UNIVERSITY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF ELECTRICAL ENGINEERING

MSC. THESIS TOPIC PROPOSAL

Modeling and Simulation of Magnetic Transmission Lines

Name of Student: Muhammad Shamaas

Registration No: 2018-MS-EE-4

Problem Statement

Although Magnetic Transmission Line is the dual counterpart of Electric Transmission Line, it has received very little attention. Its theory, construction, modeling and applications are still evolving. Intrinsically, Magnetic Transmission Line is made from a magnetic material, with a very high relative permeability, that conducts hypothetical magnetic charges called magnetic monopoles. Each magnetic monopole has a net charge given in Webers. The operation of a Magnetic Transmission Line does not involve electric charges. However, moving magnetic charges produce Electric Fields, just like moving electric charges produce Magnetic Fields. Hence, Electric Energy is stored in the Electric Field of the dielectric medium. The Time varying magnetic flux results in a fictitious, unmeasurable Magnetic current inside the Transmission Line, which has the units of Volts. Interestingly, the magnetic voltage between Magnetic Transmission Lines has the units of Amperes. These relations must be modeled using Maxwell's Equations and magnetic circuits to study the time and frequency domain behavior of 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 multi-wire magnetic transmission lines, the key matrices are the transverse impedance and the longitudinal admittance. They determine the modal propagation constants and modal characteristic wave admittances that characterize the various travelling wave modes of multi-wire magnetic transmission lines. 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 new approach, based on Maxwell's equations and Poynting vector, modeled the ideal transformer by means of an ideal magnetic transmission line. It was shown that the well-known voltage, current, and impedance ratios of the ideal transformer can be reproduced by the new Magnetic Transmission Line Model.

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. Magnetized films also act as Radio Frequency selective limiters.

Faria [7] presented an analysis of skin-effect in radially inhomogeneous tubular geometries for Euler-Cauchy structures. He addressed the evaluation of the per unit length complex magnetic reluctance of tubular ferrites, taking into account that their complex permeability strongly depended on the frequency. For frequencies up to 1 MHz the real part of the complex reluctance remained practically independent of the frequency, whereas the imaginary part increased linearly. Ferrite behavior was strongly dependent on its chemical composition, which may vary a lot among specimens. The performance of Magnetic Waveguides was critically dependent on the complex nature of magnetic reluctance.

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-liner 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.

Schneider [5] has described finite-difference methods as numerical methods for solving differential equations by approximating them with difference equations. Finite Difference Methods are discretization methods which convert Differential Equations into a system of algebraic equations, which can then be solved by matrix algebra techniques in modern computers. Yee Lattice Discretization technique is very well suited for solving Maxwell’s Equations with second order accuracy.

Sevik and Brancık [9] presented a time-domain simulation technique of non-uniform multi-conductor transmission lines based on an implicit Wendroff method to solve both voltage and current distributions along the wires, and their sensitivities with respect to lumped and distributed parameters. An experimental error analysis was done on a single transmission line with known analytical solutions. Using MATLAB simulations, the computational efficiency was assessed by means of detailed CPU times evaluation.

Oskooi et al. [6] have developed a free and open-source software package for electromagnetic simulation via the finite-difference time-domain method. MEEP 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.

Methodology

- Carry out Finite Difference Time Domain Electromagnetic Field Simulations in MEEP of dispersive Magnetic Transmission Lines in anisotropic, inhomogeneous, non-liner media.
- Carry out Finite Difference Frequency Domain Electromagnetic Field Simulations in MEEP 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 Simulator which is a script based Finite Difference Time Domain Electromagnetic Fields Simulator for solving Maxwell's Equations. 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. 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 Simulations will be carried out for dispersive Magnetic Transmission Lines in anisotropic, inhomogeneous, non-liner media. The Magnetic Transmission Lines will be constructed using Drude-Lorentz susceptibility models for magnetic conductors like Permalloy (Ni and Fe alloy) 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 sagging transmission line, shielded transmission line and the multi-wire transmission lines.

In order to study their frequency response to continuous sources, Finite Difference Frequency Domain Electromagnetic Field MEEP 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 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 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 conductors, 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 determine the modal propagation constants and modal characteristic wave admittances that characterize the various travelling wave modes of 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. 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. 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.

References

[1] J. B. Faria, *Multimodal propagation in multiconductor transmission lines*. J. Electromag. Waves Appl. 2014, p. 1677–1702

[2] J. B. Faria, *Formulation of Multiwire Magnetic Transmission-Line Theory*, Progress in Electromagnetics Research B, Vol. 49, 2013, p. 177–195.

[3] J. B. Faria, *Matrix theory of wave propagation in hybrid electric/magnetic multiwire transmission line systems*, Journal of Electromagnetic Waves and Applications, Vol. 29, No. 7, 2015, p. 925–940.

[4] J. B. 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, p. 365–373.

[5] J. B. Schneider, *Understanding the Finite-Difference Time-Domain Method*, 2017, p. 33-74.

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

[7] J. B. Faria, *Complex reluctance of inhomogeneous Euler-Cauchy tubular ferrites taking into account frequency dependent complex permeability*, Progress In Electromagnetics Research M, Vol. 25, 2012, p. 71–85.

[8] C. Paul, K. Whites and S. Nasar, *Introduction to electromagnetic fields*, 4th ed. Boston: WCB/McGraw-Hill, 1998, p.586-589.

[9] B. Sevcik and L. Brancık, *Time-Domain Simulation of Nonuniform Multiconductor Transmission Lines in Matlab*, International Journal of Mahematics and Computers in Simulation, Vol.5, No. 2, 2011, p. 1-8.

[10] G. Antonini, *A general framework for the analysis of metamaterial transmission lines*. Prog. Electromagn. Res. B., 2010, p. 353–373

[11] C. Caloz and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*, Wiley-IEEE Press, 2006, p. 27-58.

[12] IEEE, Standard for Validation of Computational Electromagnetic (CEM) Computer Modeling and Simulation, and Recommended Practice, Part I, IEEE, June 2008.

[13] C. Paul, *Introduction to Electromagnetic Compatibility*, 2nd ed. Kentucky: John Wiley and Sons, 2006, p. 559-710.

[14] L. Er-Ping, *Computational Electromagnetics for Electromagnetic Compatibility/ Signal Integrity Analysis*, IEEE EMC DL Talk, University of Missouri, 2008.

[15] T. C. Edwards and M. B. Steer, *Foundations for Microstrip Circuit Design*, 4th ed. Wiley-IEEE Press, 2016, p. 576-607.