UNIVERSITY OF INDONESIA

Design factor of High Frequency Transformer

UNDERGRADUATE THESIS

An Undergraduate thesis submitted for the requirement of
Bachelor Engineering Degree

Ikrar Mahardhika Pramono
0606142622
Faculty of Engineering
Electrical Engineering Department
Depok

February 2012

STATEMENT OF AUTHORSHIP

This thesis is the result of my own work, and all sources quoted or referenced have been stated correctly as they should be

Name: Ikrar Mahardhika Pramono

Student Number: 0606142622

Sign:

Date: February 2012

APPROVAL PAGE

This thesis which is submitted by:

Name: Ikrar Mahardhika Pramono

Student Number: 0606142616

Course: Bachelor of Engineering (Electrical)

Thesis title: Design factor of High frequency Transformer

Has been successfully defended in front of the Board of Examiners and accepted as part of the requirements necessary to obtain an Engineering Degree in Electrical Engineering, Faculty of Engineering, University of Indonesia

BOARD OF EXAMINERS

Supervisor: Prof. Dr. Ir. Rudy Setiabudy, DEA (……………………………)
Examiner : Dr. Ing. Eko Adhi Setiawan (……………………………)
Examiner : Ir. Amien Rahardjo, MT (……………………………)

Approved in: Depok

Date: 06 February 2012

ACKNOWLEDGEMENTS

I am greatly thankful to my supervisor Dr. Firuz zare and Prof. Dr. Ir. Rudy Setiabudy, DEA who kindly also constantly guiding and supporting me from the initial of this undergraduate theories into the final stages which eventually led me to develop my skill and gain a better understanding in this research.

Lastly, I would say my gratitude and blessing to my family and people who always supports me in any conditions. Furthermore, I do have a lot of respect for people that helped me in completing this thesis that I could not mention one by one.

I declare that the work presented in this research is my own work except where due reference or acknowledgement is given to the work of others.

Depok, January 2012

Ikrar Pramono

DECLARATION PAGE
OF
THESIS PUBLICATION FOR ACADEMIC PURPOSES

As a student of University of Indonesia, I the undersigned below:

Name: Ikrar Mahardhika Pramono

Student Number: 0606142622

Course: Bachelor of Engineering

Department: Electrical Engineering

Faculty: Engineering

Thesis type: Undergraduate Thesis

For the development of science, agreed to provide University of Indonesia a **Non-exclusive royalty – Free Right** on my scientific work, entitled:

Design Factor of High frequency Transformer

Along with existing devices (if needed). **Non-exclusive royalty-Free Right** allows University of Indonesia to keep, convert/format, manage in the form of a database, and publish my theories as long as putting my name as author/creator and copyright owner.

I do solemnly and sincerely declare this statement and I make this solemn declaration conscientiously believing the same to be true.

Made in: Depok

Date: February 2012

Declarer,

(Ikrar Mahardhika Pramono)

Abstract

Transformer is a device that transfers electric energy from one alternating-current circuit to one or more other circuits, either increasing (stepping up) or reducing (stepping down) the voltage. Transformers act through electromagnetic induction; current in the primary coil induces current in the secondary coil. The use of transformers includes reducing the line voltage to operate low-voltage devices (doorbells or toy electric trains) and raising the voltage from electric generators so that electric power can be transmitted over long distances.

Power electronics is a rapidly growing technology encompassing a large variety of applications including automotive, telecommunications, computers and alternative energy system. Traditionally, transformer design has been based on voltage and current operating in low frequency. In switching circuit (SMPS) transformer works at high frequencies which led to considerable reductions in the size of magnetic component. The type of signals to be transferred from the primary to secondary windings dictate the type of transformer that most suitable to the application. Operation of a transformer at higher frequencies will lead reduced magnetizing inductance compared to lower frequencies.

This project is aimed to analyse and design a transformer purposed for high frequency uses. The expected outcomes of this project are defining the design factor of a high frequency inductors and transformers. Modelling and simulation of the transformer will be performed as part of this project, along with design approach and design factor.

TABLE OF CONTENT

TABLE OF FIGURE

CHAPTER I

INTRODUCTION

I.1. Background

Transformer is essentially just two (or more) inductors, sharing a common magnetic path. Any two inductors placed reasonably close to each other will work as transformer. Nowadays power converter had become very important in portable electronic devices. Power converters are used to increase the voltage level from the battery, instead of using multiple batteries to do the same thing. Electronic switch mode converters transforming voltage level to another by storing the input energy temporarily and then releasing that energy to the output at a different voltage, the transformer and inductor are purposed to that task. Separate primary and secondary windings also provide high voltage input-output isolation, especially important for safety in off-line applications. Leakage and magnetizing inductance causes voltage spikes during the switching transition, which can damage the switches. Transformer is the heart of the power converter. The design of a transformer in power electronics has many aspects, most of which are discussed in this project. Many properties of the transformer influence the design of the power electronic converter, such as magnetizing inductance, leakage inductance, voltage, current, frequency, power loss, and so on.

In this project, student design and develop a high frequency transformer for switch mode power supply, which later will be used for another project. By going through the transformer basic theory, student investigates every parameter in transformer design phase. Below is the schematic example of how the transformer will operate.

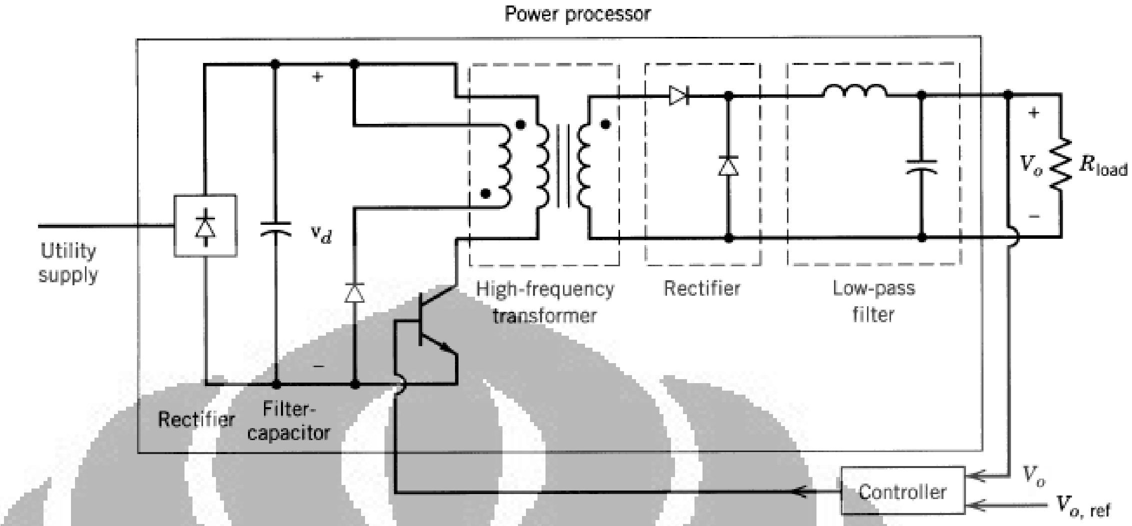


Figure 1. Power processor Schematic diagram

In this system, the utility input is rectified into a dc voltage, by operating the transistor as a switch at some high switching frequency; the dc voltage is converted into an ac voltage at the switching frequency. This allows a high-frequency transformer to be used for stepping down (or stepping up) and providing electrical isolation. Nowadays power converter had become very important in portable electronic devices. For example, instead of using multiple batteries, we use power converter to increase the voltage level from the battery.

This report will point out the design factor of high frequency transformer, the result from laboratory measurement and Matlab simulation that have been done in modeling the transformer are also included. The design process includes core size and material selection to suit the specification, determine the number of turns, and calculate the losses and high frequency effect. Matlab simulation result will be compared to laboratory measurement for model validation; furthermore the design factor of high frequency transformer and inductor is analyzed in this project.

I.2. Scope and Objectives

The purpose of this project is to define the design factor of high frequency transformer and inductor for switching converters. Among others, the following tasks will be performed:

- Understanding the fundamentals of high frequency power transformer and inductor
- Analysis of magnetic materials for power transformer
- Understanding high frequency characteristic of transformer windings
- Transformer modeling
- Laboratory measurement
- Model validation
- Defining the design factor of high frequency inductor and transformer

Design factor can be defined as parameters or key element of design process. To be able to determine design factor of transformer, designer have to understand every aspect of each element of a transformer. However there are three main things that will be investigated deeply; magnetic core selection, winding structure, and high frequency effect. Magnetic core selection becomes crucial in high frequency application due to the increase of eddy current in the core. Beside the electrical characteristic, mechanical reason such material sizing also become so important in this project, because the more compact and economical the core size are desired outcome of this project.

CHAPTER II

TRANSFORMER DESIGN CONSIDERATION

II.1 Basic Magnetic theory

In transformer, magnetic fields are the fundamental mechanism by which energy is converted from one form to another. The induced electromagnetic field equals the negative rate of time variation of the magnetic flux through the contour [].

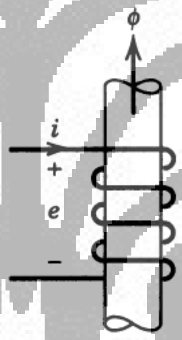


Figure 2. Flux direction and Voltage polarity

Consider a stationary coil with or without a magnetic core as shown above, after knows the current direction the right hand rule is used to establish the positive flux direction. Then by Faraday's Law, a time-varying flux linkage of the coil related to the induced voltage [3].

$$e = N\,\frac{d\phi}{dt}$$

The input current flowing through the primary winding generates a magnetic flux, and this magnetic flux induced an output voltage coming out from the secondary winding of the transformer. So transformers are basically inductors that are coupled through a shared magnetic circuit [3].

The magnetic field intensity **H** is defined by Ampere's Law [ ], which the integral of **H** [A/m] around a close path is equal to the total current passing through the interior of the path.

$$\oint \mathbf{H}.\mathrm{d}\mathbf{l} = \int \mathbf{J}.\mathrm{d}\mathbf{S} = \mathrm{Ni}$$

The magnetic field intensity **H** is in the sense a measure of the effort that a current is putting into the establishment of a magnetic field. The strength of the magnetic field flux produced in the core also depends on the material of the core [5]. The magnetic flux density **B** produced within a material is given by

$$\mathbf{B} = \mu\mathbf{H}$$

Relative permeability is a convenient way to compare the magnetizing ability of materials. So if a steel have relative permeability of 6000 means for a given amount of current, 6000 times more flux is established in a piece of steel than in a corresponding area of air. Also, instead of travelling through the surrounding air that has much lower permeability, the great majority of the flux remains inside the iron core. The small amount of leakage flux that does leave the iron core is very important in determining the flux linkages between the coil and the self-inductance of coils in transformers.

II.1.1 Transformer fundamental

The purpose of a transformer is to transfer power efficiently and instantaneously from an external electrical source to an external load. Transformer also provides important additional capabilities; the primary to secondary turns ratio can be established to efficiently accommodate widely different input/output voltage levels, multiple secondaries with different numbers of turns can be used to achieve multiple outputs at different voltage levels, and separate primary and secondary windings facilitate high voltage input/output isolation, especially important for safety in off-line applications.

