Modeling Conducted EMI in Power Electronic Systems

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Outline

• Background on electromagnetic compatibility (EMC)
• Conducted emissions testing
• Common-mode (and differential-mode) modeling tutorial
• Application and validation in UA EMI testbed
• Study of leakage current through multi-chip power module (MCPM) baseplate
The paradigm shift in power systems due to power electronics makes EMC critical to design.

**Ideal, 3-phase 60-Hz voltage supply**

![Ideal, 3-phase 60-Hz voltage supply graph]

**Two-level, VSI phase-to-neutral output**

![Two-level, VSI phase-to-neutral output graph]
Present trends in power electronics likely to worsen EMI.

- Maturation of wide-bandgap devices
- Drive for increased efficiency and/or power density
- Increased penetration of renewables and power electronics applications
- Results: higher edge rates (\(dv/dt\)), switching frequencies, and voltage levels
What is electromagnetic compatibility?

- Concerned with the generation, transmission, and reception of electromagnetic energy
- A system is electromagnetically compatible if
  1. It does not cause interference in surrounding systems;
  2. It does not allow interference from surrounding systems;
  3. It does not cause interference with itself
Some basic EMC terminology

• Emissions, interference, and susceptibility
• Conducted emissions vs. radiated emissions
• Differential-mode vs. common-mode

• Electrical length: \( \lambda = \frac{c}{f} \approx \frac{3 \times 10^8}{f} \)
  - \( f = 300 \text{ kHz}, \lambda = 1 \text{ km} \)
  - \( f = 3 \text{ MHz}, \lambda = 100 \text{ m} \)
  - \( f = 30 \text{ MHz}, \lambda = 10 \text{ m} \)
  - \( f = 300 \text{ MHz}, \lambda = 1 \text{ m} \)

• Antennae are poor radiators of signals for which \( \ell \ll \lambda \)
Spectra of Modern Power Electronics

- Traditional IGBT-based systems:
  - Operation Frequencies to ~50 kHz
  - Easily-suppressed extended dynamics
  - Packaging impedances are not critically important

- WBG-based systems:
  - Operation Frequencies to a few MHz
  - Extended dynamics to ~50 MHz
  - Packaging impedances are critically important in “Near-RF” domain

Approach to EMI challenges in PE systems

• PE emissions primarily in conducted band (~10 kHz–30 MHz)
• Objective is to prevent emissions from reaching grid (large antenna)
• Three options: reduce susceptibility, make transmission inefficient, or eliminate source

• **Our Approach:** Employ modeling to minimize conducted emissions
  – Conducted emissions simpler and possible early in design
  – Reduces potential for radiated EMI
How do you measure conducted emissions?

- **Line Impedance Stabilization Network‡:**
  - Provide a standard source impedance for evaluating/measuring EUT emissions
  - Decouple source and EUT emissions
  - Typically modeled as 50 Ω to ground

- LISN only used on input side of EUT
- Commercial LISNs are not available for voltage levels > 1 kV
- Custom LISNs designed and built at UA

‡ "DOD Interface Standard, Requirements for the control of electromagnetic interference characteristics of subsystems and equipment, Mil-Std-461G, 10 Mar. 2015.
Example: emissions from a machine-drive

- Differential mode (DM):
  \[ V_{12} \triangleq V_{1P} - V_{2P} \]
  \[ i_{12} \triangleq \frac{1}{2}(i_1 - i_2) \]

- Common mode (CM):
  \[ V_{CM} \triangleq \frac{1}{2}(V_{1P} + V_{2P}) \]
  \[ i_{CM} \triangleq i_1 + i_2 \]

Fields from CM current are more likely to radiate and couple with nearby equipment.

- Magnetic field accumulates
- Magnetic field cancels

Fields fall off $\propto \frac{1}{r}$ for long wires

$\begin{align*}
\text{Fields fall off } & \propto \frac{1}{r^2} \text{ for long wires}
\end{align*}$
The many faces of the “Common Mode”

• Bearing currents and shaft voltages
  – Cause premature bearing failure in electric machines with VFDs
  – Shock hazard and voltage stress on insulation

• Leakage currents
  – Unintended ground currents typically through capacitive couplings with chassis and heat sinks
  – Interference with low-power electronics

• Circulating currents
  – Steady-state current flow between paralleled converters
  – Can be large and low-frequency, down to DC
  – Lossy, can cause instability, and unbalanced power sharing
DIFFERENTIAL-MODE AND COMMON-MODE EQUIVALENT CIRCUIT MODELING
Objectives of modeling conducted EMI

