Modeling AND SiMULATION OF MagNETIC TRANSMISSION LINES

Muhammad Shamaas

ID # 2018-MS-EE-4



DEPARTMENT OF ELectrical Engineering

UNIVERSITY OF ENGINEERING AND TECHNOLOGY LAHORE

Contents

[List of Figures 2](#_Toc37990691)

[Abstract 3](#_Toc37990692)

[Acknowledgements 4](#_Toc37990693)

[Abstract 5](#_Toc37990694)

[1. Introduction to Magnetic Transmission Lines 6](#_Toc37990695)

[1.1. Nature of Magnetic Materials 7](#_Toc37990696)

[1.2. AC Losses in Magnetic Materials 14](#_Toc37990697)

[1.3. Literature Review 17](#_Toc37990698)

[1.4. Outline 19](#_Toc37990699)

[2. Wave Propagation in Magnetic Materials 20](#_Toc37990700)

[2.1. Plane Wave Propagation 20](#_Toc37990701)

[2.2. Power Flow Analysis 22](#_Toc37990702)

[3. Magnetic Circuit Modeling 23](#_Toc37990703)

[3.1. Reluctance Model 24](#_Toc37990704)

[3.1.1. Application 24](#_Toc37990705)

[3.2. Capacitance-Permeance Model 25](#_Toc37990706)

[3.2.1. Application 26](#_Toc37990707)

[3.3. Magnetic Transmission Line Model 27](#_Toc37990708)

[3.3.1. Application 32](#_Toc37990709)

[3.4. Summary 33](#_Toc37990710)

[4. Computational Electromagnetics 34](#_Toc37990711)

[4.1. Solving Maxwell’s Equations 34](#_Toc37990712)

[4.1.1. Analytical Methods 35](#_Toc37990713)

[4.1.2. Numerical Methods (Low Frequency Methods) 36](#_Toc37990714)

[4.1.3. Asymptotic Methods (High Frequency Methods) 39](#_Toc37990715)

[4.1.4. Hybrid Methods 40](#_Toc37990716)

[4.2. MEEP 41](#_Toc37990717)

[5. Magnetic Transmission Line Simulation 45](#_Toc37990718)

[5.1. Wideband Transformers 48](#_Toc37990719)

[5.2. Wideband Transformer Simulation in MEEP 52](#_Toc37990720)

[6. Conclusion 54](#_Toc37990721)

[7. References 55](#_Toc37990722)

[8. Appendix 60](#_Toc37990723)

# List of Figures

[Figure 1: Magnetization vs. Applied Field 9](#_Toc31074085)

[Figure 2: Hysteresis Loop 10](#_Toc31074086)

# Abstract

# Acknowledgements

# 

# Abstract

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 transmits Magnetic Flux as the effective Magnetic charge. Time varying magnetic flux results in a Magnetic Displacement Current inside the Transmission Line. This produces a gradient Magnetic Field; with Fields Lines that spread radially outwards. The magnetic current and magnetic voltage due to this Magnetic Field is measured in Volts and Amperes respectively. 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 Simulator for anisotropic, inhomogeneous, non-linear Magnetic Transmission Lines.

# Introduction to Magnetic Transmission Lines

Magnetic Transmission Lines are designed to transmit electromagnetic energy using strong magnetic fields. They are made of magnetic 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. This phenomenon is called Magnetic Transmission.

It is important to note that charge transport is not involved in magnetic communication. Isolated Magnetic charges do not exist and magnetic conduction current can never flow in a Magnetic Transmission Line. Magnetic Transmission is only possible through the alignment of magnetic dipoles in response to a stimulating Magnetomotive Force. This is termed as Magnetic Displacement Current.

Magnetic Transmission does not involve the flow of Electric charges either. Magnetic materials are very poor electric conductors; hence electric currents cannot transmit information across a Magnetic Transmission Line. Changing Magnetic Fields produce Electric Fields which are transmitted through electric displacement currents. This causes polarization of atoms in the dielectric magnetic medium which transmits Electric information across the Magnetic Material. Together, the Electric and Magnetic Fields transmit Electromagnetic Energy along the direction of propagation.

The following sections will elaborate on the subject of Magnetic Materials. A brief account on the losses in Magnetic Transmission Lines will be given as well.

## Nature of Magnetic Materials

The basic building blocks of magnetic materials are fictitious magnetic monopoles which can be considered as magnetic charge carriers. In nature, magnetic monopoles always exist in pairs called magnetic dipoles. A monopole can have either positive or negative charge which is responsible for the magnetic field around it. The force between poles is proportional to the strength of the poles (m) and inversely proportional to the square of distance (r) between them:

Magnetic dipole results from the motion of an electron in an orbit around a nucleus. This is similar to a current flowing in a loop. The identification of the North and South poles is dictated by the Flemming’s right hand rule.

Whenever a moving charge q is placed in an electromagnetic field, it experiences a force called Lorentz Force. The direction of the force represents the direction of least pressure in the electromagnetic field. Lorentz Force depends on the velocity (v) of the charge and the strength of the electric and magnetic fields:

If an orbiting electron is placed in a magnetic field, the net Ampere force on the current loop is:

The Force will produce a Torque which will rotate the dipole. The Torque can be represented in terms of the magnetic dipole moment (m) normal to the current loop:



The magnetic dipole moment () of an orbiting/spinning electron is proportional to the spectroscopic splitting factor () and the associated quantum number (n). It is measured in units of Bohr Magneton ().

The net magnetic moment of an atom or ion is the vector sum of the orbital and spin moments of all electrons in its outer shell.