The theory of transformers is based on Faraday law: the induced *emf* equals the negative rate of time variation of the magnetic flux through the contour. The input current flowing through the primary winding generates a tine varying magnetic flux, and this time varying flux will induce an output voltage coming out from the secondary winding of the transformer. Basically transformer is an inductor with multiple windings. The main difference between a transformer and inductor is that an inductor is an electrical device that stores energy in magnetic field [3]. In transformer the energy stored in the magnetic field is undesired. The use of the air gap is to store more energy in magnetic field as yields in above figure. This happen due to the total flux in the air gap is spread out over a larger cross-sectional area [4].

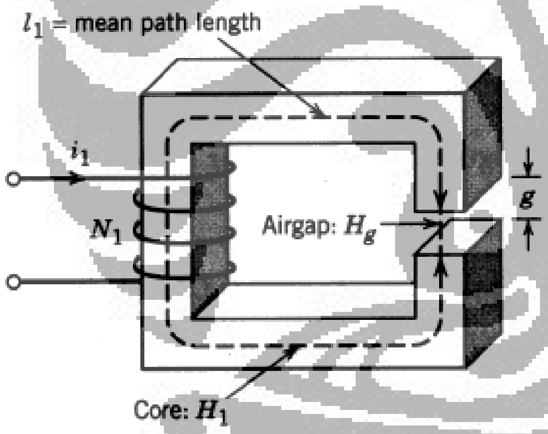


Figure 3. Transformer layout

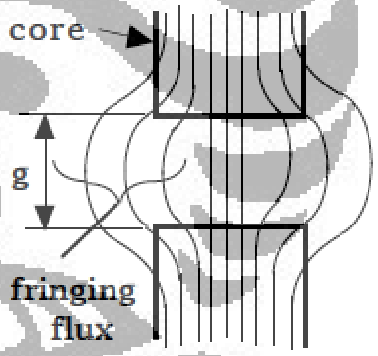


Figure 4. Fringging flux

Theoretically, a transformer is an alternating-current device that transforms voltage, currents, and impedances. Faraday law of electromagnetic induction is the principle of operation of transformers. For the closed path in the magnetic circuit, can be expressed as:

$$N_1 i_1 - N_2 i_2 = \Phi\Re$$

Where ϕ is the magnetic flux, $\Re$ is the reluctance for the magnetic path, N_1, N_2, and i_1, i_2, are the numbers of turns and the current in the primary and secondary windings, respectively. According to Lorenz law, the induced *mmf* in the secondary winding, N_2i_2, opposes the flow of the magnetic flux created by the *mmf* in the primary winding, N_1i_1. The reluctance is define as;

$$\Re = \frac{l}{\mu A_c}$$

Where l is the length of the magnetic path, μ is the permeability of the core material, and A_c is the cross section area of the path.

II.2 Magnetic core material

The fundamental requirements of magnetic material for power transformers are the highest relative permeability, the largest saturation flux density, the lowest core loss, and the lowest remanent flux density. Magnetic materials using as the cores of power transformers keep changing as the operating frequency increased. Magnetic cores play an important role in switching converter circuitry. They are made from a variety of raw materials, a range of manufacturing processes, and are available in a variety of geometries and sizes. Each material has its own unique properties; therefore, the requirements for each application of a core in the power supply must be examined in light of the properties of available magnetic materials so that a proper core choice can be made. With high permeability core material, the undesired energy stored in the core can be minimized. In power electronics there are two basic classes of materials used for magnetic cores for high frequency transformers and inductors; powder cores and ferrite cores. Characteristic of both magnetic materials with discussed thoroughly in this section.

II.2.1 Iron-based powder cores

Metal alloy tape-wound cores are used primarily at 50-60 Hz line frequencies. Insufficiently, they are generally unsuitable for high frequency application. However, lower loss amorphous metal alloys can be used in switching converter as magnetic amplifier with frequency up to 200 kHz. At switch mode power supply frequency, iron-based cores are quite lossy. But in filter inductor or continuous mode flyback application, if the percentages of flux swings are small enough, the losses maybe low enough to permit the use of this material [4]. This can happen because in those topologies, the inductive energy is stored in the non-magnetic region within the core. Powder cores are made in the three varieties; Molypermalloy, High flux, and KOOL MU. An alloy material is first ground to a fine powder. The powder is mixed with an insulating material which separates each particle from the next, thus increasing resistivity. Next, the powder is pressed into toroidal shapes. Powder cores are manufactured with a large radius on both the inside and outside diameters to facilitate winding.

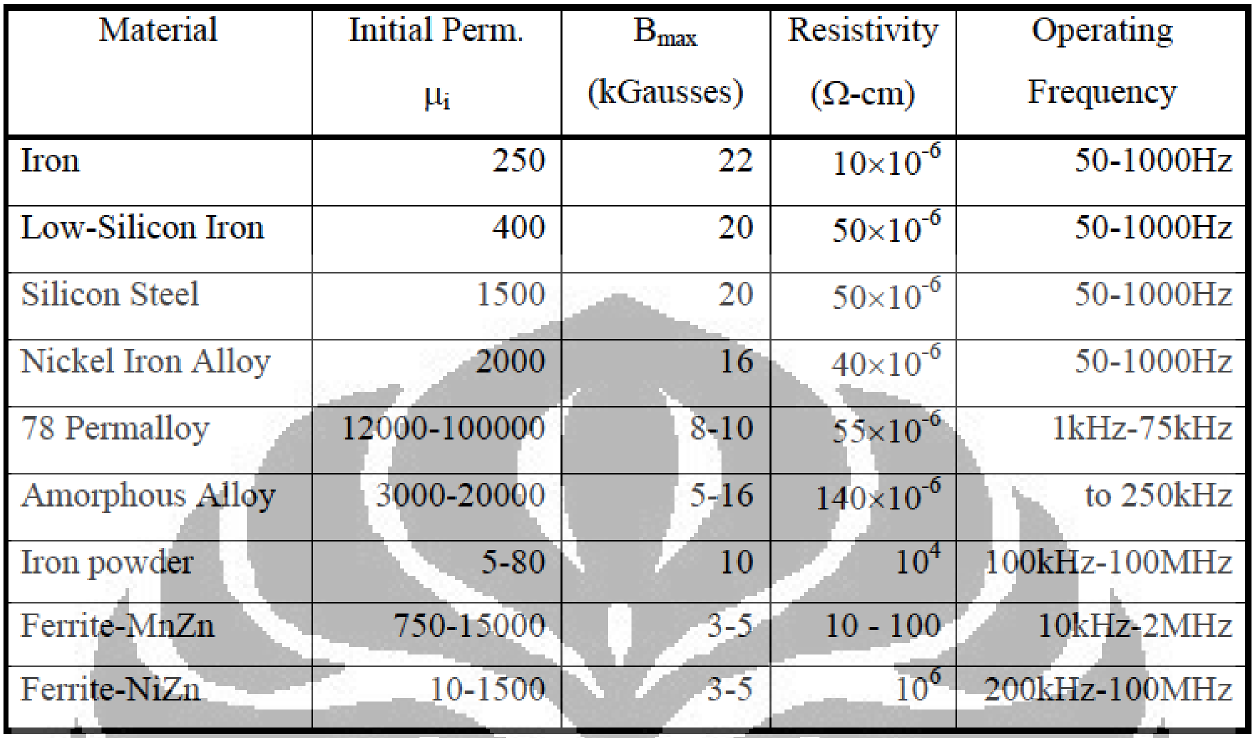
Molypermalloy powder (MPP) cores have extremely low losses and have a large energy storage capacity, making them excellent choices for chokes or power inductors at high frequency**. High flux powder cores** have higher flux density than Permalloy. These cores have a higher energy storage capacity, which allows for a higher dc flow before saturating. They also result in a lower volume and weight component. High flux cores have greater losses than Permalloy powder. Kool Mu powder cores offer an economical advantage while at the same time providing large energy storage. In some applications where heat rise can be tolerated, Kool Mu cores will offer a size reduction over iron powder in the same application. They are ideal for in-line noise filters where the inductor must support large ac voltages without core saturation occurring.

II.2.2 Ferrite material

Ferrites are ceramic materials, dark gray or black in appearance and very hard and brittle. The magnetic properties arise from interactions between metallic ions occupying particular positions relative to the oxygen ions in the crystal structure of the oxide. The electrical characteristics of ferrites are different from powder cores or metal strip cores. Currently ferrites are still the soft magnetic materials most widely used in power electronics. The most important characteristic of ferrites is the high volume resistivity of the material. In high frequency applications eddy current losses are usually dominant and increase approximately with the square of the frequency [4]. Ferrite type cores will require fewer turns, will give more impedance per turn and will couple better, whereas the Iron Powder cores will require more turns, will give less impedance per turn, will not couple as well but will tolerate more power and are more stable.

There are some magnetic properties of ferrite, such as saturation flux density, resistivity, and specific power loss. The general magnetic properties of ferrite are enumerated as follow:

- Permeability of several tens.
- A very high resistivity.
- Saturation magnetization is appreciable, but significantly smaller than that of ferromagnetic materials.
- Low coercive force
- Curie temperature varies from 100 C to several hundred.
- Dielectric constant of the order of 10-12 at high frequencies with extremely low dielectric loss.



Material	Initial Perm. μ_i	B_{max} (kGausses)	Resistivity (Ω-cm)	Operating Frequency
Iron	250	22	10×10^{-6}	50-1000Hz
Low-Silicon Iron	400	20	50×10^{-6}	50-1000Hz
Silicon Steel	1500	20	50×10^{-6}	50-1000Hz
Nickel Iron Alloy	2000	16	40×10^{-6}	50-1000Hz
78 Permalloy	12000-100000	8-10	55×10^{-6}	1kHz-75kHz
Amorphous Alloy	3000-20000	5-16	140×10^{-6}	to 250kHz
Iron powder	5-80	10	10^4	100kHz-100MHz
Ferrite-MnZn	750-15000	3-5	10 - 100	10kHz-2MHz
Ferrite-NiZn	10-1500	3-5	10^6	200kHz-100MHz

Figure 5. Core characteristic Database

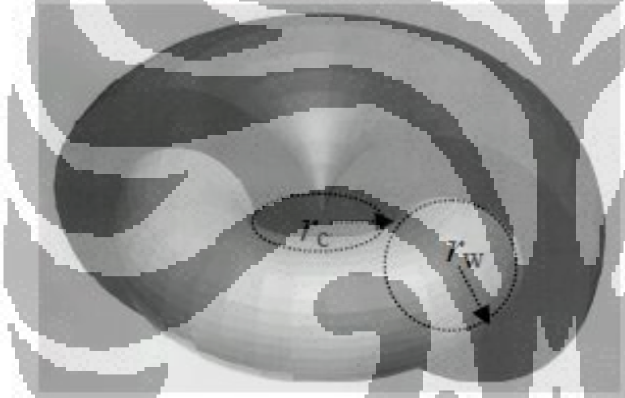
At the line frequency of 60 Hz, iron, low-silicon iron and silicon steel are the major materials for the cores of power transformers. They have high-saturation flux densities, thus they can handle high power transformation at low operating frequency. When the operating frequency of power transformer increased, the eddy currents inside the magnetic cores become a critical problem for the transformer designers. Although the laminated core materials have been used, the power losses generated by the eddy currents still heat up the core significantly, and this hot spot generated inside magnetic core can destroy the whole power transformer.

For this project, the selection of the core is based on the availability of the material in the market. Ferrite material 3C90 is used because it has considerably high permeability, and high resistivity. The designer of the transformer also needs to consider the dissipated power loss causing temperature raise in transformer operation. Although, the mechanical reason such material sizing and geometry of the core can gives huge impact in design factor of the transformer. Core database from the manufacturer are the main tools in selecting the magnetic core because it can act as the first consideration in transformer design phase.

