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Design Considerations for a High Power Medium Frequency Transformer for a DC-DC Converter Stage of a Solid State Transformer

By: Mr. Roland Nshieteh Mumuluh

A thesis submitted to
University College Dublin
in fulfilment of the degree of

Master of Engineering Science

in the
School of Electrical and Electronic Engineering

Research Supervisor: Dr. Terence O’Donnell
Head of School: Dr. Andrew Keane

May 2016

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i. DECLARATION

I certify that this thesis entitled “design considerations for a high power medium frequency transformer for a dc-dc converter stage of a solid state transformer” is entirely my own work and was completed during the period when I was registered for the Master of Engineering Science by research in the School of Electrical, Electronics and Communications Engineering at University College Dublin. This thesis has never been submitted for the award of a degree in any university, and where ideas have been taken from other publishers, the sources have been properly referenced.
ii. **ABSTRACT**

In recent years, the solid state transformer concept has challenged the conventional low frequency transformer. The conventional transformer cannot store energy and its output is easily distorted as a result of perturbations at its input. In same manner, disturbances from the output unit such as harmonics along with reactive power, as well as load transients are reflected back to the input of the conventional transformer. The size of the low frequency transformer is significantly larger. The Solid state transformer challenges the traditional low frequency transformer in that it eradicates the aforementioned drawbacks and provides multifunctional features.

In this thesis a reliable model to design and optimize a high power medium frequency transformer for a dc-dc converter that forms part of a solid state transformer is researched and established. The aim is to use this model to investigate how high can be the operating frequency for a medium frequency transformer to achieve maximum efficiency and minimum volume. The dc-dc converter consists of a transformer that provides isolation between a medium-voltage circuit and a low-voltage circuit in a distribution system, and power semiconductor devices. Transformer operation at medium frequency reduces size and volume due to the inverse relationship of transformer area product and frequency. However, at medium frequency, the transformer is less efficient as a result of increased losses due to skin and proximity effects and the temperature rise constraint. Unlike low power magnetic cores where there are standard sizes and dimensions, high power magnetic cores for medium frequency maybe designed depending on demand or in certain cases, using limited dimensional references. Thus, an optimised transformer design for high power medium frequency relies on how its dimensions are defined. The characteristics expected of a core material for high power medium frequency are that it should have a high saturation flux density; low core loss and the material should continuously operate at high temperatures. The findings revealed that the frequency can be as high as 10 kHz to achieve maximum efficiency and minimum volume. An optimum design depends upon the flux density, the winding current density, the numbers of primary turns, the operating frequency and the power level of the transformer. There is no point operating above 20 kHz as there is very little reduction in volume and the winding loss results to increased temperature and reduces the efficiency of the transformer.
iii. ACKNOWLEDGEMENT

It is my sincere wish to express my gratitude to my Supervisor Dr. Terence O’Donnell for giving me the opportunity to do the Master of Engineering Science Degree at the Electricity Research Centre of University College Dublin. The time he devoted in supervising my work enabled me learn a lot within the field of Power Electronics.

I do appreciate the financial contributions provided by SUSI and the ERC towards the cost of tuition fees. Without these financial supports, this work would not have been achieved.

Finally, I would dedicate this work most especially to my parents Mr. Tsiambuh Michael and Mrs Keng Helen, as well as my two sons Jnr. Roland and Bradley, and the rest of my family in Ireland and Cameroon for the support and encouragements provided during this period.
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<th>Description</th>
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<tr>
<td>AC</td>
<td>Alternating current</td>
</tr>
<tr>
<td>Ac</td>
<td>Area of core</td>
</tr>
<tr>
<td>Aw</td>
<td>Winding window area</td>
</tr>
<tr>
<td>Ap</td>
<td>Area product</td>
</tr>
<tr>
<td>Alw</td>
<td>Area of litz wire</td>
</tr>
<tr>
<td>Bm</td>
<td>Maximum flux density</td>
</tr>
<tr>
<td>C</td>
<td>Capacitor</td>
</tr>
<tr>
<td>CWT</td>
<td>Coaxial winding transformer</td>
</tr>
<tr>
<td>DER</td>
<td>Distributed energy resource</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>da</td>
<td>Diameter of bundle</td>
</tr>
<tr>
<td>ds</td>
<td>Diameter of strand in a bundle</td>
</tr>
<tr>
<td>dintra</td>
<td>Isolation between layers</td>
</tr>
<tr>
<td>diso</td>
<td>Minimum isolation distance</td>
</tr>
<tr>
<td>dw</td>
<td>Width of conductor</td>
</tr>
<tr>
<td>df</td>
<td>Isolation between interior part of winding and core</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromotive force</td>
</tr>
<tr>
<td>ERC</td>
<td>Electricity research centre</td>
</tr>
<tr>
<td>Es</td>
<td>Secondary emf</td>
</tr>
<tr>
<td>Ep</td>
<td>Primary emf</td>
</tr>
<tr>
<td>FB</td>
<td>Full bridge</td>
</tr>
<tr>
<td>Symbol</td>
<td>Term</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>F</td>
<td>Frequency</td>
</tr>
<tr>
<td>fw</td>
<td>Winding fill factor</td>
</tr>
<tr>
<td>GHG</td>
<td>Green house gas</td>
</tr>
<tr>
<td>HVDC</td>
<td>High voltage direct current</td>
</tr>
<tr>
<td>HV</td>
<td>High voltage</td>
</tr>
<tr>
<td>hw</td>
<td>Height of winding</td>
</tr>
<tr>
<td>h</td>
<td>Convection heat transfer coeff</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institution of electrical and electronics engineers</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and communications technology</td>
</tr>
<tr>
<td>In</td>
<td>Nominal rms current</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated gate bipolar transistor</td>
</tr>
<tr>
<td>Ip(t)</td>
<td>Primary current waveform</td>
</tr>
<tr>
<td>IBDC</td>
<td>Isolated bidirectional dc converter</td>
</tr>
<tr>
<td>Jo</td>
<td>Maximum current density</td>
</tr>
<tr>
<td>Kf</td>
<td>Rectangular waveform factor</td>
</tr>
<tr>
<td>Ku</td>
<td>Winding utilization factor</td>
</tr>
<tr>
<td>kHz</td>
<td>Kilo Hertz</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage</td>
</tr>
<tr>
<td>LFT</td>
<td>Line frequency transformer</td>
</tr>
<tr>
<td>Ls</td>
<td>Expected leakage inductance</td>
</tr>
<tr>
<td>MV</td>
<td>Medium voltage</td>
</tr>
<tr>
<td>MF</td>
<td>Medium frequency</td>
</tr>
<tr>
<td>MFT</td>
<td>Medium frequency transformer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal oxide field effect transistor</td>
</tr>
<tr>
<td>MFHP</td>
<td>Medium frequency high power</td>
</tr>
<tr>
<td>m</td>
<td>Number of layers</td>
</tr>
<tr>
<td>NBDC</td>
<td>Non bidirectional dc converter</td>
</tr>
<tr>
<td>Np</td>
<td>Number of primary turns</td>
</tr>
<tr>
<td>Ns</td>
<td>Number of secondary turns</td>
</tr>
<tr>
<td>n</td>
<td>Ratio of turns</td>
</tr>
<tr>
<td>Nh</td>
<td>Height of conductor</td>
</tr>
<tr>
<td>Nw</td>
<td>Width of conductor</td>
</tr>
<tr>
<td>Nspt</td>
<td>Number of strands per turn</td>
</tr>
<tr>
<td>Nc</td>
<td>Number of cores</td>
</tr>
<tr>
<td>PE</td>
<td>Power electronics</td>
</tr>
<tr>
<td>PSD</td>
<td>Power semiconductor devices</td>
</tr>
<tr>
<td>PD</td>
<td>Power devices</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
</tr>
<tr>
<td>Pf</td>
<td>Packing factor</td>
</tr>
<tr>
<td>PCu</td>
<td>Nominal dc power density</td>
</tr>
<tr>
<td>P_L</td>
<td>Total power losses (core and winding)</td>
</tr>
<tr>
<td>R</td>
<td>Resistor</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>SMPS</td>
<td>Switch mode power supply</td>
</tr>
<tr>
<td>Sn</td>
<td>Nominal apparent power</td>
</tr>
<tr>
<td>SST</td>
<td>Solid state transformer</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>SUSI</td>
<td>Student universal support Ireland</td>
</tr>
<tr>
<td>Rth</td>
<td>Thermal resistance</td>
</tr>
<tr>
<td>UNi</td>
<td>Minimum isolation voltage</td>
</tr>
<tr>
<td>Vp(t)</td>
<td>Primary voltage waveform</td>
</tr>
<tr>
<td>Vw</td>
<td>Winding volume</td>
</tr>
<tr>
<td>Vo</td>
<td>Output voltage</td>
</tr>
<tr>
<td>Vi</td>
<td>Input voltage</td>
</tr>
<tr>
<td>ZVS</td>
<td>Zero voltage switching</td>
</tr>
<tr>
<td>ZCS</td>
<td>Zero current switching</td>
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Chapter 1: Introduction

1.1 Background

The prospect of economies across the world firmly relies on the existence of energy and its transportation. It is certain that energy consumption will increase in the near future. Now with such demand for energy, the security, reliability and efficiency of the electricity production and distribution systems have become areas of utmost concern to researchers, energy utilities as well as customers, as the current state of the power network cannot cope with the challenges imposed by reduced oil resources, environmental pollution and global warming. The demand in energy along with environmental issues surrounding some electricity production technologies has widened the interest in other forms of renewable and sustainable electricity production technologies. So then, to resolve the aforementioned challenges, the utilization of ‘distributed energy resources’ (DER) which can be integrated into the distribution network has gained more attention. DER can be described as a small unit ‘renewable energy source’ located close to the load of which the renewable source can be supplied to the load through a grid. Photovoltaic plants, fuel cells, wind turbines and micro turbines can be considered as distributed generation and due to the intermittent state of DER, a storage unit maybe desirable during periods of unavailability.

It is also the case that, given the nature and location of some renewable sources, for example, in a wind farm located in the ocean having some distance from shore, dc distribution can be highly desirable as it may be more suitable than ac with regard to efficiency, as transmission cables do not generate nor consume reactive power at dc.

The wind turbine is still considered the most suitable technology as the power level of these turbines have increased. In recent years, several wind turbines of the multi-MW range were installed in many parts across the world. The offshore wind farms in recent years have gained particular attention as a result of space limitation and environmental issues surrounding onshore turbine installations. In existing installations, the offshore wind turbine connects to an onshore grid through the use of high Voltage ac cables and these offshore turbines are not situated far from the shore. Currently, the process of converting wind energy into electrical power requires an electrical induction machine.
along with ac-ac converters combined with a 50/60 Hz low frequency transformer and rectifiers. These combinations usually result to a heavy and very large unit which are extremely challenging in an offshore generator structure especially with the move towards larger size turbines. Therefore, a medium frequency design which would replace the 50/60 Hz transformer may be beneficial as the volume of the magnetic unit is inversely proportional to operating frequency.

Nowadays, there is an interest to expand the size of wind farms and extend the wind farm into much deeper waters. As previously mentioned, offshore wind farms located further into the ocean requires a high voltage direct current link so as to produce power economically. Thus, in the future, several offshore wind farms maybe connected through a high voltage direct current multi-terminal station. The lengthy distance from the offshore wind farm to the access point of the onshore grid is the main reason for employing direct current. The distance which the cables may need to run from offshore farms to onshore grid, along with the increasing need for reactive power compensation, makes the use of ac less efficient. The large numbers of wind turbines in a farm are usually fed onto an ac 50 Hz collector grid of which the voltage is raised to a higher value at a central station. However, with classical designs, the ac 50 Hz voltage is produced from dc. Since the wind turbine produces variable frequency ac voltage, dc conversion within the turbine is important. A potentially more reliable as well as efficient approach with these farms maybe to completely eliminate the ac converter and change the ‘low voltage direct current’ to a ‘high voltage direct current’ through the use of a dc-dc converter. Such a dc-dc converter may require the use of a medium frequency transformer for isolation and voltage step up.

Although efficiency and reliability are important for a wind farm, the volume and size of the unit are of vital importance in offshore installations. In the overall structure of the conversion system, the transformer volume is dominant and this has an impact on the foundation of the platform along with turbine body and cost. In order to overcome this challenge, medium frequency design is a suitable solution. Bearing in mind that the power of the wind usually fluctuates, it may also be desirable that the wind turbine be backed-up with a storage unit so as to supply energy in the event of insufficient wind energy. A solid state transformer can provide a means for interfacing such a dc based storage system.
Given all of the above, it can be seen that as a result of increased penetration of energy generated from photovoltaic plants and wind turbines which are fluctuating, back-up storage systems have become an essential part in a distribution system. The storage systems can compensate for power shortages during periods of unavailability. Some commonly available storage systems are batteries and capacitors.

So then, how do we connect the wind turbine, or the photovoltaic plant with the storage systems as well as the grid? This now introduces us to the concept of the solid state transformer (SST). A block diagram of an SST is shown in figure 1.

![Figure 1: A Block Diagram of a Solid State Transformer](image)

An SST consists of a rectifier (ac-dc), a converter (dc-dc) which incorporates an MFT, along with an inverter (dc-ac). As shown in figure 1, the primary of the MFT consists of an ac-dc rectifier that receives a sinusoidal voltage from the ac grid and rectifies the sinusoidal voltage into a dc voltage. Within the dc-dc converter, the dc voltage is fed into a dc-ac stage that converts this voltage into a rectangular medium frequency waveform for the transformer. On the secondary side of the MFT, an ac-dc stage changes the medium frequency rectangular waveform into a dc after which a dc-ac inverter can be employed to invert the dc voltage into the power system ac voltage at 50/60 Hz.

Now with regard to the DER and the back-up storage system, a bidirectional type of dc-dc converter is desirable for energy transfer. There are different models of dc-dc converters which can be employed for different types of applications. Some converters can be employed just for stepping down the voltage while others for stepping up purposes. Some are non-isolating while others are bidirectional.
As stated above regarding the overall structure of the conversion system of an offshore wind turbine, the transformer volume is dominant and this has an impact on the foundation of the platform along with turbine body and cost. So then to overcome this challenge, a medium frequency design is a potentially suitable solution. In these circumstances, a high power dc-dc converter employing a medium frequency transformer is highly contemplated as a suitable solution to resolve issues surrounding the increasing penetration of energy generated from DER.

Now to interconnect the back-up storage unit along with the DER requires some means to interface dc to ac, and as it would appear, solid state transformers (SST) are highly contemplated for such interconnection as it is a suitable alternative to substitute the traditional transformer and provide a means for dc connection. In addition, the advantages of the SST overcome the traditional transformer in areas such as: voltage regulation; harmonics; control of real and reactive power; input and output decoupling. The SST can be described as a complex bidirectional power electronics device for the exchange of energy.

This thesis focuses on the design and optimization of a high power medium frequency transformer in a dc-dc converter stage of a solid state transformer. This research also investigates how high can be the frequency to achieve minimum volume and maximum efficiency. It is evident that the size of a transformer is generally inversely proportional to its frequency of operation. This therefore implies that operating at medium frequencies would reduce the size of the transformer, thereby reducing the cost of installation as well as maintenance. With this concept, it is highly anticipated that dc-dc converters can be employed to interface different voltages. In this role it can be seen that the future of electricity generation and distribution largely rely on high power medium frequency dc-dc converters as an enabling technology. A block diagram of a typical high power medium frequency dc-dc converter incorporating an MFT is depicted in figure 2, where a LV dc bus and a MV dc bus are interfaced using a bidirectional dc-dc converter.
The medium frequency transformer in figure 2 functions same as the 50/60 Hz traditional transformer in that it steps up and steps down the voltage as well as provides isolation of LV and MV circuits. As the bulkiest unit within a power electronics converter can be reduced by increasing the frequency, it is important to note that high power as well as high frequency introduces high frequency effects which make the medium frequency transformer design different from the 50/60 Hz transformer. In particular, there are some extra challenges which need to be addressed with the design of a Medium frequency transformer. The challenges encountered are in the form of excessive winding loss due to skin and proximity effects, which result to increased temperature and reduces the efficiency of the medium frequency transformer. The research found that the flux density, numbers of primary turns, the winding current density, the frequency and the power level of the transformer determines the structure and performance of a transformer. With the medium frequency transformer, the core loss is the product of the volumetric power loss, the core volume and the core fill factor, which means an increase in the flux density increases the core loss. The size of the transformer increases at low current densities and reduces at high current densities, but the reduction of the transformer volume at high current densities are limited due to the temperature rise constraint. It was found that larger power levels imply larger volumes and also increases the current if the voltage remained constant. With increased current, the winding loss increases, while at larger volumes the core loss increases. So then in terms of frequency and volume reduction, a transformer with a lower power level should operate at higher frequencies, whereas high power level transformers should operate efficiently at frequencies below 5 kHz. The following section looks at the research questions.
1.2 Research Questions

Although several papers have been published regarding design and optimisation of an MFT [1], [2], [3], [4], to the best of the authors knowledge, none have investigated how high can be the value of the operating frequency to achieve maximum efficiency and minimum volume for a medium frequency transformer. Petkov in [5] highlights optimum current density and optimum flux density in achieving maximum efficiency, but the paper does not take into consideration how high can be the value of the frequency to achieve maximum efficiency and minimum volume. Sullivan in [6] proposed an optimized procedure to achieve optimal number of strands along with diameter of litz wires, while in [7] a formula for optimum layer or foil thickness is suggested. As aforementioned, none of these publications addressed the issue of optimum frequency to achieve maximum efficiency and minimum volume.

With these in mind, it is essential to investigate how high can be the value of the frequency of a medium frequency transformer to achieve minimum volume and maximum efficiency. In this regard, the aim of this research would be achieved when solutions are provided to the underneath question:

1. How can we design the medium frequency transformer in a MV-LV distribution system so as to determine how high can be the value of the frequency to achieve maximum efficiency and minimum volume?

Now in answering the above question, the following procedures were applied:

a) Develop a model of the medium frequency transformer.

b) Incorporate this model into an optimisation procedure so as to achieve maximum efficiency and minimum volume.

c) Use this optimisation procedure to investigate how high can be the operating frequency at different power levels.

Using the model of the medium frequency transformer developed above and the optimization procedure, this thesis also compares Metglas and Vitroperm500F at a power level of 150 kVA, to see at what frequency would each core material be useful than the other.

6
1.3 Outline of Thesis

There are five chapters in this thesis of which chapter one generally introduces the thesis as it provides a background and motivation for this research as well as research questions and outline of thesis.

In chapter two a review of existing papers are covered. In particular, it looks at the following: applications of solid state transformers; the need of solid state transformers in society; it compares the line frequency transformer with an SST, and the function of ICT in the smart grid. The application of dc-dc converters are covered and includes: electric cars, energy storage systems, helicopter and integrated starter and generator, telecommunication satellite applications, offshore wind farm dc collector grid, photovoltaic applications, and subsea energy production. The review continues with the state of art in medium frequency transformer design, high frequency effects, and looks at some DC-DC converter structures. It begins with the isolated bidirectional dc-dc converter and covers the following: single phase dual active bridge; three phase dual active bridge; bidirectional isolated full bridge converter; bidirectional isolated current doubler; and the bidirectional LCC converter. Also, the following non bidirectional dc-dc converters are reviewed: Phase-shift full bridge converter; series load resonant converter and the parallel load resonant converter. Finally, the literature review looks at modulation techniques for dual-active-bridge dc-dc converter incorporating an MFT. Three techniques are covered, namely: rectangular, trapezoidal and triangular modulation techniques.

Chapter three is concerned with the design methodology and optimization of a medium frequency transformer to be employed in a dual active bridge converter with rectangular modulation. In chapter three, a 120 kVA transformer operating at 20 kHz, with primary voltage of 10 kV and secondary voltage of 400 V is designed and optimized. Chapter four covers validation and it investigates how high can be the frequency to achieve maximum efficiency and minimum volume at different power levels (50 kVA, 100 kVA and 500 kVA). Also, in chapter four, Vitroperm500F is compared with Metglas (2605SA1) to see at what frequency would each core material be useful than the other. Discussions of results are also presented in chapter four. Finally, chapter five summarizes and concludes this thesis and highlights work to be done in the future. The sources quoted in this thesis are shown in the bibliography.
Chapter 2: Literature Review

2.1 Introduction
In this chapter, previous work conducted on the solid state transformer (SST) concept along with some dc-dc converters is reviewed. In this wise, the literature review covers the following: application of solid state transformers; the need for solid state transformers in society; comparison of line frequency transformer and the solid state transformer; the role of information technology in the smart grid; the application of dc-dc converters; some dc-dc converter structures; a review of the state of art in medium frequency transformer design and high frequency effects of skin and proximity.

2.2 Applications of SST
In an electrical network nowadays, the SST (solid state transformer) can be employed to substitute the conventional LFT. Due to the advantages and functions possessed by the SST over the conventional LFT, the SST maybe of vast benefit in many applications. The following applications are considered in this thesis: offshore energy production; traction system; SST based microgrid; DC fast charger based on an SST concept; harmonic filtering and compensation.

2.2.1 Offshore Energy Production
Reduction of transformer size can benefit energy production from tidal, wind and other sources of offshore generation. In recent years, the power levels of the wind turbines have increased and several wind turbines of the MW range were installed across the world. In existing wind farm conversion systems, an induction machine, ac-ac converter, a low frequency transformer (50/60 Hz) and rectifiers are employed. In this conversion system, the transformer volume is dominant and this can be challenging in offshore energy production especially with the move towards larger size turbines. Hence, reduction of size results to less expensive and smaller offshore platforms. As suggested in [8], [9], [10], unity power factor could be achieved using an SST, thus improving the efficiency of transmission. Illustration of offshore power generation is shown in figure 3.
2.2.2 Traction System
The conventional traction network shown in figure 4 consists of a conventional low frequency transformer with a back to back (BTB) converter that has an efficiency of approximately 88-92%. As suggested in figure 5, if the traditional traction system is replaced with an SST the efficiency will be > 95% [12].
Furthermore, with the SST traction system, power density ranges from about 0.5–0.75 kVA/kg. When compared with the conventional transformer and rectifier structure with power density of 0.2-0.35 kVA/kg, it can be seen that the power density of the SST based traction system is significantly improved. According to [14] the transformer used in locomotives employs 16.7 Hz and this frequency increases the weight of the locomotive, whereas the use of an SST would significantly reduce the weight and also increase efficiency as well as minimization of harmonic. As such, more passenger space will be available with reduced transformer size.

