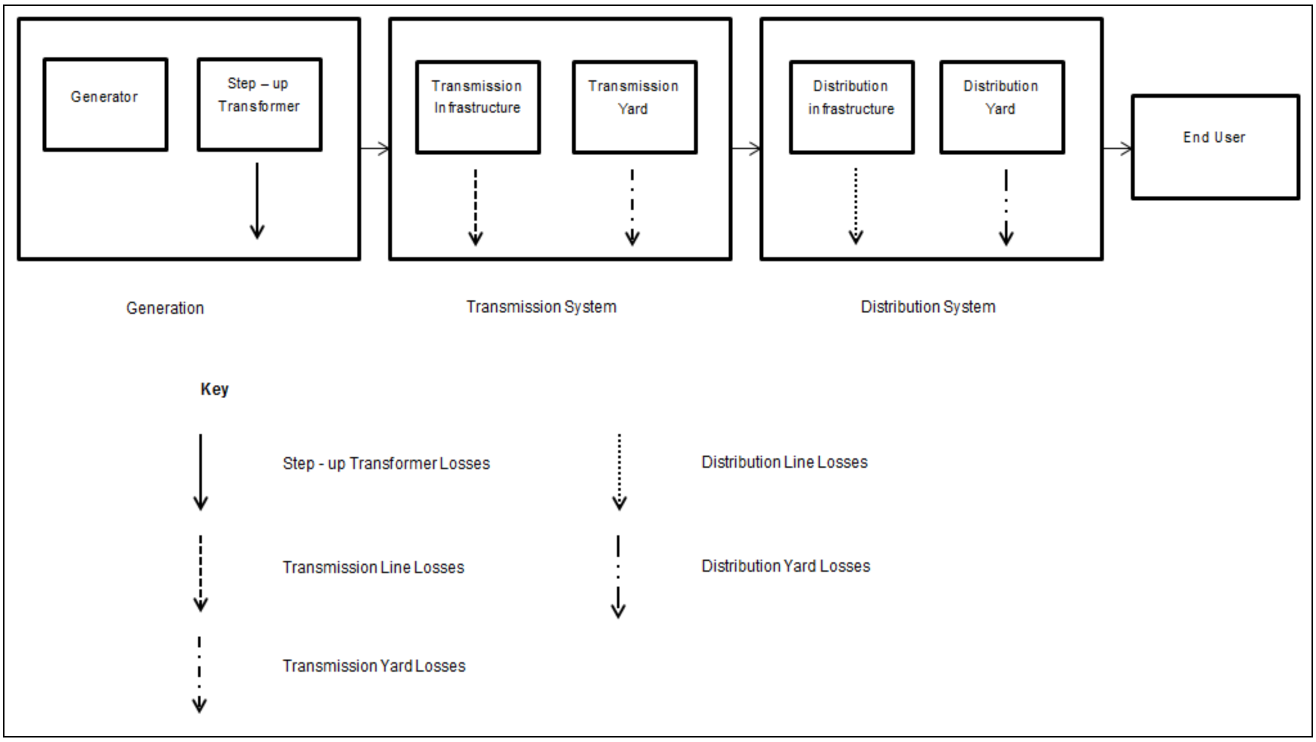


Figure 1: Electricity distribution illustrating the flow of electricity from generation to the consumer

2.2 TRANSMISSION LINE POWER LOSSES

Transmission line losses are a result of two major sources, resistive loss and corona loss. Resistive losses are losses dissipated as heat due to the resistance of the conductors, the smaller the surface area of the conductors, the smaller the power loss to heat dissipation. High voltages require less surface area, resulting in a reduction in line power loss. With high-voltage lines, the voltage can be stepped up at the generating station, transmitted through the transmission grid to a load-centre, and there it is stepped down to the lower voltages required by distribution lines [9].

Corona loss is caused by the ionization of air molecules near the transmission line conductors. These coronas do not spark across lines, but carry current (hence the loss) in the air along the wire. Corona discharge in transmission lines can lead to hissing/cackling noises, a glow, and the smell of ozone (generated from the breakdown and recombination of oxygen molecules). The colour and distribution of this glow depends on the phrase of the AC signal at any given moment in time. Positive coronas are smooth and blue in colour, while negative coronas are red and spotty [10].

Corona loss only occurs when the line to line voltage exceeds the corona threshold. Unlike resistive loss where amount of power lost was a fixed percentage of input, the percentage of power lost due to corona is a function of the signal's voltage. Corona discharge power losses are also highly dependent on the weather and temperature.

2.3 TRANSFORMER LOSSES

Transformers are designed to deliver the required power to the connected loads with minimum losses. Transformer losses are a result of the electrical current flowing in the coils and the magnetic field alternating in the core. The losses associated with the coils are called "load losses", while the losses produced in the core are called "no-load" losses. The losses are illustrated in equation (1) below [11, 12, 13].

$$P_T = P_{NL} + P_L \quad (1)$$

Where:
P_T = total loss, watt
P_{NL} = no-load loss, watt
P_L = load loss, watt

The no-load losses are related to the transformer core. They are losses due to the voltage excitation of the core, magnetic hysteresis and eddy currents [14]. The load or impedance loss varies according to the loading of the transformer. The load loss is subdivided into I^2R loss and stray losses caused by magnetic flux in the windings. These losses are created by the resistance of the conductor to the flow of current [11, 13].

The combination of no-load losses and load losses is the total loss of the transformer. Two factors account for nearly all these losses. The copper winding loss which consists of both the primary winding and secondary winding loss [15]. The second factor is the transformer core loss. This consists of hysteresis and eddy current losses. Hysteresis is a function of the core steel. It is determined by the manufacturing process. The eddy current losses are caused by the magnetic field set up.

The purpose of a distribution transformer is to reduce the primary voltage of the electric distribution system to the utilization voltage serving the customer. A distribution transformer is a static device constructed with two or more windings used to transfer alternating current electric power by electromagnetic induction from one circuit to another at the same frequency but with different values of voltage and current. Distribution transformers are responsible for approximately one third of electrical system losses. These losses represent a significant cost for the electricity utility company [16].

2.4 REDUCING DISTRIBUTION TRANSFORMER LOSSES

Although distribution transformers have relatively high efficiencies, about 99%, the total amount of loss can be considerably high due to the large quantity of distribution transformers used in the electrical grid [17, 18]. As costs of energy and system investment rise, it becomes increasingly important to consider the costs associated with distribution transformer losses. In many cases the cost of distribution transformer losses exceeds the purchase price of the transformer when the two are evaluated on the same basis. If the cost of losses are properly evaluated and added to the purchase price of the transformer, various transformers with different prices and different loss levels can be compared to find the design with the minimum total cost [19].

Transformer efficiency is a function of its loss. Decreasing the no-load losses would result in increased transformer efficiency. Increased efficiency brings long term value, but it can also have a significant impact on its initial cost. The higher the cost of raw materials, such as copper, steel, insulation materials and dielectric fluid, the greater the cost of more efficient transformers.

As the efficiency of a transformer improves, the transformer cost increases; this increase is due to the price of the laminated steel core grade. Hence it is vital to maintain the appropriate balance between transformer efficiency and its increased cost. The relationship between transformer cost and efficiency is illustrated in Figure 2 below.

