Modeling and Simulation of Non-Linear, Dispersive, Gyrotropic,

Ferromagnetic Cores

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**Abstract** –*S*

**Keywords:**I

# **Introduction**

In

# **Magnetic Circuit Modeling for Ferromagnetic Cores**

Three different Magnetic circuit models will be presented: The Reluctance Model, The Permeance-Capacitance Model and The Magnetic Transmission Line Model.

## II.A Reluctance Model

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.



## II.B Permeance-Capacitance Model

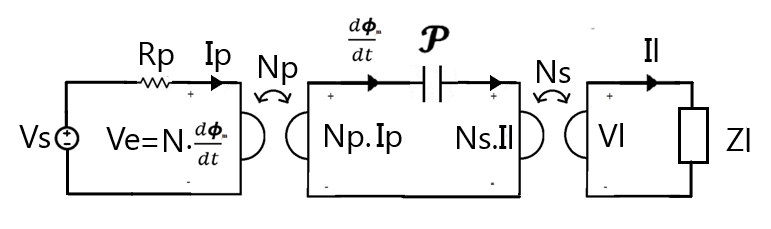
B. Tellegen’s Gyrator theory was devised to describe power invariant transformation of magnetic and electric quantities. The dual effort and flow quantities are related by the gyration constant N. According to M. Faraday’s Law, Magnetic Displacement Current flowing through a closed loop, also known as 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.

R. W. Buntenbach proposed Power Invariant Permeance-Capacitance Model. This 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.



## II.C Magnetic Transmission Line Model

In 2012, J. Faria and M. Pires presented Magnetic Transmission Line Model based on Electric 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. It is defined as:

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

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

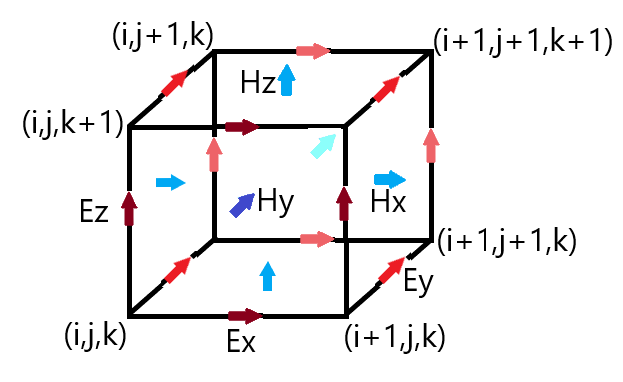


# **MEEP Simulation**

The software used for the electromagnetic simulation of the Magnetic Transmission Lines is the Finite Difference Time Domain simulator MEEP. 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. Dispersive Media: Drude-Lorentzian Model models frequency dependent permittivity and permeability. It explains the electrodynamic properties of metals 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. Nonlinear Media: 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. Gyrotropic Media: 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**

[1] G. M. Masters, *Renewable and Efficient Electric Power Systems*. John Wiley & Sons, Inc, 2004.