Modeling and Simulation of High Frequency Micro-Transformer using COMSOL Multiphysics Software for Power Electronics Applications

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LIST OF ABBREVIATIONS

2-D	Three-Dimensional
3-D	Two-Dimensional
AC	Alternate Current
CCD	Central Composite Design
DC	Direct Current
DLM	Double Layer Metal
FEM	Finite Element Method
MMF	Magneto-motive Force
NiFe	Nickel Ferrite
PCB	Printed Circuit Board
PWM	Pulse Width Modulation
RF	Radio Frequency
SiO_2	Silicon Oxide
SLM	Single Layer Metal
SMPS	Switch Mode Power Supply

LIST OF SYMBOLS

Δh	Height of insulation layer between primary and secondary
ε	Medium permittivity
μ_0	Permeability of vacuum
μ_r	Relative permeability of the magnetic core
ρ	Resistivity of copper trace
σ	Medium conductivity
ω	Angular frequency
A	Cross sectional area
A_c	Cross sectional area of magnetic core
B	Magnetic field
b_w	Width of primary trace occupied
C_{inter}	Inter winding capacitance
C_{intra}	Intra winding capacitance
d	Distance of equal layers
f	Frequency
H	Magnetic field intensity
h	Thickness of the trace
h_1	Height of primary side
h_2	Height of secondary side
J	Current density
K	K-factor
L_{lk}	Leakage inductance

L_M	Mutual inductance
L_P	Primary inductance
L_S	Secondary inductance
l	Length of copper
l_c	Length of magnetic core
l_m	Thickness of outer trace
l_w	Mean length of copper trace
n	Number of turns
Q	Quality factor
R	Resistance
R_P	Primary resistance
R_S	Secondary resistance
W	Width of coils track
W_Ω	Resistive energy in lumped sum resistor
W_{ind}	Inductive energy

Pemodelan dan Simulasi Pengubah-mikro Berfrekuensi Tinggi Menggunakan Perisian Multifizik COMSOL untuk Aplikasi Elektronik Kuasa

ABSTRAK

Tesis ini membentangkan tentang kajian pengoptimuman komponen parasit didalam pengubah-mikro berdasarkan keputusan simulasi. Pengubah-mikro beroperasi pada frekuensi tinggi adalah salah satu komponen utama didalam aplikasi elektronik yang bersangkut paut dengan penukar DC-DC. Pendekatan-pendekatan yang terdapat didalam projek ini adalah untuk mereka dan mensimulasi struktur penggulungan dan kemudian menganalisa keputusan komponen parasit menggunakan perisian Multiphysics COMSOL melalui Kaedah Elemen Terhingga (KET) supaya dapat meperolehi keputusan aruhan bocor dan aruhan saling terendah. Pemodelan pengubah-mikro, keseluruhannya melitupi kebanyakan bahagian pengecilan komponen magnetik melalui teknik fabrikasi, dimana melibatkan penggunaan bahan seperti tembaga untuk struktur penggulungan dan silica oksida untuk substrat. Tujuan kaedah ini adalah untuk memodelkan nisbah 1:1 pengubah-mikro yang boleh dioperasikan pada julat frekuensi diantara 100MHz dan 1GHz. Simulasi dalam dua-dimensi (2-D) dilaksanakan supaya dapat menentukan keputusan ketumpatan arus dan komponen parasitic terhadap kepelbagaian rekaan penggulungan manakala simulasi tiga-dimensi (3-D) digunakan untuk mendapatkan keputusan voltan penggulungan dan aliran fluks magnetik. Perbezaan jumlah gelung dengan ketebalan keatas nisbah gelung yang sama menunjukkan ketidakbergantungan hubungan antara aruhan saling dan aruhan bocor. Nisbah lebar trek pada lingkaran tembaga menunjukkan perubahan penting untuk keputusan aruhan saling. Sebagai kesimpulan, rekaan komposit terpusat (RKT) menunjukkan faktor -2,2,2,-2 mempunyai keputusan aruhan bocor terendah dan rintangan gelung yang optimum manakala nisbah lebar trek 1.2 mempunyai keputusan aruhan yang terendah pada 1 GHz dengan peratusan ralat untuk komponen parasit diantara 2.804% dan 16.526%.

Modeling and Simulation of High Frequency Micro-Transformer Using COMSOL Multiphysics Software for Power Electronics Applications