II.3 Magnetic core geometry

The window configuration is extremely important. The window should be as wide as possible to maximize winding breadth and minimize the number of layers. Also, with a wide window, the fixed creepage allowance dimension has less impact. With a wider window, less winding height is required, and the window area can be better utilized.

II.3.1 Pot Cores

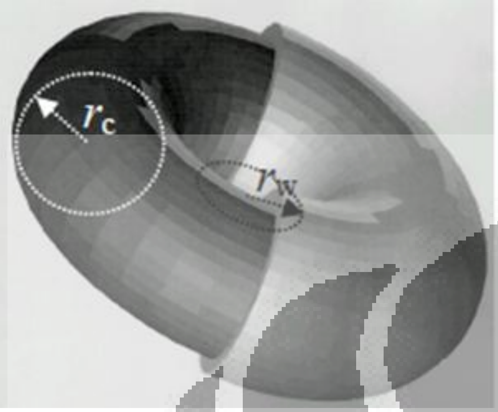


$$A_c = \pi r_c^2$$
$$l_c = \pi(2r_w + r_c)$$
$$A_w = \pi r_w^2$$
$$l_w = 2\pi(r_c + r_w)$$

Figure 6. Pot cores

When assembled, nearly surround the wound bobbin. This aids in shielding the coil from pickup of EMI from outside sources. The pot core dimensions all follow IEC standards so that there is interchange ability between manufacturers. Both plain and printed circuit bobbins are available, as are mounting and assembly hardware. Because of its design, the pot core is a more expensive core than other shapes of a comparable size. Pot cores are not suitable for high power applications.

II.3.2 Toroidal cores

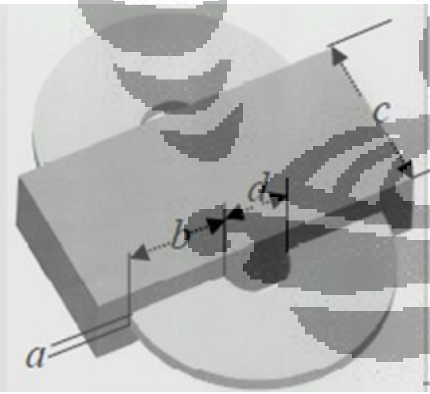


$$A_c = \pi r_c^2$$
$$l_c = 2\pi(r_w + r_c)$$
$$A_w = \pi r_w^2$$
$$l_w = \pi(2r_c + r_w)$$

Figure 7. Toroidal cores

Toroids are economical to manufacture; hence, they are least costly of all comparable core shapes. Since no bobbin is required, accessory and assembly costs are nil. Winding is done on toroidal winding machines. Shielding is relatively good.

II.3.3 Planar cores



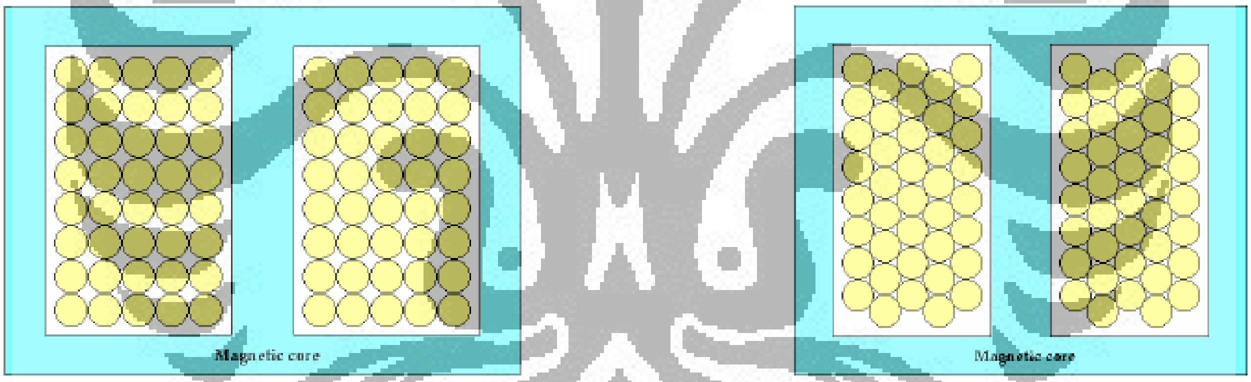
$$A_c = c \cdot d$$
$$l_c = 2a + 2b + \frac{5}{2}d$$
$$A_w = a \cdot b$$
$$l_w = 4b + 2c + 2d$$

Figure 8. Planar core

Planar transformers normally use flat copper foil or printed-circuit boards instead of round copper wire. Used together with appropriately flat ferrite cores, they result in an especially compact transformer with a very low profile.

II.4 Transformer winding structure

Transformers consist of magnetic core and coils. The coil of transformers is actually a copper winding around the magnetic materials to generate the magnetic flux by the input power source and reproduce electric energy to the loading of the transformer. At line frequency, a single copper wire with low resistance can perfectly complete this task. The dc resistance of the copper wires is the main point to be considered. The arrangement of conductors in the winding of transformer is a very important factor to determine the dc resistance of the copper winding of transformers. The cross-sections of two ideal arrangement of conductors, such as square arrangement and hexagonal arrangement are shown in figure below. The basic principle of the ideal arrangement of conductors is using the winding space in the transformer to have the maximum cross-section area of conductors.



(A) Square (B) Hexagonal

Figure 9. Transformer winding structure

When the operating frequency increased to few tens kilohertz, the skin depth of the conductor reduces the effective cross section area of the wire and increases the ac resistance of the conductor. The ac resistance of the copper wire creates a heavy power loss in the windings of high frequency transformers. This power loss can be reduced by using litz wires to replace the single copper wire. It is constructed of individually insulated copper wires either twisted or braided into a uniform pattern. Litz construction is designed to minimize the power losses exhibited in solid conductors due to the skin effect. Litz wire construction counteracts this effect by increasing the amount of surface area without increasing the size of the conductor. In general, constructions composed of many strands of finer wires are best for the higher frequency application.

II.5 Transformer losses and limitation

Transformer loss is sometimes limited directly by the need to achieve required overall power supply efficiency. Losses are difficult to predict with accuracy. Core loss date from core manufacturers is not always dependable, partly because measurements are made under sinusoidal drive conditions. Low frequency winding losses are easy to calculate, but high frequency eddy current losses are difficult to determine because of the harmonic content of the switched rectangular current wave-shape. Transformer losses can be put into two major categories: core losses and winding losses.

II.5.1 Core losses

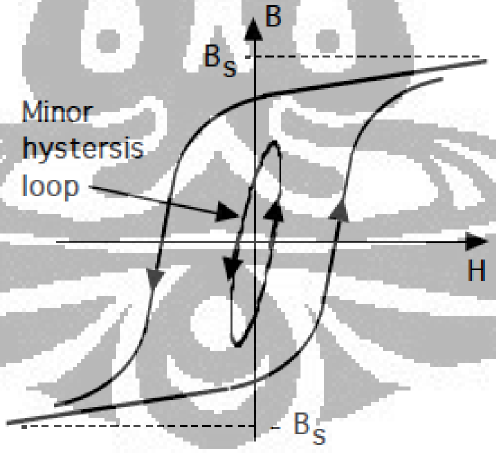


Figure 10. Hysteresis loop

Core hysteresis losses are a function of flux swing and frequency. All magnetic core exhibit some degree of hysteresis in their ***B-H*** characteristic. The hysteresis loss increase in all core material with the increases in ac flux density ($\boldsymbol{B}_{ac}$), and operating frequency (f) [3]. The general form of the loss per unit volume ($\boldsymbol{P_m}$) is

$$\boldsymbol{P}_m = kf^{a}(\boldsymbol{B}_{ac})^{d}$$

Where k, a, and d are constant that vary from one material to another. But this equation only applies over a limited range of frequency and flux density. Fortunately, the only important concern about the hysteresis loop in SMPS applications is the core loss it represents. The shape does not matter; the core loss curves provide the necessary information. In transformer applications, all we really need to know is that the magnetizing current is acceptably low (unless $\boldsymbol{I}_m$ is depended upon for some circuit function, which is risky). In filter inductor and flyback transformer applications, the hysteresis loop of the core material is totally swamped by the lossless and predictable high reluctance of the series gap, making $\boldsymbol{I}_m$ easily predictable. Core saturation is almost never a limitation in high frequency application. On the other hand, core loss is the most important limitation. Core manufacturers usually provide curves such Fig. [6] Showing core loss as a function of flux swing and frequency.

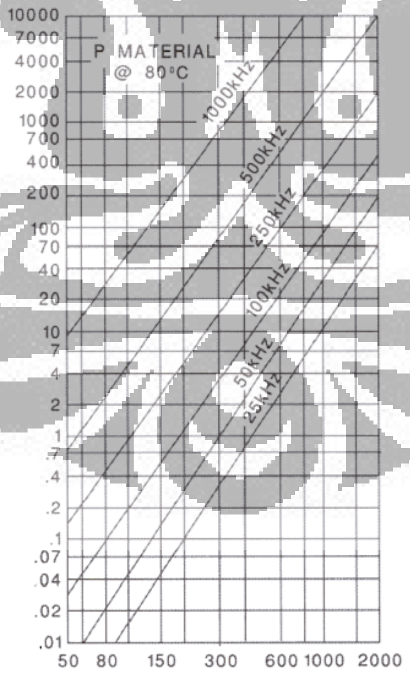


Figure 11. Flux swing vs Frequency

In above Core Loss vs. Flux Density curves, the horizontal axis labelled "Flux Density" usually represents peak flux density, with symmetrical sinusoidal excitation. In SMPS applications, peak-to-peak flux swing is calculated by *Faraday's Law*.

II.5.1.1 Eddy current loss

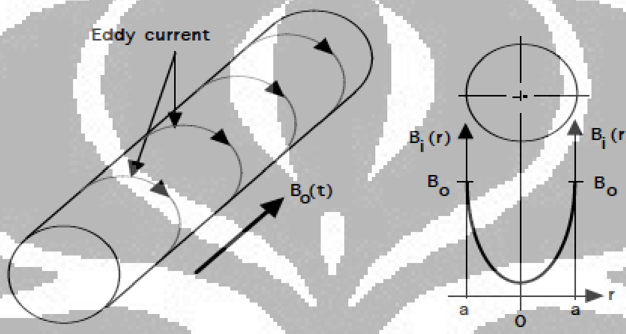


Figure 12. Eddy current

According to Faraday law, a voltage is induced in a conductor loop if it is subjected to a time varying magnetic flux. As a result a current flows in the conductor if there exists a closed path. The eddy currents generated in the conductive core dissipate power, generically termed eddy current loss in the core. The eddy current is reflected into the primary according to the ratio of the primary turns to the single turn core secondary. Generally, termed eddy current loss in the core and raise its temperature. Eddy current act as shield interior of material from magnetic field [8].If the cross-sectional dimension of the core is large compared to the skin depth, and then the core is ineffective in its intended role of providing a low reluctance return path for the applied magnetic field.

II.5.2 Winding losses

At low frequency, the most important thing to be considered in the transformer windings is the dc resistance of copper wires. When the operating frequency increases, the total number of turns decreases significantly, therefore the total length of the copper winding is also decreased. The power loss due to the dc resistance almost becomes zero suddenly. With the disappearing of the dc resistance, ac resistance increase enormously. The power loss due to ac resistance is larger than the one generated from dc counterpart.

