Electromagnetic and Coupled Field Computations for Analysis of Complex Phenomena in Power Transformers

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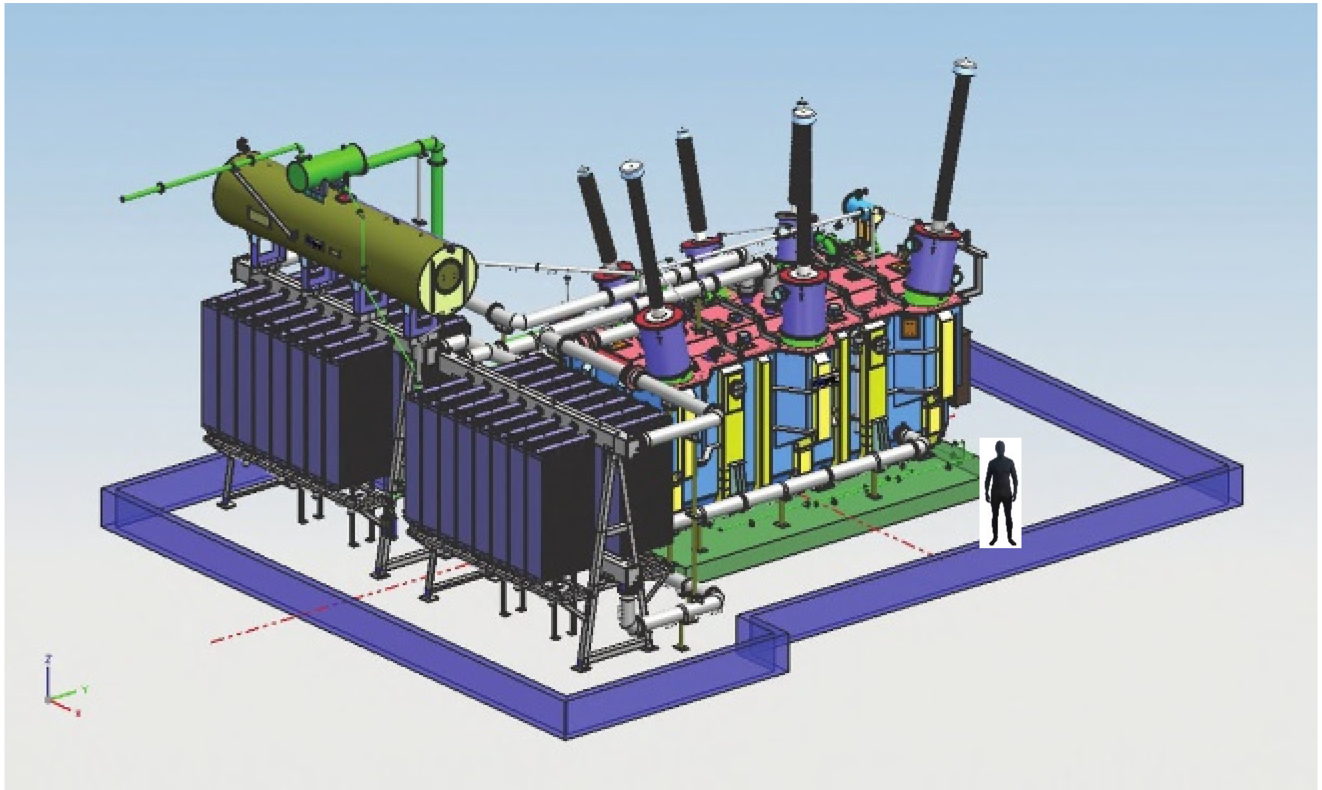
Dissemination of research work on power transformers: design, testing, operation, and diagnostics



through the book:

S.V. Kulkarni and S.A. Khaparde, *Transformer Engineering: Design, Technology, and Diagnostics*, Second Edition, CRC Press, New York, September 2012

Outline

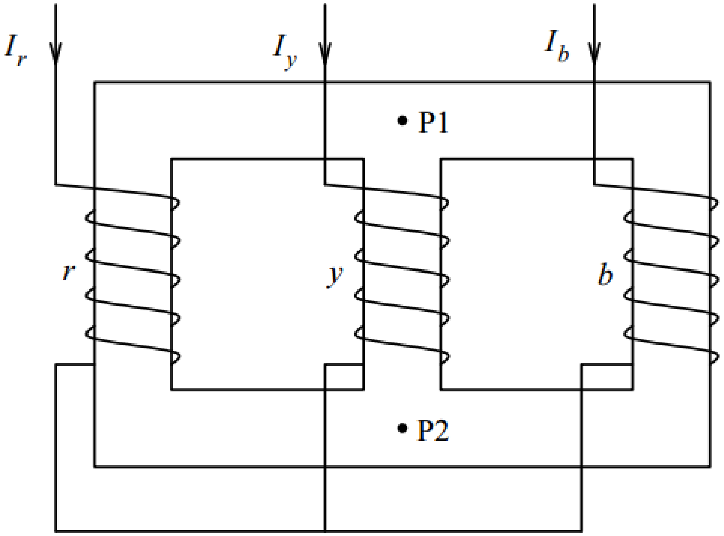
- Introduction
- Challenges in Transformer Engineering
- Electromagnetic and Coupled Fields in Transformers
- Numerical Methods
- Case Studies
- Concluding Remarks

Power Transformers

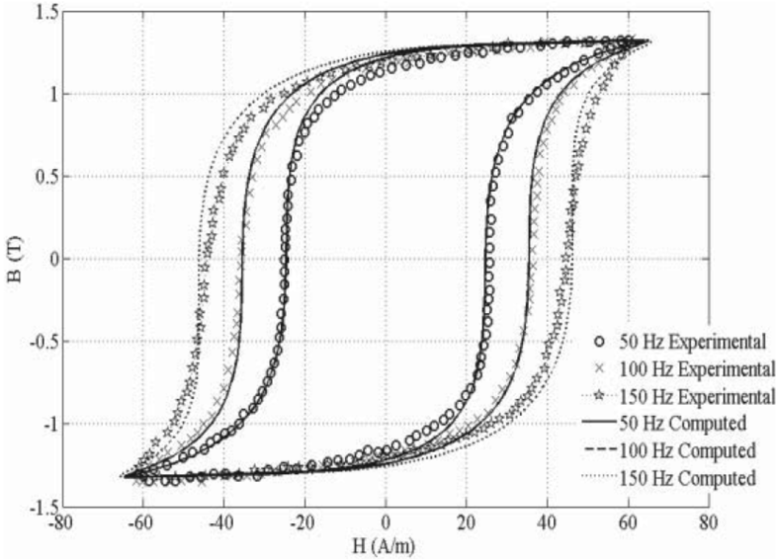
- Technology hasn't changed significantly, but the challenges are:
  - Continuous increase in ratings and sizes
  - Limitations on weight and space
  - Accurate prediction of performance parameters
  - Increasing power system complexities

- Onerous site conditions:
  - Harmonics
  - Resonances
  - Short circuits
  - Overvoltages
  - Overloading
  - Unbalanced conditions
  - Overfluxing

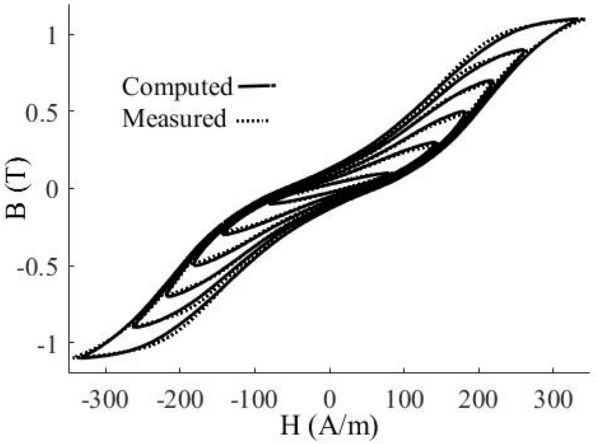
Magnetic Circuit of a Transformer



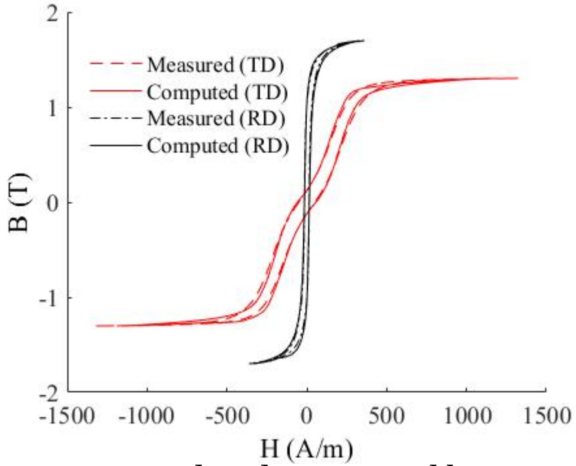
Asymmetrical structure



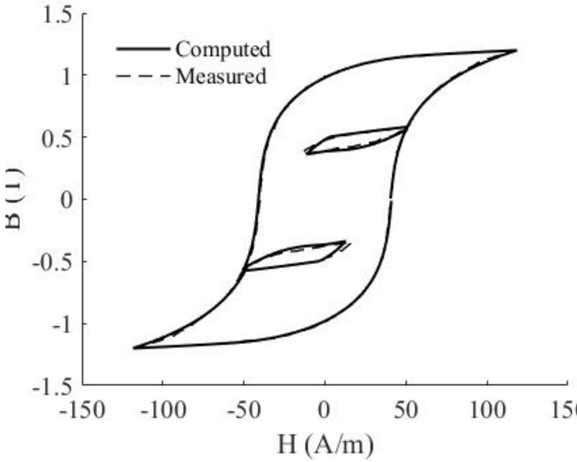
Measured and computed dynamic loops



Measured and computed minor loops along transverse direction (TD)



