High Power Electronics Design

Scott Stanton
Technical Director
Advanced Technology Initiatives

Mark Christini
Lead Application Engineer
Objectives

- ANSYS Multiphysics Inverter Design Flow
  - High-Power System Design Concept
    - IGBT Electro-Thermal Model
      - Average
      - Dynamic
    - IGBT Package Thermal Model
      - Extracted from CFD
  - EMI/EMC Analysis
    - Parameter Extraction: R, L, C
    - Radiated Emissions – Full Wave Effects
  - IGBT Package Mechanical Stress Analysis
    - Thermal Stress
    - Electromagnetic Forces
IGBT Models in Simplorer

**Average IGBT Model**
- DC core
- Energy calculation
- Thermal network

**Dynamic IGBT Model**
- DC core
- Capacities C(V), C(I) parasitics L, R, C controlled sources
- Full parameter excess
- Thermal network

**Maximum simulation speed:**
- Accurate static behavior
- Accurate thermal response
- No voltage and current transients
- Losses
- Suitable for system design (seconds)

**Maximum simulation accuracy:**
- Sophisticated semiconductor based model
- Accurate static, dynamic and thermal behaviour
- Accurate gate voltage and current waveforms
- Losses
- Suitable for drive optimization, EMI/EMC (msec)
IGBT Characterization

Extraction of the IGBT Electro-Thermal Parameters

Fig. 12 - Typ. Transfer Characteristics

$V_{CE} = 50V$, $t_p = 10\mu s$

Transfer characteristic curve from datasheet

Fitted curve vs. measured data

// Update IGBT Model Parameters
Up = 5.51895
K = 5.88228
n_fet = 1.79371
alpha_Up = -0.507243
alpha_K = -2.57592
alpha_nfet = 0.0011548

Extracted parameter values
The Average IGBT Model

- Three main parts:
  1) static core – V,I transfer and output characteristics
  2) energy calculation section – on/off and DC power
  3) thermal network- with or w/o external thermal link
- Parameters extracted through characteristic curves
The Average IGBT Model

- Switching $V$ and $I$ waveforms are square
- Switching losses are calculated at each switching period
- Turn-ON/OFF power pulses are injected into thermal network
- Amplitude of the rectangular power pulses are calculated

$$
P_{\text{ON}} = \frac{E_{\text{ON}}}{T_{\text{ON}}}, \quad P_{\text{OFF}} = \frac{E_{\text{OFF}}}{T_{\text{OFF}}}, \quad P_{\text{DC}} = V_{\text{CE,sat}} \left| V_{\text{GE}} \right| I_C \cdot I_C
$$

- $P_{\text{ON}}/P_{\text{OFF}}$ – Switching Power
- $E_{\text{ON}}/E_{\text{OFF}}$ – Energy losses
- $P_{\text{DC}}$ – Conduction power dissipation
- $T_{\text{ON}}/T_{\text{OFF}}$ – Power injection pulse durations
- $V_{\text{CE,sat}}$ – Saturation collector-emitter voltage
The Dynamic IGBT Model

- Dynamic IGBT shares the same static core as Average model
- The switching energy \( E_{\text{switch}} \) of the Dynamic IGBT model is the direct integration of the switching voltage and current
- This is the fundamental advantage over the average model

\[
E_{\text{switch}} = \int_{t_{\text{start}}}^{t_{\text{stop}}} V_{ce}(t) \cdot I_c(t) \, dt
\]
The Dynamic IGBT Model

- Dynamic IGBT accurately captures the switching waveforms
- Suitable for EMI/EMC analysis

\[ E_{\text{switch}} = \int_{t_{\text{start}}}^{t_{\text{stop}}} V_{ce}(t) \cdot I_{c}(t) \, dt \]
Temperature rise at any point in the system is the sum of the independently derived temperature increase attributable to each heat source in the system (superposition).

Assumptions:

- Temperature assumed to be a linear function of heat sources
- This requires that the fluid flow is constant (for each study) and density and all properties are constants
Each matrix element is a complete thermal transient response curve

\[
\begin{bmatrix}
\Delta T_1(t) \\
\Delta T_2(t) \\
\vdots \\
\Delta T_n(t)
\end{bmatrix}
= 
\begin{bmatrix}
\theta_{11}(t) & \varphi_{12}(t) & \cdots & \varphi_{1n}(t) \\
\varphi_{21}(t) & \theta_{22}(t) & \cdots & \varphi_{2n}(t) \\
\vdots & \vdots & \ddots & \vdots \\
\varphi_{n1}(t) & \varphi_{n2}(t) & \cdots & \theta_{nn}(t)
\end{bmatrix}
\begin{bmatrix}
h_1(t) \\
h_2(t) \\
\vdots \\
h_n(t)
\end{bmatrix}
\]
Implementation

