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Analysis of High Frequency Transformer Design in Converter Application

by

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FINAL REPORT

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
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in partial fulfilment of the requirement for the
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(Electrical & Electronics Engineering)

Approved:

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Project Supervisor

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TRONOH, PERAK

June 2008

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Fathiah Zakaria

ABSTRACT

The project is about analysis of the transformer behaviour when operating at a high frequency such as at MHz range. This is to ensure that the design can operate well in the region. There are many issues involved in designing transformer. However, this project only focuses on minimization of the losses in the transformer. A low-power-losses transformer is designed by employing the interleaved technique. When interleaved technique was applied to the winding, the primary and secondary winding AC resistances show a reduction of 43.89 % and 46.88 % respectively. This shows an agreement where AC resistances are proportional to losses. Thus, an improved transformer design with low losses has been successfully achieved.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Nowadays, switching power supplies are used in almost all electronic devices. The same goes to magnetic components. Magnetic components are parts of the main components in power switching converters or switch-mode power converter. They are the first components to be designed, followed by accompanying power circuits. Good switching power supply design starts with a good magnetic component design hence good understanding of the basic magnetic principles is required. Transformer is one of the magnetic components that are commonly used in a converter. When the switch turns on, the transformer will store energy. On the other hand, when the switch is turned off, the transformer will transfer the energy to the load [1].

When operating frequencies are raised to Megahertz range, one of the important critical issues to be considered in designing transformer is power loss. Power loss in the transformer must remain within an acceptable level and it is generally classified into two types: *core* and *copper losses*. The design of magnetic components such as transformers does not have common standard methodologies. Designers are not only required to select proper core type, core material, core size, conductor material and shape or structure of the core, but also other important parameters such as the position of the conductors in the window and the winding strategy. Incorrect winding strategy will contribute to the losses suffered by the transformer, hence the converter itself.

Designing transformer involves many steps. The best way to start a design is by virtual prototyping. This step can be done by using software that is available today such as PExprt from Ansoft. The design process will result in physical layout. Manufacturing process only takes place after the physical layout is ready. Then only transformer will become end products to the users and clients. The advantages of having virtual design are that designer can predict design problems at the early stage, reduce product development cost and meet time-to-market objectives [2].

1.2 Problem Statements

When a transformer operates in high frequency, switching losses tend to be high. High losses level in the transformer will affect the operation of the converter. At high frequency range, transformer suffers from temperature rise. This temperature rise is caused by heat dissipation from core losses as well as power dissipation in the windings [3]. Due to losses generated, transformer's design becomes difficult and complicated.

In designing a good high frequency transformer, many critical issues need to be addressed. Some of the issues are [4]:

1. *Winding strategy* of the transformer.
   Winding strategy affects strongly to the performance of the transformer. Good winding strategy such as interleaved will lead to low leakage inductance and AC resistance. Low AC resistance will result in low power losses.

2. *Materials of the magnetic core*
   Material of the magnetic core is chosen depending on the ability to operate in certain frequency range. Ferrite material can be used in high frequency applications because it has high resistivity and does not suffer from additional eddy current loss due to fringing air gap.

3. *Shape or structure of the magnetic core*

   Shape of the magnetic core has to be determined closely because every shape and structure of the magnetic core has its own characteristic and description of use based on the application of the transformer.

4. *Core size*

   The core size depends on the power requirements of a transformer

5. *Conductor type*

   In normal practice, for low frequency range, solid wire is used. For high frequency operating range, litz wire is preferred.

With good selection of these criterions, a transformer with minimum effect on temperature rise and low losses can be designed.

1.3 Objectives and Scope of Study

1.3.1 Objectives

The objectives of this project are:

1. To familiarize with transformer design using PExprt software from Ansoft Corporation.
2. To study on the minimization of losses in a transformer design.
3. To design a low-power-losses transformer by using interleaved technique.

1.3.2 Scope of Study

The scope of this project is to design high frequency transformer. The main issue considered is the power losses. This is one of the major issues that affect the operation of the transformer. In designing a low-power-losses transformer, winding techniques for the conductor required further investigation. The software used is PExprt developed by Ansoft Corporation.

CHAPTER 2
LITERATURE REVIEW

Transformer is one of the main components in high frequency converter application. The transformer that can operate at high frequency range is much smaller in size and weight, where isolation transformer is commonly used.

2.1 Isolation Transformer

The main purpose of using Isolation transformer is to separate one section over another electrically in a system. In other words, isolation transformer is used to decouple two circuits. It supplies current or energy properly from one circuit to another.

In addition, isolation transformers are used in switched-mode converters for electrical isolation between the input and output, reduction of stresses in switching devices and provision of multi-output connections [5]. With isolation transformers, the output voltage polarity reversal does not become a design issues. When operating at high frequency range, transformer suffers from core and copper losses. Heat dissipation from these losses causes the temperature rise. Temperature rise will affect the operation of the converter. In other words, a good isolation transformer will lead to better performance in converters.

2.2 Planar Magnetic Components [6]

In recent years, planar magnetic technology has become increasingly popular in high frequency converter design. Conventional magnetic structures encounter numbers of limitation when operating at high frequency. It suffers from high loss due to skin and proximity effect in the round conductors at frequency above 100 kHz [3]. Comparing with to the conventional counterparts, planar magnetic components demonstrate better performance. The main difference between conventional and planar magnetic components is the orientation of winding layer as shown in Figure 1.

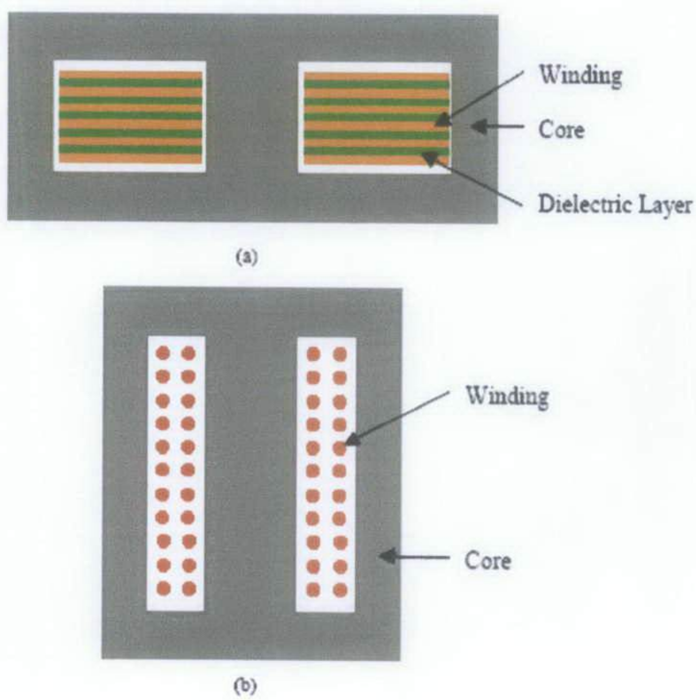

Figure 1: Magnetic components (a) Planar (b) Conventional

It can be shown that windings in the planar magnetic components have flat, wide and rectangular cross section. In addition, it also has lower profile than conventional structure.

2.2.1 Advantages and disadvantages of planar magnetic components

The advantages of planar magnetic components over conventional magnetic structures are listed below:

1. *Lower leakage inductance.*

   Interleaved technique can easily be implemented in planar structures which will reduce the leakage inductance [7].

2. *Reduced high frequency winding losses*

   Skin effect is minimized by reducing the thickness of the conductor windings to one or two times the skin depth [8].

3. *Low profile structures.*

   Planar magnetic component is a low profile magnetic. From the study, low profile magnetic will result in higher power density [9] and better volumetric efficiency [10]

4. *Better thermal management*

   More areas are contacted to heat sink because of the greater surface area to volume ratio [11].

Disadvantages of planar magnetic structures are:

1. *Large footprint area.*
2. *Increase in parasitic capacitance.*

   The windings are stacked closely, which result in high parasitic capacitance.

2.3 Losses

As mentioned before, the main losses related to the transformer are core and copper losses. The core loss in transformer is due to a variety of mechanisms related to fluctuating magnetic field such as hysterisis and eddy current. Copper loss is the term often given to heat produced by electrical currents in the conductors of transformer windings. It is resulted from Joule Heating and so is also referred to as *I squared R losses*, in deference to Joule's First Law. Joule's First Law state that energy lost each second or power increases as the square of the current through the windings and in proportion to the electrical resistance of the conductor. In high frequency converters, power losses in winding conductors increase substantially due to proximity effect and skin effect. Consequently, it becomes one of the major problems in the design of transformer [6].

By classical rule of thumb, the ratio between core and copper losses should be equal. However, the distribution of the losses has been influenced by the combination and selection of the core type, core material and wire. In other words, the ratio of the losses depends on individual design. For example, if the core size increases, the copper loss will reduce, however the core loss will increase.

2.3.1 Eddy Current

Eddy current is generated when a moving or changing magnetic field intersects with a conductor. The relative motion causes a circulating flow of current within the conductor. The eddy current effect will transform the useful forms of energy into heat thus reduces the efficiency of devices that use changing magnetic fields. These effects alter the field and current distribution within the magnetic windings which results in an increase in AC resistance as a function of frequency [6].

2.3.2 Skin Effect

Skin effect occurs in an isolated conductor and it is caused by alternating current (AC) where it tends to distribute itself within a conductor. The current density on the surface of the conductor is greater than at its core. This will cause a decline in current density versus skin depth of the material. Figure 2 illustrates a conductor carrying current *i (t)*.

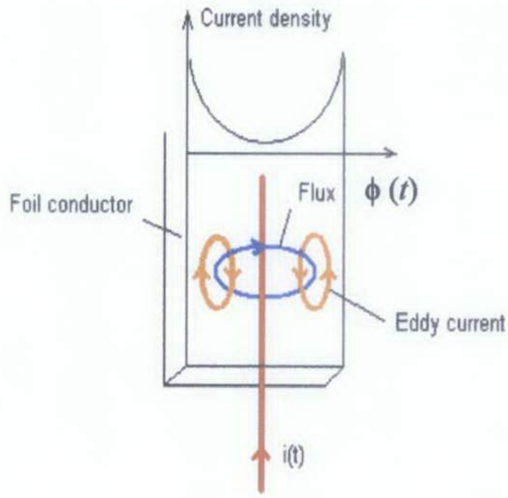

Figure 2: The skin effect in a single conductor [6]

As shown in Figure 2, the eddy current induces magnetic flux $\phi(t)$, whose flux lines follow circular paths around the current. According to Lenz's law, the AC flux in the conductor due to the eddy current tends to oppose the original AC flux ϕ (t). It can be seen that the eddy current reduces the net current density in the center of the conductor, and increases the net current density near the edges of the conductor. The current density on the surface of the conductor is greater than at its core. This will cause a decline in current density versus skin depth of the material.

Skin depth is the distance below the conductor surface where the current density fallen to 1/e or 37% of its value at the surface.

The skin depth of copper conductors is plotted in Figure 3 as a function of frequency.

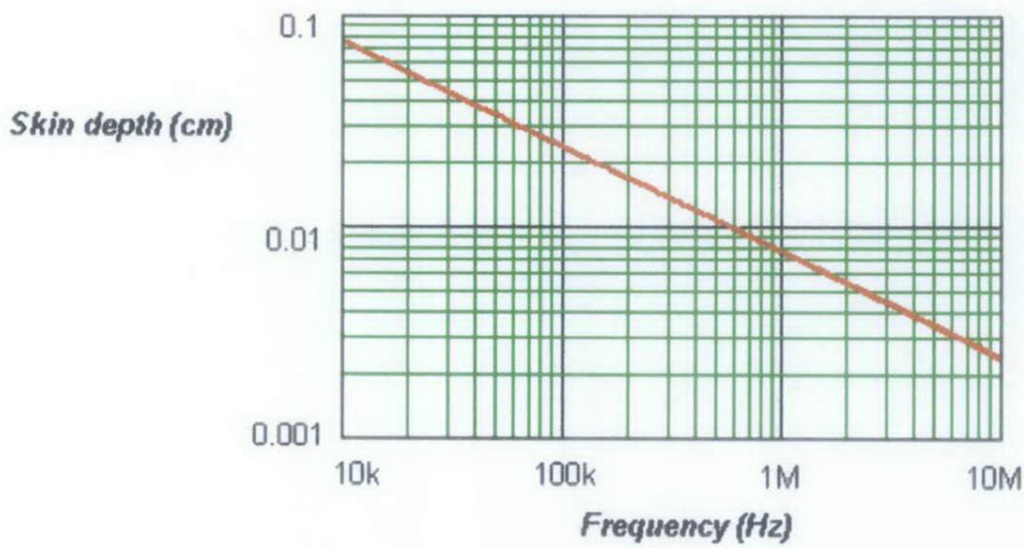

Figure 3: Skin depth as a function of frequency [6]

The skin effect causes current crowding at the surface of the conductor. Since the inside of the conductor is not utilized, the effective conductor cross sectional area is reduced.

2.3.3 Proximity Effect

Proximity effect is caused by induced eddy current in a wire due to the alternating magnetic field of nearby conductors. The distribution of the current within the conductor will be constrained only to smaller regions. This phenomenon will increase the resistance of the conductor hence the heat. The proximity effect in a conductor refers to the currents that are induced by the magnetic fields generated by the adjacent conductors.

Figure 4 illustrates two foil conductors that are placed in close proximity to each other.

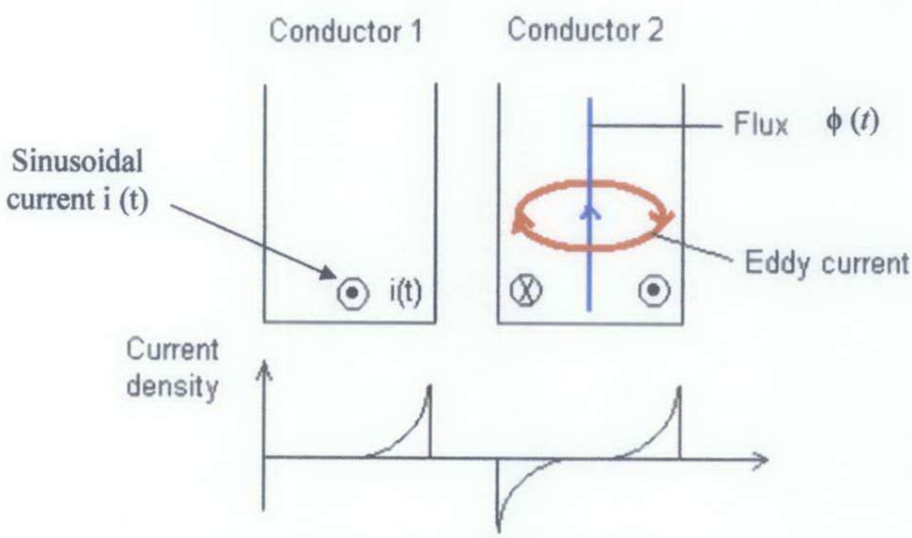

Figure 4: The proximity effect in adjacent conductors [6]

A high-frequency sinusoidal current $i(t)$ is flowing through conductor 1. Conductor 2 is open-circuited, so that it carries a net current of zero. The current $i(t)$ in conductor 1 generates a flux $\phi(t)$ in the space occupied by conductor 2. By Lenz's law, a current is induced in conductor 2, which tends to negate the flux $\phi(t)$.