Two dipoles attract each other if unlike poles are close to each other. On the other hand, two dipoles repel each other if like poles are closer. Inside an unmagnetized material, the magnetic dipoles are optimally oriented hence the net torque is zero. Only a few orientations can result in a net zero torque on all the dipoles in a magnetic material. Dipoles tend to align parallel to neighboring dipoles so that the lowest energy state can be achieved.



Atoms contain orbitals with discrete levels of energy for accommodating electrons. Electrons try to occupy the lowest energy orbitals first to minimize the energy of the system. An electron with clockwise spin can pair with an electron having anticlockwise spin. Hence, the clockwise spin cancels the effect of anticlockwise spin and no magnetic moment results.

An external magnetic field can cause a mechanical torque on a magnetic dipole. The moment tries to turn the dipole in the direction that decreases the overall energy of the system. Only unpaired spins contribute to the net magnetic moment. The resulting spin and orbital moments add up to produce a net Magnetization Vector Field M inside the magnetic material. This field is proportional to the magnetic susceptibility of the material ):

The Magnetic Field inside a magnetic material can be represented by a flow of magnet field lines. The number of lines passing through a region of space is called Magnetic Flux (equivalent to magnetic charge). Magnetic Flux Density(B) represents the number of flux lines per unit area:

Iron, Nickel and Cobalt contain 4, 3 and 2 unpaired electrons per atom respectively. Hence, the effect of Magnetization is very strong in these special elements and their alloys. Large scale cooperation between magnetic dipoles causes an enhanced Magnetic moment. Due to the high magnetic susceptibility, they are used in the production of Ferromagnetic and Ferrimagnetic materials.

The parallel alignment of magnetic dipoles causes the creation of magnetic domains to reduce the magnetic potential energy stored in the Magnetic Flux Lines. The Magnetic energy consists of the following:

1. Magnetostatic Energy: The energy needed to place the magnetic poles in a specific geometric configuration e.g. magnetized state. Magnetostatic Energy Density is proportional to the width of the magnetic strip (d) and the value of applied Magnetic Field Intensity (H). Transformers are made using insulated sheets of steelhaving high electrical resistance. Rolling of the sheets aligns the Magnetic domains and reduces the Magnetostatic Energy. The expression is given in ()
2. Magneto-crystalline Anisotropy Energy: For crystalline structures with repeating atomic units, the domain magnetization tends to align along one direction more easily than other directions.Magneto-crystalline Anisotropy Energy is greater in hard direction as compared to the easy direction. It depends on the anisotropy constants () and direction cosines () which project magnetization on the different axes.
3. Magnetostrictive Energy: Magnetization and Demagnetization can cause changes in the dimensions of the magnetic materials. These stresses are caused by shifting of atomic planes e.g. during alignment of domains. Magnetostrictive Energy represents the elastic potential energy stored in the constricted atomic configuration. It is proportional to the magnetostriction constant () and applied stress ().
4. Domain Wall Energy: A Domain wall is a region where the Magnetization in one domain gradually changes to the direction of a neighboring domain. Domain Wall Energy represents the energy in the transition region. It is related to Anisotropy Constant (), Curie Point ( and atomic spacing (a).



Naturally, the size and direction of magnetic domains is chosen to minimize the overall magnetic energy of the system. If an unmagnetized material is placed in an external magnetic field, the domains may have to align in a hard direction for Magnetization of the material. Work will be done to align the domains in the special configuration so that the preferable domains grow in size while the unfavorable domains shrink. This will involve displacement of atomic planes and domain boundaries. Hence the overall stored magnetic energy of the system will increase during magnetization.



When a demagnetized material is placed in an increasing Magnetic Field, the domain walls will start reversible movements and rotations. The Magnetization will start to increase slowly as shown in the Figure below. This corresponds to the elastic phase with minimum magnetic susceptibility. Later on, the domain wall motions increase greatly. Large scale irreversible atomic plane displacements correspond to the partial magnetism phase in magnetization curve. During this phase, the material exhibits the highest magnetic susceptibility. Soon the majority of domains get aligned with the magnetic field. In the last phase, a large amount of energy is needed to rotate the remaining domain magnetization hence the material exhibits a saturating magnetic susceptibility. At high fields, the induction saturates at Bmax.



Figure 1: Magnetization vs. Applied Field

If the applied field of the saturated material is decreased, the magnetic domains start to reverse their direction. Initially, the material exhibits a small magnetic susceptibility. This resistance results because the majority of domains are aligned in the easy direction. The favorable domains had shrunk during the magnetization. Work must be done to expand the favorable domain walls in the reverse direction. As a result, demagnetization does not follow the curve of the original magnetization. When the applied field is decreased further, the magnetic susceptibility of the material starts to increase as more domains start to align in the reverse direction.

The induction lags the applied field hence some remnant induction remains when applied field is reduced to zero. In order to demagnetize the material, some extra amount must be applied.This amount is called the coercive force. As the field keeps decreasing, the domains start aligning in the hard direction. Once all the domains have aligned, the material saturates in the reverse direction.

If the material is now magnetized again, the response will contain all the phases described earlier. The induced field will start to increase slowly, followed by a phase of large magnetic susceptibility and end by saturating. Hence magnetization and demagnetization result in a hysteresis loop.



Figure 2: Hysteresis Loop

The slope of the B-H curve is called permeability. It is closely related to the magnetic susceptibility.

When the material is saturated, the magnetic susceptibility becomes zero. Hence the permeability reduces to . Besides Magnetic Field Intensity, permeability is strongly dependent on chemical composition, crystal structure, stress, temperature and time after magnetization.