2.2.3 SST Based Micro Grid
The ac grid supplies ac loads. But now in the event that the sources of energy are batteries, or PVs, an inverter is required to produce a.c from the d.c supplies so as to power the ac grid as well as the ac loads as shown in figure 6. On the other hand, if dc loads are available when the main source of power is the ac mains, then a rectifier is required to rectify ac to dc [15]. As shown in figure 7, the dc micro grid needs an ac-dc converter so as to generate a dc voltage from the step-down transformer.
Note that batteries and PVs may be connected to the dc mains through a dc-dc converter. The advantage of dc here is that, loads requiring dc can be fed directly from a dc source, but an inverter will be required for ac loads. As the dc micro grid has fewer conversion stages, it implies that high efficiencies can be achieved. The LFT used in this system suggest that the volume and weight are higher, and possibilities of power quality problems are higher.

Now in figure 8, an SST based micro grid can be seen to contain both ac and dc micro grids. So then the SST could facilitate the integration of both the ac and dc micro grid to the distribution network. In comparison with the conventional ac and dc micro grid, the SST based micro grid eliminates the low frequency transformer and power quality issues, and it has reduced weight and volume [17]. Energy generation from renewable sources is expected to rise and the future power networks will need to employ energy management
techniques that are different from existing grid management techniques. In this regard the SST is much similar to a router. Although routers are used for data management, the SST is employed for energy management and sometimes called an energy router [18].

Figure 8: SST for Smart Grid Integration
2.2.4 DC Fast Charger Based on SST Concept
As presented in [12] the SST is useful for charging electric vehicles. In figure 9 below, a traditional dc fast charger and SST based dc fast charger are shown. With the traditional layout of a charging system, a transformer, an ac-dc rectifier and a dc-dc converter are employed for charging electric vehicles and the efficiency is approximately 90 %. Now with an SST based dc fast charger, the efficiency will be > 96 %. So then with the SST technology cost is minimised to half the cost of the conventional charging technology. Reduced weight is achieved with the SST based system.

![Diagram of traditional and SST based DC fast chargers](image)

Figure 9: (a) Traditional DC Fast Charger, (b) SST Based Fast DC Charger [19]
2.2.5 Harmonic Filtering and Compensation of Reactive Power

Depending upon the selected topology, the SST can provide active filtering of harmonic along with reactive power compensation [20]. For instance, an SST with a voltage source converter positioned towards the HV side can enhance support by compensating both reactive power and harmonics as depicted in figure 10.

![Diagram of Reactive Power Compensation and Active Harmonic Filtering by SST](image)

**Figure 10**: Reactive Power Compensation and Active Harmonic Filtering by SST [16]

According to [16], with the combination of these two aforementioned functions, the SST may be employed as a “unified power flow controller (UPQC)”. The SST based UPQC uses multilevel cascaded type converter for the shunt compensator along with a multilevel inverter for series compensation. A dc-dc converter incorporating an isolating MFT is employed to link these two units as shown in figure 11. So then with such conversion of voltage as well as isolation, the UPQC can be classified as an SST. Note that reduced volume and weight is achieved by these systems as a result of medium frequency operation.
2.3 The need for Solid State Transformers

The increasing demand in energy along with the need to dwindle greenhouse gas (GHG) emissions as well as substitute some already limited forms of energy such as peat, uranium, oil, and coal has caused the growth in renewable forms of energy [21]. This advancement in renewable technologies has increased the amount of power plants on the distribution grid which are largely influenced by weather effects thereby causing severe complications on the quality of power due to their variable nature [22]. Hence, to easily interconnect these renewable plants onto the power grid and also overcome power quality perturbations, a solid state transformer (SST) is required as suggested in [23]. The SST can be described as a complex bidirectional power electronics AC-AC converter for electricity exchange and consists of different components. It is highly contemplated that
the SST is a suitable alternative for the traditional transformer due to reduced size, the ability to interconnect renewable as well as the ability to minimise power quality perturbations [21]. In figure 12, a block diagram of a typical SST is shown.

![Figure 12: Block Diagram of Solid State Transformer](image)

As seen in figure 12, the primary of the MFT consists of an AC-DC rectifier that receives a sine wave voltage from the AC grid and rectifies the sine voltage into DC after which the DC voltage is fed into a DC-AC stage that converts this voltage into a rectangular medium frequency waveform for the transformer. On the secondary side of the MFT, the AC-DC stage changes the medium frequency rectangular waveform into a unidirectional waveform after which a DC-AC inverter can be employed to invert the DC voltage into an AC voltage.

As depicted in figure 12, there can be three ports for the SST: an AC input; AC output, and DC output. In the event that one of these ports is inactive, for example, no input from a wind turbine, the SST is cut off from the grid (Islanding).

It is suggested in [24] that an SST can act as a current limiter as it reduces current through control of DC-AC converter. With an SST the converter is blocked during an over current and the SST has under voltage protection which usually blocks the converter in circumstances where normal supply voltage is below expected value. Unlike the conventional transformer where there is a circuit breaker before and after the transformer, the SST could overcome the conventional transformer in that it acts as a circuit breaker and therefore requires no additional circuit breaker. As the SST is largely operated by semiconductors, no energy can flow through the MFT when the SST ceases to function. Harmonics injected onto the grid can be prevented if a sinusoidal current that is in phase with grid voltage is used so that unity power factor can be achieved. The SST could ensure that power quality meets IEEE 519-1992 regulations [25].
With such a device as the SST, the smart grid, similar to the web, incorporates the applications of information and communications technology in gathering and acting on data relating to the performances of electricity production units as well as customers to enhance the efficiency, reliability and sustainability of electricity production and better services to customers on the distribution grid [26].

2.3.1 Comparison between Line Frequency Transformer and SST

Ever since AC supply was introduced the line frequency transformer (LFT) has been used for transmission and distribution of AC. Taking into consideration the vast number of years the LFT has been used as well as research conducted on this equipment, its technology is matured enough and widespread application of this equipment has made it to be cheap, reliable and efficient [27]. Although the conventional transformer has operated for several years, there are still some draw backs associated with an LFT which includes [23], [27], [8] [9], [10]:

- the inability to store energy;
- voltage regulation difficulties;
- harmonic currents on the output of the transformer has an impact on the input side of the transformer and these harmonic currents can increase transformer losses;
- some undesired features such as voltage dips on the input are usually represented on the output;
- saturation of transformer core produces harmonics that can cause high inrush current;
- the volume, weight and size of an LFT are usually very large, and
- with transformers employing oil for cooling, exposure of this oil to the environment can be harmful.

Bearing in mind the above drawbacks of the LFT, the SST offers better advantages as compared with the LFT as it employs power electronic converters along with a medium or high frequency transformer for isolation and voltage conversion. The SST is multifunctional equipment and its benefit includes [8], [9], [10]:

- the capability to offer protection against unbalanced load conditions;
- it functions as a circuit breaker in that, when the power electronic devices used within the SST are switched off, the circuit is disrupted and stops the flow of electricity;
- the application of power electronics results to high controllability;
- voltage sags and swells are eliminated due to DC link within SST.
- the AC-DC unit functions as a power factor improvement device, therefore unity power factor is achieved which increases active power by 20% (it maintains unity power factor under reactive load conditions);
- since transformer size is inversely proportional to its frequency, the use of medium frequency significantly reduces size and weight.

2.3.2 The function of ICT in the Smart Grid
In [28], a smart grid is described as a modern and highly efficient, reliable electricity network structured for better integration and disconnection of alternative and renewable energy sources as well as consumers. The idea is that for such a grid to carry out such operations, it would incorporate ‘information and communications technology (ICT)’ into the system as well as energy management principles focused on optimisation of supply and demand of energy so as to make the traditional grid more reliable and efficient [29]. In such a system, there exist improved communications between all partners concerned with the system as communication is real time [30]. Lima [31] points out that partners in the ICT sector and ‘power engineering society’ have developed a three layer model of the ‘smart grid concept’ which is made up of:

- power systems and energy layer;
- communications layer, and
- information technology layer.

A model of the smart grid is shown in figure 13 with the ICT layer covering about 70% of the structure of the smart grid [26].
So far, the developments in view of transforming the existing grid into a smart grid has been carried out by firms such as Cisco, Google, IBM, Intel, Oracle in areas of ICT whereas research centres and academic institutions are contributing to modelling, building and control of the smart grid\cite{32,33,34,35}.

As suggested in \cite{26}, more energy would be generated from renewable sources by 2035 in the U.S.A and Europe and renewable energy would supersede the other types of energy sources. As such, ICT will perform an essential role in interconnecting these renewable sources. Applications of DC-DC converters are covered in the following section.

### 2.4 Applications of DC-DC Converters

There are many applications for dc-dc converters. In this review, the following applications are covered: electric cars; energy storage systems; helicopter integrated satellite applications; telecommunication satellite applications; dc-dc converters in solid state transformers; offshore wind farm dc collector grid; dc-dc converters in Photovoltaic applications, and sub-sea energy production.
2.4.1 Electric Cars

As indicated in [36], a 250 V/530 V bidirectional dc-dc converter with a power level of 30 kW is used in an electric car. The efficiency of the converter was 95 %. A block diagram of this converter is shown in figure 14.

![Figure 14: A Bidirectional DC-DC converter in an Electric Car [36]](image)

As seen in figure 14, the structure has four main blocks which consists of: two dc-dc converters; two batteries; four motor drives, and motors. Each of the dc-dc converters excites two of the motor drives of which the first converter energizes the back motor and the other converter energizes the front motor. The nominal power of each converter is 30 kW and it is sufficient to run the motors. In this application of electric cars, the dc-dc converter is not only used to run the motors, but also for battery charging. It operates in one direction as a constant voltage source and in the other direction as a constant current source for battery charging.
2.4.2 Energy Storage Systems

Systems to store energy have become an essential part in a distribution system. This is as a result of the increasing penetration of renewable energy sources such as solar and the power of the wind which are fluctuating. So then storage systems can compensate for power shortages during periods of unavailability. Batteries and capacitors are storage systems where dc-dc converters can be used. The dc-dc converter can be employed for bidirectional power flow between a capacitor bank and the distribution system [37]. In figure 15, a 200 V, 10 kW, 60000 μF energy storage system incorporating a bidirectional dc-dc converter is shown.

![Energy Storage System](image)

Figure 15: Energy Storage System Based on a Bidirectional DC-DC Converter [38]

The dc-dc converter in this application is employed to charge and discharge the electrolytic capacitor. The charging can be achieved from zero to rated voltage without external pre-charging. Across the capacitor bank, the voltage is charged up to 350 V and discharges down to 190 V. Therefore energy of 2.6 kJ can be stored into the capacitor bank as well as released from the capacitor bank when needed. The voltage (V_D1) is regulated at 320 V by a 3-phase PWM converter [38]. During the starting phase of this energy storage system, when bridge 1 produces a square voltage of V1 at V_D1= 320 and V_D2=0, the transformer and auxiliary inductor (L_a) receives an inrush current. This inrush current causes a magnetic saturation across the cores of L_a, which then results to a higher inrush current. Thus, a pre-charging mode of operation is produced which charges the capacitor from zero to the rated voltage level of 320 V which then prevents the flow of
the inrush current. The benefit of the pre-charging is that it eliminates the need of an external pre-charging unit, or start up.

2.4.3 Helicopter Integrated Starter and Generator

DC-DC converters are now employed in aircraft systems as the aviation industry is deeply interested in making aircrafts more electrical. The conventional methods of using pneumatic, hydraulics and mechanical methods of energy transfer are now being replaced with power electronic converters [39]. The integrated starter and generator (ISG) reported in [40] is one of the uses of power electronic converters. In this application a single phase AC machine functions as a starter and generator. In figure 16, a block diagram of an ISG is shown.

![Figure 16: A DC-DC Converter in an Integrated Starter and Generator [40]](image)

As seen in figure 16, a dc-dc bidirectional converter is employed to boost battery voltage, while the inverter changes this boosted voltage to AC power. The dc-dc converter in this application converts the voltage (LV) at the battery terminals into a higher value of voltage at the inverter terminals. It is termed motor mode when power is transferred from battery to the ISG. The high voltage from the converter is changed into a three phase voltage by the inverter so as to power the ISG AC machine. The term generator mode is applied when power is transferred from ISG to battery. During generator mode, ac voltage from the ISG is changed into DC by the inverter at the terminals of the dc-dc converter and the LV from the converter charges the battery. The specifications of the converter in
this application are as follows: the low voltage side has a terminal voltage of \( V_i \) (13 V ≤ \( V_i \) ≥ 28 V); at the high voltage side it has a terminal voltage \( V_o \) (270 V maximum). The nominal power is 12 kW and the frequency is 25 kHz [40].

### 2.4.4 Telecommunication Satellite Applications

Telecommunication satellite systems using “travelling wave tube amplifiers” (TWTA) often employ high DC voltages. Hence, HVDC converters are employed for these telecommunication satellite systems. A TWTA comprises of a “microwave amplifier tube” (TWT) that determines RF (radio frequency) performance, as well as an “electronic power conditioner” (EPC) to match the dc interface [41]. The EPC is often used for multiple output dc-dc converters which supplies power to the TWTA or SSPA (Solid state power amplifier) from the satellite energy bus. The energy needed by both amplifiers is properly regulated and is usually from different voltage sources. Transponders are the most essential parts of a satellite communication systems as they receive signals, process signals, perform amplification and transmit back to earth, or onto another satellite, the received signals. So then the HVDC converter may be considered to be the most essential unit in the EPC as it is the most important part in achieving high efficiency and a competitive TWTA. In these systems, the TWTA represents 35 % of the overall mass and 70 % to 90 % of the total dc power consumed. In [42] a prototype of an application that requires an output power of 150 W, an output voltage of 3.2 kV and input voltage between 26 V - 44 V is developed for a TWTA telecommunication satellite system with a minimum efficiency of 94.1 %.

### 2.4.5 DC-DC Converters in Solid State Transformers and Distribution Systems

In current ac grids the increased penetration of distributed generation has presented some challenges. The solid state transformer (SST) is contemplated to be a suitable solution for future ac grids. The SST transforms an ac voltage using medium frequency transformer and power electronic devices. With the operation of a dc-dc converter at medium frequency, the size and weight of the magnetic circuit is tremendously reduced. However, in terms of efficiency, reliability, power density and cost, the ability of the SST to compete with the low frequency 50 Hz transformer still has to be proven. The use of a
dc-dc converter in a distribution system allows energy to be transferred from the grid to AC and DC loads. As the converter is bidirectional, energy is delivered to the grid from wind turbines, PV systems and battery banks [43]. In figure 17, a bidirectional functional diagram of an SST is shown.

The SST consists of an AC-DC rectifier, a DC-DC converter to produce regulated dc, and a dc-ac inverter to produce regulated ac. These converters are all bidirectional and allow the SST to deliver power from local DESDs (Distributed energy storage devices) and DRER (Distributed renewable energy resources) to the grid. As already mentioned, energy can also be delivered from the grid to both ac and dc loads [44].

![Figure 17: Bidirectional Diagram of an SST [44]](image)
(a) Power Transferred from Grid to Loads (b) Power Transferred from DRER and DESD to Grid

The SST can provide voltage-sag compensation or the limitation of fault current, control of power flow and many other additional features. AC sources can be connected to dc grids with ease through the use of an SST. Here again, the main component in the SST is the high power dc-dc converter.
2.4.6 Offshore Wind Farm DC Collector Grid

There is an interest to expand the size of wind farms and extend the wind farm into much deeper waters [45]. According to [46], offshore wind farms located 100 km and above requires HVDC link so as to produce power economically. Thus, in the future, several offshore wind farms maybe connected through HVDC multi-terminal stations. The lengthy distance from the offshore wind farm to the access point of the onshore grid is the main reason for employing DC. The distance which the cables may need to run from offshore farms to onshore grid, along with the increasing need for “reactive power compensation” makes the use of ac less efficient [47]. Nowadays, the large numbers of wind turbines in a farm are usually fed onto an ac 50 Hz collector grid of which the voltage is raised to a higher value (eg 500 kV) at a central station. However, with classical designs, the ac 50 Hz voltage is produced from DC. Since the wind turbine produces variable frequency ac voltage, dc conversion within the turbine is important. A more reliable as well as efficient approach with these farms is to completely eliminate the ac converter and change the LVDC to HVDC through the use of dc-dc converters as shown in figure 18.

Figure 18: Application of DC-DC Converters in an Offshore Wind Farm [48]

With this approach the weight is tremendously reduced and the system is more efficient. In figure 19, different methods to design the dc collector grid are shown. The selected structure will rely on the wind farm size and the generator voltage output. However, the
demand for dc-dc converters with different power level ratings is evident. One wind generator may have similar ratings as a dc-dc converter. As stated in [48], the generator can be from 1 MW to 10 MW. And to raise the voltage to a HVDC level, a second converter with rating identical to the rating of the wind farm is required, and the range can be from 0.1 GW to 10 GW.

Figure 19: Different Topologies for DC Collector Grids [49]

(a) Dispersed converter concept with series connection, (b) Centralized converter concept, (c) Two step-up DC grid
2.4.7 DC-DC Converters in Photovoltaic Applications

As shown in figure 20, large PV systems nowadays are using the ac collector grid. As seen, a low voltage (LV) inverter is connected to a PV subfield, after which a transformer is employed to transform the LV to MV (medium voltage). The MV is also transformed into a higher voltage using another transformer.

![Figure 20: AC Collector Grid][50]

Much identical to the dc collector grid used in offshore wind farms, the benefits of dc may be employed across PV applications and the PV subfield uses dc-dc converters to feed a common MVDC collector grid as shown in figure 21. Here again, the enabling technology is the “high power dc-dc converter”.

[50]: ./images/fig20.png
2.4.8 Subsea Energy Production

Gas and oil buried under the seabed can be extracted using a submersible electrical pump [51]. These systems are installed on seabed so as to eliminate the use of an offshore platform. To supply such a facility can be a challenge since the facilities may be inaccessible after having been installed. As the amount of energy consumed by these facilities may reach 100 MW, a HV supply is inevitable. So then, employing an existing HVDC line, the facility may be efficiently energized and the system is simplified as the 50 Hz bulky component is obsolete. In the following section, a review of the state of art in medium frequency transformer design is covered.
2.5 A Review of the State of Art in Medium Frequency Transformer Design

The “medium frequency transformer” (MFT) has gained global interest as it is the main component in high power converters. The MFT replaces the conventional 50/60 Hz transformer. The bulkiest unit within future MV conversion structures is the magnetic circuit, and there is an interest to minimize the size of the magnetic circuit so as to reduce overall volume and weight of high power converters. With extensive efforts to realise this objective of magnetic circuit size reduction, the method most commonly employed is that of increasing the frequency so as to cut down the volume as frequency is inversely proportional to area product. The low frequency transformer appears to be unsuitable in certain electrical environments and applications, and therefore new design methods are to be employed. The first issue to be considered with the MFT is the type of magnetic core to be used. The characteristics expected of a core material are that it should have a high saturation flux density (Bsat); low core loss, and can continuously operate at high temperatures [52].

2.5.1 Magnetic Materials

The performance of a transformer largely depends upon the type of magnetic materials used in its construction, as different materials have different properties. So then in the design of a transformer, the selection of the core material is an important point to consider [53], [54]. In certain applications, some magnetic materials may be suitable than the others. Core loss varies with the type of magnetic material. The losses can also vary with the flux level and frequency. It is important to consider all of these issues during the initial stage of transformer design [55]. Materials with the ability to magnetize and demagnetize easily are classified as ‘soft magnetic materials’ and they are generally suitable for transformers operating at medium frequencies. On the other hand, a ‘hard magnetic material’ is that which requires an external field of energy for magnetization and demagnetization [56], [57]. There are many ‘soft magnetic materials’ which may be considered for the design of an MF transformer.

2.5.1.1 Ferrites

Ferrite is a ‘soft magnetic material’, and although ferrites are widely employed for MF applications, the ferrite core poses very low ‘saturation flux density’ of about 0.3-0.5 T.
This may result to a bulky transformer in HV applications [58], [55]. In HF applications, ferrite can present low loss densities which makes the material suitable for frequencies exceeding 25 kHz [59]. According to [60] the low ‘saturation flux density’ of ferrite will not be a penalty with high frequencies exceeding 25 kHz. Ferrite has a high electrical resistivity but ‘low saturation flux density’. Since the high resistivity reduces eddy current loss, the main loss that ferrites have is hysteresis. In [61], ferrite is employed for the design of a 150 KW transformer with ratio of 1800 V: 750 V operating between frequencies of 6 kHz to 10 kHz. The study showed that the transformer volume and cost reduces as the frequency increases. According to [62], conventional dc-dc converters nowadays employ ferrites to construct the interlinking transformer. The operating frequencies, in these applications, are often quite high such as tens of kHz (Kilo Hertz), or even some MHz (Mega Hertz), but the voltages are often quite low. Even at high frequencies, the material has low specific loss which is of advantage to ferrite. Another advantage is the absence of laminations between sheets, which results to high thermal conductivity. As already stated, it has a low ‘saturation flux density which is a disadvantage. So then to operate at high voltages and power levels, a large CSA (cross sectional area) is needed so as to prevent core saturation which leads to high cost of installation as well as high losses [63]. As suggested in [62], ferrite is unsuitable for ‘high power medium frequency operation exceeding 5 kHz.

2.5.1.2 Silicon Steel
In soft magnetic applications, silicon steel is widely used. This material has a ‘high saturation flux density’ (> 1.5 T) as well as good permeability [63]. In [64], a 75 KVA traction transformer operating at 400 Hz was developed using silicon steel (FeSi). However, the volume and height can be improved at high working frequencies. They are generally suitable for frequencies less than 1 kHz. There are suggestions to replace silicon steel with low loss amorphous cores (Metglas) so as to minimize the no load losses. As highlighted in [62], [54], with some applications (transmission or distribution) using high power nowadays, thin silicon (FeSi) plates with thickness less than 0.3 mm which are laminated from each other are used for the transformer core. These thin plates are isolated from each other to minimize eddy currents. The method of stacking the plates together enables construction of large cores with overall weight of hundreds of tons. One of the advantages of FeSi is the high saturation flux density already mentioned above. Also, the
cost of the material is low, which therefore makes it a suitable solution in applications requiring high voltage, high power and low frequency, such as conventional transformers employed across the power grid. However, there are two main disadvantages associated with laminated cores. On one side, losses significantly increase whenever the frequency increases. On the other side, the laminations between sheets reduce the thermal conductivity between the cores, resulting in a limited loss density. So then with the use of MF, the maximum flux density of the core material should be reduced so as to keep to the required temperature limits. With these, the size of the transformer increases, which makes them ill-suited for applications requiring medium and high frequencies [53], [56].