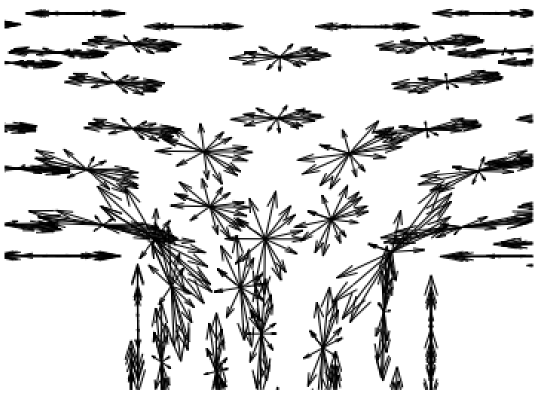
Measured and computed hysteresis loops (for RD and TD)



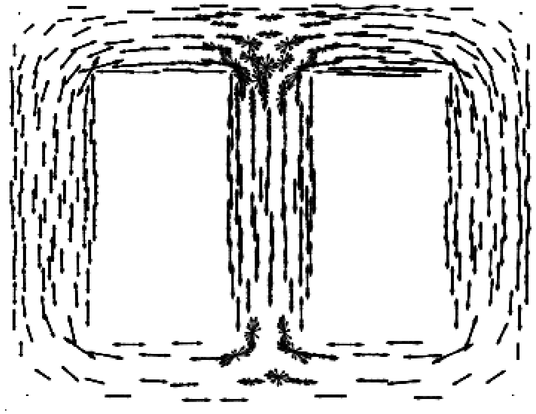
Measured and computed hysteresis loop with 3rd harmonic in B

Ref: A. P. S. Baghel and S. V. Kulkarni, "Dynamic Loss Inclusion in the Jiles-Atherton Hysteresis Model Using the Original JA Approach and the Field Separation Approach," *IEEE Transactions on Magnetics*, Vol. 50, February 2014

Rotational Flux in a T-Joint

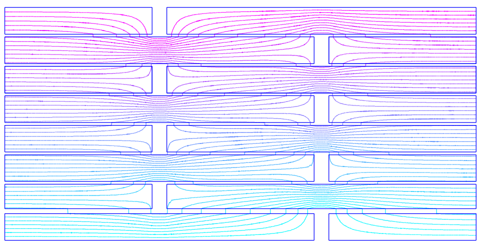


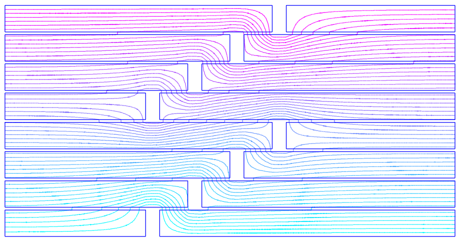
(a)

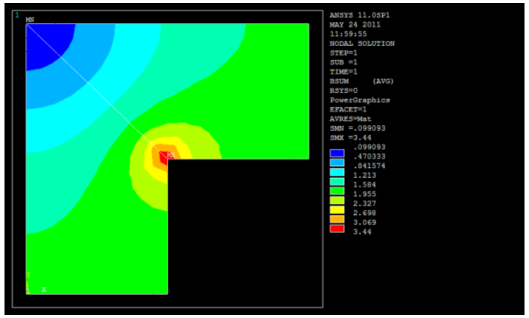


(b)

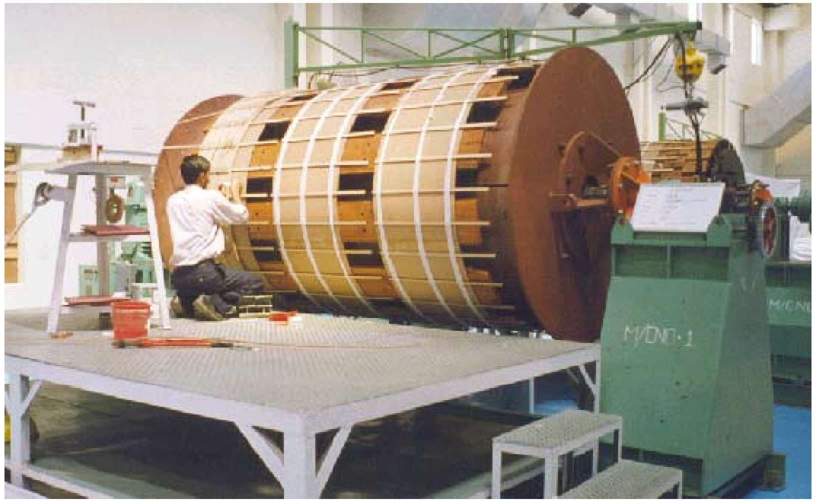
Saturation in Joints







Windings of a Transformer



Courtesy: Crompton Greaves Ltd.

Courtesy: AREVA T&D India Ltd.

- Design considerations have often conflicting requirements:
  - conductor radius : dielectric Vs mechanical
  - paper covering : dielectric Vs thermal
  - conductor thickness : mechanical Vs electromagnetic
  - first duct : thermal Vs dielectric
  - radial spacer width : thermal Vs mechanical

Need for Numerical Analysis

- Computation of *electromagnetic fields* is essential in low frequency and high frequency devices for:
  - Design optimization
  - Reliability enhancement
  - Investigative analysis
- **Numerical Methods**
  - Difference methods (FDM, FDTD)
  - Variational / weighted residual approach (FEM)
  - Integral methods (MoM, BEM)
- FEM has emerged as the most popular technique for transformers

Finite Element Formulation for Different EM Problems

- Poisson's equation: High voltage insulation design

$$\nabla^2 \mathbf{A} = -\mu \mathbf{J}_o \Rightarrow \left[K^e\right]_{3\times3} \left\{A\right\}_{3\times1} = \left\{b^e\right\}_{3\times1}$$

- Diffusion equation: Time-harmonic eddy current problems

$$\nabla^2 \mathbf{A} = -\mu \mathbf{J}_o + j\sigma\omega\mu \mathbf{A} \Rightarrow \left[K^e\right]\left\{A^e\right\} - j\omega\left[T^e\right]\left\{A^e\right\} = \left\{b^e\right\}$$

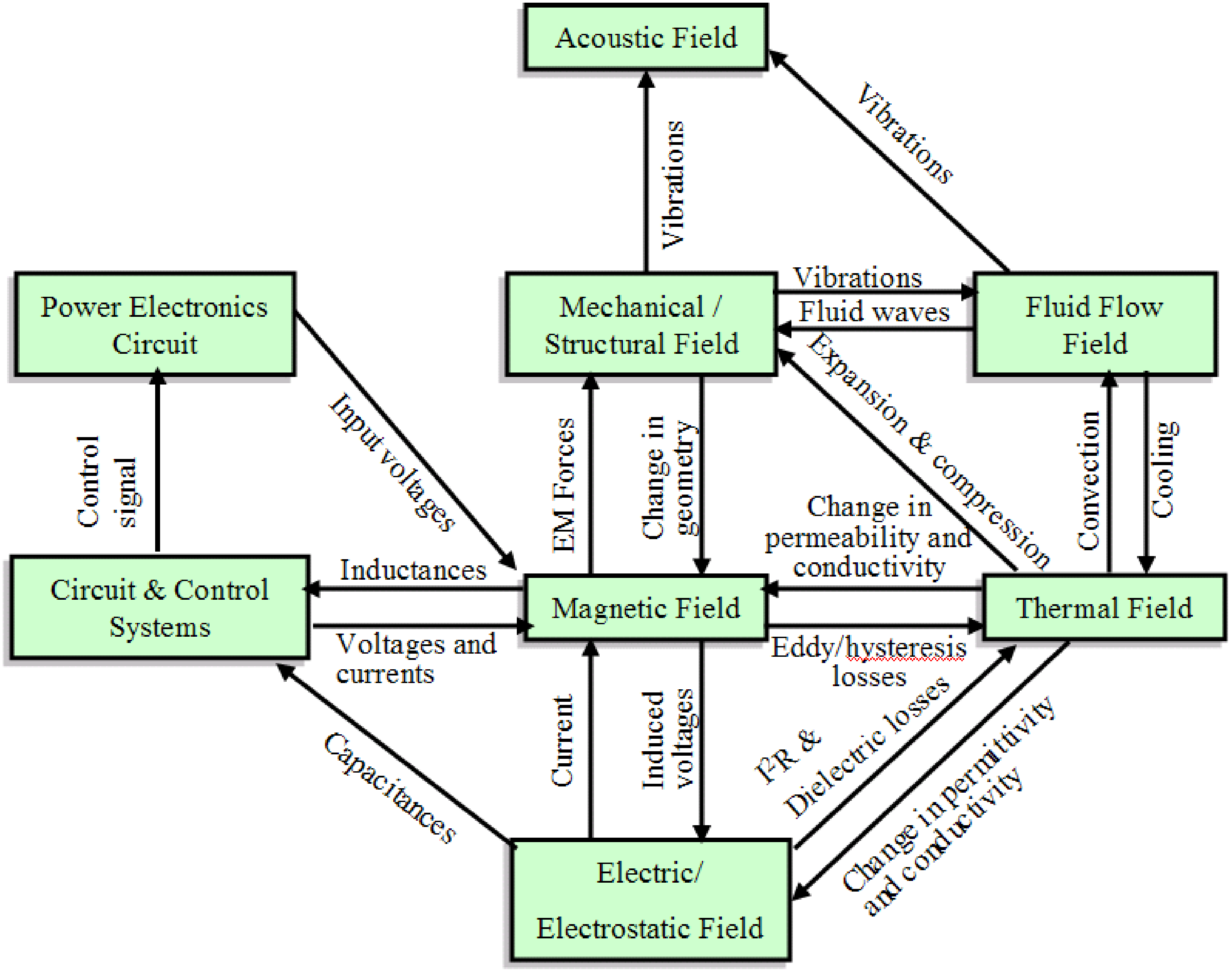
- Transient analysis: Magnetizing inrush simulation

