Modeling and Simulation of Magnetic Transmission Lines

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2018-MS-EE-4

Research Objectives

- Model and simulate dispersive, inhomogeneous and non-linear Magnetic Transmission Lines using Finite Difference Time Domain (FDTD) Method Simulator.
- Study Frequency Domain Behavior of Magnetic Transmission Lines by Decomposition of Fields into various travelling wave modes.
- Simulate cross talk between Multi-Conductor Magnetic Transmission Lines.
- Simulate Wideband Transformer and develop lumped Magnetic Transmission Line circuit.

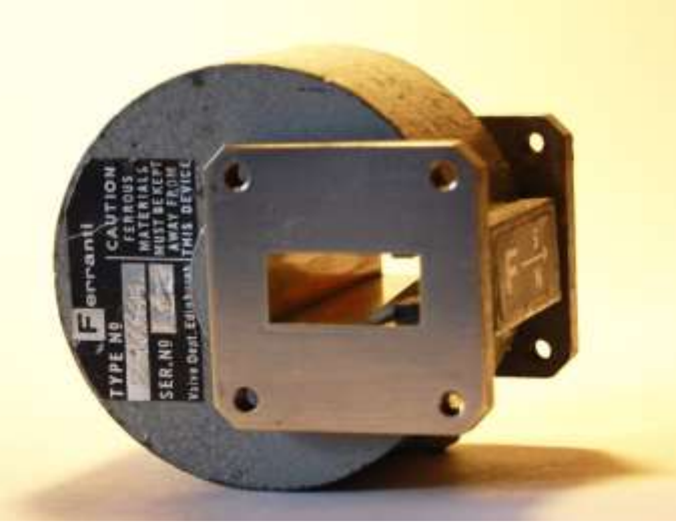
Introduction to Magnetic Transmission Lines

- Magnetic Transmission Lines are made from a magnetic material, with a very high relative permeability. They are very poor electrical conductors.
- Electric Current can generate Magnetomotive Force which produces magnetic displacement current.
- The operation of a Magnetic Transmission Line does not involve electric charges. However, changing Magnetic Fields produce Electric Fields and Electrical Energy is stored in the dielectric medium.
- Electromagnetic Energy flows simultaneously in Electrical and Magnetic domains. Normally, only one domain is studied at a time.
- The Magnetic Transmission Line behavior must be modeled using Maxwell's Equations and magnetic circuits to study the time and frequency domain behavior of Magnetic Transmission Lines.

Applications of Magnetic Transmission Lines

1. Inductors and Magnetic Amplifiers.
2. Transformers: Power Transformers, Ferro-resonant Constant Voltage Transformers, Wideband/ Pulse Transformers.
3. Alternating Current and Direct Current Machines.
4. Computers and High Frequency Electronics.
5. Noise and skin effect suppression using magnetic thin films, ferrite beads and ribbons.
6. Directional Couplers and Magnetometers.
7. Induction Heaters and Magneto-resistive Sensors.
8. Gyromagnetic Devices, Microwave generators and Magnetic Resonance Imaging.

Applications of Magnetic Transmission Lines



Magnetization and Permeability

- Magnetic Fields originate from movement of bound charges (orbital electrons, electron spin and nuclear spin) due to changing Electrical Field. This movement results in a bound current.
- Every Magnetic Dipole produces a Magnetic Moment (spin moment and orbital moment). The total magnetic dipole moment per unit volume is responsible for the Magnetization **M**.

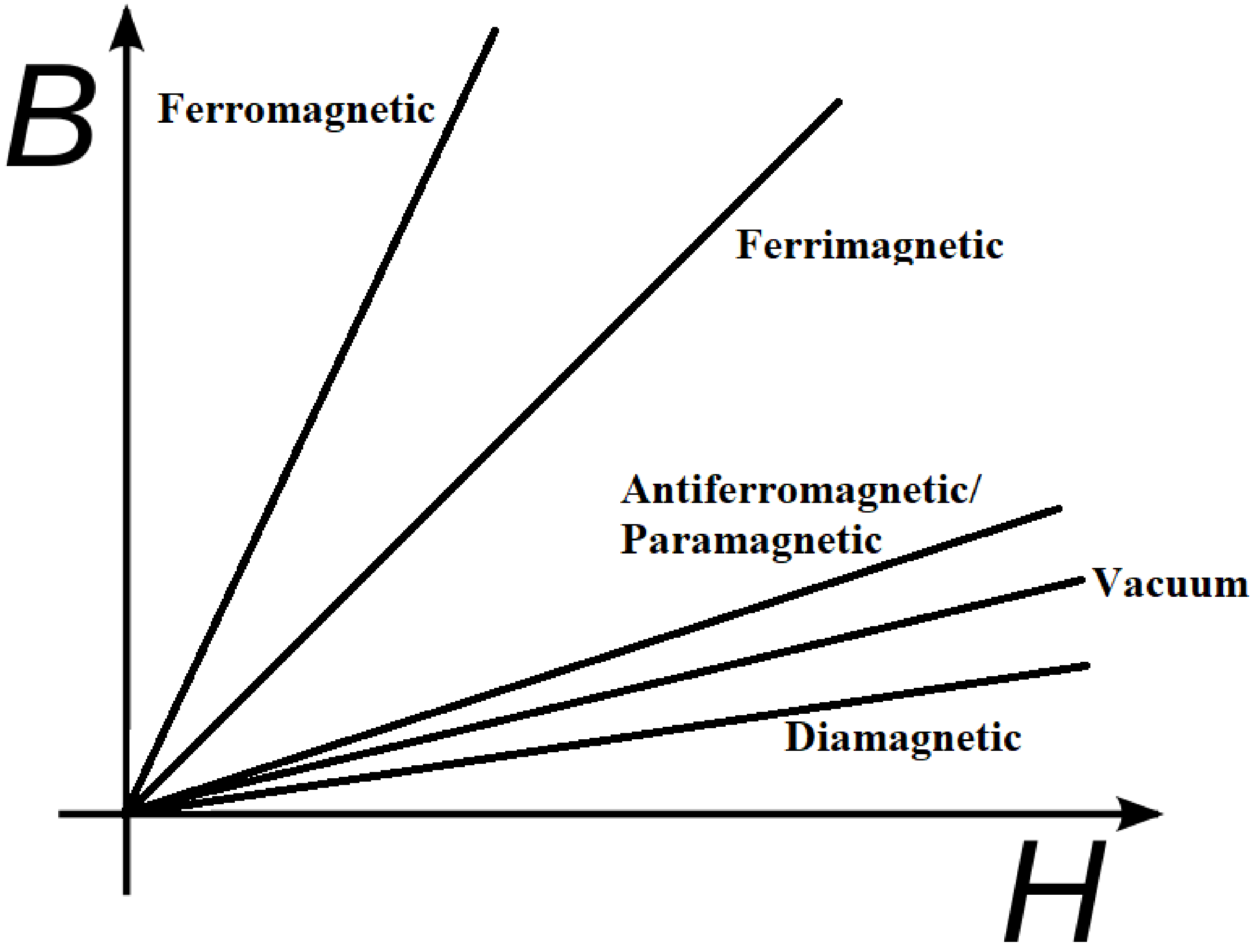
$$\mathbf{B} = \mu\mathbf{H} = \mu_0(\boldsymbol{H} + \boldsymbol{M}) \qquad \mu = \mu_0(1 + \chi_m)$$

B is the Magnetic Flux Density, **H** is the Magnetic Field Intensity, **M** is the Magnetization, μ is the Magnetic Permeability, μ_0 is the permeability of free space, χ_m is the Magnetic susceptibility.