ABSTRACT

This thesis presents the optimization study of parasitic components in micro-transformer based on the analysis of simulation results. Micro-fabricated transformer operates in high range of frequency is one of the main component in electronic applications related to DC-DC converter. The approaches in this project are to design and simulate the winding structure with different configurations, and then analyzing the result of parasitic components by using COMSOL Multiphysics software through Finite Element Method (FEM) in order to obtain the lowest possible result of leakage and mutual inductance. Modeling of micro-transformer, mainly covers most part of miniaturization of the magnetic component through the use of micro fabrication techniques, which consists the materials such as copper for winding structure and silicon oxide for substrate. The proposed method is to model a 1:1 ratio of micro-transformer that can be operated at the range of frequency between 100MHz to 1GHz. Simulation in two-dimensional (2-D) is implemented in order to determine the result of current density and parasitic components in various windings designs while the simulation in three-dimensional (3-D) is utilized to obtain the result of windings voltage and the flow of magnetic flux. Different number of turns with similar thickness to turn ratio shows the independent relationship between mutual and leakage inductance. Track width ratio of copper coils shows the significant changes for result of mutual inductance. As a conclusion, central composite design (CCD) shows that the factor of -2,2,2,-2 has the lowest and optimum result of leakage and winding resistance while track width ratio of 1.2 has the lowest result of inductance at 1 GHz with percentage errors of parasitic components between 2.804% and 16.526%.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Micro-Transformer

Transformer is a static device which transforms electrical energy from one circuit to another with the help of mutual inductance between two windings. It helps transforming electrical power without changing the operating frequency but may be in different voltage levels. Micro-transformer is a small-scaled device which is widely being used in many radio frequency circuits such as voltage-controlled oscillator, mixers, low noise amplifiers, and power amplifier (Stella C. & Siva S, 2007).

In a high frequency range of power conversion, miniaturization of component is one of the important design factors that must be considered besides cost factor, efficiency and system integration. In order to give a better picture of what happened in recent electronic design, for example the power supply, is being modified for a better purpose in high operating frequency by replacing the bulky transformer and capacitors to a smaller size and so that it can be operated as Switching Mode Power Supply (SMPS) (Amalou, F., Bornand, E. L., & Gijs, M. A. M., 2001).

There are various types of micro-transformer depends on the application that is related to operating frequency such as forward transformer and fly-back transformer which are usually being used in DC-DC converter. For the past several decades, improvisation towards optimizing the performance of micro-transformer has been done and yet still need the improvement for the power conversion applications. One of the major benefits to the micro-transformer, increment of operating frequency will lead to the reduction of number of turns in the windings hence will directly reduce the size of micro-transformer.

1.2 Problem Statement

Modeling a specified rating of micro-transformer is proposed as a method for obtaining the efficient design by validating the simulation results with theoretical design. However, the challenging process in designing micro-transformer is regarding the magnetic behavior of the transformer itself (Stella, C. & Siva, S., 2007). This is because, transformer is known as a complex magnetic device. These challenges include designing the winding of the transformer which is the main focus of the research on how it can affect the electromagnetic, thermal, power flow and parasitic behavior simultaneously.

By reducing the size, leakage inductance and alternating current (AC) resistance in transformer will drastically decrease due to proximity of the winding and high value of perimeters to area ratio of the conductor respectively. Usually, low leakage inductance is one of the desirable outputs when designing the transformer because high leakage inductance will contribute to the high power loss thus reducing the performance of transformer (Pittini, R., Zhe, Z., Ouyang, Z., Andersen, M. A. E., & Thomsen, O. C., 2012). The ideal theory of minimizing the leakage inductance might be useful for the transformer in a fly-back converter's application. However, in certain application such as phase shift modulated soft switching DC-DC converter, load range of zero voltage operation that can be achieved is determined by the amount of leakage inductance. In other word, magnitude of leakage inductance is desirable and drives to the major challenge for every researcher to design the specific amount of leakage inductance.

Second part of this work is simulation by using COMSOL Multiphysics software for observing the imaginary picture of magnetic field and analysis on parasitic components can be done through finite element method (FEM). Modeling a transformer without having a simulation will only give the specific value of parameters with no visual analysis on magnetic behavior. By using visual aided, leakage inductance, induced current density and magnetic flux can be observed at any places of the transformer's core and winding.

Parasitic components are the important considerations in designing micro-transformer which consists of leakage inductance, intra-winding capacitances, inter-winding capacitances, winding resistances and mutual inductance. All these components can be obtained by manipulating and controlling the trace thickness, layer spacing, frequency of operation and the number of turns used. Parasitic components are important to control because these parameters will validate the final output of micro- transformer in terms of performance efficiency.

1.2.1 Advantages of Micro-Transformer

Several advantages of micro-transformer compared to planar or wire-wound transformer in terms of size, magnetic characteristic and parasitic components:

i. Higher thermal efficiency - Micro-fabricated transformer with silicon base can be operated in high temperature compared to material such as printed circuit board (PCB) which being applied as planar type transformer.

ii. Low leakage inductance - The winding design of micro-transformer allows magnetic flux to flow properly between the copper coils in every layer. Due to planar surface of the design, it is easier to interleave the winding or sandwiches the layer in order to control the leakage inductance.

iii. Lower high frequency losses - Easy design method makes the optimization of skin effect becomes more achievable due to high frequency effect between two skin depths. Gap width and height between copper coils can easily be manipulated in order to observe total current density produced over frequency changes.

iv. High reproducibility – Micro-transformer can be produced easily with minimal errors compared to wire wound transformer due to winding design. Wire wound transformers may have different amount of losses when being mass produced because it is hard to copy the exact same wire winding between them while micro-transformer can easily be simulated using FEM (Katz, S., Brouk, I., Stolyarova, S., Shapira, S., & Nemirovsky, Y. 2009).