2.5.1.3 Amorphous and Nanocrystalline Alloys
Amorphous and nanocrystalline alloys are the best materials for construction of the core of a high power MFT. Silicon steel is the most affordable magnetic material, but in the frequency range of 1 kHz to 25 kHz, Silicon steel exhibits high losses. So then to reduce these losses, amorphous and nanocrystalline alloys are suitable alternatives to minimize the high losses associated with silicon alloy [65],[66], [67]. Among currently available magnetic materials, amorphous and nanocrystalline offers the best characteristics for ‘high power medium frequency’ applications. They are an excellent compromise between ‘high saturation flux density’ laminated silicon steel sheets and low loss ferrites [62]. In recent years, different prototypes and design methods have been introduced to optimize efficiency as well as maximise power density. In [68], three 10 kVA, 3 kHz, 3.8 kV / 400 V transformer with Metglas SA2605A1 amorphous core was investigated. The results showed that an efficiency of 97% was achieved with Metglas. A comparative study conducted in [69] showed that for different core materials operating at 250 kVA, 20 kHz, 5 kV/380 V, nanocrystalline scored the best points on overall performances, while amorphous alloy was preferred with regard to cost. As reported in [70] regarding the design of an MFT, four different transformers specified as follows: 33.3 kVA at 20 kHz; 33.3 kVA at 3 kHz; 100 kVA at 20 kHz, and 100 kVA at 3 kHz are shown. In this report, Metglas was selected as the efficiency was 99%.

In relation to cost, amorphous alloy (Metglas SA2605A1) is less expensive as compared to nanocrystalline, and amorphous alloy large C-cores are available which makes it suitable for high power applications. However, with frequencies exceeding tens of kHz,
the loss of amorphous alloy may be controlled using low flux density which results to a large core volume [66]. With nanocrystalline, it turns out to be a suitable candidate as it satisfies efficiency and power density requirements. This material has a higher saturation flux density than ferrite and the core loss of nanocrystalline is lowest as compared to the other materials, of which this can result to high efficiency [65]. Some of the drawbacks of nanocrystalline may relate to cost as it is expensive. Silicon steel possess a high permeability as well as high “saturation flux density”. The material loss at high frequencies is unacceptable for the design of the MFT. As regards ferrite, though it is less expensive and the core loss is moderate, their “low saturation flux density” makes them unsuitable for the MFT as they will require a large magnetic core which then conflicts with the requirements of reduce volume and weight for the MFT [62]. So in all, amorphous and nanocrystalline alloys are the best materials for construction of the core of a high power MFT.

2.5.2 Transformer Structure
In order to satisfy the high efficiency as well as “high power density” requirements, the structure of the transformer is an influential factor. The ‘core type’ structure, the shell type structure and the matrix structure were investigated in [11]. During this test, the transformer was specified at 1 MW, 20 kHz, 12 kV/1.2 kV, and the core material was Vitroperm 500F. The results revealed as follows, for the core-type, the overall volume of the transformer was 4.8 litres and the total losses were 2.81 kW. Now with the shell-type, the volume was 11.9 litres, while the total losses were 3.76 kW. And for the matrix type, the total volume was 11 litres while the losses were at 4.5 kW. These results indicate that the core type was much suitable for a HPMFT (High Power Medium Frequency) design, as the overall losses were 2.81 kW and a volume of 4.8 litres, which makes the core type structure more efficient than the shell and matrix type. However, it is important to note that these transformers had other important differences which contributed to the size (such as the manner in which the windings were insulated).
2.5.3 Transformer Insulation Design and Thermal Management

The next stage to consider in the design process are the insulation design along with thermal management as they turn to be a complex issue with the MFHPT than a LFT due to reduced size and absence of oil as a cooling agent. With the MFHPT, cooling can be achieved using natural ventilation, However, other heat dissipation methods such as water cooling heat sinks and fan cooling can be employed in certain applications most especially at high power densities [11]. In relation to insulating material, the solid type such as exopy can be applied upon areas where air insulation is not sufficient for high voltages at highly compact designs [68], [69]. In [11], it is suggested that HV insulation wire can minimize complexities in transformer design. The following section looks at high frequency effects.

2.6 High Frequency Effects

As Hurley [71] points out, high frequency transformer operation reduces size but transformer losses increases at high frequencies resulting in increase temperature thereby requiring other forms of heat dissipation, or larger cores may be employed due to skin and proximity effects. So then, with the design of a “high power medium frequency” transformer, skin and proximity effects must be considered [72].

The effects of high frequency resulting in increase core loss can be understood from “Steinmetz improved generalised equation” [73].

\[ P_c = 2^{a+b} \cdot k_i \cdot f^a \cdot B_m^{\beta} \cdot D^{\beta-a+1} \] (2.1)

Where:

\[ k_i = K / (2\pi)^{a+1} \int_0^{2\pi} [\cos \phi]^a 2^{\beta-a} d\Theta, \] the material characteristics K, a, and \( \beta \) are same as in the original Steinmetz equation, \( f \) is the frequency, \( B_m \) is peak magnetic induction of the square wave excitation and \( D \) is the duty ratio of a square voltage waveform [60].

It can be seen from equation (2.1) that increasing the frequency (f), or increasing the maximum flux density (\( B_m \)) in the above equation would result to increased core losses. So reducing maximum flux density is one way to reduce the core loss. In [71] it is suggested that an optimum design has core loss equal to winding losses. In a transformer,
windings losses increases at high frequency due to skin and proximity effects caused by non-uniform circulation of current in the windings.

The effects of high frequency can also be clarified from the expression relating to the winding loss in a transformer.

\[ P_w = I_s^2 R_{acp} + I_s^2 R_{acs} \]  \hfill (2.2)

In equation (2.2), I is the rms current, \( R_{acp} \) is the primary ac resistance, \( I_s \) is the secondary rms current, and \( R_{acs} \) is the secondary ac resistance.

The skin and proximity effect influences the ac resistance. As the frequency increases, the ac resistance increases, and this increases the winding loss. The skin and proximity effects, in other words, can be described as an increase in resistance when the frequency increases. Should the skin and proximity effects be represented by a factor termed the resistance factor (Fr), then the ac resistance is the product of the resistance factor (Fr) and the dc resistance \( R_{dc} \). Note that the dc resistance is constant with the frequency but the ac resistance varies with frequency. In a circular litz wire the resistance factor can be determined using the expression (2.3).

\[
\text{Resistance factor } (F_r) = \frac{\Upsilon}{2} [ K_p - 2\pi \left( 4\left(\frac{m^2 - 1}{3}\right) K_s \right) ] \]  \hfill (2.3)

Where: \( \Upsilon \) is the penetration ratio, \( K_p \) is the proximity effect factor, \( m \) is the number of layers and \( K_s \) is the skin effect factor.

### 2.6.1 Skin Effect Factor

Skin effect can be described as the propensity of current (AC) flow in a conductor in such manner that current density is higher near conductor surface and lower at greater depths into the conductor [74]. So current circulates mainly at conductor ‘skin’ (outer surface) and a certain level known as skin depth. Skin effect results to increased conductor resistance at high frequencies.
According to [72] skin effect is caused by changing magnetic field of the AC current. Generally, conductors made of wires are usually used to transfer energy and in the case of a wire transferring AC a magnetic field is produced around that conductor. If intensity of current in these wires changes, then magnetic field also changes. This change in magnetic field also produces an electric field that resists the change of current intensity. This opposing field is known as 'back emf'. So then, at centre of conductor there exists a strong back emf which opposes the conducting electrons and sends them back to conductor surface. Despite the back emf opposing force, a greater current intensity exists at conductor’s surface and while at conductor depth, reduced current exists.

Skin effect can also be described as a decline in the intensity of current. In figure 22, the skin effect in a conductor is illustrated [74]. A “magneto-motive force” (mmf) occurs and this generates eddy current in the wire. This “eddy current” has a direction such that it adds to current at wire surface and subtracts from wire centre current [73].

![Diagram of Skin Effect in a Conductor](image)

Figure 22: Skin Effect in a Conductor [74]

In [60], Villar points out that the magnetic field of a conductor carrying AC current does not rely only on the current amplitude and radial distance from conductor centre, but it also relies on operating frequency of waveform. Although overall current may not change
in the conductor, the density of current will be non-uniform and more pronounced at high frequencies as a result of the linear relationship between current density and frequency. Most of these currents flow at equivalent penetration depth (skin thickness) or skin depth defined as [74].

\[ \delta = \frac{K_m}{\sqrt{f}} \quad \text{or} \quad \delta = \frac{66}{\sqrt{f}} \quad \text{for copper at 20°C} \tag{2.4} \]

Where \( \delta \) is skin depth (mm), \( f \) is the frequency (Hz), \( K_m \) is a material constant and ranges from 75 for copper at 100 °C to 66 for copper at 20 °C.

### 2.6.2 Proximity Effect

The circulation of current through a conductor is largely influenced by an alternating magnetic field, and current flowing in an isolated conductor produces a magnetic field around the conductor which can induce eddy currents in nearby conductors thereby changing the original circulation of current in the conductors [73]. The AC resistance of nearby conductors is increased due to proximity effects. This effect would increase with increasing frequency, and AC resistance of a conductor can be ten times DC resistance at very high frequency. According to [71] proximity effect occurs when current circulation in one winding layer influences circulation in another layer.

![Proximity Effect](image)

**Figure 23: Proximity Effect**
An illustration of proximity effect is shown in figure 23 where current flows towards other windings due to incident fields of neighbouring conductors [74]. As seen in figure 23, when conductors are wound to produce one or many layers, a “magneto-motive force” develops along winding plane. The conductor’s useful area is reduced as a result of proximity effect. The following section looks at some dc-dc converter structures.

2.7 Some DC-DC Converter Structure

2.7.1 The Isolated Bidirectional Converter

The isolated type of converter uses a transformer to provide galvanic isolation of the input circuit from the output [75]. The structure shown in figure 24 is a typical “isolated bidirectional dc-dc converter (IBDC)” suitable for medium and high power applications.

![Figure 24: Elementary Circuit of IBDC](image)

As shown in figure 24, it has two dc-ac converters operating at medium frequency. Having a circuit comprising of two dc buses (LV DC Bus and MV DC Bus), isolation between both sources as required by some electrical safety standards is achieved using the medium frequency transformer (MFT) [76]. It is pointed out in [77] that some safety standards such as: UL 1950; VDE 0805; EN 6095; IEC 950 and EN61010 are in operation to minimize and prevent the users of electronic devices from electrocution. Another useful aspect of the MFT is in facilitating voltage matching in circumstances where the voltage ratio for both sources is higher. The converter in figure 24 has bidirectional features to enable power transfer between both circuits thereby providing a path for absorbing or
generating energy using the dc buses [78]. As shown in figure 25, the following can be connected to the dc buses:

- storage battery
- super capacitor
- electric vehicle
- PV array
- fuel cell
- wind energy

Figure 25: IBDC Typical Application in Micro Grid Distribution System [79]

The term bidirectional suggest two directions of operation for the IBDC in relation to energy transfer. It should be borne in mind that other designations are used in different publications, for example, the term “step - up” is often used in place of “boost”, while “step-down” is applied to “buck converters” [80]. The reasons for such terminologies emerged from the fact that each section of the converter has a voltage whose amplitude is different from the other, and as such, boosting and bucking of the voltage occurs as well as energy transfer. Other motives for these terminologies originate from the use of
conventional “buck” or “boost” converters. In some publications, the term charging and discharging are employed for reasons that one of the sources connected to the dc buses could be a battery or capacitor [79].

2.7.1.1 Single Phase Dual-Active Bridge

A “dual active bridge” converter (DAB) designed using LT Spice is shown in figure 26. The converter in figure 26 is a dc-dc DAB converter and the converter consists of a transformer that provides galvanic isolation having full bridge circuits on both primary and secondary sections of the transformer. It uses eight MOSFETS. The transformers leakage inductance is utilized by the DAB for energy storage and to adjust the waveform. The waveform of this converter is shown in figure 27, where V (N005, N006) represents the input voltage waveform and V (N004, N006) represents the output voltage waveform.

![Figure 26: Single Phase Dual Active Bride DC-DC Converter](image-url)
According to [76], a transformer is used to interface two active bridges of which the control of energy flow from one of its d.c. sources to the other is achieved by phase-shifting the two active bridges from each other. It operates at a fixed frequency square-wave utilizing the transformers leakage inductance as the principal energy transfer component. The transformer can function at medium frequency and allows high power density operations. Both active bridges on each side use soft switching that reduces stress in the circuit, thereby reducing switching losses. A duty cycle of 50% rectangular wave is produced by each full bridge having a phase displacement between two of the a.c. waveforms [81]. As already mentioned above, both circuits linked to the isolation transformer have “full bridge voltage fed converters” that are operated using soft switching phase shifting techniques. A fixed frequency can be used to operate the transformer. It has been found in [82] that the direction of power flow between primary and secondary circuits is controlled using the angle of the phase shift. As mentioned in [83] at a phase angle of about 90% maximum power transfer is produced. The average power can be calculated using equation (2.5) [76] [81] [84]:

Figure 27: DAB Voltage Waveform
\[ P = \frac{VA \cdot VB \cdot \omega (1 - \omega)}{N \pi L_k \omega} \]  \hspace{1cm} (2.5)

Where

\( L_k = \) Leakage inductance of the transformer (including any series inductance)
\( N = \) transformer turns ratio
\( \omega = \) angular frequency

The value of the leakage inductance \( L_k \) is useful for the determination of maximum energy transferred at a known switching frequency. Most often with unidirectional dc-dc converters, the voltage of the input buses fluctuates while the voltage at the output is regulated. Now with the IBDCs, both dc buses experience voltage fluctuations due to other parts of the network. So then an essential design component associated with IBDC which influences soft switching and some performance elements is the ratio of the voltage, usually defined as:

\[ d = \frac{V_2}{n \cdot V_1} \]  \hspace{1cm} (2.6)

The advantages and disadvantages of this converter are as follows [76] [83] [85],[85], [81] [84]:

**Advantages:**

- good option for bidirectional energy flow.
- it has constant frequency
- soft-switching is available on both the primary and secondary sections and current in the switches are evenly shared.
- the resonant inductor is designed into the transformer.
- there are no inductors at the output for filtering.
- low amount of passive devices used, and
- the efficiency of the converter is good.
On the other hand, the disadvantages of the DAB converter are outlined below:

- large number of switching units makes the circuit too complex and results to increased cost.
- high ripple current of the output capacitor requires the appropriate filtering circuit.
- at low loads soft switching can be lost and additional inductive energy maybe required at very low loads so as to complete a resonant transition.

### 2.7.1.2 Three Phase DAB Converter

The topology for this converter is shown in figure 28 [84]. As seen, both primary and secondary sections of the transformer have three half bridges. Three inductors are required to store energy. According to [86], though three medium frequency transformers can be used, a single medium frequency three phase transformer can be employed for same services and it is operated with phase shift modulation much similar to the single phase DAB. It is pointed out in [81] that the overall efficiency is good and the ratings for the switches, inductors, transformers can be lower as compared to the single phase DAB. It also has lower components rating as well as lower rms currents as compared to the single phase DAB. A major drawback for this structure is the amount of switches (power semiconductor devices) required [8]. As seen in figure 28, twelve power switches are used.

![Figure 28: Three Phase DAB Converter](84)
Unlike the single phase DAB, additional performance features derived from other modulation techniques cannot be applied to the three phase DAB. Other disadvantages of the three-phase DAB are high switching and conduction losses during operations at wide voltage and power ratings [86].

2.7.1.3 Bidirectional Isolated Full Bridge Converter
This converter is depicted in figure 29, and as seen, it has a medium voltage (MV) section with full bridged voltage source while the low voltage side (LV) has a full bridge current source [87]. It is suggested in [88] that power flow can be controlled using the duty cycle (d). So then, appropriate control of LV section is needed to facilitate bidirectional energy flow. This converter allows ZVS for switches located on the MV side, while ZCS is applied to switches located at the LV side [84]. With this converter, switching operations at high frequencies as well as high power density are possible.

![Bidirectional isolated full bridged converter](image)

Figure 29: Bidirectional isolated full bridged converter [8]

According to the author in [84] the disadvantage associated with this converter is the need of a snubber unit to circumvent voltage spikes when switching operations are performed. These spikes are produced as a result of the switches located at the secondary which repeatedly links the transformers stray inductances with the inductor positioned at the secondary.
2.7.1.4 Bidirectional Isolated Current Doubler

The full bridged isolated converter discussed in section 2.7.1.3 can be modified to form the “bidirectional isolated current doubler” by replacing two of the upper located secondary switches with inductors so as to allow high current operations and reduced conduction losses. The bidirectional isolated current doubler converter can be seen in figure 30.

![Bidirectional Isolated Current Doubler Diagram](image)

Figure 30: Bidirectional Isolated Current Doubler [84]

This layout is suitable for vehicle applications and the inverter section is same as compared to the conventional full bridge converter comprising of four switches on two legs. The main difference can be seen on the section with the rectifier that consists of two switches only, rather than four. The direction of current flow in the output passes through the inductor and the transformer. So then this layout is termed “current doubler” for reasons that the amount of current flow through the transformer has been reduced to a half [84]. This implies that losses are reduced due to less current. In comparison to conventional full bridge converter, this layout has two inductors that carry just half the output current. Current is always present in these inductors and this current flows to the load. Comparing this layout with current doubler layout consisting of a centre tapped transformer, it would appear that this layout has a simpler transformer design which results to a smaller size. The requirement of a transformer having higher power ratings can be a drawback to this structure as well as inductors on the secondary [8].
2.7.1.5 Bidirectional LLC Converter

This converter is shown in figure 31 and the transformer current generated by the DC-DC resonant converter is almost sinusoidal and allows switching at a high frequency due to reduced switching losses. As seen, the leakage inductance of the transformer is connected in series with a capacitor and such an arrangement stops dc and ensures that the HF transformer is not saturated [89].

![Bidirectional Isolated LLC Converter](image)

Figure 31: Bidirectional Isolated LLC Converter [90]

The primary and secondary of the transformer are both connected to the FB. The fact that the main switching can vary with the load along with supply voltage is a disadvantage to this configuration. The rms current and switching losses in the LLC converter are lower as compared to the DAB. In circumstances where a variable switching frequency is needed, the LLC converter can be employed [90].

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2.7.2 Non Bidirectional DC-DC Converters

2.7.2.1 Phase-Shift Full-Bridge Converter

In figure 32, the structure of the “phase-shift full-bridged converter” is shown. The structure is same as the hard-switched full-bridged converter. The primary voltage of the transformer is controlled using phase shift [91]. Soft switching can be achieved by correct operation and proper design of the transformer, and the required amount of energy can be stored by the leakage inductance of the transformer during each cycle if designed properly, so that a switch command to turn OFF power interchanges with a snubber capacitor connected just across the switch to achieve soft switching at turn-off [92]. It is found in [82], [93], that soft-switching can also be achieved during turn-on if a diode (free-wheel) is in its conducting mode during turn-on. However, it should be borne in mind that when operating at very low loads soft-switching can be lost.

![Figure 32: Phase-Shift Full-Bridged DC-DC Converter [94]](image)

The merits of this converter are as follows [83]:

- losses and stresses are low especially at high loads due to soft-switching;
- constant frequency during operation, and
- low magnetic mass and lack of large resonant capacitors and inductors.
2.7.2.2 Series Load Resonant Converter

The structure of the “series load resonant (SLR)” converter is shown in figure 33. Generally, LC tanks are usually included in the resonant converter. In this structure, the load at the output is often connected in series with resonant tank and controlled using variable frequency. It requires a high resonant inductor which therefore implies the magnetic mass has to be heavy [92].

![Figure 33: Series Load Resonant Converter](image)

Though the control signal has variable frequency, the duty ratio is constant. The converter can operate either on discontinuous state or continuous state depending on issues such as ratio of the switching frequency to the resonant frequency [83]. The performance of the SLR can be considered sufficient, but, however, the variable frequency puts some limitations on the transformer design [82].

2.7.2.3 Parallel Load Resonant Converter

According to [91] ‘Parallel load resonant’ converter PLR has an LC tank connected in parallel to a load and as such requires high resonant inductor which therefore implies the magnetic mass has to be heavy. The layout of this converter is shown in figure 34 [92]. The PLR is similar to the SLR in the sense that it uses the LC tank for generating voltages and currents that oscillates, but differs from the SLR in that, in the PLR, its output load is connected across (in parallel) the capacitor of the resonant tank [83].
Figure 34: Layout of a Parallel Load Resonant Converter

It is found in [82] that the operation of the PLR converter is slightly different from the SLR as the PLR, during operation depends both on the ratio of the frequency and load conditions. Gain can be provided by the PLR without the use of a transformer. It should be noted that this gain is often small. During operations at partial load there are high losses due to high circulating currents. Hence the PLR is unsuitable in inter-grid array applications requiring a step-up voltage [92].

2.7.3 Comparison between some suitable DC-DC Converters

Most often, a converter described as dc-dc is basically a circuit using electronic switches (transistors and diodes) to transfer energy to storage components (inductors and capacitors) after which the transferred energy is switched on to the load. The dc-dc converter has attracted wide attention as a result of the proliferation of energy sources producing dc. In most cases, the dc voltage supplied to the input terminals of the dc-dc converter can be an unregulated voltage source, but at the output terminals is a regulated dc voltage. A dc-dc converter can be described as an electronic device that can be employed to change a dc voltage from one state to another. The electronic switches influence the transfer of voltage from the input to the output by their duty ratio. The dc-dc converter receives constant voltage at its input from an ac-dc rectifier and the dc-dc converter delivers a constant voltage output to a dc-ac inverter. A comparison between some suitable dc-dc converter structures can be seen in table 1. The research conducted
found that the single phase DAB (Dual Active Bridge) having good efficiency along with minimum amount of passive components is suitable for the dc-dc converter.