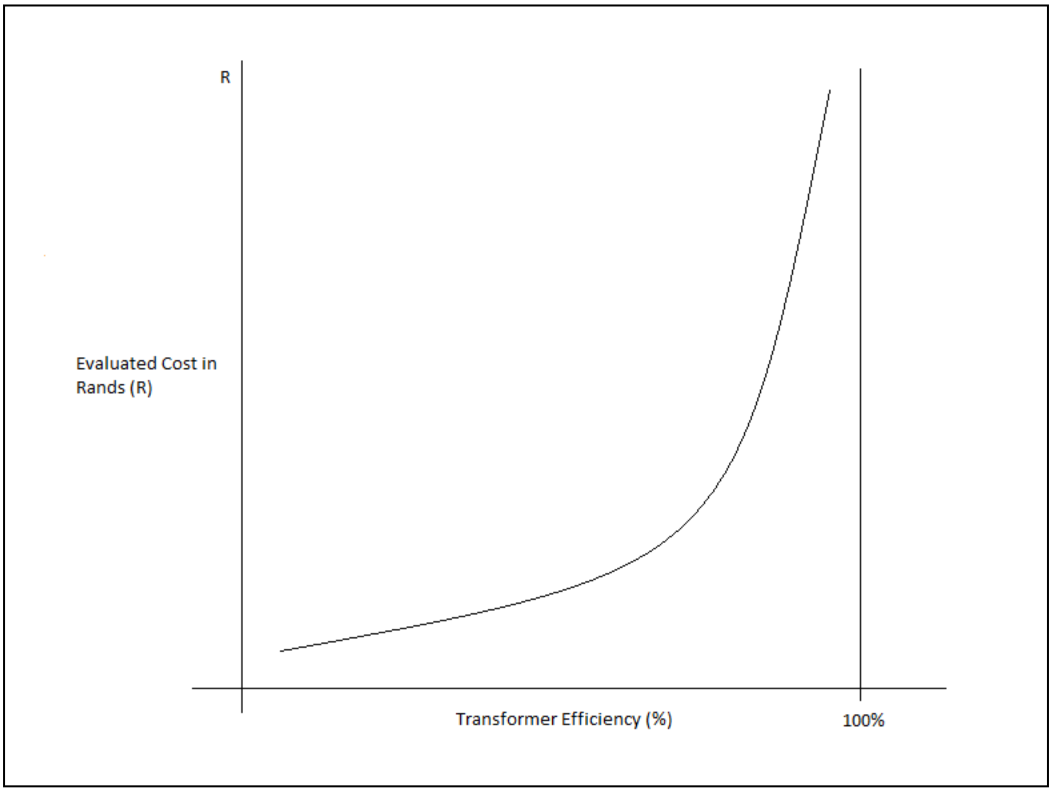


Figure 2: Transformer cost and efficiency relationship, an increase in efficiency results in an increase in the capital cost of the transformer

2.4.1 Background studies

Over the years, there have been a number of studies on the effect of transformer losses in the electrical grid.

In 1977 a study was done to estimate transformer losses in America. It was discovered that electrical steel losses found in transformers approached 41 x 109 kWHr, and if the energy cost was assumed to be $0.03/kWHr, the total yearly cost of these losses was $1.23 billion or R 10.38 billion [20]. In 1977, utilities, on the average, evaluated transformer no-load loss, on an equivalent investment cost basis, at about $16001kW. The average evaluation on an equivalent investment cost was about $4,000/kW in 1985 with some evaluations approaching $13,500/kW. Thus, in some cases, the evaluated cost of a transformer's no-load loss can well exceed the first cost of the transformer itself. The subject of transformer no-load losses, the factors that influence them and their measurement therefore become important subjects [21].

Distribution transformer efficiencies steadily increased with the introduction of improved materials and manufacturing methods in the 1980s and 1990s [22]. Even so, 26.6% of the average transmission and distribution losses are still associated with distribution transformers [23].

The evaluated cost of transformer no-load loss can, in some cases, exceed the first cost of the transformer. Thus, the subjects of transformer no-load losses, the factors that influence them and their measurement assume greater importance [24].

Further studies in 2010 indicated that the losses in The European Union distribution transformers are estimated at about 33 TW · h/year, whereas reactive power and harmonic losses add a further 5 TW · h/year. The reduction of distribution transformer no-load loss is particularly important as the ratio of no-load to load losses is nearly three [25].

A more recent study in 2010 in America estimated that distribution transformer losses are 2 – 3% of the total electric energy and costs about 25 billion dollars annually [18].

In a typical power system, the losses incurred during transmission and distribution accounts as 2 – 3% for transmission line losses and 5 – 6% % for transformer losses [26, 27, 28]. No-load losses represent 2 – 3% of generation in transformers. Reducing these losses is important for distribution transformers.

The above studies all indicated that transformer losses are significant and can result in huge expenditure as they are used extensively in the electrical network. It is therefore beneficial to decrease these losses.

Transformer losses can be reduced by improving the core material. Transformer cores are made from laminations of silicon steel more commonly referred to as electrical steel. Iron is a good conductor of electricity and can be used with a rapidly changing field. Intense eddy currents appear due to the presence of the varying magnetic field.

2.4.2 Methods to Reduce Losses

Although there have been numerous studies on transformer efficiencies, the topic of transformer loss reduction still continues to be a topic of huge interest. This present study is part of such effort to reduce transformer no-load losses in South Africa. The objective of this research is to find ways to reduce the distribution transformer losses and evaluate a single method of loss reduction for use in the South African Eskom Distribution network.

2.4.2.1 Use of Electric Shields

Transformer losses can be reduced by using electromagnetic shields to prevent stray losses [29]. Electromagnetic shields are placed in the transformer tank walls for the reduction of losses. An experiment has been conducted in 2003 where the transformer tank was lined with aluminium foil. In the transformer, the leakage flux is high in the tank walls, which causes high-power losses [30]. The objective was to concentrate in reducing the area of stray losses [31]. A reduction of the magnetic flux is required to reduce these losses. This can be achieved by placing a physical barrier in the form of a shield between the electromagnetic field source and the tank walls. In this study, an increase of the stray losses by 20.9% was observed when the aluminium shield of 10 mm was not used. On the other hand, there were not significant changes in the losses when the 1.2-mm shield was used with respect to unshielded case, since the depth of penetration was larger than the shield thickness and the magnetic flux could reach the carbon steel.

2.4.2.2 Smart Grid Monitoring

Distribution losses can be reduced by the use of smart grid monitoring. A study was performed in 2009 on how to utilize a Smart Grid monitoring system in conjunction with loss of life calculations in order to identify overloaded transformers [32]. The study concluded that a Smart Grid has the capability of actively monitoring distribution transformers, which if applied to Smart Grid software or a multi-agent, has the ability to identify overloaded transformers without human interaction. By utilizing actual demand data, unlike many existing programs, the accuracy of calculating transformer loss of life is improved.

2.4.2.3 Amorphous Metal Core Transformers

Amorphous metals were first produced in the early 1960s. The magnetic properties of these metals were only discovered in the 1970s. The extreme low magnetising losses of these materials made it ideal for use as core steel for transformers. Experimental transformers that were produced with amorphous metal cores resulted in a 70% core loss reduction when compared to conventional transformers [33, 34].

Amorphous metal alloys differ from metals as there is no crystallization of the atoms. Its atoms are bonded in an instructed way similar to that of metal and glass. Amorphous metals are easier to magnetise and demagnetise, hence they have lower losses [35]. Research has found that transformers made by amorphous metals can reduce no-load losses by anywhere between 60 – 70% [35].

It was estimated that if all the distribution transformers in the USA were replaced with amorphous core units, 6-14 billion kW per year could be saved [33]. In 1983, the Electric Power Research Institute (EPRI), Transformer Business Department of General Electric Company, and the Empire State Electric Energy Corporation (ESEERCO) began a project to develop a distribution transformer with amorphous metal core. A research and development effort was established to prove the feasibility of manufacturing and using amorphous metals for transformers cores, and to substantiate the long term performance of transformers with amorphous metal cores. In 1985, the project resulted in the development of a cost effective distribution transformer design, establishment of a pilot manufacturing facility, and the production of 1000, 25-kVA, 15-kV pole-mounted distribution transformers [33].

The capital cost of amorphous transformers compared to conventional transformers is normally 20 – 30% higher. The valuation of losses must be done in order to determine a total ownership cost (TOC) [36].

A study was performed by the Vattenfall Group's Distribution Network on the amorphous transformers and new conventional transformers installed in 2009 in Sweden. The results are illustrated in Table 1 below [36].

Table 1: Transformer loss parameters

Power [kVA]	Country	Conventional Transformer		Amorphous Transformer	
		No-load Loss [kW]	Load Loss [kW]	No-load Loss [kW]	Load Loss [kW]
100	Sweden	0.215	1.6	0.075	1.5
400	Poland	0.56	4.8	0.2	4.3
630	Germany	0.538	8.18	0.32	6.2

From Table 1 above, it can be seen that the no-load losses of amorphous transformers are significantly lower than that of the conventional transformer.

2.4.2.4 Superconducting Transformers

Superconducting wire is characterized by a high current density and the absence of a DC resistance. A transformer manufactured with this wire thus has the advantages of reduced weight and loss. One of the major disadvantages of superconducting transformers was that it required Low Temperature Superconducting (LTS) wires. This required cooling by liquid helium to about 4.2K with advanced cryogenic technology that is expensive in terms of cost and power required for refrigeration [37].

With the advent of High Temperature Superconducting (HTS) materials, there is no need for cryogenic cooling. The technology for new materials requires cooling by liquid nitrogen of up to 78K.

The discovery of HTS materials lead to the development of superconducting transformers that is more competitive in cost when compared to conventional transformers. Several superconducting single phase transformers have been developed and tested, [38, 39]. A superconducting transformer has advantages of reduced size and weight, high efficiency, environmental benignity and the capability of over-capacity operation comparing with conventional transformer [40, 41].