## AC Losses in Magnetic Materials

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. The various loss mechanisms are:

1. Hysteresis 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 (disaccommodation), frequency and temperature. Fields inside Anisotropic media can be represented by a 33 permeability/ magnetic susceptibility tensor:

This hysteresis loss is equal to the area inside the DC hysteresis loop:

Hysteresis loss increases with the applied field strength and frequency. The empirical formula for Hysteresis Loss Density is:

1. Eddy Current Losses: Ferromagnetic materials are semiconductors with resistivity () ranging from 0.1Ωm to greater than 1MΩm. 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.



These losses can be reduced by using thin laminated magnetic films or magnetic grains for manufacturing. The Eddy current losses depend on the shape and size (d) of the material, the frequency (f), the applied field intensity () and the resistivity () or conductivity (). The empirical formula for Eddy Current Loss Density is:

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 Dimensional 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. The associated loss tangents are:



1. Residual Losses: 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. The associated loss tangent is .



The total loss tangent due to hysteresis loss, eddy current loss and residual loss is:

In conclusion, the losses due to hysteresis, Eddy currents, Piezomagnetism, Magnetoresistance, Magnetostriction and other residual loss mechanisms can be expressed as heat losses across an effective resistance or conductance.

## Literature Review

Faria [1-4] 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.

## Outline

# Wave Propagation in Magnetic Materials

## Plane Wave Propagation

Ideal Magnetic Transmission Lines can be modeled as linear, isotropic, homogeneous media.

The corresponding Maxwell’s equations are:

The solution is given by the Helmholtz Equations:

For sinusoidal steady state:

The propagation constant () dictates the wave propagation in the medium. Considering plane wave propagation in the z direction, the solution is:

The attenuation constant () represents the loss or attenuation of fields. The skin depth () is defined as the penetration measured from the surface at which the amplitude reduces by a factor of 1/e:

The phase constant dictates the phase velocity (u) and wavelength (𝜆):

The ratio of matching Electric Field Intensity and Magnetic Field Intensity determines the intrinsic impedance of the material:

For lossless magnetic materials with very small ,

where , , and represent the free space phase constant, phase velocity wavelength, intrinsic impedance respectively.

## Power Flow Analysis

The power flow density of an electromagnetic wave is given by the Poynting vector **S**. It has the units of W/m2. The Poynting flux is indicative of the amount of power flowing across a surface:

The expression can be expanded using:

The flow of Poynting flux can be separated into the Ohmic Power dissipation, Electric Power flow and Magnetic Power flow:

From these expressions, it is clear that the Electric Energy and Magnetic Energy of a system is:

# Magnetic Circuit Modeling

In this section, three different Magnetic circuit models will be presented: The Reluctance Model, The Capacitance Permeance Model and The Magnetic Transmission Line Model.

The Reluctance Model is the oldest and most popular model, even though it is not a power invariant model. It only has one component called the Magnetic Reluctance which resists the flow of Magnetic Flux.

The Capacitance Permeance Model overcomes the weaknesses of the Reluctance Model by considering the rate of change of Magnetic Flux as the Magnetic Current. It is a power invariant model because it correctly encompasses the transformation of Magnetic and Electric Energy. This model has the shortcoming that it does not incorporate Electric Energy Storage and Electromagnetic losses in a Magnetic material.

The Magnetic Transmission Line model improves the Capacitance Permeance Model by including a component for Electric Energy Storage and a component for magnetization, polarization and conduction losses.



## Reluctance Model

H. A. Rowland’s Law (1873) is the counterpart of G. Ohm’s Law (1827) for Magnetic circuits. Complex Reluctance Model defines Magnetic reluctance as the ratio of sinusoidal Magnetomotive Force and sinusoidal 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.



In 1969, R. W. Buntenbach proved that the Reluctance model is not power invariant. Reluctance Power Loss cannot be calculated using Joule Heating Law (1842) analogy due to dimensional inconsistency:

Hence this is not an accurate model for Power and Energy Flow.

## Application

## Capacitance-Permeance Model

B. Tellegen’s Gyrator theory (1948) can describe power invariant transformation of magnetic and electric quantities. The dual effort and flow quantities are related by the gyration constant (N). R. W. Buntenbach proposed Power Invariant Permeance-Capacitance Model (1969) to replace Reluctance Model.



Magnetic Displacement Current is the rate of change of Magnetic Flux which results from the polarization of Magnetic Dipoles. For a magnetic core, the magnetic current and Magnetomotive Force are given by:

and

Magnetic Permeance is defined as:

This represents an equivalent magnetic capacitor which stores magnetic charge (magnetic flux).

M. Faraday’s Law (1831): Electric Voltage is responsible for producing Magnetic Current (rate of change of magnetic flux).

A. Ampere’s Law (1861): Magnetic Voltage is responsible for producing Electric Current (rate of change of electric flux).

## Application

## Magnetic Transmission Line Model

J. A. B. Faria and M.P. Pires presented Magnetic Transmission Line Model (2012) based on Electric Transmission Line Model in terms of per unit length transverse Impedance and per unit length Longitudinal Admittance.

The propagation of electromagnetic waves is governed by the Maxwell’s Equations:

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. It is defined in terms of per unit length Magnetic charge and scalar magnetic voltage as

The per unit length longitudinal capacitance represents an Electric Energy storage element. It is defined in terms of electric displacement flux and magnetic displacement current as



Assuming TEM-guided propagation in z-direction (), the relation between the magnetic voltage and magnetic current for a homogeneous magnetic transmission line is derived by substituting the previous expressions in the Maxwell’s Equations.