Properties of Magnetic Materials

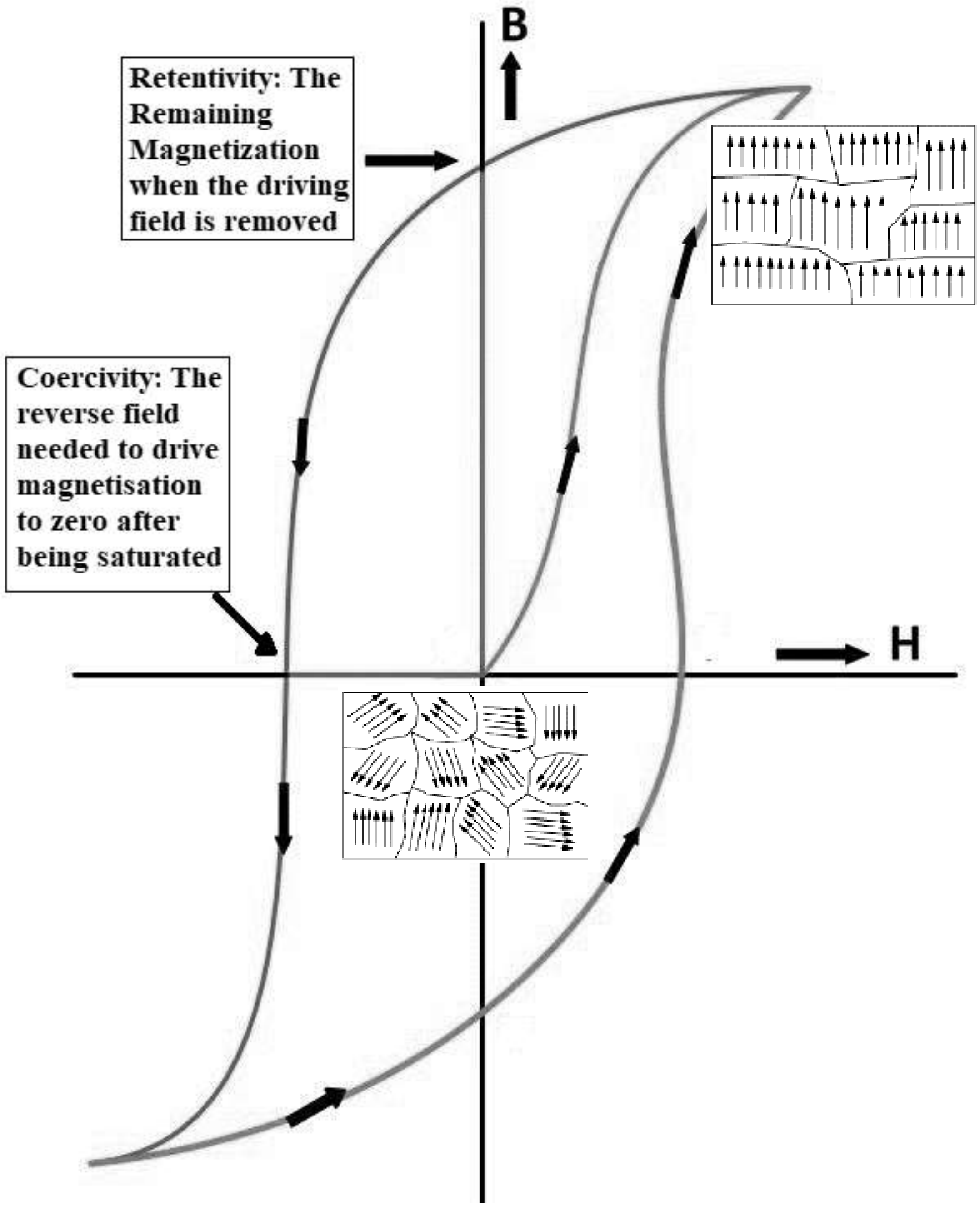
	Magnetic Moments	Susceptibility χ_m
Diamagnetism	no magnetic moment $m_{orb} + m_{spin} = 0$	Small & negative, -10^{-6} to -10^{-5}
Paramagnetism	randomly oriented $m_{orb} + m_{spin} = small$	Small & positive, 10^{-5} to 10^{-3}
Antiferromagnetism	antiparallel aligned $\lvert m_{orb}\rvert \ll \lvert m_{spin}\rvert$	Small & positive, 10^{-5} to 10^{-3}
Ferrimagnetism	mixed parallel and antiparallel aligned $\lvert m_{orb}\rvert \ll \lvert m_{spin}\rvert$	large (below T_{Curie}), 10^{-3} to 10^{2}
Ferromagnetism	parallel aligned $\lvert m_{orb}\rvert \ll \lvert m_{spin}\rvert$	large (below T_{Curie}), 10^{2} to 10^{6}

Properties of Magnetic Materials



Magnetic Hysteresis

- Ferromagnetic materials are non-linear as their permeability varies with the strength of applied field intensity.
- The flux in a ferromagnetic material depends on the instantaneous Magnetomotive force and its history.
- At high magnetic field intensity, the material saturates, limiting further increase of Magnetic Flux.



IEC 60404-1:2016 Classification of Magnetic Materials

Magnetically Soft Materials (coercivity $\leq$ 1 kA/m)