<table>
<thead>
<tr>
<th>CONVERTERS</th>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual active bridge-single phase</td>
<td>• Good efficiency</td>
<td>• High ripple current of the output capacitor requires an appropriate filtering circuit.</td>
</tr>
<tr>
<td></td>
<td>• Low amount of passive devices used.</td>
<td></td>
</tr>
<tr>
<td>Dual active bridge-three phase</td>
<td>• Low rating for inductors, switches and transformers as compared to single phase DAB;</td>
<td>• High switching and conduction losses during operations at wide voltages and power ratings.</td>
</tr>
<tr>
<td></td>
<td>• Lower rms current</td>
<td>• 12 power switches are required;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Additional features from other modulation techniques cannot be applied unlike the single phase DAB;</td>
</tr>
<tr>
<td>Bidirectional isolated full bridge converter</td>
<td>• High switching frequency and high power density</td>
<td>• The need of a snubber circuit</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• It requires and additional inductor.</td>
</tr>
<tr>
<td>Bidirectional isolated current doubler</td>
<td>• Good thermal performances</td>
<td>• The operating voltage is limited</td>
</tr>
<tr>
<td></td>
<td>• Reduced ripple current</td>
<td>• It requires two additional inductors</td>
</tr>
<tr>
<td></td>
<td>• Low transient response from current doubler rectifier</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Reduced converter size</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Fewer switches</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• High current operations</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Comparison between some DC-DC Converters
2.8 DAB Modulation Technique

Most often the modulation method applied to the ‘dual active bridge (DAB)’ are: rectangular modulation; trapezoidal and triangular modulation technique. A DC-DC conversion system receives constant voltage at its input from an AC-DC rectifier and the DC-DC converter delivers a constant voltage output to a DC-AC inverter. So there is a certain range of operation of the input voltage, output voltage as well as load that results to low losses. As the input and output voltage ratio for the DAB is constant, the load remains the only parameter that changes [8]. The three different modulation techniques investigated are given below.

2.8.1 Rectangular Modulation

This modulation method is also known as phase shift and it operates by suitable control of primary and secondary sections at 50% duty cycle [95]. It is suggested in [96] that transfer of power between primary and secondary can be achieved by regulating switching waveform angle of primary and secondary. Shri in [8] points out that although this method can be easily implemented and shows good control performance, its overall efficiency is insufficient. The method has the following as advantages [95], [96], [97]:

- high power transfer;
- low control intricacies;
- low rms current as compared to the other modulation techniques;
- losses are symmetrically shared by all switches, and
- in the event that one of the voltages are zero, power transfer is still possible

On the other hand the disadvantage of rectangular modulation includes [95], [96],[97]:

- reduced efficiency,
- with different input voltages and no power transfer, there are high losses due to reactive power (Ω ≠ 0, Udci ≠ Udce),
- it requires eight commutations to be performed.

The principle of operation of rectangular modulation can be described as follows: On primary side of DAB the semiconductors (T1 to T4) are commuted to produce rectangular voltage waveform (Vi) with a duty cycle always at 50%. On secondary side the
semiconductors (T5 to T8) are switched to produce rectangular voltage waveforms (Vo) but with some ability to cause phase shift (Ø) of Vi and Vo [96]. Variation of duty cycle of secondary circuit generates the phase shift and this is responsible for transfer of power. An AC current is produced when a differential voltage is effected on inductor of intermediary circuit. In figure 35, voltage and current waveforms of intermediary circuit can be seen. Semiconductors T1 and T2 are switched “on” for generation of positive half-wave of Vi while T3 and T4 are switched “on” for generation of negative half-wave [95].

![DAB Circuit Diagram (a) and (b) Voltage and Current Waveform for Rectangular Modulation](image)

Figure 35: DAB Circuit Diagram (a) and (b) Voltage and Current Waveform for Rectangular Modulation [95]
2.8.2 Trapezoidal Modulation

It is suggested in [97] that with this method, turn-off switching losses are reduced by means of adding a blanking period to the switching voltage of the primary. Adding a blanking time necessitates high r.m.s current so as to transfer same level of power which then leads to high conduction. Waveforms of current and voltage for trapezoidal modulation are shown in figure 36. The blanking time is usually defined by speed of semiconductor switch and typical values are between 2 us and 7 us. As compared to phase shift modulation, trapezoidal control mode forces zero voltage level for Vi and Vo by adding blanking time. Doing so achieves four zero current switching (ZCS) turn-off with losses nearly at zero [96].

![Figure 36: Voltage and Current Waveform for Trapezoidal Modulation](image)

This method has the following as advantages [8], [97]:

- it can be used for large voltage ranges;
- possibility of high power transfer;
- reduced switching losses;
- it has a high efficiency (four turn-offs semiconductors),
- can be employed for different and equal input voltages.
On the other hand the following can be considered as disadvantages [8], [97]:

- inability to function under no-load conditions;
- complications in modulation and algorithm control;
- increased conduction losses,
- unsymmetrical share of losses occurs in the event when primary voltage is different from secondary voltage.

### 2.8.3 Triangular Modulation

This method employs phase shift or a blanking period to produce an overlap of primary and secondary voltage. The phase shift or blanking time causes primary switching voltage to overlap from the secondary. It is a type of trapezoidal technique having one edge of $V_i$ and $V_o$ overlapping so as to cause a rectangular shape of transformer current, and this type of modulation can only be effective should input voltage and output voltage be unequal, but if one of these voltages is zero then this method cannot be employed [8],[95], [97]. A voltage and current waveform of triangular modulation are shown in figure 37.

![Figure 37: Voltage and Current Waveform of Triangular Modulation [8]](image)

The advantages of triangular modulation are given below:

- low switch loss as compared to phase shift and trapezoidal methods;
- there are only two switch-offs per period of switching, and
- ideal method of modulation if two voltages (input and output) are unequal.
Now on the other hand, the disadvantages of triangular modulation are:

- the rms current is high as compared to trapezoidal and rectangular types;
- complicated modulation and control algorithm;
- if input or output voltage is zero, triangular mode is not possible, and
- limited power transfer (inefficient use of period of power transfer).

### 2.8.4 Comparison between Modulation Technique

The three modulation technique presented above are compared and presented in table 2 below:

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>• Low rms current</td>
<td>• High losses at low power levels</td>
</tr>
<tr>
<td></td>
<td>• Simple control and algorithm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• High power transfer</td>
<td></td>
</tr>
<tr>
<td>Trapezoidal</td>
<td>• High voltage range</td>
<td>• Complications in modulation and algorithm control.</td>
</tr>
<tr>
<td></td>
<td>• Reduced switching loss</td>
<td>• Inability to function under no-load condition</td>
</tr>
<tr>
<td></td>
<td>• High efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• High power transfer</td>
<td></td>
</tr>
<tr>
<td>Triangular</td>
<td>• Low switching loss</td>
<td>• High rms current</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Complicated modulation and control</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Limited power transfer</td>
</tr>
</tbody>
</table>

Table 2: Comparison between DAB modulation methods

As depicted in table 2, rectangular modulation appears to be simple for implementation and its low rms current implies lower rating for components. The advantages of rectangular modulation outweigh its disadvantages of high turn-off losses. Given all of the above it can be seen that phase shift modulation (rectangular modulation) is most suitable for a Dual active Bridge (DAB) dc-dc converter.
2.9 Conclusions

The review found that the solid state transformer (SST) can be employed to substitute the low frequency transformer due to the advantages offered by the SST over the low frequency transformer. With the SST, size reduction can be achieved, power quality issues are minimised and it can interconnect renewable sources into the grid.

Back-up storage systems have become an essential part in a distribution system due to the increased penetration of energy generated from renewable sources which are fluctuating. The storage systems can compensate for power shortages during periods of unavailability. The storage systems most commonly used are batteries and capacitors. A solid state transformer can provide a means for interfacing such a dc based storage system.

There are several types of dc-dc converters which can be used for different types of applications and some converters can be employed just for stepping down the voltage while others for stepping up the voltage. Some dc-dc converters are non-isolating while others are bidirectional. It was found that for the construction of a dc-dc converter stage of an SST, a single phase DAB (Dual Active Bridge) can be employed as it is efficient and fewer passive components are used. The appropriate method of modulation for the DAB is “Phase Shift Modulation (PSM)” also known as “rectangular modulation”. The PSM is selected due to its simplicity in implementation and its low rms current implies lower rated components are used.

The type of magnetic material employed for the construction of the core of a medium frequency transformer significantly influences its performance. There are several types of magnetic material possessing different properties and the core loss varies with the type of material used. The transformer losses vary with the flux density and the frequency. So when designing a transformer the selection of the core material is an important point to consider. It is important that the core material should have a high saturation flux density, low core loss, and the material can operate at high temperatures. Though at medium frequency, transformer size is reduced, the winding loss increases due to skin and proximity effect which increases the ac resistance, and results to high temperatures. The following chapter looks at medium frequency transformer design.
Chapter 3: Medium Frequency Transformer Design Considerations

3.1 Introduction
In this chapter, a design approach for a high power medium frequency transformer is developed. This methodology shows that variation of the winding current density, the flux density and the number of primary turns can be used to find an optimum design.

3.2 Overview of Transformer Principle of Operation
Generally speaking a transformer possesses no moving parts and can be described as a ‘static electrical devices’. As the name may suggest, it gives an idea of transforming one thing into the other. This electrical equipment functions on “Faraday’s law of electromagnetic induction”. As shown in figure 38, the first coil that receives energy from an ac supply is called the primary winding and the other coil that supplies energy if a load was connected to its output can be called the secondary winding.

![Figure 38: Single phase E-core transformer](image)

Iron core
Primary windings
Secondary windings

Figure 38: Single phase E-core transformer
So then if an ac supply is connected to the primary it produces an alternating flux in the magnetic core. When this fluctuating flux in the core cuts across the secondary windings, the emf induced in each coil is usually same for the primary and secondary. Given their static characteristics and the application of the laws of electromagnetic induction, its secondary circuit may receive energy from its primary when the magnetic flux linking both primary and secondary windings on the core rises and falls. So then, a transformer may function with ac only. Transformers are commonly used in ‘transmission and distribution of energy’ and they are one of the main components in a dc-dc converter that forms part of an SST, but some additional design considerations must be applied to the transformer for operation at medium frequency. In circumstances where these machines are described as step-up or step-down transformers, it is often referred to the voltage. As already described above, it can be seen as shown in figure 38 that there are three essential parts that form the construction of a transformer, namely: the primary circuit; secondary circuit, and magnetic core. During operation, it transforms power (high voltage-low current) from one level to another (low voltage-high current) through electromagnetic induction without changing the frequency. Although not limited to changing voltage levels, they can be employed for isolating two circuits, and as impedance matching in the event of maximum power transfer.

3.3 The Voltage Equation

The voltage equation of a transformer originated with Michael Faraday and it is often described as Faraday’s law. It describes how a voltage may be induced as a result of a changing magnetic field. So then, an impressed voltage (U) across a winding has a relationship with the rate of variation of the magnetic flux density (B) in a core. This relationship is shown in equation (3.1).

\[ U = -N \cdot A_c \cdot \frac{dB}{dt} \]  

(3.1)

Where \( N \) represents number of turns. The area of the core may be determined from the magnetic core cross-sectional-area (Ac) along with core stacking factor [98]. In figure 39, waveforms of voltage and current in a medium frequency transformer designed using LT Spice is shown. It consists of the voltage waveform (a), the current waveform (b), and the
voltage and current waveform (c). In figure 39, the input voltage waveform is represented by V (N005, N006), the output voltage is represented by V (N004, N007) and I (L1) represents the current through the inductor.

(a) Voltage Waveform

(b) Current Waveform

(c) Voltage and Current Waveform

Figure 39: Waveforms of Voltage and Current in a Medium Frequency Transformer

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In figure 39, the voltage waveform is produced from a DAB with Phase Shift Modulation. The transformer is employed to interface two active bridges of which the control of energy flow is achieved by phase-shifting the two active bridges from each other. A duty cycle of 50% rectangular wave is produced by each full bridge having a phase displacement between two of the a.c. waveforms. As already discussed above, both circuits linked to the isolation transformer have “full bridge voltage fed converters” that are operated using soft switching phase shifting techniques. The voltage waveform produced is a rectangular waveform and not a sine wave. The voltage equation can be determined as shown below.

Integration can be employed to calculate average value of impressed voltage $U_{avg}$ as:

$$U_{avg} = \frac{1}{\tau} \int_0^\tau U \, dt = \frac{1}{\tau} \cdot N \cdot B_m \cdot A_c \quad (3.2)$$

Where $U_{avg}$ represents average value of impressed voltage at time period $\tau$ ($\tau$ is the time period for the flux to go from zero to $B_m$).

The ratio of the rms value as well as the average value of the waveform gives the form factor ($F$), and for a trapezoidal voltage, the form factor can be calculated as:

$$F = \frac{U_{rms}}{U_{avg}} \quad (3.3)$$

In half a cycle, the flux alternates from $+\Phi_m$ to $-\Phi_m$. Therefore average variation in flux $= 2\Phi / 1/2f = 4f\Phi_m$ (webers/seconds). Now combining (3.2) and (3.3) gives the classic voltage equation across the winding of a transformer (3.4) [99].

$$U_{rms} = F \cdot U_{avg} = 4 \cdot f \cdot N \cdot B_m \cdot A_c \quad (3.4)$$

It is evident from the transformer equation that the circuit with the greater number of turns induces larger emf thereby developing higher voltages and vice versa for the circuit with
the smaller number of turns. The circuit with the higher number of turns is called the ‘high voltage’ (HV) circuit and the circuit with the smaller number of turns is termed the ‘low voltage’ (LV) circuit. It can be seen from the transformer equation that the emf largely depends upon the number of turns, the flux, and the frequency. Thus, any variation of frequency, flux, or number of turns will vary the emf.

3.4 Design Challenges
When designing transformers the design engineer faces some constraints that need to be observed throughout the design stages. The product of the maximum current demand (load current) and the operating voltage gives the output power, and the output power is a constraint. The load must be able to receive energy within stated regulation limits from the secondary winding. The value of the minimum efficiency is another constraint, and it depends upon the overall energy losses of the transformer. Another constraint is the maximum allowable temperature rise of the transformer during operation in certain types of environments.

Transformer design often begins with selection of a suitable magnetic core material and each of these magnetic materials do have their own optimum point in relation to size, frequency, efficiency and cost spectrum. It is essential to be aware of the differences in cost between ferrite, Metglas, silicon steel, and nanocrystalline. In some application where the minimization of weight and size is a priority, then other constraints may relate to volume of the transformer. Some constraints may dominate the others depending upon the type of application. Parameters that affect others can be traded-off so as to achieve the desired design. Due to the interdependence as well as interactions, it is often not a possibility in one design to optimise all of the parameters. For instance, in the event where weight and volume are of significant importance, operating at higher frequency would reduce the weight and volume, but may cause some issues with efficiency. Also, in the case where frequency cannot be altered, weight and volume reduction can be achieved by choosing a core material which is efficient, but cost maybe an issue to consider. So then it can be seen that judicious trade-offs are important in achieving design goals.
3.5 Design Methodology

There are different approaches to design transformers. Manufacturers, for many years, have used numeric codes to represent the core. These codes indicate the power level of the core and each core is given a number which is the product of the csa (cross sectional area) of the core ($A_c$) and the winding window area ($A_w$). With low power magnetic cores, there are standards dimensions and sizes. As low power cores are widely used, optimised transformer designs rely on available tables depicting various cores, and the most suitable core can be selected depending upon the application and power handling capabilities.

Now with high power as well as medium frequency, magnetic cores are designed depending on demand or in certain cases, it may be designed using limited dimensional references. Hence, an optimised transformer design for high power depends on how its most suitable dimensions are defined. It should also be borne in mind that at high power medium frequency, the waveform across the transformer is a square wave. Unlike with the line frequency transformer where the original Steinmetz equation is used for calculation of core loss, with the MFT, the improved generalised Steinmetz is used since it is a square waveform.

As aforesaid, there are different methods to design an MFT. In [60], look up tables are used to determine winding dimensions which is much different from the method used in this thesis. In [100], a different approach is used to design an MFT, of which the core column width (A), the core window width (B), the core window height (C) and the core column depth (D) are variables, whereas with the method used in this thesis, the core window width (B), and the core window height (C) are calculated. With the method employed in [101], A and D are variables and the maximum flux density ($B_m$) is calculated, whereas in this thesis, $B_m$ is a variable, while A and D are assumed to be equal (calculated from the square root of $A_c$). In [102], the value of the maximum current density and flux density are calculated, while with the approach applied in this thesis, the maximum flux density as well as the maximum current density are variables.

The approach used in this thesis is shown in figure 40. With this method, the transformer core dimensions (A, B, C, D, E, and F) are calculated. The winding dimensions are calculated as well ($A_w$, $W_w$, $V_w$, $l_w$, $h_w$). With this approach the core CSA ($A_c$) is employed to determine the core column width (A), and the core column depth (D), of which A, and D (are assumed to be equal), and are calculated as the square root of $A_c$. 
This method considers the winding window area \( A_w \) as the product of the core window width \( B \) and the core window height \( C \). This work assumes that \( B \) is the sum of the thickness of coil former to central limb \( d_{\text{former}} \), the required clearance distance to the core \( d_{\text{air}} \) and the winding width \( W_w \).

In figure 40, a flow chart of the proposed methodology for the design of a medium frequency transformer is shown. This approach shows that by varying the winding current density, the flux density and the number of primary turns, an optimum design can be achieved for the transformer. As seen in figure 40, the transformer specifications are defined at the initial stage of the design and the specifications consist of: the power level; input and output voltage; operating frequency; the expected leakage inductance; the minimum isolation voltage; winding utilization factor; the temperature rise; the waveform factor, and the efficiency. The next stage of the design method relates to transformer configuration, after which the next step is to select initialized variables such as: the maximum flux density; the maximum current density and the number of primary turns. At this point, the area product is calculated; after which the core cross sectional area \( A_c \) and the winding window area \( A_w \) are calculated. The next step in the design process is to calculate the secondary number of turns after which the winding dimensions and core dimensions are calculated. The next step in the design flow chart is to calculate the core loss and winding loss which are helpful to determine the temperature rise of the transformer.

The single phase Dual Active Bridge (DAB) dc-dc converter is selected as a suitable topology for the above mentioned design approach. The DAB converter is employed as it is efficient and fewer passive components are used. Phase Shift Modulation is employed for the DAB converter. Though there are other modulation techniques such as Trapezoidal modulation and Triangular modulation, Phase shift modulation appears to be simple for implementation and its low rms current implies lower rating for components. With Phase Shift Modulation, the semiconductors on the primary side of the transformer are commuted to produce a rectangular voltage waveform \( V_i \) with a 50 % duty cycle. Now on the secondary of the transformer the semiconductors are switched to generate a rectangular voltage waveform \( V_o \) but with the ability to cause a phase shift \( \theta \) of \( V_i \) and \( V_o \). The following page shows the design flow chart for the medium frequency transformer.
Figure 40: Proposed design method for medium frequency transformer
3.5.1 Specifications

The first step of the proposed methodology is to define the transformer specifications which are listed below: Power level; primary rms voltage ($V_p$); secondary rms voltage ($V_s$); operational frequency ($f$), turns ratio ($n$), expected leakage inductance ($L_o$); square waveform factor ($K_f$); maximum current density ($J$); window utilization factor ($K_u$), and temperature rise.

3.5.1.2 Square Waveform Factor

The voltage across the medium frequency transformer in a dc-dc converter is usually a square waveform. Since the dc-dc converter consists of a medium frequency transformer and power semiconductor devices, the switching operations of the power semiconductor devices (as each bridge is usually controlled to produce a medium frequency square wave) produces a square wave voltage across the medium frequency transformer. In a square-wave-form the slope factor of the applied voltage is zero, and the ratio of the rms value to the average value is one. In half a cycle of a square-wave-form, the flux alternates from $+\Phi_m$ to $-\Phi_m$ which is equal to $4f\Phi_m$, where 4 is the square wave form factor, $f$ is the frequency and $\Phi_m$ is the maximum flux density.

3.5.1.3 Window Utilization Factor

In a transformer, the amount of winding that occupies the window area is usually described as the window utilization factor. It is the ratio of the overall winding area to the overall window area. This factor is largely influenced by the wire insulation, the fill factor, the effective window area, and the insulation factor. In this design, the window utilization factor ($K_u$) was assumed to be 0.5.

3.5.2 Transformer Configuration

3.5.2.1 Determination of Core and Material

The core of most traditional transformers operating at 50 Hz or 60 Hz are made of silicon, or nickel steel and the core losses of these materials increases when there is a rise in frequency. Hence, improvements have been made with different materials by changing
the processing quality as well as changing some of the ingredients used in producing these materials [103].

Before amorphous and nanocrystalline were developed, ferrite was widely used for magnetic cores for most power electronics applications as it exhibited reduced eddy current losses and the electrical resistivity was high, but due to reduced “flux saturation density (Bsat)”, they can be best suitable for applications requiring low power as well as voltage. Now with regard to medium frequency and high power, the characteristics expected of the core material are given below [52]:

- high saturation flux density (Bsat)
- low core losses, and
- the material should be able to continuously operate at high temperatures.

In contrast with the past, new core materials have been introduced which exhibit acceptable medium and high frequency characteristics and four of such materials evaluated for the transformer core are shown in table 3 [103], [104].