II.5.2.2 Skin and Proximity effect

The skin effect occurs in the copper conductor used in inductor and transformer windings as described for the magnetic core. As a result of the magnetic field generates by eddy current, the total current density is largest at the surface of the conductor, and it decays exponentially with distance into the interior of the conductor.

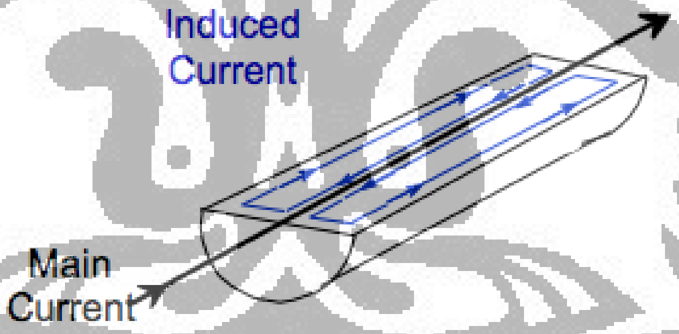


Figure 13. Skin effect

A single straight isolated conductor carrying an alternating current, shown in figure above, will be surrounded by a concentric magnetic field. This field will induce opposing eddy currents within the conductor itself as shown in the centre diagram. These currents trend to oppose the main current in the vicinity of the axis of the conductor and to enhance it at the surface.

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}}$$

Skin effect may be virtually eliminated by using conductors consisting of thin insulated strands so composed that individual strands weave cyclically from the centre of the conductor to the outside and back as they run along the length of the conductor. Such a stranding and transposition makes the current density uniform. However, since skin effect is not usually the most important form of eddy current losses in winding conductors, it is not usual to use this special stranding. To battle the proximity effect loss described in the next section, bunched conductor is often used. In practice, such bunched conductors are usually made up of groups of strands, then the appreciable transposition of the strands occurs. Careful measurements have shown that most bunched conductors behave as though the strands are transposed almost perfectly and the skin effect can be ignored.

II.5.3 Leakage inductance

Ideally, a transformer stores no energy or all energy is transferred instantaneously from input to output. Although in practice all transformers do store some undesired energy; Leakage inductance represents energy stored in the non-magnetic regions between windings, caused by imperfect flux coupling. In the equivalent electrical circuit, leakage inductance is in series with the windings; Mutual inductance represents energy stored in the finite permeability of the magnetic core and in small gaps where the core halves come together. In the equivalent circuit, mutual inductance appears in parallel with the windings. Not all the magnetic flux created by primary winding of transformer follows the magnetic circuit and links to other windings. The flux linkage between primary and secondary windings or parts of the same winding is never complete. Some flux leaks from the core and returns through the air, thus some flux is not linked by the other causing imperfect coupling. In addition, to the mutual flux, which does link both of the windings, is leakage flux. The voltage ratio of the transformer is no longer related by the turn ratio, as modelled in ideal transformer. It is necessary to subtract the voltage drop across the leakage inductances from the terminal voltages to get the ideal transformer winding voltages.

Leakage inductance is a very important factor for transformer design, it interferes with the basic operation of a transformer. The leakage inductance can cause over voltage in power switch at turn-off action, and requiring a snubber circuit to protect the switch. Leakage inductance is the key factor in this project, and will be discussed in the next two sections with the simulation results.

II.5.4 Stray Capacitance

Aside from power ratings and power losses, transformers often harbor other undesirable limitations which circuit designers must be made aware of. Like their simpler counterparts -- inductors -- transformers exhibit capacitance due to the insulation dielectric between conductors: from winding to winding, turn to turn (in a single winding), and winding to core. Usually this capacitance is of no concern in a power application, but small signal applications (especially those of high frequency) may not tolerate this quirk well. Also, the effect of having capacitance along with the windings designed inductance gives transformers the ability to *resonate* at a particular frequency, definitely a design concern in signal applications where the applied frequency may reach this point (usually the resonant frequency of a power transformer is well beyond the frequency of the AC power it was designed to operate on). Flux containment (making sure a transformer's magnetic flux doesn't escape so as to interfere with another device, and making sure other devices' magnetic flux is shielded from the transformer core) is another concern shared both by inductors and transformers.

II.5.3 Temperature raises

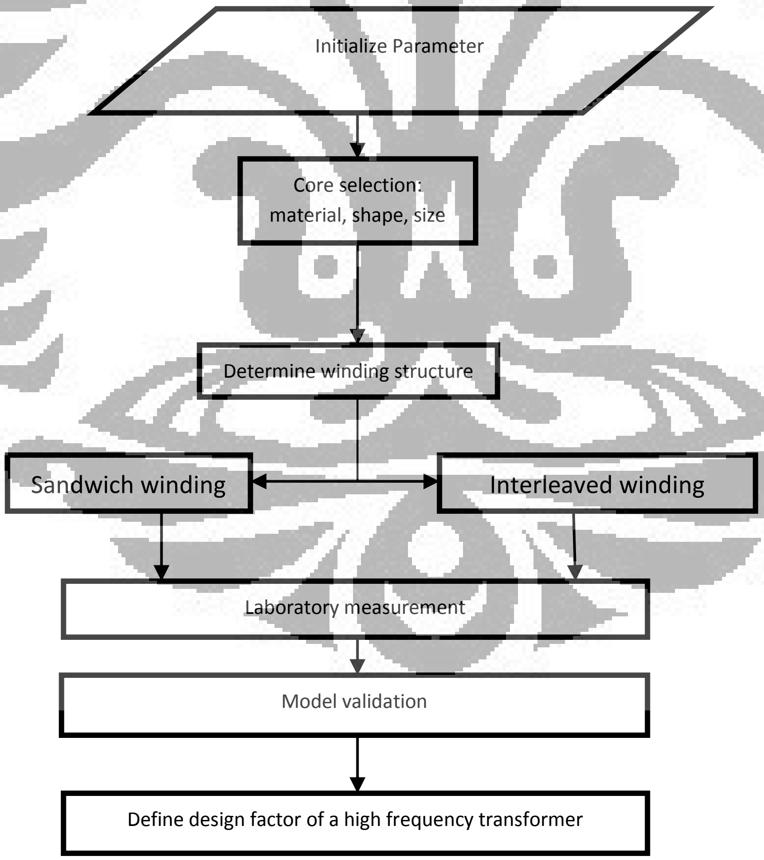
The last but not least, increases in the temperature of the core and winding materials degrade the performance of magnetic materials in several aspect. To keep the performance degradation within bounds, the temperature of the core and windings must be kept at or below some maximum value [2]. Temperature raise often become the operation limitation of the transformer, because the temperature raise of the core usually considered first in transformer design phase. Although here is the equation for temperature raise calculation.

$$P_{sp} = \frac{T_s - T_a}{R_{\theta sa}(V_w + V_c)} \; ; R_{\theta sa} = \frac{h}{A_s}$$

CHAPTER III

TRANSFORMER MODELLING

This chapter will demonstrate how the designer achieved the best transformer model for a specific application. In electrical engineering, it is often useful to use an equivalent circuit model to describe the non-ideal operation of a device such as a transformer. While an ideal model may be well suited for rough approximations, the non-ideal parameters are needed for careful transformer circuit designs. Knowing the non-ideal parameters allows the engineer to optimize a design using equations rather than inefficiently spending time testing physical implementations



Since time is the limitation in doing this project, designer of transformer have to come back to the basic things that affect transformer performance; leakage inductance and stray capacitance. The transformer design in this project will be used as a power converter in switching circuitry. In switching converter circuit, leakage inductance become a very important because of causing over voltage and breaks the switch. However, stray capacitance which normally can be ignored in high power application, but in high frequency circuit it can be a major problem. Parasitic capacitance between the output and input can act as a feedback path, causing the circuit to oscillate at high frequency.

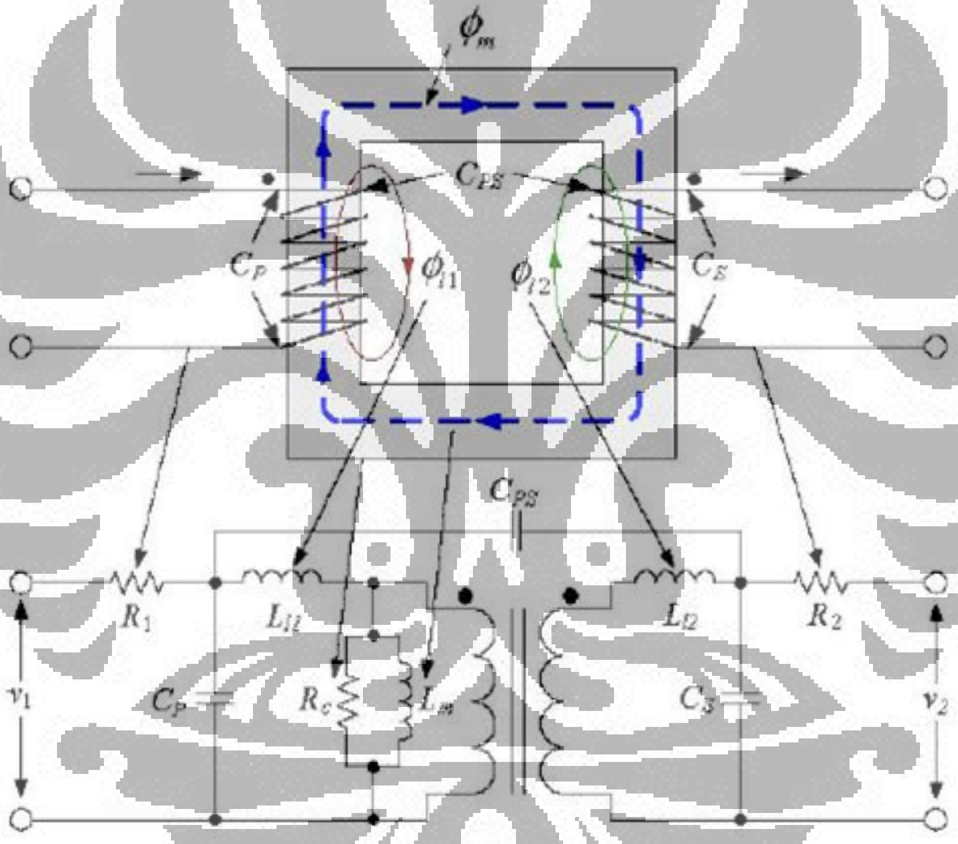


Figure 14. Real transformer model

To overcome those challenge, two different transformer configurations will be modeled and measured to look at the parasitic component. This section will include transformer configuration design approach, laboratory measurement, and validation of the model. The parasitic component that will be discussed in this section is the magnetizing inductance (L_M), leakage inductance (L_{l1} and L_{l2}), intrawinding capacitance (C_P and C_S) and interwinding capacitance (C_{PS}).

III.1 Transformer configuration

Two factors that contribute to the transformer losses are stray capacitance and leakage inductance. So it is very important for the designer to optimize their design by controlling these two factors. Leakage inductance arises because not all the flux links the windings via the core. Losses are a function of ohmic values in the circuit, and therefore the inductive and capacitive elements are best viewed as reactance X_L and X_C rather than **L** and **C**. High magnetizing current consequent excessive voltage drop that can break the switch.

