Modeling and FDTD Simulation of Non-Linear, Dispersive, Gyrotropic, Ferromagnetic Transmission Lines

**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*

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# 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. 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. 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 resonance.

Complex permittivity can be represented as:

The real part is responsible for the displacement current, whereas the imaginary part contributes to the conduction current. During Lorentzian resonance, the lattice vibrations of the atomic harmonic oscillators become extreme, and the electric conductance of the magnetic material increases greatly. Hence the material acts like an electric conductor with a very low resistivity. This resonance causes a peak in electric losses.

Complex permeability can be represented as:

Although Magnetic conduction currents do not exist, Magnetic displacement currents can flow inside a magnetic material. During Lorentzian resonance, the real permeability drops, the magnetic displacement currents are restricted and the magnetic susceptibility falls. This causes failure of the magnetic system.

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.

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 ferromagnetic 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 intrinsic impedance and propagation constant was used to determine the per unit length electric 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.

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].

The electric transmission line model is not suitable for modeling the behavior of ferromagnetic materials because they are not designed to conduct electric charge upon application of electromotive force. A magnetic circuit must be used for the system level modeling of ferromagnetic materials which transmit magnetic flux as the effective magnetic charge due to the application of Magnetomotive force.

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.

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. 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. Solutions to Electromagnetic equations were presented in the form of a superposition of natural modes of propagation. Simulations showed that they exhibit super-luminal phase velocity and almost zero attenuation dispersion in the microwave frequency range. The Magnetic Transmission Line exhibited the behavior of a high 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.

This research attempts to extend the Magnetic Transmission Line Model for the modeling of non-linear, dispersive, gyrotropic ferromagnetic transmission lines, and studying the frequency response of magnetic transmission line parameters.

# Ferromagnetic Transmission Lines

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

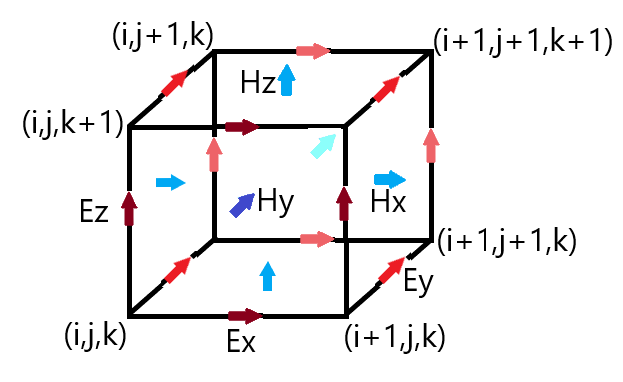
The Magnetic Transmission Line model cannot model non-linear or gyrotropic media because a closed form solution does not exist for such problems. An electromagnetic simulator will be used for this.

# Finite Difference Time Domain Electromagnetic Simulation

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

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# Discussion

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# Conclusion

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