$$\nabla^2 \mathbf{A} = -\mathbf{J}_o + \sigma \frac{\partial \mathbf{A}}{\partial t} \Rightarrow [K]\left\{A^e(t)\right\} - [T]\frac{\partial}{\partial t}\left\{A^e(t)\right\} = \left\{b^e\right\}$$

Coupled Fields in Transformers

- Classification:
  - Weakly coupled fields
  - Strongly coupled fields
- Weak or indirect coupling:
  - Solution of one field as load to another field
  - Approach is flexible, modular and easy to use
- Strong or direct coupling:
  - Coupled field equations are solved simultaneously
  - Concurrent handling of all physical aspects of fields
  - The approach is essential for nonlinear phenomena and when the coupled fields have comparable time constants

Coupled Fields in Transformers



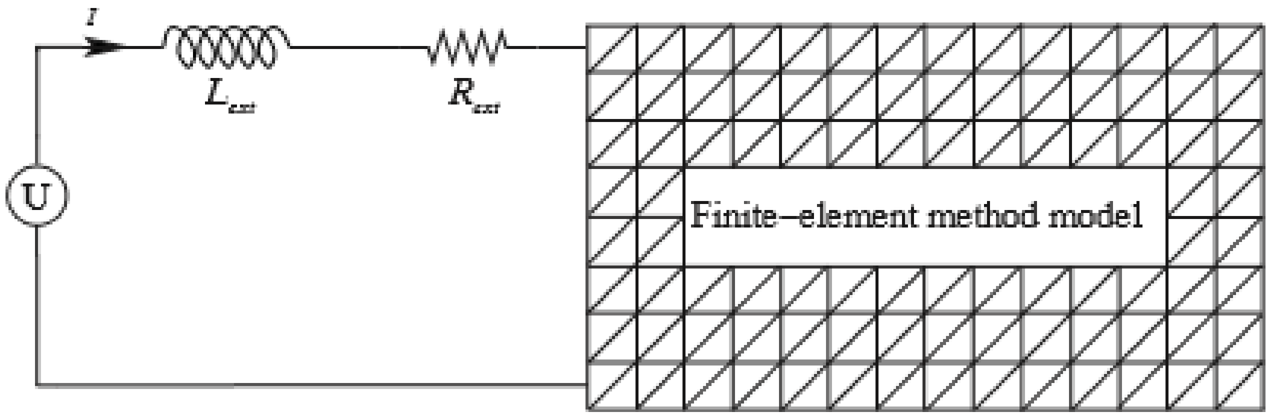
Coupled Field Formulations: Field-Circuit Coupling

- *Electromagnetic model*:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{J}_0 - \sigma \frac{\partial \mathbf{A}}{\partial t} - \sigma \nabla V + \nabla \times \mathbf{M} + \sigma \upsilon \times (\nabla \times \mathbf{A})$$

here, **M** is the magnetization vector and υ is the velocity of conductors

- *Circuit coupling*:

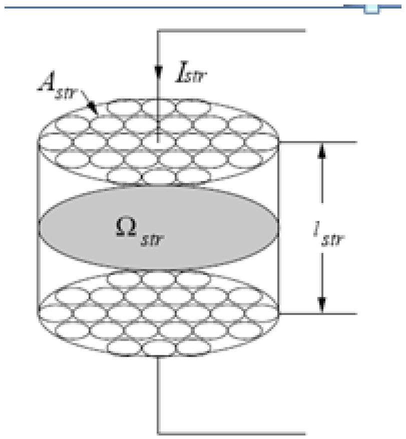


Field-circuit coupling mechanism

Coupled Field Formulations: Field-Circuit Coupling

$$\begin{bmatrix} [\mathbf{0}] & [\mathbf{0}] \\ [\mathbf{G}] & [\mathbf{L}] \end{bmatrix} \begin{Bmatrix} \{\dot{\mathbf{A}}\} \\ \{\dot{\mathbf{I}}\} \end{Bmatrix} + \begin{bmatrix} [\mathbf{K}] & [\mathbf{D}] \\ [\mathbf{0}] & [\mathbf{R}] \end{bmatrix} \begin{Bmatrix} \{\mathbf{A}\} \\ \{\mathbf{I}\} \end{Bmatrix} = \begin{Bmatrix} \{\mathbf{0}\} \\ \{\mathbf{U}\} \end{Bmatrix}$$

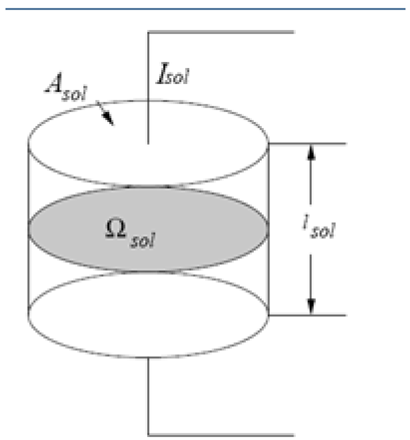
(a) Stranded (electrically thin) conductor



(a)

$$\begin{bmatrix} [\mathbf{Q}] & [\mathbf{0}] & [\mathbf{0}] \\ [\mathbf{B}]^T & [\mathbf{0}] & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{0}] & -[\mathbf{M}] \end{bmatrix} \frac{d}{dt} \begin{Bmatrix} \{\mathbf{A}\} \\ \{\mathbf{V}\} \\ \{\mathbf{I}\} \end{Bmatrix} + \begin{bmatrix} [\mathbf{C}] & [\mathbf{B}] & [\mathbf{0}] \\ [\mathbf{0}] & [\mathbf{S}] & [\mathbf{P}] \\ [\mathbf{0}] & [\mathbf{P}]^T & -[\mathbf{R}] \end{bmatrix} \begin{Bmatrix} \{\mathbf{A}\} \\ \{\mathbf{V}\} \\ \{\mathbf{I}\} \end{Bmatrix} = \begin{Bmatrix} \{\mathbf{0}\} \\ \{\mathbf{0}\} \\ \{\mathbf{U}\} \end{Bmatrix}$$

(b) Solid (electrically thick) conductor



(b)

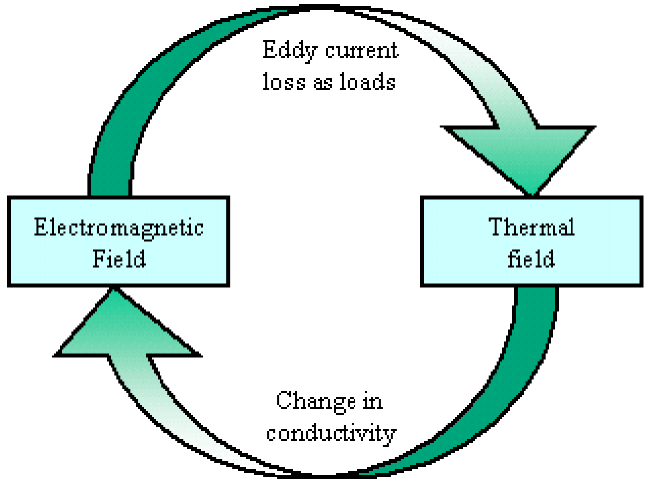
Coupled Field Formulations: Magnetic-Thermal

- *Governing Equations*:

$$\nabla \cdot \left(\frac{1}{\mu} \nabla \left(A_z \right) \right) = -\sigma \left(T \right) \frac{V}{l} + \sigma \left(T \right) \frac{\partial A_z}{\partial t}$$

$$\nabla \cdot \left(k \nabla \left(T \right) \right) = -q \left(A_z , T \right) + mc \frac{\partial T}{\partial t}$$

where, k is the thermal conductivity, m is the mass density, c is the specific heat, and q is the loss term.