In 1999 the Seoul National University in Korea had developed and tested a three phase 100 kVA (440/220 V) superconducting transformer for the analysis of its fundamental characteristics. The transformer losses, which include the core losses, the AC losses in the superconducting windings, and the cryostat losses were analysed. Considering these losses, it was estimated that the efficiency of the transformer was 96% [42].

In 1997 ABB announced that it had successfully connected the world's first operational high-temperature superconducting distribution transformer to the power supply network of the City of Geneva, Switzerland. The three-phase transformer has an output of 630 kVA and is designed to convert power from 18.7 kV to 420 V. The HTS transformer takes advantage of the superconductor's unique ability to transmit electricity with no resistance when cooled below a certain temperature. By using HTS windings instead of copper, the transformer can be designed lighter, more compact, with much reduced energy losses. For both the coolant and the insulating fluid, the transformer uses liquid nitrogen, which is a non-flammable, non-hazardous substance [43].

Superconducting transformers are not readily available in the market and Eskom was not too keen on the aspect of the hydrogen cooling aspect as they have very limited experience in this regard. Hence this type of efficient transformer was not considered for evaluation in South Africa.

2.4.2.5 Influence of Transformer Core Design

The magnetic properties of a transformer core are influenced by three basic factors: quality (grade) of material, processing of steel sheet during core manufacture, and core design [44]. The manufacturing of a three-phase transformer with a triangular core was attempted in the 1880s [45].

Symmetric core design applies to three phase transformers. In a symmetric core transformer each leg is identically connected to the other two. This results in a 120° radical symmetry which results in a triangular shaped core. The advantage of this type of transformer is that the core is completely symmetrical, thus resulting in a reduction in no-load losses.

In wound core transformers, minimum losses occur when the rolling direction of the electrical steel coincides with flux magnetic lines. This condition is not satisfied in the core joints of transformers that are produced from stacks of electrical laminations, because there are air gaps within the joints that cause local disturbances of magnetic flux. The main advantages of wound cores include reduction of joints and the use of the grain direction of the steel for the flux path [29, 45]. However it was found that this technology was complex and very expensive to implement in the past.

There has been a recent advance in triangular core transformers. ABB introduced a new three-phase triangular dry core transformer, the ABB TriDry Transformer. [46] The advantage of this transformer is that it is lighter and more efficient.

Hexaformer AB in Sweden launched a new wound triangular core transformer named the hexa-transformer. This transformer uses oil for cooling [45]. The Hexa-transformer reduces no-load losses by up to 50% [47].

Both the ABB TriDry Transformer and Hexa-transformer are more efficient than the conventional E-core transformer [46, 47]. The increased efficiency is a result of the core being completely symmetrical; all windings have equal reluctances with equal (shorter) lengths of flux paths. A higher magnetic field with the same magneto force is produced. The magnetising current is thus lower. [45].

Eskom currently does not use dry type of transformers for electricity distribution; hence it was decided to evaluate the hexa-transformer for use in the Eskom distribution networks.

2.4.3 Summary

There have been numerous studies on transformer efficiency and methods to decrease transformer losses in the electrical grid. A few of these studies were briefly presented. It was established that transformer losses are influenced by the core design, type of core material used, and type of core windings.

A study was conducted by the US department of energy in 2007 on the impact of distribution transformers [48]. Various design options were considered to increase transformer efficiency. Table 2 below summarises the design considered and their impact on transformer losses [48].

Table 2: Transformer loss reduction methods

To decrease no-load losses	**No-load losses**	**Load Losses**	**Cost impact**
Use lower-loss core materials	Lower	No change	Higher
Decrease flux density by: a) Increasing core cross-sectional area (CSA) b) Decreasing volts per turn	 Lower Lower	 Higher Higher	 Higher Higher
Decrease flux path length by decreasing conductor CSA	Lower	Higher	Lower
Use 120° symmetry in three-phase cores**	Lower	Lower	Unknown
To decrease load losses			
Use lower-loss conductor material	No change	Lower	Higher
Decrease flux density by: a) Decreasing core CSA b) Increasing volts per turn	 Higher Higher	 Lower Lower	 Lower Lower

Use 120° symmetry in three-phase cores**	Lower	Lower	Unknown

** First commercialized by Hexaformer AB of Sweden.

The cost impact of the symmetric core transformer was not yet known when the study was conducted. From Table 2 it can be seen that there are number of methods to decrease transformer losses, some resulting in a higher cost impact. The symmetric core (Hexa-transformer) is the only design to decrease both the load and no-load losses.

It was decided to evaluate the use of a triangular core transformer for use in the Eskom distribution network. This is because Eskom has very limited expertise on amorphous and superconducting materials. Eskom does not use dry type of transformers in their networks; hence the hexa-transformer will be evaluated for use in South Africa. Table 2 above also confirms that the symmetric core design is the best way to decrease both and no-load transformer losses.

2.5 SUMMARY

South Africa is currently facing a shortage of electric power; this problem is being rectified with two new coal fired power stations under construction by Eskom. These take time to construct and will only be available in 2015 and 2018. In the interim Eskom is currently looking at methods to reduce grid losses. Eskom decided to focus on improving the efficiency on distribution transformers since they are used extensively in the electrical grid. There have been many studies done around the world on transformer losses in the electrical grid. All of which has indicated that transformer losses are significant and cannot be ignored. The efficiency of distribution transformers depends on the dimensions, quality, and quantity of materials used for the transformers core and windings. The core design also plays a role in transformer losses. Various methods were presented on reducing losses; it was decided to evaluate a symmetrical three core transformer, the hexa-transformer for use in Eskom.

3. CHAPTER 3 – THE HEXA-TRANSFORMER

This chapter provides information on the hexa-transformer. It provides the reader with technical information on the transformer. A cost analysis comparing the transformer to an E-core unit of the same rating is also presented. The manufacturing processes of the hexa-transformer and transformer comparison with an E-core unit are discussed.

3.1 BACKGROUND

The Hexaformer or hexa-transformer is a three phase transformer with a specially shaped core. The core consists of nine rolls of laminated steel bands and core legs that have a cross section shape of a hexagon, hence the name hexa-transformer. Refer to Figure 3 and 4 below [49].

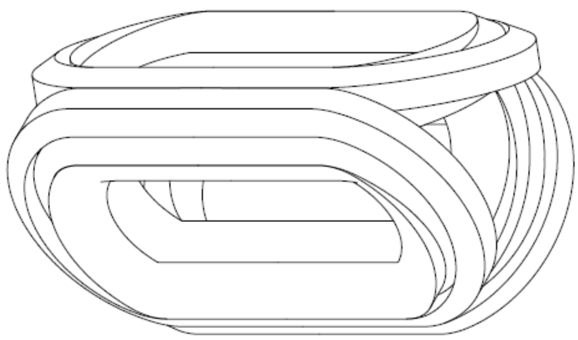


Figure 3: The Hexa-transformer illustrating the nine rolls of steel bands
(with courtesy of Hexaformer AB in Sweden)

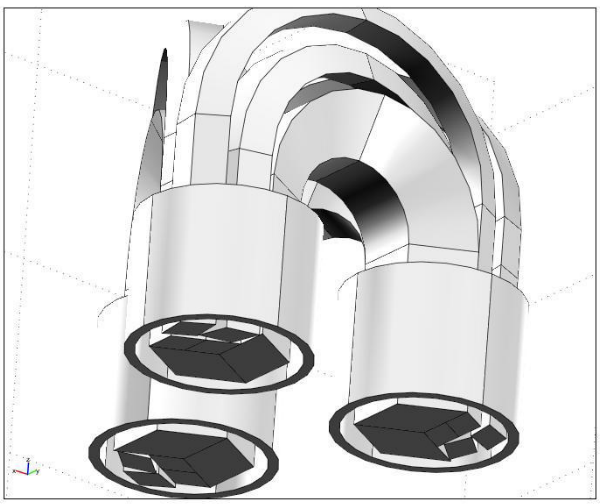


Figure 4: Model of the hexa-transformer illustrating cross section legs
(with courtesy of Hexaformer AB)

3.1.1 Background and specifications

The hexa-transformer is presently only manufactured by a Swedish company called Hexaformer AB. The transformers are covered by a global patent based on an innovation by Lennart Hoglund [50].

The advantages of using the Hexa-transformer as claimed by the manufacturer are as follows [50]:

- Reduction of no-load losses by 50 %
- Operating costs reduced by 50 %
- Smooth start with low inrush currents
- Low audio noise level (due to less vibrations of the core [47])
- Weight reduction by up to 30 %
- Core has weak magnetic stray flux
- Lower third harmonic
- Reduction in reactive current (in each of the legs due to its symmetric design)
- Three coils operate under identical currents, phases are hence symmetrical
- Reduction in losses means that there is a lesser need for cooling
- Lower vibrations

The hexa-transformer is constructed using nine rolls of laminated electrical steel. The core is symmetrical hence the flux is uniformly distributed throughout the core. This would account for the increased efficiency. Refer to Table 5 on page 25 of this report.