1.3 Research Objectives

The aim of this research is to design a model of micro-transformer using the numerical and mathematical data and then simulate the model using COMSOL Multiphysics software for high frequency operation of micro-transformer. In order to design micro-transformer, the value of parasitic components must be obtained at the lowest possible amount. Specific research objectives for this research are shown as below:

i. To investigate the efficient configuration of winding based on optimum total current density obtained in the coils of micro-transformer.

ii. To analyze the effect of changing the thickness of conductor, width of conductor, height gap between the conductors and width gap between the conductors to the results of parasitic components.

iii. To model a design of 0.5 W 1:1 coreless micro-transformer with operating frequency between 100 MHz to 1 GHz by optimizing the parasitic components.

1.4 Scope of Research

This research is based on the following scopes:

i. At the beginning of the study, emphasis is given to the literature review and theoretical understanding of magnetic field, induced current, magnetic flux density, materials selection and windings method regarding the design specification of micro-transformer. Studies of COMSOL multiphysiscs software also need to perform to further investigate the simulation results of the designed model of micro-transformer.

ii. To determine the magnetostatics and electrostatics parameters of micro-transformer for physics setting regarding electrical conductivity, material of primary and secondary windings, surface current density and relative permittivity.

iii. To design the layout of micro-transformer for geometry modeling in COMSOL Multiphysics software regarding the winding configuration and track width ratio in two-dimensional (2-D).

iv. To perform eddy current analysis in winding coils for optimizing the skin effect produced by induced currents.

v. To perform magnetostatic and electrostatic analysis of micro-transformer in 2-D for the results of mutual inductance, leakage inductance, winding resistance, inter and intra-winding capacitance based on the obtained total energy from the simulation.

vi. To design the layout of micro transformer in three-dimensional (3-D) based on the optimized result from 2-D simulation.

vii. To perform magnetostatic and electrostatic analysis of micro-transformer in 3-D for the result of potential voltage and flow of magnetic flux density.

viii. To validate the result of parasitic components between simulation and calculation method in term of percentage error.

1.5 Thesis Arrangement

Chapter 1 has discussed the introduction to micro-transformer due to application, basic configuration and the advantages over planar transformer. Chapter 2 provided the information regarding high frequency application of micro-transformer with the emphasize on parasitic components and simulation by using FEM. Informative data from literature review based on the conference and journal papers provides the rough idea for executing the methodology along the research milestone. Chapter 3 explained the direction of the research milestone due to proper executed methodology with the description of every design involved in the simulations. Chapter 4 discussed the result of every simulation involved in this research in term of graphical analytical method. The last chapter of this thesis which is Chapter 5, concluded the simulation result and the possibilities of improvement for future works

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A lot of data and information of micro-transformer are gathered regarding parasitic components, trade-off analysis, fabrication process, central composite design (CCD) and COMSOL Multiphysics software. This information is important to help better understanding of future research's works. Equations regarding parasitic components are gathered in order to compute the error between the result of calculation and simulation.

2.2 Parasitic Components

Parasitic components obtained from high operating frequency micro-transformer are usually complex and non-linear due to planar form of winding geometries. Mostly, all of them are being implemented in low voltage and high current applications, which rarely utilized in high voltage schemes (Cove, S. R., Ordonez, M., Luchino, F., & Quaicoe, J. E., 2013). On-chip micro-transformer is recognized to be high efficient performance in high operating frequency due to coupling factor, K as shown in Equation (2.1) which relates mutual inductance, L_M, primary inductance, L_P and secondary inductance, L_S. Coupling factor, K is usually used to determine the strength of magnetic coupling between the windings. If the magnetic coupling is perfect, K is unity while the uncoupled coils will have zero value of K (Long, J.R, 2000).

$$K = \frac{L_M}{\sqrt{L_p L_s}} \tag{2.1}$$

The relationship between frequency, f, secondary inductance, L_S, and secondary winding resistance, R_S can be applied to represent quality factor, Q as shown in Equation (2.2). Higher the value of Q indicates the proper configuration of winding coils. (Jumril, Y., Azrul, A. H., & Burhanuddin Y. M., 2009).

$$Q = \frac{2\pi f L_S}{R_S} \tag{2.2}$$

Assorted designs of micro-transformer's windings can be utilized to improve the coupling between regular planar and solenoid shape. Theoretical formula such as in Equation (2.3) is applied to calculate winding resistance based on relationship between resistivity of coil material, ρ total length of coil tracks, l and cross sectional area of track, A.

$$R = \rho \frac{l}{A} \tag{2.3}$$

Length of copper, l can be estimated by using Equation (2.4) by referring to the number of turns, n and width of the coils track, W.

$$l = 2nW \tag{2.4}$$

Inductance of coils can be calculated by using the relationship of permeability of vacuum, μ_0, relative permeability of the magnetic core, μ_r, cross sectional area of magnetic core, A_c, number of turns, n, and length of magnetic core, l_c, shown in Equation (2.5). The