Weakly coupled model

- *Coupling Relation*:

Temperature dependence:

$$\sigma\left(T\right) = \frac{\sigma_{ref}}{\left(1 + \alpha_\sigma \left(T - T_{ref}\right)\right)}$$

Loss calculation:

$$q(A,T) = \frac{1}{\Omega_c} \int_{\Omega_c} \sigma \left(\frac{V}{l} - \frac{\partial A}{\partial t} \right)^2 d\Omega$$

Coupled Field Formulations: Magnetic-Structural

- *Coupled Equations*:

$$\begin{bmatrix} [\mathbf{M}] & [\mathbf{C}] \\ [\mathbf{D}] & [\mathbf{K}] \end{bmatrix} \begin{Bmatrix} \{\mathbf{A}\} \\ \{\mathbf{X}\} \end{Bmatrix} = \begin{Bmatrix} \{\mathbf{I}\} \\ \{\mathbf{F}\} \end{Bmatrix}$$

M and **K** are magnetic and mechanical stiffness matrices respectively. **A** and **X** are nodal values of magnetic vector potential and displacements.

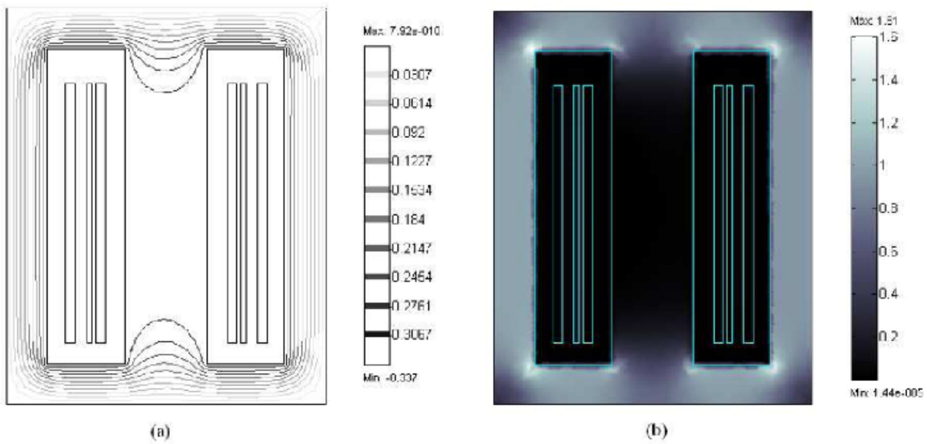
- *The formulation with suitable modifications can be used for:*
  - Analysis of core noise: Magnetostriction phenomenon
  - Computation of noise due to winding vibration ($\mathbf{J}\times\mathbf{B}$ force)
  - Analysis of winding deformations due to short circuit forces
  - Design of high current carrying bars in large rectifier and furnace duty applications

Case Studies

1. Half-Turn Effect

Single-phase three-limb transformer

	Measured	FEM
Flux density in end limbs (T)	**1.04**	**0.93**
Extra core loss due to the half-turn effect (kW)	**4.2**	**3.9**



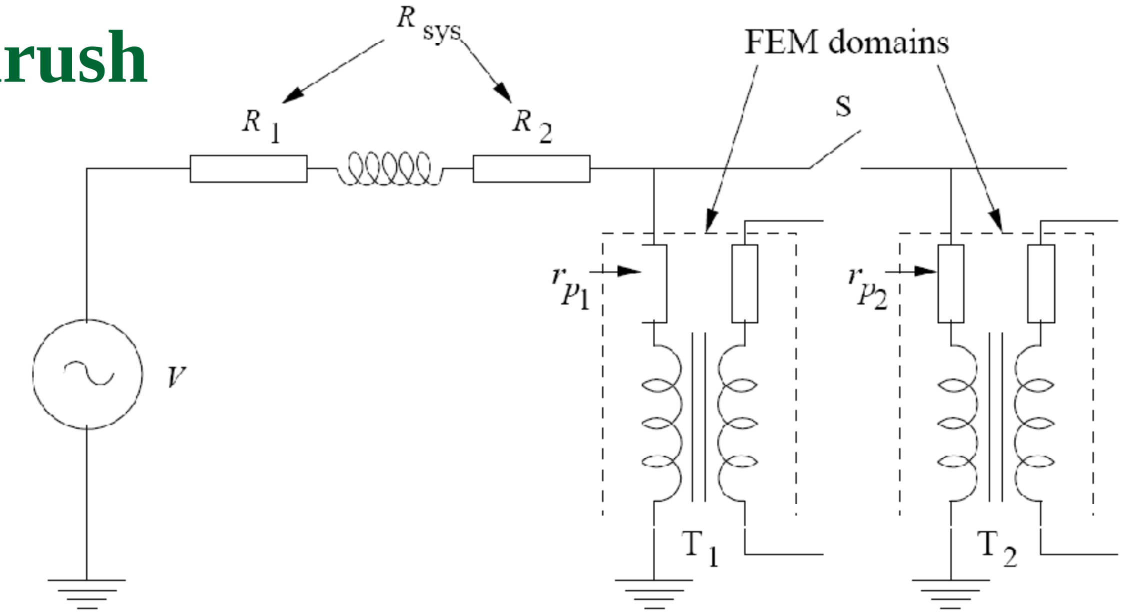
(a) Flux lines (b) flux density plots with half-turn

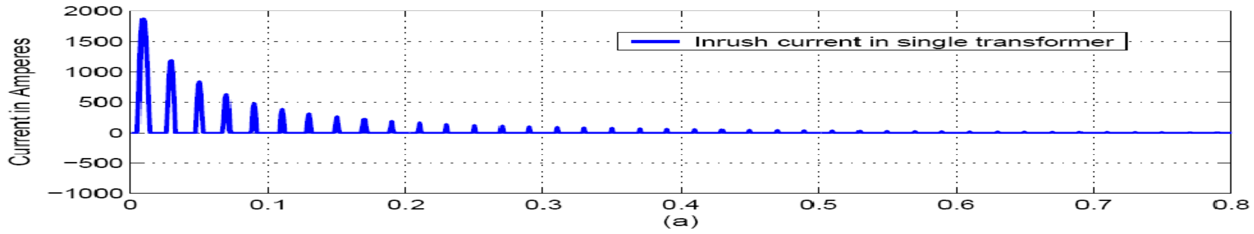
Three-phase five-limb transformer

	Flux density (T) for unbalanced currents in windings		
	Balanced	10% unbalance	20% unbalance
Without half-turn	**0.02**	**0.035**	**0.045**
With half-turn	**0.04**	**0.108**	**0.25**

Ref: G. B. Kumbhar, S. V. Kulkarni, and V. S. Joshi, "Analysis of half-turn effect in power transformers using nonlinear-transient FE formulation," *IEEE Transactions on Power Delivery*, vol. 22, Jan 2007, pp. 195-200.