3.2 COST ANALYSIS

The hexa-transformer's technical specifications indicate that it is more efficient in terms of losses when compared to an E-core transformer of a similar rating. This would not be feasible to implement from an economic perspective if there is a huge cost difference between the two transformers. The cost of a conventional E-core transformer was compared to that of the hexa-transformer of a similar rating. It is not enough to just compare capital costs; the lifecycle costs of the transformers were also evaluated. Table 3 below indicates the capital costs of the transformers.

Table 3: Transformer capital costs

Unit	Specs	Cost - Euros	**Cost - Rand
100 kVA E-core Transformer [51]	11 kV, Dyn 11	-	37 620.00
100 k VA Hexa-transformer [52]	11 kV, Dyn 11	3240	**36 582.81

** Conversion as at 22 June 2009.

The cost analysis was performed using life cycle costing analysis as it more accurately illustrates the total cost of the transformer. Eskom Distribution uses the following formula for determining their transformer lifecycle costs [53].

Total cost = A + CiPi + CcPc (2)

Where:

A = cost of purchasing in Rands, R;

Pi = no-load losses, kW;

Pc = load losses, kW;

Ci = capitalised cost of no-load loss, R/kW

Cc = capitalised cost of load loss, R/kW

The economic life of a transformer is assumed to be 25 years. The different parameter values are shown in the Table 4 below.

The values for Cc and Ci were obtained from the Eskom distribution buyers guide for a 100 kVA, 11/0.42 kV transformer unit [53].

Table 4: Total transformer cost parameters

	Hexa-transformer	ABB E-core Transformer
A	R36 582.21	R37 620
PI	0.145 kW	0.3 kW
Pc	1.5 kW	1.7 kW
CI	11942	11942
Cc	1418	1418

From formula (2) and Table 4 above, the life cycle costs for the hexa-transformer and the ABB E-core transformer were calculated to be R 40 885.79 and R 43 613.2 respectively. Implementation of the hexa-transformer for use in Eskom distribution would therefore result in a total cost saving of R 2 727.41 per a transformer over the lifespan of the transformer.

It must be noted that the shipping cost of R 28 830.90 was not taken into consideration, if the hexa-transformer is to be used within Eskom, a local manufacturer would most likely be the supplier of choice.

3.3 TRANSFORMER COMPARISON

Table 5 below summarizes the differences between the hexa-transformer and the conventional E-core transformer.

Table 5: Hexa-transformer and E-core transformer characteristics

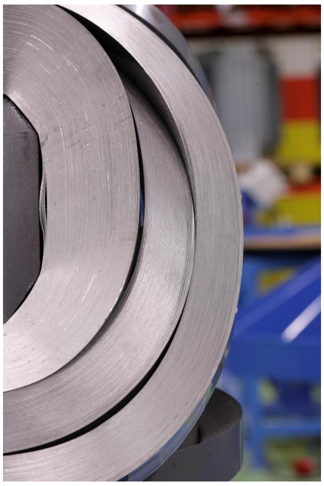
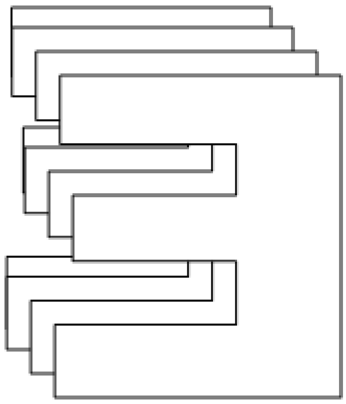
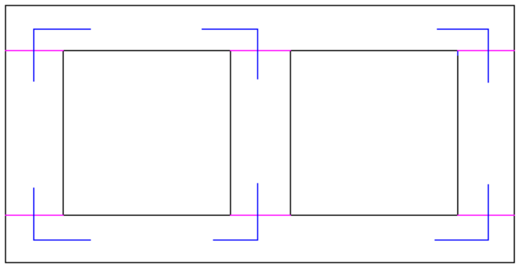
Hexa-transformer	E-Core Transformer
Three phase triangular core	Three phase E-core shape
The core is completely symmetrical. The distance between all the core legs is the same; hence the flux loss is reduced.	The core is asymmetrical. The middle winding has the smallest flux path and the lease flux loss.
Core is wound from nine rolls of electrical steel. Refer to Figure 5 below [54].  **Figure 5: Wound core hexa-transformer, the core is wound continuously** (with courtesy of Hexaformer AB) Wound core: therefore flux paths are closed, the flux has to pass through one layer of insulation. The blue lines in Figure 6 below illustrate the flux path [49].	Core is made up of stacks of lamination sheets with distributed borders to avoid short circuits. Hence the flux needs to pass through at least four borders as illustrated in Figure 7 below.  **Figure 7: E-core transformer consisting of staples laminations of electrical steel** The flux is not a closed path. It must pass at least four borders (corners) as illustrated by the pink; and the flux path is illustrated by the blue as shown Figure 8 below.

 **Figure 6: Continuous magnetic flux path in the hexa-transformer** (with courtesy of Hexaformer AB)	 **Figure 8: E-core with magnetic flux illustration**

3.4 MANUFACTURING PROCESS

The manufacturing process details were obtained from Hexaformer AB in Sweden [54]. Refer to Appendix A for a detailed review of the manufacturing process. A summary of the process is presented below.

The Core: The inner core ring is wound using electrical steel. Two outer rings are added using half width bands of the same electrical steel. See Figure 9 below.

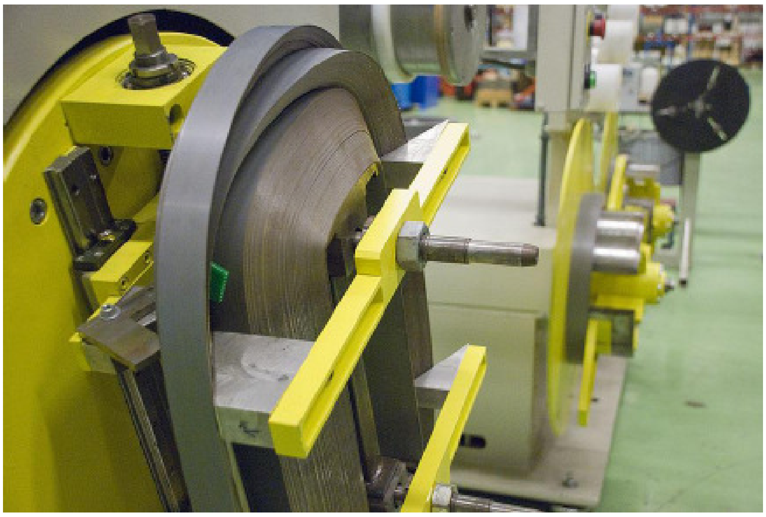


Figure 9: Hexaformer core is wound using continuous electrical steel

The high voltage copper winding is wound using a tube that rotates around the core leg as illustrated in Figure 10 below.

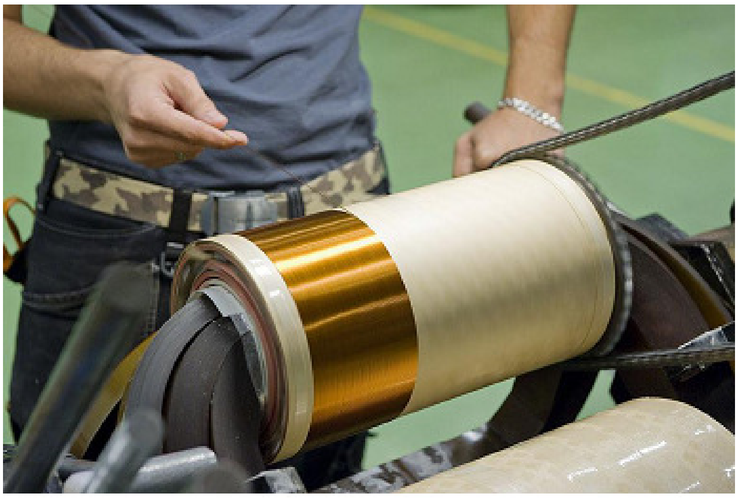


Figure 10: High voltage winding is wound using a tube that rotates

The hexa-transformer tank is filled with oil under a vacuum in the final stage of the manufacturing process, refer to Figure 11 below:

Figure 11: Oil filling; the transformer is filled with oil under a vacuum

3.5 RECOMMENDATIONS

The Recommendations from the literature review are as follows:

The cost of the 50 kVA and the 100 kVA Hexaformer are R33000 and R36000 respectively.

