International Conference on Power & Energy Systems: Towards Sustainable Energy - PESTSE - 14

Tutorial on

Computational Electromagnetics in Design and Analysis of Machines

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Imagination at work.

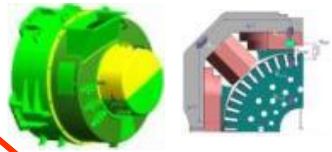
13 March 2014

Outline

1. **Introduction to GE Global Research, Bangalore**
   - Electromagnetic system lab
2. **Basic Electromagnetics**
   - Magnetostatics & time-varying magnetic fields
3. **Electromagnetic (EM) problems**
   - Low frequency & high frequency problems
4. **Basics of Finite Element Method (FEM)**
   - Very simple and basic formulation
5. **Case studies**
   - Leakage Inductance of Transformer
   - Power loss in metallic plate
   - Torque computation in Induction motor

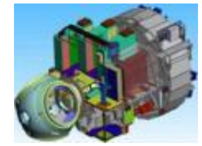
GE Global Research Electromagnetic Systems Lab

Electrical Machines



DC Motors

PM Machines



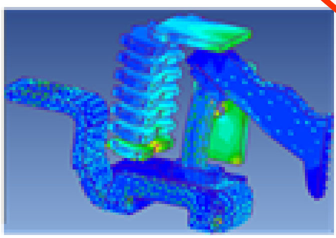
Wind: Direct Drive

Electrical Machines & Drives

Focus Areas

Monitoring and diagnostics

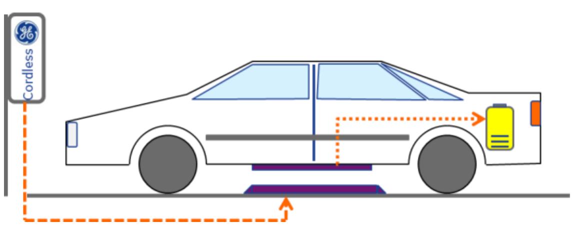
Electromagnetic Devices



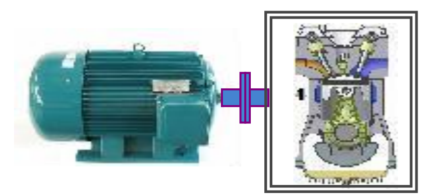
Circuit breaker / Arc physics

Motor Diagnostics

Bearing Failure Detection



Contactless Power Transfer



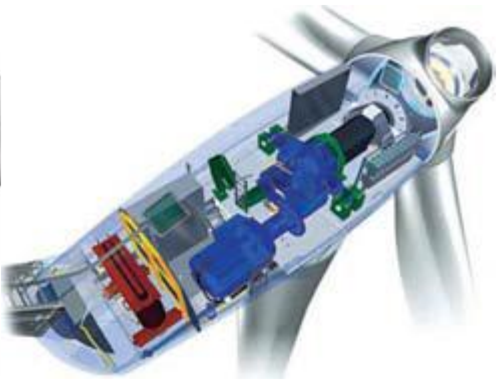
Drivetrain Diagnostics

Electromagnetic Devices

