Modeling and FDTD Simulation of Non-Linear, Dispersive, Gyrotropic, Ferromagnetic Transformer Cores

**Muhammad Shamaas1 and Muhammad Asghar Saqib2**

1, 2Department of Electrical Engineering, University of Engineering and Technology, Lahore 54890, Pakistan

12018msee004@student.uet.edu.pk, 2saqib@uet.edu.pk

**Abstract** –*S*

**Keywords:**I

# Introduction

Ferromagnetic materials have been used in transformers for almost two centuries. They are widely used in bulk power transmission and distribution, power electronic converters and radio frequency communication. Transformers are designed to transmit electromagnetic energy using strong magnetic fields. They are made of ferromagnetic materials having very high magnetic permeability and a strong affinity for magnetic flux. When an external magnetic field is applied, magnetic dipoles react to align with it. This large scale cooperation enhances the Magnetic Flux Density inside the magnetic material. When the applied field is varied, the changing Magnetic Flux Density transmits the magnetic information across the magnetic material.

The cyclic magnetization of a Magnetic Material causes many energy losses. The atomic plane displacements and domain wall rotations cause mechanical losses in the material. Induced voltages cause circulating currents and electrical losses. At microwave frequencies, magnetic resonance and complex permeability can cause a significant increase in the losses. During the traversal of magnetization loop, energy is lost as heat during irreversible domain changes. The permeability changes with position, the applied field strength, time after demagnetization, frequency and temperature. Hysteresis loss increases with the applied field strength and frequency. Ferromagnetic materials are semiconductors with resistivity ranging from 0.1 Ωm to greater than 1 MΩm. The associated permittivity causes dielectric losses. Whenever a changing electromagnetic field is impressed induced voltages are developed in the material. These generate circulating eddy currents in the material and produce Ohmic losses. The Eddy current losses depend on the frequency, the applied field intensity and the resistivity. The Eddy Current Losses can be enhanced at high frequencies due to dimensional resonance. If a dimension of the magnetic material is equal to a quarter multiple of the electromagnetic wavelength, a standing wave can develop inside it. Under this condition, the in-phase flux cancels the anti-phase flux so the observed permittivity and permeability drops to zero. The resulting Eddy Current loss shows a peak during resonance. We can represent complex permittivity and complex permeability as:

The real part is responsible for the displacement current, whereas the imaginary part contributes to the conduction current. During Resonance, the electric conductance of the magnetic material increases greatly. Hence the material acts like an electric conductor with a very low resistivity. Although Magnetic conduction currents do not exist, Magnetic displacement currents can flow inside a magnetic material. When the real permeability drops, the magnetic displacement currents are restricted and the magnetic susceptibility falls. This causes failure of the magnetic system. Besides hysteresis loss and eddy current loss, several processes can contribute to losses when the eddy currents are negligible and the applied flux density is extremely small. These stray losses are independent of the flux density but they increase with frequency.

Magnetic Reluctance circuit model [2], based on the G. Ohm’s Law, depicts magnetic core as a Magnetic reluctance which resists the flow of Magnetic Flux. The Reluctance model is only suitable for low frequency steady state simulations of transformers if the reluctance profile of the magnetic core is already known. Better models are needed for modeling the complex behavior of ferromagnetic materials.

Frequency dependent parasitic core capacitance is responsible for the high frequency self-resonance and frequency limitation of the magnetic core. H. Zhao, Y. Li, Q. Lin, and S. Wang [16] presented a closed form solution for estimating parasitic capacitance of a ferromagnetic core, which stores electric energy in the gradient electric field developed inside the core. The frequency independent power losses due to Ohmic losses were also considered in an equivalent core impedance. The results were verified experimentally and through electromagnetic simulations for the microwave frequency range. The results were only applicable for toroid core geometry.

R. Buntenbach [2] proposed Power Invariant Permeance-Capacitance Model based on B. Tellegen’s Gyrator Theory. The Permeance-Capacitance model uses a nonlinear permeance to model nonlinearity and hysteresis losses of magnetic materials. It is valuable for simulating transient behavior of Ferromagnetic elements like RF inductors, transformers and filters. The Permeance-Capacitance model is only suitable for low frequency model simulations of ferromagnetic materials. J. Allmeling, W. Hammer, and J. Schonberger [2] presented a permeance-capacitance model for a ferromagnetic transformer core. The circuit adopted a gyrator for the transformation between electric and magnetic domains. Nonlinear permeance elements were used to model core hysteresis losses and magnetic flux leakage. A magnetic conductance was used to represent eddy current losses. Unlike the traditional coupled-inductor model, the transformer magnetic circuit was derived using the core geometry. The model was modified to include Hysteresis, Eddy currents, Piezomagnetism, Magnetoresistance, Magnetostriction and other residual losses. The model did not account for the dispersion characteristics of the magnetic core. M. Luo, D. Dujic, and J. Allmeling [11] presented a permeance-capacitance model for a laminated steel ferromagnetic transformer core to model hysteresis losses and frequency dependent eddy current losses. The non-linear core permeance was designed to approximate the results obtained for a low frequency excitation. The model was not valid for high frequency simulations.

