UNIVERSITY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING

MSC. THESIS TOPIC PROPOSAL

Modeling and Simulation of Magnetic Transmission Lines

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Problem Statement

Magnetic Transmission Line is the dual counterpart of Electric Transmission Line. Its theory, encompasses a diverse range of applications including Transformers, Dynamic Machines, Microwave Generators, Tuners, Couplers, Isolators, Power Dividers etc. Intrinsically, Magnetic Transmission Line is made from a non-conducting magnetic material, with a high permeability. It conducts Magnetic Flux which acts as the Magnetic charge. Time varying magnetic flux results in a Magnetic Displacement Current inside the Transmission Line, which has the units of Volts. This produces a gradient Magnetic Field; with Fields Lines that spread radially outwards. The magnetic voltage due to this Magnetic Field is measured in Amperes. Although, the operation of a Magnetic Transmission Line does not involve electric charges, Magnetic Displacement Current produces an Electric Field with closed Field Lines encircling the Magnetic Transmission Line. Together, the Electric and Magnetic Fields transmit Energy along the direction of propagation. These relations will be modeled using Maxwell's Equations and magnetic circuits to study the time and frequency domain behavior of Magnetic Transmission Lines. Furthermore, Finite Difference Time Domain Electromagnetic Field Simulations will be carried out in MEEP [6] Simulator for anisotropic, inhomogeneous, non-linear Magnetic Transmission Lines.

Objectives and Aims

- Research about the Duality of Magnetic Transmission Lines and Electric Transmission Lines.
- Study the Time Domain evolution of Electromagnetic Fields of practical Magnetic Transmission Lines.
- Study the Frequency Domain behavior of Magnetic Transmission Lines.
- Study Cross Talk between Magnetic Transmission Lines.
- Develop Power Flow Equations for Magnetic Transmission Lines in terms of Lumped parameters.

Literature Survey

Faria [1-4] has 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.

Antonini [10] presented an in-depth analysis of meta-material transmission lines. The ladder network structure of the transmission line was used to obtain dominant zeros and poles. This lead to a rational form of the two port network transfer function. The rational form of the transfer functions provided an efficient time-domain macro model; which accurately captured the physics of composite meta-material transmission lines. Caloz and Itoh [11] also presented non-linear electromagnetic meta-material Transmission Lines focusing on their complex permittivity and permeability. They used the transmission matrix method to formulate equations for the dispersive, distributed non-linear system. These results are very useful in understanding the complex dispersive and radiative nature of Magnetic Transmission Lines.

Edwards and Steer [15] compared copper, ferrite meta-conductor and magnetized permalloy meta-conductor based coplanar waveguides. Magnetized ferrite layer provided some skin effect suppression compared to copper waveguide; however, permalloy provided the most uniform current profile. Some applications of Ferrite materials are high frequency phase shifters, circulators and isolators [18]. Phase shifters used in test and measurement systems can be controlled using the bias magnetic field. Electronically controlled phase shifters are used in phase array antennas for steering antenna beam in space. Microwave circulators use ferrites to separate received and transmitted waves in radar systems. Magnetized films also act as Radio Frequency selective limiters. Microwave Ferrite isolators are used for unidirectional transmission in plasma systems. Their blocking capability protects precious microwave sources.

Neuber et al. [16], [17] presented gyromagnetic Non Linear Transmission Lines constructed out of nickel-zinc (NiZn), magnesium-zinc (MgZn), manganese-zinc (MnZn) and yttrium iron garnet (YIG) ferrites. Biased Anisotropic Magnetic Transmission lines functioned as microwave sources because of Gyromagnetic Precession. Their performance strongly depended on Magnetic Saturation experienced at high biasing Field Strengths.

Paul [13] has presented Time domain and frequency domain Lumped Inductive-Capacitive Coupling Circuits for cross talk between different Electric Transmission Line Conductors. The generator-receptor model is well suited for studying Radiated/ Conducted Emissions and Susceptibility. Such models must be developed for Magnetic Transmission Lines as well; to study their Electromagnetic Interference and Electromagnetic Compatibility.