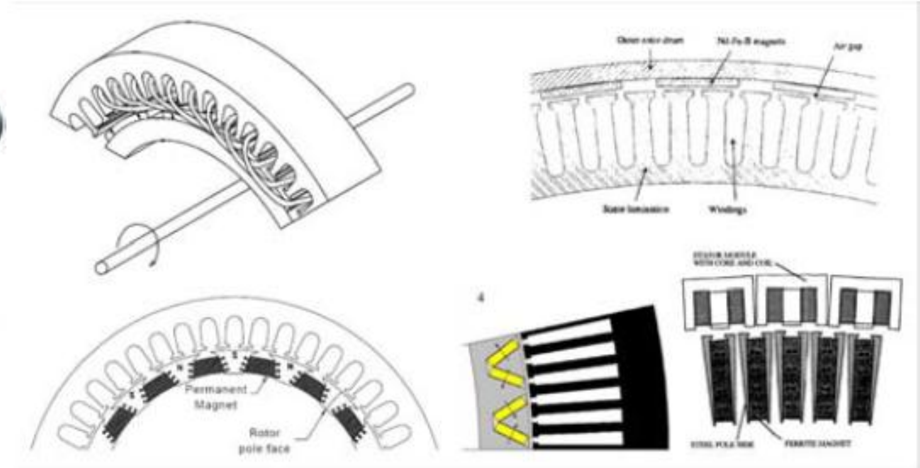
Diagnostics thru Electrical Machines

Motivation

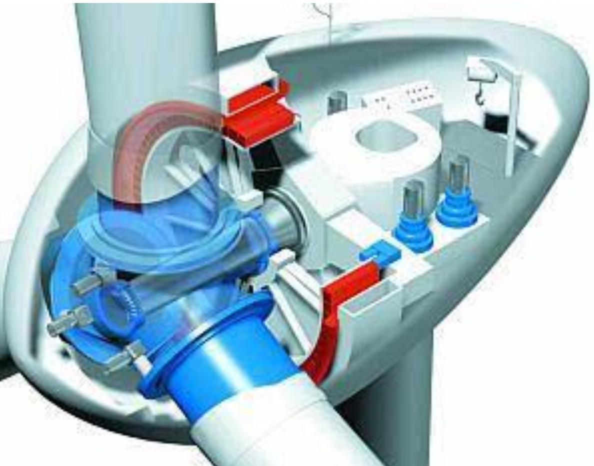
Induction Generator



DFIG

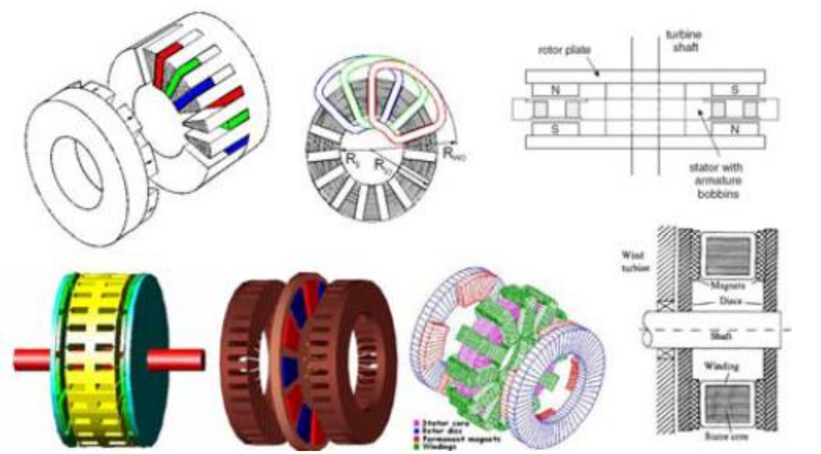


Other radial machine config



Sync. Generator

Permanent Magnet Syn Gen

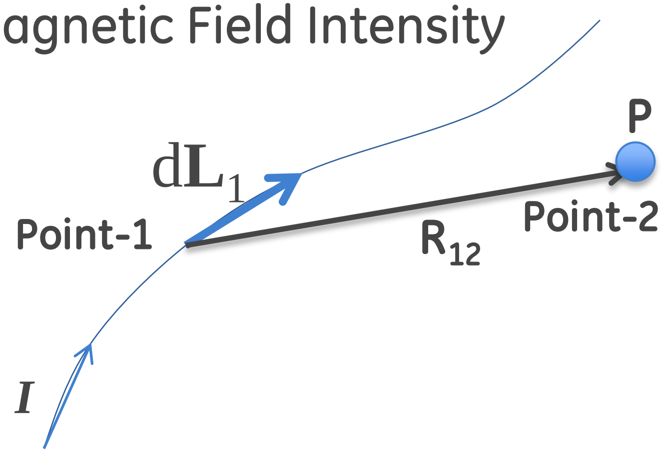


Other axial flux machines

- Global competition towards development of wind generator with higher-&-higher torque density
- Techniques, like FEM, enable for customized development of new topologies of generators with significant reduction in design-cycle

Basics of Electromagnetics

Magnetic Field Intensity

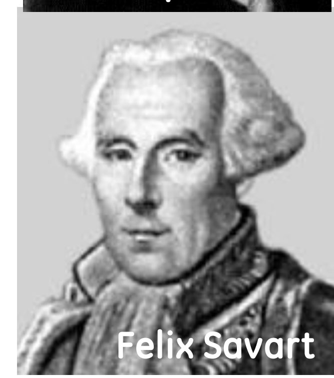


Cross Product?

$$d\mathbf{H} = \frac{I d\mathbf{L} \times \mathbf{a}_R}{4\pi R^2} \quad \text{A/m}$$

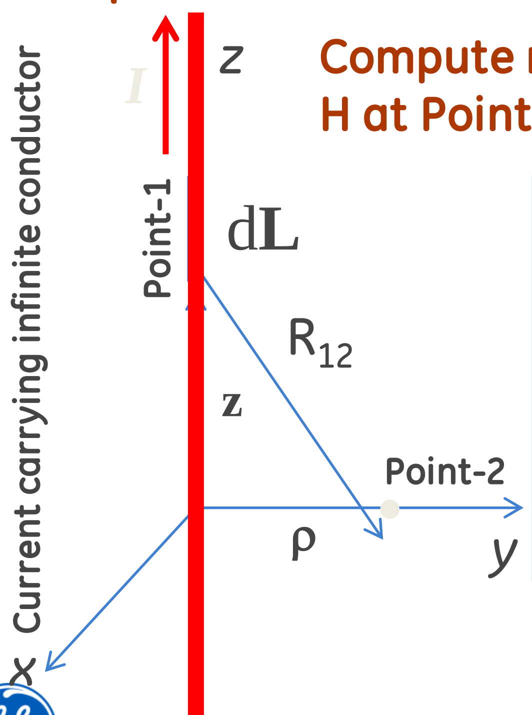
$$H = \oint \frac{I d\mathbf{L} \times \mathbf{a}_R}{4\pi R^2} \text{(Integral Form) A/m}$$

Biot-Savart Law



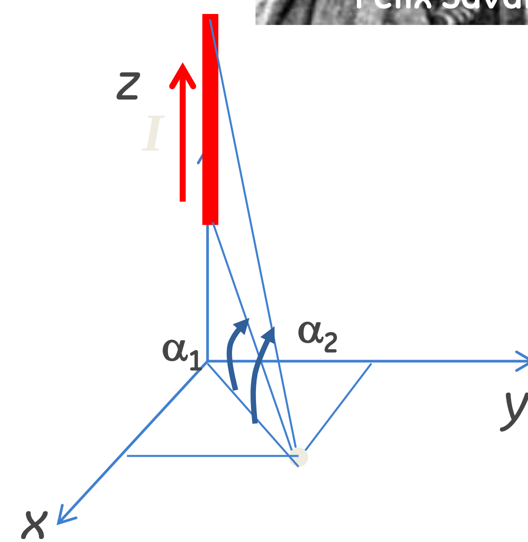
Example

Compute magnetic field intensity H at Point-2?



$$\mathbf{H} = \frac{I}{4\pi}\int_{-\infty}^{\infty} \frac{\rho \, \mathrm{d}z \, \mathbf{a}_\phi}{\left(\rho^2 + z^2\right)^{3/2}} \text{A/m}$$

$$\mathbf{H} = \frac{I}{2\pi\rho}\mathbf{a}_\phi \quad \text{A/m}$$



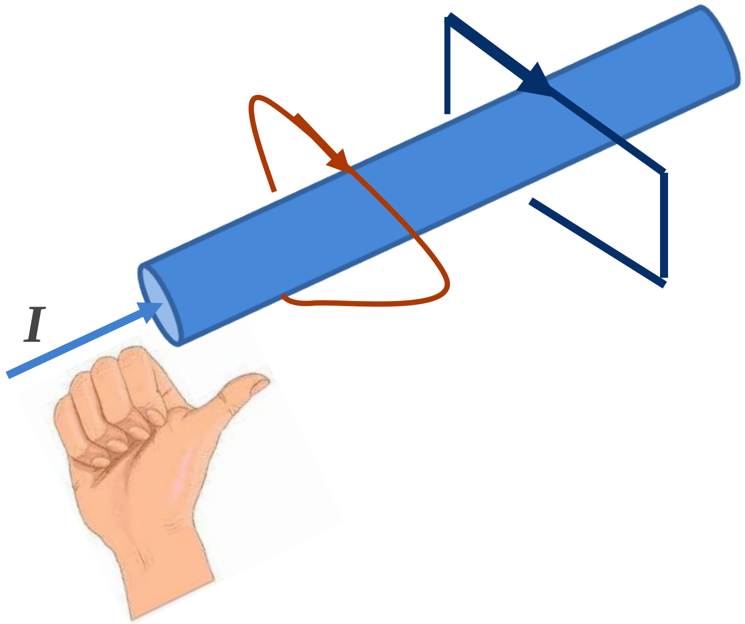
$$\mathbf{H} = \frac{I}{4\pi}\left(\sin\alpha_2 - \sin\alpha_1\right)\mathbf{a}_\phi \quad \text{A/m}$$

