Coupled Electromagnetic and Thermal Analysis of Ferrite Core Electronic Planar Transformer

Mark Christini
ANSYS, Inc
Outline

• Introduction
• Maxwell 3D Eddy Current and Electrostatic Simulation
• ANSYS Mechanical Thermal Simulation
• 2-way Thermal Coupling back to Maxwell
• Simppler System Simulation using Maxwell State Space Dynamic model
• Summary
Introduction

• Coupled electromagnetic-thermal analysis of a ferrite core electronic planar transformer

• Magnetic simulation done at fundamental frequency = 100kHz with harmonics up to 5MHz

• All sources of losses considered including: eddy current, skin, and proximity losses in the windings as well as eddy current and hysteresis losses in the ferrite core

• Losses are directly coupled into an ANSYS Mechanical Thermal simulation in order to determine temperature rise using element by element coupling

• Temperatures fed back to Maxwell for material changes

• System simulation done inside of Simpler using dynamic state space frequency dependent model
Coupled Electromechanical Design Flow

Q3D
Parasitics

Simplorer
System Design

RMxprt
Motor Design

ANSYS CFD
Fluid Flow

PExpert
Magnetics

ANSYS
Mechanical
Thermal/Stress

Maxwell 2D/3D
Electromagnetic Components

Model order Reduction
Co-simulation
Field Solution
Model Generation
FEA Adaptive Meshing

In 2D, finite elements are triangles.

In 3D, finite elements are tetrahedra.
Transformer Design Challenges

- **Magnetic effects:**
  - nonlinear materials
  - frequency dependent materials
  - temp dependent materials
  - eddy currents
  - proximity effects
  - time diffusion of magnetic fields
  - transient excitations

- **Electric Field effects:**
  - varying dielectric permitivities
  - varying dimensions and shape
  - 3D field effects
ANSYS Comprehensive Solution

ANSYS Mixed-Signal Multi-Domain System Simulator

Model Order Reduction & Cosimulation

ANSYS Workbench

System
Circuit
Component

Electrical  Magnetic  Fluid  Mechanical  Thermal  Acoustic
Workbench Coupling Technology
Electronic Planar Transformer

- Ferrite PQ Core
- Primary turns = 4
- Secondary turns = 2
- Insulation layers between conductors
- Fundamental Frequency = 100kHz
Maxwell 3D Source Setup

- Load case with Ipri = 50A and Isec = 80A
- Unbalanced A-turns for core excitation
Ferrite Core Properties

Frequency dependent permeability and imaginary permeability

Use Simplorer Sheetscan utility to grab permeability data points

Fig. 1 Complex permeability as a function of frequency.

Datasheet  Sheetscan
Frequency Dependent Core Properties in Maxwell

Required inputs for Maxwell are real permeability and loss tangent

Loss tangent based on series equivalent model

Temp = 0° C

<table>
<thead>
<tr>
<th>frequency</th>
<th>perm</th>
<th>perm_imag</th>
<th>loss tangent</th>
</tr>
</thead>
<tbody>
<tr>
<td>100000</td>
<td>1939</td>
<td>6</td>
<td>0.0032</td>
</tr>
<tr>
<td>200000</td>
<td>1977</td>
<td>13</td>
<td>0.0068</td>
</tr>
<tr>
<td>300000</td>
<td>2015</td>
<td>22</td>
<td>0.0110</td>
</tr>
<tr>
<td>400000</td>
<td>2052</td>
<td>35</td>
<td>0.0173</td>
</tr>
<tr>
<td>500000</td>
<td>2090</td>
<td>51</td>
<td>0.0244</td>
</tr>
<tr>
<td>600000</td>
<td>2165</td>
<td>79</td>
<td>0.0363</td>
</tr>
<tr>
<td>700000</td>
<td>2281</td>
<td>119</td>
<td>0.0522</td>
</tr>
<tr>
<td>800000</td>
<td>2322</td>
<td>174</td>
<td>0.0750</td>
</tr>
<tr>
<td>900000</td>
<td>2446</td>
<td>264</td>
<td>0.1078</td>
</tr>
<tr>
<td>1000000</td>
<td>2533</td>
<td>336</td>
<td>0.1326</td>
</tr>
<tr>
<td>1500000</td>
<td>2581</td>
<td>998</td>
<td>0.3869</td>
</tr>
<tr>
<td>2000000</td>
<td>2029</td>
<td>2101</td>
<td>1.0351</td>
</tr>
<tr>
<td>3000000</td>
<td>828</td>
<td>2178</td>
<td>2.6306</td>
</tr>
<tr>
<td>4000000</td>
<td>227</td>
<td>1626</td>
<td>7.1618</td>
</tr>
<tr>
<td>5000000</td>
<td>97</td>
<td>1093</td>
<td>11.2199</td>
</tr>
<tr>
<td>6000000</td>
<td>61</td>
<td>663</td>
<td>10.8398</td>
</tr>
<tr>
<td>7000000</td>
<td>47</td>
<td>424</td>
<td>8.9644</td>
</tr>
<tr>
<td>8000000</td>
<td>39</td>
<td>327</td>
<td>8.3658</td>
</tr>
<tr>
<td>9000000</td>
<td>34</td>
<td>271</td>
<td>7.9437</td>
</tr>
<tr>
<td>10000000</td>
<td>31</td>
<td>228</td>
<td>7.4132</td>
</tr>
</tbody>
</table>
Core Material Properties - Inputs