The resulting Transmission Line Equations are

A forward travelling and a backward travelling wave can simultaneously exist on the transmission line. The solution for the Magnetic voltage and Magnetic current is

The propagation constant is defined as

The characteristic impedance is the ratio of Magnetic Current to the Magnetic Voltage. It is calculated as

The average power flow in the Magnetic Transmission Line can be represented in terms of three distinct components: the average power in the forward travelling wave, the average power in the backward travelling wave and the dissipated power.



In a non-ideal magnetic transmission line, magnetic voltage drop can be accounted by including magnetic reluctance/ conductance. It represents all the magnetization, polarization and conduction losses due to electric conductivity, complex permittivity and complex permeability. Magnetic Inductance and Magnetic Capacitance are energy storage elements in this model.

Energy is dissipated in Magnetic Conductance:

Electrical Energy is stored in Magnetic Capacitance; and Magnetic Energy is stored in Magnetic Inductance.

The resulting Magnetic Transmission Line Equations are:

Assuming sinusoidal steady state, the equations can be expressed in terms of phasor quantities as follows:

The Magnetic Transmission Line Equations can be solved just like Electric Transmission Line Equations. The solutions are compared in the table below.

|  |  |
| --- | --- |
| Electric Transmission Line | Magnetic Transmission Line |
|  |  |
|  |  |
|  |  |
|  |  |
|  |  |

For Transmission Lines of similar geometry, the Transmission Line parameters / matrices are closely related:

Magnetic cores are often manufactured using layers of laminated magnetic sheets to prevent the flow of Eddy Currents. In such materials, magnetic flux from one transmission line can link with a neighboring magnetic transmission line and disturb the information. The Magnetic Transmission Line Model can be extended to the generator-receptor Magnetic Transmission Line model. This is well suited for studying Electromagnetic Coupling of Magnetic Transmission Lines which are in close proximity.



## Application

Permanent Magnet Synchronous Machine Model

## Summary

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Reluctance Model** | **Permeance-Capacitance Model** | **Transmission Line Model** |
| **Conserved Quantity** | ? | Magnetic Flux  [Volt-Second] | Magnetic Flux  [Volt-Second] |
| **Flow Variable** | Magnetic Flux  [Volt-Second] | Rate of change of Magnetic Flux [Volt] | Rate of change of Magnetic Flux [Volt] |
| **Effort Variable** | Magnetomotive Force [Ampere] | Magnetomotive Force [Ampere] | Magnetomotive Force  [Ampere] |
| **Energy Dissipation Element** | Magnetic Reluctance [] | ? | Magnetic Conductance  [Ohm] |
| **Electrical Energy Storage Element** | ? | ? | Magnetic Capacitance  [Farad] |
| **Magnetic Energy Storage Element** | ? | Magnetic Permeance  [Henry] | Magnetic Inductance  [Henry] |

# Computational Electromagnetics

This section discusses the different time domain and frequency domain methods for solving Maxwell’s Equations.

## Solving Maxwell’s Equations

## Analytical Methods

1. Separation of Variables
2. Conformal Transformation

## Numerical Methods (Low Frequency Methods)

1. Integral Equation (IE) based Methods: Method of Moments (MoM), PEEC, Fast Multipole Method (FMM)
2. Partial Differential Equation (PDE) based Methods:Finite Element Method (FEM), Finite Difference Time Domain Method (FDTD), FIT, TLM, FVTD: K. S. Yee’s Method (1966) or Finite Difference Time Domain Method is a differential numerical modeling technique for computational electrodynamics. J. C. Maxwell’s Equations (1861) are discretized using central difference approximations to the space and time partial derivatives. For example,

Finite Difference Time Domain Method discretizes space into a grid of small elements called Yee Lattice (1966). Each element can have a different conductivity, permittivity and permeability. The different field components at a grid location are stored in the edges and faces of a cubic element. They are evolved in discrete time steps .



The location of field components and the central difference operations implicitly enforce the two Gauss’s Law relations.

The finite region of space must always be terminated with some boundary conditions. Some examples include:

1. Bloch-periodic Boundaries: These are used for simulation of periodic structures . Periodic Bloch Boundaries copy the field component at one cell’s edge and reinject them at a neighboring cell’s edge.
2. Metallic Walls: All fields are forced to be zero at the boundaries (perfect reflector has zero absorption and zero skin depth).
3. Perfectly Matched Layers: All the fields pass through the open boundary with no reflection. These absorbing boundary layers (ABC) absorb all incident fields.

## Asymptotic Methods (High Frequency Methods)

1. Geometric Optics (GO): GTD, UTD
2. Physical Optics (PO): PTD, UAT

## Hybrid Methods

1. Numerical Method cum Numerical Method: FEM-MoM
2. Numerical Method cum Asymptotic Method:MoM-PO/ GTD/ PTD

## MEEP

MEEP (2006) is a script based Simulator 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.

* C++ interface: Features variable resolution and normalized units.
* Material Library: Sample data for several materials is provided in libraries for building accurate test structures.
* Current Sources: A wide variety of electric or magnetic soft current sources can be simulated.
* Derived components: Electric/ Magnetic/ Thermal Energy Density, Poynting Flux etc. can be evaluated.
* Mathematical operations: Averaging, symmetry and integration are allowed in cylindrical and rectangular coordinates.
* Data Visualization: The fields can be printed as image or video files.
* A. Ampere’s Law (1861)
* M. Faraday’s Law (1831)
* J. C. F. Gauss’s Law for Electricity (1813)
* J. C. F. Gauss’s Law for Magnetism (1813)

1. 1-D, 2-D and 3-D simulation is possible. Hence every space vector can have up to three spatial coordinates.
2. The simulation can be carried out in rectangular or cylindrical coordinates. Hence different homogeneous/inhomogeneous structures can be built inside the space.
3. Symmetry can be used to create complex geometries as well.