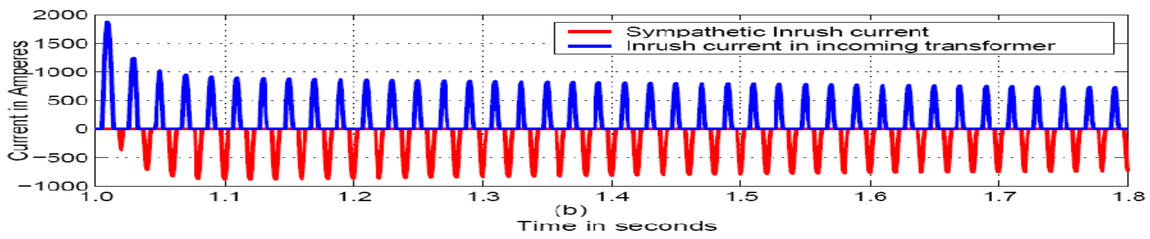
2. Sympathetic Inrush





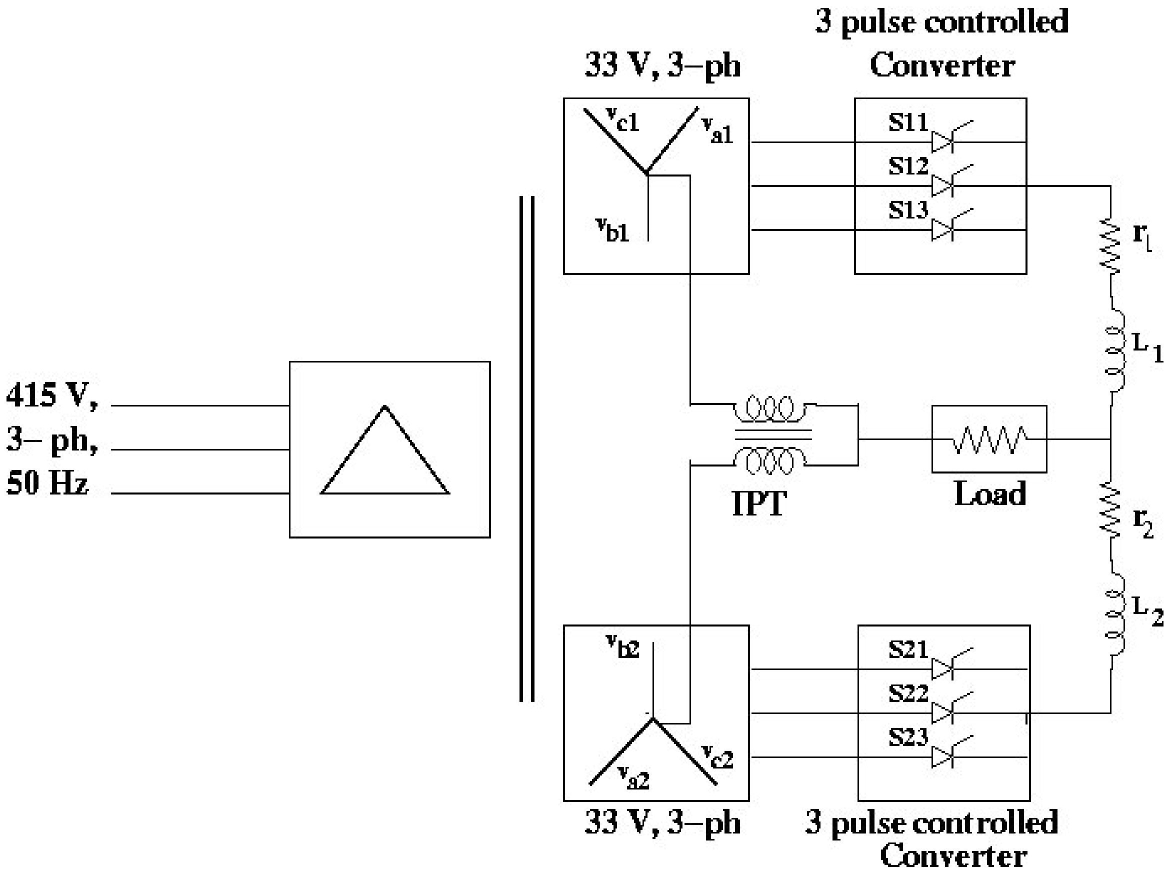
Simple Inrush

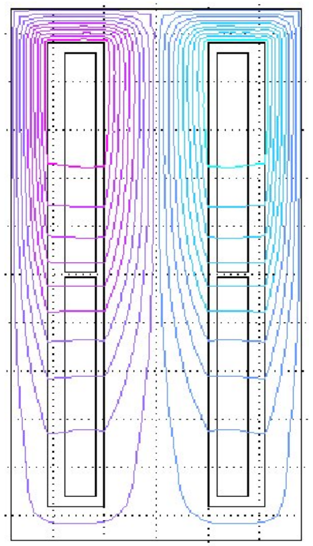
Sympathetic Inrush



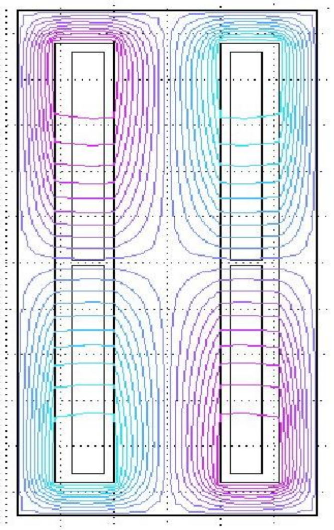
Ref: G. B. Kumbhar and S. V. Kulkarni, "Analysis of Sympathetic Inrush Phenomena in Transformers Using Coupled Field-Circuit Approach," *IEEE PES General Meeting*, June 24-28, 2007, Tampa, USA.

3. Interphase Transformer (IPT)





Unbalanced case



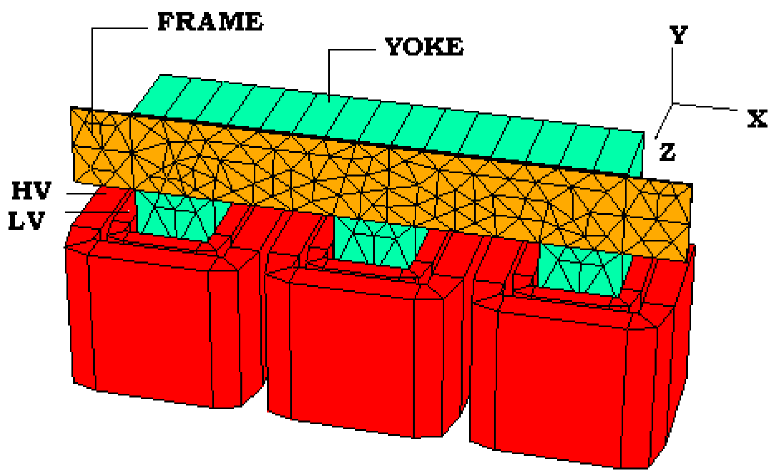
Balanced case

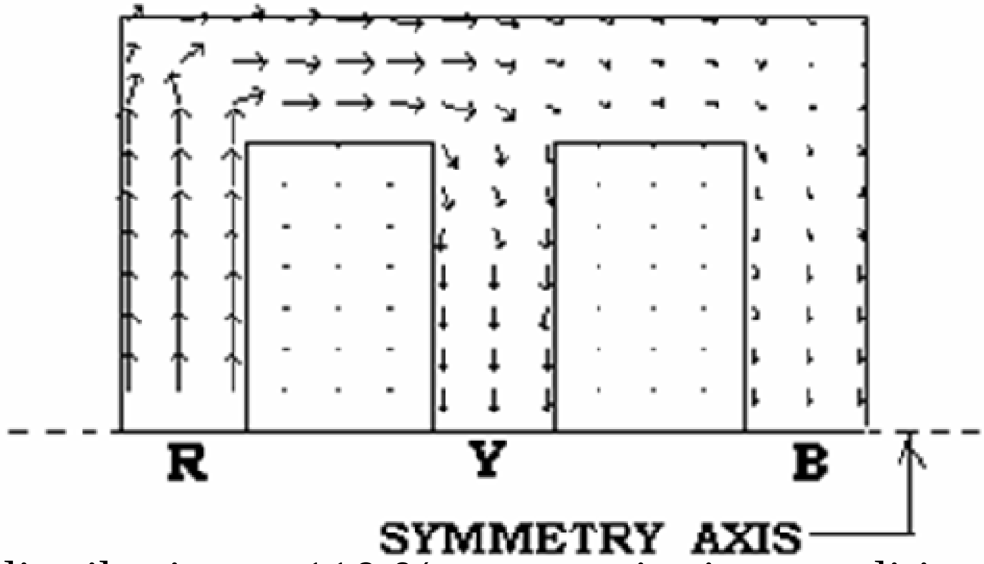
Flux in the IPT Core

Ref: R. S. Bhide, G. B. Kumbhar, S. V. Kulkarni, and J. P. Koria, “Coupled circuit-field formulation for analysis of parallel operation of converters with interphase transformer,” *Electric Power Systems Research*, Vol. 78, Issue 1, January 2008, pp. 158-164.

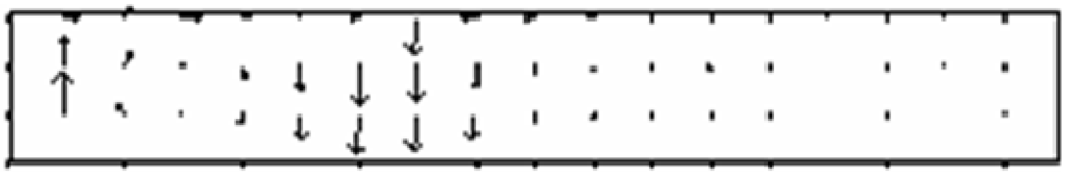
4. Over-excitation Conditions

- Commonly specified over-excitation conditions are: 110% or 115% continuous, 125% for 1 minute. 140% for 5 seconds. 150% for 1 second





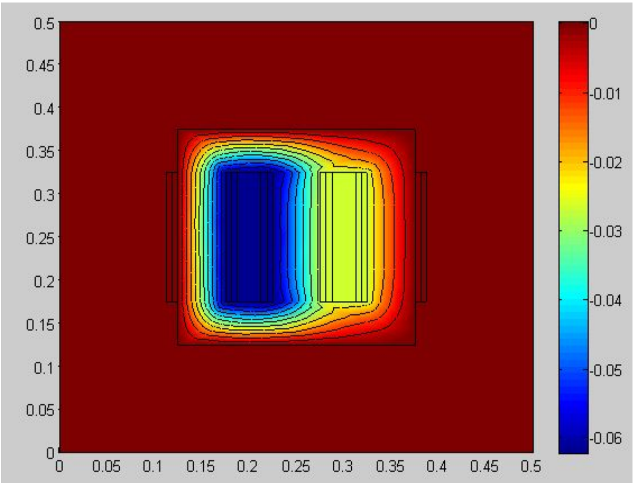
Flux distribution at 110 % over-excitation condition



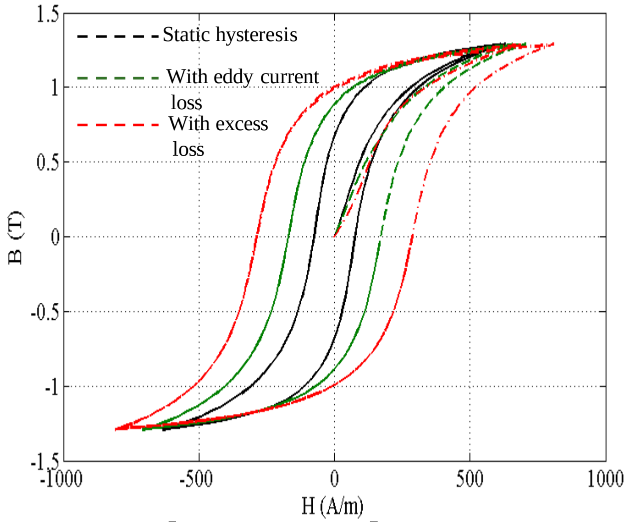
Eddy currents in frame

Ref: D. A. Koppikar, S. V. Kulkarni, and S. A. Khaparde, "Overfluxing simulation of transformer by 3D FEM analysis," *Fourth Conference on EHV Technology*, IISc Bangalore, 17-18 July 1998, pp. 69-71.