**Icepak**
- Specify the geometry of the multi-heat-source system
- Apply each heat source individually
- Measure temperature at nodes of interest (parametric analysis)

**Simplorer**
- Data processing
  - Transfer $T(t)$ into $Z(t)$
- Filter
- Normalize
- Extract parameters through curve fitting
- Generate model
Implementation

Icepak

Specify the geometry of the multi-heat-source system

Apply each heat source individually measure temperature at nodes of interest (parametric analysis)

Data processing

Transfer T(time) into Zth(time)

Filter

Normalize

Simplorer

Extract parameters through curve fitting

Generate model

© 2010 ANSYS, Inc. All rights reserved.
Implementation

**Icepak**
- Specify the geometry of the multi-heat-source system
- Apply each heat source individually measure temperature at nodes of interest (parametric analysis)

**Simplorer**
- Data processing
- Transfer T(time) into Zth(time)
- Extract parameters through curve fitting
- Generate model

Filter
Normalize
Implementation

Icepak

Specify the geometry of the multi-heat-source system

Apply each heat source individually measure temperature at nodes of interest (parametric analysis)

Data processing

Transfer T(time) into Zth(time)

Filter

Normalize

Extract parameters through curve fitting

Generate model

Simplorer
Implementation

Icepak

Specify the geometry of the multi-heat-source system

Apply each heat source individually and measure temperature at nodes of interest (parametric analysis)

Data processing

Transfer T(time) into Zth(time)

Filter

Extract parameters through curve fitting

Normalize

Generate model

© 2010 ANSYS, Inc. All rights reserved.
IGBT Thermal Model Validation

- Simple 4-node system
- Air at a constant speed of 1 m/s
IGBT Thermal Model Results

Node 1 – self-heating

Node 1 – Due to Source 2

Node 1 – Due to Source 3

Node 1 – Due to Source 4
Temperature at Node 1 with constant heat flux applied at all 4 nodes
IGBT Thermal Model Validation

Temperature at Node 1 with time-variant heat flux
IGBT Inverter System
EMI/EMC: L,R,C Extraction

- Extract the resistance, inductance, capacitance and conductance (R,L,C) parameters of the entire package

Frequency can have a significant impact on the design performance.
• Extracting parameters is straightforward as the nets are automatically assigned
EMI/EMC: Mesh and Field Result

The structure is meshed using automatic and adaptive meshing

<table>
<thead>
<tr>
<th>Pass</th>
<th>Type</th>
<th># Triangle</th>
<th>DeltaR</th>
<th>DeltaL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>11558</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>15269</td>
<td>4.2826</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>20267</td>
<td>2.6867</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>27011</td>
<td>2.5257</td>
<td>6.1143</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>35472</td>
<td>0.36587</td>
<td>2.0524</td>
</tr>
</tbody>
</table>
EMI/EMC: Methodology

- The simulation outputs consist of the RLC matrices for different frequencies
System Integration

Circuit Design based on Parametrized IGBT and Frequency Dependent Model
System Integration

Extract Power Loss

FFT
Full Wave Effect

Ansoft HFSS

Multiplied magE plots by Simplorer

Emission Test

MagE@10m by specified inputs

Freq. res.

Normalized S para.
Emitted Fields

- The E field is very localized close to the module even at 100 MHz.
- However, the very high power can lead to large values of E field even far from the module.
- This design is fine at 110 MHz.

mag E @ 100 MHz, Power = 10 000W

<table>
<thead>
<tr>
<th>Spectrum (MHz)</th>
<th>Power (W)</th>
<th>E field at 1m (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>115.7024793</td>
<td>2308.359536</td>
<td>10.35553171</td>
</tr>
</tbody>
</table>
IGBT Thermal and Structural Analysis
Motivation and Methodology

• The high currents that flow through IGBT’s make them susceptible to failure due to the large stresses
  – Lorentz forces
  – Switching losses
  – Conduction losses

Thermal stresses

Electrical Circuit (Simplorer) \(\rightarrow\) Switching Losses

Electromagnetics (Maxwell 3D) \(\rightarrow\) Conduction Losses + Lorentz Forces
**Workflow**

- **Simplorer V9** Solve IGBT Circuit
- **Maxwell V14** Solve for Magnetostatics
- **ANSYS Thermal** Solve Temperature
- **ANSYS Mechanical** Solve Static Structural
- **ANSYS Workbench R13**

**Terminal Current**
- Ohmic Losses
- Lorentz Forces

**Switching Losses**
- Temperature Distribution

**Stress and Deformation**
Step 1

- **Simplorer V9**
  - Solve IGBT Circuit
  - Terminal Current
  - Switching Losses

- **Maxwell V14**
  - Solve for Magnetostatics
  - Lorentz Forces
  - Ohmic Losses

- **ANSYS Thermal**
  - Solve Temperature
  - Temperature Distribution
  - Stress and Deformation