• Analytically predict parasitic/undesirable behavior of power electronic systems
• Inform/guide measurements to support modeling and analysis
• Predict the impact of new technologies (e.g., WBG devices)
• Evaluate methods to mitigate EMI and CM current through design
Modified definition for CM voltage enables rigorous & flexible model generation

Common Mode

\[ v_{CM} \triangleq \frac{1}{N} \sum_{n=1}^{N} v_{nP} \]

\[ i_{CM} \triangleq \sum_{n=1}^{N} i_n \]

Differential Mode

\[ v_{mn} \triangleq v_{nP} - v_{nP} \]

\[ i_{mn} \triangleq \frac{1}{2}(i_m - i_n) \]

P is arbitrary

DM and CM definitions can be viewed generally as a space transformation

\[
P \triangleq \begin{bmatrix}
  v_{12} & -1 & 0 & \cdots & 0 & 0 \\
  v_{23} & 0 & 1 & -1 & 0 & \cdots & 0 \\
  \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
  v_{mn} & 0 & \cdots & 0 & 1 & -1 \\
  v_{(N-1)N} & 0 & \cdots & 0 & 1 & -1 \\
  v_{CM} & 1 & 1 & \cdots & 1 & 1 & 1
\end{bmatrix}
\]

\[
P \triangleq \begin{bmatrix}
  i_{12} & -\frac{1}{2} & 0 & \cdots & 0 & 0 \\
  i_{23} & 0 & \frac{1}{2} & -\frac{1}{2} & 0 & \cdots & 0 \\
  \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
  i_{mn} & 0 & \cdots & 0 & \frac{1}{2} & -\frac{1}{2} & 0 \\
  i_{(N-1)N} & 0 & \cdots & 0 & \frac{1}{2} & -\frac{1}{2} & 0 \\
  i_{CM} & 1 & 1 & \cdots & 1 & 1 & 1
\end{bmatrix}
\]

\[P\] is arbitrary

These specific definitions lay the foundation for CM equivalent circuit modeling.

Example microgrid

CM equivalent circuit theory

Reduced CM model

Why don’t we just simulate mixed-mode circuits?

OR, why do we need CM equivalent circuits?

• Wide range of time-constants
• Often a large number of electrical components
• Recipe for numerical heartache as number of components increase
• Does not give any design insight unless run many simulations and interpret a lot of data
Example: platform developed for in situ emissions characterization of intermediary conversion systems.

- Architecture inspired by MIL-STD-461 CE-102
- Terminations at input and output representative of fielded applications
- Platform provides DM and CM model validation environment for EUT
- Employed to study leakage currents through module parasitics
An example application of the modeling approach

Half-bridge configuration of UA EMI testbed

Half-bridge EMI testbed

CM equivalent circuit theory

CM equivalent model

CM model development in four steps

1. Add important parasitics to MM component models
2. Partition MM model around switches
3. Transform components to CM equivalent circuits
4. Connect component equivalent circuits using CM reference to form system model
1) Create the mixed-mode model

2) Partition model around switches

3) Decompose components into equivalents

4) Combine equivalents using CM reference

Left multiply by $T_3^\gamma$ and sub in $(T_3^\gamma)^{-1}i_{DCM}$
Step 1: Create the mixed-mode model

- Add parasitics to the standard MM model (if desired or necessary)
- Assuming symmetric parasitics for sake of demonstration
Step 2: Partition MM model around switches

Focus on the non-power-electronic elements – partition into groups
Step 3: Symmetric lines transform following simple parallel addition rules in CM.

Mixed-mode Model

CM Equivalent Circuit

Step 3(a) Detail

Mixed-mode Model

\[ P - v_{1P} + \]
\[ + v_{2P} + \]
\[ v_{P} - \]

\[ R \quad L \quad i_1 \]
\[ R \quad L \quad i_2 \]
\[ C \quad C \]

\[ i'_1 \quad i'_2 \]
Step 3(b): three-line example

Parasitic baseplate capacitance

Mixed-mode Model

\[
\begin{bmatrix}
v_{1P} \\
v_{2P} \\
v_{3P}
\end{bmatrix}
+ \begin{bmatrix}
1 \\
1 \\
1
\end{bmatrix}
= \left( \frac{S_p}{p} + R_h \right)
\begin{bmatrix}
i_1 \\
i_2 \\
i_3
\end{bmatrix}
\]

\[
R_h = R_h
\begin{bmatrix}
1 & 1 & 1 \\
1 & 1 & 1 \\
1 & 1 & 1
\end{bmatrix}
\]

\[
S_p = \frac{1}{C_p}
\begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
T^\nu_3 =
\begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
\frac{1}{3} & \frac{1}{3} & \frac{1}{3}
\end{bmatrix}
\]

\[
T^i_3 =
\begin{bmatrix}
\frac{1}{2} & -\frac{1}{2} & 0 \\
0 & \frac{1}{2} & -\frac{1}{2} \\
1 & 1 & 1
\end{bmatrix}
\]