5. Dynamic Hysteresis



Flux for single phase excitation

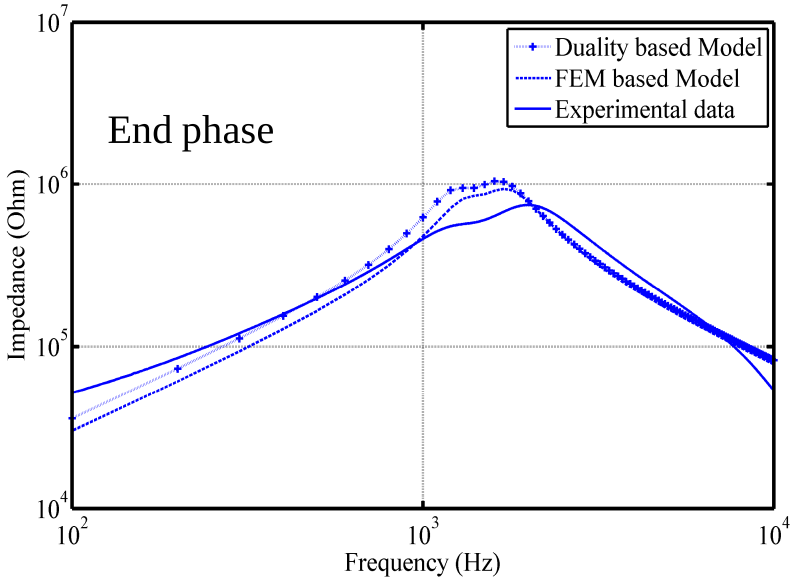


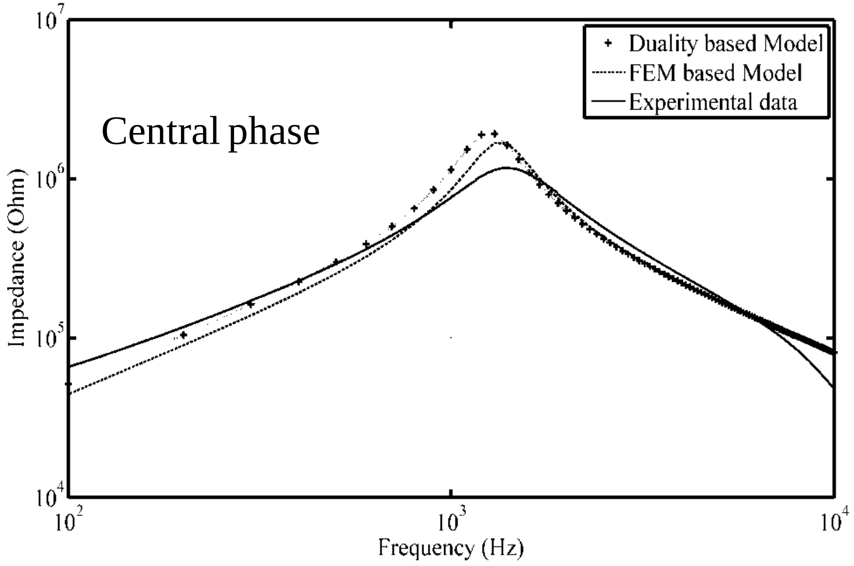
Dynamic hysteresis loops

- Hysteresis phenomenon is modelled using the Jiles-Atherton model
- Dynamic losses are included using the field separation approach
- Fixed point method is used to account for nonlinearities

Ref: A. P. S. Baghel and S. V. Kulkarni, "Modeling of magnetic characteristics including hysteresis effects for transformers," *Invited paper, 3rd International Colloquium Transformer Research and Asset Management*, Split, Croatia, October 15 – 17, 2014.

6. Frequency Response Analysis

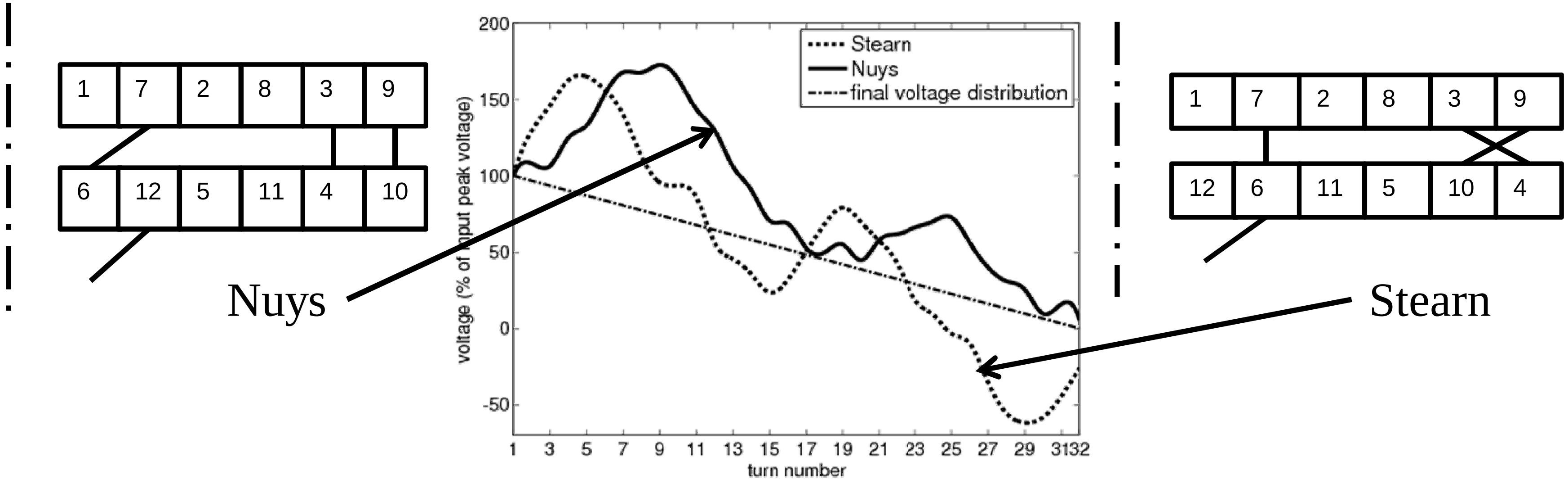




Ref: K. P. Badgujar, A. P. S. Baghel, and S. V. Kulkarni, "A Coupled Field-Circuit Formulation and a Duality Based Approach for Analysis of Low-Frequency Response of Transformers," *Annual IEEE India Conference* (*INDICON*), Mumbai, 2013.