* Drude-Lorentzian Model (1900) models frequency dependent permittivity and permeability. Flux Densities contain terms for infinite frequency response and frequency dependent Polarization vector.
* andare represented as a sum of harmonic resonances and a term for frequency independent electric conductivity.

is the electrical/magnetic conductivity. couples the polarization to the driving field, is the angular resonance frequency, is a damping factor.

* Dispersion Drude-Lorentzian Model (1900) 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.



* In Pockels and Kerr Non-linearity model (1875), and can be changed by the field intensity.

sum is the Pockels effect; whereas sum is the Kerr effect.

* 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.
* Landau-Lifshitz-Gilbert model (1955) 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 . couples the polarization to the driving field, is the angular resonance frequency, is a damping factor.

* For such anisotropic media, non-diagonal susceptibility tensor is used to relate Magnetization and Field intensity.
* G. Green’s Functions (1835) give the Field Patterns from a localized point source at a particular frequency .

The point current source is placed at . The field component is observed.

* A frequency domain solver is also provided for multidimensional Fourier transformation (1822) and the decomposition of fields into travelling modes.
* Broadband response: The 3 Dimensional Discrete Fourier transform (1822) of the response to a short impulse can give useful information about the transmitted power and losses.
* The Transmitted Power can be computed using the integral of Poynting Vector (1884); over a surface on the far end of the transmission line.
* Transmitted power and incident power can be used to find power losses in transmission line.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Property** | **Symbol** | **Standard Scale in SI Units** | **Conversion Factor** | **Normalized MEEP Units** |
| **Length** |  | 1.00000e-3 m | = 1.00000e3 | 1 |
| **Speed of Light** |  | 2.99792e8 | = 3.33564e-9 | 1 |
| **Current** |  | 1.00000 A | = 1.00000 | 1 |
| **Time** |  | = 3.33564e-12 s | = 2.99792e+11 | 1 |
| **Frequency** |  | = 2.99792e+11 Hz | = 3.33564e-12 | 1 |
| **Permittivity** |  | 8.85418e-12 | = 1.12940e+11 | 1 |
| **Permeability** |  | 1.25663e-6 | = 7.95774e5 | 1 |
| **Electric Field Intensity** |  | = 3.76730e5 | = 2.65441e-6 | 1 |
| **Electric Flux Density** |  | = 3.33564e-6 | = 2.99792e5 | 1 |
| **Magnetic Field Intensity** |  | = 1.00000e3 | = 1.00000e-3 | 1 |
| **Magnetic Flux Density** |  | = 1.25663e-3 | = 7.95774e2 | 1 |
| **Electric Conductivity** |  | = 2.65441 | = 3.7673e-1 | 1 |
| **Electric Current Density** |  | = 1.00000e6 | = 1.00000e-6 | 1 |
| **Energy Density** |  | = 1.25663 | = 7.95774e-1 | 1 |
| **Poynting Vector** |  | = 3.76730e8 | = 2.65441e-9 | 1 |
| **Courant Factor** |  | = 3.33564e-9 | = 2.99792e8 | 1 |

# Magnetic Transmission Line Simulation

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.

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.

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.

## Wideband Transformers

Wideband Transformers are widely used in RF Electronics for voltage, current and impedance matching of unbalanced loads. They provide DC isolation and common mode rejection for efficient AC transmission.

Wideband Transformers provide impedance matching for interfacing different systems through accurate current and voltage transformation. The impedance transformation ratio is dictated by the square of the effective turns ratio between the primary and secondary side.

Unlike an unbalanced network, a balanced network has none of its terminals connected to ground. It is difficult to interface balanced systems with unbalanced systems due to common mode currents. Balun transformer is used for providing DC isolation and maximum power transfer between a balanced and an unbalanced system. A Unun transformer is used for interfacing two unbalanced impedances, whereas a Balbal transformer connects two balanced systems.

Usually wideband transformers are required in high frequency communication applications that require processing of small amounts of RF power in a wide frequency range. For high power applications in Base Station Amplifiers, Repeaters, Satellites, Radar and VFDs, the power limitations of the core and winding must be controlled along with the parasitic losses.

1. Telecommunication Applications: 4G, CDMA, EDGE, GSM, LMDS, LTE, MMDS, Handsets (Cellular, PHS, DECT, TV), Node B, Pagers, TD-SCDMA, TMA, UMTS, W-CDMA, Wi-Fi, WiMAX, Wireline (DSL, ADSL, DSLAM etc.), W-LAN, WLL.
2. Automotive Applications: IVHS, GPS, Tracking
3. Wireless Communication: Audio Systems, AMR, EPIRB, Marine Radar, Marine GPS, RFID Reader/ TAGS, Security Monitoring Systems, Radio Astronomy, Jammers.
4. STATCOM: DBS, LNBs, MODEMs, TMBs, V-SAT.
5. Medical Applications: CT, MR, Ultrasound, Telemetry.
6. Cable/ CATV and Broadband Fiber Communication: BPON, Cable (Set Top Box), Fiber Optic, FTTH, GPON, Hybrid Fiber Coax Network, MOCA.
7. Broadcast Applications: Radio, TV, LMDS.
8. Avionics: Radar, Surveillance Radar, MLS, TACAN, TCAS.