<table>
<thead>
<tr>
<th>Types of Magnetic material</th>
<th>Nanocrystalline</th>
<th>Fe-Amorphous</th>
<th>Ferrite</th>
<th>Silicon steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer</td>
<td>Vacuumschmelze</td>
<td>Metglas</td>
<td>Ferroxcube</td>
<td>JFE</td>
</tr>
<tr>
<td>Material</td>
<td>Vitroperm500F</td>
<td>2605SA1</td>
<td>3C93</td>
<td>10JNHF600</td>
</tr>
<tr>
<td>Bsat [T] @ 25°C</td>
<td>1.2</td>
<td>1.56</td>
<td>0.52</td>
<td>1.87</td>
</tr>
<tr>
<td>Rel. Permeability (0.1 T, 100 kHz)</td>
<td>15500</td>
<td>1200</td>
<td>1800</td>
<td>800</td>
</tr>
<tr>
<td>Curie Temp. (°C)</td>
<td>600</td>
<td>395</td>
<td>240</td>
<td>700</td>
</tr>
<tr>
<td>Continuous Operating Temp. (°C)</td>
<td>120</td>
<td>150</td>
<td>140</td>
<td>150</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mK)</td>
<td>10</td>
<td>10</td>
<td>~ 4</td>
<td>19.6</td>
</tr>
<tr>
<td>Cost</td>
<td>€€€€€€</td>
<td>€€€€€€</td>
<td>€€€€€€</td>
<td>€€€€€€</td>
</tr>
<tr>
<td>Density (g/cm3)</td>
<td>7.3</td>
<td>7.18</td>
<td>4.5</td>
<td>7.53</td>
</tr>
<tr>
<td>Electrical resistivity μΩm</td>
<td>1.15</td>
<td>1.37</td>
<td>5x10⁶</td>
<td>0.82</td>
</tr>
<tr>
<td>Lamination Thickness (mm)</td>
<td>0.023</td>
<td>0.025</td>
<td>0.028</td>
<td>0.1</td>
</tr>
<tr>
<td>Core fill Factor</td>
<td>0.7</td>
<td>0.83</td>
<td>1</td>
<td>0.9</td>
</tr>
<tr>
<td>Magnetostriction (ppm)</td>
<td>0.5</td>
<td>27</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Core Loss @ 0.3T, 20kHz (W/Kg)</td>
<td>10</td>
<td>43</td>
<td>8</td>
<td>80</td>
</tr>
</tbody>
</table>

Table 3: Characteristics of Magnetic Materials
As seen in table 3, Silicon steel possesses the highest value for saturation flux density (1.87 T) along with thermal conductivity of 18.6 W/mK and continuous operating temperature of 150 °C. It has a magnetostriction of 0.1 which means its audible noise is very low. Now with regard to lamination thickness, silicon steel has a high thickness than the other materials. Due to high thickness of silicon steel, this results in high core losses of this material. It can also be seen that Fe-amorphous from Metglas strikes a good balance between continuous operating temperature, saturation flux density and core loss, but its 27 ppm for magnetostriction and 10 W/mK for thermal conductivity are not as good as compared to those of Silicon steel. Nanocrystalline and Ferrite would appear to be materials with low core losses as compared to Fe-amorphous and Silicon steel but Ferrite has the lowest saturation flux density ($B_{sat}$) as compared to all the other materials. The main advantage of Ferrite is its high resistivity. In relation to cost, Nanocrystalline turns out to be the most expensive of all the materials. In all, Nanocrystalline appears to be the most suitable material in circumstances where cost is not considered. Metglas 2605SA1 and Vitroperm500F are considered in this thesis.

Another point to consider is the configuration of the core as it is an important point in transformer design and to the best of the authors’ knowledge there are four main concepts for transformer core for medium frequency operations as shown in figure 41 [63]:

a. Core type  

b. Shell type  

c. Matrix type, and  

d. Coaxial winding transformer (CWT)

![Figure 41: MFT Topologies](Image)

Figure 41: MFT Topologies-(a) Core Type (b) Shell Type (c) Matrix Type (d) CWT [63]
As seen in figure 41, the core type is made using single magnetic core designed such that there are two legs, with windings of LV coils on one side and HV coils on the other side. Shell type core is somewhat contrary to core type as it consists of two cores that encircle a single winding while the Matrix type is a combination of Shell and Core type topologies. Matrix core comprises of many parallel cores on its outer legs with LV windings while one central HV coil can be connected to its middle leg.

One of the principal advantages of the core type is that it reduces height of transformer as it employs two circuits for the primary and secondary windings. Nonetheless, the shell type can be considered to possess much better performances in regard to thermal management than the Core type. With the core type, the core material is covered by windings, and as a result of insulating materials poor conductivity as well as magnetic materials high sensitivity, thermal management of core type concept is considered poor [11]. Matrix concept has both advantages of Core and Shell types but there are two drawbacks associated with Matrix concept. The first drawback relates to cost, volume, weight and losses in the transformer, as they increase due to many parallel core units. Secondly the leakage inductance is high due to the fact that the primary as well as secondary turns are separated from each other and connected on different limbs [63], [105]. As such, with high leakage inductance the Matrix type is unsuitable for converters employing high power. The CWT has as its primary a single coil connected from an outer U-shaped conducting tube (LV winding) while inside the tube consists of the HV winding. Its magnetic core can be seen around outer conductor. Losses at high frequencies with Coaxial transformers are low as well as low leakage inductance [106]. Since the tube has limited current carrying ability, implementation of this concept can be limited to low power high frequency applications. The Shell type core is considered in this thesis.

3.5.2.2 Determination of Winding Material and Topology

The type of conductor to be employed for designing transformer windings of HV along with LV circuit must be taken seriously considering the fact that the design is applied to ‘medium frequency high power applications’ involving large currents which implies larger cross section of the conductor. So then a trade off involving the following parameters needs to be considered [60]:

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- effective utilisation of winding area
- low loss
- good thermal behaviour
- good electrical isolation

Now at high frequencies, eddy current will influence the selection of a conductor with smaller thickness. As a consequence, Litz conductor with wire strands that are separately insulated is considered and several topologies for Litz wire are shown in figure 42 (b-e) [63].

![Figure 42: Wire Structure in MFTs, (a) Solid, (b) and (c) Circular Litz, (d) Rectangular Litz, (e) Monofilar Rectangular, and (f) Foil [63]](image)

As shown in figure 42 (d) the rectangular Litz can be packed tightly around the conductors. Employing such a conductor would yield better use of space for the winding as well as higher copper density. Also it is possible to estimate conduction losses as the layers are parallel with the overall fluxes along the conductor. The thin foil depicted in figure 42 (f) can be used to minimise eddy current in high power transformers most especially for the primary winding as well as to enable the filling factor to be at its maximum. With these foil conductors, each turn is a winding layer and its thickness relies on skin depth. In cases of unity turns ratio, where the current magnitude is high, foil conductors can be used for the primary and secondary windings. Losses due to skin and proximity effects are minimized using Litz wires. The Litz wire is constructed so as to circulate the current density across the entire CSA of the wire, and they are made up of a group of strands which are individually insulated from each other. The strands can be woven or twisted. Litz wire is selected for the design of the transformer windings due to their ability to improve the efficiency of the transformer.
3.5.2.3 Insulation of Winding Material

Another point to consider after selecting the proper wire is insulation of the said wire, and one of its principal aims in MFHP is to facilitate insulation of high and low voltage circuits and to transport energy losses in the core and windings. Most commonly available solid materials for insulation are: epoxy, micares and PVC. There are three requirements expected from the insulation [60], [107]:

a. high dielectric strength, as this is necessary so that isolation distance can be small thereby making the transformer more compactable;

b. low loss, as it is most essential for insulation to possess low dielectric loss so as to reduce heat generated, and

c. high maximum operating temperature is a determinant factor which can limit transformer size and power density. It is important for the thermal behaviour to be stable.

In this design, the following assumptions are made. It is assumed that the distance through the insulation (diso) is 0.2 cm and the thickness of the interlayer insulation (dintra) is 0.026 cm.

3.5.3 Initialized Variables

At this stage, the following specifications are considered the initialized variables which are essential during optimization as they significantly influence the volume and efficiency of the transformer:

- current density \((J_o)\)
- number of primary turns \((N_p)\)
- maximum flux density \((B_m)\)
- frequency \((f)\)
- Number of strands per turn.
- the number of layers \((m)\)

The design variables are important in producing an optimum design. It may be asked that how can we find a suitable range of design variables to produce an optimum design. Firstly it is important to know our design goals, or objectives, of which in this case, it is
to achieve maximum efficiency and minimum volume. Secondly it is essential to understand the impact of the design variables upon the structure and performance of the transformer. For example, what would be the effect of higher current densities upon the structure and performance of the transformer? As a guide, some of the design equations (equations: 3.5, 3.6, 3.10, 3.14, 3.29, 3.31, and 3.38) gives an idea of what may be the impact of a low or higher value of any of the design variables. Note that there are some constraints involved, for example, the maximum allowable temperature rise. It would be unreasonable to proceed with the design of a 100 kVA transformer which achieves 99.9% efficiency with a volume of 0.01 m³ and a temperature rise of 5000 °C. So then several trial and errors were performed to ascertain the suitable range of values for the numbers of primary turns, the flux density and the winding current density to produces designs not exceeding 100 °C at maximum efficiency and minimum volume. Typical ranges for the numbers of primary turns can vary from 5 to 150, while typical ranges for the flux density can vary from 0.01 to 0.98 T, and for the winding current density, it can vary from 0.001 to 6 A/mm². Microsoft excel solver tool was employed to find the parameters for maximum efficiency. Although these may not correspond to the parameters for minimum volume, it gives a good indication of the values to be varied. So then, the choice of values used for the number of primary turns, the flux density and the current density were obtained from an optimization performed using MS excel solver.

3.5.4 Area Product
An MFT can be incorporated to substitute the traditional distribution transformer as it has been proven mathematically that operation at MF allows significant reduction in weight and size of the transformer, thus resulting to a small and highly efficient design which reduces maintenance and installation costs [63]. The benefit of raising transformer operating frequency is clarified from the equation relating to the transformer area product [98]:

\[
\text{Ap} = \frac{\sum \text{VA}}{\text{Kf} \cdot \text{Ku} \cdot \text{Bm} \cdot \text{Jo} \cdot f} \quad (3.5)
\]
Where: $A_p$ is the area product; $\Sigma VA$ is the power rating; $K_f$ is the square waveform factor; $K_u$ is the winding utilization factor; $B_m$ is the maximum flux density; $J_o$ is the maximum current density and $f$ is the frequency. As seen in (3.5), the area product ($A_w . A_c$) of the transformer is directly proportional the power rating (VA) and inversely proportional to waveform factor ($K_f$), winding utilization factor ($K_u$), maximum flux density ($B_m$), maximum current density ($J_o$) and the frequency. The reduced volume of the MFT causes a high loss density and when insulation is considered this small volume may present some challenges [60]. So then with exception of the frequency ($f$) all other variables found on the RHS of equation (3.5) can be obtained using the material properties, or the power rating ($U_{rms} . I_{rms}$). So then from equation (3.5), it is obvious that the winding window area and core area of the transformer is inversely proportional to the frequency. This therefore means that a transformer designed using large core and winding window area would employ low frequency as it has been the case with the traditional transformer.

### 3.5.5 Core Cross Sectional Area

In this design process the core cross sectional area ($A_c$) is calculated as shown in equation (3.6)

$$A_c = \frac{V_p}{K_f \cdot cf \cdot f \cdot N_c \cdot B_m \cdot N_p}$$  \hspace{1cm} (3.6)

Where $V_p$ is the rms primary voltage; $K_f$ is the square waveform factor; $cf$ is the core fill factor; $f$ is the frequency; $N_c$ is the number of c-cores forming overall core ($N_c = 2$ for shell type core), and $N_p$ is the number of primary turns.

### 3.5.6 Winding Window Area

The transformer winding window area is calculated as shown in equation (3.7)

$$A_w = B \cdot C$$  \hspace{1cm} (3.7)

Where: $B$ is the width of the core window and $C$ is the height of the core window.
3.5.7 Number of Secondary Turns

The secondary number of turns ($N_s$) is calculated as shown in equation (3.8)

$$N_s = \frac{N_p \cdot V_s}{V_p} \tag{3.8}$$

Where $V_p$ is the primary voltage; $N_p$ is the primary number of turns and $V_s$ is the secondary voltage.

3.5.8 Winding Dimensions

In relation to winding arrangements, although split winding arrangements can be used the concentric type is considered in this thesis. It is assumed that the height and width of the whole winding for the concentric arrangement are towards same direction as shown in figure 43.

![Concentric Winding Arrangement](image)

The direction of the layer is assumed to be in the perpendicular direction and depending on the number of turns as well as number of layers it is possible to calculate winding height when the type of conductor to be used has been chosen. The expression for winding height for a concentric arrangement is calculated using equation (3.9) [101]:

\[
\text{Winding height (hw)} = \left( \frac{N}{m} + 1 \right) d \tag{3.9}
\]

Where $N$ is the number conductors; $m$-represents number of winding layers and $d$ represents the diameter of a single conductor. The diameter of a single conductor is calculated using the expression.
\[ d = \sqrt{\frac{A_{wt} \cdot 4}{\pi}} \]  \hspace{1cm} (3.10)

Where \( A_{wt} \) is the area of a single conductor calculated using equation (3.11)

\[ A_{wb} = \frac{1}{J_0} \]  \hspace{1cm} (3.11)

In the above expression, \( I \) represents the current and \( J_0 \) is the maximum current density.

Same as the winding height the winding width is calculated using the expression [60]:

Primary winding width \((w_w)\) = \(2[m_p.d + (m-1)d_{intra}] + d_{iso}\)  \hspace{1cm} (3.12)

Where: \( d \) represents the diameter of a single conductor; \( d_{intra} \) signifies isolation between layers while \( d_{iso} \) represents minimum isolation distances and \( m \) represents number of winding layers. The mean length turn \((l_w)\) for a concentric winding is calculated as [101].

\[ l_w = (\frac{D}{2}.N_c + df + \frac{w_w}{2}) \cdot 2\pi + 2D \]  \hspace{1cm} (3.13)

Where, \( N_c \) is the number of cores (1 for core type and 2 for shell type); \( D \) represents core column depth; \( df \) is the thickness of the coil former to the central limb, \( w_w \) is the winding width

In order to comply with minimum clearance as well as creepage distances of the core, the coil former height and width are usually selected, and the winding volume is calculated as [60]:

\textbf{Winding volume (Vw)} = \( A_w \cdot l_w \)  \hspace{1cm} (3.14)

Where: \( l_w \)- represents mean length of winding; \( A_w \)- represents the winding window area.

The area occupied by the Litz wire \((Alw)\) is calculated as:

\textbf{Area of Litz wire (Alw)} = \( A_w \cdot K_u \)  \hspace{1cm} (3.15)

Where \( A_w \) is the winding window area and \( K_u \) is the window utilization factor.
3.5.9 Core Dimensions

The main dimensions of a shell type core are shown in figure 44. In figure 45, the front view of the shell core is shown.

![Core Dimensions](image)

Figure 44: Core Dimensions

![Shell Type Core](image)

Figure 45: Shell Type Core
So then the width of the core window is calculated as:

\[
\text{Width of core window (B)} = d_f + w_w + d_{\text{air}}
\]  
(3.16)

Where: \(d_{\text{air}}\) is the clearance distance to core; \(d_f\) is considered to be the isolation between interior part winding and core. Also, the height of core window is calculated as:

\[
\text{Height of core window (C)} = h_w + 2d_{\text{air}}
\]  
(3.17)

So then with dimensions of the core window it is possible to establish the external geometry of the core (E and F):

\[
\text{External width of core (E)} = 2B + 2A
\]  
(3.18)

\[
\text{External height of core (F)} = C + 2A
\]  
(3.19)

The mean core path \( (l_m) \) and the core volume \( (V_c) \) can be calculated using the expressions:

\[
l_m = 2(C+B) + 4A
\]  
(3.20)

\[
V_c = A_c . l_m
\]  
(3.21)

At this stage, core geometrical dimensions needed to hold the winding are established and the following equations are useful to calculate the core dimensions [60], [101].

\[
C = h_w + 2d_{\text{air}}
\]  
(3.23)

\[
B = d_f + w_w + d_{\text{air}}
\]  
(3.24)

\[
F = C + 2A
\]  
(3.25)

\[
E = 2B + 2A
\]  
(3.26)

\[
A_c = N_c . A . D . l_f
\]  
(3.27)

\[
l_m = 2(C+B) + 4A
\]  
(3.28)

\[
V_c = A_c . l_m
\]  
(3.29)
3.5.10 Core Loss

The voltage across the transformer in most power electronics applications appear to be a rectangular waveform while the magnetic induction is trapezoidal. The core loss can be calculated using the product of the volumetric power loss (equation 3.31), the core volume and the core fill factor. Note that the core volume is the product of the core cross sectional area and the mean core path (equation 3.29). Hence, increasing the core cross sectional area will increase the core loss. According to equation (3.4), the maximum flux density is directly proportional to the voltage and inversely proportional to $4*f*N*A_c$, where $f$ is the frequency, $N$ is the number of turns, and $A_c$ is the cross sectional area of the core. Increasing the flux density will increase the core loss. Figure 46 is the voltage and current waveforms of the Dual Active Bridge converter of figure 26, which was designed using LT Spice. As seen in figure 46, the input voltage is represented by $V (N005, N006)$, the output voltage is represented by $V (N004, N007)$ and $I (L1)$ represents the current through the inductor.

![Voltage Waveform](image1.png)

(a) Voltage Waveform

![Current Waveform](image2.png)

(b) Current Waveform

Figure 46: Voltage and Current Waveform for the Medium Frequency Transformer
As shown in figure 46, the voltage across the MF transformer is either positive, zero voltage, or negative, and the magnetic fluxes in the transformer core is either ramping upwards, ramping downwards or it remains constant. Hence, for an efficient design of the core, the core loss must be determined and the power equation given below is usually employed as it characterises loss in the core [108]:

\[
P_v = K \cdot f^\alpha \cdot B_m^\beta
\] (3.30)

This equation is widely known as “Steinmetz equation” where: Bm - is the peak induction of the sinusoidal excitation; f – is the frequency; the values of K, α, and β are the Steinmetz parameters and can be established from the material characteristics. Pv - is the time average power loss per unit volume. This equation is valid for limited frequencies as well as the range of flux density and has a major drawback due to the fact that it is valid for sinusoidal waveforms whereas the waveform for the MFT and most power electronics systems are non sinusoidal [109]. So then to overcome this challenge and calculate losses for non-sine waveforms, there are several other methods developed to calculate core loss, and these methods are shown in table 4 [60].

<table>
<thead>
<tr>
<th>Method</th>
<th>Waveform</th>
<th>Power equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Steinmetz equation (OSE)</td>
<td>Sine</td>
<td>( K \cdot f^\alpha \cdot B_m^\beta )</td>
</tr>
<tr>
<td>Modified Steinmetz equation (MSE)</td>
<td>Non-sine</td>
<td>(((8/\pi)^{\alpha-1} \cdot K \cdot f^\alpha \cdot B_m^\beta \cdot D^{\beta-\alpha+1}))</td>
</tr>
<tr>
<td>Improved generalized Steinmetz eq. (IGSE)</td>
<td>Non-sine</td>
<td>(2^{\alpha+\beta} \cdot k_i \cdot f^\alpha \cdot B_m^\beta \cdot D^{\beta-\alpha+1})</td>
</tr>
</tbody>
</table>

Table 4: Steinmetz Equations

As core losses are not usually zero during the period when zero voltage is supplied across the transformer as a result of magnetic relaxation, the “improved generalized Steinmetz equation” (3.31) is employed for determination of core losses as it includes relaxation effects:

\[
P_v = 2^{\alpha+\beta} \cdot k_i \cdot f^\alpha \cdot B_m^\beta \cdot D^{\beta-\alpha+1}
\] (3.31)
Where:

\[ k_i = \frac{K}{(2\pi)^{a+1}} \int_{0}^{2\pi} [\cos \phi]^a 2^{\beta-a} d\Theta \]

the material characteristics \( K, \alpha, \) and \( \beta \) are same as in the original Steinmetz equation, \( f \) is the frequency, \( B_m \) is peak magnetic induction of the square wave excitation and \( D \) is the duty ratio of a square voltage waveform [60].

3.5.11 Winding Loss

When transformer frequency increases to medium and high frequency range, skin and proximity effects cause ohmic losses to increase. Therefore increasing transformer frequency increases ohmic losses [108]. So then the following effects must be taken into account with wires incorporating many strands:

- the skin effect of each strand and entire wire;
- proximity effects from internal fields within, along with proximity effects due to external fields of other wires.

Now to reduce effects of skin along with proximity, Litz wire can be employed. Usually, Litz wires have circular shapes and each strand is placed such that they equally occupy each position within the cable, but nowadays specially compact Litz wires having rectangular shapes exist [98]. Now with skin effect, the current may flow mainly at the skin of the conductor (outer surface) and a certain level known as skin depth, and most of these current flows at equivalent penetration depth (skin thickness) or skin depth defined as [74]:

\[
\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}
\]

(3.32)

Where \( \delta \) is skin depth (mm), \( f \) is the frequency of the waveform (Hz), \( \mu \) is the permeability of the material and \( \sigma \) is the conductivity.

Due to non-sinusoidal currents through the transformer windings, harmonics are considered when calculating the winding loss. Harmonics introduce power quality issues and they produce overheating in transformers, capacitor banks and cause the false tripping of protective equipments. They reduce the efficiency and reliability of the power system.
The winding loss in a medium frequency transformer increases due to harmonics. In this thesis, winding loss includes losses up to the 9th harmonic because as shown in figure 47 the first 9 harmonics are the largest. Note that the winding loss is high when a high level of harmonic is considered and vice-versa, but at a certain region, an increase in harmonics does not result to a significant change in winding loss. For example, the winding loss at the 25th harmonic is similar to the winding loss at 100th harmonic. In figure 47, a waveform of the harmonic current through the medium frequency transformer is shown.

Figure 47: Harmonic analysis of the current waveform as shown in figure 46

Figure 48: Percentage of Harmonic Currents and Order of Harmonic Components
Figure 48 shows the percentage of harmonic currents in figure 47. As previously mentioned, the results show that as from the 7th harmonic, the percentage of harmonic currents is below 10%. The percentage harmonic currents between the 25th and the 51st harmonic are approximately equal.