First design approach

Second design approach

Figure 15. Winding configuration

The first design approach is to put the primary winding and secondary winding in the same core leg. Theoretically if we put the primary and secondary winding in the same leg, the flux leaks from the core through the air will reduce. This happen because the magnetic field created by the primary winding goes through the secondary winding only struggle in one leg of the core. For an optimum design of the transformer, it is very important to determine which winding structure gives the lowest winding loss at high operating frequency.

III.2 Transformer equivalent circuit

A transformer equivalent circuit shown in figure below consist of: ideal transformer, loss components, magnetizing inductance, and parasitic component.

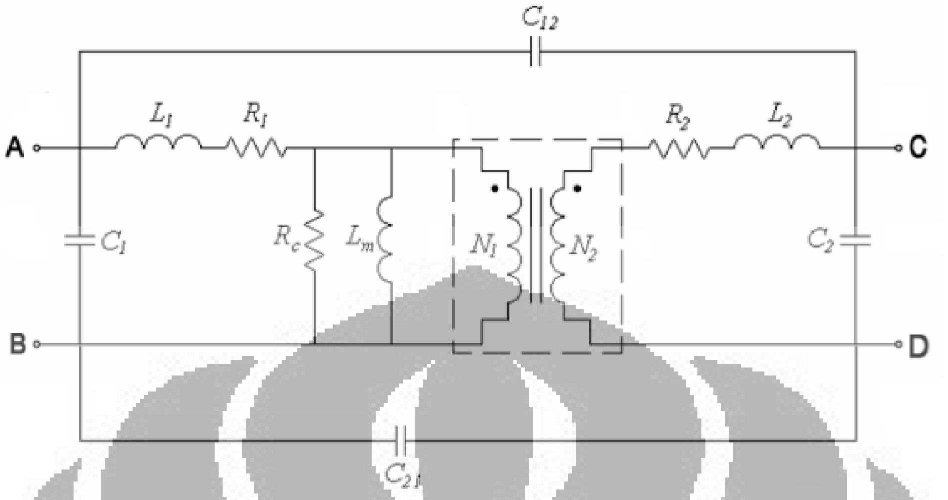


Figure 16. Transformer equivalent circuit

where

N_1 = number of primary turns

N_2 = number of secondary turns

R_C = core loss resistance

R_1 = primary resistance

R_2 = secondary resistance

L_M = magnetizing inductance

L_1 = primary leakage inductance

L_2 = secondary leakage inductance

C_1 = primary intrawinding capacitance

C_{12} = primary to secondary capacitance

C_2 = secondary intrawinding capacitance

III.3 Laboratory measurement

The purpose of this laboratory measurement is to see the frequency response of the transformer, and to model the parasitic component of it. In order to do it, a network analyser used to test the transformer that being designed previously. A network analyser is an instrument that measures the network parameters of electrical networks. Frequency response measurements are more crucial to the power supply industry than any other. Please note the AB-CD node from the equivalent circuit above for further measurement method.

Figure 17. Network analyzer

III.4 Measurement method

There are two popular tests in transformer component measurement, which are open circuit test and short circuit test. As the name suggests, the secondary winding is kept open circuited and nominal value of the input voltage is applied to the primary winding and the input current and power are measured. The purpose of this test is to look at the magnetizing inductance and core loss of the transformer. Due to core leakage inductance is small compared to leakage inductance in primary and secondary, so the inductance value seen on the frequency response from open circuit test is the value of magnetizing inductance. The core loss of the transformer also can be seen on open circuit test, which approximately at resonant frequency.

At short circuit test, the secondary winding is short-circuited. So now the mutual inductance between the windings is gone. Now the value of inductance seen in the frequency response is the series of leakage inductance in primary and secondary, due to the core leakage inductance in secondary is divided by the number of turns squared. And to find the intrawinding capacitance in primary and secondary, which very difficult when using open and short circuit test, the primary winding needs to remove first. After that we short the AB node (primary winding) and CD node (secondary winding) to get the primary intrawinding capacitance in parallel with the secondary intrawinding capacitance. There are several more measurement method perform in order to get the coupling capacitance between primary and secondary winding. As described above, this following measurement method will be perform:

- AB-open
- AB-short
- CD-short
- AB-CD
- AC-short
- BD-short
- AC-BD
- CD (primary winding removed)

Matlab software use to help student doing research, the software is used to plot the graph so the measurement result can be easily read and investigate. After the data matrix from the network analyser is plotted, we look at the angular phase response to frequency, to look at which frequency the impedance is inductive or capacitive. This procedure will perform during measurement:

- To look at the frequency response of transformer.
- Decide at which frequency the data needs to be analyzed.
- Get the reactance value from the matrix data.
- By knowing the frequency and reactance value, component value can be achieved using impedance formula.
- Take the mean of at least ten points on each element, to get the real value of the parasitic component of transformer.

CHAPTER IV

RESULT AND ANALYSIS

In this research, two types of transformer configuration have been measured. The purpose is to find the most suitable transformer winding configuration for switching converter application. Stray capacitance and leakage inductance are the factors that will be controlled to get the best result. Therefore the result of the frequency response for both transformer configurations will be compared and analysed.

IV.1 Measurement result

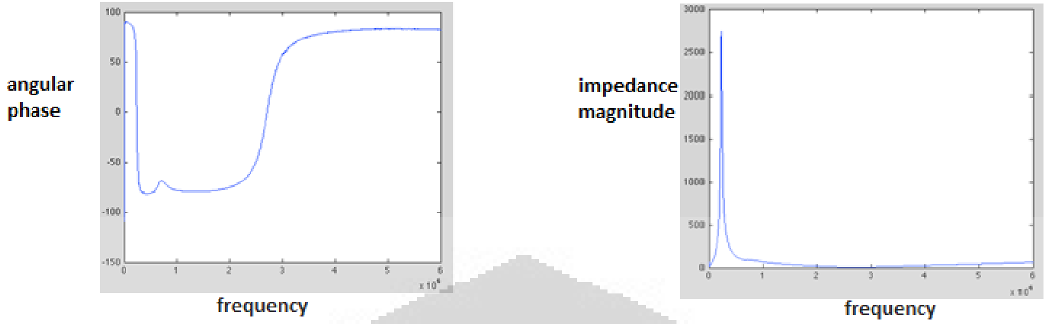
From the network analyser, student gets a matrix data of frequency response of the transformer, which in angular phase and linear impedance magnitude.. Impedance can be split into two parts: Resistance (R) and Reactance (X). There are two types of reactance; capacitive reactance (Xc) and inductive reactance (Xl). These two values are result that will be investigated from the laboratory measurement,

$$Xc = \frac{1}{2\pi f C}$$

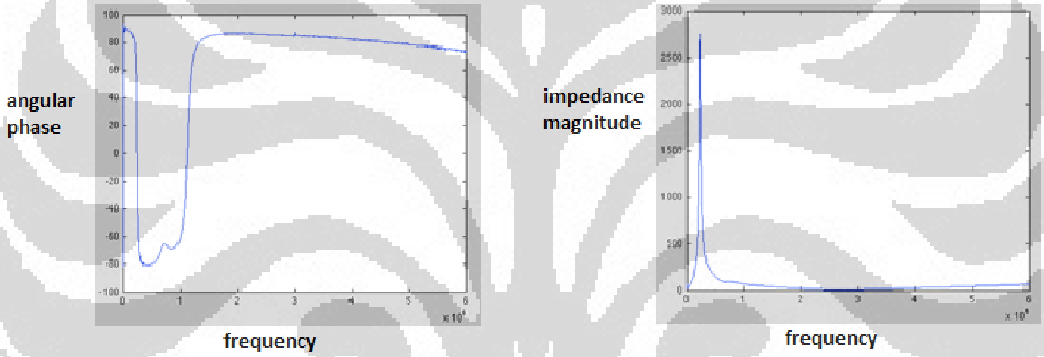
$$Xl = 2\pi f L$$

By knowing the frequency and the reactance the parasitic value of C and L can be achieved. C refers to stray capacitance, and L refers to leakage inductance and magnetizing inductance. By looking at the angular phase vs frequency figure, the range of frequency that shows when the impedance is inductive or capacitive. We take that frequency range and look at the linear magnitude vs frequency figure to find the approximated value of the component. To plot the graph and to calculate the magnitude capacitive and inductive value MATLAB software is used to help student doing research.

IV.1.1 AB-OPEN



Transformer 1



Transformer 2

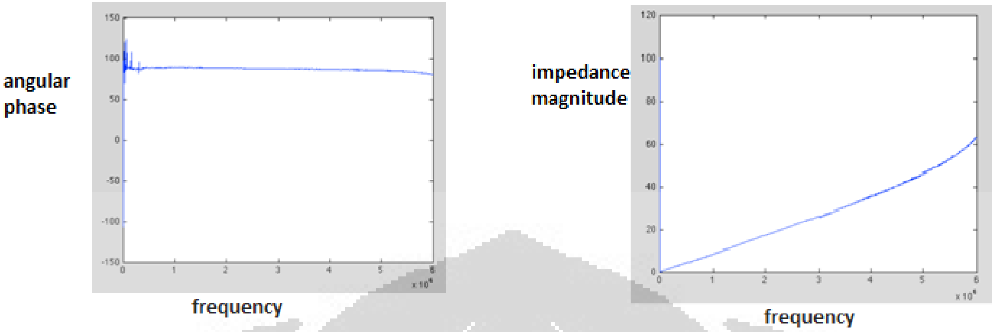
From this test, it is seen that in the second transformer configuration the value of magnetizing inductance is almost twice as big as in the first transformer configuration. It is also seen that in the second transformer configuration the angular phase begin to act as inductive reactance in $2x10^6$ Hz frequency or it can be said the interleaved winding configuration stores more undesired energy compared to sandwich winding configuration. Using this equation, the result achieved from this test is shown below:

Result achieved from this test:

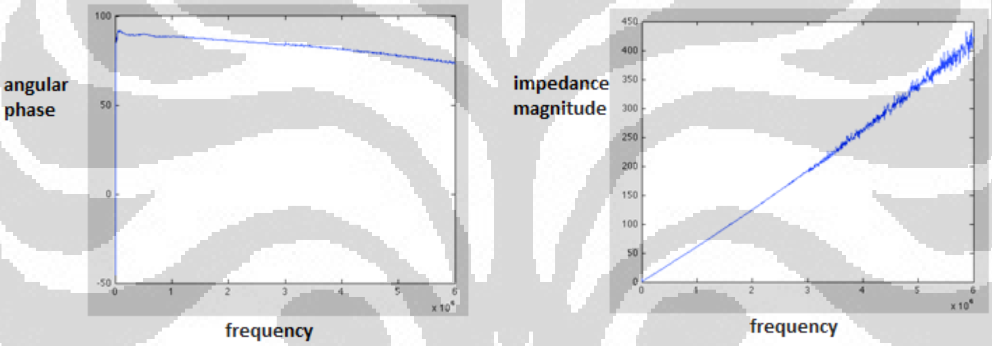
- **L_{M1} = 4.6e-6 H**
- **R_C = 2.7 kΩ**

- **L_{M2} = 7.8e-6 H**
- **R_C = 2.7 kΩ**

IV.1.2 AB-SHORT



Transformer 1



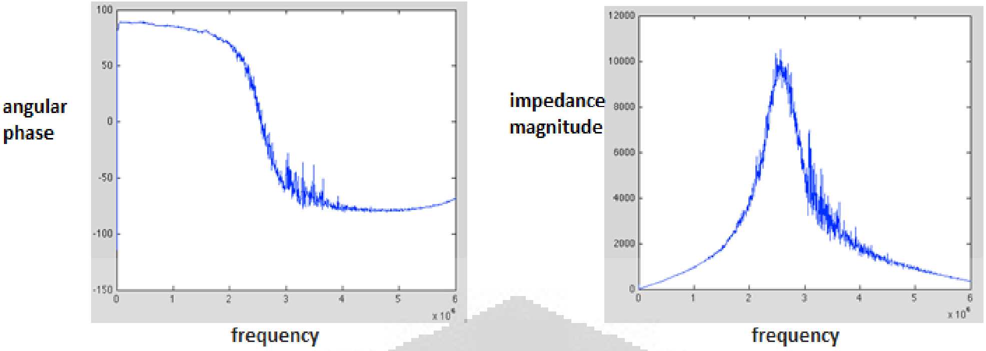
Transformer 2

The real equation is $Lp + \frac{Ls}{N^2}$. Because the turn ratio is 10 so the secondary leakage is so small compared to the primary leakage. However the inductive value gets from this test is the primary leakage inductance L_P. From result above, it is seen that the primary leakage inductance in the first transformer is slightly smaller than the secondary leakage inductance. This may prove the theory is right that the leakage inductance can be reduced by placing the windings in the same core leg, because the flux only struggle to travel in one leg. Using the same method here is the result achieved from this test.