Paul, Whites and Nasar [8] have presented a step-by-step method to solve the Maxwell's equations in sinusoidal steady state; due to a given current distribution in a homogeneous, linear, isotropic medium. First, magnetic potential field is calculated at all desired points in space, due to the current distribution. The curl of the magnetic potential field is used to obtain the magnetic field. The Divergence of the magnetic potential field is used to obtain the scalar Electric Potential. In turn, the magnetic potential field and the gradient of the electric potential are used to derive the Electric field. The procedure is much more complicated for waveguides in inhomogeneous, anisotropic, and non-linear media; hence, numerical methods are suggested where a closed form solution is not possible.

Er-Ping [14], [12] has discussed a wide range of standard time and frequency domain Computational Electromagnetics Methodologies. Time Domain Methods include Analytical Methods, Finite Difference Methods (FDTD), Finite Integral Methods (FIT), Finite Volume Methods (FVTD), Fast Multipole Method (FMM), Partial Element Equivalent Circuit Method (PEEC), Transmission Line Method (TLM) etc. Frequency Domain Methods include Method of Moments (MoM), Finite Element Method (FEM), Geometric Theory of Diffraction (GTD), Physical Theory of Diffraction (PTD) etc. He compared Finite Difference Methods, Method of Moments and Finite Element Method, in respect of Principle, geometry materials, Meshing, Matrix Equation and Boundary Treatment. He gave a list of commercially available simulators along with some common applications like high-speed electronics, photonics, microwave circuits, integrated circuits and Antennas. The Finite Difference Method can obtain response over a broad band of frequencies for many non-linear and inhomogeneous media without using matrix equations. This method is well suited for simulation of dispersive, non-uniform Magnetic Transmission Lines.

Methodology

- Carry out Finite Difference Time Domain Electromagnetic Field Simulations in MEEP [6] of dispersive Magnetic Transmission Lines in anisotropic, inhomogeneous, non-linear media.
- Carry out Finite Difference Frequency Domain Electromagnetic Field Simulations in MEEP [6] for Decomposition of Fields into various travelling wave modes. Also, study Frequency Domain Behavior using lumped Magnetic Transmission Line circuit.
- Carry out MATLAB Lumped Magnetic Circuit Simulations for cross talk between Multi-Conductor Transmission Lines.
- Develop Power Flow Equations for Magnetic Transmission Lines in terms of Lumped parameters.

Experimentation

The Electromagnetic simulations will be carried out in MEEP [6] Simulator which is a script based Finite Difference Time Domain Electromagnetic Fields Simulator for solving Maxwell’s Equations. MEEP [6] is ideal for modeling the time domain and frequency domain behavior of a variety of arbitrary materials including anisotropic, dispersive, non-linear dielectrics, electric/ magnetic conductors, media with saturable gain/ absorption, and gyrotropic media. This simulator is well suited for Finite Difference Electromagnetic simulation of non-uniform, dispersive Magnetic Transmission Lines exhibiting complex permittivity and permeability. The C++ interface has the features of variable resolution and normalized units. Each spatial unit is modeled as a Yee’s Cell. This is ideal for modeling nonlinear, anisotropic, inhomogeneous media. Also, sample data for several materials is provided in libraries for building accurate test structures. The space is divided into independent chunks so that the program can be run on parallel processors. The boundaries can be modeled as perfectly matched layers to prevent reflection of fields. Hence, a wide variety of electric or magnetic current sources can be simulated. The program is solved for all Electric and Magnetic field components. Many derived components can be evaluated like Curl, Divergence, Energy Density, Potential, Flux, Poynting vector etc. Several Mathematical operations like averaging, symmetry and integration over a line, surface or volume are allowed in cylindrical and rectangular coordinates. The fields can be printed as image or video files as well. A frequency domain solver is also provided for multidimensional Laplace transformation and the decomposition of fields into travelling modes.

Lumped circuits are used for studying linear, time invariant, distributed systems like Magnetic Transmission Lines. The distributed parameters can be calculated using mathematical formulas. MATLAB will be used for modeling the time and frequency domain behavior of Magnetic Transmission Lines in terms of simplified Lumped Circuits.