If the entire strands are transposed evenly, current in the primary is distributed among individual strands and local skin effects are produced. In round conductors the value of the skin effect can be calculated using this expression [73]:

\[ K_s = \frac{ber_2(Y) \ \text{ber}'(Y) - \text{bei}(Y) \ \text{bei}'(Y)}{\text{ber}'(Y)^2 + \text{bei}'(Y)^2} \]  \hspace{1cm} (3.33)

In [60] the expression is reduced to a low penetration ratio and expressed as:

\[ K_s = \frac{2}{r} + \frac{y^3}{96} \] \hspace{1cm} (3.34)

As equation (3.33) is expressed in Bessel function, Taylor series expansion can be used to obtain these values as suggested in [110]. Hence, equation (3.35) is applied for theoretical implementation of skin effect loss [73].

\[ K_s = \frac{2}{\sqrt{2}} \left( \frac{1}{\xi} + \frac{1}{328} \xi^3 - \frac{1}{3214} \xi^5 + - - - \right) \] \hspace{1cm} (3.35)

When a conducting object is subjected to a magnetic field that varies in time, eddy currents are usually induced in that conducting material and quite often eddy current exists in most electrical equipments. Irrespective of the fact that they can be useful in the case of induction heating or, be of disadvantage in the case of the cores of transformers and electrical machines, a method to ascertain these losses is essential in the design phase of the MF transformer. In each strand, the AC leakage flux induces circulating eddy currents and there are power losses as a result of eddy current induced by the external AC leakage [108]. In a round conductor, the proximity effect can be calculated as shown in equation 3.36.

\[ K_p = \frac{ber_2(Y) \ \text{ber}'(Y) + \text{bei}_2(Y) \ \text{bei}'(Y)}{\text{ber}'(Y)^2 + \text{bei}'(Y)^2} \] \hspace{1cm} (3.36)

In [60] the equation is reduced to low penetration ratio. Therefore proximity loss is:
\[ K_p = -\frac{\gamma^3}{16} \] (3.37)

As equation (3.36) is expressed in Bessel function, Taylor series expansion can be employed to obtain these values. Thus, equation (3.37) is employed for theoretical implementation of proximity effect losses [73], [110]:

\[ K_p = \frac{1}{\sqrt{2}} \left( -\frac{1}{2^5} \zeta^3 + \frac{1}{2^{12}} \zeta^7 + \cdots \right) \] (3.37)

Note that in a transformer the dc resistance is usually constant but the ac resistance varies with the frequency. The skin and proximity effect influences the ac resistance. As the frequency increases, the ac resistance increases as well. The skin and proximity effects, in other words, can be described as an increase in resistance when the frequency increases. Should the skin and proximity effects be represented by a factor termed the resistance factor \((F_r)\), then the ac resistance is the product of the resistance factor \((F_r)\) and the dc resistance \(R_{dc}\). The winding loss is calculated using the expression

\[ P_w = I_s^2 R_{acp} + I_s^2 R_{acs} \] (3.38)

Where: \(I\) is the rms current, \(R_{acp}\) is the primary ac resistance, \(I_s\) represents the secondary rms current, and \(R_{acs}\) is the secondary ac resistance. The winding loss will be determined for each harmonic current along with their resistance factor.

In a round litz wire, the resistance factor \((F_r)\) is calculated as shown in equation (3.39).

\[
\text{Resistance factor } (F_r) = \frac{\Upsilon}{2} \left[ K_p - 2\pi \frac{4(m^2 - 1)}{3} K_s \right]
\] (3.39)

Where: \(\Upsilon\) is the penetration ratio, \(K_p\) is the proximity effect factor, \(m\) is the number of layers and \(K_s\) is the skin effect factor.

With regard to each harmonic component, the penetration ratio is calculated as:

\[
\text{Penetration ratio } \Upsilon = \frac{d_w}{\delta} = \frac{d_w}{\delta} \sqrt{\pi \cdot f \cdot \mu_0 \cdot \sigma}
\] (3.40)
Where: \(d_w\) is the diameter of a single conductor; \(\delta\) is the skin depth; \(f\) is the frequency; \(\nu\) is the harmonic number; \(\mu_0\) is the permeability of free space (H/m), and \(\sigma\) is the electrical conductivity (S/m).

The dc resistance can be determined as shown in equation 3.41.

\[
R_{dc} = \frac{\text{MLT} \cdot N}{N_{spt} \cdot \pi \cdot \sigma \cdot r_s^2}
\]  

(3.41)

Where: MLT is the mean length turn of the winding, \(N\) is the number of turns, \(N_{spt}\) is the number of strands per turn, \(\sigma\) is the conductivity of copper and \(r_s\) is the radius of a single strand.

The radius of a single strand \((r_s)\) is calculated using the expression shown (3.42). Where \(d_{sst}\) is the diameter of a single strand.

\[
r_s = \frac{d_{sst}}{2}
\]  

(3.42)

Now the diameter of a single strand can be calculated using the expression (3.43), where \(d_w\) is the diameter of a single turn and \(N_{spt}\) represents the number of strands per turn.

\[
d_{sst} = \frac{d_w}{N_{spt}}
\]  

(3.43)

### 3.5.12 Temperature Rise

Thermal considerations of transformer design ensures that temperature rise due to losses is within certain limits. As it was assumed during the initial stage of this design that temperature rise is 75°C it is essential to verify the validity of such assumptions. A design can be considered acceptable if the calculated temperature rise is below the assumed temperature rise. In the event that the calculated temperature rise exceeds the assumed value, the design procedure needs to be repeated with possible modification of initialized variables such that the core sizes can be modified [111]. Also, excessive temperatures can deteriorate transformer windings and to minimise such event, a heat dissipation method should be employed. In some cases, oil immersion, or other forms of cooling can be
employed but the MFT is often quite small and cooling through natural convection can be sufficient to dissipate heat.

In this thesis, the method for heat dissipation is natural air cooling largely through convection and Newton convection expression is used to calculate temperature rise. With these, temperature rise is determined from thermal resistance of selected core along with overall losses (core and winding losses), of which the thermal resistance is provided from manufacturer’s data, or can also be known from the volume of the winding and the winding fill factor. Thus, temperature rise is calculated as shown in equation 3.44 [71].

\[ \Delta T = R_{th} \cdot P_L \]  

(3.44)

Note that the path of the thermal resistance of the core loss and winding loss are usually in parallel. So then equivalent \( R_{th} \) (thermal resistance) can be calculated as:

\[ \frac{1}{R_{th}} = \frac{1}{R_w} + \frac{1}{R_c} = h \cdot A_t \]  

(3.45)

Where: \( R_{th} \) is thermal resistance of transformer surface and ambient; \( P_L \) represents total losses (core and winding losses), \( R_w \) is the thermal resistance path of the winding; \( R_c \) is the thermal resistance path of the core; \( H \) is the height of the transformer; \( A_t \) is transformer surface area, and \( h \) is convection heat transfer coefficient. In a transformer, the relationship between ‘h’ and ‘H’ can be described as shown in expression (3.46).

\[ h = 1.42 \left( - \frac{\Delta T}{H} \right)^{0.25} \]  

(3.46)
3.6 Design of a High Power Medium Frequency Transformer

In this section, the design methodology shown in figure 40 was employed to design a high power medium frequency shell type transformer in a dual active bridge (DAB) dc-dc converter stage of a solid state transformer. The details of the transformer are shown in table 5.

<table>
<thead>
<tr>
<th>Specifications</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power rating (kVA)</td>
<td>120 kVA</td>
</tr>
<tr>
<td>Primary voltage ($V_p$)</td>
<td>10 kV</td>
</tr>
<tr>
<td>Secondary voltage ($V_s$)</td>
<td>400 V</td>
</tr>
<tr>
<td>Frequency (f)</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Square waveform factor ($K_f$)</td>
<td>4</td>
</tr>
<tr>
<td>Temperature rise</td>
<td>75 °C</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>25 °C</td>
</tr>
<tr>
<td>Window utilization factor ($K_u$)</td>
<td>0.8</td>
</tr>
<tr>
<td>Minimum isolation voltage ($U_{Ni}$)</td>
<td>1500 V</td>
</tr>
<tr>
<td>Expected leakage inductance ($L_s$)</td>
<td>1.6 μH</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.99</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Selected core</td>
<td>Vitroperm500F²</td>
</tr>
<tr>
<td>Core fill factor</td>
<td>0.84</td>
</tr>
<tr>
<td>$B_{sat} = 1.2$ T, $\alpha = 1.32, \beta = 2.1, K_c = 2.3$</td>
<td></td>
</tr>
<tr>
<td>Density of Vitroperm500F² = 7350 kg/m³</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Initialize variables</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current density ($J_o$)</td>
<td>0.02 A/mm²</td>
<td>1.18 A/mm²</td>
</tr>
<tr>
<td>Flux density ($B_m$)</td>
<td>0.1 T</td>
<td>0.25 T</td>
</tr>
<tr>
<td>Primary number of turns</td>
<td>8</td>
<td>58</td>
</tr>
</tbody>
</table>

Table 5: Transformer Details

The transformer was designed using excel. The overall aim of this work was to achieve a compact and efficient design using the design approach shown in figure 40. In all, one thousand three hundred and fifteen (1315) transformers were designed to operate at 120 kVA, 20 kHz, with a primary voltage of 10 kV and secondary voltage of 400 V by varying the current density ($J_o$), the flux density ($B$) and the number of primary turns ($N_p$). This represents a “brute force” optimization approach where all designs with a given range of the variables $J_o, B$ and $N_p$ are evaluated. All transformer designs corresponding to every
given combination of these variables were evaluated. The start, end points and step size of the variables were specified. In this example, the current density was varied between 0.02 A/mm$^2$ to 1.18 A/mm$^2$ with a step size of 0.04 A/mm$^2$. The flux density was varied between 0.1 T to 0.25 T with a step size of 0.05 T, and the number of primary turns was varied between 8 to 58 with a step size of 5.

3.6.1 Results

3.6.1.2 Volume Reduction and Temperature Rise

One of the principal aim of using medium frequency as discussed in the literature is to achieve a reduction of the size of the transformer. This section shows the result of thirty (30) transformer designs with varying current densities. In figure 49 on the next page, results of the relationship between transformer efficiency, temperature rise and current density are shown. In figure 50, results of the relationship between transformer volume, temperature rise and current density are shown. The winding current density is one of the parameters which has a very significant influence on the size and efficiency of the transformer. To illustrate this in this section we show the variation of transformer size with current density only, with number of turns and flux density fixed. The current density is varied from 0.02 A/mm$^2$ to 1.18 A/mm$^2$ with a step size of 0.04 A/mm$^2$ in each design, and the flux density was fixed at 0.1 T. The number of primary turns was fixed at 8. As seen in figure 49, higher current densities imply higher temperature rise. The efficiency increases as the current density increases but the maximum efficiency is limited due to the temperature rise exceeding the specified limit of 100 $^0$C. As seen in figure 49, the transformer efficiency was set to zero to indicate that the temperature rise is greater than 100 $^0$C. Also, in figure 50, the volume of the transformer was set to zero to indicate that the temperature rise has exceeded 100 $^0$C. According to figure 50, transformer volume reduces when the current density increases, but the reduction of volume is limited by the temperature rise. Low current density results to a large volume and low temperature. According to equation (3.5), with a fixed power level, an increase in current density reduces the area product of the transformer which clarifies why the volume reduces when the winding current density increases. Also, as highlighted in equation (3.11), the area of a single conductor reduces when the current density increases. According to the results,
the temperature rise is proportional to the current density. The effects of varying $J_0$, $B$ and $N_p$ are shown on the next page.

Figure 49: Result of Efficiency, Temperature rise and Current density

Figure 50: Result of Temperature rise versus Volume and Current density
3.6.1.3 The Effect of Varying $J_0$, $B$ and $N_p$

Figure 51 shows the impact of varying the current density ($J_0$), and the number of primary turns ($N_p$) while keeping the flux density ($B$) fixed. The graph shows the result of sixty (60) transformers designed to operate at 120 kVA, 20 kHz, with a primary voltage of 10 kVA and secondary voltage of 400 V. During this investigation, the numbers of primary turns was 8 for thirty transformers and $N_p$ was changed to 13 for the remaining transformers. When $N_p$ was 8 (the red curve), the current density varied from 0.02 A/mm$^2$ to 1.18 A/mm$^2$ with a step size of 0.04 A/mm$^2$ in each design, and the flux density was 0.1 T. Now for the remaining thirty transformers the number of primary turns was changed to 13 (the blue curve) and the current density varied from 0.02 A/mm$^2$ to 1.18 A/mm$^2$ with a step size of 0.04 A/mm$^2$ in each design.

These curves show that by increasing the number of turns the relative magnitudes of the winding and core loss can be changed and in particular for $N = 13$, winding and core loss became much more similar in value. Efficiency is increased only slightly. As seen in figure 51, when $N_p$ was 8 (the red curve), the maximum efficiency obtained was 97.44 % with a core loss of 2250 W and winding loss of 902.83 W. This efficiency was achieved at the point where the current density was 0.8 A/mm$^2$. Now when the current density was 0.82 A/mm$^2$, the transformer efficiency was zero. The reason for the zero efficiency is as a result of the temperature rise exceeding its stated limit as discussed earlier. When the primary number of turns were 13 (the blue curve), the maximum efficiency was 97.94 % and this occurred at the point where the current density was 0.42 A/mm$^2$ with a core loss of 1330 W and winding loss of 1192 W. This result when $N_p$ was equal to 13 showed

![Figure 51: Result of Sixty Transformers, for N=8, Red curves and N = 13, Blue curves](image-url)
that, the optimum design still seems to be roughly in the region where the core loss and the winding loss are equal. In all, the results indicated that, an optimum design for the MFT can be achieved by varying the number of primary turns, the flux density and the current density. The relationship between the transformer efficiency, current density and transformer volume are shown in figure 52. Here it can be seen that transformer volume reduces as the current density increases and both transformer efficiency and volume fall to zero when the temperature exceeds the specified limit as previously discussed in section 3.6.1.2. The results here suggest that with higher numbers of primary turns (the blue curve Np=13), the transformer volume and efficiency fell to zero at approximately 0.45 A/mm$^2$, while in relation to the design with Np = 8 (the red curve), the efficiency and volume fell to zero at approximately 0.82 A/mm$^2$.

![Figure 52: Result of Sixty Transformers, for N=8, Red curves and N = 13, Blue curves](image)

In figure 52 it can be seen that with lower numbers of primary turns, it is possible to operate the transformer at higher current densities but this results to a high core loss as shown in figure 51. Also, the results showed that, with a higher number of turns, reduced volume and core loss were achieved (Np=13) than with fewer number of turns (Np=8) as shown in figure 51. With Np=13, the core loss was equal to the winding loss for many designs. These suggest that the optimum number of primary turns for the design of the medium frequency transformer can be 13.
3.6.1.4 Transformer Losses and Volume

The results shown in this section include only designs not exceeding the specified temperature limits. Here the designs are plotted as losses vs. volume and temperature (figure 53), which includes core loss, winding loss and the temperature rise.

![Graph showing losses vs. volume and temperature](image)

Figure 53: Transformer losses and Volume

In figure 54, the designs are plotted as core loss and volume only, while figure 55 shows the winding loss and transformer volume. Figure 55 shows the efficiency vs. volume relationship. According to figure 53, at minimum volume the winding loss tends to dominate the core loss as the volume reduces. Core loss was high at larger volumes and reduces with volume reduction. Figure 53 show that volume reduction is limited by the temperature rise, mainly caused by the winding loss due to skin and proximity effects. As seen, when the volume reduces the winding loss increases as well as the temperature.

With fewer number of primary turns such as 8, the core loss increases. Core loss relates to the cross sectional area of the core ($A_c$), so with a constant voltage, reduction in the numbers of primary turns increases the core cross sectional area.

With figure 54, the designs are plotted as core loss versus transformer volume only, it shows how the core loss reduces with volume reduction. According to the results, core losses are much higher at larger volumes. This means the core loss largely depends upon the volume of the transformer.
Figure 54: Core losses versus Volume

Figure 55 shows the designs plotted as winding loss versus transformer volume. It shows that, with larger transformer volumes, winding losses are minimized, while as the transformer volume reduces the winding loss increases. The reduction of transformer volume is limited by the winding loss. So then as volume reduction was good for the core loss as shown in figure 54, on the other hand, volume reduction caused an increase in winding loss as shown in figure 55.

Figure 55: Winding losses versus Volume

Figure 56 shows how efficiency varies with transformer volume for the designs shown in figure 53, and allows us to see the limits of the efficiency-volume trade-off. In general higher efficiencies are achievable at lower volumes. The achievement of higher efficiency and lower volume is not possible due to the temperature rise constraint. In all, the best
design was found at the point where the number of primary turns was 13, the current density was 0.42 A/mm\(^2\) and the flux density was 0.1 T and the transformer efficiency was 97.94 % with a volume of 0.154 m\(^3\). At that point, the core loss was 1330 W and winding loss 1192 W. In figure 57, the Pareto extract of the designs in figure 56 are shown.

Figure 56: Transformer Efficiency and Volume

Figure 57: Pareto extract of Figure 54
3.7 Conclusion

In this chapter, a high power medium frequency transformer was designed and optimized. The work done shows the limits of the efficiency and volume trade off. The findings revealed that the achievement of reduced volume and higher efficiency in a transformer is not possible due to the temperature rise constraint caused by the winding loss due to skin and proximity effects.

It was found that an optimum design can be achieved by varying the numbers of primary turns, the winding current density and the flux density. The winding current density has a significant influence upon the structure and performance of the transformer. Higher current densities imply higher temperature rise. Though the efficiency increases as the current density increases, the maximum efficiency is limited due to the temperature rise. Low current density results to a large volume and low temperature. With a fixed power level, an increase in current density reduces the size of the transformer. Also, the area of a single conductor reduces when the current density increases, and increases at low current densities.

The number of primary turns employed for the design of the transformer has an effect upon the relative magnitude of the winding and core loss. There are regions where the core loss equals the winding loss at a particular number of turns. This shows that the optimum design still seems to be roughly in the region where the core loss and the winding loss are equal. With lower numbers of primary turns, it is possible to operate the transformer at higher current densities but this result to a high core loss. Reduced number of primary turns produces larger core volumes and high core loss, but with a higher number of turns, the core volume and loss are minimised. Core loss relates to the cross sectional area of the core ($A_c$), so with a constant voltage, reduction in the numbers of primary turns increases the core cross sectional area. It was found that the optimum number of primary turns for the design of the medium frequency transformer can be 13. The flux density also has an effect on the core loss. With higher flux densities, core loss increases and vice-versa.

In all, it has been shown that, at minimum volume the winding loss tends to dominate the core loss. Core loss was high at larger volumes and reduces with volume reduction. Transformer volume reduction is limited by the temperature rise, mainly caused by the winding loss due to skin and proximity effects.
Chapter 4: Validation and Investigation of Optimum Frequency

4.1 Introduction
This chapter validates the design methodology used in chapter three by comparing the results obtained from this design with those of other publications. It also investigates how high can be the frequency to achieve minimum volume and losses using different power levels (50 kVA, 100 kVA, and 500 kVA,) when the transformer is constructed using Vitroperm500F. Metglas (2605SA1) was compared with Vitroperm500F to see which material is suitable than the other.

4.2 Validation
A spread sheet was developed for design and optimization of the medium frequency transformer and validation was performed by verifying the results produced by the tool with those of other designs. As seen in table 6, the parameters used in comparing the results are the power level of the transformer, its frequency, the input and output voltages, core loss, winding loss, efficiency, winding type and the type of core used.

As seen in table 6 on the following page, the work carried out in [112] shows that a transformer can be developed with a power level of 120 kW operating at 20 kHz with a primary voltage of 10 kV and secondary voltage of 400 V. During this simulation, the numbers of primary turns were 8, the winding current density was 0.02 A/mm\(^2\), and the peak flux density was 0.12 T. The results of this test carried out in [112] is as follows: the efficiency was 95.72 %, the winding loss was 1.13 kW; the core loss was 4.24 kW; the core cross sectional area was 775 cm\(^2\); the winding window area was 1451 cm\(^2\); the core volume was 0.41 m\(^3\); the volume of the transformer was 0.835 m\(^3\), and the temperature rise was 61.13 °C. The results produced from the design tool in this thesis are identical to the results in [112]. Note that the transformer was not built and tested.

The work carried out in [113] showed that an efficiency of 99.54 % can be achieved from a 25 kVA / 4 kHz transformer that has a flux density of 0.1 T and a winding current density of 2 A/mm\(^2\). The core and winding losses were 58 W and 57.7 W respectively. Now when compared with this design, an efficiency of 99.52% was achieved, and the core and winding losses were 65.2 W and 54.5 W respectively as shown in table 6.
<table>
<thead>
<tr>
<th>Description</th>
<th>M</th>
<th>C</th>
<th>M</th>
<th>C</th>
<th>M</th>
<th>C</th>
<th>M</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>[112]</td>
<td>[113]</td>
<td>[98]</td>
<td>[60]</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Power Level</td>
<td>120 kW</td>
<td>120 kW</td>
<td>25 kVA</td>
<td>25 kVA</td>
<td>3 MW</td>
<td>3 MW</td>
<td>36.3 kW</td>
<td>36.3 kW</td>
</tr>
<tr>
<td>Frequency</td>
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<td>20 kHz</td>
<td>4 kHz</td>
<td>4 kHz</td>
<td>500 Hz</td>
<td>500 Hz</td>
<td>2 kHz</td>
<td>2 kHz</td>
</tr>
<tr>
<td>Vin</td>
<td>10 kV</td>
<td>10 kV</td>
<td>2.4 kV</td>
<td>2.4 kV</td>
<td>300 kV</td>
<td>33 kV</td>
<td>1.1 kV</td>
<td>1.1 kV</td>
</tr>
<tr>
<td>Vout</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>400 V</td>
<td>3 kV</td>
<td>3 kV</td>
<td>1.1 kW</td>
<td>1.1 kW</td>
</tr>
<tr>
<td>Core loss</td>
<td>4.24 kW</td>
<td>4.6 kW</td>
<td>58.03 W</td>
<td>65.2 W</td>
<td>3.34 kW</td>
<td>4.14 kW</td>
<td>112 W</td>
<td>123.4 W</td>
</tr>
<tr>
<td>Winding loss</td>
<td>1.13 kW</td>
<td>1.1 kW</td>
<td>57.7 W</td>
<td>54.5 W</td>
<td>3.4 kW</td>
<td>3.6 kW</td>
<td>108 W</td>
<td>92 W</td>
</tr>
<tr>
<td>Efficiency</td>
<td>95.72 %</td>
<td>95.52 %</td>
<td>99.54 %</td>
<td>99.52 %</td>
<td>99.78 %</td>
<td>99.74 %</td>
<td>99.39 %</td>
<td>99.4 %</td>
</tr>
<tr>
<td>Volume</td>
<td>835 Ltrs</td>
<td>722 Ltrs</td>
<td>2.3 Ltrs</td>
<td>2.6 Ltrs</td>
<td>500 Litre</td>
<td>520 Ltrs</td>
<td>10 Ltrs</td>
<td>9.7 Ltrs</td>
</tr>
<tr>
<td>Winding Typ.</td>
<td>Litzwire</td>
<td>Litzwire</td>
<td>Litzwire</td>
<td>Litzwire</td>
<td>Litzwire</td>
<td>Litzwire</td>
<td>Litzwire</td>
<td>Litzwire</td>
</tr>
<tr>
<td>Core</td>
<td>VP500F</td>
<td>VP500F</td>
<td>VP500F</td>
<td>VP500F</td>
<td>VP500F</td>
<td>Metglas</td>
<td>Metglas</td>
<td>Metglas</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

M – Measured, C – calculated

Table 5: Validation Table

In [98], a transformer is developed with a power level of 3 MW, it has a maximum flux density of 1 T and a maximum current density of 4 A/mm². The transformer had 110 primary turns and 10 secondary turns. Though the author in [98] did not provide the number of strands used, a trial and error based design approach was conducted for the number of strands. The measured results indicate 3.34 kW for core loss and 3.39 kW for winding loss. The results in table 5 indicate that the calculated winding loss and core loss are identical to the measured value. The measured value for the transformer volume was 0.5 m³ while the calculated value was 0.52 m³.