Basics of Electromagnetics

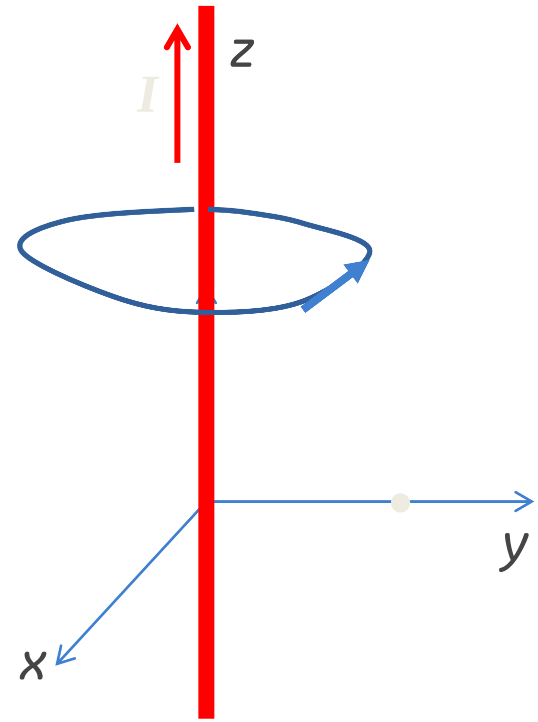
Ampere's Circuital Law

Andre-Marie-Ampere

The line integral of **H** about any closed path is the current enclosed by that path



$$\oint \mathbf{H} \cdot \mathrm{d}\mathbf{L} = I \text{ A}$$



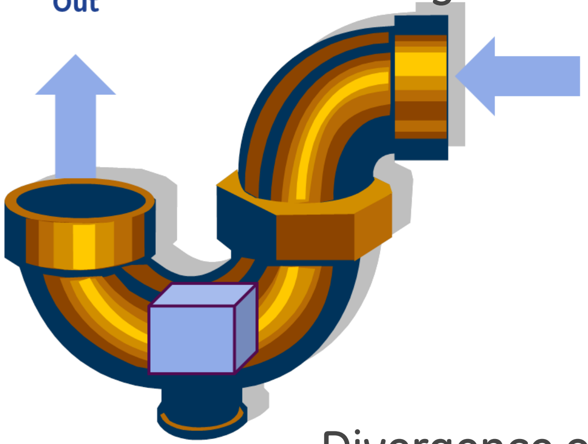
Compute magnetic field intensity H at Point-2? By Ampere Circuital Law

$$\oint \mathbf{H} \cdot \mathrm{d}\mathbf{L} = \int_0^{2\pi} H_\phi \rho \, \mathrm{d}\phi = H_\phi 2\pi\rho = I \;\Rightarrow\; H_\phi = \frac{I}{2\pi\rho}$$

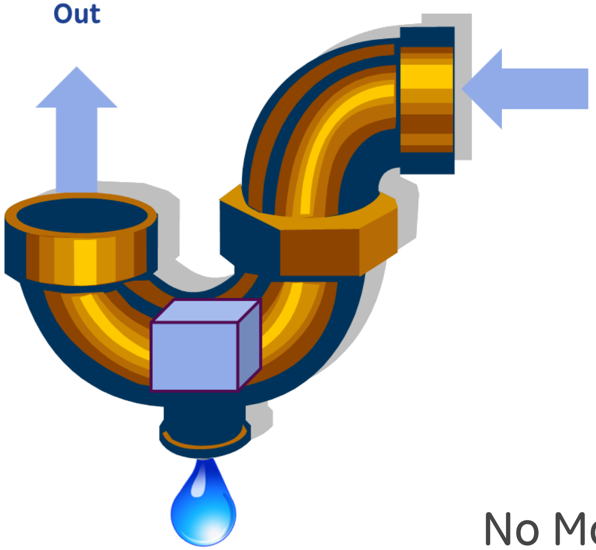
Basics of Electromagnetics

Divergence

Divergence of water flow = 0



Divergence of water flow ≠ 0

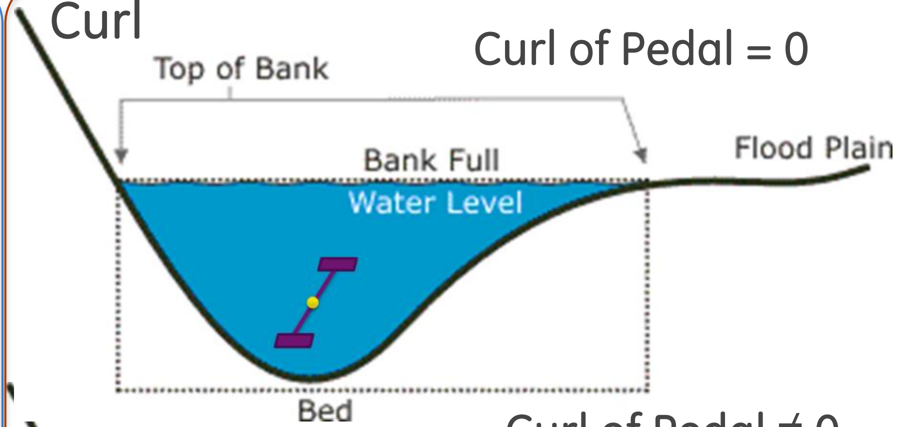


$$\nabla \cdot \mathbf{B} = 0$$

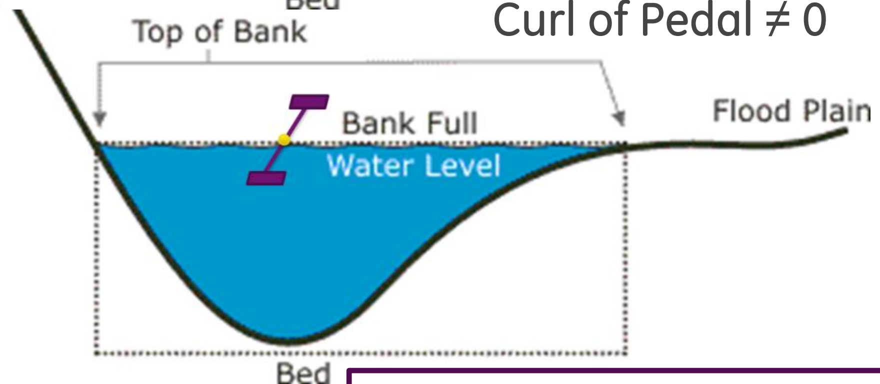
No Mono-pole exist

Curl

Curl of Pedal = 0



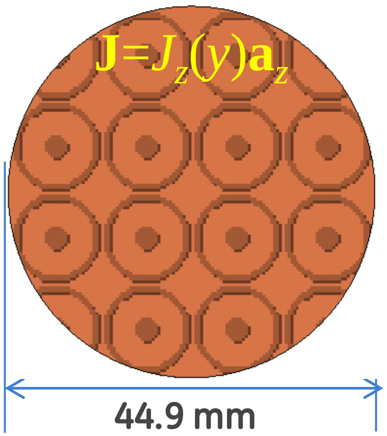
Curl of Pedal ≠ 0

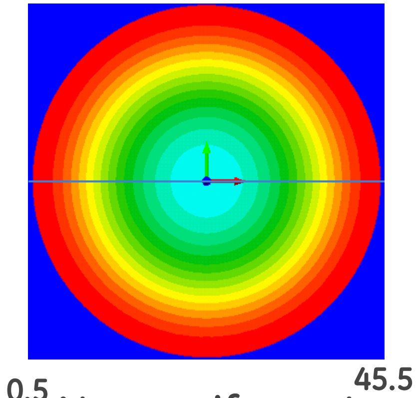


$$\nabla \times \mathbf{H} = \begin{vmatrix} \mathbf{a}_x & \mathbf{a}_y & \mathbf{a}_z \\ \dfrac{\partial}{\partial x} & \dfrac{\partial}{\partial y} & \dfrac{\partial}{\partial z} \\ H_x & H_y & H_z \end{vmatrix} = \mathbf{J}$$