The combination of skin and proximity effect losses significantly influences the design of magnetic components leading to inefficiency when operating at high frequency, especially in power converters. Eddy current, together with skin and proximity effect will make the AC resistance increase and so does the switching frequency. Consequently, the losses occur from an increase in AC resistance.

2.3.4 Copper and Core Losses Calculation [12]

2.3.4.1 Copper Loss Calculation

By using the software, copper power loss is calculated by using the formula (1) below:

$$P = I^2_{DC} * R_{DC} + I^2rms\_{_1} * R_{AC\_1} + I^2rms\_{_2} * R_{AC\_2} + \ldots\ldots\ldots\ldots\quad (1)$$

Where $I^2rms\_{_i}$ is the rms value of the harmonic i and R_{AC_i} is the resistance at the frequency of the harmonic calculated with the effective area, accounting for the skin effect at each frequency.

2.3.4.2 Core Loss Calculation

Core power loss on the other hand is calculated by using the formula (2) below:

$$P_{core} = f^{\alpha} + B^{\beta} * Volume \ldots\ldots\ldots\ldots\quad (2)$$

Where B is the flux density, f is the operating frequency and volume is the volume of the core.

2.4 Interleaved Technique

In order to reduce the losses, a winding technique called interleaved is applied. The main different feature of the winding techniques is the position of a primary winding and secondary winding. When winding's arrangement has a high degree of interleaving between primary and secondary windings, this will lead in very low AC conductor losses resulted from skin and proximity effect [13].

The changes in the windings resistance and leakage inductance will be strongly dependent upon the physical winding layouts of the transformer. Figure 5(a) and 5(b) below show winding technique without interleaved and interleaved.

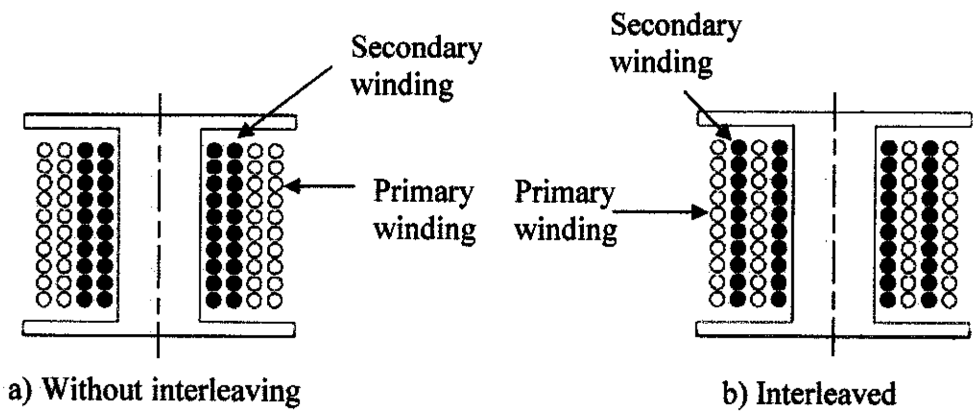

Figure 5: Winding configurations [13]

The black circles represent secondary winding and the white circles, the primary winding. Below are the configurations of the winding techniques:

- Without interleaved technique:
  1 turn primary: 1 turn primary: 1 turn secondary: 1 turn secondary
- Interleaved technique:
  1 turn primary: 1 turn secondary: 1 turn primary: 1 turn secondary

Advantages of applying interleaved technique compared to other winding techniques are [14]:

- Leakage inductance is reduced because magnetic field energy (H) stored in the window, reduces and this makes a higher coupling among the windings.
- AC resistance reduces because of the optimization of current distribution or current density (J) in the conductors. When AC resistance reduces, eddy current loss also reduces.

Figure 6 shows the improvement of magnetic field distribution and current density distribution after interleaved winding is applied:

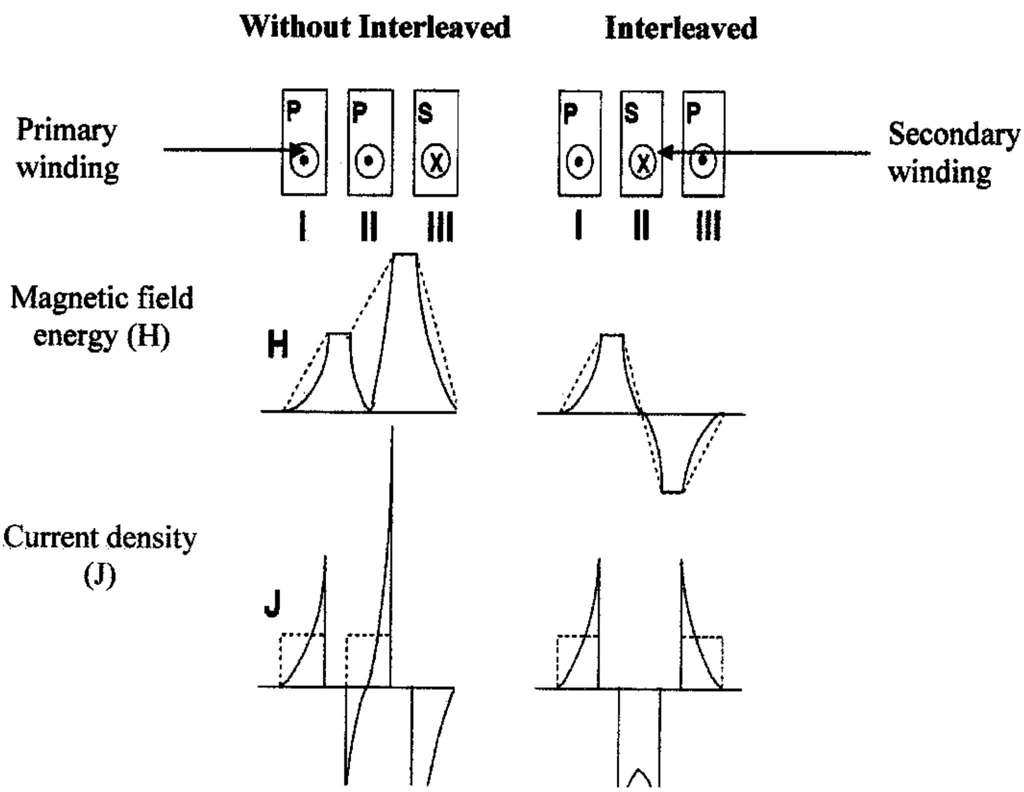

Figure 6: Comparison of magnetic field energy (H) and current density (J) distribution without interleaved and interleaved windings [14]

When interleaved technique is applied, magnetic field energy (H) reduces because of high coupling in the winding. Magnetic field energy (H) directly relates to the leakage inductance. Low magnetic field energy leads to low leakage inductance. Interleaved technique therefore results in optimization of current distribution or current density (J) in the conductor. When the current is distributed well in the conductor, AC resistance in it is reduced.

Interleaved winding strategy is easily applicable for planar transformer geometry. The entire transformer designing processes use this type of geometry.

2.5 Design Approach

There are many methods available in designing magnetic components. They can be categorized into analytical methods and CAD simulation (modelling methods).

2.5.1 Analytical Methods

Analytical method is one of the approaches that are available. However, most of the design approaches that have been introduced suffered drawbacks. Analytical method would require CAD simulation to justify the design. The methods available under this approach are described briefly as below:

1. *McLyman method*

   The method was introduced by McLyman, called McLyman method [15]. This approach is suitable to determine size of area product and appropriate core material but it lacks of control on skin and proximity effects in the windings that become major drawbacks.

2. *Vandelac-Ziogas Approach*[16]

   In this approach, the skin and proximity effect are taken into account. This method determines the magneto-motive force distribution in coil winding. However, it requires lots of computational efforts.

3. *Finite Element Method*[16]

   The algorithm is based on method introduced by Vandelac-Ziogas. It provides numerically based solution using computer and magnetic design with low core and copper loss. It is a reliable method to be used to design good magnetic components in a converter.

2.5.2 CAD Simulation

Magnetic components need to be modelled using CAD simulator. By using the CAD simulator a design of magnetic component can be justified.

2.6 Modelling Techniques for Transformer Design

In order to do the theoretical and simulation analysis, Computer Aided Design (CAD) software is employed. Because of the losses involved in designing transformer, magnetic modelling is important. Some of the modelling techniques are listed below:

1. *Reluctance Model*[17]

   It does not consider winding resistance and only applicable for lower frequency range.

2. *Vandelac and Ziogas Model*

   Magnetic field calculation and current distribution in the windings are available.

3. *Finite Element Analysis*

   This method can avoid the numerically trial and error process in the design. Numerically based solutions are provided to avoid the lengthy computational techniques by using personal computer. It is a reliable method as it produces correlating results to the conventional techniques. It is the best solution to design magnetic component because it gives an accurate method to calculate leakage inductance and resistance. The only drawback is that it is a time consuming.

CHAPTER 3
METHODOLOGY

3.1 General Project Work Flow

The general methodology throughout the completion of this project is shown in Figure 7.

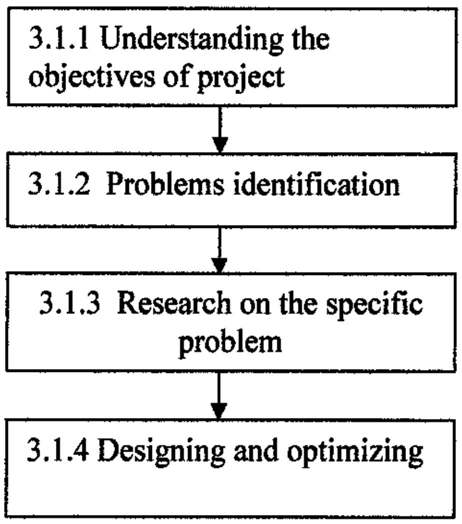

Figure 7: Project Work Flow

3.1.1 Understanding the Objectives

The first step in embarking this project is to understand the objectives.

3.1.2 Problems Identification

After determining the objectives, problems are identified. Eventhough, there are many problems in designing transformer such as power losses, thermal management and cost, the scope of the project will only focus on the selected problem. It is the power losses.

3.1.3 Research

Then, research is done on the losses involved in designing and modelling the transformer.

3.1.4 Designing and Optimizing

The designing process throughout this project is done by using PExprt software from Ansoft Corporation. Designing a transformer involves many steps and further details are described in section 3.2. Once design process is successful, the next step is to optimize the design by applying interleaved technique. Further details are described in section 3.4.

3.2 General Design Work Flow

In designing a transformer, there are eight steps involved as described in Figure 8. Further explanations are in the next sections.

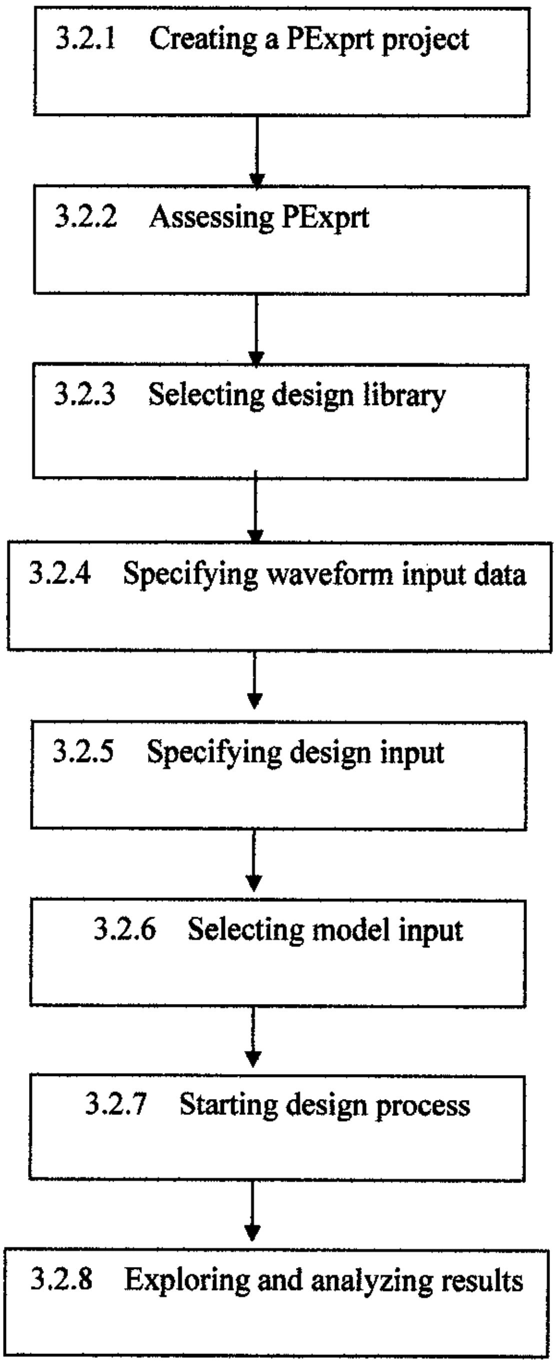

Figure 8: Design Work Flow

3.2.1 Creating a PExprt Project

The first step in designing a transformer using PExprt is to create a project directory. To access PExprt, *Maxwell Control Panel* needs to be accessed first. *Maxwell Control Panel* creates and opens projects for all Ansoft products. To start *Maxwell control panel, Maxwell* icon is double clicked. *Maxwell Control Panel* appears as shown in Figure 9.

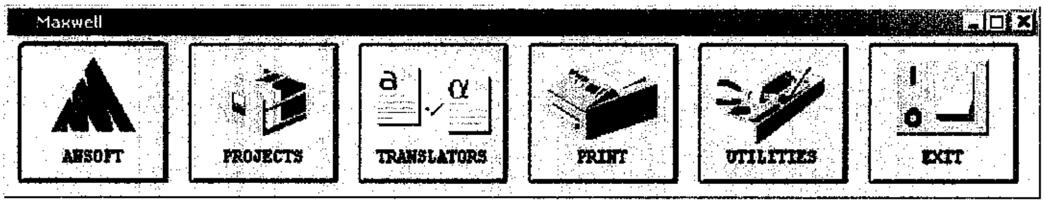

Figure 9: Maxwell Control Panel

To create, rename or delete project files, *Project Manager* as in Figure 10 is referred. *PROJECTS* in the *Maxwell Control Panel* is selected.

