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

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**Abstract** –*S*

**Keywords:**I

# Intriduction

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.

H. A. Rowland’s Law is the counterpart of G. Ohm’s Law for Magnetic circuits. Reluctance Model defines Magnetic reluctance as the ratio of Magnetomotive Force and Magnetic Flux. The Reluctance model is only suitable for steady state simulations of transformers if the reluctance profile of the magnetic core is already known.

R. W. Buntenbach 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. It cannot model magnetic losses due to Hysteresis, Eddy currents, Piezomagnetism, Magnetoresistance, Magnetostriction and other residual losses. The model must be modified to include these losses.

In 2012, J. Faria and M. Pires presented Magnetic Transmission Line Model based on Electric Transmission Line Model. Faria presented a Time and Frequency domain theory of multi-wire magnetic transmission lines based on the matrix theory of multi-conductor electric transmission lines. 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. 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 because a closed form solution does not exist for such problems. An electromagnetic simulator will be used for this.

# Magnetic Circuit Models

1. Complex Reluctance Model

H. A. Rowland’s Law is the counterpart of G. Ohm’s Law for Magnetic circuits. Reluctance Model defines Magnetic reluctance as the ratio of Magnetomotive Force and Magnetic Flux.

Lossy Complex Magnetic Reluctance is non-linear and varies with the magnetic field. It resists both Magnetic flux and changes in Magnetic flux. The Reluctance model is only suitable for steady state simulations of transformers if the reluctance profile of the magnetic core is already known.

1. Permeance-Capacitance Model

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 dual effort and flow quantities are related by the gyration constant N. According to M. Faraday’s Law, Magnetic Displacement Current flowing through a closed loop, also known as the rate of change of magnetic flux linkage, is responsible for generating Electric Voltage in the loop.

According to A. Ampere’s Law, Electric Conduction Current flowing through a closed loop is responsible for generating Magnetic Voltage in the loop.

The Permeance is measured in units of Henry. It is the opposite of Magnetic Reluctance and is proportional to the Magnetic Inductance of the core.

Magnetic Permeance is defined as a magnetic capacitor which stores magnetic flux measured in Volt-seconds.

The Permeance resists changes in Magnetic voltage.

The Permeance-Capacitance model is only suitable for low frequency model simulations of ferromagnetic materials. It cannot model magnetic losses due to Hysteresis, Eddy currents, Piezomagnetism, Magnetoresistance, Magnetostriction and other residual losses. The model must be modified to include these losses.

1. Magnetic Transmission Line Model

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 which resists changes in magnetic flux linkage.:

The per unit length longitudinal capacitance represents an Electric Energy storage element which resists changes in electric flux linkage.:

The per unit length Magnetic conductance dissipates energy due to Hysteresis, Eddy currents, 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

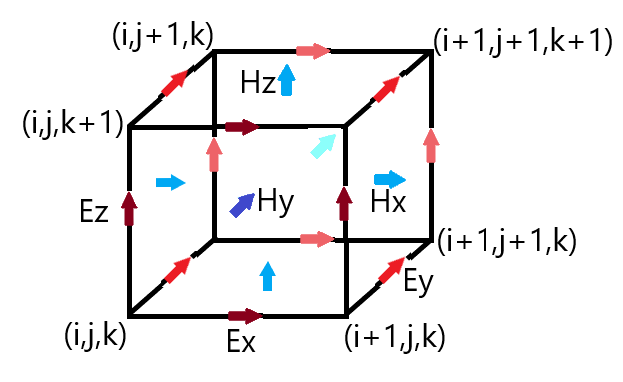
The Magnetic Transmission Line model cannot model non-linear or gyrotropic media because a closed form solution does not exist for such problems. An electromagnetic simulator will be used for this.

# MEEP Finite Difference Time Domain Simulator

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 ε and 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.

# Analysis of Protection Schemes

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# Proposed Protection Scheme

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# Discussion

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# Conclusion

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# References

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