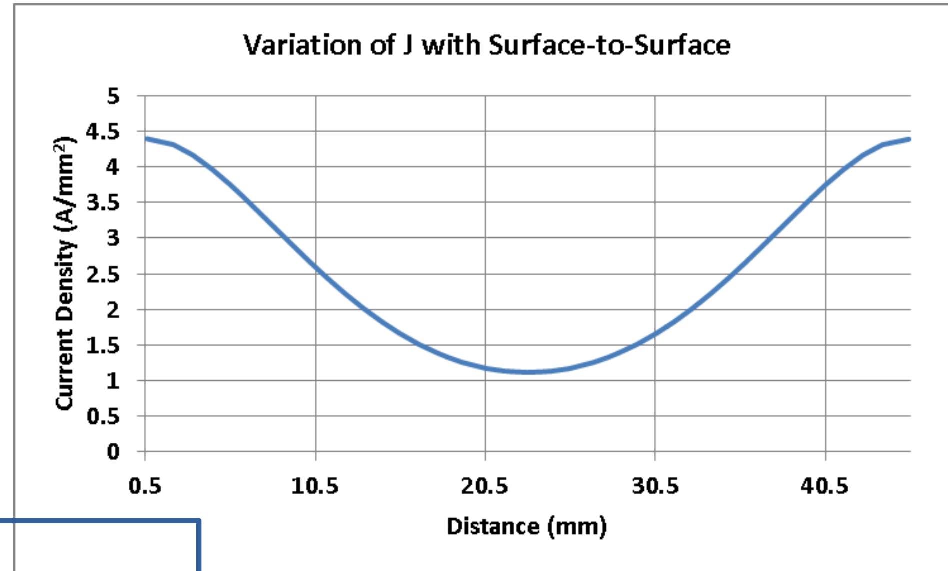
Basics of Electromagnetics: Time Varying Fields

Skin Effect



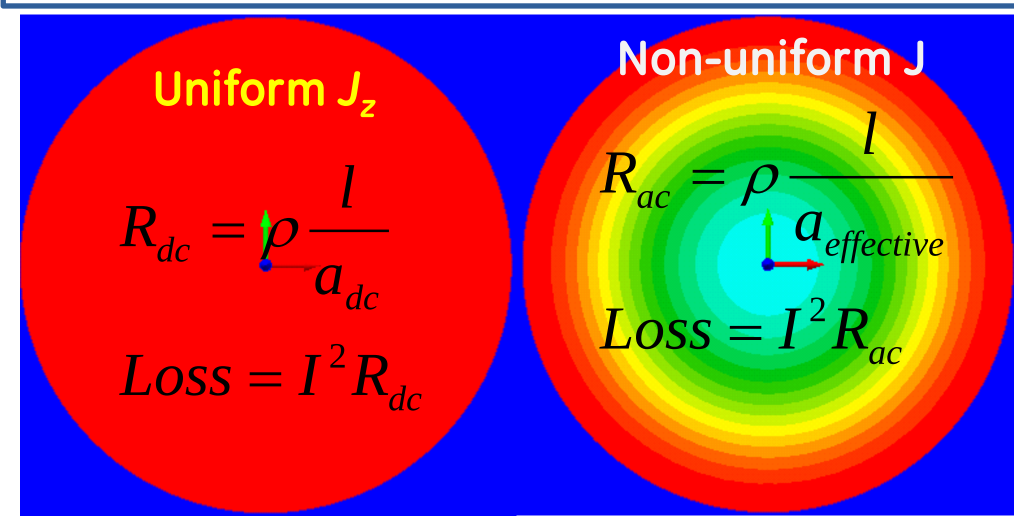


Non-uniform J



At a distance $\delta = \dfrac{1}{\sqrt{\pi f \mu \sigma}}$ m J_z reduces by 37%

Skin Depth



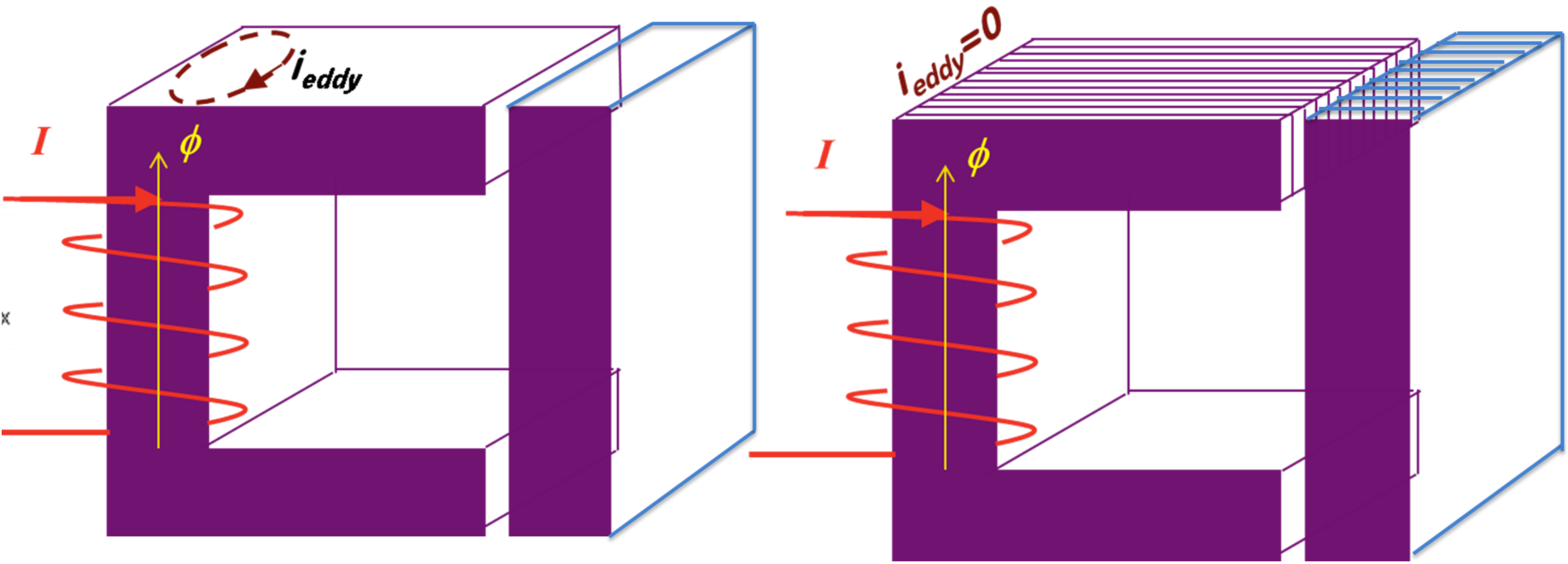
- $R_{ac} > R_{dc}$, hence Loss due to R_{ac} is more than R_{dc}, typically called AC Loss and DC Loss