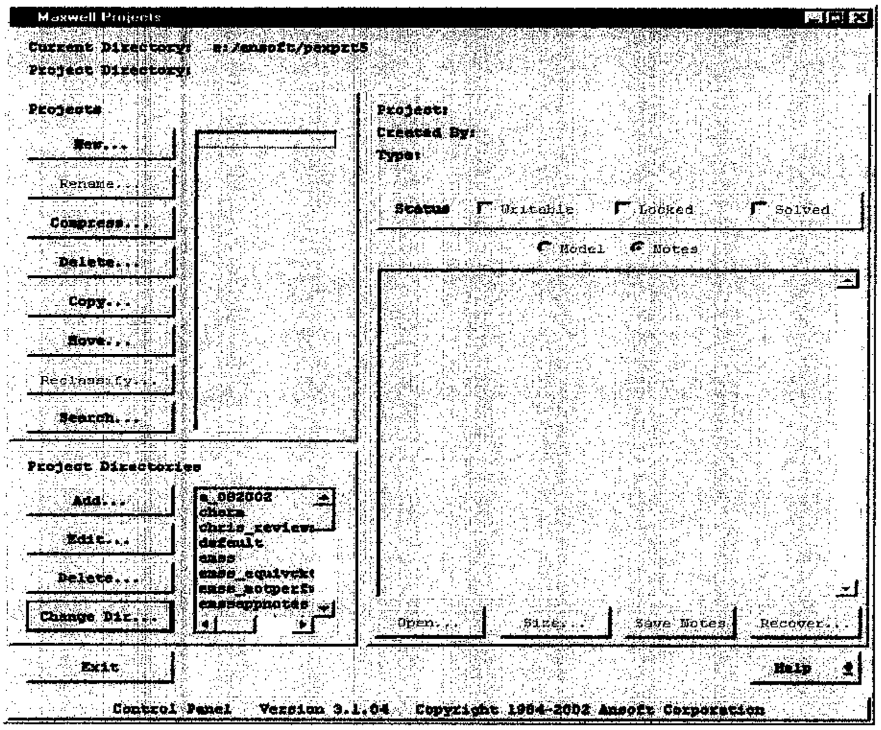

Figure 10: Project Manager Window

A new project directory is added by clicking *Add* button. *New* button is then clicked to create a new project name. New PExprt project is now ready to open and PExprt runs.

3.2.2 Accessing PExprt

The new project name is selected. PExprt is then opened, and selection of the magnetic component type window appears as shown in Figure 11.

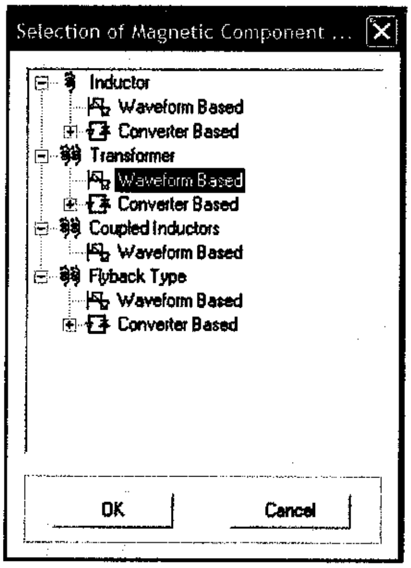

Figure 11: Selection of magnetic component type window

In transformer design, waveform based transformer type is chosen. *OK* button is clicked and PExprt working windows appears as shown in Figure 12.

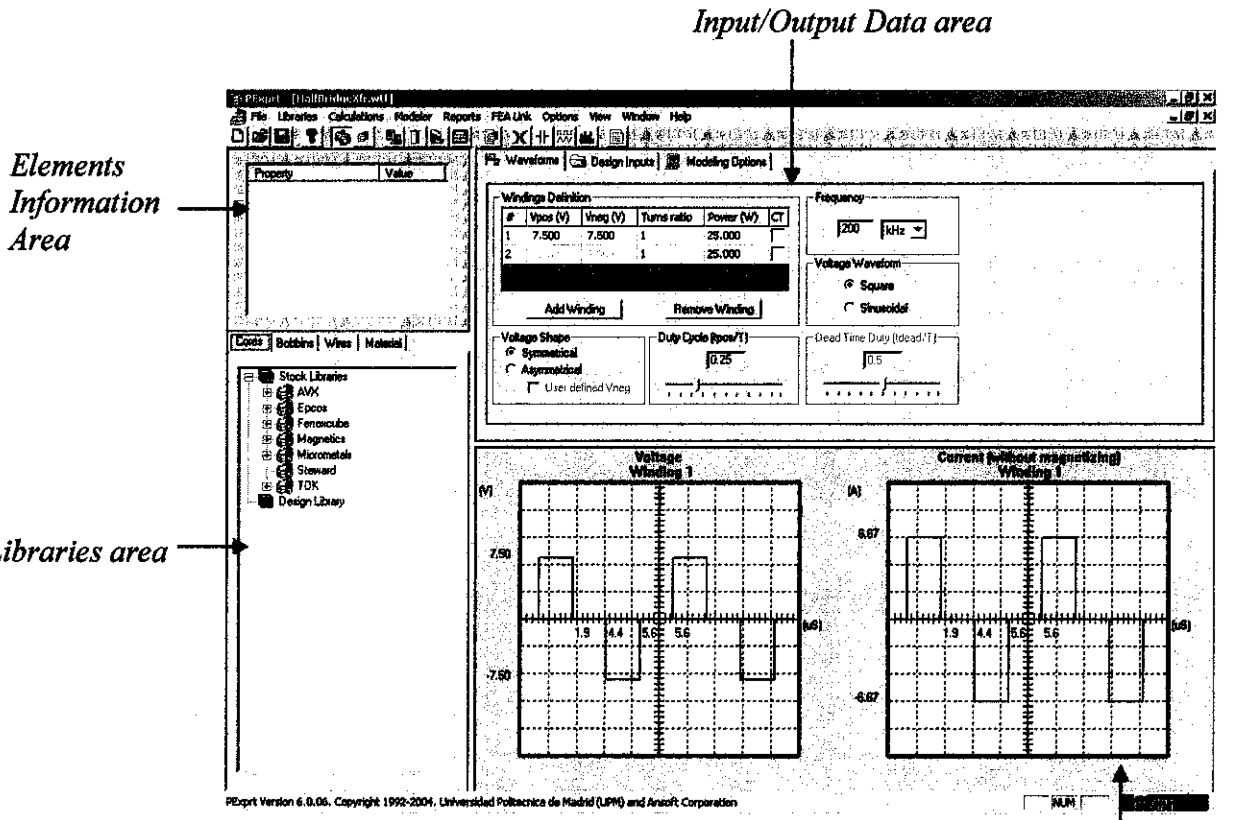

Figure 12: PExprt working windows

PExprt working window is divided into four sections: the *Input/Output Data area*, the *Elements Information area*, the *Libraries area* and the *Graphical Information area.*

Input/Output Data area is used to define inputs and other specifications. The *Elements information area* contains information about each element included in the libraries. The *libraries area* contains a tree with stock and design libraries used in PExprt. The *Graphical Information area* displays different type of graphical information, depending on the design status and which tab is selected in the *Input/Output Data area.*

3.2.3 Selecting Design Library

PExprt libraries contain cores, wires and core materials which are required to design magnetic components. Seven libraries are provided by the Ansoft: *Ferroxcube, Epcos, TDK, Magnetics, AVX, Micrometals and Stewards*. One of loaded stock libraries is dragged and dropped onto the design library tree folder.

3.2.4 Specifying Waveform Input Data

After the design library is selected, the waveform specifications need to be introduced. Waveform specifications include waveform type and voltage shape. There are two types of voltage available to apply to the transformer: *square* and *sinusoidal*. Here, *square* voltage waveform is selected. Once the *square* waveform is selected, two additional choices appear for the voltage shape: *symmetrical* and *asymmetrical*. Symmetrical voltage is then chosen.

The waveform data is based on the converter information. The parameters used in this project are [18]:

1. Input Voltage : 48V
2. Output Voltage : 12 V
3. Switching Frequencies : 100 kHz, 1 MHz, 50 MHz
4. Output Power : 60 Watt
5. Duty Cycle : 25%
6. Turn ratio : 1:1

The waveform parameters are entered in the *Input/Output data area* as shown in Figure 13.

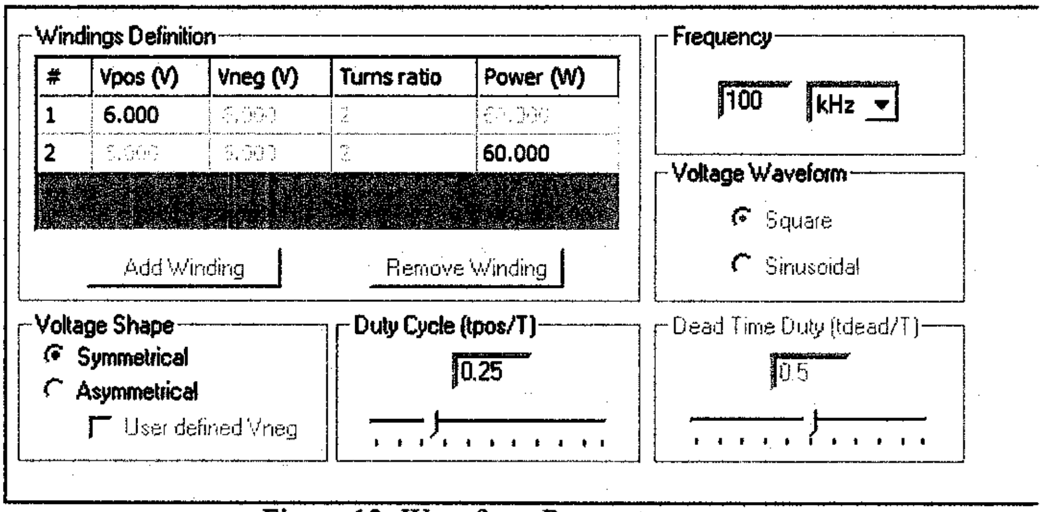

Figure 13: Waveform Parameter

3.2.5 Specifying Design Input

Design input tab in the *Input/Output Data* area is clicked. The *design input tab* appeared as shown in Figure 14.

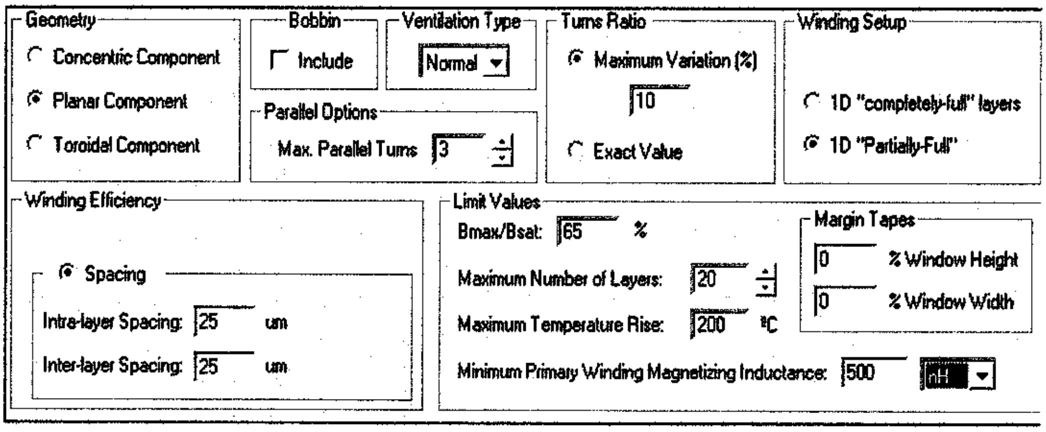

Figure 14: Design input tab

The parameters selection and impact to the design are further explained in **Appendix A.**

3.2.6 Selecting Model Input

Modelling options tab in the *Input/Output Data area* is then referred. The *modelling options tab* appeared as in Figure 15.

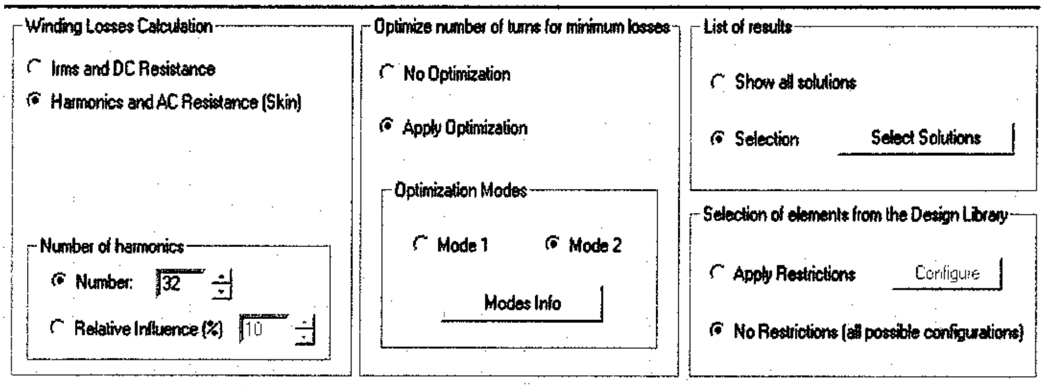

Figure 15: Modelling Options tab

The parameters selection and impact to the design are explained as in **Appendix B.**

3.2.7 Starting Design Process

Once all the parameters have been defined, the design process begins. *Start Design Process* in the calculations toolbar is selected in order to start the design process. After the design process completes, a design report message is generated.

3.2.8 Exploring and Analyzing Results

After the design process has been completed, the list of results appears on the list of *results tab* of the *Input/Output Data area.* At this stage, the results are ready to be analyzed. For this project, only the best result with minimum losses is chosen to be analyzed.

3.3 Determination of Suitable Core for Transformer Design

The steps involved in determining the most suitable core are illustrated in Figure 16. Detail explanations are further explained in the next sections.