7. MTL-based Modeling: VFTO Analysis

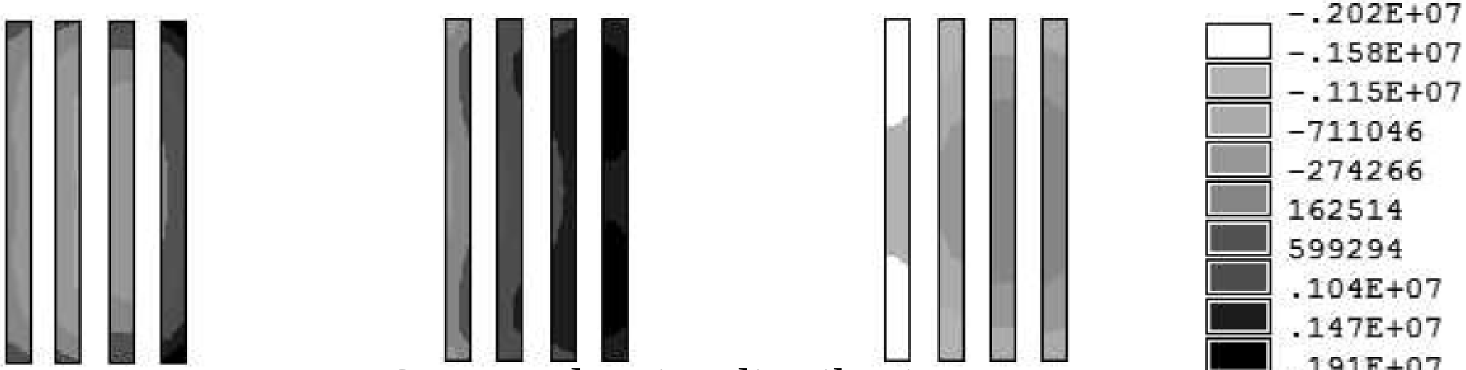
VFTO: Very Fast Transient Overvoltages



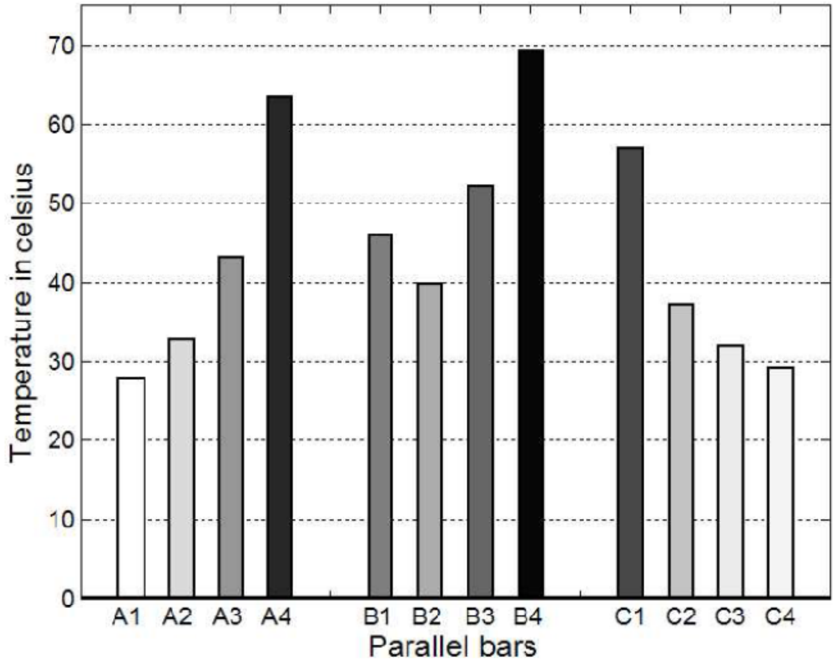
- MTL (multi-conductor transmission line): bridge between circuit and detailed field modeling
- Each turn ⇨ transmission line
- Suitable for very high frequencies
- Nuys → sections oscillate together, Stearn → incoherent

Ref: M. M. Kane and S. V. Kulkarni, "MTL-Based Analysis to Distinguish High-Frequency Behavior of Interleaved Windings in Power Transformers," *IEEE Transactions on Power Delivery*, vol. 28, pp. 2291-2299, Oct. 2013.

8. Current Distribution and Temperature Rise of Bars



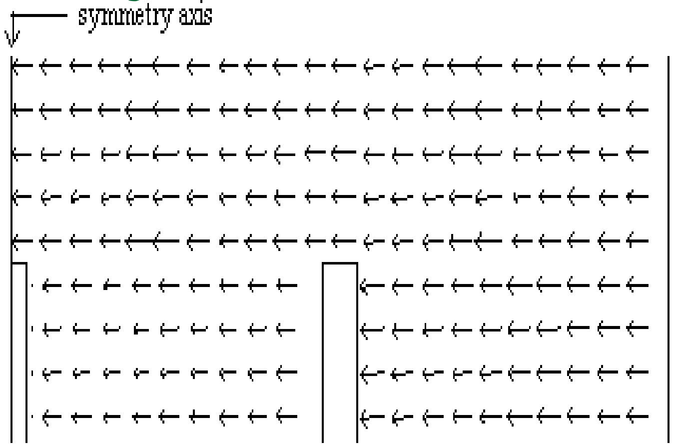
Current density distributions



Current density distribution is completely different in bars due to unequal mutual impedances and proximity effects

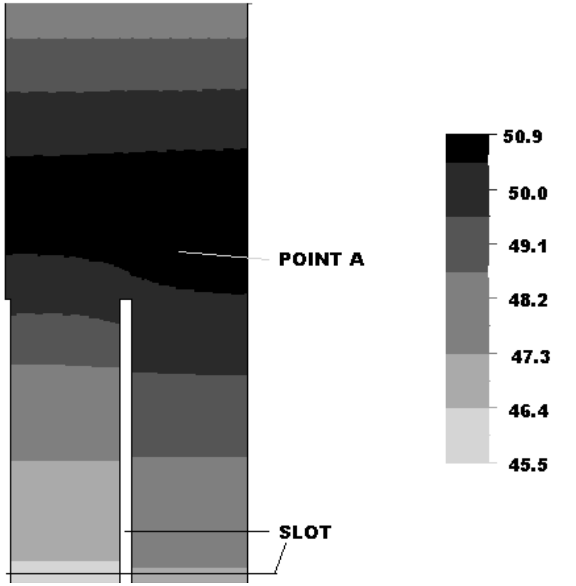
Ref: G. B. Kumbhar, S.V. Kulkarni, R. Escarela-Perez, and E. Campero-Littlewood, "Applications of coupled field formulations to electrical machinery," *The International Journal for Computation and Mathematics in Electrical and Electronic Engineering*, Vol. 26, 2007, pp. 489-523.