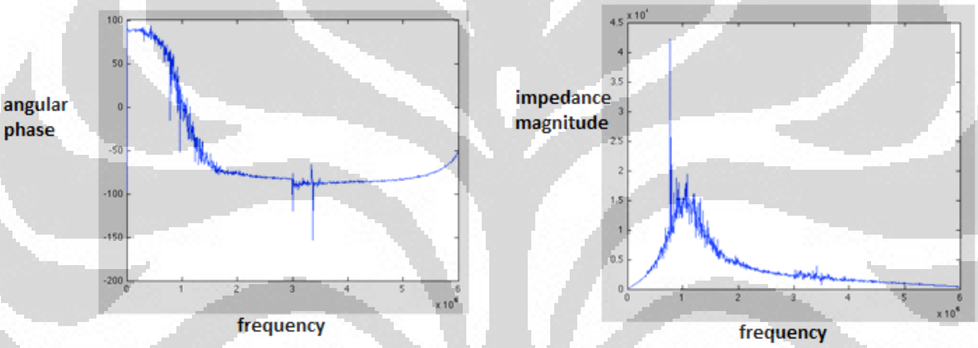
Result achieved from this test:

- **L_{P1} = 1.04e-6 H**
- **L_{P2} = 1.35e-6 H**

IV.1.3 CD-SHORT



Transformer 1



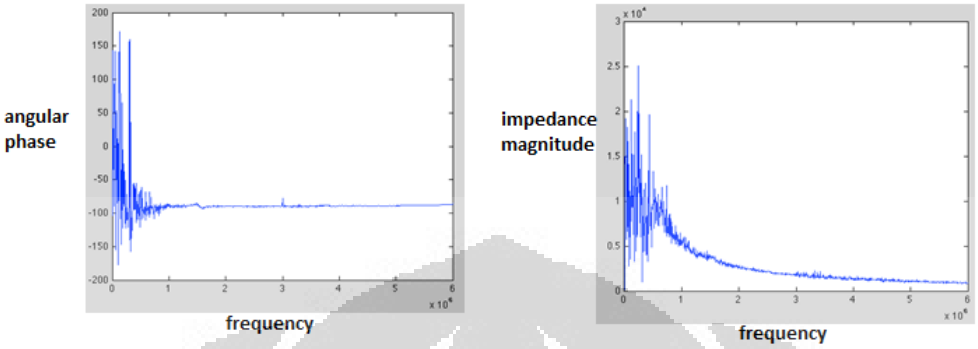
Transformer 2

From this measurement the leakage inductance in the secondary can be achieved. However the inductive value gets from this test is the is $Lp + LsN^2$ thus we know the value of L_P so now the value of L_S can be obtained. By looking at approximately 0 – $2x10^6$ Hz, and using the same method like the previous test, and considering the transformer equation the achieved from this test is shown below.

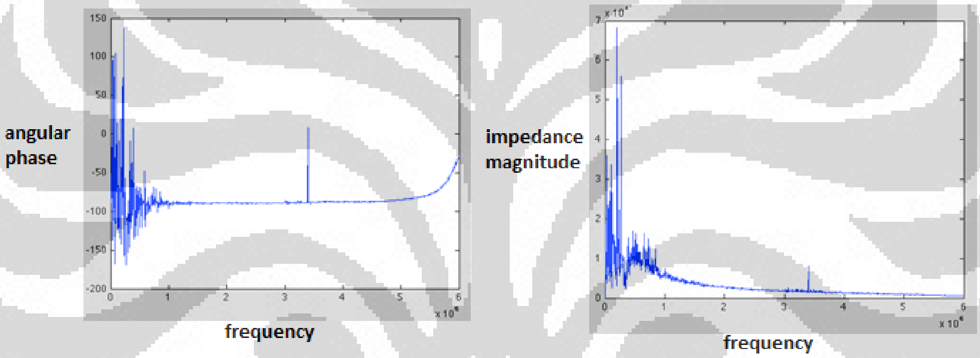
Result achieved from this test:

- **L_{S1} = 0.5e-6 H**
- **L_{S2} = 0.03e-6 H**

IV.1.4 AB-CD



Transformer 1



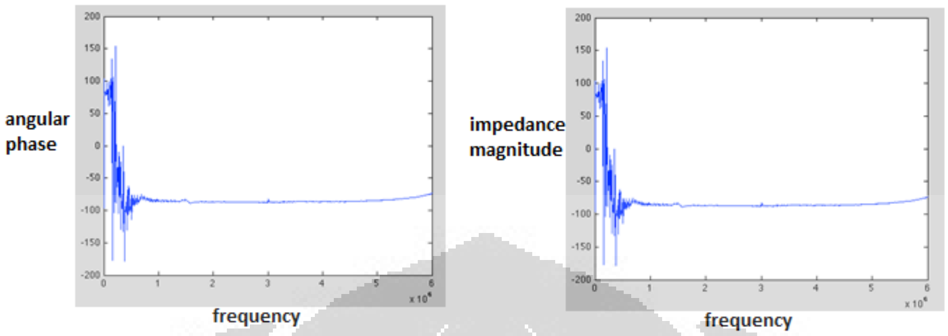
Transformer 2

The purpose of this measurement is to find the coupling capacitance between windings. Both C12 and C21 should be the same value if the winding structure is symmetrical. By looking the frequency response above $2x10^6$ Hz, we can get the capacitive reactance which needed to find the capacitive value C.

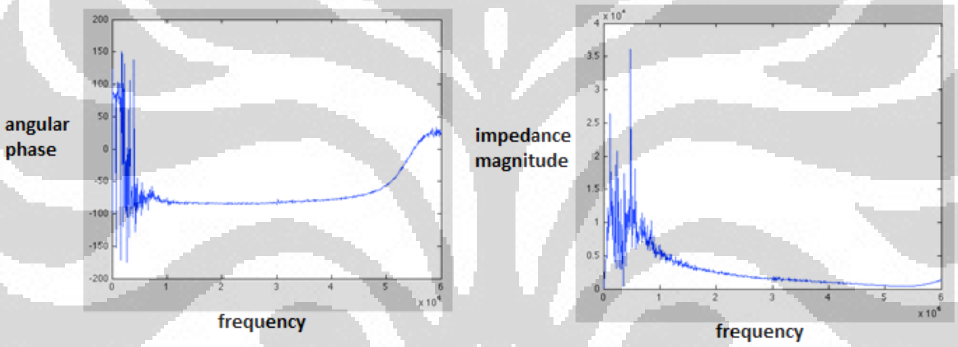
Result achieved from this test:

- $C_{eq1} = C_{12} + C_{21}$
  $= 30$ pF
- $C_{eq2} = C_{12} + C_{21}$
  $= 26$ pF

IV.1.5 AC-SHORT



Transformer 1



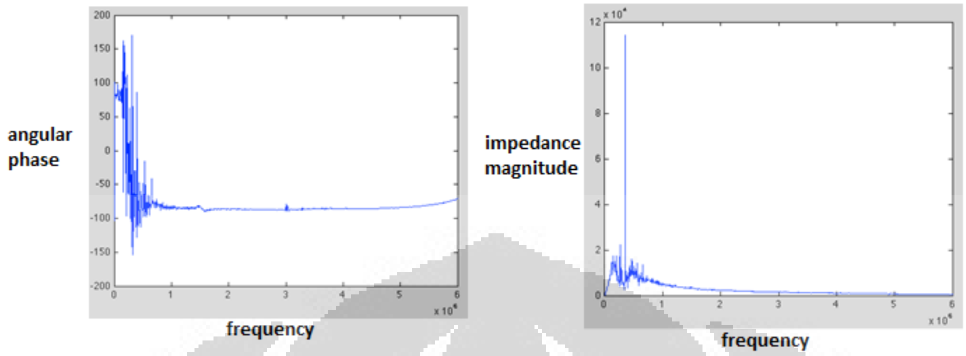
Transformer 2

The purpose of this measurement is to find the coupling capacitance between windings and to see whether the winding structure is symmetrical or not. By looking the frequency response from $2x10^6$ to $4x10^6$ Hz, we can get the capacitive reactance xC, which needed to find the capacitive value C.

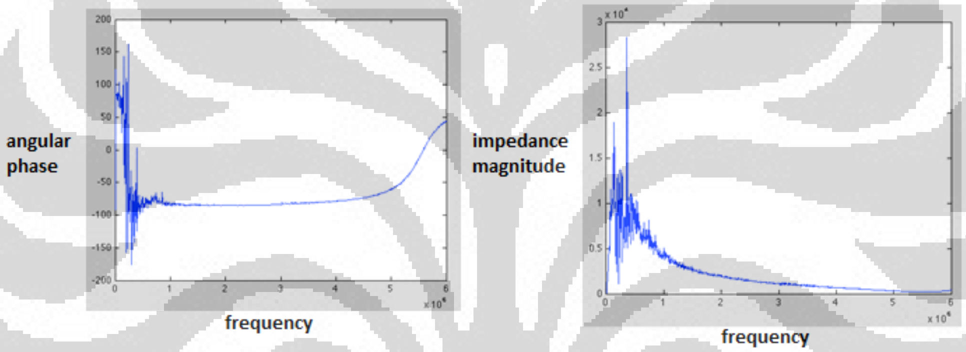
Result achieved from this test:

- $C_{eq'1} = C_{12} + \frac{Cp \times Cs}{Cp+Cs}$
  $= 48$ pF
- $C_{eq'2} = C_{12} + \frac{Cp \times Cs}{Cp+Cs}$
  $= 33$ pF

IV.1.6 BD-SHORT



Transformer 1



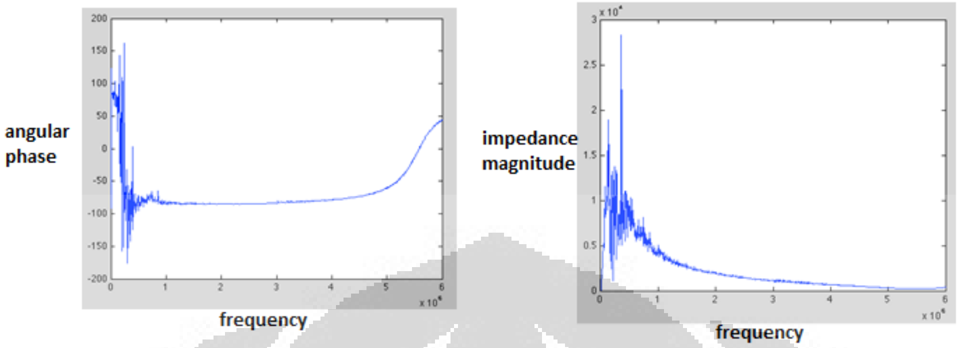
Transformer 2

The purpose of this measurement is to compare the stray capacitance between windings. Since the result showing in this measurement show different result from the previous test (AC-short) than it is confirm that the winding structure that has been tailored for the transformers is asymmetrical. By looking at $2x10^6$ to $4x10^6$ Hz, here is the result achieved from this measurement.

