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:

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

Rotational Flux in a T-Joint

Saturation in Joints
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
  \[ \nabla^2 A = -\mu J_o \]
  \[
  \begin{bmatrix}
  K^e 
  \end{bmatrix}_{3\times3} \{A\}_{3\times1} = \{b^e\}_{3\times1}
  \]

- Diffusion equation: Time-harmonic eddy current problems
  \[ \nabla^2 A = -\mu J_o + j\sigma\omega\mu A \]
  \[
  \begin{bmatrix}
  K^e 
  \end{bmatrix}\{A^e\} - j\omega \begin{bmatrix}
  T^e 
  \end{bmatrix}\{A^e\} = \{b^e\}
  \]

- Transient analysis: Magnetizing inrush simulation
  \[ \nabla^2 A = -J_o + \sigma \frac{\partial A}{\partial t} \]
  \[
  \begin{bmatrix}
  K 
  \end{bmatrix}\{A^e(t)\} - \begin{bmatrix}
  T 
  \end{bmatrix} \frac{\partial}{\partial t} \{A^e(t)\} = \{b^e\} 
  \]
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

- Power Electronics Circuit
- Circuit & Control Systems
- Magnetic Field
- Electric/Electrostatic Field
- Acoustic Field
- Mechanical/Structural Field
- Fluid Flow Field

Connections:
- Control signal
- Input voltages
- Inductances
- Voltages and currents
- Capacitances
- Current
- Induced voltages
- EM Forces
- Change in geometry
- Change in permeability and conductivity
- Eddy/hysteresis losses
- FR & Dielectric losses
- Change in permittivity and conductivity
- Vibrations
- Fluid waves
- Expansion & compression
- Convection
- Cooling
**Coupled Field Formulations: Field-Circuit Coupling**

- **Electromagnetic model:**
  \[
  \nabla \times \left( \frac{1}{\mu} \nabla \times A \right) = J_0 - \sigma \frac{\partial A}{\partial t} - \sigma \nabla V + \nabla \times M + \sigma \nu \times (\nabla \times A)
  \]

  here, \( M \) is the magnetization vector and \( \nu \) is the velocity of conductors

- **Circuit coupling:**

Field-circuit coupling mechanism
Coupled Field Formulations: Field-Circuit Coupling

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

(a) Stranded (electrically thin) conductor

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

(b) Solid (electrically thick) conductor
**Coupled Field Formulations: Magnetic-Thermal**

- **Governing Equations:**

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

\[
\nabla \cdot (k \nabla (T)) = -q(A_z,T) + mc \frac{\partial T}{\partial t}
\]

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

- **Coupling Relation:**

Temperature dependence:

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

**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:**

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

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 (\(J \times B\) 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**

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>FEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux density in end limbs (T)</td>
<td>1.04</td>
<td>0.93</td>
</tr>
<tr>
<td>Extra core loss due to the half-turn effect (kW)</td>
<td>4.2</td>
<td>3.9</td>
</tr>
</tbody>
</table>

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

**Three-phase five-limb transformer**

<table>
<thead>
<tr>
<th></th>
<th>Flux density (T) for unbalanced currents in windings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Balanced</td>
</tr>
<tr>
<td>Without half-turn</td>
<td>0.02</td>
</tr>
<tr>
<td>With half-turn</td>
<td>0.04</td>
</tr>
</tbody>
</table>

2. Sympathetic Inrush

3. Interphase Transformer (IPT)

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

5. Dynamic Hysteresis

- 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

6. Frequency Response Analysis

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

8. Current Distribution and Temperature Rise of Bars

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

9. Eddy Currents in Flitch Plates

Eddy currents in a magnetic clamp plate

Eddy currents in a non-magnetic clamp plate

10. Eddy Current Loss in Bushing Mounting Plates

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Method A (W)</th>
<th>Method B (W)</th>
<th>Method C (W)</th>
<th>Method D (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>56</td>
<td>66</td>
<td>65</td>
<td>58</td>
</tr>
<tr>
<td>2250</td>
<td>68</td>
<td>84</td>
<td>74</td>
<td>70</td>
</tr>
<tr>
<td>2500</td>
<td>81</td>
<td>103</td>
<td>95</td>
<td>93</td>
</tr>
<tr>
<td>2800</td>
<td>98</td>
<td>130</td>
<td>119</td>
<td>116</td>
</tr>
</tbody>
</table>

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

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

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. ABB Transformer factories around the world use this popular text as a reference book.”
Thank You