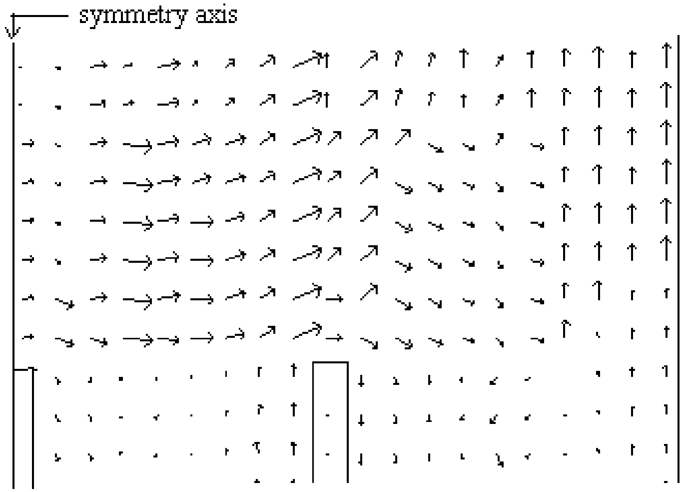
9. Eddy Currents in Flitch Plates



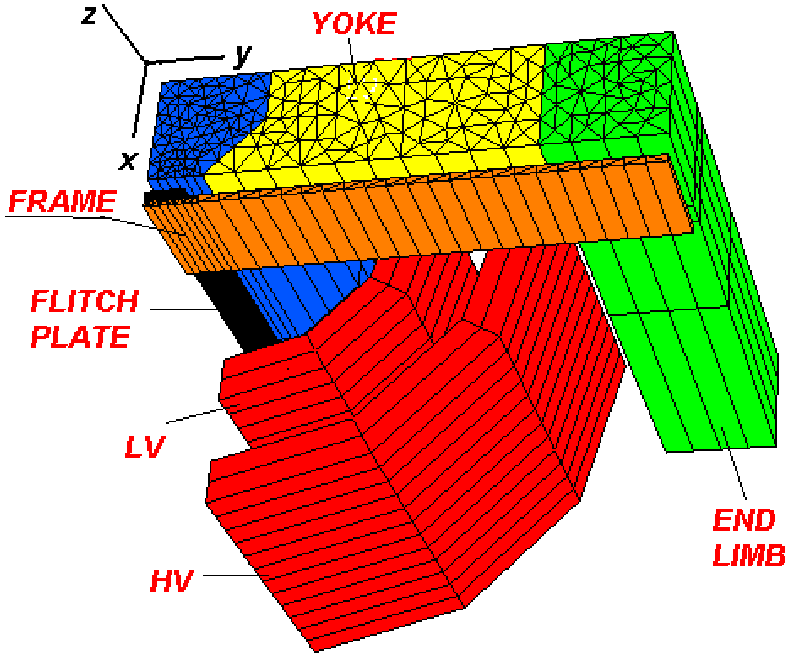
Eddy currents in a magnetic clamp plate

Temperature profile



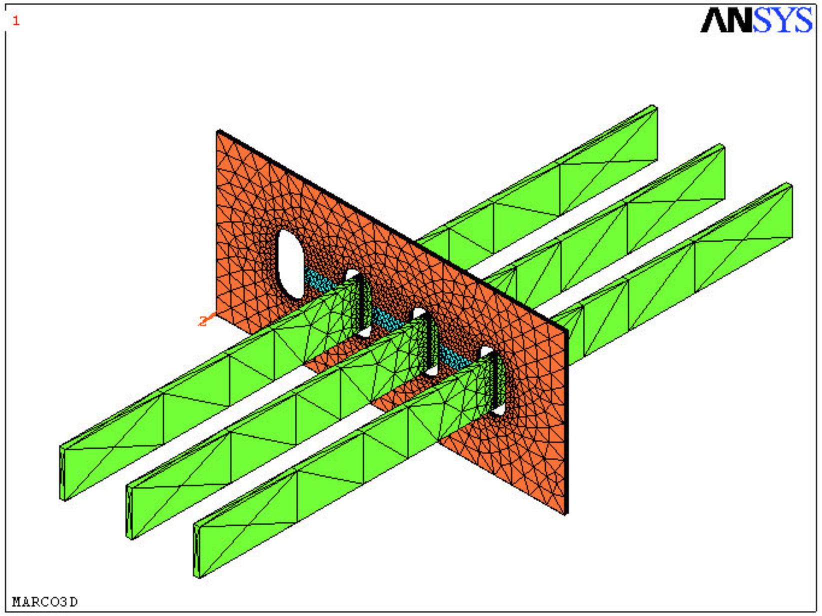


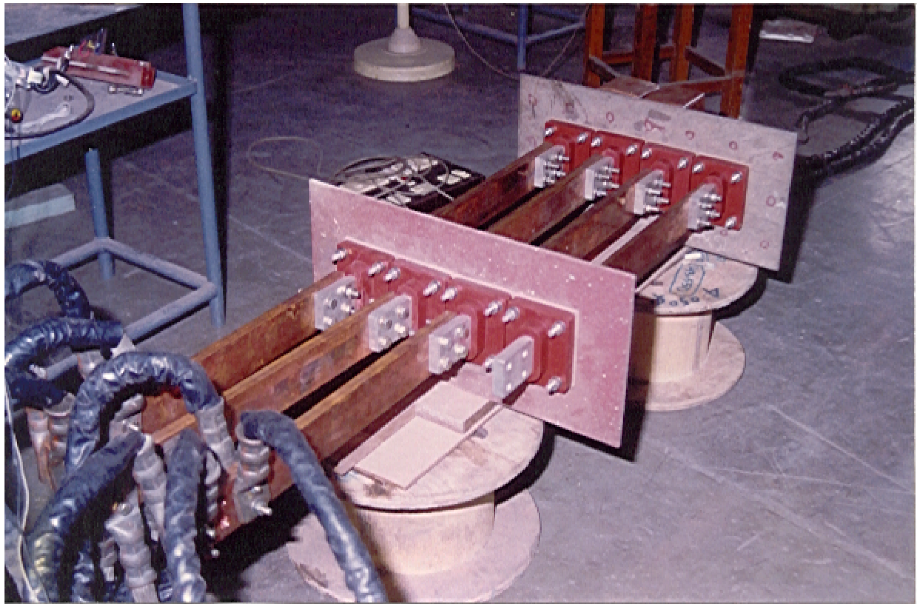
Eddy currents in a non-magnetic clamp plate



Ref: D. A. Koppikar, S. V. Kulkarni, P. N. Srinivas, S. A. Khaparde, and R. Jain, "Evaluation of flitch plate losses in power transformers," *IEEE Transactions on Power Delivery.*, vol. 14, no. 3, July 1999, pp. 996-1001.

10. Eddy Current Loss in Bushing Mounting Plates



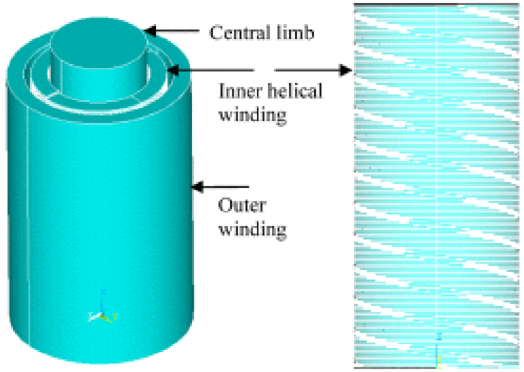


Current (A)	Method A (W)	Method B (W)	Method C (W)	Method D (W)
2000	56	66	65	58
2250	68	84	74	70
2500	81	103	95	93
2800	98	130	119	116

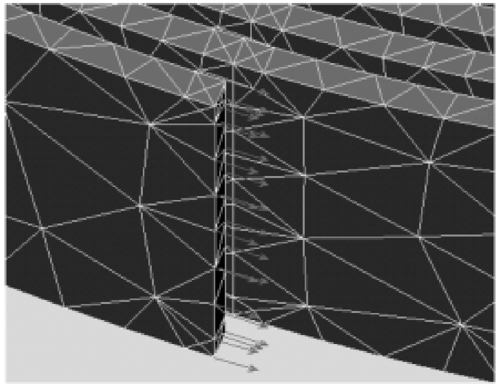
A. Analytical
B. 3D FEM
C. From Steady State Temp. Rise
D. From Transient Temp. Rise

Ref: S. V. Kulkarni, J. C. Olivares, R. Escarela-Perez, V. K. Lakhiani, and J. Turowski, "Evaluation of eddy losses in cover plates of distribution transformers," *IEE Proceedings -Science, Measurement and Technology*, vol. 151, no. 5, Sep. 2004, pp. 313-318

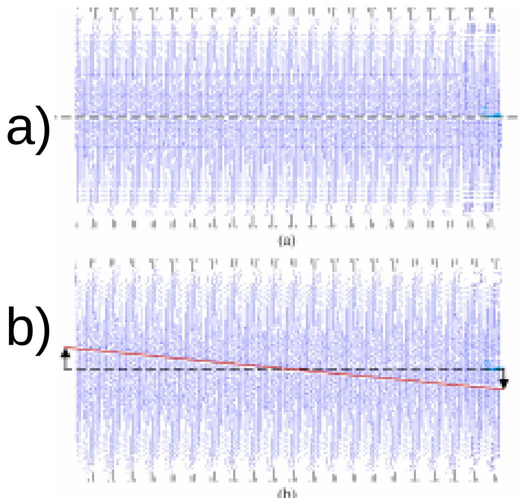
11. Electromagnetic-Structural Analysis of Spiraling Phenomenon in a Helical Winding



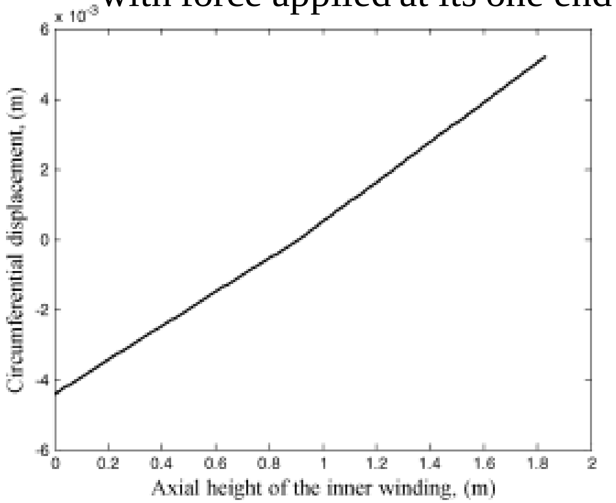
3-D model of the transformer winding



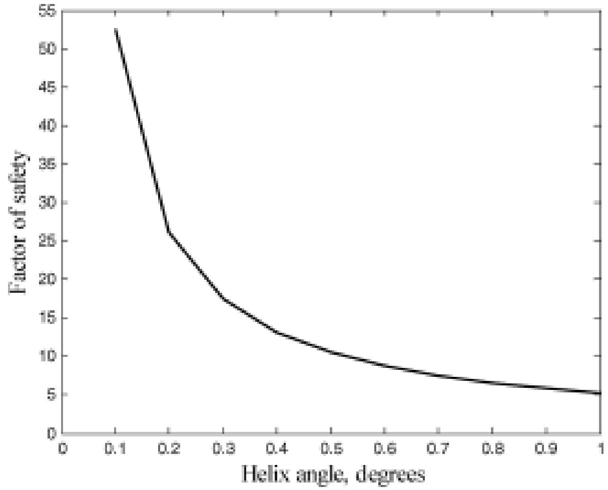
Meshed model of the inner winding with force applied at its one end



Circumferential displacement plot of the winding conductors. (a) Healthy condition (b) Short-circuit condition



Circumferential displacement of the conductors



Variation of the factor of safety with the helix angle

Ref: A. Bakshi and S. V. Kulkarni, “Coupled Electromagnetic-Structural Analysis of the Spiraling Phenomenon in a Helical Winding of a Power Transformer,” *IEEE Transactions on Power Delivery*, Vol. 29, Feb. 2014, pp. 235-240.

Conclusions

- Coupled field treatment is required to solve many intricate problems in the transformers
- Analysis of some diverse and important problems associated with power transformers is presented
- The considered problems are such that they could only be solved accurately using the coupled-field formulations
- The work has dealt with real life practical problems faced by transformer researchers and most of the studies are applicable to a wide range of transformers
- The developed competence can be used to solve complex coupled problems in other electrical machines and power apparatus

Testimonials/Feedback

- Prof. Francisco de Leon, New York University

"The impact of his book is tremendous. I have had several post-doctoral fellows, who move to/from New York City from their countries, and the only book they carry with them is Prof. Kulkarni's transformer book."

- Mr. P Ramachandran, Technical Advisor, ABB India Ltd

"Frequent references to this book in various technical discussion fora and electrical engineering websites show the wide popularity and acceptance of this book around the world. Transformer factories around the world use this popular text as a reference book."

Thank You