Skin Depth of Cu at 50 Hz = 10.69 mm

Conductor cross-section in Machines is kept at $\delta/3$

Basics of Electromagnetics: Time Varying Fields

Eddy current loss in Core



Skin Depth of CRGO at 50 Hz = 1-2 mm

Each lamination should be at $\delta/3$ of iron

Basics of Electromagnetics: Time Varying Fields

Magnetic Vector Potential (MVP)

$$\nabla \cdot \mathbf{B} = 0$$

No magnetic monopole exist

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Lenz's law of induction

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Ampere-Circuital law

- Divergence of Curl of any vector = 0

$$\nabla \cdot (\nabla \times \mathbf{F}) = 0$$

- So, Magnetic Vector Potential, **A**

$$\nabla \cdot \mathbf{B} = \nabla \cdot (\nabla \times \mathbf{A}) = 0 \Rightarrow \mathbf{B} = \nabla \times \mathbf{A}$$

Magnetic governing equation for all electromagnetic problems

$$\frac{1}{\mu}\nabla^2 \mathbf{A} = -\mathbf{J}_0 + \sigma \frac{\partial \mathbf{A}}{\partial t}$$

Spatial derivative — *Applied external current density* — *Eddy current density*

Note: Magnetic Vector Potential does not exist physically; merely mathematical quantity

Basics of Electromagnetics: Time Varying Fields

Why Magnetic Vector Potential (MVP) **A** ?

All quantities can be computed using Magnetic Vector Potential formulation

- Magnetic flux density (**B** in Wb/m^2)
- Magnetic field intensity (**H** in A/m)
- Magnetic forces and torque (**F** in N & **T** in N-m)
- Impedance (Z in Ω)
- Inductance (L in H)
- Eddy currents (I in A)
- Power loss (P in W/m)
- Flux linkage (λ in Wb)

Electromagnetic Problems

Low Frequency	High frequency	Others
Transformers	Antennas	Plasma devices
Motors	Waveguides	Nanotechnology
Generators	Resonant cavities	Photonic crystals
Electromagnetic forming	Wireless communications	Magnetic storage technology
Induction heating	Magnetic Imaging systems	
Circuit breakers	Optoelectronics and photonics	
	Microwaves	

Static
Magnetostatics or electrostatic problem, e.g., DC excitation, electromagnet, computation of transformer leakage inductance

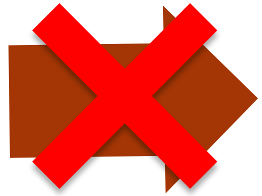
Time-harmonic
Sinusoidal excitation problems, e.g., eddy current loss computation, induction heating, etc.

Transient
Time-varying excitation, e.g., in-rush currents, time-varying torque/force computation,

Electromagnetic Problems

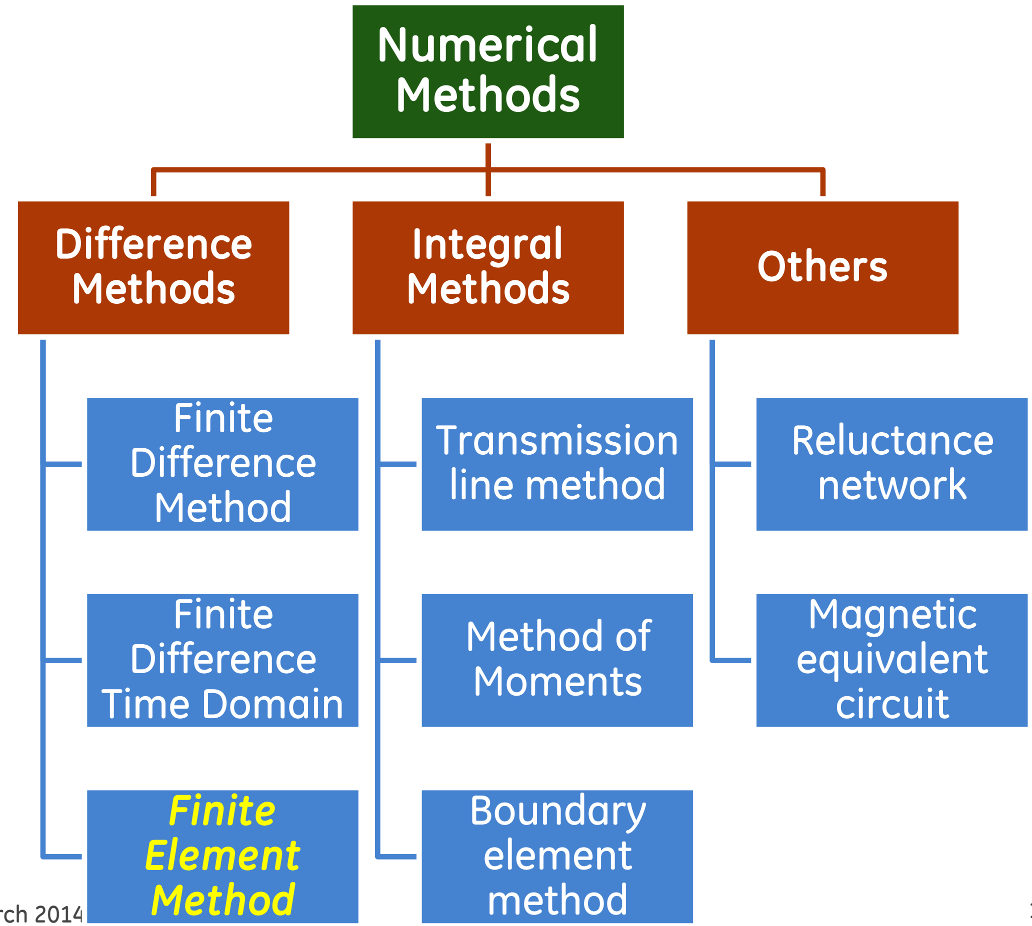
Analytical Methods

- Separation of variables
- Method of Images
- Conformal mapping
- Schwartz-Christoffel Transformation