The performance of wideband transformer can be analyzed by the following performance parameters:

1. Bandwidth: The range of frequencies between the two maximum allowable attenuation (1 dB/ 2 dB/ 3 dB) points fmin and fmax. A high fractional bandwidth of 1000 or more can only be achieved if the primary and secondary windings are strongly coupled. Besides attenuation, wideband transformer may also introduce undesirable phase noise in the system causing distortion of RF signal. The transformer must be designed to have a flat phase response in the desired frequency range.
2. Insertion Loss: The ratio of power transfer between the source and an ideal load upon direct connection; and when the transformer is used for the connection. It is indicative of the power loss through the transformer under matched conditions. For a typical wideband transformer, the insertion loss increases at low frequencies due to the low magnetizing reactance. At high frequencies, the insertion loss increases due to the inter-winding capacitance and the leakage inductance. Often, mid-band insertion loss (e.g. 0.5 dB) is taken as reference value.
3. Return Loss: The ratio of applied power and reflected power due to impedance mismatch between the source and load. Optimal impedance matching must maximize the return loss (e.g. 14 - 25 dB) over the entire operational bandwidth i.e. minimum input power must be reflected back to the source.
4. Amplitude balance: The absolute difference in signal amplitude between the outputs of a center-tapped transformer.
5. Phase balance: The absolute difference in signal phase between the outputs of a center-tapped transformer.



The equivalent circuit diagram of a wideband transformer is given below.



represents the primary leakage inductance.

represents the secondary leakage inductance referred to the primary side.

represents the primary winding resistance.

represents the secondary winding resistance referred to the primary side.

is the shunt resistance representing core loss.

nM is the magnetizing inductance of the core.

is the shunt capacitance associated with the primary windings.

is the shunt capacitance associated with the secondary windings.

is the capacitance between the primary and secondary windings.

The operation of wideband transformer can be divided into three distinct segments:

1. Low Frequency Region: The low frequency droop in the transfer characteristics is attributed to the diminishing shunt magnetizing reactance. The loss can be reduced by inserting capacitance in series with the primary or secondary winding.
2. Mid-band Region: The parasitic inductances and capacitances can be ignored in the mid-band region. The response is mainly effected by the series resistance of the windings and the shunt resistance of the core.
3. High Frequency Region: The high frequency droop results from the losses in leakage inductances and shunt capacitances of the windings. The reactance of leakage inductances increases greatly whereas the reactance of shunt capacitance decreases at high frequencies.



## Wideband Transformer Simulation in MEEP

* The Magnetic Transmission Lines will be constructed for inhomogeneous, dispersive, non-linear ferromagnetic conductors like Ferromagnetic, Permalloy and Cobalt alloys.
* The Transmission Lines will be excited using continuous current sources.
* The terminations can be modeled by Perfectly matched layers for complete absorption; or as perfect reflectors for no load.
* Different Transmission Line structures can be simulated like shielded transmission line and multi-wire transmission lines.
* The multi-dimensional discrete Fourier transform (1822) and mode decomposition will be used to determine the Absorbance, Transmittance and Broadband Response.
* A wideband transformer passes a frequency band of several decades and are usually designed to handle complex waveforms like rectangular pulses. They are used for impedance matching, voltage/ current transformation, DC isolation, mixing, power splitting, coupling and signal inversion.
* A wideband transformer will be simulated. It will be excited by a small pulse to examine the Frequency Response. The 3 dimensional discrete Fourier Transform will be used to determine Absorbance, Transmittance and Broadband Response. The results can be compared with published datasheet.

The Loss tangent has the following components:

* DC Resistance Loss Tangent
* Skin Effect Loss Tangent
* Proximity Effect Loss Tangent
* Self Capacitance Dielectric Loss Tangent
* Self Capacitance Circulating Currents Loss Tangent
* Core Residual Loss Tangent
* Core Eddy Current Loss Tangent ,
* Core Hysteresis Loss Tangent ,

Non-linear components must be used for these complex effects. Network Equivalent Magnetic circuits and coupled equations will be used to simplify analysis of the transient and steady state behavior.

* Magnetic coupling between magnetic transmission lines results in sharing of electromagnetic energy. This division of power is very useful in design of Radio frequency devices like sensors, antennas and communication systems.
* Magnetic Coupling is also very important in the working of DC and AC machines like induction motor, hysteresis motor and Reluctance motor.
* The study of capacitive/ inductive coupling in Multi-Conductor Transmission Lines will provide useful knowledge about the Radiated/ Conducted Emissions and Radiated/ Conducted Susceptibility.
* The results can be compared with MATLAB linear circuit models for cross talk between Magnetic Transmission Lines.
* The aim will be to minimize Electromagnetic Radiation; that can be picked up by unintentional receivers like digital Computers.

The simulators can not be used to model the following magnetic effects:

1. Magnetostriction
2. Accoustic effects
3. Relativistic Effects
4. Piezomagnetism
5. Gravitomagnetism

# Conclusion

The conventional reluctance model is not accurate for the modeling of magnetic circuits. It must be replaced by Magnetic Transmission Line Model for accurate modeling of such inhomogeneous, dispersive, non-linear structures.

The power invariant Magnetic Transmission Line model can also be used for accurate modeling of

* AC and DC Machines
* Micro-strip Antennas
* Gyromagnetic NLTLs
* Magnetic Transistors and Magnetic Microprocessors

# References

[1] H. Al-Barqawi, N. Dib and M. Khodier, “A Full-Wave Two-Dimensional Finite-Difference Frequency-Domain Analysis of Ferrite-Loaded Structures”. Mosharaka International Conference on Communications, Propagation and Electronics, 2008.