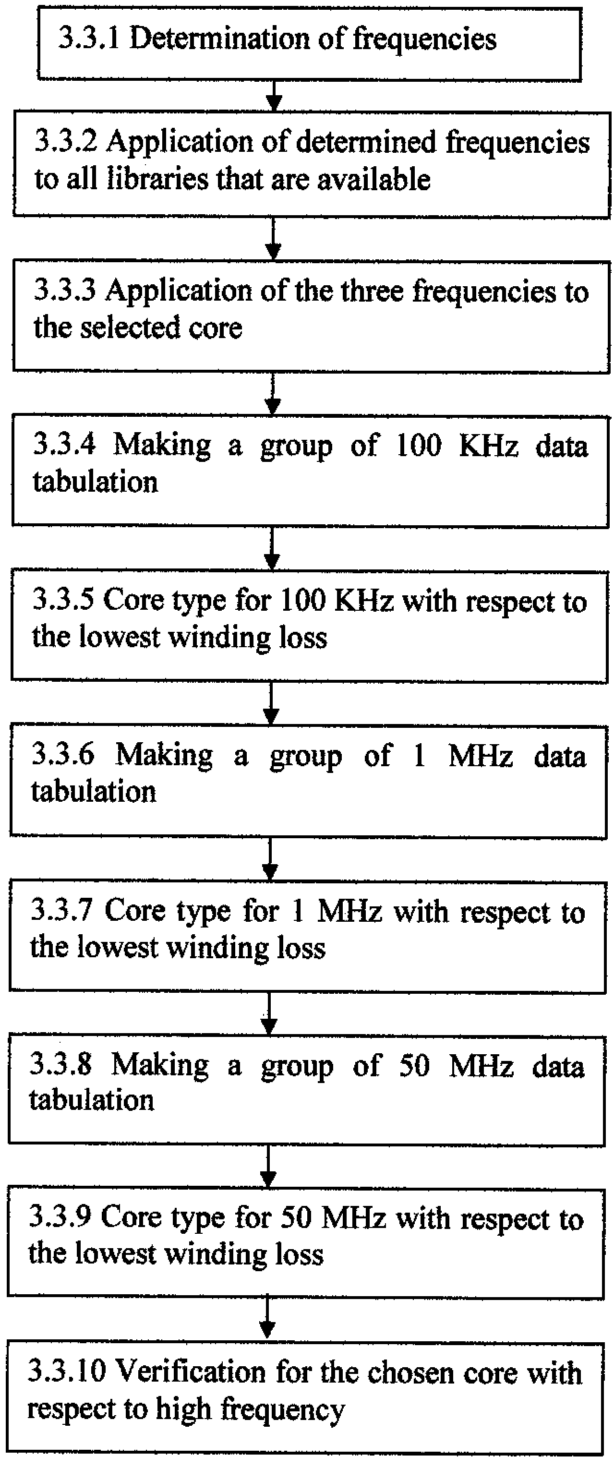

Figure 16: Flow diagram of determination of suitable core for transformer design

3.3.1 Determination of Frequencies

The frequencies are determined. They are 100 KHz, 1 MHz and 50 MHz

3.3.2 Application of Determined Frequencies to All Libraries That Are Available

Every frequency is applied to the available libraries in the software. There are three frequencies that have been determined and seven libraries available. The results are as shown in Table I (Section 4.11, page 37).

3.3.3 Application the Three Frequencies to the Selected Core

From section 3.3.2, a list of core types were obtained. With every core type available and its parameters and characteristics have been swept with three frequencies (100 kHz, 1 MHz and 50 MHz). The results are shown in Table II (Section 4.12, page 38).

3.3.4 Making a Group of 100 KHz Data Tabulation

Data obtained from Table II (Section 4.12, page 39) are grouped with respect to the frequency. A data tabulation table for 100 kHz is shown in Table III (Section 4.13, page 40).

3.3.5 Core Type for 100 KHz With Respect To the Lowest Winding Loss

From the data tabulated in Table III (Section 4.13, page 40), the best core type is chosen based on lowest loss.

3.3.6 Making a Group of 1 MHz Data Tabulation

With respect to the frequency, the data in Table II (Section 4.12, page 38) are grouped. Then a group of data of data as shown in Table V (Section 4.14, page 45) is tabulated for 1 MHz.

3.3.7 Core Type for 1 MHz With Respect To the Lowest Winding Loss

The core with lowest loss for 1 MHz is selected. The selection is made based on data tabulated in Table V (Section 4.14, page 45).

3.3.8 Making a Group of 50 MHz Data Tabulation

Data tabulation for 50 MHz is done as shown in Table VII (Section 4.15, page 50). The tabulation is made based on the data obtained from Table II (Section 4.12, page 38) where they are grouped with respect to the frequency.

3.3.9 Core Type for 50 MHz With Respect To the Lowest Winding Loss

With respect to the lowest loss, a core type is chosen. The selection is made based on data tabulated in Table VII (Section 4.15, page 50).

3.3.10 Verification for the Chosen Core Type With Respect to High Frequency

The chosen core type for high frequency region is verified by applying frequencies ranging from 1 MHz to 50 MHz. Results on losses and operating frequency is observed. The result is tabulated in Table X (Section 4.1.6, page 56)

3.4 Application of Interleaved Technique and Optimizing

Results obtained from the methodology in section 3.2 can be further analyzed by applying interleaved technique. In other words, it is an optimizing step to reduce the copper or winding loss. The flow of applying interleaved technique to a winding by using PExprt software is shown in Figure 17. Detail explanations are discussed in the following sections.

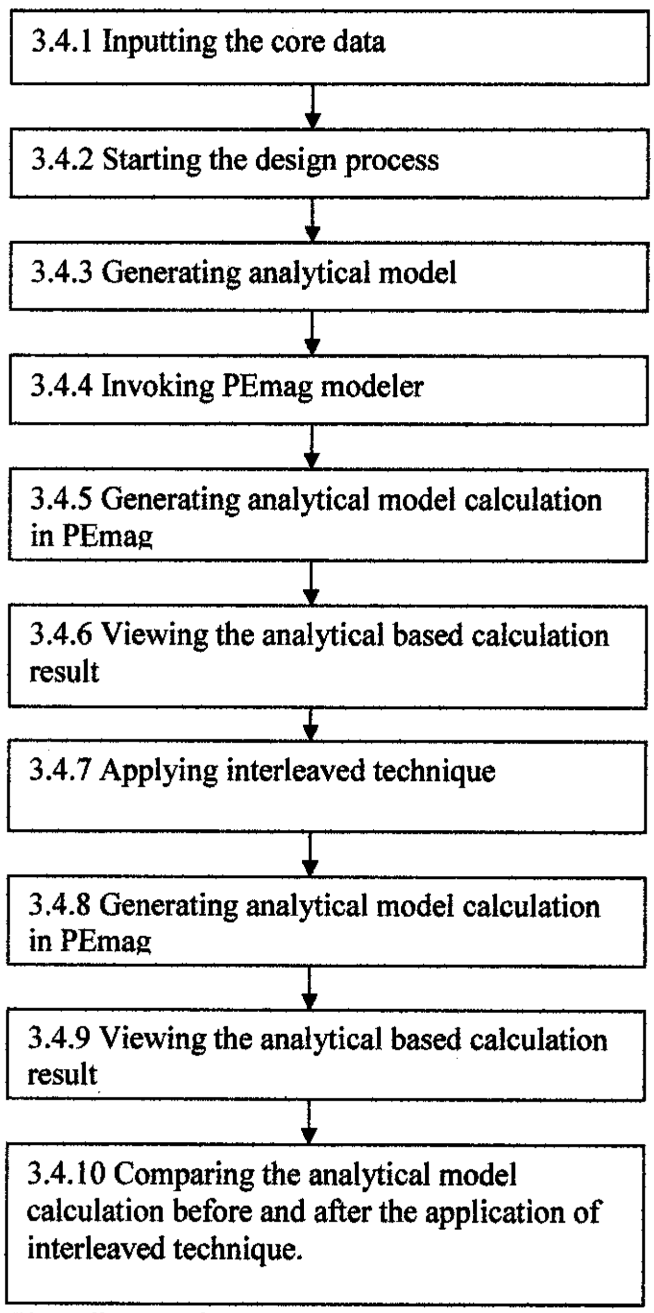

Figure 17: Flow diagram for application of interleaved technique

3.4.1 Inputting the Core Data

The input data is obtained from result in section 4.1. The core types, core material, conductor type selected are used in this step.

3.4.2 Starting the Design Process

By using the same parameters and the chosen core type, the design process begins. Once the design process has been completed, a list of results is generated and the design with minimum losses achieved.

3.4.3 Generating Analytical Model

On the selected design, analytical model is applied by clicking the *modeler* menu at the toolbar. Then, analytical model is chosen. The software will generate the analytical model calculation for the chosen design.

3.4.4 Invoking PEmag Modeler

The next step is to invoke the PEmag modeler. PEmag is a modelling module which allows user to generate models for the design created in the PExprt. It allows user to modify the winding setup of the current design in order to compare different winding strategies.

To invoke PEmag modeler, *modeler* menu in the toolbar is clicked. Then, *invoke PEmag modeler* is chosen and window as shown in Figure 18 invokes.

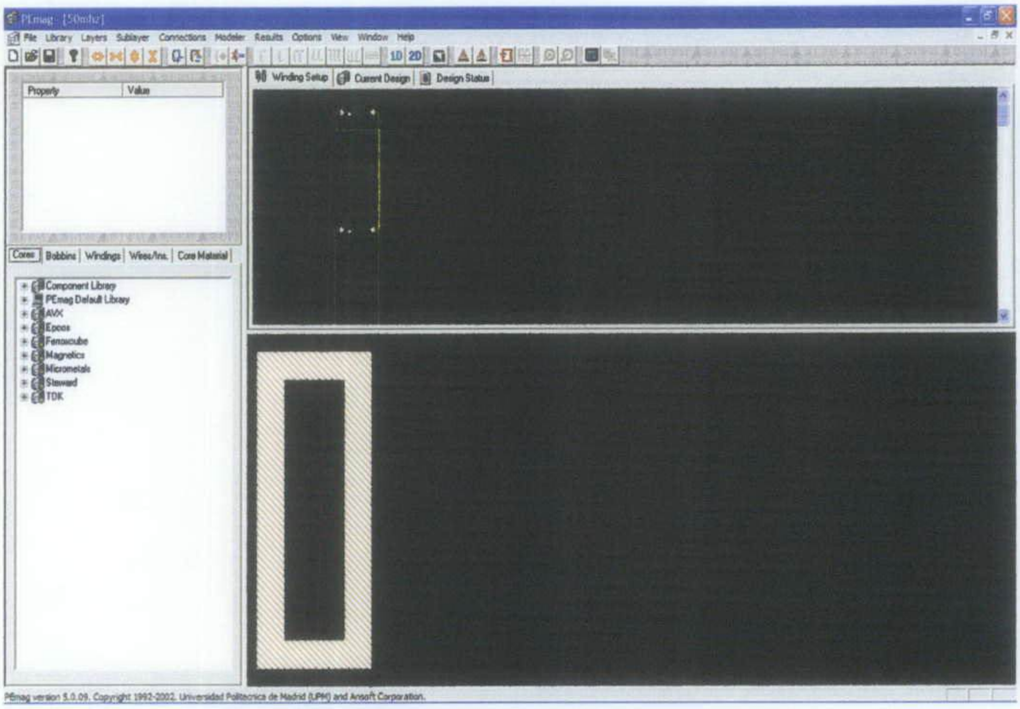

Figure 18: PEmag modeler window

3.4.5 Generate Analytical Model Calculation in PEmag

The next step is to start the analytical model. From the toolbar, the *modeler* menu is chosen, as well as the *analytical modeler*. Then, 1D model generation starts. The *select analytical calculations* window appears as shown in Figure 19.

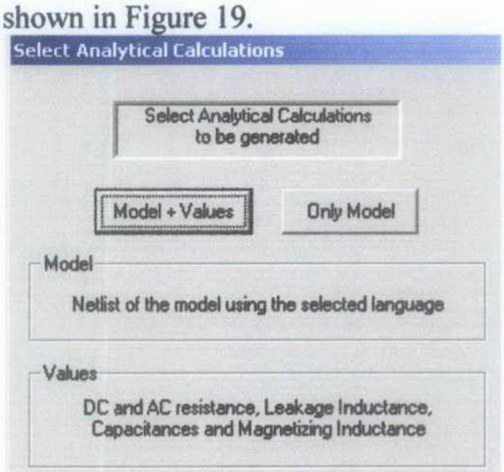

Figure 19: Analytical calculations Window

The *Model+Values* button is selected and the analytical calculations are successfully done.

3.4.6 Viewing the Analytical Based Calculation Result

Once the analytical calculation is done, the analytical calculation result can be viewed. The results include the values of AC and DC resistance, leakage inductance and magnetizing inductance.

3.4.7 Applying Interleaved Technique

To create winding setup with interleaved application, the *Remove* and *Add* connection features are used. Previously, the winding setup was not in interleaved application. At this stage, the primary and secondary winding are arranged by using interleaved technique.

3.4.8 Generating Analytical Model Calculation in PEmag

The analytical model is calculated. This calculation is for the winding that has been applied with interleaved application.

3.4.9 Viewing the Analytical Based Calculation Result

The analytical based calculation result is viewed after the new analytical model calculation is done.

3.4.10 Comparing the Analytical Model Calculation before and after Interleaved Technique Applied

Two different analytical based calculation results are obtained and comparison between the values from the calculation is done. The results of the comparison are as in section 4.2.

CHAPTER 4

RESULTS AND DISCUSSION

Before the designing process starts, that is to determine the best core characteristics at three different frequencies, the parameters of the converter have to be defined. The design input, modelling input and waveform specifications are required.

The results of the simulations can be explored by using *performance results tab* and *constructive result tab* as illustrated in Figures 20 and 21.

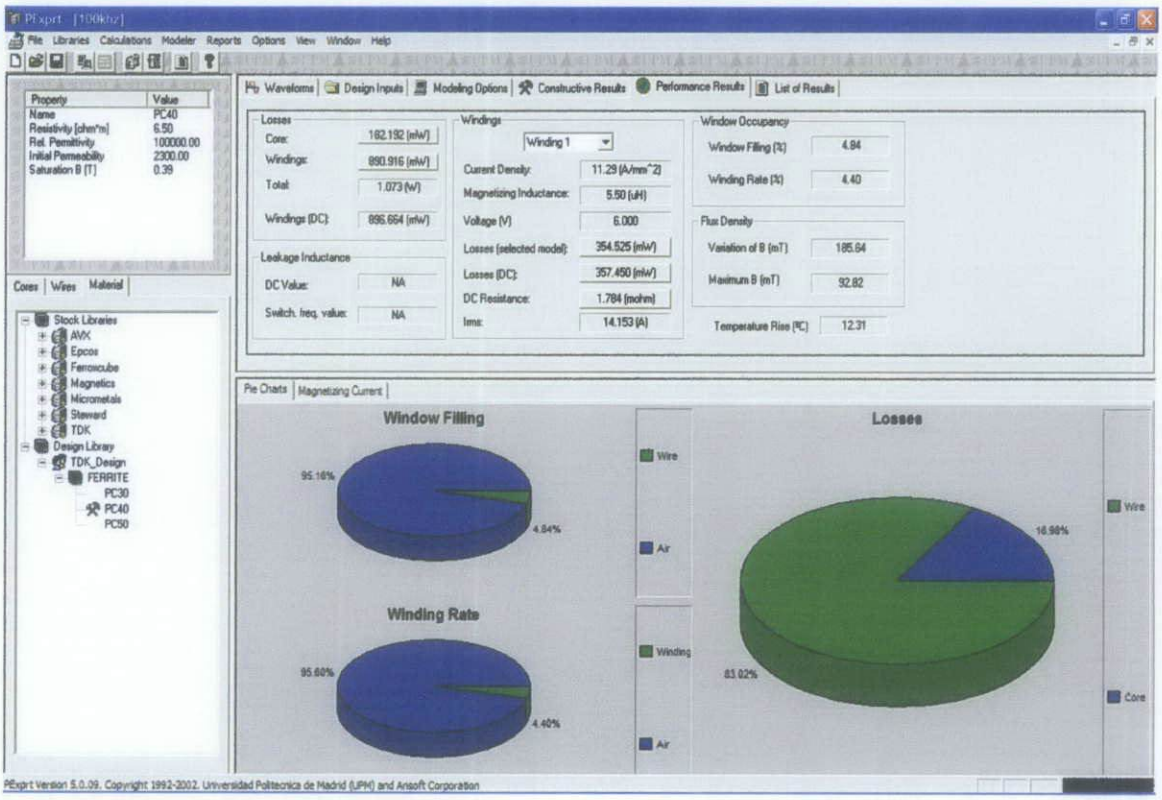

Figure 20: The performance result of the design

Performance result tab consists of two sections that are: *output data area* and *graphical information area*. The *output data area* shows the numerical values of the performance results such as losses while *graphical information area* graphically represents the power losses distribution, window filling and window rate.