Datasets used to define properties vs. frequency:
- Relative Permeability = \text{pwl}(\text{perm}, \text{Freq})
- Magnetic Loss tangent = \text{pwl}(\text{losstan}, \text{Freq})

Relative permitivity = 12
Conductivity = 0.5 (S/m)
Core Material Properties - Outputs

Use “named expression” in calculator to verify the real and imaginary permeability

Use report to plot $\mu'$ and loss tangent vs. frequency

**Real permeability - $\mu'$**
- Num > Vector > 1,0,0
- Material > perm > multiply
- complex > real > mag
- constant > $\mu_0$ > divide

**Real permeability - $\mu''$**
- Num > Vector > 1,0,0
- Material > perm > multiply
- complex > imag > mag
- constant > $\mu_0$ > divide

**Loss tangent**
- $\delta = \frac{\mu''}{\mu'}$
Temperature Settings in Maxwell

- Initial temperature = 22 °C
- Core and windings have temp dependent materials

<table>
<thead>
<tr>
<th>Object No.</th>
<th>Material</th>
<th>Temperature Dependent</th>
<th>Temperature</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>bounding_box</td>
<td>air</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>core_bol</td>
<td>M_3c95_temp</td>
<td>✓</td>
<td>22</td>
<td>cel</td>
</tr>
<tr>
<td>core_top</td>
<td>M_3c95_temp</td>
<td>✓</td>
<td>22</td>
<td>cel</td>
</tr>
<tr>
<td>insulation</td>
<td>polyethylene</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>primary</td>
<td>copper_temp</td>
<td>✓</td>
<td>22</td>
<td>cel</td>
</tr>
<tr>
<td>sec</td>
<td>copper_temp</td>
<td>✓</td>
<td>22</td>
<td>cel</td>
</tr>
</tbody>
</table>
Temperature dependent copper conductivity for 2-way coupling to Maxwell

\[ \sigma = \frac{1}{(1 + 0.0039 \times (Temp - 22))} \]
Initial Conductivity at 100kHz, 22 deg C

- Conductivity = $5.8 \times 10^7$ (S/m)
- Conductivity is constant throughout winding
Temperature dependent ferrite permeability for 2-way coupling to Maxwell
2-way coupling for temperature dependent permeability