Left multiply by \(T^\nu_3\) and sub in \((T^i_3)^{-1}i_{dcm}\)

CM Equivalent Circuit

\[
\begin{bmatrix}
v_{12} \\
v_{23} \\
v_{cm}
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
1
\end{bmatrix}
= \left( \frac{S_p'}{p} + R_h' \right)
\begin{bmatrix}
i_{12} \\
i_{23} \\
i_{cm}
\end{bmatrix}
\]

\[
R_h' = R_h
\begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 1
\end{bmatrix}
\]

\[
S_p' = \frac{1}{C_p}
\begin{bmatrix}
3 & 0 & 0 \\
0 & 3 & 0 \\
0 & 0 & \frac{1}{3}
\end{bmatrix}
\]

Step 3(b) Detail
Step 4: Form system model by specifying reference point(s)
Step 4: Form system model by specifying reference point(s)

- Select shared reference point and connect CM equivalent circuits
- Phase node A is selected in this example

Intrinsic CM voltage sources

\[ v_i^{cm} = \frac{1}{2}(v_{UA} + v_{LA}) = \frac{1}{2}(v_{Q1} - v_{Q2}) \]

\[ v_o^{cm} = \frac{1}{2}(v_{AA} + v_{NA}) = \frac{1}{2}v_{NA} \]

\[ v_p^{cm} = \frac{1}{2}(v_{UA} + v_{AA} + v_{LA}) = \frac{1}{3}(v_{Q1} - v_{Q2}) \]
Overall system model

Half-bridge configuration of EMI testbed

Half-bridge EMI testbed CM equivalent circuit theory CM equivalent model
How to model effects of asymmetry?

• Asymmetry between lines of a CM path produces “mode conversion”

• Introduce an asymmetry factor $k$ in module parasitics to investigate impact
Decomposition approach to asymmetric components

Parasitic baseplate capacitance

\[
\begin{bmatrix}
i_1 \\ i_2 \\ i_3
\end{bmatrix} = pC_p
\begin{bmatrix}
1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & k
\end{bmatrix}
\begin{bmatrix}
v_{1,Cp} \\ v_{2,Cp} \\ v_{3,Cp}
\end{bmatrix}
\]

Left multiply by \( T_3^i \) and sub in \((T_3^v)^{-1}v_{dcm}\)

\[
T_3^v = \begin{bmatrix}
1 & -1 & 0 \\ 0 & 1 & -1 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3}
\end{bmatrix}
\]

\[
T_3^i = \begin{bmatrix}
\frac{1}{2} & -\frac{1}{2} & 0 \\ 0 & \frac{1}{2} & -\frac{1}{2} \\ 1 & 1 & 1
\end{bmatrix}
\]

\[
C_p = C_p
\begin{bmatrix}
\frac{1}{2} & 0 & 0 \\ -\frac{1}{6}(1 - k) & \frac{1}{6}(1 + 2k) & \frac{1}{2}(1 - k) \\ \frac{1}{3}(1 - k) & \frac{2}{3}(1 - k) & 2 + k
\end{bmatrix}
\]
Decomposition approach to asymmetric components

Parasitic baseplate capacitance

Mixed-mode Model

\[
\begin{bmatrix}
v_{1p} \\
v_{2p} \\
v_{3p}
\end{bmatrix} + v_{P_g} \begin{bmatrix}
1 \\
1 \\
1
\end{bmatrix} = \left( \frac{S_p}{p} + R_h \right) \begin{bmatrix}
i_1 \\
i_2 \\
i_3
\end{bmatrix}
\]

CM Equivalent Circuit

\[
v_{p_{cm}} + v_{P_g} = -\frac{1}{3(2+k)} \left( v_{Cp}^{dm12} + 2v_{Cp}^{dm23} \right) + \frac{1}{p(2+k)C_p + R_h} i_{Cp}^{cm}
\]