[2] J. Allmeling, W. Hammer, and J. Schonberger, “Transient simulation of magnetic circuits using the permeance-capacitance analogy,” *2012 IEEE 13th Workshop on Control and Modeling for Power Electronics (COMPEL)*, 2012.

[3] B. Anderson and R. Newcomb, “A capacitor-transformer gyrator realization,” *Proceedings of the IEEE*, vol. 53, no. 10, pp. 1640–1640, 1965.

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

[5] J. Atulasimha and S. Bandyopadhyay, Nanomagnetic and Spintronic Devices for energy-efficient memory and computing. Chichester, West Sussex: Wiley, 2016.

[6] J.-W. B. Bragg, J. C. Dickens, and A. A. Neuber, “Material selection considerations for coaxial, ferrimagnetic-based nonlinear transmission lines,” *Journal of Applied Physics*, vol. 113, no. 6, p. 064904, 2013.

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

[8] S. Chua, Y. Chong, A. D. Stone, M. Soljacic and J. Bravo-Abad, “Low-threshold lasing action in photonic crystal slabs enabled by Fano resonances” Optics Express, vol. 19, no. 2, p. 1539, 2011.

[9] S. O. Demokritov, Magnonics: From Fundamentals to Applications. Berlin: Springer, 2013.

[10] J. Dickens and A. Neuber, Material selection considerations for coaxial, ferrimagnetic-based nonlinear transmission lines, Journal of Applied Physics, 113, 064904, 2013, p. 1-5.

[11] D. Dinulovic, M. Shousha, M. Haug, and K. E. Shafey, “Miniaturized Planar Transformer Embedded in Ferrite Substrate for Isolated High- Frequency Low-Power Applications,” *2019 20th International Symposium on Power Electronics (Ee)*, 2019.

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

[13] I. Eichwald, S. Breitkreutz, G. Ziemys, G. Csaba, W. Porod, and M. Becherer, “Majority logic gate for 3D magnetic computing,” *Nanotechnology*, vol. 25, no. 33, p. 335202, 2014.

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

[15] L. Er-Ping, “Computational Electromagnetics for Electromagnetic Compatibility/ Signal Integrity Analysis” IEEE EMC DL Talk, Missouri, 2008.

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

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

[18] 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.

[19] 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.

[20] J. B. Faria, Electromagnetic Foundations of Electrical Engineering, Chichester: John Wiley and Sons, 2008, p. 305-394.

[21] A. Goldman, Modern Ferrite Technology, New York, NY: Springer, 2010, p. 1-49.

[22] G. G. González and M. Ehsani, “Power-Invariant Magnetic System Modeling,” *International Journal of Magnetics and Electromagnetism*, vol. 4, no. 1, pp. 1–9, Dec. 2018.

[23] A. P. Guimaraes, Principles of Nanomagnetism. Cham: Springer, 2018.

[24] B. Gustavsen, “A hybrid measurement approach for wide-band characterization and modeling of power transformers,” *2011 IEEE Power and Energy Society General Meeting*, 2011.

[25] D. Hamill, “Gyrator-capacitor modeling: a better way of understanding magnetic components,” *Proceedings of 1994 IEEE Applied Power Electronics Conference and Exposition - ASPEC94*.

[26] V. G. Harris, “Modern Microwave Ferrites,” *IEEE Transactions on Magnetics*, vol. 48, no. 3, pp. 1075–1104, 2012.

[27] M. Holynska, Single-Molecule Magnets: Molecular Architectures and Building Blocks for Spintronics. Newark: John Wiley and Sons, 2019.

[28] “IEEE Standard for Computer-Type (Square-Loop) Pulse Transformers.”

[29] “IEEE Standard for High-Power Wide-Band Transformers.”

[30] “IEEE Standard for Low Power Pulse Transformers.”

[31] “IEEE Standard for Low Power Pulse Transformers.”

[32] “IEEE Standard for Pulse Transformers.”

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

[34] “IEEE Standard for Wide-Band (Greater Than 1 Decade) Transformers.”

[35] M. A. Imtaar, P. Li, E. Varga, G. Csaba, G. H. Bernstein, G. Scarpa, W. Porod, and P. Lugli, “Nanomagnetic logic devices fabrication using nanoimprint lithography,” *2013 13th IEEE International Conference on Nanotechnology (IEEE-NANO 2013)*, 2013.

[36] “Interfacing FDTD Solver with Lumped Systems” Time Domain Computer Analysis of Nonlinear Hybrid Systems, p. 251-283, 2018.

[37] S. Y. Karelin, “FDTD analysis of nonlinear magnetized ferrites: application to modeling of oscillation forming in coaxial line with ferrite,” *Radiofizika I Elektronika*, vol. 22, no. 1, pp. 51–56, 2017.

[38] A. Khitun and A. Kozhanov, “Magnonic Logic Devices,” *Nanomagnetic and Spintronic Devices for Energy-Efficient Memory and Computing*, pp. 189–219, May 2016.

[39] M. N. Leuenberger and D. Loss, “Quantum computing in molecular magnets,” *Nature*, vol. 410, no. 6830, pp. 789–793, 2001.

[40] M. Luo, D. Dujic, J. Allmeling, Modeling Hysteresis of Ferrite Core Materials using Permeance-Capacitance Analogy for System Level Circuit Simulations, IEEE Transactions on Power Electronics, 2018, p. 1-16.

[41] M. Luo, D. Dujic, and J. Allmeling, “Modelling hysteresis of soft core materials using permeance-capacitance analogy for transient circuit simulations,” *2017 19th European Conference on Power Electronics and Applications (EPE17 ECCE Europe)*, 2017.