Not Suitable for

- Complex geometries
- Non-uniformities
- Material anisotropy
- Material non-linearity



Difference methods

- Simple to use
- Less computational intensive
- Can account for Material non-homogeneity

Integral methods

- Mathematically more intensive
- Sparse matrix cannot be formed

Finite Element Method (FEM) in Electromagnetics

Historic development

- **1940** Proposed: Group of Mathematicians
- **1943** Applied by Courant for Structural
- **1965** *Zienkiewicz* and *Cheung* reported applicable all Fields

Minimum energy principle : Every state always put efforts to attend minimum energy level

Steps in FEM

Pre-processor

- Geometry & physics definition
- Material
- Meshing

Solution

- Applying loads
- Boundary conditions
- Type of solution: static, time-harmonic, transient

Post-processor

- Boundary conditions
- Solution
- Parameter computation

Finite Element Method (FEM) in Electromagnetics

Finite Element Software demos: Transformer and motor models

Live demo will be shown here, with problem solving of by FEM

Finite Element Method (FEM) in Electromagnetics

Key factors about Meshing

- Element size?
  - Should be dense at field region

- Eddy current loss computation?
  - At-least 3 elements in one skin depth in the eddy-loss region

- Force / Torque computation?
  - FEM package computes force/torque on the body which is completely surrounded by air
  - Air-gap is extremely crucial for meshing, minimum 4 air-gap layers for accurate torque computation

Finite Element Methods to EM Problems

Static problem

Applications of static excitation are

- Permanent magnets
- The steady flow of DC current.
- An applied constant voltage
- A moving conductor
- An applied external field

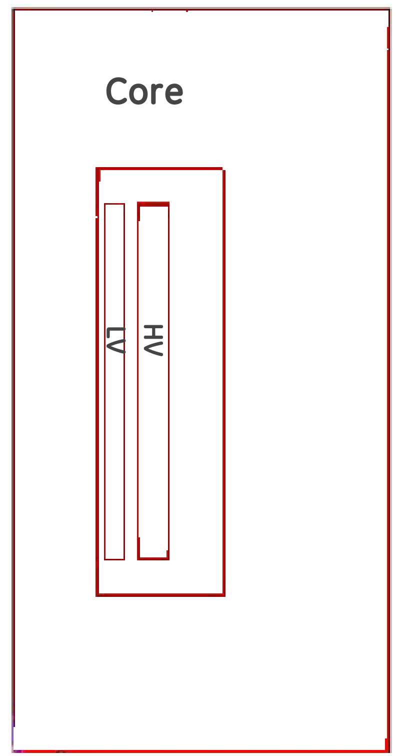
Magnetic governing equation

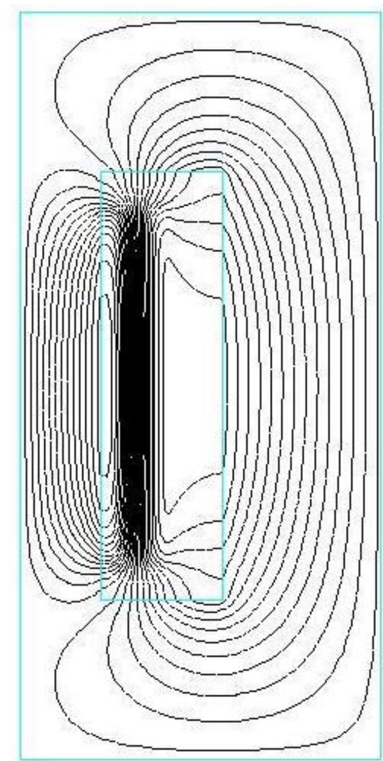
$$\underbrace{\frac{1}{\mu}\nabla^2 \mathbf{A}}_{\textit{Spatial derivative}} = \underbrace{-\mathbf{J}_0}_{\textit{Applied external current density}} + \underbrace{\cancel{\sigma \left.\frac{\partial \mathbf{A}}{\partial t}\right|_{=0}}}_{\textit{Eddy current density = 0}}$$

$$[\mathbf{K}(\mathbf{A})]\{\mathbf{A}\} = \{\mathbf{b}\}$$

Computation of transformer leakage inductance

$$\underbrace{W = \iiint_V \frac{B^2}{2\mu}\,\mathrm{d}V}_{\text{Magnetic Energy}} \qquad \underbrace{L = \frac{2}{I^2} W}_{\text{Inductance}}$$





Leakage flux Plot

Results:

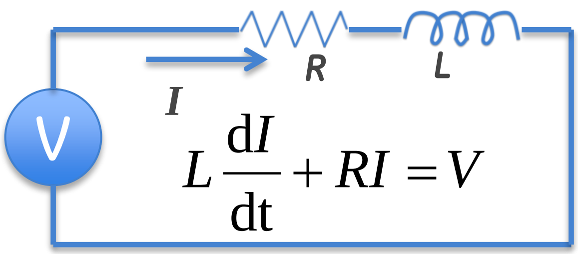
Leakage Inductance Model (%)	Leakage Inductance Experiment (%)
14.2%	14%

Finite Element Methods to EM Problems

Time-harmonic problem

example $V = V_m \sin(\omega t)$

transient voltage signal fed to *R-L* circuit



$$L\frac{\mathrm{d}I}{\mathrm{d}t} + RI = V$$

Magnetic governing equation

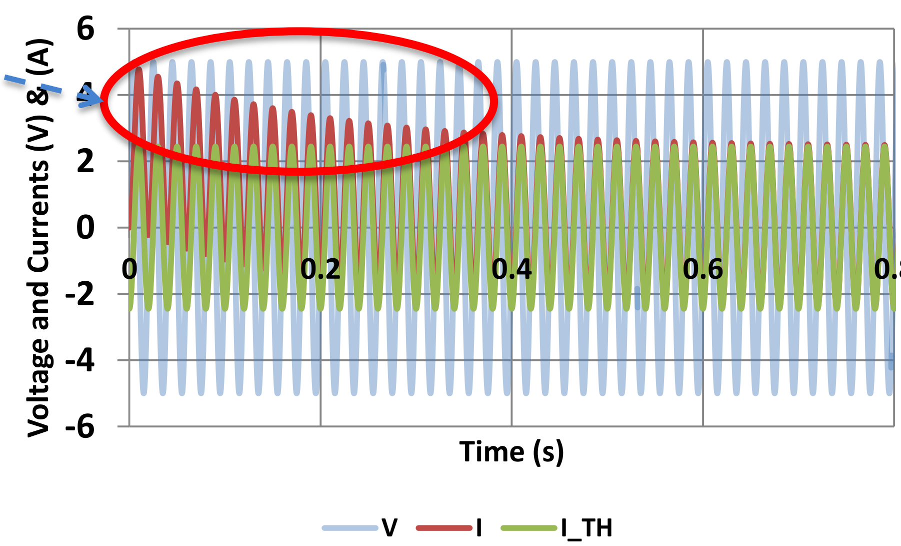
$$\frac{1}{\mu}\nabla^2\mathbf{A} \quad = \quad -\mathbf{J}_0 \quad + \quad \sigma\frac{\partial\mathbf{A}}{\partial t}$$