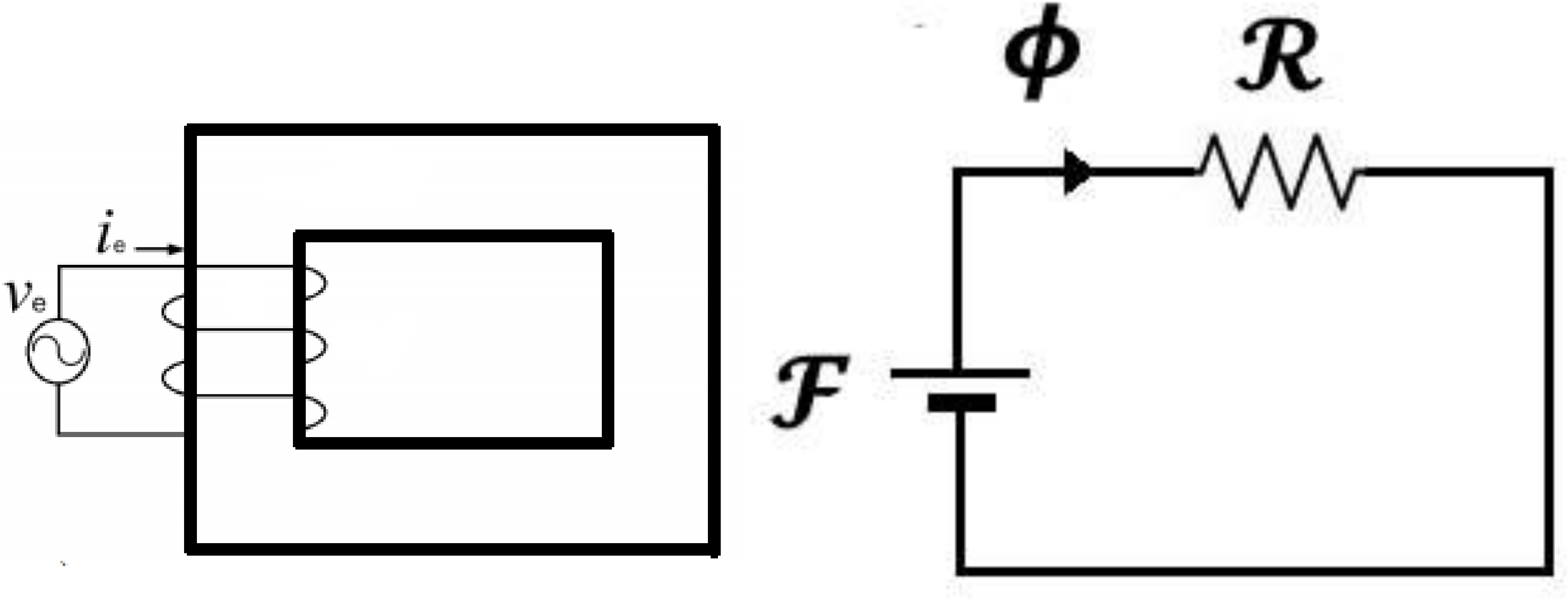
- Class A – Irons
- Class B – Low Carbon Mild Steels
- Class C – Silicon Steels
- Class D – Other Steels
- Class E – Nickel-iron Alloys
- Class F – Iron Cobalt Alloys
- Class G – Other Alloys
- Class H – Magnetically Soft Materials made by powder metallurgical techniques
- Class I – Amorphous soft Magnetic Materials
- Class J – Nano-crystalline soft Magnetic Materials

Magnetically Hard Materials (coercivity > 1kA/m)

- Class Q – Magnetostrictive Alloys – Rare Earth iron Alloys
- Class R – Magnetically Hard Alloys
- Class S – Magnetically hard ceramics – Hard Ferrites
- Class T – Other Magnetically Hard Materials – Martensitic Steels
- Class U – Bonded Magnetically Hard Materials

Magnetic Circuit Modeling

Lossy Complex Magnetic Reluctance Model for Magnetic Circuits



Lossy Complex Magnetic Reluctance Model for Magnetic Circuits

- 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.

$$\boldsymbol{\mathcal{R}}_m = \frac{\boldsymbol{\mathcal{F}}_m}{\boldsymbol{\phi}_m} = \frac{\oint \boldsymbol{H}.dl}{\iint \boldsymbol{B}.dS} = |\boldsymbol{\mathcal{R}}_m| e^{j\emptyset}$$

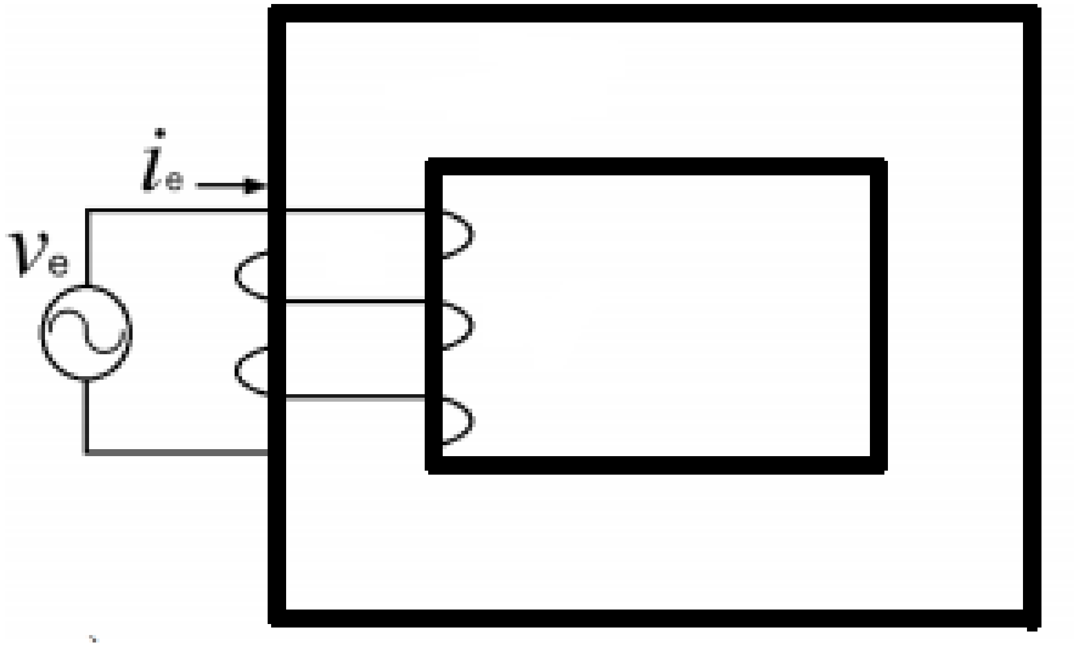
- Lossy Complex Magnetic Reluctance is non-linear and varies with the magnetic field. It resists both Magnetic flux and changes in Magnetic flux.
- In 1969, R. W. Buntenbach proved that the model is not power invariant. Reluctance Power Loss cannot be calculated using Joule Heating Law (1842) Analogy due to dimensional inconsistency:

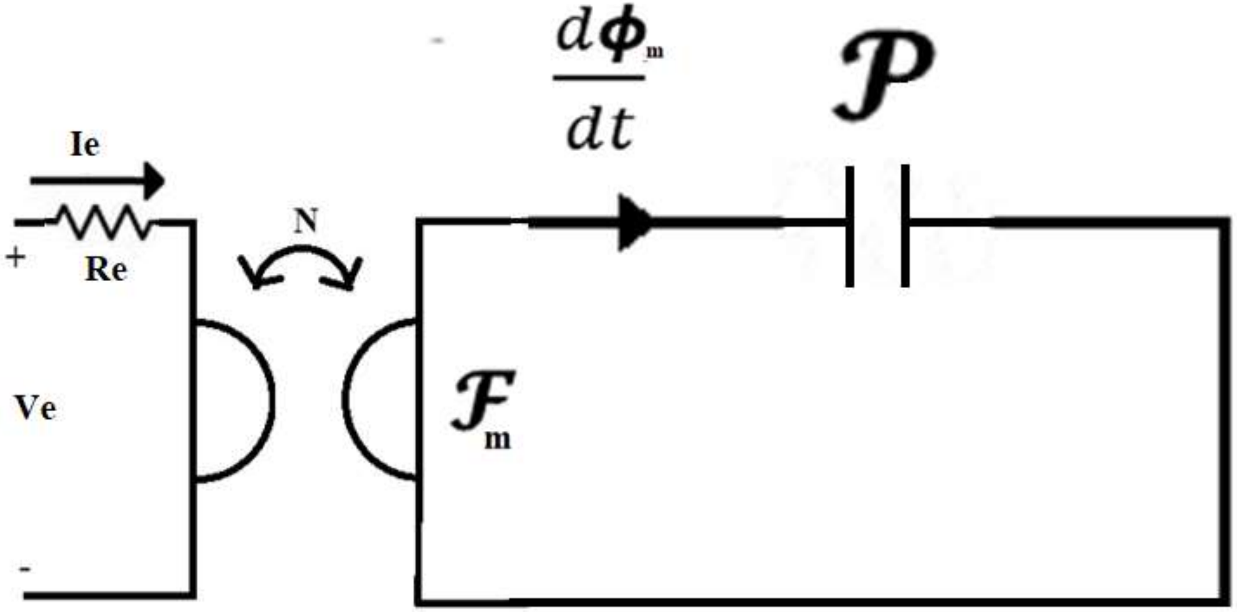
$$[P_e] = [I_e^2][R_e] = Ampere.Volt$$
$$but$$
$$[P_m] \neq [\boldsymbol{\phi}_m^2][|\boldsymbol{\mathcal{R}}_m|] = Volt.Second.Ampere$$

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

Power Invariant Permeance-Capacitance 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.





Power Invariant Permeance-Capacitance 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:

$$\boldsymbol{I}_{m,disp} = \frac{d\boldsymbol{\phi}_m}{dt} = -\frac{1}{N}\boldsymbol{V}_e \; [Volt]$$

and

$$\boldsymbol{V}_m = \boldsymbol{\mathcal{F}}_m = N\boldsymbol{I}_e \qquad [Ampere]$$

- Magnetic Permeance is defined as:

$$P_m = \frac{\boldsymbol{\phi}_m}{\boldsymbol{\mathcal{F}}_m} = \frac{\iint \boldsymbol{B}.dS}{\oint \boldsymbol{H}.dl} = \mu\frac{A}{l} \; [Henry]$$

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

Validation of Permeance-Capacitance Model

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

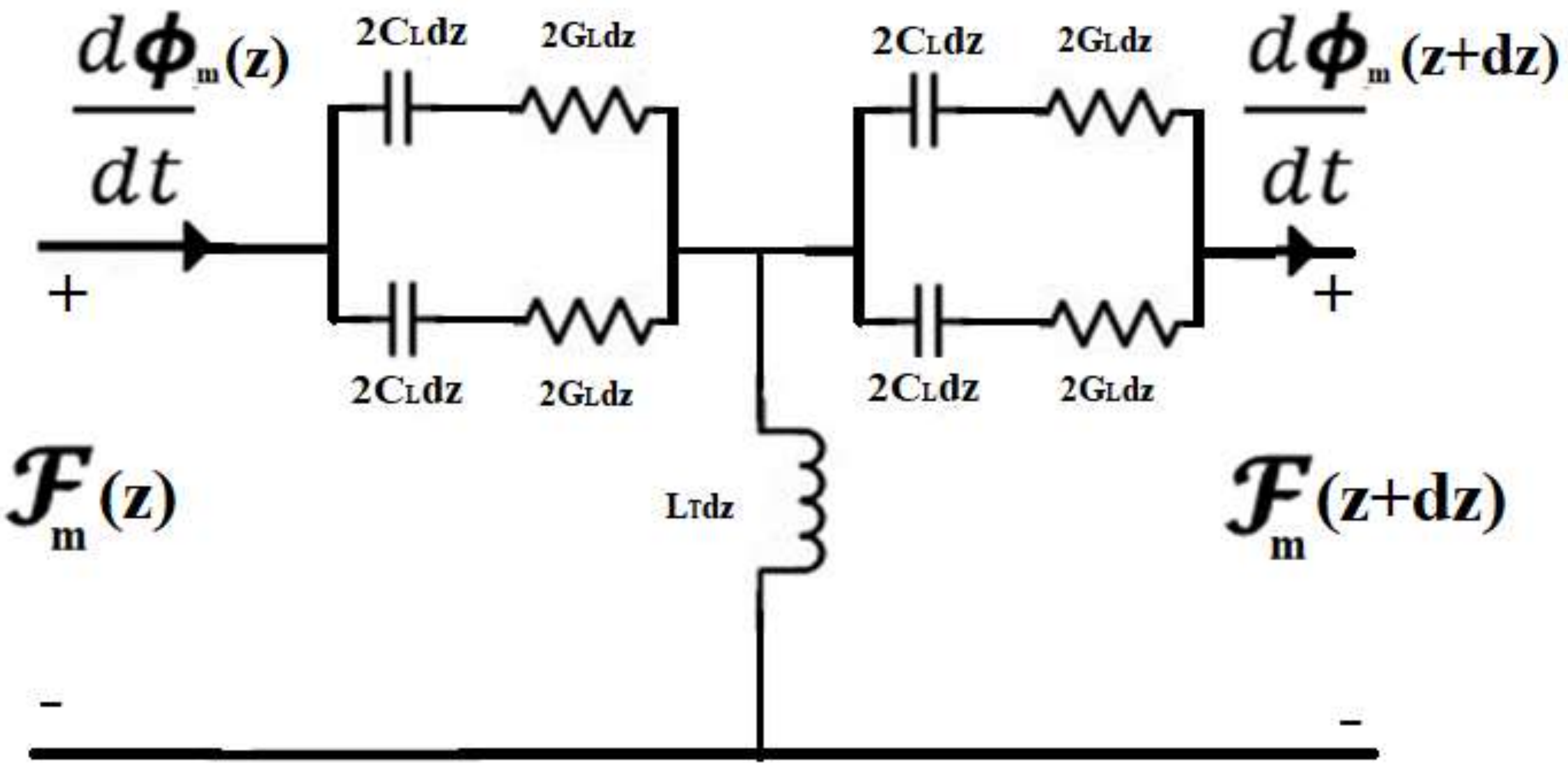
$$\boldsymbol{V}_e = -N\frac{d\boldsymbol{\phi}_m}{dt}$$
$$\oint \boldsymbol{E}.dl = -\frac{d}{dt}\iint \boldsymbol{B}.dS$$

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

$$\boldsymbol{\mathcal{F}}_m = N\frac{d\boldsymbol{\phi}_e}{dt}$$
$$\oint \boldsymbol{H}.dl = \frac{d}{dt}\iint \boldsymbol{D}.dS$$

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.