Result achieved from this test:

- $C_{eq'1} = C_{21} + \frac{Cp \times Cs}{Cp+Cs}$
  $= 37$ pF
- $C_{eq'2} = C_{21} + \frac{Cp \times Cs}{Cp+Cs}$
  $= 34$ pF

IV.1.7 CD



Secondary winding capacitance

The purpose of this measurement is to find the capacitance value in the secondary winding, however the primary winding needs to removed first in order to find intrawinding capacitance in secondary winding. By looking the frequency response of the transformer from $1x10^6$ to $4x10^6$ Hz, here is the result of this test as follow.

Result achieved from this test:

- **C_S = 25 pF**
- **C_{eq} = C_1+ C_2**
  = 380 pF
- **C_P = 355 pF**

IV.2 Model Validation

To validate our transformer model, it is important to compare our laboratory measurement with any valid model of a transformer. In this project matlab Simulink is used to valid the transformer by model a linear transformer with the same component as our model of transformer.

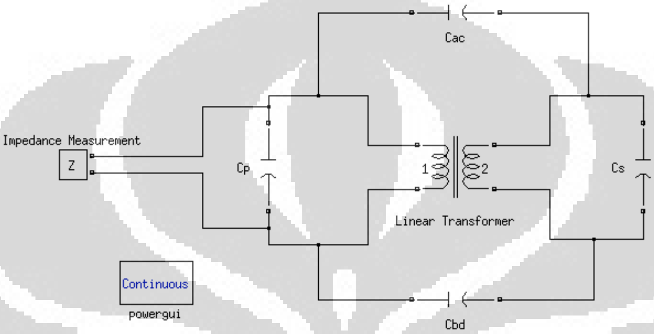


Figure 18. Transformer simulink model

All the component value achieved from the laboratory measurement inserted to the Simulink model and the result will be compared to the result from laboratory measurement. If the frequency response of both model is fluctuating in a very near value than the transformer modeling can considerably correct. However, it is very difficult to get the real value of the component because it is the case of sensitivity. Even after doing the measurement over and over again, student might get different result of each measurement.

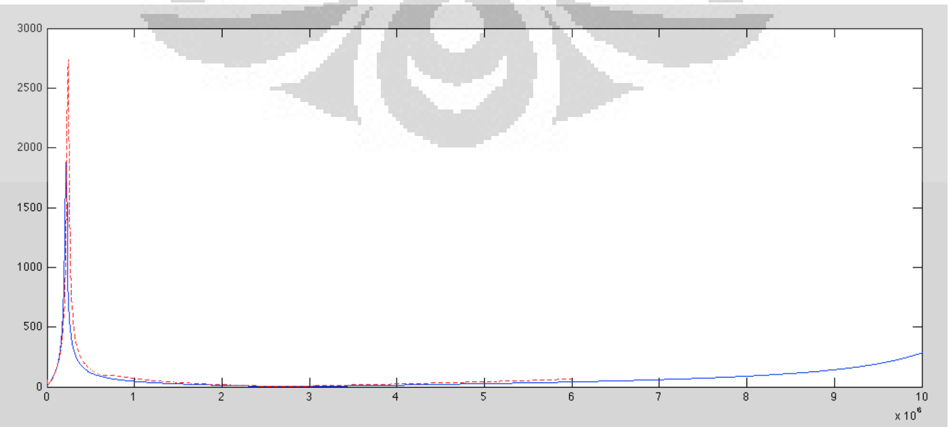


Figure 19. Model validation graph

IV.3 Model Comparison

After the transformer has been successfully modeled and validated, it is time for the designer to look at the design factor of a high frequency transformer. Theoretically, transformer with separate windings has a very small coupling capacitance and high leakage inductance. This consideration will be compared to the result from the laboratory measurement. Furthermore the design factor of the high frequency transformer can be accomplished.

After looking at both transformers with windings in the same leg or separated, the designer can see that when configuring windings in the same leg of the core, the leakage and magnetizing inductance can be reduced. On the other hand the coupling capacitance between primary and secondary winding increase as the distance between them is decreased. However theoretically in separate winding structure the coupling capacitance is very small so it can be neglected, which different forms the measurement result. It is also seen that when the winding structure of the transformer is not symmetrical, because the value of interwinding capacitance C12 and C21 are not the same.

Furthermore, due to the transformer designed in this project will be used in switching circuit, it is more important to reduce the leakage inductance in the core. The first design approach or sandwich winding configuration will be used for the project. The laboratory measurement also shows that designer of the transformer needs to provide a very good isolation between windings, because the parasitic component of transformer is varied especially in high frequency.

IV.4 Design factor of High frequency Transformer

After research and modelling has been done, it is time for student to achieve the final result of this project which is the design factor of high frequency transformer. Student has come back to the simplest theory to get all the factors that contribute in designing a simple transformer. Also with help from supervisor and fellow research student this project has been successfully finish. Although all the factors in designing this transformer has been mentioned above, here is the design factor of high frequency transformer.

- **Core Material**
  Ferrite material 3C90 is used in this project, with permeability around 2300 and very high resistivity considerably the most suitable for this application, see **Appendix 1**. Amorphous alloy core which also has very high permeability and resistivity considered not suitable for the application due to mechanical reason (bulky).
- **Core Geometry**
  To choose the optimum core geometry of transformer, designer has to know exactly the purpose of the transformer. The optimum core geometry selection will lead to optimum winding configuration; which give more compact and economical transformer.
- **Winding Loss**
  It is proven that the usage of Litz wire in high frequency transformer significantly reduces the power loss of i^2R. The constructions of individually insulated copper which can counteract the effect of skin effect occur in the real transformer. Also by applying sandwich windings configuration as modeled in this project proves to reduce both magnetizing and leakage inductance in high frequency transformer.

IV.5 Suggestion for Future work

High frequency magnetic materials, such as ferrites and power cores, have improved to suit the requirement of high frequency operation. Parasitic element of the transformer itself makes it very difficult to design high frequency magnetic. For this reason, it seems like that commercial switching frequency will be limited to about 1MHz. Litz wire techniques and new winding configuration needs to be develop and put into practice to reduce the losses in high frequency transformer. However, the development of planar transformer have brought application of transformer to a whole new level.

IV.5.1 Plannar Transformer

Planar transformer normally uses flat copper foil or printed-circuit boards instead of round copper wire. Used together with appropriately flat ferrite cores, they result in a special compact transformer with a very low profile. Planar transformers are primarily planar technology products but they can be fabricated by the micro-fabrication techniques and make them to the possible as integrated magnetic.

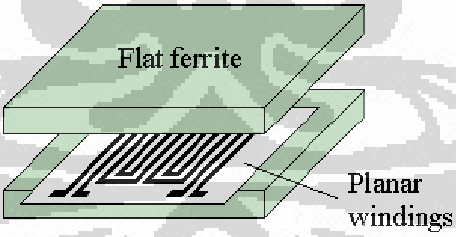


Figure 20. Planar transformer

Planar transformer has advantages of low profile, high power density and good heat transfer properties. Planar transformer can be implanted with integrated circuits to form hybrid power IC. The manufacturing cost is also relatively low by using micro-fabrication techniques. This type of transformers can provide an excellent solution for the high frequency switching converter application.

CHAPTER V

CONCLUSION

In conclusion, this report ilustrates the degree of knowledge and understanding I have obtained through research and simulations that have been done about high frequency transformer and inductorduring the last semesters.

Understanding of the power electronic converter to which the high frequency transformer and inductor is connected to is also necessary. Especially, when modeling the trasformer to analyse winding parasiticparameter. More trial and patience are the key in simulating this model. Not rare the modeling failed because the winding parasitic parameters should be taken into account before starting the simulations. And, by having good understanding from those simulations, conclusion came at that stage.

This project has given me a new experience that will be useful for my continuing professional development in my disciplinary background, electrical engineering. However, many simulations resulting far away from my expectation but this also improve my understanding in those limitations existed in the model.

Lack of knowledge and experience in designing and making the high frequency transformer model also one of the issue. But by trying to understand the concept, mechanism, and analysis of the simulations, this project is heavily worth for my knowledge in the dynamics of power system. Hence my main expectation in gaining knowledge in a well developed sustainable energy is acquired.

Bibliography

[1] Karampoorian, H.R.; Gh, P.; Vahedi, A.; Zadehgol, A.; , "Optimum design of high frequency transformer for compact and light weight switch mode power supplies (SMPS)," *GCC Conference (GCC), 2006 IEEE* , vol., no., pp.1-6, 20-22 March 2006

doi: 10.1109/IEEEGCC.2006.5686207

[2] Petkov, R.; , "Design issues of the high-power high-frequency transformer," *Power Electronics and Drive Systems, 1995., Proceedings of 1995 International Conference on* , vol., no., pp.401-410 vol.1, 21-24 Feb 1995

doi: 10.1109/PEDS.1995.404888

[3] Mohan, Ned., Undeland, Tore M., Robbins, William P. (2003). *Power Electronics* (3rd ed.). Hoboken, NJ: John Wiley & Sons, Inc.

[4] Lowdon, Eric. (1989). *Practical transformer design handbook* (2nd ed.). Blue Ridge Summit, PA: Tab Books, Inc.

[5] Bossche, Alex van den. (2005). *Inductors and Transformers for Power Electronics*. Boca Raton, FL: Taylor & Francis Group

[6] Goldman, Alex. (2002). *Magnetic component for Power Electronics*. Norwell, Massachusetts: Kluwer Academic Pubishers.