From the technical review the hexa-transformer was found to have a 50% reduction in no-load losses when compared to an e-core transformer of similar rating.

It can be seen from the literature review that the hexa-transformer is an extremely efficient transformer that is available at a competitive price. It was therefore recommended to purchase a 100 kVA unit for testing. The transformer is currently manufactured by a Swedish company called Hexaformer AB. Hexaformer AB is currently the sole manufacturer of the hexa-transformer. The company was contacted in order to purchase a 100 kVA unit for testing purposes. The unit was procured for testing.

The transformer was delivered directly to Cape Town where testing would occur. During the literature survey, various local transformer manufacturing companies were contacted in order to determine if any research has been done pertaining to triangular core transformers. The results indicated that most companies are not yet looking into this type of technology. Powertech transformers were however very keen to get involved, hence it was recommended that the 100 kVA hexa-transformer unit be tested in collaboration with Powertech Distribution Transformers situated in Cape Town.

3.6 SUMMARY

The hexa-transformer is a three phase triangular core transformer that consists of nine rolls of electrical steel. A cross sectional view of each leg would result in a hexagonal shape. The transformer is symmetrical resulting in a reduction in no-load losses.

An economic analysis between the hexa-transformer and an E-core transformer of similar rating indicated that implementation of a 100 kVA 11/0.42 kV hexa-transformer unit would result in a cost saving of R 2 727.41 over the lifetime of the transformer.

It was recommended to purchase a 100 kVA 11/0.42 kV unit for testing in order to verify the transformer performance.

4. CHAPTER 4 – HEXA-TRANSFORMER TESTING

A 100 kAV unit was purchased from Hexaformer AB in Sweden for testing purposes. The main aim was to evaluate the efficiency of the device.

The hexa-transformer was tested in collaboration with Powertech Distribution Transformers situated in Cape Town. Refer to Appendix B for further details. Tests were performed in accordance with the following standards:

- IEC 60076- Power Transformers
- IEC 60567 – Oil-filled electrical equipment
- IEC 60599 – Mineral oil – Guide to interpretation dissolved and free gas analysis
- SANS 780 – Distribution Transformers

The aims of the initial tests were to verify the electrical efficiency and core integrity of the hexa-transformer. The tests also covered the routine tests needed by Eskom Distribution in order to install the transformer in the network for further monitoring. The various tests conducted on the transformer are discussed in this chapter. The test results and analysis of the results are presented and compared to that of Hexaformer AB in Sweden.

4.1 TESTS CONDUCTED

The following tests in Table 6 below were conducted during the initial testing phase.

Table 6: Transformer tests

Routine	No-load test
	Exciting current test
	Applied potential test
	Insulation resistance test

4.2 TEST RESULTS

The hexa-transformer was tested at Powertech Distribution Transformers in Cape Town, South Africa. The testing equipment details are given in Table 7 below.

Table 7: Hexa-transformer test details

Date Used:	Operator Name:	Test Location:	Specifics:	Instrument Details:	Date of Calibration:	Serial No:
17.02.10	W. Brandt	Main test bay	Resistance Test	Tinsley 5896	03.06.09	0075665/6
17.02.10	W. Brandt	Main test bay	Iron and Copper Loss	Norma 04355	12.01.10	A46020306A
17.02.10	W. Brandt	Main test bay	Flash and Vector Test	Fluke 177	14.01.10	86100478

Details of these records can be found in the Appendix B.

The results of the tests performed at Powertech Transformers on the hexa-transformer is summarised in Table 8 below.

Table 8: Hexa-transformer test results

Test		Eskom/Powertech Results
Ratio Test	TAP 1	47.66
	TAP 2	46.52
	TAP 3	45.39
	TAP 4	44.25
	TAP 5	43.11
No-Load Loss (W)		178
Mag Current (%)		0.35% (0.478A)
Resistance Test (Ω)	AB	17.308
	BC	17.31
	CA	17.312
	ab	0.017967
	bc	0.017936
	ca	0.018016
Ambient Temperature (℃)		21
Retention Temperature (℃)		75
Load Loss (W)		1569
Reactance (%)		3.37
Impedance (%)		3.72
Test Amps (A)		5.25
Test Volts (V)		398.4
Test Watts (W)		1330
Applied Voltage test at 75%		Supply 21 kV for 60 sec. to HV with LV earthed. Supply 2.5 kV for 60 sec. to LV with HV earthed.

The induced voltage test on the LV side was performed at 840 V for 15 seconds. The applied voltage test was performed at 75%. The HV side was energised by

21 kV for one minute with a short circuit on the LV. Thereafter the LV was energised by 2.5 kV.

4.3 ANALYSIS

The results from the tests conducted at Powertech transformers were compared to those from Hexaformer AB in Sweden. The Chalmers University of Technology in Sweden conducted independent tests on a 100 kVA, 11/0.42kV Hexa-transformer unit. They compared the Hexa-transformer to a conventional E-type transformer of a similar rating [45]. The tests conducted at Powertech Transformers were also compared to their test results.

The test objective was to verify the hexa-transformer efficiency and manufacturing test results. A summary of both the manufacturing tests and the verification tests conducted at Powertech Transformers are presented in Table 9 below. The results were quite similar to that of the manufacturer. No-load losses of 178 W was measured, this verified the test results by Hexaformer AB in Sweden. The measured magnetising current was 0.478 A, whereas Hexaformer AB measured 0.28 A. Lower load losses were measured compared to that of the manufacturer. Refer to Table 8 on page 31. The results of the tests conducted by the Chalmers University of Technology indicated no-load losses of 156 W for a 100 kVA Hexa-transformer unit. This is lower than both the Powertech and Hexaformer AB results. A magnetising current of 0.27 A was measured, by the Chalmers University of Technology. Refer to Table 9 below [45].

Table 9: Chalmers University Hexa-transformer test results

Type	Voltage	Im (A)	No load Power (W)
E-core	420	0.46	191
Hex core	420	0.27	156
%difference	0	41	18

The no-load losses measured at Powertech and Hexaformer AB was identical. The no-load test result by the Chalmers University of technology is lower. The magnetising current measured by Hexaformer AB and the Chalmers university of technology are similar, the results of the tests conducted at Powertech are much higher than expected. This could be due to a difference in temperature and the use of different equipment.

All the tests results have indicated that the hexa-transformer exhibits lower losses than an E-core transformer as illustrated in Table 10 below.

Table 10: Eskom/Powertech results comparison with Hexaformer AB

Test		Guaranteed Values	Tolerances (SANS 780)	Hexaformer Result	Eskom/Powertech Result
Ratio Test	TAP 1	47.6314	± 0.5%	47.66	47.66
	TAP 2	46.4973	± 0.5%	46.52	46.52
	TAP 3	45.3632	± 0.5%	45.39	45.39
	TAP 4	44.2292	± 0.5%	44.25	44.25
	TAP5	43.0951	± 0.5%	43.11	43.11
No-Load Loss (W)		170	15%	178	178
Mag Current (%)			30%	0.2% (0.28A)	0.35% (0.478A)
Resistance Test (Ω)	AB			17.34	17.308
	BC			17.34	17.31
	CA			17.35	17.312
	ab			0.01793	0.017967
	bc ca			0.01797 0.01791	0.017936 0.018016
Ambient Temperature - ℃				20.2	21
Retention Temperature - ℃				75	75
Load Loss (W)			15%	1645	1569
Reactance (%)				4.03	3.37
Impedance (%)			± 10%	4.35	3.72
Test Amps (A)				5.25	5.25
Test Volts (V)				470	398.4
Test Watts (W)				1416	1330

Table 11 summarises the test results of three 100 kVA 11/0.415 KV E-core transformers tested by Powertech Transformers on the same day as the hexa-transformer. The no-load losses were measured in the range of 325 – 345 W, the average being 337 W. The E-core transformer power losses are almost double that of the no-load losses of 178 W as measured in the hexa-transformer.