The results obtained in [60] were identical to those obtained from the design in this thesis. The prototype produced in [60] had 38 turns for the primary and secondary windings. The maximum flux density was at 0.48 T, while the maximum current density was at 1.75 A/mm², with a primary current of 33 A. The measured winding loss was 108 W and the measured core loss was 112 W. The results obtained from this design tool indicate 92 W for the winding loss and 123.4 W for the core loss. The volume of the transformer in [60] was 10 litres while the calculated volume was 9.7 litres. Although in [60] the number of strands were omitted from the report, a trial and error based design approach was
performed for the number of strands. In all, the measured results are identical to the calculated results.

As already mentioned above, and as seen in table 6, the results obtained from this design tool are similar to the values compared in other publications. In all, results presented in this section confirm the validity of this tool as a useful instrument for design and optimization of a medium frequency transformer.

4.3 Optimum Value of the Operating Frequency

This section investigates how high can be the frequency to achieve minimum volume and losses. In achieving this, a graph of efficiency and volume was plotted for transformers operating at 5 kHz, 10 kHz, 20 kHz and 30 kHz. Three graphs are plotted to investigate how high is the frequency at power levels of 50 kVA, 100 kVA and 500 kVA. A “brute force” optimization approach was employed. The transformers were designed to operate at a primary voltage of 10 kVA and secondary voltage of 800 V. The current density is varied between 0.1 A/mm² to 7.35 A/mm² with a step size of 0.25 A/mm². The flux density is varied between 0.05 T to 0.2 T with a step size of 0.05 T, and the number of primary turns is varied between 10 to 110 with a step size of 10.

4.3.1 Optimum Operating Frequency at 50 kVA

Results for optimum designs for a 50 kVA transformer operating at 5 kHz, 10 kHz, 20 kHz and 30 kHz shown in this section. In figure 58, all of the designs not exceeding the temperature limit are shown. Figure 58 shows the relationship between the transformer efficiency and volume for the aforementioned frequencies. In figure 59, an extract of the Pareto front for the results in figure 58 are shown. The Pareto frontier is a technique used to represent the most efficient results among a group of designs, and these results are known as the Pareto optimal results. A set containing all of the Pareto optimal results forms the Pareto front. It allows decisions to be made for a group of designs using just the most efficient results and provide a solution in the midst of conflicting objectives. In this case, we were concerned with the efficiency and volume of the transformer. The Pareto analysis were carried out using Microsoft excel, where among several transformer designs, the transformer volume was sorted from the smallest value to the largest value,
after which the transformer designs were divided into groups and the maximum efficiency among each group of transformer volumes were identified and used to plot the Pareto front. This was done for each of the frequencies (5 kHz, 10 kHz, 20 kHz and 30 kHz). With figure 58 and figure 59, the limits of the efficiency and volume trade-off can be clearly seen.

Figure 58: Efficiency versus Volume for Vitroperm500F at 50 kVA

Figure 59: Pareto extract of Figure 58
These results show that, designs employing 30 kHz are less efficient, meanwhile designs at 20 kHz were more efficient than those at 30 kHz, and reduction in volume from 20 kHz to 30 kHz was insignificant. The temperature rise constraint limited volume reduction at 30 kHz. The best designs were achieved at 10 kHz in terms of volume reduction and efficiency. These results suggest that 5 kHz and 10 kHz appear to be the suitable frequencies for the 50 kVA transformer. Although in equation (3.5), it can be seen that higher frequencies imply reduced volume, the reasons for the limitation of volume reduction with increasing frequency are shown in figure 60.

Figure 60: Transformer Volume versus Temperature

In figure 60, the temperature versus volume graph is shown. The limitation of volume reduction with increasing frequency is caused by the temperature rise, as the frequency increases, the temperature increases as well. Designs at 30 kHz were produced at a higher temperature than those at 20 kHz. Though the temperature rise for the 5 kHz and 10 kHz designs were lower than those at 20 kHz and 30 kHz, it can be seen for all of the
frequencies that, as the volume reduces the temperature increases such that it gets to a region where the design exceeds the specified temperature limit and results to an invalid design. The reasons for the rise in temperature with volume reduction are clarified in figure 61 and figure 62 on the next page. The reduction in efficiency can be as a result of a number of factors such as: the numbers of primary turns used; the flux density, the winding current density and the frequency. Note that the ac resistance increases with frequency. As the frequency increases, the ac resistance increases which results to an increase in winding loss. In figure 61 the relationship between the winding loss and volume for all of the frequencies are shown, while in figure 62, the core loss versus volume graph is shown. It can be seen that as the transformer volume reduces, the winding loss increases which results to increased temperature. In figure 61 it can be clearly seen that at 30 kHz the winding loss is much higher than the winding losses at 5 kHz and 10 kHz. Higher frequencies imply higher winding losses due to skin and proximity effects and leads to higher temperatures as shown in figure 60.

Figure 61: Transformer Winding loss and Volume Reduction
In figure 62, the results show that the core loss is proportional to the volume of the transformer. With larger volumes, the core loss is much higher, whereas as the volume reduces, the core loss reduces. It can be seen that, while the winding loss rises as the volume reduces, on the other hand, the core loss falls as the transformer volume reduces. As the frequency increases, the core loss increases as shown in figure 62.

Table 6 on the next page shows the design variables that produced the design at minimum volume and the designs at maximum efficiency for all of the frequencies. Note that the core loss and the winding loss are roughly of the same magnitude, so then there are designs for which they can be equal. According to figure 58 and figure 59, along with table 6, the design which gave the minimum volume was not same as the design which gave the maximum efficiency for the 5 kHz, 10 kHz and 20 kHz frequencies. In relation to the 30 kHz frequency, the design which gave the minimum volume was same as the design which gave the maximum efficiency.
Table 6: Optimum Designs at 50 kVA

<table>
<thead>
<tr>
<th>Freq. (kHz)</th>
<th>Design</th>
<th>Np</th>
<th>J₀  (A/mm²)</th>
<th>Bₘ (T)</th>
<th>Pₚ (W)</th>
<th>Pₖ (W)</th>
<th>Volume (m³)</th>
<th>η (%)</th>
<th>ΔT (⁰C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Min. Vol.</td>
<td>110</td>
<td>4.85</td>
<td>0.4</td>
<td>143.2</td>
<td>207</td>
<td>0.0091</td>
<td>99.3</td>
<td>94.8</td>
</tr>
<tr>
<td>5</td>
<td>Max. η</td>
<td>110</td>
<td>0.6</td>
<td>0.1</td>
<td>73.2</td>
<td>101</td>
<td>0.0826</td>
<td>99.65</td>
<td>11.13</td>
</tr>
<tr>
<td>10</td>
<td>Min. Vol.</td>
<td>110</td>
<td>2.6</td>
<td>0.3</td>
<td>135</td>
<td>198</td>
<td>0.0078</td>
<td>99.34</td>
<td>99.04</td>
</tr>
<tr>
<td>10</td>
<td>Max. η</td>
<td>90</td>
<td>0.85</td>
<td>0.1</td>
<td>142</td>
<td>116</td>
<td>0.035</td>
<td>99.48</td>
<td>27</td>
</tr>
<tr>
<td>20</td>
<td>Min Vol.</td>
<td>70</td>
<td>3.6</td>
<td>0.1</td>
<td>354.1</td>
<td>114</td>
<td>0.0135</td>
<td>99.07</td>
<td>97.9</td>
</tr>
<tr>
<td>20</td>
<td>Max. η</td>
<td>60</td>
<td>1.6</td>
<td>0.6</td>
<td>294</td>
<td>153</td>
<td>0.018</td>
<td>99.11</td>
<td>74.37</td>
</tr>
<tr>
<td>30</td>
<td>Min Vol.</td>
<td>30</td>
<td>1.1</td>
<td>0.1</td>
<td>355</td>
<td>344</td>
<td>0.023</td>
<td>98.62</td>
<td>99.4</td>
</tr>
<tr>
<td>30</td>
<td>Max. η</td>
<td>30</td>
<td>1.1</td>
<td>0.1</td>
<td>355</td>
<td>344</td>
<td>0.023</td>
<td>98.62</td>
<td>99.4</td>
</tr>
</tbody>
</table>

In relation to the design which gave the minimum volume for the 5 kHz frequency, it can be seen that the core loss dominated the winding loss mainly due to the flux density. According to equation 3.31, (improved generalized Steinmetz equation), higher flux densities imply higher core loss. The minimum volume achieved at 5 kHz was largely due to the higher value of winding current density used. Note that a higher value of winding current density reduces the volume of the transformer but increases the temperature rise. This can be justified from equation (3.11) and equation (3.5).

With the design at minimum volume for the 10 kHz frequency, the core loss dominated the winding loss due to a high flux density, but for the design with maximum efficiency, the value of the flux density was low and the winding loss dominated the core loss due to the ac resistance. The volumes achieved for the 10 kHz designs were much better than those for the 5 kHz frequency, but the reduction in volume is limited by the temperature rise.

In relation to the 20 kHz designs, the skin and proximity effects were severe due to increased frequency which increased the ac resistance thereby increasing the winding loss. The winding loss dominated the core loss at this frequency but the reduction in
volume was limited by the temperature rise. It can be seen that at 20 kHz volume reduction is impossible due to increased winding loss which reduces the efficiency.

With regards to the 30 kHz frequency, the design which gave the minimum volume was same as the design at maximum efficiency and the winding loss dominated the core loss. The transformer is less efficient here due to high frequency effects, as compared to the 5 kHz, 10 kHz and 20 kHz designs. The temperature rise constraints seriously limited volume reduction at this frequency caused by both the core and winding losses. The number of primary turns used for the designs at 30 kHz as shown in table 6 seriously increased the core loss. Note that when the voltage is constant, a reduction in the numbers of primary turns increases the cross sectional area of the core. The core loss is the product of the volumetric power loss (equation 3.31), the core volume and the core fill factor. Since the core volume is the product of the core cross sectional area and the mean core path, so then increasing the core cross sectional area increases core loss. These results suggest that there is no point operating the 50 kVA transformer at 20 kHz and 30 kHz as it is less efficient as compared to the 5 kHz and 10 kHz frequencies. In all, the best design for the 50 KVA transformer was achieved with the 10 kHz frequency at minimum volume. As such, the frequency can be as high as 10 kHz to achieve minimum volume and maximum efficiency.
4.3.2 Optimum Operating Frequency at 100 kVA

In this section, optimum designs at 100 kVA are shown. It begins with the efficiency versus volume graph shown in figure 63 for all of the designs at 100 kVA which do not exceed the temperature limits, and a Pareto extract of the results in figure 63 are shown in figure 64. As seen, the 10 kHz frequency produced the best designs, followed by the 5 kHz frequency. Designs at 20 kHz were less efficient and resulted to larger volumes. The worst designs were produced with the 30 kHz frequency. In all, the designs produced at 100 kVA are less efficient to those at 50 kVA. This is clarified on the next page.

Figure 63: Efficiency versus volume for Vitroperm at 100 kVA

Figure 64: Pareto extract of Figure 63
The difference in efficiency and volume between the 5 kHz and the 30 kHz designs are now much greater than in the case of the 50 kVA transformer. This indicates that increasing the frequency has a more detrimental effect on high power designs. When the power level increases and the voltage remain constant, the current in the circuit will increase. This increase in current causes an increase in temperature which reduces the efficiency and limits volume reduction. In figure 65, the temperature versus volume graph for all of the frequencies at 100 kVA are shown.

![Temperature limits volume reduction](image)

Figure 65: Temperature limits volume reduction

The temperature increases as the volume reduces. The temperature rise between the 5 kHz and the 10 kHz designs are somewhat identical largely due to variations in the numbers of primary turns, the current density and the flux density, which causes a change in core and winding losses. In circumstances where the flux density is much higher for a design at 5 kHz than the design at 10 kHz, it produces approximately similar values in temperature rise. Also, where higher current densities are employed for designs at 5 kHz than those at 10 kHz, it results to approximately equal temperatures. But with the 20 kHz and 30 kHz designs, the high frequency effects are more severe, which clearly shows how high frequencies limit volume reduction due to increased temperature. Generally, the results in figure 65 show that volume reduction was limited due to increased temperature.
It can be seen that designs at 100 kVA were produced at higher temperatures than those at 50 kVA. As previously mentioned, when the voltage remains constant, the current increases when the power level increases, and this causes an increase in temperature. The increase in current increases the $I^2R_{ac}$ loss. So then with larger currents the winding loss increases. Therefore, increasing the power level increases the winding loss which reduces the efficiency in figure 63 and figure 64 and also limits the reduction of volume. In figure 66 and figure 67 the winding loss versus volume and the core loss versus volume graph are shown respectively.

Figure 66: Transformer Winding loss and Volume Reduction

Figure 67: Transformer Core loss and Volume Reduction
Here again the winding loss rises as the volume reduces while the core loss reduces as
the volume reduces. It is clear that now winding loss are gotten much larger than in the
case of the 50 kVA designs which is to be expected due to the high current associated
with high power. But the increase in winding loss as frequency increases is very severe.
The winding loss is worst at 100 kVA than at 50 kVA, and winding loss now totally
dominates over the core loss indicating that the problem of increasing the frequency is
mostly the winding loss. In table 7, the variables that produced designs at minimum
volume and maximum efficiency are shown. It includes the values obtained for the
winding loss, the core loss, the volume, the efficiency and the temperature rise achieved
for each of the designs.

<table>
<thead>
<tr>
<th>Freq. (kHz)</th>
<th>Design</th>
<th>N_p</th>
<th>J_o (A/mm²)</th>
<th>B_m (T)</th>
<th>P_w (W)</th>
<th>P_c (W)</th>
<th>Volume (m³)</th>
<th>η (%)</th>
<th>ΔT (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Min. Vol.</td>
<td>80</td>
<td>3.1</td>
<td>0.3</td>
<td>375</td>
<td>273</td>
<td>0.0218</td>
<td>99.35</td>
<td>98.9</td>
</tr>
<tr>
<td>5</td>
<td>Max. η</td>
<td>50</td>
<td>0.85</td>
<td>0.1</td>
<td>379.6</td>
<td>225</td>
<td>0.156</td>
<td>99.39</td>
<td>25</td>
</tr>
<tr>
<td>10</td>
<td>Min. Vol.</td>
<td>70</td>
<td>2.1</td>
<td>0.2</td>
<td>378</td>
<td>249</td>
<td>0.02</td>
<td>99.38</td>
<td>99.7</td>
</tr>
<tr>
<td>10</td>
<td>Max. η</td>
<td>50</td>
<td>1.6</td>
<td>0.1</td>
<td>406</td>
<td>205</td>
<td>0.058</td>
<td>99.39</td>
<td>48.6</td>
</tr>
<tr>
<td>20</td>
<td>Min Vol.</td>
<td>25</td>
<td>1.1</td>
<td>0.1</td>
<td>737</td>
<td>469</td>
<td>0.0518</td>
<td>98.8</td>
<td>99.9</td>
</tr>
<tr>
<td>20</td>
<td>Max. η</td>
<td>25</td>
<td>1.1</td>
<td>0.1</td>
<td>737</td>
<td>469</td>
<td>0.0518</td>
<td>98.8</td>
<td>99.9</td>
</tr>
<tr>
<td>30</td>
<td>Min Vol.</td>
<td>20</td>
<td>0.85</td>
<td>0.04</td>
<td>1820</td>
<td>317</td>
<td>0.132</td>
<td>97.9</td>
<td>97.86</td>
</tr>
<tr>
<td>30</td>
<td>Max. η</td>
<td>20</td>
<td>0.85</td>
<td>0.04</td>
<td>1820</td>
<td>317</td>
<td>0.132</td>
<td>97.9</td>
<td>97.86</td>
</tr>
</tbody>
</table>

Table 7: Optimum Designs at 100 kVA for Vitroperm500F

According to table 7, the results suggest that the efficiency can be as high a 10 kHz to
achieve minimum volume and maximum efficiency. The transformer efficiency reduced
at 20 kHz as compared to the efficiency at 5 kHz and 10 kHz. The transformer was indeed
less efficient at 30 kHz due to increased temperature caused by the winding loss. The
temperature rise limited the reduction of volume such that, only designs at larger volumes
could be achieved. The design which gave the minimum volume was not same as the
design which produced the maximum efficiency for the 5 kHz and 10 kHz frequencies,
but for the 20 kHz and 30 kHz frequencies, the design which gave minimum volume was same as the design which gave the maximum efficiency. Here again the best design was produced with the 10 kHz frequency and the winding loss limited volume reduction.

4.3.3 Optimum Operating Frequency at 500 kVA
In this section the results for transformer designs at a power level of 500 kVA are shown. In figure 68 and figure 69, the relationship between the transformer efficiency and volume are shown, and the 5 kHz frequency produced higher efficiencies and smaller volumes than the 10 kHz. But the designs produced at 500 kVA were at a much larger volume as compared to designs at 50 kVA and 100 kVA. Here again the temperature rise limits volume reduction for the 500 kVA transformer. In particular, it limited the 10 kHz frequency from any gains in volume and efficiency due to high frequency effects and increased current which results to excessive winding loss. An extract of the Pareto front and a temperature versus volume graph are shown on the next page.

Figure 68: Efficiency versus Volumes for Vitroperm at 500 kVA
Figure 69: Pareto extract of Figure 68

Figure 70: Temperature Limits Volume Reduction
The temperature rise constraint remains the major issue that limits the reduction of volume for all of the power levels investigated. As seen in figure 70, the temperature rises as the volume reduces. In figure 70, higher frequencies imply higher temperatures. It can be seen that as the power level increases, it is impossible to achieve optimum designs at higher frequencies. With regards to the 10 kHz, just a single design was produced due to excessive temperature. It was impossible to produce a design at 20 kHz and 30 kHz within the specified volume scale. The losses versus volume graph are shown in figure 71.

![Figure 71: Transformer losses and volume reduction](image)

The winding and core losses at 10 kHz are not shown in figure 71 for reasons that just a single design was produced and this occurred at a volume of 0.79 m$^3$, whereas the maximum volume scale in figure 71 is specified at 0.21 m$^3$ so as to clearly show the core and winding losses at 5 kHz. With regards to the 10 kHz frequency, the design which gave the minimum volume was same as the design which produced the maximum efficiency and the efficiency at 10 kHz was 98.4 % as shown in table 8. According to figure71, the winding loss dominated the core loss for both the 5 kHz and 10 kHz frequencies. It can be seen that as the frequency increased from 5 kHz to 10 kHz, the winding loss was approximately seven times the value of the core loss. As aforementioned, the rationale for the high winding loss is due to high currents caused by
an increase in the power level while the voltage remained constant. Also, the skin and proximity effect increases the ac resistance as the frequency increases thereby increasing the winding loss. In table 8, the design variables that produced the designs for the minimum volume and maximum efficiency are shown; it also includes the losses, the volume, the efficiency and the temperature rise produced in each design.

<table>
<thead>
<tr>
<th>Freq. (kHz)</th>
<th>Design</th>
<th>(N_p)</th>
<th>(J_o) (A/mm(^2))</th>
<th>(B_m) (T)</th>
<th>(P_w) (W)</th>
<th>(P_c) (W)</th>
<th>Vol (m(^3))</th>
<th>(\eta) (%)</th>
<th>(\Delta T) ((^0)C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Min. Vol.</td>
<td>30</td>
<td>0.85</td>
<td>0.2</td>
<td>1874</td>
<td>894</td>
<td>0.175</td>
<td>99.45</td>
<td>97.7</td>
</tr>
<tr>
<td>5</td>
<td>Max. (\eta)</td>
<td>30</td>
<td>0.85</td>
<td>0.2</td>
<td>1874</td>
<td>894</td>
<td>0.175</td>
<td>99.45</td>
<td>97.7</td>
</tr>
<tr>
<td>10</td>
<td>Min Vol.</td>
<td>20</td>
<td>0.1</td>
<td>0.08</td>
<td>7028</td>
<td>1060</td>
<td>0.79</td>
<td>98.4</td>
<td>99.7</td>
</tr>
<tr>
<td>10</td>
<td>Max. (\eta)</td>
<td>20</td>
<td>0.1</td>
<td>0.08</td>
<td>7028</td>
<td>1060</td>
<td>0.79</td>
<td>98.4</td>
<td>99.7</td>
</tr>
</tbody>
</table>

Table 8: Transformer Designs at 500 kVA for Vitroperm500F

Table 8 shows that the design which gave the minimum volume was same as the design which gave the maximum efficiency for both 5 kHz and 10 kHz frequencies. According to equation (3.6), with less number of turns, the core cross sectional area (\(A_c\)) increases, and this increases the core volume which accounts for the high core losses produced for both frequencies. The winding loss remained the main issue that limits volume reduction and table 8 shows that the winding loss dominated the core loss for both frequencies. When compared to the designs at 50 kVA and 100 kVA, it can be seen that both core and winding losses at 500 kVA were much higher than losses at 50 kVA and 100 kVA. In all these results suggest that, it is possible to operate transformers with smaller power levels at higher frequencies, and when the power level increases, the transformers were less efficient due to high currents and high frequencies. It would appear that the best design for the 500 kVA transformer was produced using the 5 kHz frequency. This result indicates that an optimum design largely depends upon the power level of the transformer. The results also show that the frequency should not exceed 10 kHz.
4.5 Comparison between Vitroperm and Metglas at 150 kVA

This section compares Metglas (2605SA1) and Victroperm500F to see at what frequency would each core material be useful than the other at 150 kVA. The primary voltage was 10 kVA and the secondary voltage was 800 V. The winding current density varied between 0.1 A/mm$^2$ to 7.35 A/mm$^2$ with a step size of 0.25 A/mm$^2$. The flux density varied between 0.05 T to 0.2 T with a step size of 0.05 T, and the number of primary turns varied between 10 to 110 with a step size of 10. The results are shown in figure 72 and figure 73.