J. Faria [6] – [8] presented Magnetic Transmission Line Model based on the conventional Electric Transmission Line Model. For magnetic transmission lines, transverse impedance and the longitudinal admittance determine the propagation constants for the wave modes. Simulations showed that they exhibit super-luminal phase velocity and almost zero attenuation dispersion in the microwave frequency range. He also established a relationship between voltages and currents at the multi-conductor transmission line ports by employing the transmission matrix techniques. Mathematical models were developed for studying the Frequency Domain Behavior of non-uniform Magnetic Transmission Lines. Solutions to Electromagnetic equations were presented in the form of a superposition of natural modes of propagation. The Magnetic Transmission Line exhibited the behavior of a high pass filter, blocking all DC signals. DC signals produce the most severe transients in Electric Transmission Lines; which behave like a low pass filter. Moreover, he developed a model for ideal transformers using magnetic transmission line theory. The Magnetic Transmission Line model cannot model non-linear or gyrotropic media.

N. Shirdel, A. Akbari, H. Mirzaei, and M. Abrishamian [13] presented a FDTD simulation for propagation of UHF Gaussian pulse partial discharges in a dispersive, anisotropic, conductive three phase transformer core. The model did not include non-linear and gyrotropic nature of the core. J. Xu, M. Koledintseva, Y. Zhang, Y. He, B. Matlin, R. Dubroff, J. Drewniak, and J. Zhang [15] presented an experimental setup for calculating frequency domain behavior of complex permeability and permittivity of a ferromagnetic transmission line. The measured transmission line intrinsic impedance and propagation constant was used to determine the per unit length transmission line parameters. The results were compared with electromagnetic FDTD simulation and analytical results. The model used genetic algorithm for estimating the transmission line parameters hence the results were only valid for the particular core geometry.

H. Al-Barqawi, N. Dib and M. Khodier [1] presented a closed form solution for analyzing the electromagnetic fields in a waveguide filled with an anisotropic, dispersive, gyromagnetic ferrite. Two dimensional Finite Difference Time Domain simulation was also carried out for the structure and the frequency variation of propagation constant was studied for the microwave frequency range. The simulation results matched very closely with the analytical closed form solution. The analysis did not account for non-linearity of the magnetic material. J. Bragg, J. Dickens, and A. Neuber [4]. T. Deng and Z. Chen [5].

# Magnetic Transmission Line Model for Transformer

The Magnetic Transmission Line Model is used for modeling linear, dispersive ferromagnetic materials. It provides a closed form solution for electric and magnetic parameters using a system level circuit.

Analogous to the scalar Electric Potential, scalar magnetic potential can be defined as

The Magnetic Displacement Current is defined as the rate of change of magnetic flux :

The per unit length transverse magnetic inductance represents a magnetic Energy storage element storing magnetic flux:

The per unit length longitudinal capacitance represents an Electric Energy storage element storing electric charge:

The per unit length Magnetic conductance dissipates energy due to Hysteresis, Eddy currents, Skin effect, Proximity effect, Piezomagnetism, Magnetoresistance, Magnetostriction and other residual losses. It is closely related to the magnetic reluctance:

The Magnetic Transmission Line Equations are

The characteristic impedance is the ratio of Magnetic displacement current to the Magnetic Voltage. It is calculated as

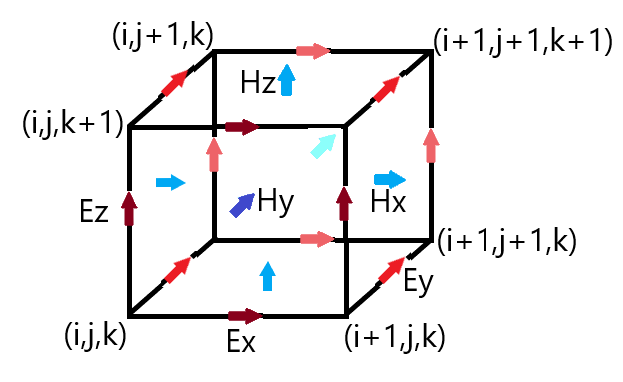
The Magnetic Transmission Line model cannot model non-linear or gyrotropic media because a closed form solution does not exist for such problems. An electromagnetic simulator will be used for this.

# Finite Difference Time Domain Electromagnetic Simulator MEEP

MEEP software was used for the electromagnetic simulation of the Magnetic Transmission Lines using the Finite Difference Time Domain. Maxwell’s Equations are discretized using central difference approximations to the space and time partial derivatives. The different field components at a grid location are stored in the edges and faces of a cubic element called Yee’s Cell. They are evolved in discrete time steps .