Table 11: E-core test results

Test		Guaranteed Values	E-core 10693702/01	E-core 10693702/02	E-core 10693702/03
Ratio Test	TAP 1	48.66	48.66	47.66	47.66
	TAP 2	47.29	47.29	46.52	46.52
	TAP 3	45.91	45.91	45.39	45.39
	TAP 4	44.53	44.53	44.25	44.25
	TAP 5	43.16	43.16	43.11	43.11
No-Load Loss (W)		300	345	325	341
Mag Current (%)			2.9%	2.7%	2.8%
Resistance Test (Ω)	AB		18.94	19.08	19.13
	BC		18.91	19.21	19.01
	CA		18.99	19.15	19.08
	Ab		0.025890	0.025740	0.025750
	Bc		0.026120	0.026050	0.025840
	Ca		0.026010	0.025970	0.025780
Ambient Temperature (℃)			40	40	40
Retention Temperature (℃)			75	75	75
Load Loss (W)		1700	1804	1812	1806
Reactance (%)			4.30	4.26	4.25
Impedance (%)			4.66	4.63	4.62
Test Amps (A)			3.2	3.2	3.2
Test Volts (V)			316.5	310.9	303.6
Test Watts (W)			634	624	609

4.4 SUMMARY

The hexa-transformer and three E-core transformers of the same ratings were routinely tested in collaboration with Powertech Distribution Transformers situated in Cape Town. Tests were performed in accordance with IEC standards. The results were compared to that of Hexaformer AB in Sweden and the Chalmers University of Technology.

The magnetising current measurement of 0.478 A at Powertech was not as expected. Hexaformer AB and the Chalmers University of Technology measured values of 0.28 A and 0.27 A respectively. The difference could be due to the rating of equipment used and a difference in temperature.

The hexa-transformer no-load losses were measured to be 178 W which was verified by the results of Hexaformer AB who measured no-load losses of 178 W. The measured no-load losses of the E-core transformers were measured in the range of

325 W – 345 W, the average being 337 W. All the tests results have indicated that the hexa-transformer exhibits lower losses than an E-core transformer.

5. CHAPTER 5 – TRANSFORMER CORE AND OIL ANALYSIS

The improved efficiency of the hexa-transformer was previously confirmed, the transformer was also routinely tested according to various standards and specifications in Chapter four of this dissertation. It was decided to determine the manufacturing integrity of the hexa-transformer during the next phase of the project.

Tests were conducted on various points on the B-H curve in order to determine the integrity of the hexa-transformer core. This chapter provides the reader with information on the tests performed to determine the core integrity of the transformer. B-H curve tests results are presented and compared to that of Hexaformer AB. Oil tests and results are also present and analysed. Refer to Appendix C for further details.

5.1 B-H CURVE TESTS

The B-H curve tests were conducted at Powertech Distribution Transformers in Cape Town, South Africa. The test results are illustrated on Table 12 below.

Table 12: Hexa-transformer B-H curve test results

AMPS				WATTS								
A PHASE	B PHASE	C PHASE	AVE.	A PHASE	B PHASE	C PHASE	SUM		Amps	Volts	Watts	
0.422	0.311	0.521	0.418	0.756	0.844	0.848	2.44	10%	0.418	42	2.44	10%
0.428	0.32	0.526	0.424	6.41	6.36	6.09	18.8	30%	0.424	126	18.8	30%
0.444	0.331	0.54	0.438	15.46	14.64	14.44	44.5	50%	0.438	210	44.5	50%
0.459	0.351	0.556	0.455	29.92	25.9	26.41	82.2	70%	0.455	294	82.2	70%
0.49	0.371	0.572	0.477	50.7	40.6	43.3	134	90%	0.477	378	134	90%
0.51	0.381	0.576	0.489	64.2	51	55.1	170	100%	0.489	420	170	100%
0.545	0.405	0.612	0.52	88.3	66.9	77.4	232	110%	0.52	462	232	110%
0.584	0.453	0.642	0.559	102.2	78.5	90.8	271	115%	0.559	483	271	115%
0.73	0.666	0.812	0.735	122.9	97.8	115.4	336	120%	0.735	504	336	120%
1.179	1.236	1.373	1.26	142.4	112.2	148.5	403	125%	1.26	525	403	125%

The magnetization curve is illustrated in Figure 12 below.

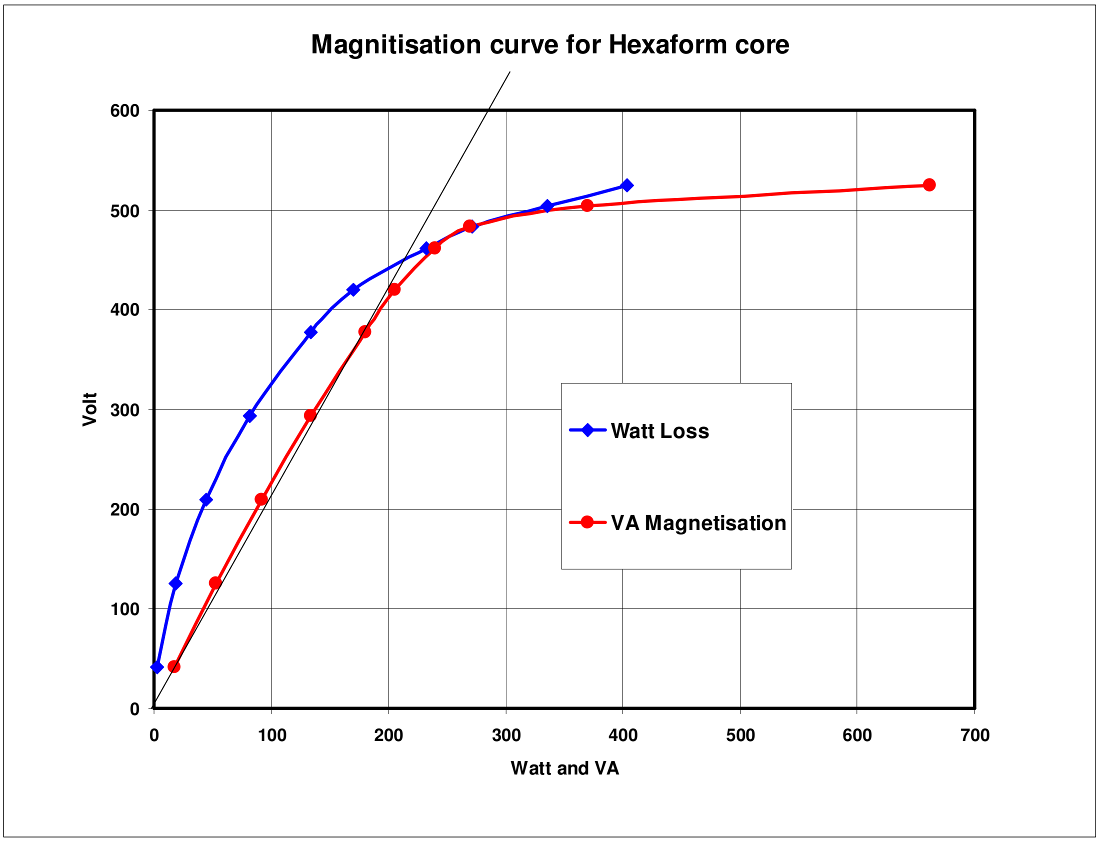


Figure 12: Eskom/Powertech magnetization curve of the hexa-transformer core

5.1.1 Tests conducted by Hexaformer AB

Tests on the B-H curve were also conducted by Hexaformer AB in Sweden. The results are summarized in the Table 13 below [55].

Table 13: B-H Curve test results (Hexaformer AB)

	AMPS				WATTS								
VOLTS	A PHASE	B PHASE	C PHASE	AVE.	A PHASE	B PHASE	C PHASE	SUM		Amps	Volts	Watts	
42	0.039	0.038	0.037	0.038	0.89	0.85	0.85	2.6	10%	0.038	42	2.6	10%
126	0.091	0.087	0.089	0.089	6.42	6.19	6.33	18.9	30%	0.089	126	18.9	30%
210	0.143	0.139	0.142	0.141	16.07	15.52	15.93	47.5	50%	0.141	210	47.5	50%
294	0.199	0.195	0.199	0.198	29.78	28.87	29.70	88.4	70%	0.198	294	88.4	70%
378	0.251	0.248	0.255	0.251	48.34	46.88	48.61	143.8	90%	0.251	378	143.8	90%
420	0.275	0.272	0.280	0.276	60.26	58.61	61.15	180.0	100%	0.276	420	180.0	100%
462	0.307	0.303	0.313	0.308	75.78	74.13	77.78	227.7	110%	0.308	462	227.7	110%
483	0.354	0.351	0.358	0.354	86.84	86.12	89.21	262.2	115%	0.354	483	262.2	115%
504	0.506	0.502	0.497	0.502	103.62	102.09	103.32	309.0	120%	0.502	504	309.0	120%
525	1.064	1.061	0.998	1.041	133.80	118.77	122.27	374.8	125%	1.260	525	374.8	125%

The magnetization curve is illustrated in Figure 13 below.