Spatial derivative — *Applied external current density* — *Eddy current density = 0*

$$[\mathbf{S}(\mathbf{A})]\{\mathbf{A}(t)\} + [\mathbf{T}]\frac{\partial}{\partial t}\{\mathbf{A}(t)\} = \{\mathbf{J}(t)\}$$

$$I = \frac{V_m \sin\left[\omega t - \tan^{-1}\left(\frac{\omega L}{R}\right)\right]}{\sqrt{R^2+\omega^2L^2}} + \frac{V_m \sin\left[\tan^{-1}\left(\frac{\omega L}{R}\right)\right]}{\sqrt{R^2+\omega^2L^2}} e^{-\frac{R}{L}t}$$

Transient part



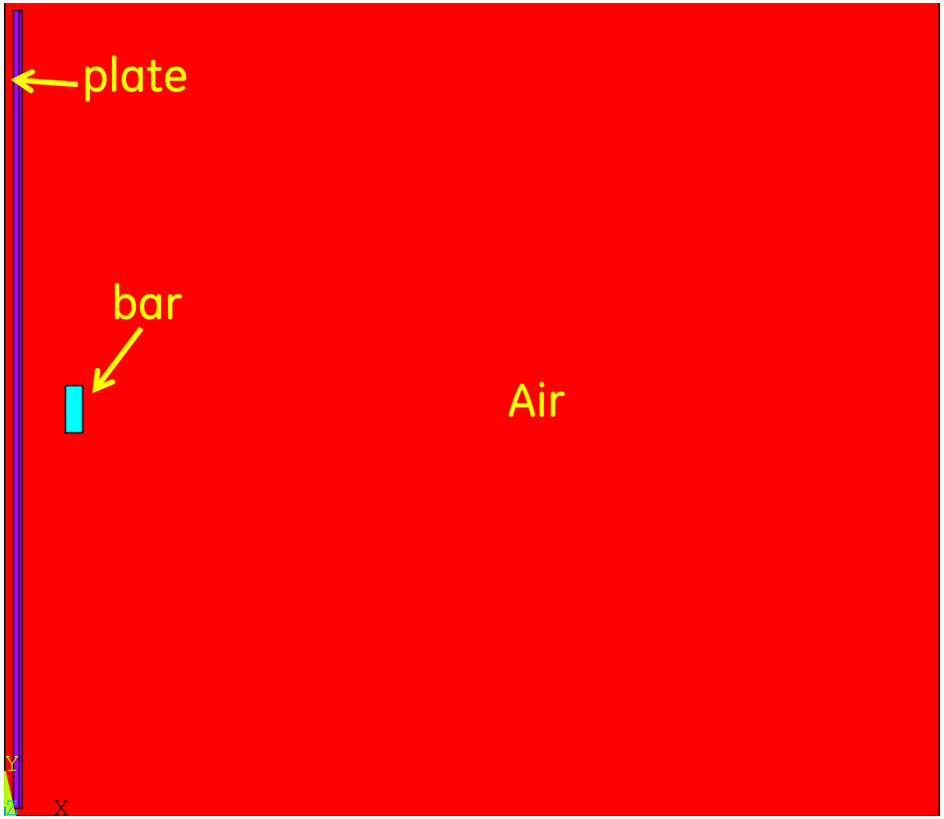
Applications of TH excitation are

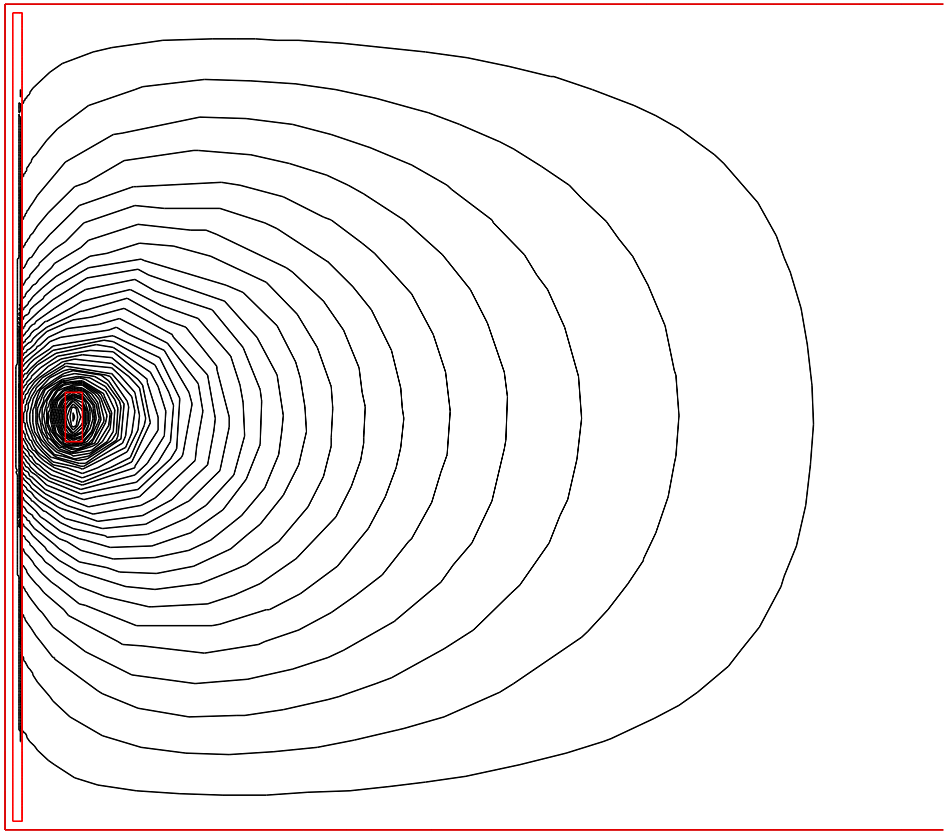
- Eddy current loss
- Steady state currents, voltages, etc.
- Steady state machine equations

Finite Element Methods to EM Problems

Time-harmonic problem

Computation of eddy current loss in metallic plate near current carrying bus-bar





Power loss (W) $P_{loss} = \oiiint_V \rho J^2 \mathrm{dV}$ where J is eddy current density $\mathbf{J} = j\omega\sigma\mathbf{A}$

Finite Element Methods to EM Problems

Transient problem

Applications of Transient excitation are

- In-rush currents
- Transient torque/force
- Problem with motion (stator-rotor in electrical machines)
- Circuit-coupled problem