<table>
<thead>
<tr>
<th>deg C</th>
<th>perm</th>
<th>perm modifier</th>
</tr>
</thead>
<tbody>
<tr>
<td>-50</td>
<td>1247</td>
<td>0.73</td>
</tr>
<tr>
<td>-25</td>
<td>1440</td>
<td>0.85</td>
</tr>
<tr>
<td>0</td>
<td>1700</td>
<td>1.00</td>
</tr>
<tr>
<td>25</td>
<td>2031</td>
<td>1.19</td>
</tr>
<tr>
<td>50</td>
<td>2442</td>
<td>1.44</td>
</tr>
<tr>
<td>74</td>
<td>2982</td>
<td>1.75</td>
</tr>
<tr>
<td>89</td>
<td>3252</td>
<td>1.91</td>
</tr>
<tr>
<td>100</td>
<td>3368</td>
<td>1.98</td>
</tr>
<tr>
<td>113</td>
<td>3483</td>
<td>2.05</td>
</tr>
<tr>
<td>125</td>
<td>3522</td>
<td>2.11</td>
</tr>
<tr>
<td>137</td>
<td>3560</td>
<td>2.09</td>
</tr>
<tr>
<td>149</td>
<td>3586</td>
<td>2.11</td>
</tr>
<tr>
<td>162</td>
<td>3650</td>
<td>2.15</td>
</tr>
<tr>
<td>175</td>
<td>3753</td>
<td>2.21</td>
</tr>
<tr>
<td>183</td>
<td>3869</td>
<td>2.28</td>
</tr>
<tr>
<td>189</td>
<td>3985</td>
<td>2.34</td>
</tr>
<tr>
<td>191</td>
<td>4113</td>
<td>2.42</td>
</tr>
<tr>
<td>194</td>
<td>4267</td>
<td>2.51</td>
</tr>
<tr>
<td>195</td>
<td>4370</td>
<td>2.57</td>
</tr>
<tr>
<td>197</td>
<td>4524</td>
<td>2.66</td>
</tr>
<tr>
<td>200</td>
<td>4576</td>
<td>2.69</td>
</tr>
<tr>
<td>202</td>
<td>4524</td>
<td>2.66</td>
</tr>
<tr>
<td>204</td>
<td>4422</td>
<td>2.60</td>
</tr>
<tr>
<td>205</td>
<td>4023</td>
<td>2.37</td>
</tr>
<tr>
<td>206</td>
<td>494</td>
<td>1.47</td>
</tr>
<tr>
<td>209</td>
<td>514</td>
<td>0.30</td>
</tr>
<tr>
<td>211</td>
<td>180</td>
<td>0.11</td>
</tr>
<tr>
<td>213</td>
<td>77</td>
<td>0.05</td>
</tr>
<tr>
<td>216</td>
<td>39</td>
<td>0.02</td>
</tr>
<tr>
<td>221</td>
<td>13</td>
<td>0.01</td>
</tr>
<tr>
<td>225</td>
<td>13</td>
<td>0.01</td>
</tr>
</tbody>
</table>

![Graph showing permeability and permeability modifier over temperature range from -50 to 250 degrees Celsius.](image)
Initial Permeability at 100kHz, 22 deg C

Real Permeability

Imaginary Permeability
Current Density at 100kHz

- Load case with $I_{pri} = 50A$ and $I_{sec} = 80A$
Magnetic Flux Density at 100kHz
Winding Eddy Current Loss Density at 100kHz

Winding losses considers skin and proximity effects.
Core Loss Density at 100kHz

\[ P_{eddy} = \frac{1}{2\sigma} \iiint_{vol} \text{Re} (\vec{J} \cdot \vec{J}^*) dV \]

\[ P_{hysteresis} = -\frac{1}{2} \omega \iiint_{vol} \text{Im} (\vec{B} \cdot \vec{H}^*) dV \]

**Ohmic Loss**

**Hysteresis Loss**

<table>
<thead>
<tr>
<th>Freq [kHz]</th>
<th>core_hyst_loss</th>
<th>core_eddy_loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.001082</td>
<td>0.001897</td>
</tr>
<tr>
<td>2</td>
<td>1.211527</td>
<td>0.191875</td>
</tr>
<tr>
<td>3</td>
<td>44.428733</td>
<td>5.032800</td>
</tr>
</tbody>
</table>
Simulated Resistance

![Graph showing simulated resistance](image)

- **Curve Info**
  - Matrix1.R(pri_in,pri_in)
  - Setup1: LastAdaptive
  - Matrix1.R(sec_in,sec_in)
  - Setup1: LastAdaptive
Simulated Inductance

![Graph showing simulated inductance vs frequency]

- **Curve Info**
  - Matrix1.L(pri_in,pri_in)
    - Setup1: LastAdaptive
  - Matrix1.L(sec_in,sec_in)
    - Setup1: LastAdaptive
Simulated Capacitance