Experimental Setup

Finite Difference Time Domain Electromagnetic Field MEEP [6] Simulations will be carried out for dispersive Magnetic Transmission Lines in anisotropic, inhomogeneous, non-linear media. The Magnetic Transmission Lines will be constructed using Drude-Lorentz susceptibility models for ferromagnetic conductors like Nickel, Iron and Cobalt alloys. The Transmission Lines will be excited using continuous point sources. The terminations can be modeled by Perfectly matched layers for Surge Impedance Loading; or as perfect reflectors for no load. Different Transmission Line structures can be simulated like the Wideband Transformer and Transmission Line Transformer [7].

In order to study their frequency response to continuous sources, Finite Difference Frequency Domain Electromagnetic Field MEEP [6] Simulations will be carried out. The multi-dimensional Fourier transform and mode decomposition will be used for this study. In order to simplify analysis, the Distributed System will be linearized to obtain a lumped model. The frequency Domain Behavior will also be studied using Transfer Function of Equivalent T-model Transmission Line circuit.

Multi-conductor Transmission Lines introduce many complexities like capacitive/ inductive coupling. MEEP [6] Simulations and MATLAB Lumped Circuit Simulations will be carried out for studying cross talk between Conductors of multi-wire Magnetic Transmission Lines.

As in the case of Electric Transmission Lines, Power Flow Equations can be developed for Magnetic Transmission Lines in terms of Lumped parameters; like per unit length transverse impedance and the per unit length longitudinal admittance. The results can be verified using electromagnetic simulations.

Results Expected and Method of Analysis

The Electromagnetic MEEP [6] Simulations will help to probe the stored Electric/ Magnetic Energy Density, geometric parameters, per unit length losses and Transmission Efficiency of Magnetic Transmission Lines. Among the different magnetic materials, the best alloy will be chosen based on desired performance metrics. A suitable candidate must exhibit minimal radiation and line losses. The transverse impedance and longitudinal admittance dictate the propagation of wave modes in magnetic transmission lines. Simulations will be used to estimate per unit length transverse inductance and longitudinal capacitance, which contribute to the transverse impedance and longitudinal admittance respectively. These parameters are pivotal in determining the lumped model of the distributed Transmission Line system.

The Magnetic Transmission Lines will be excited by continuous sources to examine their Frequency Response. The Fourier Transform will decompose the Fields into the various travelling wave modes. This will aid the study of the effects of magnetic hysteresis and saturation on power quality [9]. The T-model Equivalent Magnetic circuits and coupled equations will be used to simplify analysis of the transient and steady state behavior. According to theory, Magnetic Transmission Lines must exhibit 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. However, this also implies that Magnetic Transmission Lines must be operated at higher frequencies than Electric Transmission Lines. Poorly designed Magnetic Transmission Lines may amplify high frequency noise which can be damaging for the power system. The imaginary part of Transmission Line Magnetic Reluctance, which is a strong function of frequency, contributes to line losses. Hysteresis losses also increase significantly at higher frequencies [9]. Hence, an appropriate frequency must be chosen, considering the complex nature of the magnetic material.

The study of capacitive/ inductive coupling in Multi-Conductor Transmission Lines will provide useful knowledge about the Radiated/ Conducted Emissions and Susceptibility. The generator-receptor model is well suited for studying Electromagnetic Interference and Electromagnetic Compatibility of Magnetic Transmission Lines. The results can be compared with mathematical formulas to build linear circuit models for cross talk between Magnetic Transmission Lines. The aim will be to minimize Electromagnetic Radiation; that can be picked up by intentional receivers like Radio and Television; or unintentional receivers like digital Computers. This will prevent malfunction of the sensitive electronic equipment.

Power Flow Equations for Magnetic Transmission Lines will help to compare the Electromagnetic and Magnetic circuit models. The Power Flow will be represented in the form of Magnetic Current and Magnetic Voltage for circuit Model. For the Electromagnetic Model, the Power Flow will be represented in the form of Magnetic Field and Electric Field. Accurate Estimation of Lumped parameters; like per unit length transverse impedance and the per unit length longitudinal admittance is necessary for producing a valid lumped magnetic circuit for Magnetic Transmission Lines.

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