Magnetic governing equation

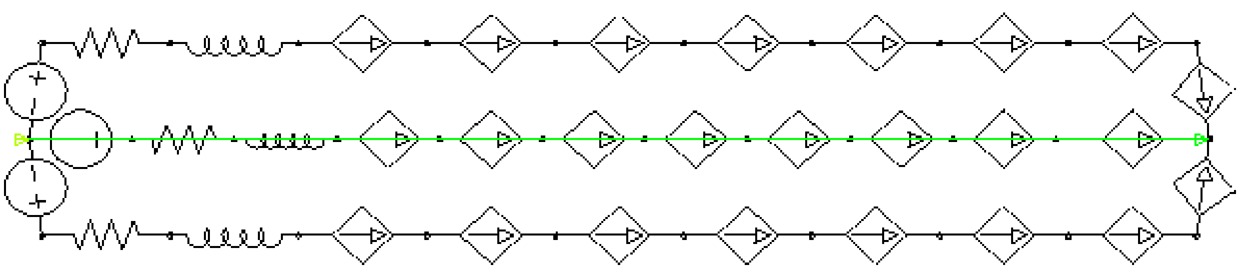
$$\frac{1}{\mu}\nabla^2\mathbf{A} = -\mathbf{J}_0 + j\omega\sigma\mathbf{A}$$

Spatial derivative

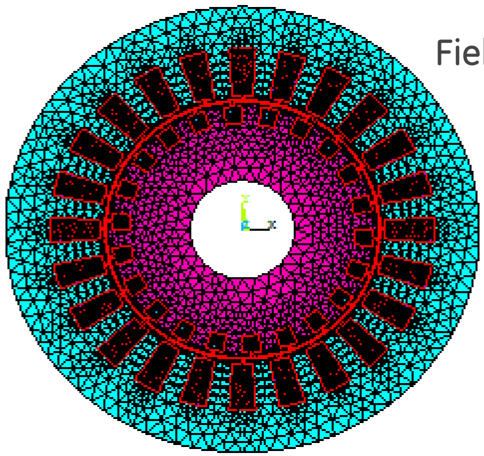
Applied external current density

Eddy current density = 0

Torque computation in 2.2 kW, 24 slots, 4 pole, 1500 rpm, Induction motor

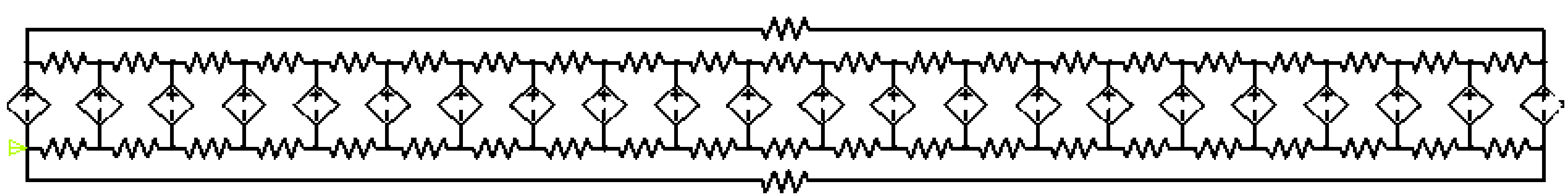


Stator circuit



Field

Rotor circuit

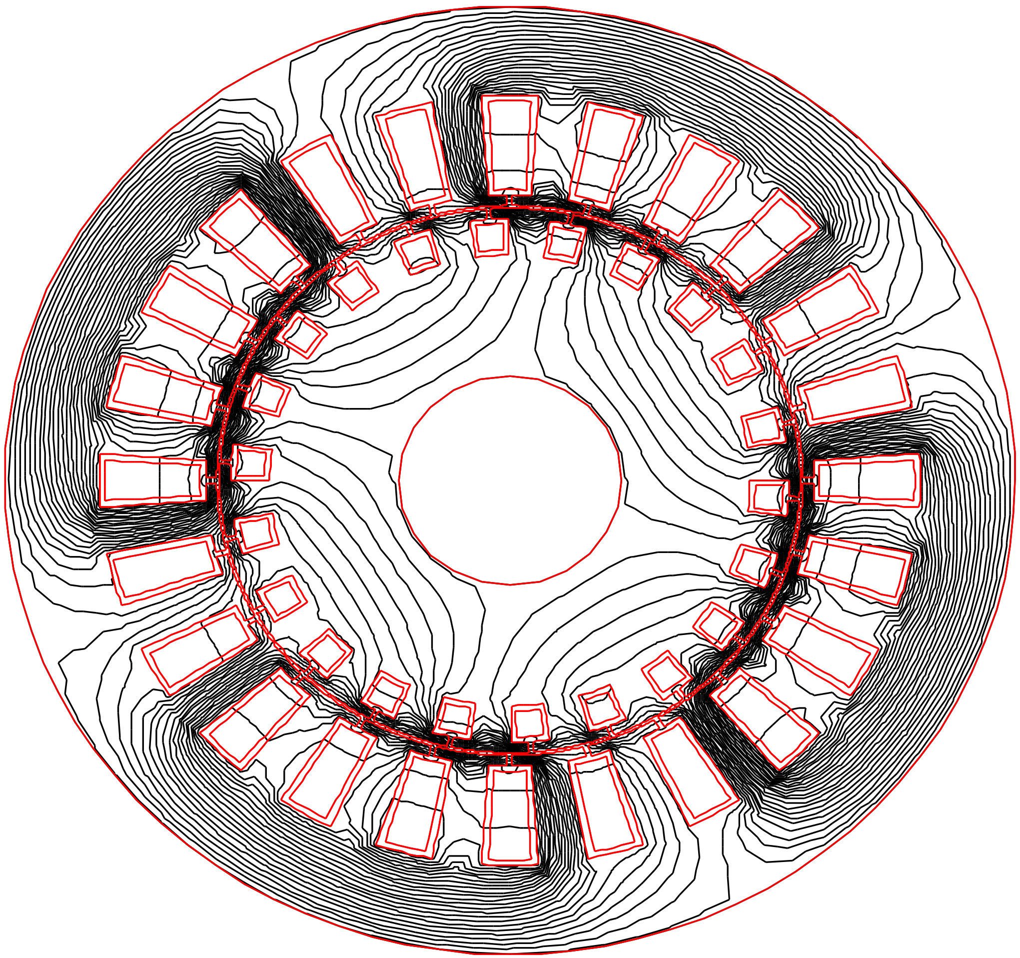


Finite Element Methods to EM Problems

Transient problem

2D FE non-linear transient analysis

- Non-linear B-H curve
- With motion
- Circuit-coupled analysis



Comparison of computed and practical torques

Analytical value	FEM Package
14.3 Nm	14.13 Nm