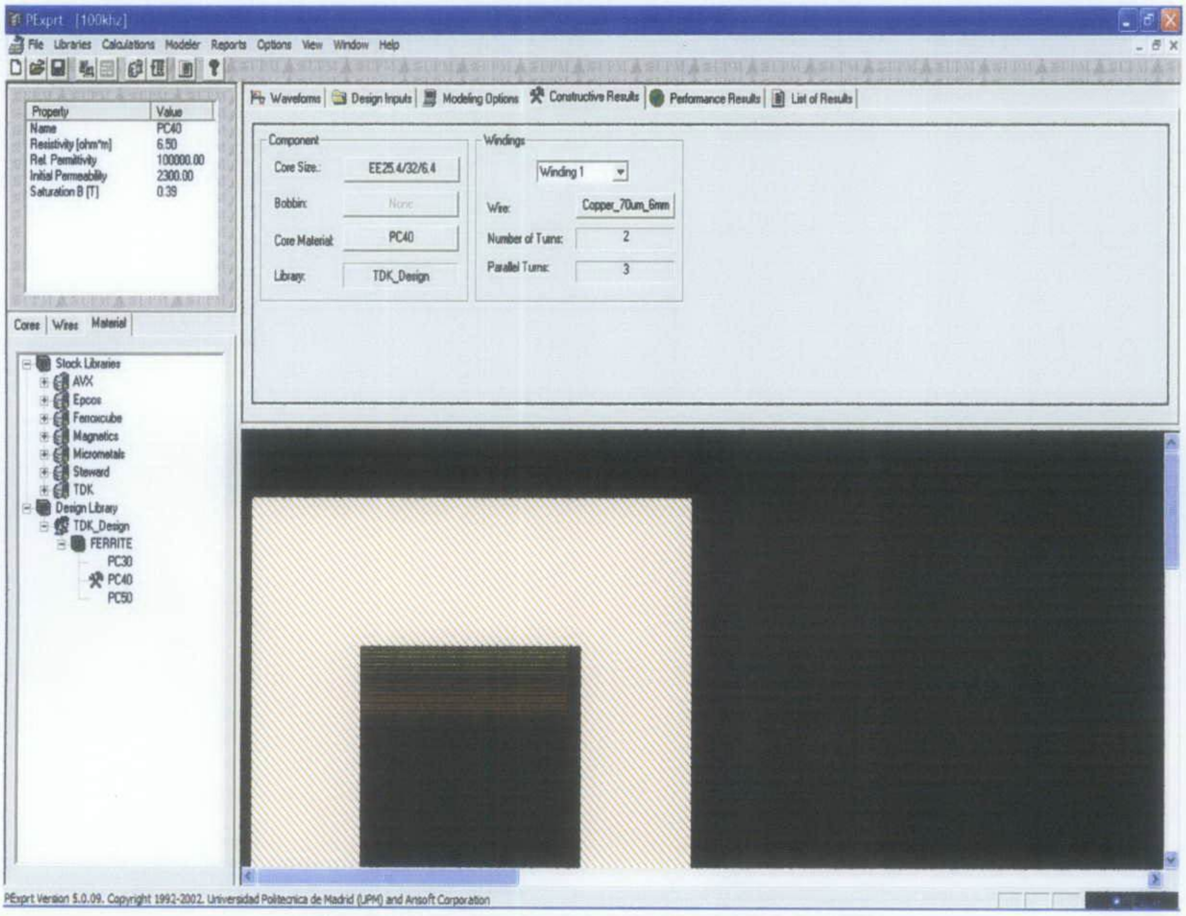

Figure 21: The constructive result of the design

Constructive results tab has two sections. They are *input/output data area* and *graphical information area* where the cross-section of the design is available. Parameters obtained from this constructive result tab are the component and winding description of the design.

4.1 The Suitable Core for 100 kHz, 1 MHz, 50 MHz

4.1.1 Frequency Variation for Every Library

The simulation is done by varying three frequencies values: 100 kHz, 1 MHz and 50 MHz having the same parameters to every manufacturer that are available in the software's library. The steps involved are as explained in section 3.2.

From the simulation, the best core types, core materials and conductor types with respect to the winding losses, core losses and values of temperature rise are determined. The detail of the results is shown in Table I.

Table I: Results when frequency is varied for every manufacturer's library

MANUFACTURER	FREQUENCY (HZ)	CORE TYPES	WINDING LOSS (W)	CORE LOSS (W)
AVX	100 k	RM1400B	0.585	0.0581
	1 M	E-2506C	0.453	0.0359
	50 M	E-2506C	1.427	95.138 u
MICROMETALS	100 k	E125	4.883	1.595
	1 M	E137	1.155	0.3543
	50 M	E137	3.588	0.0063
MAGNETICS	100 k	RM12	1.525	0.1185
	1 M	RM12	0.534	0.0298
	50 M	EE43007	1.503	0.1287
EPCOS	100 k	RM12	0.532	0.0831
	1 M	E 30/15/17	0.486	0.0404
	50 M	E 30/15/17	1.531	392.271
FERROXCUBE	100 k	RM 12/ILP	0.531	0.2515
	1 M	RM 12/ILP	0.541	0.03167
	50 M	E 25/16/6	1.424	0.0125
TDK	100 k	RM12	0.527	0.1122
	1 M	EE 30/30/7	0.479	0.047
	50 M	EE 25.4/32.6.4	1.427	0.0015
STEWARDS	No design available			

From the result obtained, every manufacturer with three different frequencies (100 kHz, 1 MHz and 50 MHz) gives result in different core types, values of the winding losses and core losses. As tabulated in Table I, *Steward* Manufacturer do not has any design that is appropriate for the specifications and parameters defined. In the next steps, *Steward* will not be considered in the designing process.

4.1.2 Frequency Variation for Every Selected Core Types

This is the result obtained for the methodology explained in section 3.3.3.

The values of winding losses and core losses for every core with respect to the frequencies have been obtained and tabulated in Table II.

Table II: Results when every core have been swept with three different frequencies

MANUFACTURER	CORE TYPES	FREQUENCY (HZ)	WINDING LOSS(W)	CORE LOSS(W)
AVX	RM 1400B	100 k	0.5854	0.0581
		1 M	0.5961	0.0018
		50 M	1.878	4.882
	E-25060	100 k	0.8910	0.1548
		1 M	0.4532	0.0698
		50 M	1.427	95.138 u
MICROMETALS	E125	100 k	6.315	1.595
		1 M	1.160	0.3543
		50 M	3.605	0.0063
	E137	100 k	6.311	0.1185
		1 M	1.155	0.0298
		50 M	3.588	0.0028
MAGNETICS	RM12	100 k	0.5251	0.3079
		1 M	0.5342	0.2219
		50 M	1.683	0.1287
	EE43007	100 k	2.161	0.083
		1 M	0.9555	0.012
		50 M	1.503	449.025 u
EPCOS	RM12	100 k	0.5322	0.1013
		1 M	0.5414	0.0404
		50 M	1.706	292.271
	EE43007	100 k	0.955	0.2515
		1 M	0.4862	0.0317
		50 M	1.531	936.559

Table II (continue): Results when every core has been swept with three different frequencies

MANUFACTURER	CORE TYPES	FREQUENCY (HZ)	WINDING LOSS(W)	CORE LOSS(W)
FERROXCUBE	RM12	100 k	0.5309	0.8885
		1 M	0.5413	0.4222
		50 M	1.706	0.0125
	E25/16/6	100 k	0.5928	0.8885
		1 M	0.4522	0.0688
		50 M	1.424	0.0125
TDK	RM12	100 k	0.5266	0.1122
		1 M	0.5356	0.0095
		50 M	1.688	145.222 u
	EE30/30/7	100 k	0.9349	0.0861
		1 M	0.4768	0.047
		50 M	1.502	714.834 u
	EE 25.4/32.6.4	100 k	0.1822	0.1832
		1 M	0.4532	0.4532
		50 M	1.427	0.0115

4.1.3 Core Types and Characteristics for 100 kHz

This is the result obtained for methodology explained in section 3.3.4. For 100 kHz operating frequency, the suitable core types are as described in Table III.

Table III: List of core types that are available for 100 kHz

MANUFACTURER	CORE TYPES	WINDING LOSS (W)	CORE LOSS (W)	TOTAL LOSS (W)
AVX	RM 1400B	0.5854	0.0581	0.6435
	E-25066	0.8910	0.1548	1.0458
MICROMETALS	E125	6.315	1.595	7.9100
	E137	6.311	1.614	7.9250
MAGNETICS	RM 12	0.5251	0.1185	0.6436
	EE43007	2.161	0.3079	2.4689
EPCOS	RM12	0.5322	0.083	0.6152
	E 30/15/17	0.955	0.1013	1.0563
FERROXCUBE	RM 12/ILP	0.5309	0.2515	0.7824
	E25/16/16	0.5928	0.8885	1.4813
TDK	RM12	0.5266	0.1122	0.6388
	EE30/30/7	0.9349	0.0861	1.0210
	EE 25.4/32.6.4	0.1822	0.1832	0.3654

Analysis is made from the result obtained in Table III. With respect to lowest total loss below are the details of the selected core:

Manufacturer : TDK

Core Types : EE 25.4/32.4

Core Material : PC40

Wire : Copper_70 um_6 mm

Winding Loss : 0.1822 W

Core Loss : 0.1832 W

Temperature Rise : 12.31 °C

4.1.3.1 EE 25.4/32.4 Core Properties

The selected core is EE25.3/32/6.4. This is the suitable core for 100 kHz, based on the parameters that are set before. This core type has its own properties as shown in Figure 22.

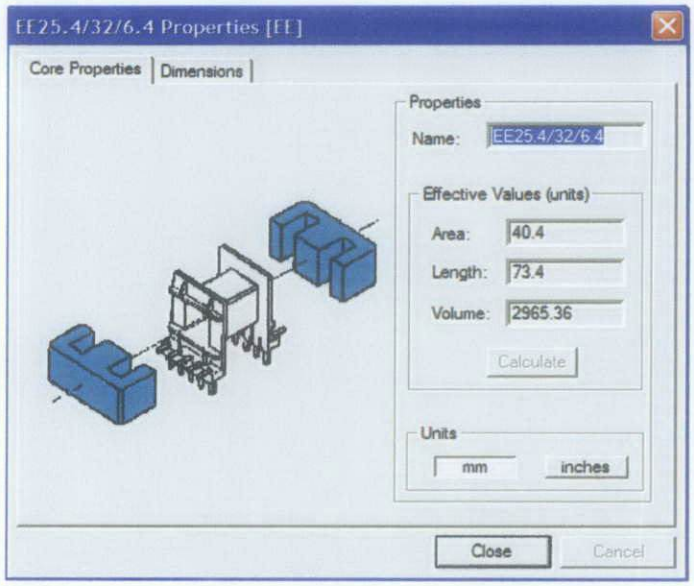

Figure 22: Core properties for EE 25.4/32/6.4 operating at 100 kHz

From Figure 2, the extracted properties are:

Area of the core	: 40.4 mm^2
Length of the core	: 73.4 mm
Volume of the core	: 2965.36 mm^3.

4.1.3.2 Copper_70um_6mm Conductor Properties

The wire or conductor that is chosen for 100 kHz is copper_70um_6mm. Properties of the wire is shown in Figure 23.

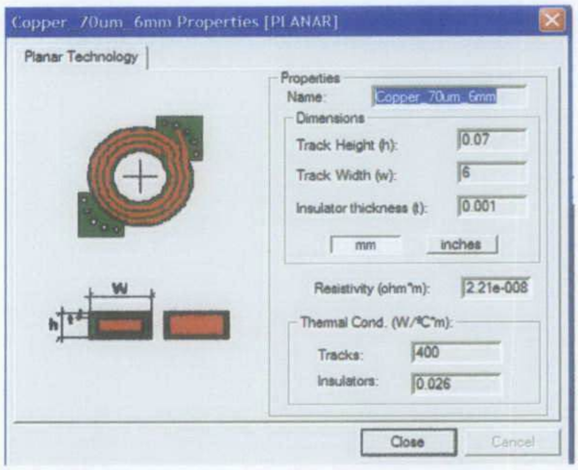

Figure 23: Conductor properties operating at 100 kHz

For the dimension of the conductor, below are the details:

Track Height: 0.07 mm
Track Width: 6 mm
Insulator thickness: 0.001 mm

4.1.3.3 PC 40 Material Properties

PC40 is selected as the material and the properties are illustrated in Figure 24.

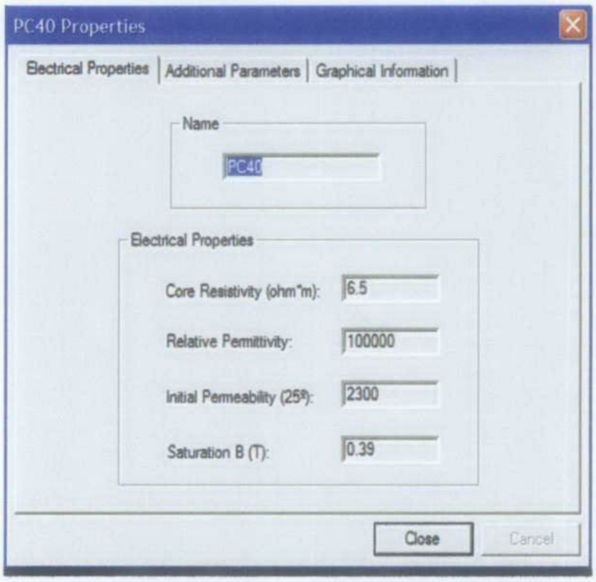

Figure 24: Material properties for PC40 material type

The electrical properties for PC40 are:

Core Resistivity	: 6.5 Ω-m
Relative Permittivity	: 100000 F/m
Initial Permeability	: 2300 H/m
Saturation of flux	: 0.39 T

4.1.3.4 Summary of the Core Types and Characteristics for 100 kHz

Based on the data and information collected, for 100 KHz operating frequency, the most suitable core type and its properties is shown in Table IV.