Figure 72: Efficiency versus Volume Comparison for Vitroperm and Metglas

Figure 73: Pareto extract of Figure 72
In figure 72, the results for all of the designs not exceeding the temperature limit are shown. It shows the minimum volumes and maximum efficiencies that each material can attain for different frequencies. Figure 73 is an extract of the Pareto front for the results in figure 72. Vitroperm500F operated as high as 20 kHz but Metglas was unable to produce a design at 20 kHz. As seen, Vitroperm500F achieved a higher value of efficiency with minimum volume than Metglas at 5 kHz. With regard to the 10 kHz frequency, Vitroperm500F scored better values in terms of volume and efficiency than Metglas. As previously mentioned, Metglas could not produce any design at 20 kHz but Vitroperm500F achieved some results at 20 kHz. The losses appears to be the main reasons for Vitroperm500F being more efficient than Metglas. Figure 74 shows the relationship between the core losses for both materials at different frequencies.

Figure 74: Core loss versus volume for Vitroperm and Metglas at 150 kVA.

The core loss for Metglas at 5 kHz was much higher than the core loss for Vitroperm500F at 5 kHz, while at 10 kHz, the core loss for Metglas dominated the core loss of Vitroperm500F. Vitroperm500F produced fewer results at 20 kHz due to higher temperatures, and the designs produced at that step were those with very low flux densities. In all Vitroperm500F was more efficient than Metglas. Table 9 shows the volume and efficiency achieved for the designs which gave the minimum volume and maximum efficiency; it includes the core and winding losses for each of the designs. With the 5 kHz frequency, Vitroperm500F was more efficient than Meglas for the design with
minimum volume, while for the design that produced the maximum efficiency, Vitroperm500F was efficient than Metglas. Table 9 also shows that Vitroperm500F was efficient than Metglas for the 10 kHz and 20 kHz frequencies. Metglas scored zero efficiency at 20 kHz due to excessive temperatures above the specified temperature limit. The findings revealed that Vitroperm500F was more efficient than Metglas for all of the frequencies investigated.

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Material</th>
<th>Design</th>
<th>Volume (m$^3$)</th>
<th>$\eta$ (%)</th>
<th>$P_c$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Metglas</td>
<td>Min Vol.</td>
<td>0.039</td>
<td>99.38</td>
<td>388</td>
</tr>
<tr>
<td>5</td>
<td>Vitroperm500F</td>
<td>Min Vol</td>
<td>0.031</td>
<td>99.45</td>
<td>154</td>
</tr>
<tr>
<td>5</td>
<td>Metglas</td>
<td>Max $\eta$</td>
<td>0.075</td>
<td>99.4</td>
<td>389</td>
</tr>
<tr>
<td>5</td>
<td>Vitroperm500F</td>
<td>Max $\eta$</td>
<td>0.17</td>
<td>99.61</td>
<td>217</td>
</tr>
<tr>
<td>10</td>
<td>Metglas</td>
<td>Min. Vol = Max $\eta$</td>
<td>0.097</td>
<td>98.8</td>
<td>630</td>
</tr>
<tr>
<td>10</td>
<td>Vitroperm500F</td>
<td>Min. Vol = Max $\eta$</td>
<td>0.042</td>
<td>99.3</td>
<td>305</td>
</tr>
<tr>
<td>20</td>
<td>Metglas</td>
<td>Min. Vol = Max $\eta$</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Vitroperm500F</td>
<td>Min. Vol = Max $\eta$</td>
<td>0.15</td>
<td>98.43</td>
<td>335</td>
</tr>
</tbody>
</table>

Table 9: Comparison between Metglas and Vitroperm500F
4.6 Discussion of Results

The results for optimum transformer designs using Vitroperm500F at power levels of 50 kVA, 100 kVA, and 500 kVA are discussed in this section. It also includes discussions for Meglas and Vitroperm500F at 150 kVA.

In section 4.3.1, optimum designs for a 50 kVA transformer are shown. Though an increase in transformer frequency theoretically implies a reduction of transformer size according to equation (3.5) relating to the transformer size, this expression was true up to a certain frequency, after which an increase in frequency did not reduce the volume of the transformer due to increased temperature caused by the winding loss. It was also identified that when the frequency increases, the efficiency increases, but there was a region where an increase in frequency resulted to less efficient designs at very high temperatures caused by the winding loss. So then, higher frequencies imply less efficient designs at very high temperatures, and the temperature rise constraint limited the reduction of transformer size. Figure 59 clearly show the efficiency and volume trade-off. It can be seen that designs employing 30 kHz were less efficient due to very high winding loss at that frequency which resulted to very high temperatures and limited the reduction of transformer volume as shown in figure 60. Now with the 20 kHz frequency, the designs produced were more efficient than those at 30 kHz for reasons that the ac resistance was much higher at 30 kHz than at 20 kHz. Since the ac resistance increases with frequency, so then at 30 kHz, it is obvious that the $I^2R_{ac}$ loss should be higher than at 20 kHz as shown in figure 61. With higher $I^2R_{ac}$, less efficient designs at higher temperatures were produced.

The reduction of volume from 20 kHz to 30 kHz was insignificant as shown in table 6. Significant gains in volume reduction were achieved up to 10 kHz, after which, an increase in frequency produced very little reduction in volume. Though the temperature rise for the 5 kHz and 10 kHz designs were lower than those at 20 kHz and 30 kHz as shown in figure 60, it can be seen for all of the frequencies that, as the volume reduces the temperature increases such that it gets to a region where the design exceeds the specified temperature limit and the efficiency falls to zero. The reasons for the rise in temperature with volume reduction are caused by the winding loss as discussed above. As shown in figure 61, as the transformer volume reduces, the winding loss increases. This shows that high frequencies do not favour the winding loss. On the other hand, the core loss reduces with volume reduction as shown in figure 62. So then high frequencies
do favour the core loss. The core loss is proportional to the volume of the transformer. With larger volumes, the core loss is much higher, whereas as the volume reduces, the core loss reduces. While the dc resistance is constant with frequency variations, the ac resistance changes with frequency. As discussed above, as the frequency increases, the ac resistance increases which results to an increase in winding loss. In figure 61 it can be clearly seen that at 30 kHz the winding loss was much higher than the winding losses at 5 kHz and 10 kHz. Higher frequencies imply higher winding losses due to skin and proximity effects and leads to higher temperatures.

As depicted in figure 59 and table 6, the design which gave the minimum volume was not same as the design which gave the maximum efficiency for the 5 kHz, the 10 kHz and the 20 kHz frequencies. In relation to the 30 kHz frequency, the design which gave the minimum volume was same as the design which gave the maximum efficiency. According to table 6, the values of the primary number of turns, the winding current density, the flux density and the frequency significantly influenced the transformer performance and structure. The best designs were achieved at 10 kHz in terms of volume reduction and efficiency. These results suggest that the 5 kHz and the 10 kHz appear to be the suitable frequencies for the 50 kVA transformers.

With regard to transformer designs at 100 kVA shown in section 4.3.2, it can be seen that, the best designs were produced at 10 kHz, followed by the 5 kHz frequency. Designs at 20 kHz were less efficient and resulted to lager volumes as shown in figure 64. The worst designs were produced with the 30 kHz frequency. In all, the designs produced at 100 kVA were less efficient to those produced at 50 kVA. It can be seen that the designs at 50 kVA were more efficient than those at 100 kVA due to a change in the value of the current. As the power level increased and the voltage remained constant, the current in the circuit increased as well. The increase in current resulted to higher $I^2R_{ac}$ losses. So then with larger currents the winding loss increases. Therefore, increasing the power level, increases the winding loss, and reduces the efficiency of the transformer as shown in figure 63 and figure 64. The increase in current produces higher temperatures and limits volume reduction. In figure 65, the temperature versus volume graph for all of the frequencies at 100 kVA are shown. The temperature rise between the 5 kHz and the 10 kHz designs were approximately equal largely due to variations in the current density, the flux density and the number of primary turns, which causes a change in core and winding losses. But with the 20 kHz and 30 kHz designs, the high frequency effects were more
severe and higher frequencies limited volume reduction due to increased temperature. It can be seen that designs at 100 kVA were produced at higher temperatures than those at 50 kVA. In figure 66 and figure 67 the winding loss versus volume and the core loss versus volume graph are shown respectively. Here again, the winding loss rises as the transformer volume reduces while the core loss reduces as the volume reduces. So then transformer core loss is proportional to the volume of the transformer. Larger volumes imply high core loss and smaller volumes imply low core losses. Generally, transformer losses at 100 kVA were much higher than losses at 50 kVA and the winding loss dominated the core loss at 100 kVA. In all, it has been shown that increased temperature is produced by both core and winding losses and the winding loss limits the reduction of volume, as it increases with volume reduction. The transformer efficiency can be as high as 10 kHz to achieve minimum volume and maximum efficiency as shown in table 7. The design which gave the minimum volume was not same as the design which gave the maximum efficiency for the 5 kHz and 10 kHz frequencies, but for the 20 kHz and 30 kHz frequencies, the design which gave the minimum volume was same as the design which gave the maximum efficiency. According to table 7, transformer efficiency reduced at 20 kHz as compared to the efficiency at 5 kHz and 10 kHz. The transformer was indeed less efficient at 30 kHz due to increased temperature caused by the winding loss. The temperature rise limited the reduction of volume such that, only designs at larger volume could be achieved. Here again the best design was produced with the 10 kHz frequency.

Due to high currents, very limited designs were produced at 500 kVA. As previously discussed, as the power level increases while the voltage remained constant, the current increases. Here the best results were produced at 5 kHz. The volumes for designs produced at 500 kVA were very large as compared to those produced at 50 kVA and 100 kVA. The limits of the volume and efficiency trade-offs are clearly visible as shown in figure 68 and figure 69. The temperature rise limited volume reduction for the 500 kVA transformer. In particular, it limited the 10 kHz frequency from any gains in volume and efficiency due to high frequency effects and increased current. The temperature rise constraint caused by the winding loss remained the major issue that limited the reduction of volume for all of the power levels. In figure 70, the temperature rises as the volume reduces and the transformer efficiency was set to zero to indicate that, the temperature rise was greater than the specified limit. It can be seen that as the power level increases, it is impossible to achieve optimum designs at higher frequencies. In relation to the 10
kHz frequency, just a single design was produced due to excessive temperature. It was impossible to produce a design at 20 kHz and 30 kHz within the specified volume and temperature scale. The design which gave the minimum volume was same as the design which gave the maximum efficiency for both 5 kHz and 10 kHz frequencies as shown in table 8. With less number of turns, the core cross sectional area (A_c) increases, and this increases the core volume which accounts for the high core losses produced for both frequencies. The winding loss remained the main issue that limited volume reduction and table 8 shows that the winding loss dominated the core loss for both frequencies. Now when compared to the designs at 50 kVA and 100 kVA, it can be seen that both core and winding losses at 500 kVA were much higher than losses at 50 kVA and 100 kVA. From all these results it can be deduced that, it is possible to operate transformers with smaller power levels at higher frequencies, while high power level transformers can operate much better at frequencies below 5 kHz. It would appear that the best design for the 500 kVA transformer was produced using the 5 kHz frequency. These results indicate that an optimum design largely depends upon the power level of the transformer, the numbers of primary turns, the flux density, the current density and the frequency.

Now when Vitroperm500F was compared with Metglas at 150 kVA, to see at which frequency would each material be useful than the other, the results show that Vitroperm500F was more useful than Metglas for all of the frequencies investigated, as shown in figure 72 and figure 73. Vitroperm500F achieved a higher value of efficiency with minimum volume than Metglas at 5 kHz. With regard to the 10 kHz frequency, Vitroperm500F scored better values in terms of volume and efficiency than Metglas, and though Metglas could not produce a design at 20 kHz, it can be seen that Vitroperm500F produced designs at 20 kHz. The transformer losses were the main reasons for Vitroperm500F being more efficient than Metglas. Figure 74 shows the relationship between the core losses for both materials at different frequencies. According to figure 74, the core loss for Metglas at 5 kHz was much higher than the core loss for Vitroperm500F at 5 kHz, while at 10 kHz, the core loss for Metglas dominated the core loss of Vitroperm500F. In all, Vitroperm500F was more efficient than Metglas for all of the frequencies.

Generally, the results show that, designs at 5 kHz were good, and designs at 10 kHz were the best. The 20 kHz frequency produced less efficient designs as compared to the 50 kHz and 10 kHz designs. But with the 30 kHz frequency, the worst designs were produced.
The issues surrounding theses results have been discussed above. According to the results, the transformer frequency can be as high as 10 kHz to produce minimum volume and maximum efficiency.
Chapter 5: Conclusions

5.1 Summary
The solid state transformer is a complex bidirectional power electronics ac-ac converter for the exchange of electrical energy. The solid state transformer consists of a rectifier (ac-dc), a converter (dc-dc) which has a medium frequency transformer, along with an inverter (dc-ac). The primary section of the medium frequency transformer consists of an ac-dc rectifier that receives a sinusoidal voltage from the ac grid and rectifies the sinusoidal voltage into a dc voltage. Within the dc-dc converter, the dc voltage is fed into a dc-ac stage that converts this voltage into a rectangular medium frequency waveform for the transformer. The secondary side of the transformer, an ac-dc stage changes the medium frequency rectangular waveform into a direct current after which a dc-ac inverter is employed to invert the direct current voltage into the power system ac voltage at 50 Hz.

It is highly contemplated that the SST is a suitable alternative for the traditional transformer due to reduced size, the ability to interconnect renewable energy sources and it has the ability to minimise power quality issues.

There are different types of dc-dc converter structures that are suitable for different applications. Some converter can be employed just for stepping up the voltage while others are employed for stepping down the voltage. There are other converters which are bidirectional while others are non-bidirectional. In all, designing a high power medium frequency transformer for a dc-dc converter stage of a solid state transformer requires the selection of the most suitable type of converter. The single phase Dual Active Bridge (DAB) circuit topology is suitable for the medium frequency transformer. The DAB converter is efficient and consists of fewer passive components. Phase shift modulation (rectangular modulation) is the appropriate modulation technique for the DAB dc-dc converter as it is simple for implementation. It has low rms current and lower rated components can be employed.

The design of a transformer usually begins with the selection of a suitable magnetic core. Most often, these magnetic materials do have their own optimum point in relation to size, frequency, efficiency and cost spectrum. It is important to be aware of the differences in cost between Metglas, Vitroperm500F, silicon steel, and ferrite. The properties expected of the core material for the high-power medium frequency transformer are: high-saturation flux density \( B_{\text{sat}} \); low core loss; and the ability to continuously operate at
elevated temperatures. So then for the core material, Vitroperm500F appears to be the most suitable material as it was more efficient than Metglas. The shell type core is selected as it posses better performances than the core type. The shell core is also much better than the matrix type and coaxial core.

High frequency transformer operation reduces size but transformer losses increases at high frequencies resulting to increase temperature thereby requiring other forms of heat dissipation, or larger cores may be employed due to skin and proximity effects. The skin and proximity effect influences the ac resistance. As the frequency increases, the ac resistance increases, and this increases the winding loss. The skin and proximity effects, in other words, can be described as an increase in resistance when the frequency increases. So then litz wires were employed for the transformer winding so as to minimize this loss, but the results still indicates that the winding loss is still an issue to be addressed. The winding loss worsens as the power level increases due to increased current. Also, at high power levels, high frequency effects along with high currents produce very high winding loss. As such, high power transformers should operate at frequencies below 5 kHz.

It was identified that the energy loss from the core are not usually zero during the period when zero voltage is supplied across the transformer due to magnetic relaxation. The waveform of the voltage across the transformer appears to be a square waveform rather than a sinusoidal wave and contain harmonics. The core loss is calculated using “improved generalized Steinmetz equation”. The overall winding loss \( P_w \) in the transformer is calculated as: \( P_w = I_p^2 R_{acp} + I_s^2 R_{acs} \), where \( R_{acp} \) is the ac resistance of the primary winding and \( R_{acs} \) is the ac resistance of the secondary winding. The ac resistance is calculated from the resistance factor and the dc resistance of the winding. While the dc resistance is constant with frequency, the ac resistance varies with frequency. Harmonics increases the winding loss and results to increased temperature. The winding loss is high when a high level of harmonic is considered and vice-versa, but at a certain region, an increase in harmonics does not result to a significant change in winding loss.

With regard to thermal considerations of transformer design, it is important to ensure that temperature rise caused by losses is to be kept within certain limits. The temperature rise appears to be an issue as it seriously limits the achievements of higher efficiencies and reduced volumes. The design of a transformer is considered acceptable if the calculated temperature rise is below the assumed temperature rise and in the event that the calculated
temperature rise exceeds the assumed value, the design procedure needs to be repeated with possible modification of the design variables such that the core sizes can be modified. In transformer design, there are some constraints which must be observed. In applications where size reduction is a priority, then volume of the transformer is a constraint. Some constraints may dominate the others depending upon the type of application. Parameters that affect others can be traded-off so as to achieve the desired design. Due to the interdependence as well as interactions, it is often not possible in one design to optimise all of the parameters. For example, in the event where transformer volume is of significant importance, then operating at a higher frequency would reduce the volume, but may cause some issues with temperature and efficiency. So then it can be seen that judicious trade-offs are essential in achieving design goals.

Optimum designs can be achieved by varying the numbers of primary turns, the winding current density and the flux density. The winding current density influences the volume and efficiency of the transformer. With a high current density, the transformer temperature increases. Although the transformer efficiency increases as the current density increases, the maximum efficiency is limited due to the temperature rise. Low current density results to large volumes and low temperatures, while with a fixed power level, an increase in current density reduces the volume of the transformer. The area of a single conductor also reduces when the current density increases, and the area of a single conductor increases at low current densities. An optimum design largely depends upon the power level and the frequency, and the optimum design would appear to be in the region where the core loss and the winding loss are equal. The possibilities of transformer size reduction are limited as a result of the temperature rise constraint, and higher efficiencies as well as lower volumes are not possible as a result of increased temperature. Higher efficiencies are often achieved at larger volumes.

The transformer frequency can be as high as 10 kHz to achieve maximum efficiency and minimum volume. In all, no significant gains were achieved in terms of volume reduction at 20 kHz, instead at this frequency, the winding loss was high leading to increased temperature. Designs at 20 kHz were less efficient, while the worst designs were produced at 30 kHz. Good designs were produced at 5 kHz and the best designs were produced at 10 kHz.
5.2 Conclusions

This thesis has presented design considerations for a high power medium frequency transformer for a dc-dc converter stage of a solid state transformer (SST). The limits of the efficiency and volume trade off have been shown. The design which gives the maximum efficiency for a transformer may not be the same design which gives the minimum volume, so a trade off exists here. The research identified some constraints surrounding transformer design. Although raising the frequency reduces the volume, it produces high winding loss due to skin and proximity effects which cause increase temperature and limit volume reduction. The finding revealed that the numbers of primary turns, the flux density, the current density, the power level and frequency significantly influence the structure and performance of a transformer.

In a medium frequency transformer, the core loss is proportional to the flux density and with higher flux densities, the core loss is high, and core loss reduces as the flux density reduces. The core loss is the product of the volumetric power loss, the core volume and the core fill factor, which implies that an increase in the flux density increases the core loss. As aforementioned, the current density alters the structure and performance of the transformer. With low current densities, the size of the transformer increases and the efficiency reduces, but as the current density increases, the transformer volume reduces and the efficiency increases, but the maximum efficiency is limited by the temperature rise constraint. With low current density the area of a single conductor increases and the current also increases. Based on this, it can be seen that with low current densities, the size of the transformer will increase and high current densities reduces the size of the transformer. Though high current densities reduces the volume and increases the efficiency, it has some undesirable effects as it increases the temperature.

The research found that larger power levels imply larger volumes. The transformer area product is proportional to the power level and inversely proportional to the product of the rectangular waveform factor, the winding utilization factor, the maximum flux density, the maximum current density and the frequency, so then, it can be seen that if the power level increases, the area product will increase. Also, the area product of a transformer is the product of the winding window area and the core cross sectional area. As the power level increases the product of the winding window area and the core cross sectional area increases. Therefore, the volume of the transformer increases, and when the power levels increases and the transformer voltage remains constant, the current increases thereby
increasing the $I^2R_{ac}$ losses which increases the temperature and limits volume reduction. So then in terms of frequency and volume reduction, a transformer with a lower power level should operate at higher frequencies, whereas high power level transformers should operate efficiently at frequencies below 5 kHz.

Although there are several publications suggesting that an increase in transformer frequency reduces transformer size, these suggestions may exist only in theory, as the research found that there is a certain region after which an increase in frequency does not reduce the size of the transformer. It was identified that when the frequency increases, the efficiency increases, but there was a region where an increase in frequency resulted to less efficient designs at very high temperatures caused by the winding loss. So then, higher frequencies imply less efficient designs at very high temperatures, and the temperature rise constraint limited the reduction of transformer size. The frequency above where there is very little reduction in volume is dependent on the power level. It was found that the transformer efficiency can be as high as 10 kHz to produce designs at minimum volume and maximum efficiency. Significant gains in volume reduction are achievable up to the 10 kHz frequency, after which less efficient designs are produced. Now at 20 kHz and 30 kHz, gains in volume reduction were insignificant and resulted to high winding losses due to skin and proximity effects thereby producing higher temperatures. It has been shown that variation of flux density, current density and the numbers of primary turns can produce an optimum design. In all, high frequencies reduce the core loss as the volume reduces, but it increases the winding loss as the volume reduces. The winding loss was identified as the main issue with the design of the medium frequency transformer.

It has been shown that Vitroperm500F was more suitable than Metglas. Using Vitroperm500F, highly efficient designs at minimum volumes were produced for all of the frequencies investigated. The core loss for Metglas was higher than the core loss for Vitroperm500F.

The research has shown that the benefits of transformer size reduction are limited due to increased winding loss caused by the skin and proximity effects, which produce increased temperature. The best designs were produced with the 10 kHz frequency. Above the 10 kHz frequency the transformer was less efficient and no significant gains in volume were produced.
5.3 Future Work

The winding loss appears to be an issue with the design of the medium frequency transformer and the winding loss resulted in higher values of temperature which seriously limited the efficiency of the medium frequency transformer as compared to the conventional transformer. With these in mind, further work is required in relation to the winding loss issue as well as reducing the temperature rise of the transformer. Further work is also required to establish suitable cooling alternatives for the windings.

So then in relation to future works after this MEngSc thesis, it is highly contemplated that the following areas could serve as a suitable PhD topic to be covered:

- The development of a solid state transformer, or
- A cost benefits analysis of implementing a solid state transformer in a medium voltage-low voltage distribution system.
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