- **ANSYS Mechanical**
  - Solve Static Structural
    - Stress and Deformation
Create Simplorer Solution

- Launch ANSYS Workbench R13
- Drag and Drop a Simplorer Analysis System onto the project page
- Right click on Setup and select Edit to launch Simplorer V9
IGBT Circuit

- Input Pulse
- IGBT Unit
- Ammeter (Gives Terminal Current through IGBT)
- Multiplier (Gives Switching Losses across IGBT)
Step 2

Maxwell V14
Solve for Magnetostatics

Terminal Current

Simplorer V9
Solve IGBT Circuit

Switching Losses

Ohmic Losses

ANSYS Thermal
Solve Temperature

Lorentz Forces

Temperature Distribution

ANSYS Mechanical
Solve Static Structural

Stress and Deformation
Create Maxwell System

- Select a Maxwell Analysis System
- Drag and drop it on Project Schematic page as a Standalone system
- Right click on “Geometry” tab and select Edit to Launch Maxwell
Complete IGBT Module

The Current through one phase is shared equally between two IGBT’s.
Material Definition

- Import the IGBT model
- Set Solution type to “Magnetostatic”
- Set material properties of all the objects
- Diodes and IGBT units which are OFF mode are applied with Vacuum material
Set Current Excitations

- Maximum current through IGBT was calculated by Simplorer which will be set as terminal current
- Set Current excitations of 20A to positive terminals
- Set Current excitation of 40A as Phase current
  - The value is set as twice the terminal current
Solve

- Add solution Setup and solve the case with proper settings
- Plot J field to check the results
- Close Maxwell and return to Project Page
Create Steady State Thermal System

- Select Steady State Thermal Analysis system
- Drag and drop it on Solution tab of Maxwell 3D
- This will enable transfer of Ohmic losses calculated in Maxwell to ANSYS Mechanical
Creating Material Data

- Right click on Engineering Data and select Edit to access Material database
- Add needed required material from database to the project and return to project page
- Double click on “Model” tab to launch ANSYS Mechanical
Steady State Thermal Setup

- Specify appropriate materials to all objects
- Apply mesh sizes on required objects and Generate Mesh
- Maxwell link
• Right Click on “Imported Load (Maxwell3DSolution) tab and select “Insert → Heat Generation”

• Under “Geometry”, select all the volumes from the geometry and select “Import Load”

• Conduction losses will be mapped from Maxwell to ANSYS Mechanical
In addition to conduction losses, we also need to apply switching losses of 49.5 W, which was calculated in Simplorer.

We need to divide the switching losses by the volume of all bodies which carry current since the losses will be shared among them.

The resulting value is around 0.01683 W/mm$^3$.

We will apply this value through command line.

This value will add to the conduction losses already applied.
Temperature Distribution

B: Steady-State Thermal
Temperature
Type: Temperature
Unit: °C
Time: 1

- **96.34 Max**
- 89.237
- 82.133
- 75.029
- 67.925
- 60.821
- 53.718
- 46.614
- 39.51
- **32.406 Min**
Step 4

- Simpler V9
  - Solve IGBT Circuit
  - Terminal Current
  - Switching Losses

- Maxwell V14
  - Solve for Magnetostatics
  - Ohmic Losses

- ANSYS Thermal
  - Solve Temperature
  - Temperature Distribution

- ANSYS Mechanical
  - Solve Static Structural
  - Lorentz Forces
  - Stress and Deformation
Create Static Structural System

- Select Static Structural system, Drag and drop it on the “Solution” tab of Steady State Thermal System
- Select “Solution” tab of Maxwell 3D system, drag and drop it on “Setup” tab of Static Structural
- Right click on “Setup” and select “Edit” to launch ANSYS Mechanical

Mapping Electromagnetic Force

Thermal Loading
Setup

- Right Click on “Imported Load (Maxwell3DSolution) tab and select “Insert → Body Force Density”
- Under “Geometry”, select Bondwires to which we want to apply Lorentz Forces
- The forces calculated by Maxwell will be applied to the Bondwires
Results

Equivalent Stress
Max Value: 120 MPa

Deformation
Max Value: 0.044 mm
Summary

• ANSYS Workbench is used to simulate multiphysics problem of IGBT accurately taking into account:
  – Electric Circuits
  – Electromagnetics
  – Thermal
  – Stress

• On the Workbench platform, Simulor, Maxwell3D and ANSYS Mechanical were used for various simulations and data transfer
Conclusion

• ANSYS Integrated Simulation Environment Allows Engineers to Analyze:
  – Average and Dynamic IGBT Models
  – Conducted Emissions: L,R,C Extraction
  – Thermal Effects: Network Model
  – Radiated Emissions
  – Thermal and Electromagnetic Stress

ANSYS technology provides the most comprehensive state-of-the-art high power inverter solutions in the industry.