Use DC conduction solver to assign +1V and -1V to coils and on core

\[
\begin{bmatrix}
Q_1 \\
Q_2 \\
Q_3
\end{bmatrix} =
\begin{bmatrix}
C_{10} + C_{12} + C_{13} & -C_{12} & -C_{13} \\
-C_{12} & C_{20} + C_{12} + C_{23} & -C_{23} \\
-C_{13} & -C_{23} & C_{30} + C_{13} + C_{23}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix}
\]
• Maxwell 3D Eddy Current calculates losses and couples directly to ANSYS thermal
• Maxwell 3D Electrostatic calculates capacitances between winding and core
• Maxwell 3D Eddy Current calculates R,L vs. frequency and inports directly into Simplorer via the State-space dynamic link
Workbench Coupling

Engineering Data allows materials to be chosen including thermal conductivity
Workbench Coupling

- Workbench geometry imported directly into Workbench
- Appropriate materials can then be assigned
Workbench Coupling

- Workbench mesh is different than Maxwell 3D mesh
- Set maximum element size = 0.5mm
• Fixed temperature cold plate assigned to base = 22 °C
• Convection boundaries assigned to outer surfaces of core and coils = 5 W/m²-°C
Workbench Coupling

- Imported Loss Density on core and windings at 100kHz
- Matches Maxwell 3D loss density

**Total Losses**

<table>
<thead>
<tr>
<th>Object</th>
<th>Total Loss</th>
<th>Scaling Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>core_bot</td>
<td>0.702112W</td>
<td>1.00679</td>
</tr>
<tr>
<td>core_top</td>
<td>0.701290W</td>
<td>1.00652</td>
</tr>
<tr>
<td>sec</td>
<td>6.712708W</td>
<td>1.01602</td>
</tr>
<tr>
<td>primary</td>
<td>6.657986W</td>
<td>1.03279</td>
</tr>
</tbody>
</table>
Ferrite Core Transformer Temperature at 100kHz
Export temperature back to Maxwell
Resolve in Maxwell with actual temp
Updated Copper Conductivity with 2-way coupling

Uniform conductivity
= $5.8 \times 10^7$ (S/m) at 22°C

Varying conductivity with varying temperature
(decreases as temp increases)
Simplorer Architecture

C/C++ User Defined Model
Matlab® Real Time Workshop

Matlab Simulink®
ANSYS MBD
ANSYS Maxwell

Simulation Data Bus/Simulator Coupling Technology

Blocks:
Circuits:
States:

Model Extraction: Equivalent Circuit, Dynamic State Space, Impulse Response Extracted LTI, Stiffness Matrix

Electromagnetic (FEA)
Mechanical (FEA)
Thermal (FEA)
Fluidic (CFD)

VHDL-AMS
IF (domain = quiescent_domain)
V0 == init_v;
ELSE
Current == cap*voltage'dot;
END USE;

IF (domain = quiescent_domain)
V0 == init_v;
ELSE
Current == cap*voltage'dot;
END USE;
Maxwell 3D Frequency Sweep

- Adaptive Frequency: 100 kHz
- Enable Iterative Solver
- Relative Residual: 0.0001
- Use higher order shape functions

- Sweep Setup:
  - Type: Linear Step
  - Start: 10000 Hz
  - Stop: 5000000 Hz
  - Step Size: 100000 Hz
  - Save Fields (All Frequencies)
  - List of frequencies: 10000 Hz, 100000 Hz, 500000 Hz, 1000000 Hz, 2000000 Hz, 3000000 Hz, 4000000 Hz, 5000000 Hz

- Use Defaults
Simplorer System Simulation
Simplorer System Simulation
Conclusions

- Maxwell 3D determines loss components (eddy current, hysteresis, proximity, skin) at multiple frequencies as well as R, L and C

- Workbench allows Maxwell losses to be spatially coupled to ANSYS Mechanical for temperature rise calculation

- Resulting temperature rise can be coupled back to Maxwell in order to used to change material properties such as permeability and conductivity

- Maxwell 3D can export a frequency dependent transfer function using Dynamic State Space coupling inside of Simplorer to allow for a complete system simulation