Components in Transmission Line Model

- Per unit length Magnetic Conductance, Magnetic Inductance and Magnetic Capacitance are defined as:

$$G_m = \frac{\boldsymbol{\mathcal{F}}_m}{\boldsymbol{I}_m} = \frac{\oint \boldsymbol{H}.\,dl}{\oint \boldsymbol{E}.\,dl} \qquad [Ohm/m]$$

$$L_m = \frac{\boldsymbol{\phi}_m}{\boldsymbol{\mathcal{F}}_m} = \frac{\iint \boldsymbol{B}.\,dS}{\oint \boldsymbol{H}.\,dl} \qquad [Henry/m]$$

$$C_m = \frac{\boldsymbol{\phi}_e}{\boldsymbol{I}_m} = \frac{\iint \boldsymbol{D}.\,dS}{\oint \boldsymbol{E}.\,dl} \qquad [Farad/m]$$

Energy Loss and Energy Storage

- Energy is dissipated in Magnetic Conductance due to skin effect.

$$P_{loss} = I_m^2 G_m$$

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

$$W_e = \frac{1}{2} C_m V_m^2 = \frac{1}{2} \iiint \boldsymbol{B}.\boldsymbol{H}\, dV$$

$$W_m = \frac{1}{2} L_m I_m^2 = \frac{1}{2} \iiint \boldsymbol{D}.\boldsymbol{E}\, dV$$

- The Magnetic Transmission Line Equations can be solved just like Electric Transmission Line Equations.

Lossless Transmission Lines

Electric Transmission Line	Magnetic Transmission Line
$\frac{d\boldsymbol{I}_e}{dz} = -C\frac{d\boldsymbol{V}_e}{dt}$ $\frac{d\boldsymbol{V}_e}{dz} = -L\frac{d\boldsymbol{I}_e}{dt}$	$\frac{d\boldsymbol{I}_m}{dz} = -L_m\frac{d\boldsymbol{V}_m}{dt}$ $\frac{d\boldsymbol{V}_m}{dz} = -C_m\frac{d\boldsymbol{I}_m}{dt}$
$\frac{d^2\boldsymbol{I}_e}{dz^2} = \gamma^2\frac{d^2\boldsymbol{I}_e}{dt^2}$ $\frac{d^2\boldsymbol{V}_e}{dz^2} = \gamma^2\frac{d^2\boldsymbol{V}_e}{dt^2}$	$\frac{d^2\boldsymbol{I}_m}{dz^2} = \gamma^2\frac{d^2\boldsymbol{I}_m}{dt^2}$ $\frac{d^2\boldsymbol{V}_m}{dz^2} = \gamma^2\frac{d^2\boldsymbol{V}_m}{dt^2}$
$\boldsymbol{V}_e(z) = \boldsymbol{V}_{e_i}(0)e^{-\gamma z} + \boldsymbol{V}_{e_r}(0)e^{+\gamma z}$ $\boldsymbol{I}_e(z) = \boldsymbol{I}_{e_i}(0)e^{-\gamma z} - \boldsymbol{I}_{e_r}(0)e^{+\gamma z}$	$\boldsymbol{V}_m(z) = \boldsymbol{V}_{m_i}(0)e^{-\gamma z} + \boldsymbol{V}_{m_r}(0)e^{+\gamma z}$ $\boldsymbol{I}_m(z) = \boldsymbol{I}_{m_i}(0)e^{-\gamma z} - \boldsymbol{I}_{m_r}(0)e^{+\gamma z}$
$\gamma = j\omega\sqrt{\mathrm{lc}} = j\omega\sqrt{\mu\varepsilon} = j\beta$	$\gamma = j\omega\sqrt{L_m C_m} = j\omega\sqrt{\mu\varepsilon} = j\beta$

Lossy Transmission Lines

Electric Transmission Line	Magnetic Transmission Line
$\frac{d\boldsymbol{I}_e}{dz} = -\mathrm{G}\boldsymbol{V}_e - C\frac{d\boldsymbol{V}_e}{dt}$ $\frac{d\boldsymbol{V}_e}{dz} = -\mathrm{R}\boldsymbol{I}_e - L\frac{d\boldsymbol{I}_e}{dt}$	$\frac{d\boldsymbol{I}_m}{dz} = -L_m\frac{d\boldsymbol{V}_m}{dt}$ $\frac{d\boldsymbol{V}_m}{dz} = -G_m\boldsymbol{I}_m - C_m\frac{d\boldsymbol{I}_m}{dt}$
$\frac{d^2\boldsymbol{I}_e}{dz^2} = \gamma^2\frac{d^2\boldsymbol{I}_e}{dt^2}$ $\frac{d^2\boldsymbol{V}_e}{dz^2} = \gamma^2\frac{d^2\boldsymbol{V}_e}{dt^2}$	$\frac{d^2\boldsymbol{I}_m}{dz^2} = \gamma^2\frac{d^2\boldsymbol{I}_m}{dt^2}$ $\frac{d^2\boldsymbol{V}_m}{dz^2} = \gamma^2\frac{d^2\boldsymbol{V}_m}{dt^2}$
$\boldsymbol{V}_e(z) = \boldsymbol{V}_{e_i}(0)e^{-\gamma z} + \boldsymbol{V}_{e_r}(0)e^{+\gamma z}$ $\boldsymbol{I}_e(z) = \boldsymbol{I}_{e_i}(0)e^{-\gamma z} - \boldsymbol{I}_{e_r}(0)e^{+\gamma z}$	$\boldsymbol{V}_m(z) = \boldsymbol{V}_{m_i}(0)e^{-\gamma z} + \boldsymbol{V}_{m_r}(0)e^{+\gamma z}$ $\boldsymbol{I}_m(z) = \boldsymbol{I}_{m_i}(0)e^{-\gamma z} - \boldsymbol{I}_{m_r}(0)e^{+\gamma z}$
$\gamma = \sqrt{(r + j\omega l)(g + j\omega c)}$ $= \sqrt{(\rho + j\omega\mu)(\sigma + j\omega\varepsilon)} = \alpha + j\beta$	$\gamma = \sqrt{(j\omega L_m)(G_m + j\omega C_m)}$ $= \sqrt{(j\omega\mu)(\sigma + j\omega\varepsilon)} = \alpha + j\beta$

Comparison of Different Models

	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 [Henry^{-1}]	?	Magnetic Conductance [Ohm]
Electrical Energy Storage Element	?	?	Magnetic Capacitance [Farad]
Magnetic Energy Storage Element	?	Magnetic Permeance [Henry]	Magnetic Inductance [Henry]

MEEP: Electromagnetic Simulations

Introduction to 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 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.