Table IV: Summary of the core types and characteristics

Manufacturer	**TDK**
Core Types	**EE 25.4/32.4** Area : 40.4 mm^2 Length : 73.4 mm Volume : 2965.36 mm^3
Core Material	**PC40** Core resistivity : 6.5 Ω-m Relative permittivity : 100 000 F/m Initial permeability : 2300 H/m Saturation : 0.39 T
Wire	**Copper _70um_6mm** Track height : 0.07 mm Track width : 6 mm Insulator thickness : 0.001 mm
Winding Loss	0.1822 Watt
Core Loss	0.1832 Watt
Total Losses	0.3654 Watt
Temperature Rise	12.31 °C

4.1.4 Core Types and Characteristics for 1 MHz

Based on methodology describe in section 3.3.6, the results obtained as shown in Table V where list of core types that are available for 1 MHz is tabulated.

Table V: List of core types that are available for 1MHz

MANUFACTURER	CORE TYPES	WINDING LOSS (W)	CORE LOSS (W)	TOTAL LOSS (W)
AVX	RM 1400B	0.5961	0.0018	0.5979
	E-25066	0.4532	0.0698	0.5230
MICROMETALS	E125	1.160	0.3502	1.5102
	E137	1.155	0.3543	1.5093
MAGNETICS	RM 12	0.5342	0.0298	0.5640
	EE43007	0.9555	0.2219	1.1774
EPCOS	RM12	0.5414	0.012	0.5624
	E 30/15/17	0.4862	0.0404	0.5266
FERROXCUBE	RM 12/ILP	0.5413	0.0317	0.5730
	E25/16/16	0.4522	0.0688	0.5210
TDK	RM12	0.5356	0.0095	0.5451
	EE30/30/7	0.4768	0.047	0.5238
	EE 25.4/32.6.4	0.4532	0.0994	0.5526

Based on results tabulated in Table V, the core with lowest winding loss is selected. Below are the details of the selected core:

Manufacturer : Ferroxcube

Core Types : E25/16/16

Core Material : 3C18

Wire : Copper_70 um_6 mm

Winding Loss : 0.4522 W

Core Loss : 0.0688 W

Temperature Rise : 6.38 °C

4.1.4.1 EE 25/16/16 Core Properties

The selected core was EE25/16/16. This is the best core to be used at 1 MHz, based on the parameters set before. This core type has its own properties as shown in Figure 25.

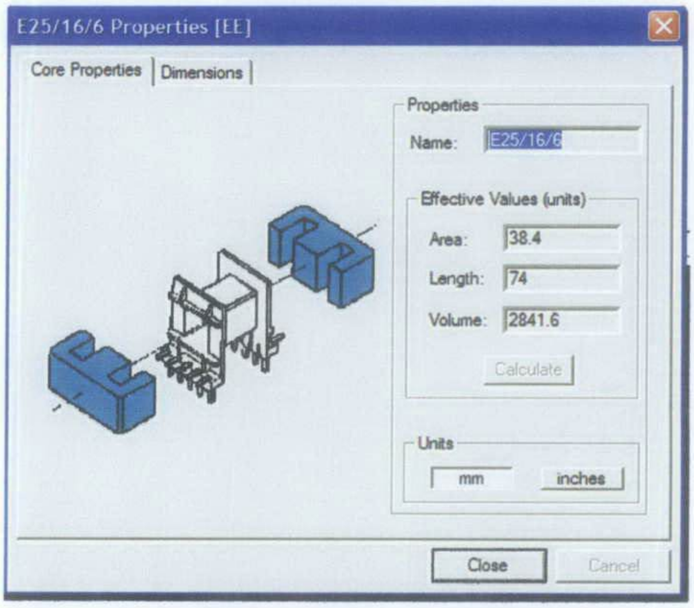

Figure 25: E25/16/16 core properties operating at 1 MHz

Data that can be extracted from Figure 25 are as below:

Area of the core	: 38.4 mm^2
Length of the core	: 74 mm
Volume of the core	: 2841.6 mm^3

4.1.4.2 Copper_70um_6mm Conductor Properties

For 1 MHz operating frequency, the wire or conductor selected is copper_70um_6mm and its properties is shown in Figure 26.

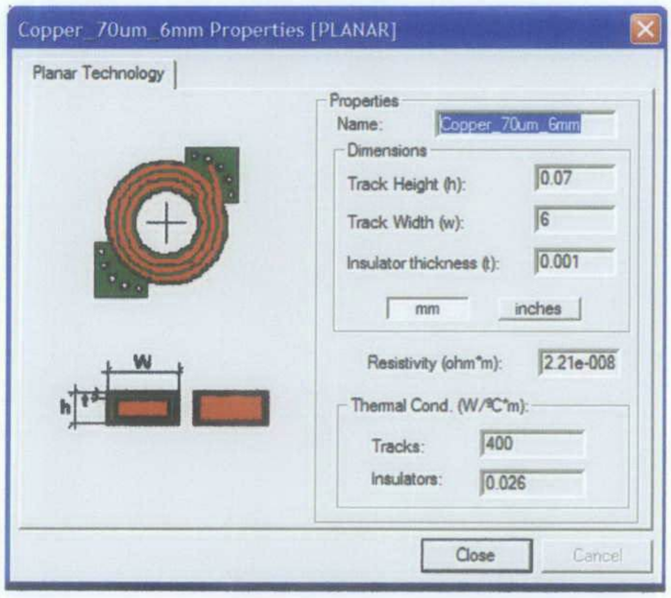

Figure 26: Wire or conductor properties operating at 1 MHz

Details of the dimension for this wire type or conductor are as below:

Track Height: 0.07 mm
Track Width: 6 mm
Insulator thickness: 0.001 mm

4.1.4.3 *3C81 Material Properties*

Material that may be used for 1 MHz is 3C81. The properties of selected material is shown in Figure 27.

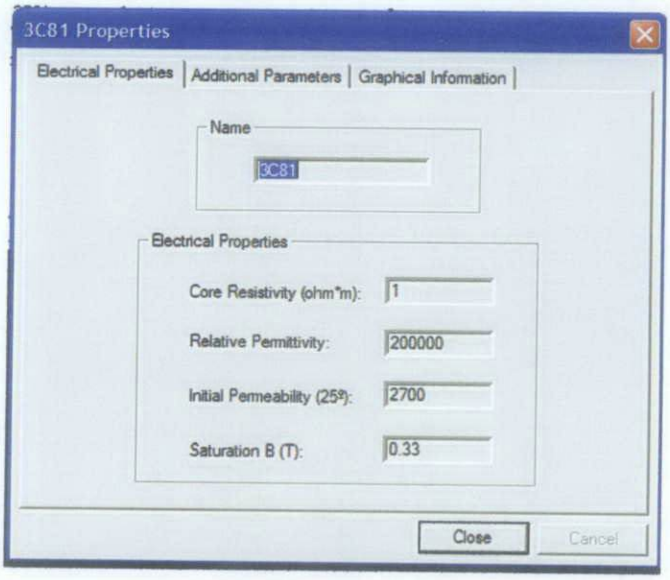

Figure 27: 3C81 core material properties

3C81 material has its own properties as listed below:

Core Resistivity	: 1 Ω-m
Relative Permittivity	: 200000 F/m
Initial Permeability	: 2700 H/m
Saturation of flux	: 0.33 T

4.1.4.4 Summary of the Core Types and Characteristics for 1 MHz

Based on the data and information collected, for 1 MHz operating frequency, the most suitable core type and its properties are shown in Table VI.

Table VI: Summary of the core types and characteristics

Manufacturer	**Ferroxcube**
Core Types	**E 25/16/16** Area : 38.4 mm^2 Length : 74 mm Volume : 2841.6 mm^3
Core Material	**3C18** Core resistivity : 1 Ω-m Relative permittivity: 200 000 F/m Initial permeability : 2700 H/m Saturation : 0.33 T
Wire	**Copper _70um_6mm** Track height : 0.07 mm Track width : 6 mm Insulator thickness: 0.001 mm
Winding Loss	0.4522 Watt
Core Loss	0.0688 Watt
Total Losses	0.5210 Watt
Temperature Rise	6.38 °C

. 4.1.5 Core Types and Characteristics for 50 MHz

List of the core types that are suitable for 50 MHz is shown in Table VII. This result obtained based on methodology explained in section 3.3.8.

Table VII: List of core types that are available for 50MHz

MANUFACTURER	CORE TYPES	WINDING LOSS (W)	CORE LOSS (W)	TOTAL LOSS (W)
AVX	RM 1400B	1.878	4.882	6.7600
	E-25066	1.427	95.138 u	1.4270
MICROMETALS	E125	3.605	0.0062	3.6112
	E137	3.588	0.0063	3.5943
MAGNETICS	RM 12	1.683	0.0028	1.6858
	EE43007	1.503	0.1287	1.6317
EPCOS	RM12	1.706	449.025 u	1.7084
	E 30/15/17	1.531	292.271 u	1.5313
FERROXCUBE	RM 12/ILP	1.706	936.559 u	1.7069
	E25/16/16	1.424	0.0125	1.4365
TDK	RM12	1.688	145.222 u	1.6881
	EE30/30/7	1.502	714.834 u	1.5027
	EE 25.4/32.6.4	1.427	0.0115	1.4385

Data tabulated in Table III is analyzed. By choosing the lowest winding loss, below are the details of the selected core:

Manufacturer	:	Ferroxcube
Core Types	:	E25/16/16
Core Material	:	3C18
Wire	:	Copper_70 um_6 mm
Winding Loss	:	1.424 W
Core Loss	:	0.0125 W
Temperature Rise	:	12.86 °C

4.1.5.1 EE 25/16/16 Core Properties

The properties for EE25/16/16 are shown in Figure 28.

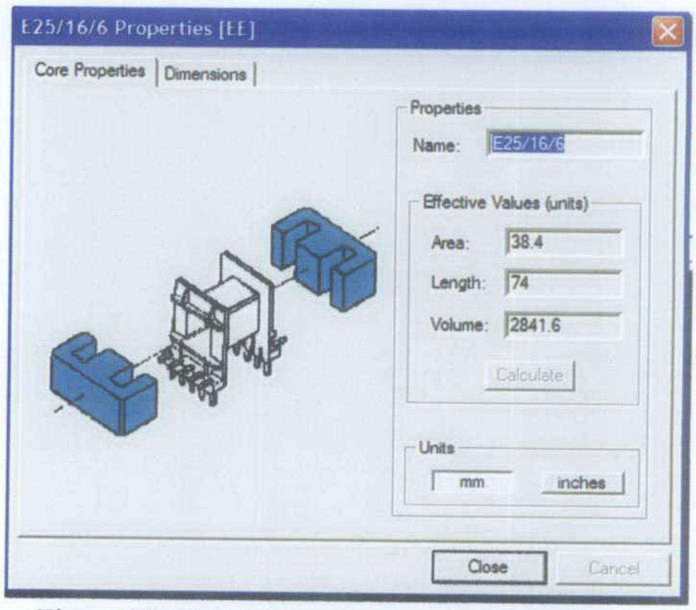

Figure 28: E25/16/6 core properties operating at 50 MHz

From Figure 28, characteristics of the effective values for E 25/16/16 are:

Area of the core	:	38.4 mm^2
Length of the core	:	74 mm
Volume of the core	:	2841.6 mm^3

4.1.5.2 Copper_70um_6mm Conductor Properties

For 50 MHz, the selected wire or conductor is copper_70um_6mm. Figure 29 shows the properties of the selected wire:

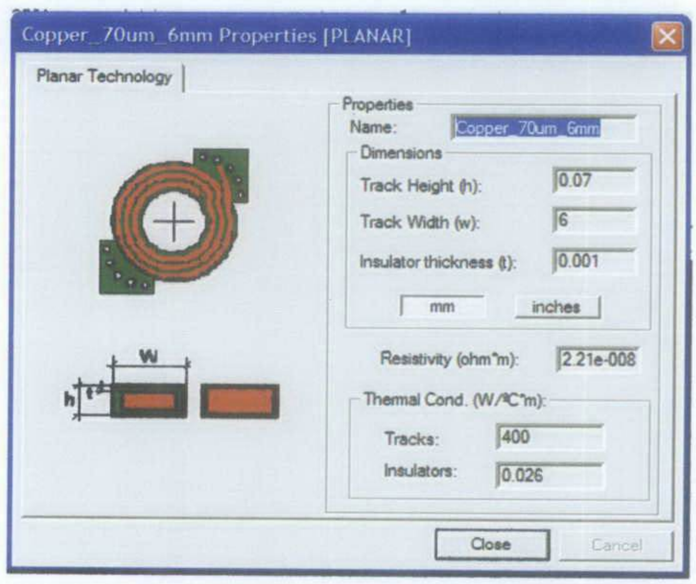

Figure 29: Wire or conductor properties operating at 50MHz

The dimension of the selected conductor, areas below:

Track Height: 0.07 mm

Track Width: 6 mm

Insulator thickness: 0.001 mm

4.1.5.3 3C18 Material Properties

For 50 MHz, the selected material is 3C81.Figure 30 shows the properties the core material:

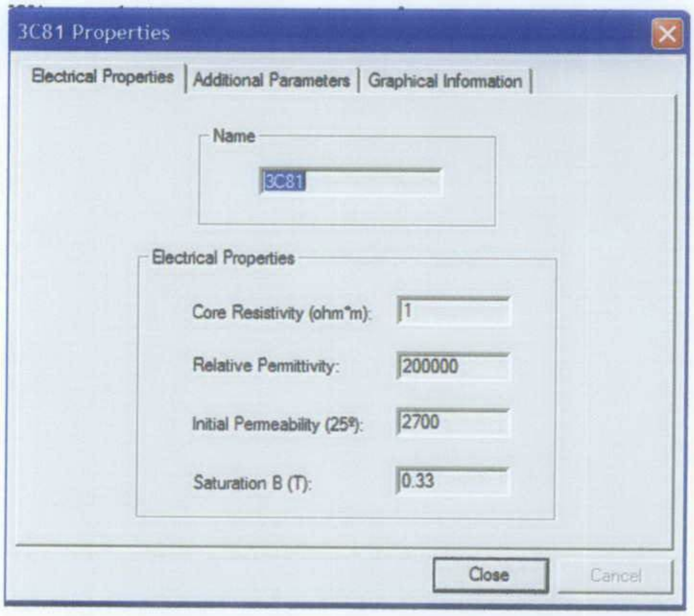

Figure 30: 3C81 properties operating at 50 MHz

Based on Figure 30, the electrical properties for 3C81 are:

Core Resistivity	: 1 Ω-m
Relative Permittivity	: 200000 F/m
Initial Permeability	: 2700 H/m
Saturation of flux	: 0.33 T

4.1.5.4 Summary of the Core Types and Characteristics for 50 MHz

Summary for the core type and its characteristics for 50 MHz operating frequency are summarized as shown in Table VIII.

Table VIII: Summary of the core types and characteristics

Manufacturer	Ferroxcube
Core types	E 25/16/16 Area : 38.4mm^2 Length : 74 mm Volume : 2841.6 mm^3
Core material	3C18 Core resistivity : 1 Ω-m Relative permittivity: 200 000 F/m Initial permeability : 2700 H/m Saturation : 0.33 T
Wire	Copper _70um_6mm Track height : 0.07 mm Track width : 6 mm Insulator thickness: 0.001 mm
Winding loss	1.4240 Watt
Core loss	0.0125 Watt
Total Losses	1.4365 Watt
Temperature rise	12.86 °C

4.1.6 Summary of the Suitable Core for 100 KHz, 1 MHz and 50 MHz

The summary for the results obtained for section 4.1 is summarized as shown in Table IX.