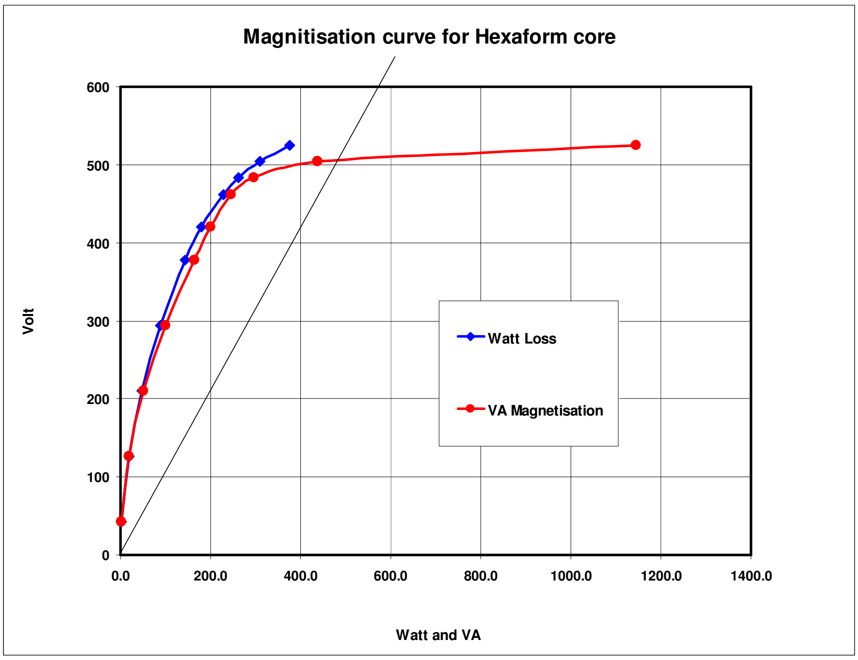


Figure 13: Hexaformer AB magnetization curve of the hexa-transformer core

5.1.2 Analysis

The hexa-transformer is designed to be completely symmetric. Hence it is therefore expected that the current on each phase would be the same. The tests conducted at Powertech Transformers indicated that the current in phase C is larger than that of Phases A and B. Other discrepancies include:

- Powertech measured no-load current at 100% (420 V) is 0,489 A, i.e. 0, 36% whereas Hexaformer AB measured 0,20% no-load current.
- There are considerable differences between no-load (magnetizing) currents in all phases (66% between phase B and C at 420 V). This is not possible since the core is completely symmetrical.
- Magnetizing current at 10% load (42 V) is 0,418 A, i.e. 85% from the measured current at 100%, i.e. 420 V (0,489 A).

As a result of the above mentioned discrepancies, Hexaformer AB in Sweden conducted the same measurements on the B-H curve. The results indicate [55]:

- Measured no-load current at 100% (420 V) is 0,276 A, i.e. 0, 20%.

- Differences between no-load (magnetizing) currents in all phases are very small (3% between phase B and C at 420 V).
- Magnetizing current at 10% load (42 V) is 0,038 A, i.e. 14% from the measured current at 100%, i.e. 420 V (0,276 A).

There is no explanation for the Powertech results, the no-load loss tests previously proved to be 50% more efficient compared to a conventional transformer. The no-load loss was measured to be 150 W which was as expected. The discrepancies on the B-H curve may be attributed to the test equipment and setup used. Unfortunately the tests could not be repeated.

5.2 OIL TESTING

An oil sample was taken in order to determine the transformer oil characteristics of the hexa-transformer. The following tests were performed:

- Dielectric strength
- Water content
- Tan delta
- Polychlorinated Biphenyl (PCB) Content

The results are summarized in Table 14 below:

Table 14: Hexa-transformer oil test results

Test	Results
Electric Strength	79 kV
Moisture reading	2 mg/kg
PCB (ppm)	<1
Tan delta at 90 °C	0.004

The sample conforms to the ESP 32-406 specification with regards to moisture, electric strength and tan delta. It is also classified as PCB free material which is level 0 according to the SANS 290:2007. The PCB concentration is below 1mg/kg.

5.3 SUMMARY

Tests were conducted along various points on the B-H curve to determine the integrity of the hexaformer core. The results indicated that the current on phase C was larger than that of phase A and phase B. This was not expected as all three phases are completely symmetrical. Hexaformer AB in Sweden decided to perform the same tests. They found no discrepancies. There is no explanation for the difference in results. The discrepancies may be attributed to the equipment used and test setup; unfortunately the tests could not be repeated.

An oil sample was taken in order to determine the oil characteristics of the hexa-transformer. The sample was found to conform to the ESP 32-406 specification with regards to moisture, electric strength and tan delta. The PCB concentration was found to be below 1mg/kg, hence it can be classified as PCB fee according to SANS 290:2007.

6. CHAPTER 6 - TRANSFORMER INSPECTION

In order to determine the mechanical integrity of the transformer, the transformer was opened and its construction was carefully examined. Refer to Appendix D. This chapter provides a detailed account of the transformer inspection. The interior and exterior observations are also discussed in this chapter.

6.1 EXTERIOR OBSERVATIONS

The complete tank unit was carefully examined prior to dismantling. The key parameters considered are as follows:

- Bushing sealing materials and technology
- Mounting detail
- Paint and corrosion protection
- Photographic evidence of the complete unit
- Physical attributes

6.1.1 Complete Unit

The mild steel tank is galvanized; Hexaformer AB uses hot-dip galvanizing process. The transformer has lifting lugs on the cover of the tank, and a drain valve at the bottom for oil sampling.

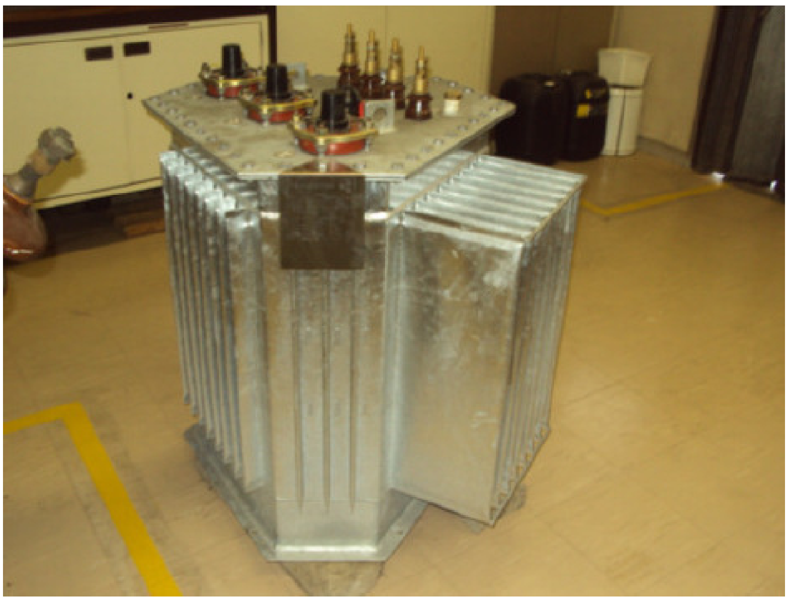


Figure 14: Hexa-transformer complete unit

It can be seen from Figure 14 above that the cooling fins on one side of the tank are larger than the rest. This is to cater for the expansion and contraction of the oil. In hermetically sealed designs the cooling fin design enables a degree of flexibility which is needed to accommodate the expansion and contraction of the oil as it heats and cools, due to load and ambient temperature variations (i.e. the in case of hermetically sealed transformers without conservator the corrugated walls will absorb the changes of oil volume due to thermal expansion).

Hexaformer AB has conducted measurements (temperature rise test) between all phases and confirmed that heat is distributed evenly. Besides, top oil temperature rise and winding temperature rise are a few degrees lower than allowed temperature rise limits according to the standard IEC 60076-2 [55].

6.1.2 Transformer Bushings

Porcelain and elastimold bushings are used. Elastimold is only used for high voltage. Refer to Figure 15 and 16 respectively.

Figure 15: Porcelain bushings are attached to lid of the hexa-transformer unit

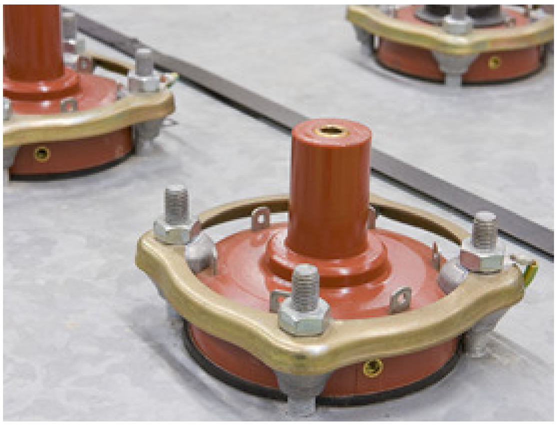


Figure 16: Elastimold bushings as found on the hexa-transformer lid

Creepage distance for bushings [55]:

- 1 kV, 250 A – 50 mm
- 10 kV, 250 A – 295 mm

These values are for porcelain bushings. The creepage distance for Elastimold (plug-in type) is not applicable.