MEEP: Fully Symmetric Maxwell's Equations (1861) with Fictitious Magnetic Monopoles

- A. Ampere's Law (1861)

$$\nabla \times \boldsymbol{H} - \boldsymbol{J_D} - \sigma_D \boldsymbol{D} = \frac{d\boldsymbol{D}}{dt}$$

- M. Faraday's Law (1831)

$$-\nabla \times \boldsymbol{E} - \boldsymbol{J_B} - \sigma_B \boldsymbol{B} = \frac{d\boldsymbol{B}}{dt}$$

- J. C. F. Gauss's Law for Electricity (1813)

$$\nabla . \boldsymbol{D} = \rho_e$$

- J. C. F. Gauss's Law for Magnetism (1813)

$$\nabla . \boldsymbol{B} = \rho_m$$

MEEP: Finite Difference Time Domain Method

- 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,

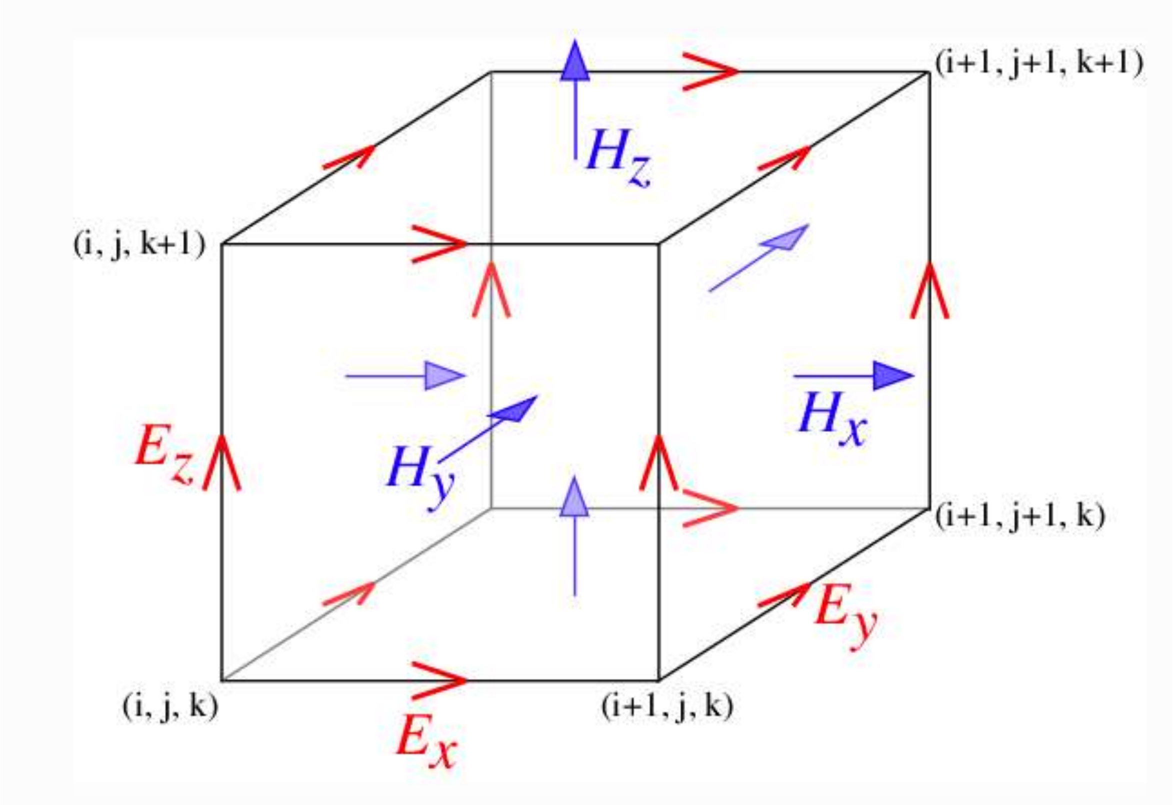
$$\nabla \times H = \left(\frac{\Delta H_z}{\Delta y} - \frac{\Delta H_y}{\Delta z}\right) a_x + \left(\frac{\Delta H_x}{\Delta z} - \frac{\Delta H_z}{\Delta x}\right) a_y + \left(\frac{\Delta H_y}{\Delta x} - \frac{\Delta H_x}{\Delta y}\right) a_z$$

$$\frac{\Delta H_z}{\Delta y} = \frac{H_z^n\left(x, y + \frac{\Delta y}{2}, z\right) - H_z^n(x, y - \frac{\Delta y}{2}, z)}{\Delta y}$$

where n represents the discrete time step.

MEEP: Yee Lattice

- Finite Difference Time Domain Method discretizes space into a grid of small elements called Yee Lattice (1966). 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.



MEEP: Boundary Conditions

The finite region of space must always be terminated with some boundary conditions. Three types of terminations are supported:

1. Bloch-periodic Boundaries: These are used for simulation of periodic structures $f(x) = f(x + L)e^{-jkL}$. 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.

MEEP: Material Inhomogeneity

- $\varepsilon(x)$ and $\mu(x)$ can vary with position inside a material. They can be declared at each individual point x in space using a function.
- 1-D, 2-D and 3-D simulation is possible. Hence every space vector can have up to three spatial coordinates.
- The simulation can be carried out in rectangular or cylindrical coordinates. Hence different homogeneous/inhomogeneous structures can be built inside the space.
- Symmetry can be used to create complex geometries as well.

MEEP: Material Dispersion

- Drude-Lorentzian Model (1900) models frequency dependent permittivity and permeability. Flux Densities contain terms for infinite frequency response and frequency dependent Polarization vector.

$$\boldsymbol{D} = \varepsilon_\infty \boldsymbol{E} + \boldsymbol{P}$$
$$\boldsymbol{B} = \mu_\infty \boldsymbol{H} + \boldsymbol{M}$$