Overall system model

Half-bridge configuration of UA EMI testbed

**Bonus: Analyze/approximate output CM voltage source**

\[ v^\text{cm}_o \triangleq \frac{1}{2} v^\text{NA} \]

\[ v^\text{cm}_o = \frac{1}{2}(v^\text{Q1} - v^\text{Cn1}) \]

\[ = -\frac{1}{2}(v^\text{Q2} + v^\text{Cn2}) \]

\[ = \frac{1}{4}(v^\text{Q1} - v^\text{Q2}) - \frac{1}{4}(v^\text{Cn1} + v^\text{Cn2}) \]

The second term is the CM voltage of the neutral-clamping capacitors. If \( C_n \) is large, this voltage is approximately constant:

\[ v^\text{cm}_o = \frac{1}{4}(v^\text{Q1} - v^\text{Q2}) - \frac{1}{4}v^\text{cm}_o \]

\[ \approx \frac{1}{4}(v^\text{Q1} - v^\text{Q2}) \]

**Bonus: Analyze/approximate mode conversion source**

The second term is the CM voltage of the neutral-clamping capacitors. If $C_n$ is large, this voltage is approximately constant:

$$v_{C_p}^{\text{cm}} = \frac{1 - k}{3(2 + k)}(v_{C_p}^{\text{dm}12} + 2v_{C_p}^{\text{dm}23})$$

$$\approx \frac{1 - k}{3(2 + k)}(v_{Q1} + 2v_{Q2})$$

$$\approx -\frac{1 - k}{6(2 + k)}(v_{Q1} - v_{Q2}) + \frac{1 - k}{2(2 + k)}v_{C_{dc}}$$

Summary: CM equivalent model of the testbed

- CM voltage sources dominated by switching
  - $\frac{dv}{dt}$ & switching frequency critical parameters
- Voltage ripple at neutral point injected into CM
  - Self-resonant behavior of $C_n$ must be avoided (ESL critical)
- Voltage ripple at dc input injected due to mode conversion
  - Self-resonant behavior of $C_{dc}$ must be avoided (ESL critical)

APPLICATION AND VALIDATION OF CM MODELING APPROACH
UA SiC EMI Characterization Testbed Implementation

- Identical, characterized input and output termination impedances
- Natural convection cooling to avoid corruption from thermal management
- Diff. probes and current probes used for utility ground isolation
- Testbed and utility ground connected only through DC supply
- Testbed configured with half-bridge inverter EUT employing Cree CAS120 1.2-kV SiC half-bridge MCM

Leakage current through MCPM was measured in the EMI characterization testbed.

- Half-Bridge EUT with shorted load (only LISN impedance)†
  - Measured displacement current through MCPM baseplate through LISNs on input and output.
  - 100 kHz fixed-duty PWM, 300 ns dead time, 600 V DC bus
- Results were compared against nominal model with measured parasitic baseplate capacitances

Characterizing the MCPM Baseplate Capacitance

- Baseplate capacitance was not measured previously
- Cannot be measured from the terminals
- A sample module (Cree CAS120) from the EMI testbed was deconstructed to accurately quantify the capacitances

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{ug}$</td>
<td>U-to-baseplate capacitance</td>
<td>191 pF</td>
<td></td>
</tr>
<tr>
<td>$C_{ag}$</td>
<td>A-to-baseplate capacitance</td>
<td>255.7 pF</td>
<td></td>
</tr>
<tr>
<td>$C_{lg}$</td>
<td>L-to-baseplate capacitance</td>
<td>102.6 pF</td>
<td></td>
</tr>
<tr>
<td>$C_{bp}$</td>
<td>total baseplate capacitance</td>
<td>549.3 pF</td>
<td></td>
</tr>
</tbody>
</table>
CM voltage noise source modeling

- The dominant component of the CM voltage is proportional to $v_{Q1} - v_{Q2}$
- This term is readily modeled from the nominal input voltage, duty cycle, and average rise and fall time of the switch voltage:

$$c_n^+ \propto 4dV_{dc} \text{sinc}(nd) \text{sinc}(nf_{sw}T_{rf})$$
Equivalent model reduced and analyzed to predict baseplate current.

- The expression for the equivalent CM source with respect to the baseplate is approximately
  \[ V_{bp,eq}^{cm} = \frac{k - 2}{8(2 + k)}(V_{Q1} - V_{Q2}) \]
- Model indicates strong influence of MCPM parasitic asymmetry and potential compensation†

STUDY OF BASEPLATE CAPACITANCE IN MULTICHIp POWER MODULES
Unbalanced baseplate capacitance is a critical factor affecting leakage current through baseplate.