Table IX: Overall summary of the core types and characteristics

	100 kHz	1 MHz	50 MHz
Manufacturer	**TDK**	**Ferroxcube**	**Ferroxcube**
Core Types	**EE 25.4/32.4** Area : 40.4 mm^2 Length : 73.4 mm Volume : 2965.36 mm^3	**E25/16/16** Area : 38.4 mm^2 Length : 74 mm Volume : 2841.6 mm^3	**E25/16/16** Area : 38.4 mm^2 Length : 74 mm Volume: 2841.6 mm^3
Core Material	**PC40** **Core resistivity :** 6.5 Ω-m **Relative permittivity:** 100 000 F/m **Initial permeability:** 2300 H/m **Saturation :** 0.39 T	**3C81** **Core resistivity :** 1 Ω-m **Relative permittivity:** 200 000 F/m **Initial permeability:** 2700 H/m **Saturation :** 0.33 T	**3C81** **Core resistivity :** 1 Ω-m **Relative permittivity :** 200 000 F/m **Initial permeability:** 2700 H/m **Saturation :** 0.33 T
Wire	**Copper_70um_6mm** **Track height :** 0.07 mm **Track width :** 6 mm **Insulator thickness:** 0.001 mm	**Copper_70um_6mm** **Track height :** 0.07 mm **Track width :** 6 mm **Insulator thickness:** 0.001 mm	**Copper_70um_6mm** **Track height :** 0.07 mm **Track width :** 6 mm **Insulator thickness:** 0.001mm
Winding Loss (W)	0.1832	0.4522	1.424
Core Loss (W)	0.1822	0.0688	0.0125
Temperature Rise	12.31 °C	6.38 °C	12.86 °C

Table IX shows the selected cores for 100 kHz, 1 MHz and 50 MHz and their characteristics as well. The wire or conductor types selected are the same for the three frequency range, which are Copper_70um_6mm. It is a planar type wire. Figure 31 shows the graph of total losses corresponds to every core types for 100 kHz.

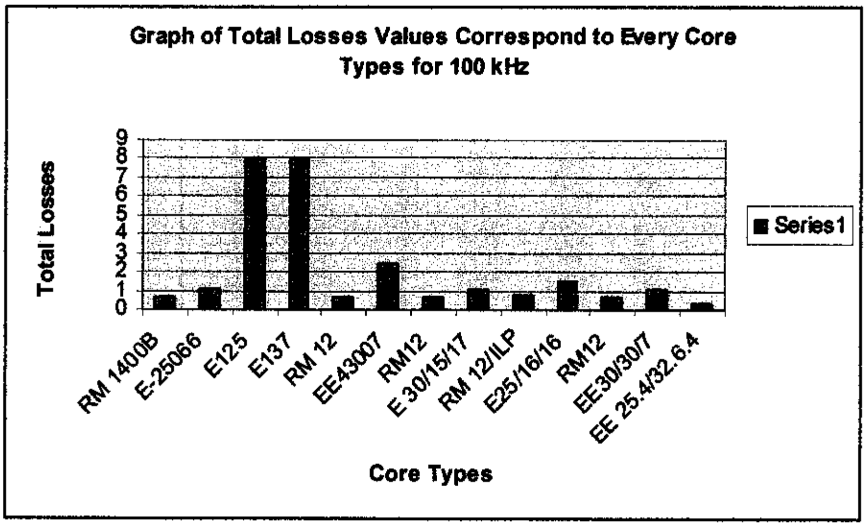

Figure 31: Graph of total losses values correspond to every core types for 100 kHz

From the graph, the core type of EE 25.4/32.4 is selected to be the suitable core to be used at 100 kHz corresponds to minimum total losses.

In term of core type and material of the core, both 1 MHz and 50 MHz selected the same cores and materials which are E25/16/16 from Ferroxcube and the materials is 3C81. E25/16/16 is one of the EE core shape and 3C81 is one of the ferrite materials.

For high operating frequency, E25/16/16 from Ferroxcube is one of the core types that suitable to be used. From the simulation, E25/16/16 is able to work at 1 MHz until 50 MHz frequency. It is proven as listed in Table X.

Table X: Verification for the chosen core with respect to high frequency

	1 MHz	**10 MHz**	**20 MHz**	**30 MHz**	**40 MHz**	**50 MHz**
Winding Loss (W)	0.1832	0.6810	0.9115	1.10	1.268	1.424
Core Loss (W)	0.1822	0.0531	0.0285	0.0120	0.0153	0.0125
Total loss (W)	0.3654	0.7341	0.9400	1.1120	1.2833	1.4365
Temperature Rise (°C)	6.38	7.14	8.10	9.74	11.22	12.86

As the frequency is increased, the value of the total losses and temperature rise also increased. This is proven that temperature will rise when the operating frequency increase. When operating in high frequency range, transformer suffer temperature rise, caused by heat dissipation from high frequency losses.

4.2 Interleaved Technique (Optimization of the Design)

Based on the work flow in section 3.3, it is expected that the leakage inductance and AC resistance as well as winding losses will reduce.

4.2.1 Before Interleaved

The results obtained for methodology describe in section 3.4.3 leads to two factors to be analyzed, which are AC resistance and Leakage inductance.

4.2.1.1 AC Resistance

Graph of AC resistance for both primary and secondary winding are analyzed. Figure 32 shows the graph of the AC resistance value for the primary winding before the interleaved technique is applied to the winding.

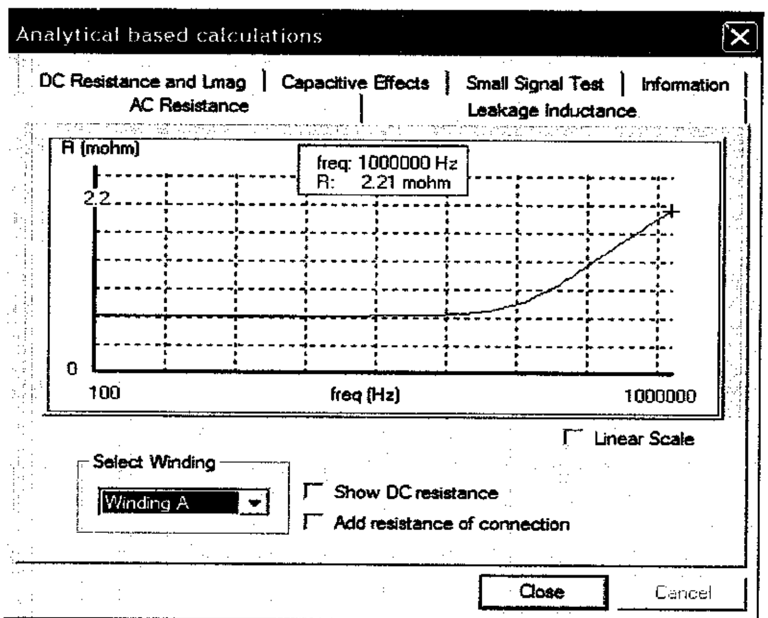

Figure 32: AC resistance value for primary winding before application of interleaved technique

From the graph, the value of the AC resistance is 2.21 mΩ. Figure 33 shows the plot of the AC resistance value for the secondary winding. From the graph, the value is 3.77 mΩ.

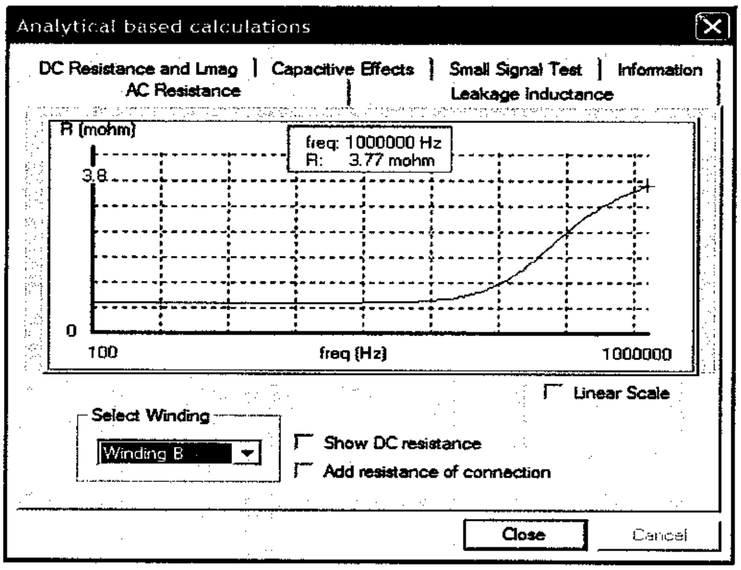

Figure 33: AC resistance value for secondary winding before application of interleaved technique

4.2.1.2 Leakage Inductance

Graph of leakage inductance for primary and secondary windings also analyzed. Value of the leakage inductance for primary winding before the application of interleaved technique is shown as in Figure 34.

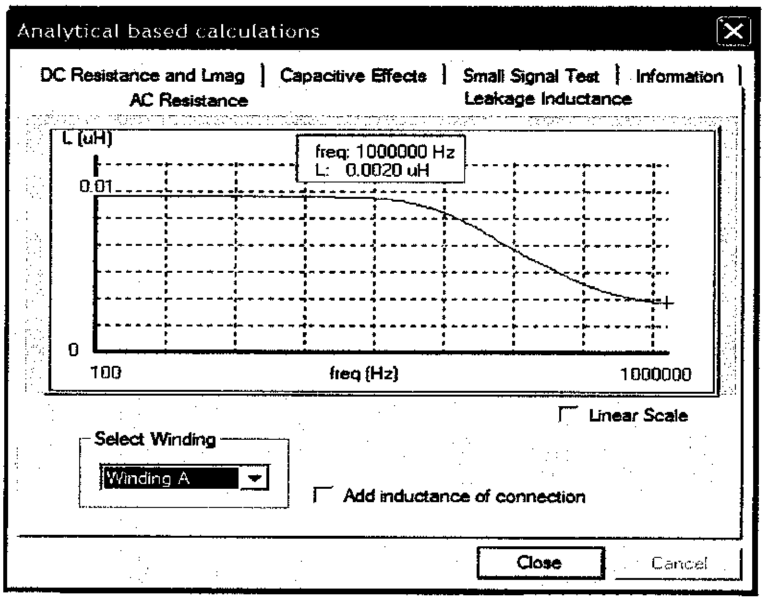

Figure 34: Leakage inductance value for primary winding before application of interleaved technique

From the graph, the value of the leakage inductance for primary winding is 0.0020 uH.

Figure 35 shows the plot of the leakage inductance for secondary winding before interleaved technique is applied.

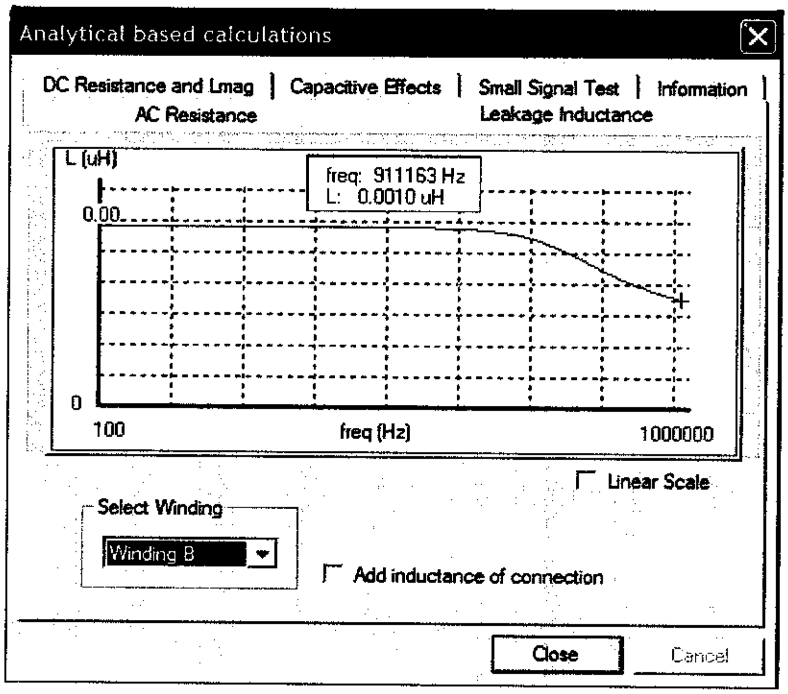

Figure 35: Leakage inductance values for secondary winding before application of interleaved technique

From the graph, the value of the leakage inductance for secondary winding is 0.0010 uH.

4.2.2 Application of Interleaved Techniques

Based on methodology in section 3.4.9, graphs of AC resistance and Leakage inductance values are analyzed.

4.2.2.1 AC Resistance

Figure 36 shows the graph of the AC resistance value for the primary winding after the interleaved technique is applied to the winding.

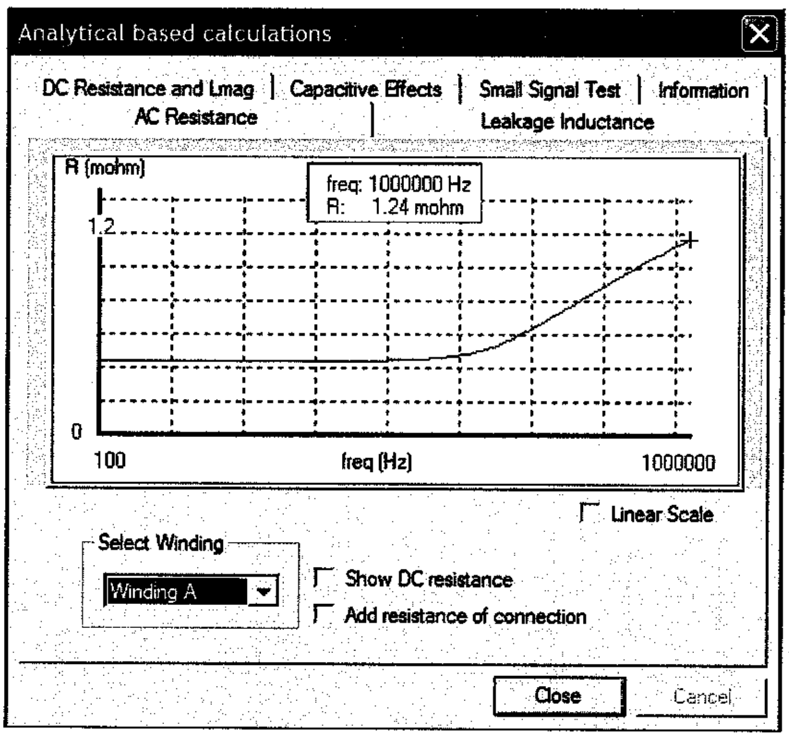

Figure 36: AC resistance value for primary winding after application of interleaved technique

From the graph, the value of the AC resistance is 1.24 mΩ. Figure 37 shows the plot of the AC resistance value for the secondary winding. From the graph, the value is 1.79 mΩ.