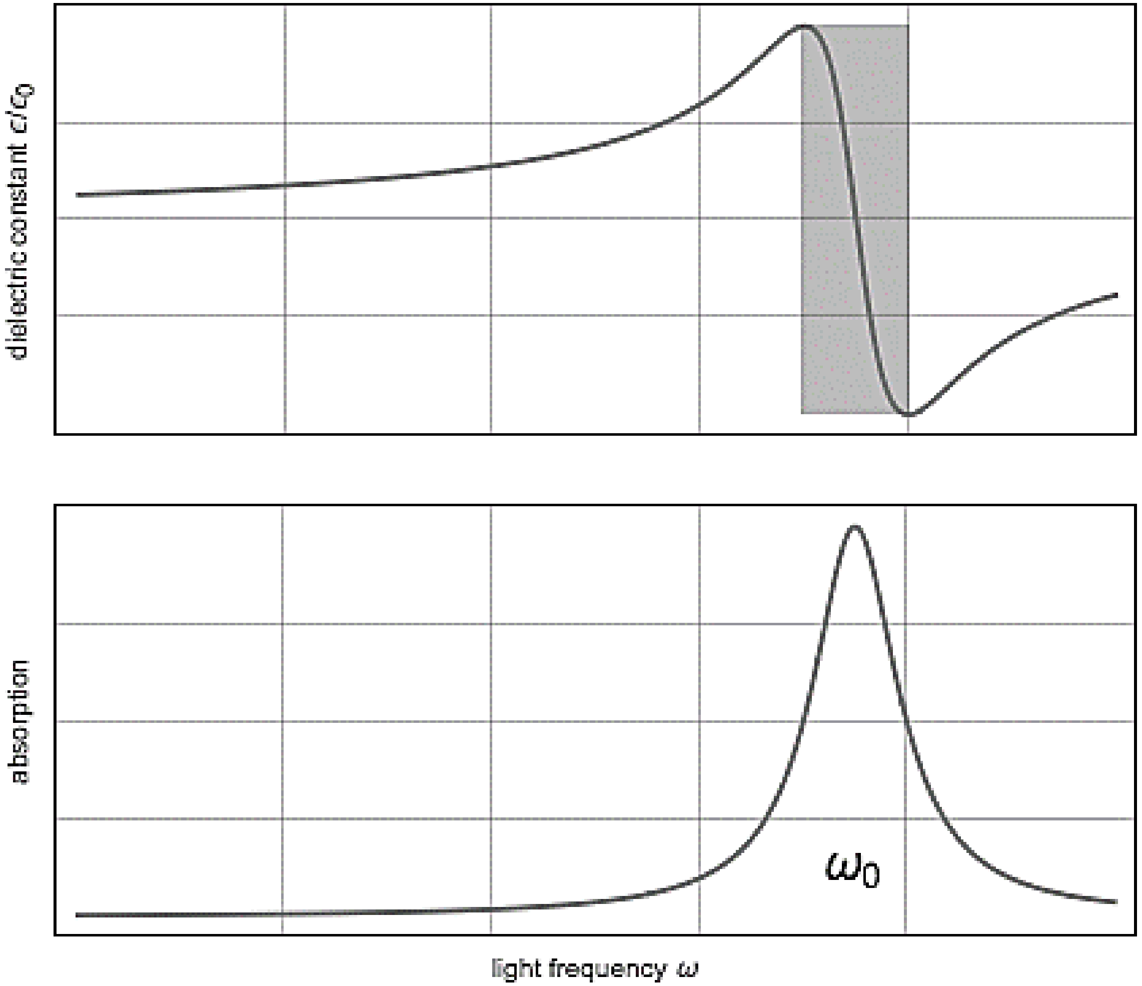
- ε and μ are represented as a sum of harmonic resonances and a term for frequency independent electric conductivity.

$$\varepsilon(\omega, x) = (1 + \frac{j\sigma_D}{\omega})(\varepsilon_\infty(\boldsymbol{x}) + \sum_N \frac{\sigma_n(\boldsymbol{x})\omega_n^2}{\omega_n^2 - \omega^2 + j\omega\gamma_n})$$
$$\mu(\omega, x) = (1 + \frac{j\sigma_B}{\omega})(\mu_\infty(\boldsymbol{x}) + \sum_N \frac{\sigma_n(\boldsymbol{x})\omega_n^2}{\omega_n^2 - \omega^2 + j\omega\gamma_n})$$

$\sigma_D/\sigma_B$is the electrical/magnetic conductivity. σ_N couples the polarization to the driving field, ω_N is the angular resonance frequency, γ_N is a damping factor.

MEEP: Material Dispersion Drude-Lorentzian Model (1900)

- 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.



MEEP: Material Non-Linearity

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

$$\boldsymbol{D} = (\varepsilon_{\infty}(\boldsymbol{x}) + \chi^{(2)}(\boldsymbol{x}).\,diag(\boldsymbol{E}) + \chi^{(3)}(\boldsymbol{x}).\,|\boldsymbol{E}|^2)\boldsymbol{E} + \boldsymbol{P}$$
$$\boldsymbol{B} = (\mu_{\infty}(\boldsymbol{x}) + \chi^{(2)}(\boldsymbol{x}).\,diag(\boldsymbol{H}) + \chi^{(3)}(\boldsymbol{x}).\,|\boldsymbol{H}|^2)\boldsymbol{H} + \boldsymbol{M}$$

$\chi^{(2)}$ sum is the Pockels effect; whereas $\chi^{(3)}$ 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.

MEEP: Gyromagnetism

- Landau-Lifshitz-Gilbert model (1955) describes the precessional motion of saturated magnetic dipoles in a magnetic field.

$$\frac{d\boldsymbol{M}_n}{dt} = \boldsymbol{b}_n \times \left(-\sigma_n \boldsymbol{H} + \omega_n \boldsymbol{M}_n + \alpha_n \frac{d\boldsymbol{M}_n}{dt} \right) - \gamma_n \boldsymbol{M}_n$$

$\boldsymbol{M}_n$describes the linear deviation of magnetization from its static equilibrium value. Precession occurs around this unit bias vector $\boldsymbol{b}_n$. σ_n couples the polarization to the driving field, ω_n is the angular resonance frequency, γ_n is a damping factor.

- For such anisotropic media, non-diagonal susceptibility tensor is used to relate Magnetization and Field intensity.

$$\boldsymbol{M}_n = \begin{bmatrix} \chi_{\perp} & -j\eta & 0 \\ j\eta & \chi_{\perp} & 0 \\ 0 & 0 & \chi_{||} \end{bmatrix} \boldsymbol{H}$$

MEEP: Field Patterns and Green's Functions

- G. Green's Functions (1835) give the Field Patterns from a localized point source at a particular frequency ω.

$$G_{ij}(\omega; x, x')$$

The point current source j is placed at x'. The i^{th} field component is observed.

$$J(x) = \widehat{e_j}.\, e^{-j\omega t}.\, \delta(x - x')$$

- A frequency domain solver is also provided for multidimensional Fourier transformation (1822) and the decomposition of fields into travelling modes.

MEEP: Transmittance Spectra

- 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.

$$P(\omega) = Re\,\{\hat{n}.\int E_\omega(x)^* \times H_\omega(x)\,d^2x\}$$

- Transmitted power and incident power can be used to find power losses in transmission line.

Simulations for Magnetic Transmission Lines

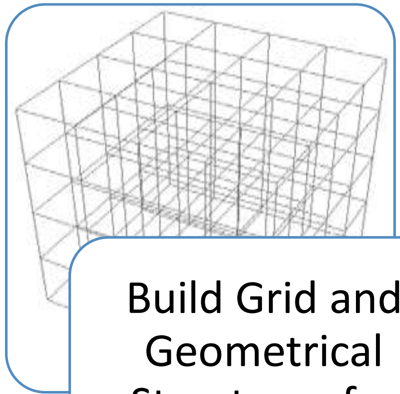
MEEP Simulations for Magnetic Transmission Lines

- 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.