Faraday’s Law can be expanded as follows:

Similarly, Ampere’s Law can be approximated as follows:



The simulator can simulate anisotropic, non-linear, dispersive and gyromagnetic materials.

1. Dispersion Model

Drude-Lorentzian Model models frequency dependent permittivity and permeability. It explains the electrodynamic properties by regarding conduction band electrons as non-interacting electron gas. When the material is excited by an external source of resonant frequency, the material absorption loss increases greatly. Electromagnetic Energy is converted into other forms of energy. Flux Densities contain terms for infinite frequency response and frequency dependent Polarization vector.

and are represented as a sum of harmonic resonances and a term for frequency independent electric conductivity.

is the electrical/magnetic conductivity. is the oscillator strength, is the angular resonance frequency, is a damping factor.

1. Nonlinearity Model

The Pockels and Kerr Non-linearity model explains how μ can change as a function of the field intensity. Ferromagnetic materials are non-linear as their permeability varies with the strength of applied field intensity. At high magnetic field intensity, the material saturates, limiting further increase of Magnetic Flux. Hence, the susceptibility decreases rapidly.

sum is the Pockels effect constant; whereas sum is the Kerr effect constant.

1. Gyrotropy Model

Landau-Lifshitz-Gilbert model describes the precessional motion of saturated magnetic dipoles in a magnetic field.

describes the linear deviation of magnetization from its static equilibrium value. Precession occurs around this unit bias vector . represents oscillator strength, is the angular resonance frequency, is the oscillator damping factor.

# Simulation Results

The

# Discussion

The

# Conclusion

Di

# References

[1] H. Al-Barqawi, N. Dib and M. Khodier, “A Full-Wave Two-Dimensional Finite-Difference Frequency-Domain Analysis of Ferrite-Loaded Structures”. Mosharaka International Conference on Communications, Propagation and Electronics, 2008.

[2] J. Allmeling, W. Hammer, and J. Schonberger, “Transient simulation of magnetic circuits using the permeance-capacitance analogy,” *2012 IEEE 13th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2012.

[3] S. Blundell, *Magnetism in condensed matter*. Oxford: Oxford University Press, 2014.

[4] J. Bragg, J. Dickens, and A. Neuber, “Material selection considerations for coaxial, ferrimagnetic-based nonlinear transmission lines,” *Journal of Applied Physics*, vol. 113, no. 6, 2013.

[5] T. Deng and Z. Chen, “Design of frequency-dispersive magnetic material for application of microwave attenuation,” *2016 46th European Microwave Conference (EuMC)*, 2016.

[6] J. Faria and M. Pires, “Theory of Magnetic Transmission Lines,” *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no. 10, pp. 2941–2949, 2012.

[7] J. Faria, “Formulation of Multiwire Magnetic Transmission-Line Theory”, *Progress in Electromagnetics Research B*, Vol. 49, 2013.

[8] J. Faria, “A physical model of the ideal transformer based on magnetic transmission line theory”, *Journal of Electromagnetic Waves and Applications*, Vol. 27, No. 3, 2013.

[9] “IEEE Standard for Pulse Transformers," in ANSI/IEEE Std 390-1987, vol., no., pp.1-32, 14 Oct. 1987.

[10] “IEEE Recommended Practice for Validation of Computational Electromagnetics Computer Modeling and Simulations," in IEEE Std 1597.2-2010, vol., no., pp.1-124, 25 Feb. 2011.

[11] M. Luo, D. Dujic, and J. Allmeling, “Permeance based modeling of magnetic hysteresis with inclusion of eddy current effect,” *2018 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2018.

[12] A. Oskooi, D. Roundy, M. Ibanescu, P. Bermel, J. Joannopoulos, and S. Johnson, “MEEP: A flexible free-software package for electromagnetic simulations by the FDTD method”, *Computer Physics Communications*, Vol. 181, pp. 687-702, 2010.

[13] N. Shirdel, A. Akbari, H. Mirzaei, and M. Abrishamian, “Three-dimensional simulation of UHF signal propagation in transformer using FDTD method,” *2011 International Conference on Power Engineering, Energy and Electrical Drives*, 2011.

[14] A. Taflove and S. Hagness, *Computational Electrodynamics: The Finite-Difference Time-Domain Method*, 3rd ed. Boston: Artech House, 2005.

[15] J. Xu, M. Koledintseva, Y. Zhang, Y. He, B. Matlin, R. Dubroff, J. Drewniak, and J. Zhang, “Complex Permittivity and Permeability Measurements and Finite-Difference Time-Domain Simulation of Ferrite Materials,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 52, no. 4, 2010.

[16] H. Zhao, Y. Li, Q. Lin, and S. Wang, “The Parasitic Capacitance of Magnetic Components with Ferrite Cores Due to Time-Varying Electromagnetic (EM) Field,” *2018 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2018.