[42] R. A. Mack and J. Sevick, Sevick’s Transmission Line Transformers: Theory and practice, 5th ed. Edison, NJ: Scitech Publishing, 2014.

[43] J. Macías-Díaz, “Persistence of nonlinear hysteresis in fractional models of Josephson transmission lines,” *Communications in Nonlinear Science and Numerical Simulation*, vol. 53, pp. 31–43, 2017.

[44] A. Moryc and W. Gwarek, “An equivalent lumped circuit describing magnetized plasma and its application in FD-TD modeling,” *15th International Conference on Microwaves, Radar and Wireless Communications (IEEE Cat. No.04EX824)*.

[45] M. C. Nitu, M. Nicola, M. Duta, and M. A. Benea, “Methods for Determining Dielectric Stresses in the Windings of a Transformer Subjected to Lightning Impulse,” *2019 International Conference on Electromechanical and Energy Systems (SIELMEN)*, 2019.

[46] 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.

[47] U. Ozgur, Y. Alivov, and H. Morkoc, “ChemInform Abstract: Microwave Ferrites. Part 2. Passive Components and Electrical Tuning,” *ChemInform*, vol. 41, no. 36, Dec. 2010.

[48] U. Ozgur, Y. Alivov, and H. Morkoc, “ChemInform Abstract: Microwave Ferrites. Part 2. Passive Components and Electrical Tuning,” *ChemInform*, vol. 41, no. 36, Dec. 2010.

[49] J. Parson, A. Neuber, J. Dickens and J. Mankowski, Investigation of a stripline transmission line structure for gyromagnetic nonlinear transmission line high power microwave sources, Review of Scientific Instruments, Vol. 87, 2016, p. 1-7.

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

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

[52] C. R. Paul, Analysis of Multiconductor Transmission Lines, 2nd ed. Hoboken: Wiley-Interscience, 2008, p. 240-342.

[53] D. Pozar, Microwave Engineering, 4nd ed. Kentucky: John Wiley and Sons, 2012, p. 1-271.

[54] “Pulse Transformers,” *Foundations of Pulsed Power Technology*, pp. 63–96, Jul. 2017.

[55] D. V. Reale, J. M. Parson, A. A. Neuber, J. C. Dickens, and J. J. Mankowski, “Investigation of a stripline transmission line structure for gyromagnetic nonlinear transmission line high power microwave sources,” *Review of Scientific Instruments*, vol. 87, no. 3, p. 034706, 2016.

[56] D. V. Reale, J. M. Parson, A. A. Neuber, J. C. Dickens, and J. J. Mankowski, “Investigation of a stripline transmission line structure for gyromagnetic nonlinear transmission line high power microwave sources,” *Review of Scientific Instruments*, vol. 87, no. 3, p. 034706, 2016.

[57] P. Ripka and M. Janosek, “Advances in magnetic sensors,” *2008 IEEE Sensors*, 2008.

[58] I. V. Romanchenko, P. V. Priputnev, and V. V. Rostov, “RF pulse formation dynamics in gyromagnetic nonlinear transmission lines,” *Journal of Physics: Conference Series*, vol. 830, p. 012034, Apr. 2017.

[59] K. Sato, E. Saitoh A. Willoughby and P. Capper, Spintronics for next generation Innovative Devices. John Wiley and Sons, 2015.

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

[61] J. Sevick, R. Mack, Sevick’s Transmission Line Transformers Theory and Practice, 5th ed. SciTech Publishing, 2014.

[62] N. Shirdel, A. Akbari, H. R. Mirzaei, and M. S. Abrishamian, “Three-dimensional simulation of UHF signal propagation in transformer using FDTD method,” *2011 International Conference on Power Engineering, Energy and Electrical Drives*, 2011.

[63] R. Slatter, “High accuracy, high bandwidth magnetoresistive current sensors for spacecraft power electronics,” *2015 17th European Conference on Power Electronics and Applications (EPE15 ECCE-Europe)*, 2015.

[64] E. C. Snelling, Soft Ferrites: Properties and Applications. Mendham, NJ: PSMA, 2005.

[65] A. Taflove and S. C. Hagness, Computational Electrodynamics: The Finite-Difference Time-Domain Method, 3rd ed. Boston: Artech House, 2005, p. 1-406.

[66] A. Taflove, A. Oskooi and S. C. Hagness, Advances in FDTD computational electrodynamics: photonics and nanotechnology, 3rd ed. Boston: Artech House, 2013, p. 567-592.

[67] M. R. Ulmasculov, K. A. Sharypov, S. A. Shunailov, V. G. Shpak, M. I. Yalandin, M. S. Pedos, and S. N. Rukin, “Gyromagnetic nonlinear transmission line generator of high voltage pulses modulated at 4 GHz frequency with 1000 Hz pulse repetition rate,” *Journal of Physics: Conference Series*, vol. 830, p. 012027, Apr. 2017.

[68] M. Vacca, M. Graziano, and M. Zamboni, “Nanomagnetic Logic Microprocessor: Hierarchical Power Model,” *IEEE Transactions on Very Large Scale Integration (VLSI) Systems*, vol. 21, no. 8, pp. 1410–1420, 2013.

[69] J. Xu, M. Y. Koledintseva, Y. Zhang, Y. He, B. Matlin, R. E. Dubroff, J. L. Drewniak, and J. Zhang, “Complex Permittivity and Permeability Measurements and Finite-Difference Time-Domain Simulation of Ferrite Materials,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 52, no. 4, pp. 878–887, 2010.

# Appendix