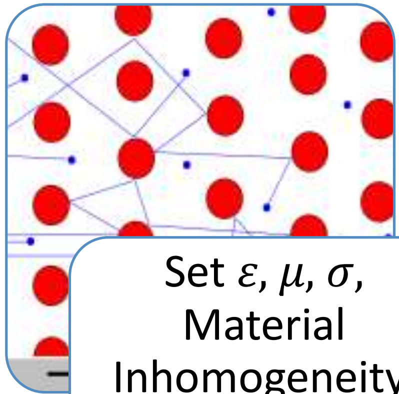
MEEP Simulation for Wideband Transformer

- 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.

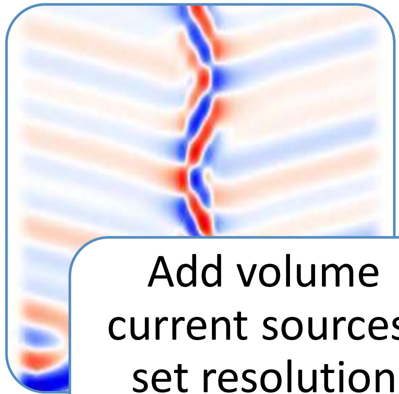
MEEP Simulation for Wideband Transformer: Flow chart



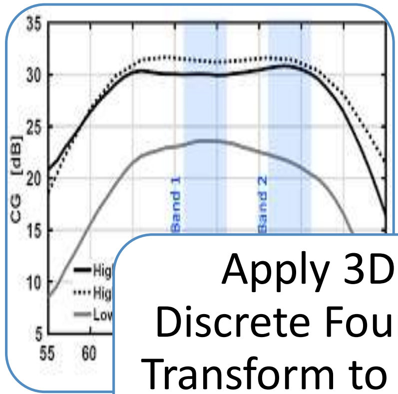
Build Grid and Geometrical Structures for transformer, windings and boundaries.



Set ε, μ, σ, Material Inhomogeneity, Dispersion and Non-Linearity Model Parameters.



Add volume current sources, set resolution and run Simulation for desired discrete steps.



Apply 3D Discrete Fourier Transform to find transmitted Poynting Flux and Broadband Response.

Simulation for Wideband Transformer: Losses

The Loss tangent $tan\delta$ has the following components:

- DC Resistance Loss Tangent $tan\delta_{dc}$
- Skin Effect Loss Tangent $tan\delta_{se}$
- Proximity Effect Loss Tangent $tan\delta_{pe}$
- Self Capacitance Dielectric Loss Tangent $tan\delta_{cp}$
- Self Capacitance Circulating Currents Loss Tangent $tan\delta_{cs}$
- Core Residual Loss Tangent $tan\delta_{r}$
- Core Eddy Current Loss Tangent $tan\delta_{f}$, $P_e = \frac{(\pi f \tau B_{max})^2 V}{6\rho}$
- Core Hysteresis Loss Tangent $tan\delta_{h}$, $P_h = \eta V f B_{max}^n$

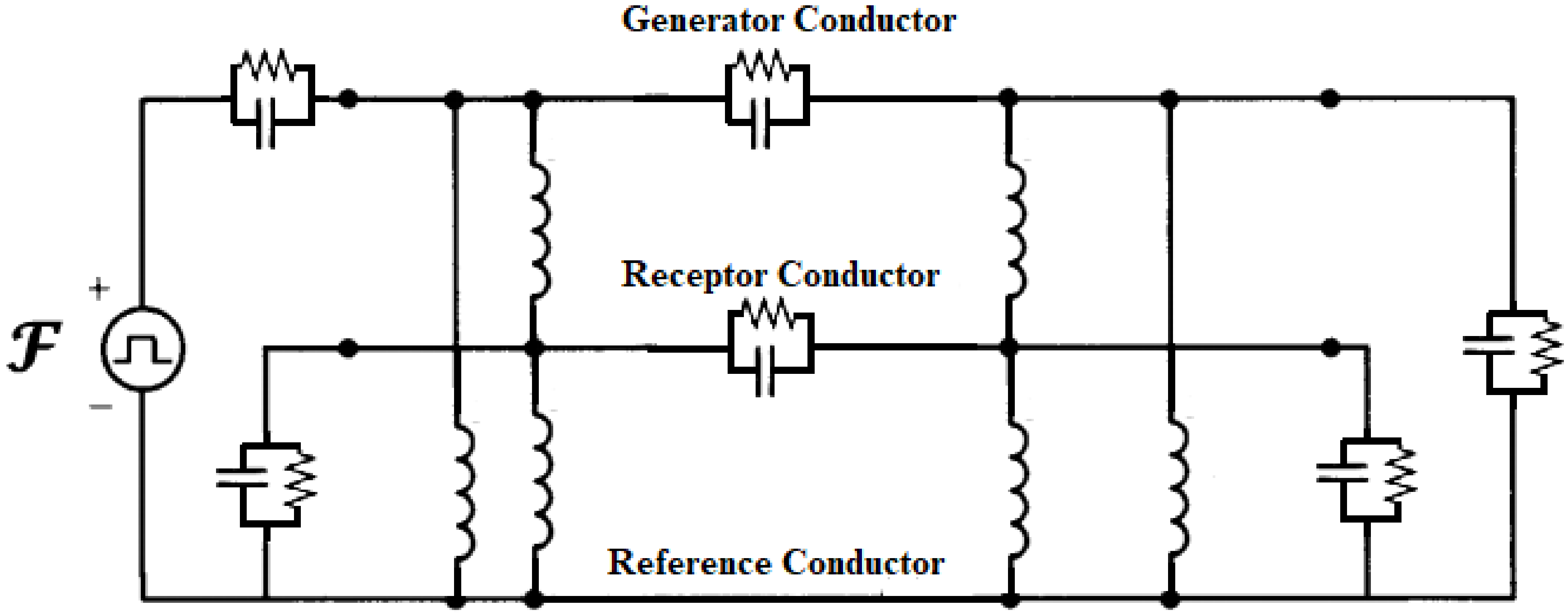
Non-linear components must be used for these complex effects. Network Equivalent Magnetic circuits and coupled equations will be used to simplify analysis of the transient and steady state behavior.

Simulation for Wideband Transformer: Cross Talk and Shielding

- 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.

MATLAB Simulation for Wideband Transformer: Cross Talk and Shielding

The generator-receptor Non-Linear Magnetic circuit model is well suited for studying Electromagnetic Interference and Electromagnetic Compatibility of Magnetic Transmission Lines.



Limitations of simulators

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

1. Magnetostriction
2. Accoustic effects
3. Relativistic Effects
4. Magnetohydrodynamics
5. Gravitomagnetism
6. Optical Effects

Conclusion and Scope for Further Work

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
- Waveguides
- Gyromagnetic NLTLs

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