6.1.3 Tank Sealing Material

Sealing material on the lid is a form of Silicon structure. It is a soft seal gasket tape. Refer to Figure 17 below:

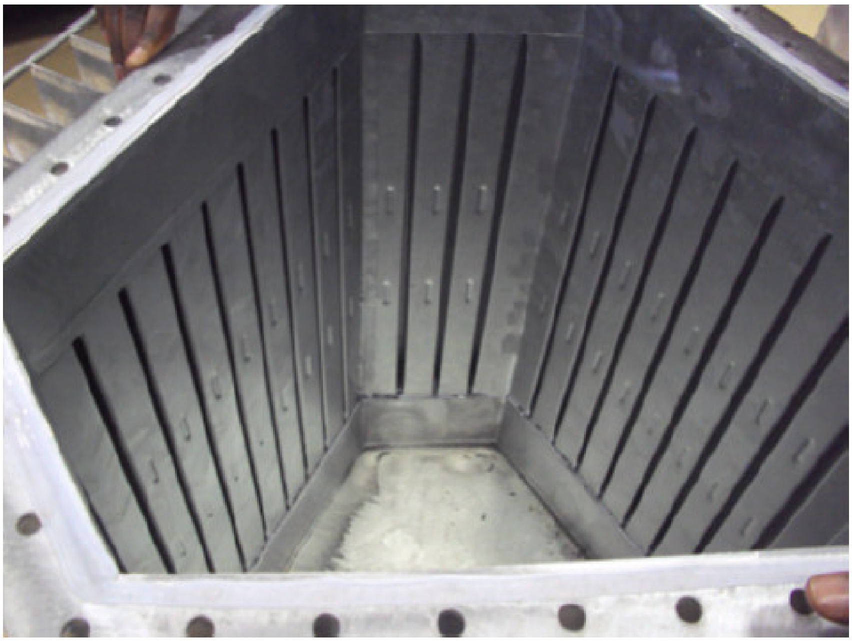


Figure 17: Tank Sealing Material of the hexa-transformer unit

Description of material:

SOFTSEAL^{TM} is a joint sealant consisting of 100% virgin PTFE which has been fully mono-axially expanded by a unique process. The product is soft, easily pliable and highly compressible. The seal is supplied in tape form with an adhesive backing strip for easy installation [56].

Characteristics: SOFTSEAL^{TM} has a very good adaptability to uneven or warped flanges and does not require a high seating stress to seal effectively. It is ideal for weak flanges or flanges of plastic, glass or enamel etc. SOFTSEAL^{TM} has very good chemical resistance and very little cold flow. It does not get hard and is easy to install and remove [56].

6.1.4 Name plate

The rating plate on the hexa-transformer has the following information:

- Year of manufacture
- Transformer rating and weight
- Transformer rating
- Type
- Serial number

Refer to Figure 18 below for the name plate illustration.

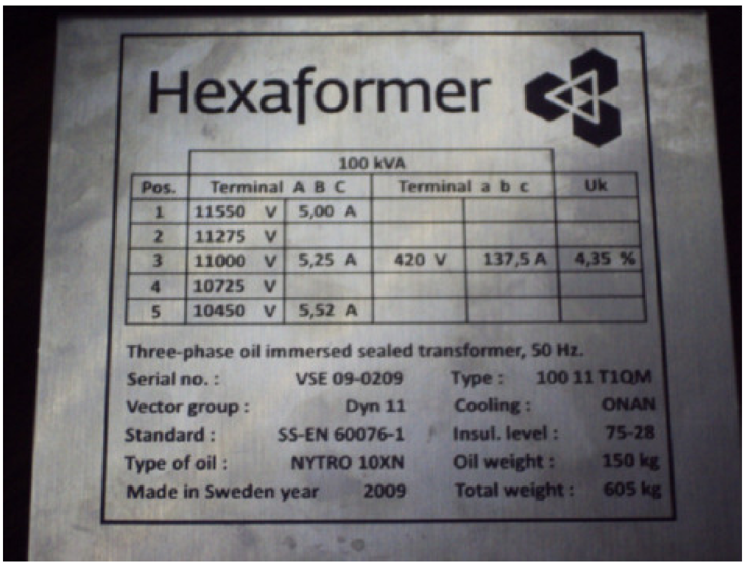


Figure 18: Hexa-transformer nameplate details

6.2 INTERIOR OBSERVATIONS

The transformer was slowly opened to examine the core and core windings. The oil was drained prior to opening the unit. Refer to Appendix D for a detailed procedure and all observations. Key observations are highlighted.

6.2.1 Complete Unit

The unit was completely removed from the tank. Figure 19 below illustrates the complete unit.

Figure 19: Hexa-transformer unit removed from tank

6.2.2 Windings

The core windings are made from copper material. These are connected to the tap changer.

6.2.3 Cross sectional view

The core was cut to obtain a set of windings for further inspection. A cross sectional view of the core is illustrated in Figure 20 below. The hexagonal shape of the core can be seen.

Figure 20: Cross sectional view of the Hexa-transformer core

6.2.4 Paper Insulation

Diamond duct epoxy coated insulation has been used. The paper adhered very well to the windings.

The advantages of using diamond dotted paper are [57]:

- Safe tolerance of axial and mechanical forces
- Helps in faster drying & filling as the liquid insulating agent penetrates the pressboard insulation completely in a short period
- Minimised danger of partial discharges

6.3 SUMMARY

The hexa-transformer has been examined both externally and internally. The tank was designed to have cooling fins on the one side. This is to cater for expansion and contraction of the oil. In hermetically sealed transformers without a conservator, the corrugated walls will absorb the changes of oil volume due to thermal expansion. The interior examination of a core leg revealed a cross sectional view of a hexagon. Diamond duct epoxy dotted insulation has been used between each copper winding.

7. CHAPTER 7 - CONCLUSION AND RECOMMENDATIONS

The hexa-transformer is a three-phase transformer with a symmetrical core. The transformer core consists of nine rolls of laminated steel bands, with the core legs having a cross sectional shape of a hexagon.

The aim of this task was to evaluate the hexa-transformer for use in Eskom's Distribution network. The literature review indicated that the hexa-transformer no-load loss is approximately half of the no-load loss associated with an E-core transformer of the same rating. The transformer is currently only manufactured by Hexaformer AB, a Swedish based company.

The objective was to verify the very low no-load loss claim. A 100 kVA 11/0.420 kV unit was therefore purchased for testing. Tests were conducted by Powertech Distribution transformers in Cape Town. A 178 W no-load loss was measured; this confirmed the manufacturer test value. Three conventional E-core transformers of the same rating were also tested. The no-load loss was measured to be in the range of 337 W.

Savings = E-core losses – Hexa-transformer losses

= 337 – 178

= 159 W

The saving scale for a 1000 units is thus 159 kW

To put 159 kW into context:

159 kW is equivalent to 2650 units of 60 W incandescent light bulbs or 10 600, 15 W fluorescent light bulbs enough for 1766 small houses (with 6 bulbs per house). Note this is the saving associated with replacing 1000, 100 kVA hexa-transformer units. If these hexa-transformer units are to be implemented on a larger scale across the electrical distribution network; the magnitude of savings would be enormous.

The aim of this task was to evaluate the design of the hexa-transformer. Tests were performed on the B-H curve at Powertech transformers to determine the core integrity. The no-load tests results proved the transformer indicated an efficiency improvement of more than 50% when compared to a conventional E-core transformer. The results showed that the current on all three phases were not the same. This was not as expected, due to the core being completely symmetrical.

The manufacturer, Hexaformer AB performed the same tests on a similar unit; the results showed that the current on each phase was the same. The specific tests done by Powertech are suspected of being inaccurate due to the instrumentation setup.

Oil samples were taken and analysed to determine the transformer oil properties. The oil conforms to the ESP 32-406 specification with regards to moisture, electric strength and tan delta. It is also classified as PCB free material which is level 0 according to the SANS 290:2007. The PCB concentration is below 1mg/kg.

The oil was drained from the tank and the transformer was opened. A set of windings were removed for analysis. Enamel copper windings were used with diamond dotted paper insulation. Overall the unit was found to be constructed extremely robust.

It is recommended that a few of these units be purchased and installed in various Eskom Distribution substations. The aim would be to monitor the performance of these transformers. It is also further recommended that Eskom join or encourage local transformer manufacturers to consider producing these units in South Africa. This would eliminate the shipment costs.

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