- DBC substrate geometry leads to capacitive coupling between terminals and baseplate
- High $dv/dt$ drives leakage current through the baseplate
- Low-side source terminal ($S_2$) usually occupies much less substrate area than $D_1$ and $S_1D_2$ (which are similar)
- In general, $D_1$, $S_1D_2$, and $S_2$ substrate areas are all different, leading to unequal $C_{ug}$, $C_{ag}$, and $C_{lg}$
Relaxed concept of CM voltage and flexible DM and CM definitions permit derivation of CM equivalent model.

Half-bridge EMI testbed

CM equivalent circuit theory

CM equivalent model

Analysis of leakage current through the MCPM baseplate

- The equivalent CM ac voltage driving BP current is given by

\[
\nu_{cm,ac} = \left[ \frac{Z_{in}}{2(Z_{in} + Z_{out})} - \frac{C_{ag}}{C_{bp}} \right] \frac{\nu_{Q1} - \nu_{Q2}}{2}
\]

\[
\approx \left( \frac{1}{4} - q_{ac} \right) \frac{\nu_{Q1} - \nu_{Q2}}{2}
\]

where

\[
q_{ac} \triangleq \frac{C_{ac}}{C_{bp}}, \quad C_{bp} = C_{ug} + C_{ag} + C_{lg}
\]

- In a typical module, \( C_{ug} \approx C_{ag} > C_{lg} \)

---

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</tr>
<tr>
<td>( C_{lg} )</td>
<td>L-to-baseplate capacitance</td>
<td>102.6</td>
<td>pF</td>
</tr>
<tr>
<td>( C_{bp} )</td>
<td>total baseplate capacitance</td>
<td>549.3</td>
<td>pF</td>
</tr>
</tbody>
</table>

Experimental setup was devised to validate the CM model predictions.

- Discrete capacitors were placed between the module terminals and the baseplate.
- The $q_{ac}$ parameter was swept across the range including the “critical” value of 1/4.
- Total baseplate capacitance ($C_{bp}$) was held constant for all cases.

### Table: External Caps Added for Sweep of $q_{ac}$

<table>
<thead>
<tr>
<th>Study</th>
<th>Tab</th>
<th>Capacitors Added</th>
<th>Number</th>
<th>Value (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ($q_{ac} \approx \frac{1}{6}$)</td>
<td>$C_{UG}$</td>
<td>17</td>
<td>563.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{AG}$</td>
<td>2</td>
<td>69.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{LG}$</td>
<td>20</td>
<td>660.7</td>
<td></td>
</tr>
<tr>
<td>2 ($q_{ac} \approx \frac{1}{3}$)</td>
<td>$C_{UG}$</td>
<td>16</td>
<td>529.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{AG}$</td>
<td>4</td>
<td>135.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{LG}$</td>
<td>19</td>
<td>626.8</td>
<td></td>
</tr>
<tr>
<td>3 ($q_{ac} \approx \frac{1}{4}$)</td>
<td>$C_{UG}$</td>
<td>15</td>
<td>497.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{AG}$</td>
<td>6</td>
<td>200.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{LG}$</td>
<td>18</td>
<td>594.7</td>
<td></td>
</tr>
<tr>
<td>4 ($q_{ac} \approx \frac{3}{10}$)</td>
<td>$C_{UG}$</td>
<td>14</td>
<td>464.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{AG}$</td>
<td>8</td>
<td>266.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{LG}$</td>
<td>17</td>
<td>562.2</td>
<td></td>
</tr>
<tr>
<td>5 ($q_{ac} \approx \frac{1}{3}$)</td>
<td>$C_{UG}$</td>
<td>13</td>
<td>432.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{AG}$</td>
<td>10</td>
<td>332.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$C_{LG}$</td>
<td>16</td>
<td>529.1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$C_{BP}$</td>
<td>39</td>
<td>1,293</td>
<td></td>
</tr>
</tbody>
</table>

Results of the $q_{ac}$ sweep experiments

- Model accurately predicts the polarity inversion and symmetry about the “critical” $q_{ac}$ value of 1/4
- Model accurately predicts BP current RMS amplitude over full sweep
- Cancellation occurs at the $q_{ac} = 1/4$

Model accurately predicts all significant characteristics of the BP current including ringing frequency and amplitude.

Acknowledgment

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