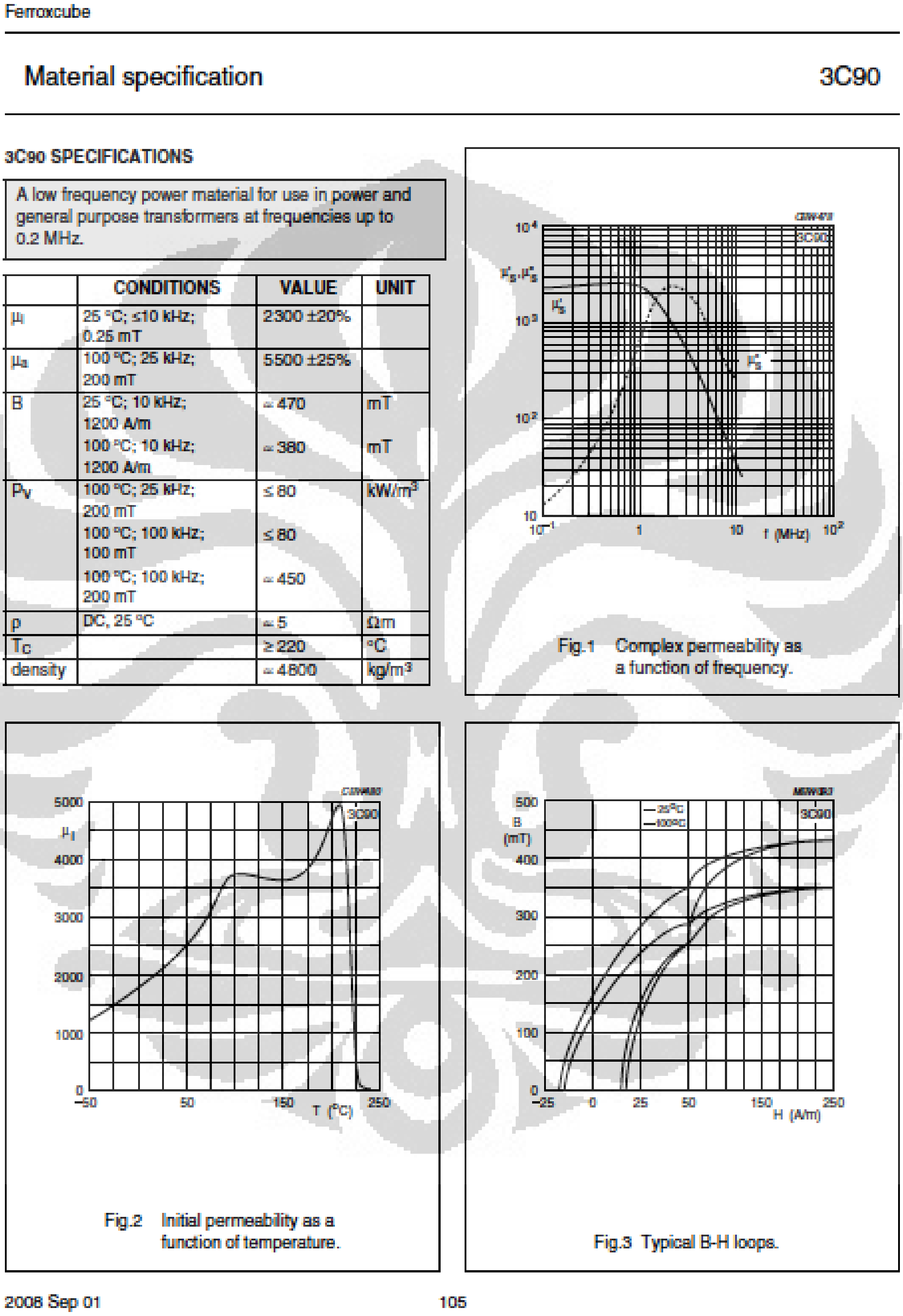
[7] Hurley, W.G.; Wolfle, W.H.; Breslin, J.G.; , "Optimized transformer design: inclusive of high-frequency effects ," *Power Electronics, IEEE Transactions on* , vol.13, no.4, pp.651-659, Jul 1998

doi: 10.1109/63.704133

[8] Petkov, R.; , "Optimum design of a high-power, high-frequency transformer," *Power Electronics, IEEE Transactions on* , vol.11, no.1, pp.33-42, Jan 1996

doi: 10.1109/63.484414

APPENDIX 1 - 3C90 Ferroxcube Core Database



Ferroxcube

Material specification 3C90

3C90 SPECIFICATIONS

A low frequency power material for use in power and general purpose transformers at frequencies up to 0.2 MHz.

	CONDITIONS	VALUE	UNIT
μ_i	25 °C; ≤10 kHz; 0.25 mT	2300 ±20%	
μ_a	100 °C; 25 kHz; 200 mT	5500 ±25%	
B	25 °C; 10 kHz; 1200 A/m	≈ 470	mT
	100 °C; 10 kHz; 1200 A/m	≈ 380	mT
P_V	100 °C; 25 kHz; 200 mT	≤ 80	kW/m^3
	100 °C; 100 kHz; 100 mT	≤ 80	
	100 °C; 100 kHz; 200 mT	≈ 450	
ρ	DC, 25 °C	≈ 5	Ωm
T_C		≥ 220	°C
density		≈ 4800	kg/m^3

Fig.1 Complex permeability as a function of frequency.

Fig.2 Initial permeability as a function of temperature.

Fig.3 Typical B-H loops.

2008 Sep 01

105

Material specification 3C90

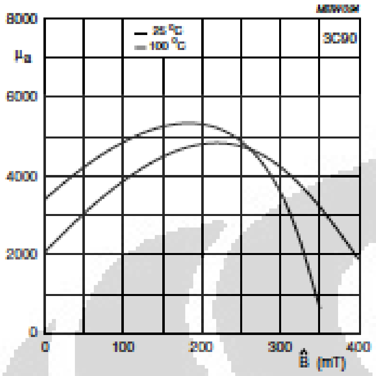


Fig.4 Amplitude permeability as a function of peak flux density.

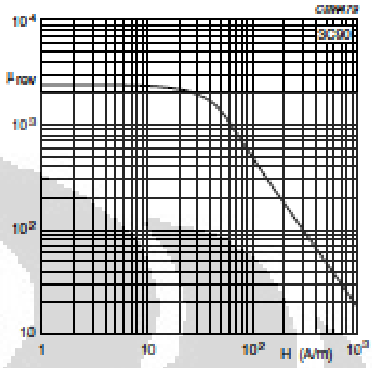


Fig.5 Reversible permeability as a function of magnetic field strength.

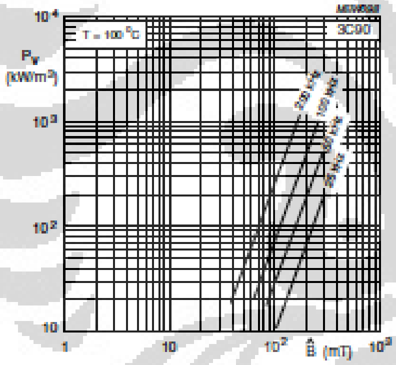


Fig.6 Specific power loss as a function of peak flux density with frequency as a parameter.

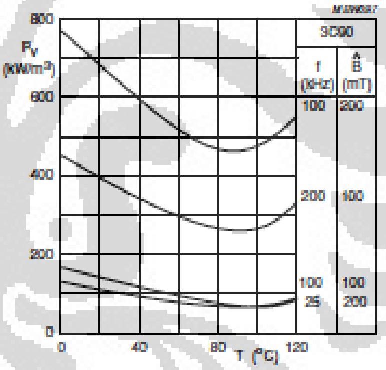
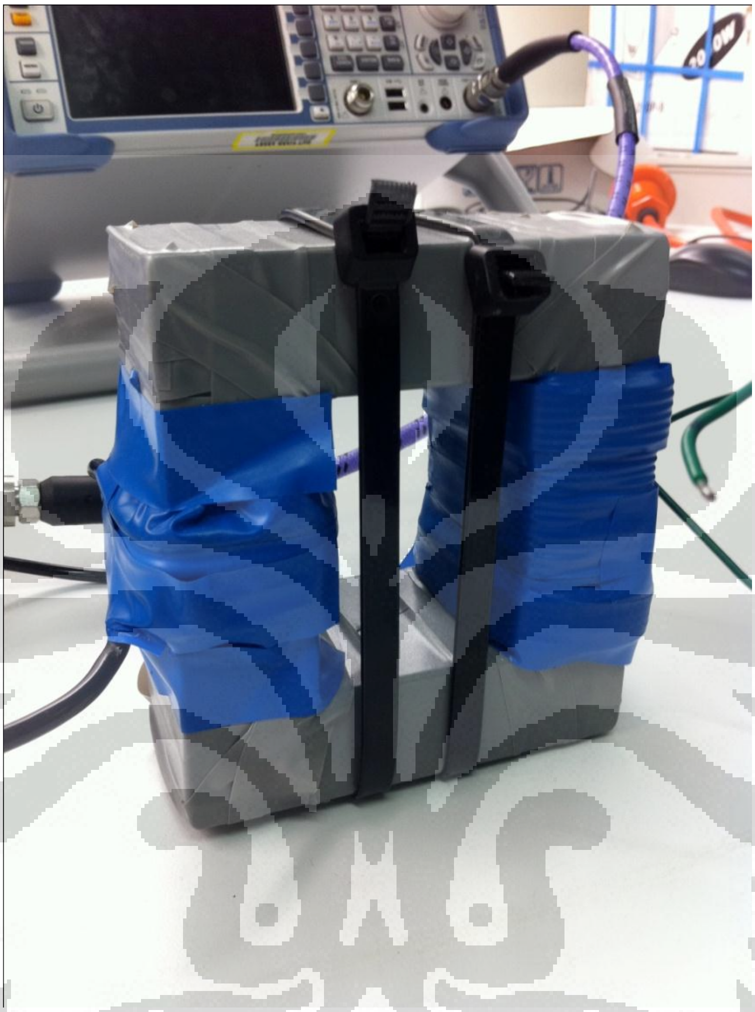


Fig.7 Specific power loss for several frequency/flux density combinations as a function of temperature.

Appendix 2 – Transformer picture



Appendix 3 - Ferrite Material Parameters

Ferrite Material Parameters

MANUFACT. Bsat [mT @ 100 °C]	SUGGESTED MAX FREQ [kHz]	C(T)	MATERIAL	Kc	a	b	μ_a/μ_o
			SIEMENS				
370	1000	0.74353	N27	2.1566E-05	1	2.34	5000
350	1000	0.62004	N41	1.66E-04	1	1.98	4800
300	2000	0.79307	N49	1.2322E-06	1	2.89	2100
360	1000	1.058	N53	2.6E-06	1	2.666	4300
310	3000	1.01975	N59	5.66E-06	1	2.7926	1700
320	1000	0.66403	N61	1.26E-05	1	2.420	3600
340	1000	1.04602	N62	9.92E-07	1	2.808	4600
380	1000	1.25767	N63	1.9E-06	1	2.757	4700
340	1000	1.1317	N67	9.8288E-07	1	2.851	4300
330	1000	0.7942	N72	6.20E-07	1	2.869	4000
340	1000	1.2119	N87	4.12E-07	1	3.00	4600
			PHILIPS				
320	1000	0.7098	3B8	7.10E-07	1.6	2.5	4000
350	1000	1.19713	3C15	1.20E-07	1.7	2.8	5000
350	1000	1.416	3C30	4.25E-07	1.5	2.7	5000
310	100	1.0033	3C80	9.63E-06	1.42	2.2	4000
320	1000	0.6658	3C81	7.99E-07	1.56	2.55	5500
310	2000	1.0999	3C85	4.95E-07	1.6	2.6	4000
330	1000	1.1194	3C90	5.60E-07	1.5	2.6	5500
330	1000	1.1423	3C94	1.60E-07	1.6	2.7	5500
330	2000	0.9167	3F3	1.38E-06	1.3	2.5	4000
350	3000	0.9678	3F35	1.19E-08	1.5	3.52	2500
310	5000	0.8455	3F4	1.73E-07	1.35	3.11	1700
180	10000	0.88	4F1	1.58E-05	1.35	2.25	300
			Transfer	Data			
330			21	1.5992E-07	1.6	2.7	5500