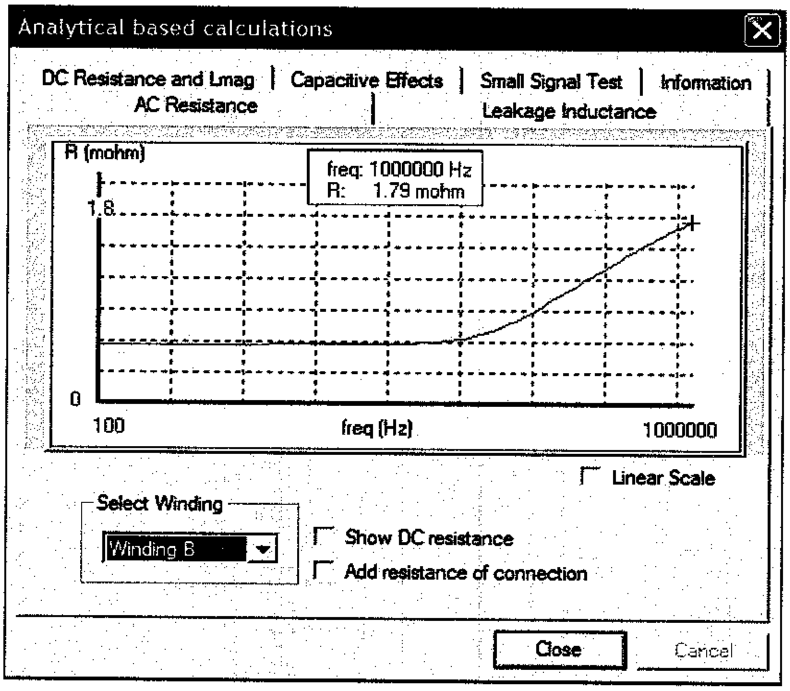

Figure 37: AC resistance value for secondary winding after application of interleaved technique

4.2.2.2 Leakage Inductance

The graph of the leakage inductance after the interleaved technique is applied shown as in Figure 38.

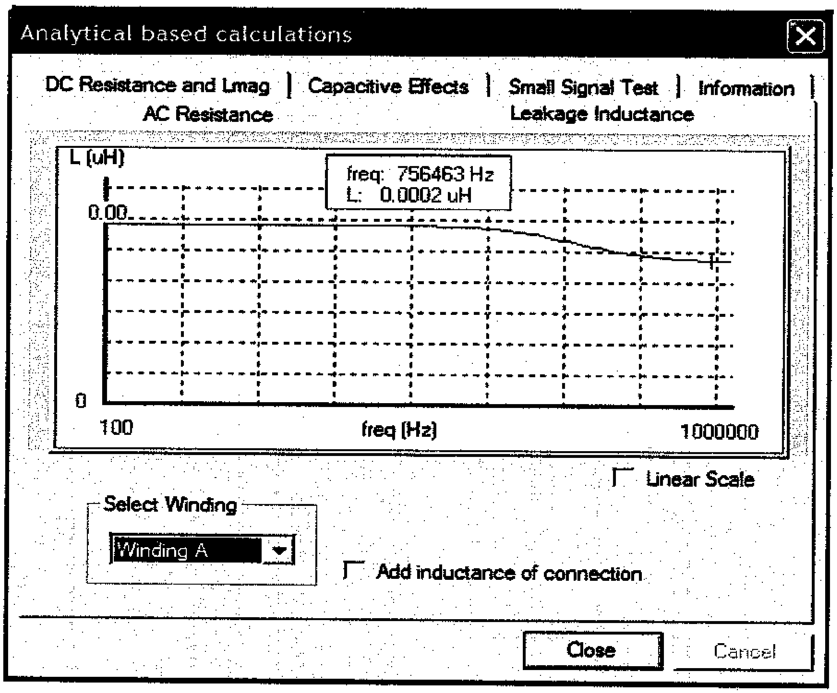

Figure 38: Leakage inductance value for primary winding after application of interleaved technique

From the graph, the value of the leakage inductance is 0.0002 uH. The leakage inductance value for secondary winding is shown in Figure 39.

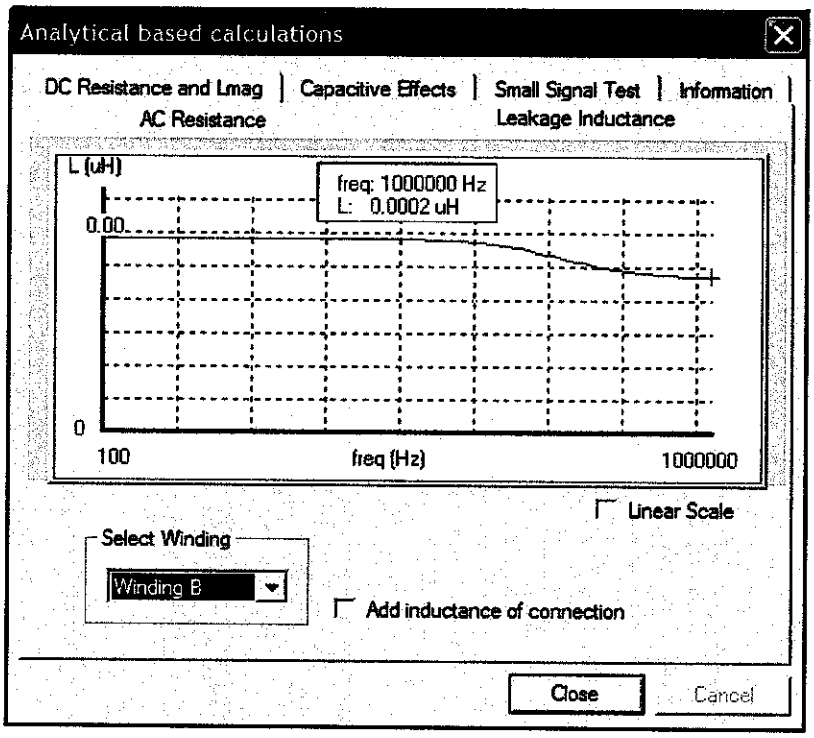

Figure 39: Leakage inductance value for secondary winding after interleaved winding is applied

From the graph, the value of the leakage induction for secondary winding is 0.002.

4.2.3 Summary of the Results

Summary of the results is shown in Table XI. The values of the AC resistance and Leakage inductance between interleaved application and normal winding are compared.

Table XI: Comparison of AC resistance and Leakage inductance values

		Before Interleaved	After Interleaved
AC Resistance	Primary Winding	2.21 mΩ	1.24 mΩ
	Secondary Winding	3.37 mΩ	1.79 mΩ
Leakage Inductance	Primary Winding	0.0020 uH	0.0002 uH
	Secondary Winding	0.0010 uH	0.0002 uH

Comparison of AC resistance values before and after application of interleaved technique is illustrated in Figure 40. Interleaved technique will cause significant reduction of AC resistance values for both primary and secondary windings.

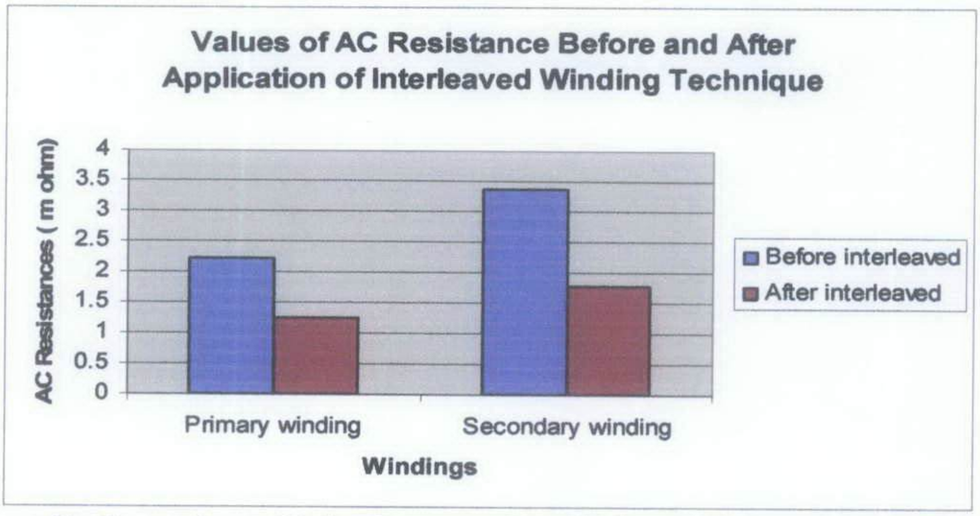

Figure 40: Comparison of AC resistances values before and after application of interleaved technique

Application of the interleaved technique results in reduction of leakage inductance values as well. Both primary and secondary values reduced when interleaved technique is applied. The comparison is illustrated as shown in Figure 41.

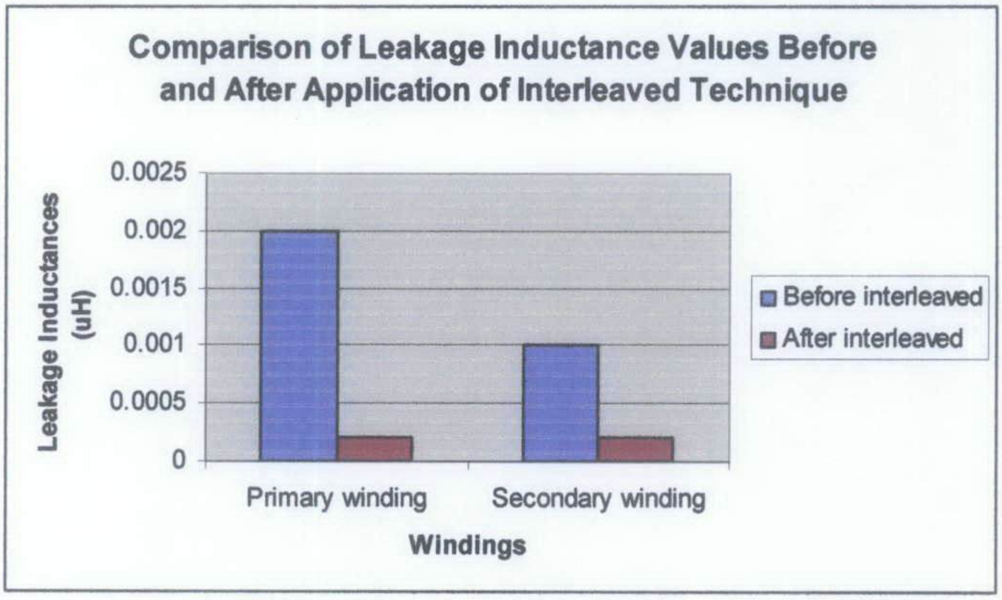

Figure 41: Comparison of Leakage Inductance values before and after application of interleaved technique

Based on calculation, after interleaved technique has been applied, AC resistance for primary winding and secondary winding reduce by 43.89 % and 46.88 % respectively. Leakage inductance for primary winding and secondary winding also reduce by 90 % and 80 % respectively.

It is proven that the AC resistance and leakage inductance are reduced when interleaved technique is applied to the windings. The reduction of AC resistance values will result in reduction of the power losses. AC resistance and copper loss are directly proportional to each other and this proves Formula 1 (section 2.3.4.1).

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Study on how to minimize power losses in a transformer has been successfully done. From this project, suitable core to be used depends on the switching frequency have been obtained.

A low-power-loss transformer has been designed. The suitable core has been optimized by applying interleaved technique. When interleaved technique is applied to the winding, the AC resistance and Leakage inductance are reduced. For primary winding, AC resistance and leakage inductance are reduced by 43.89 % and 90 % respectively. For secondary winding, AC resistance and leakage inductance are decreased by 46.88 % and 80 %. The reduction of the AC resistance will result in reduction of losses as well. Hence, a low-power-loss transformer is successfully designed.

5.2 Recommendation

This project offers lots of research and design opportunities for others. For the next project execution, the study and research may be done on the other issues such as core losses, thermal management and cost in the transformer design.

The PExprt that has been used in this project is not the latest version. PExprt version 6 is the latest version that is available at this point of writing. The features for previous and latest version are slightly different. Most of the papers and guidelines available today are from the use of latest version.

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Design Parameters

- **Waveform specifications**

Winding definition	: Based on converter specifications - Primary with no center tapped and secondary with center tap
Voltage shape	: Symmetrical - Absolute values of the positive and negative levels of voltage are the same.
Voltage waveform	: Square - Typical waveform in converter not sinusoidal, but square waves

- **Design input**

Table A : The parameters, available options and design impact for design inputs

Parameter	Available options	Design impact
Geometry	• Concentric component • Planar component • Toroidal component	Planar component
Thermal parameters	Ventilation: Low, Normal, High	Normal ventilation
	Ambient temperature	25°C
Turns ratio	• Maximum variation (as a percentage of the input turns ratio) • Exact value	Select maximum variation in order to allow PExprt find the design with the optimal degree of freedom for the turns ratio
Bobbin	Include	For Planar component, bobbin does not included
Winding setup	• 2D winding setup	2D winding strategy:

	• 1D " completely-full layers" • 1D "partially-full"	allows more than one winding in the same layer. For example, two parallel windings may be placed in the same layer
Parallel options	Maximum parallel turns	This value used for the maximum number of parallel windings to be considered during design process.
Winding efficiency	Awire/ Awinding (Wire area/Winding area spacing)	Determines how to modify the wire spacing. The smaller the winding spacing, the fewer number of wires that fit in the window.
Bmax/Bsat	Bmax/Bsat	Specified as a percentage of the saturation flux density and is the maximum value of flux density that will be considered for calculations
Maximum number of layer	Maximum number of layer	Useful in the design of planar components, where the costs of the components depends strongly on the number of layers.

Maximum temperature	Maximum temperature	Presents solutions with a temperature below the value
Minimum primary winding magnetizing inductance	Minimum primary winding magnetizing inductance	Presents solution with a higher magnetizing inductance than the one specified in this field.

- **Modelling inputs**

Table B: The parameters, available options and design impact for modelling inputs

Parameter	**Available options**	**Design impact**
Winding losses calculation	• I_{rms} and DC resistance • Harmonics and AC resistance (Skin) • Harmonics and AC resistance (Dowell)	$P = I^2_{DC} * R_{DC} + I^2rms\_1 * R_{AC\_1} + I^2rms\_2 * R_{AC\_2} + \ldots\ldots$ where I_{rms_i} = rms value of the harmonic I_{RAC}_i = resistance at the frequency of the harmonic i calculated with the effective area accounting for the skin effect at each frequency
Core losses calculation	• Steinmetz • Jiles Atherton (Hysterisis) • Jiles Atherton (Hysterisis)+Eddy	Steinmetz: core losses are calculated as Pcore $=f^{\alpha} * B^{\beta} *$ volume
Optimize number of turns for minimum losses	• No optimization • Apply optimization	PExprt optimizes number of turns for minimum losses