Modeling and Validation of EMI Trends in Medium Voltage Isolated dc-dc Converters

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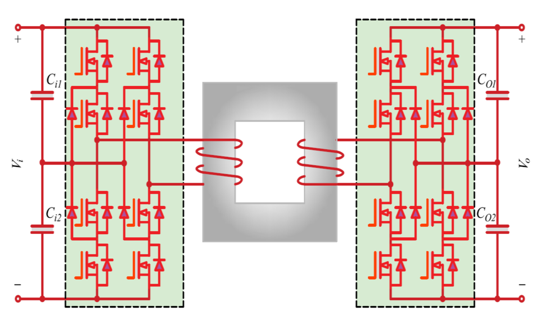
Introduction

• The studied topology for this project is a Medium Voltage, Medium Frequency, Bi-Directional Dual Active Bridge



• The topology consists of a 3-level Neutral Point Clamped Full-Bridge Converter on both sides of a High-Frequency Transformer

• With the emerging field of power electronics, we aim to develop an integrated EMI characterization platform for new generations of power electronic converters using Wide Band Gap (WBG) power semiconductors for medium voltage systems

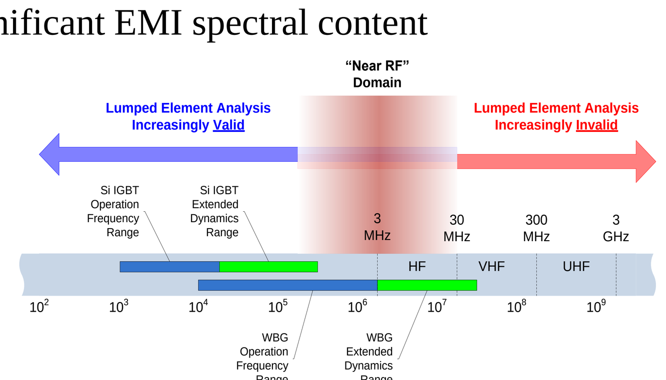
• A Common-Mode (CM) equivalent model for the system is derived. A simulation software, PLECS, is then used to compare measured results from a Mixed-Mode (MM) circuit and the derived CM circuit

• Eventually, we will be able to have compared results from a hardware implementation within our EMI characteristic testbed

Characterization of EMI

• WBG devices have transformative impacts on power delivery, management, and increased power density.

• When using WBG converters you will encounter higher switching frequency, high voltage edge rates (dv/dt) and increased dc bus voltage. This results in significant EMI spectral content



• Traditional IGBT based systems:

  Operational Frequency: 1-50 kHz

  Extended Dynamics: up to 500 kHz

• WBG based systems:

  Operational Frequency: 10 kHz - 1 MHz

  Extended Dynamics: up to 100 MHz

• WBG devices result in CM voltage sources, thus CM emissions, that are spectrally rich throughout the conducted emissions band (10 kHz – 30 MHz)

• In this "Near RF" range, lumped element analysis starts to become inadequate and changes how we look at EMI characterization, modeling, and mitigation

• Packaging impedance is important in this "Near RF" range

Impacts of EMI

• Spectral content in the "Near RF" range means

  • capacitor and low turn inductors exhibit behavior dominated by parasitic effects

  • bus planes, cabling, and high turn-count inductors become "electrically small" and exhibit wave-like behavior

• In the presence of high frequency switching power semiconductors, there is a propagating path for *dV/dt* induced current across the modules' direct bonded copper substrates

• High electrical potentials on isolated heat sinks and high-frequency magnetic cores in the presence of high *dV/dt* induced displacement currents into the equipment chassis introduce coupling effects that can lead to degradation of equipment

• Therefore, it is SO important to understand EMI management in WBG devices compared to the outdated Silicon devices

Methodology

• To understand the impacts of the displacement currents through equipment chassis we turn to Common-Mode equivalent models

• With this equivalent model, we can begin to accurately model the voltage stresses induced from switching across various points throughout the system

• The equivalent model are derived using techniques that facilitate the transformation of MM system components into CM equivalent components which can be systematically assembled

• In symmetric systems, the Differential-Mode (DM) and CM behaviors are completely decoupled

• When asymmetry is in the system, the DM behaviors are integral in understanding the CM behavior

Basic Procedure:

1. Starting with CM and DM definitions

Differential mode (DM):

$$v_{DM} \equiv v_{1P} - v_{2P}$$
$$i_{DM} \equiv \tfrac{1}{2}(i_1 - i_2)$$

Common mode (CM):

$$v_{CM} \equiv \tfrac{1}{2}(v_{1P} + v_{2P})$$
$$i_{CM} \equiv i_1 + i_2$$

2. Use KVL/KCL and apply Transformation Matrices

$$\begin{bmatrix} i_{n(n+1)} \\ \vdots \\ \vdots \\ \vdots \\ i_{(N-1)N} \\ i^{(c)} \end{bmatrix} \triangleq \begin{bmatrix} \frac{1}{N_i} & -\frac{1}{N_i} & 0 & 0 & \dots & 0 \\ 0 & \frac{1}{N_i} & -\frac{1}{N_i} & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & 0 & \frac{1}{N_i} & -\frac{1}{N_i} & 0 \\ 0 & \dots & \dots & 0 & \frac{1}{N_i} & -\frac{1}{N_i} \\ 1 & 1 & \dots & \dots & 1 & 1 \end{bmatrix} \begin{bmatrix} i_n \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ i_N \end{bmatrix} \quad \begin{bmatrix} v_{n(n+1)} \\ \vdots \\ \vdots \\ \vdots \\ v_{(N-1)N} \\ v^{(c)} \end{bmatrix} \triangleq \begin{bmatrix} 1 & -1 & 0 & 0 & \dots & 0 \\ 0 & 1 & -1 & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & \ddots & 0 & 1 & -1 & 0 \\ 0 & \dots & \dots & 0 & 1 & -1 \\ \frac{1}{N} & \frac{1}{N} & \dots & \dots & \frac{1}{N} & \frac{1}{N} \end{bmatrix} \begin{bmatrix} v_{nP} \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ v_{NP} \end{bmatrix}.$$

3. Use derived CM equation and systematically assemble CEM

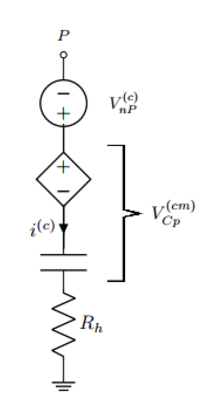
$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \hat{p} \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \begin{bmatrix} V_{Cp,1} \\ V_{Cp,2} \end{bmatrix}$$

$$\begin{bmatrix} \frac{1}{2} & -\frac{1}{2} \\ 1 & 1 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \hat{p} \begin{bmatrix} \frac{1}{2} & -\frac{1}{2} \\ 1 & 1 \end{bmatrix} \begin{bmatrix} C_1 & 0 \\ 0 & C_2 \end{bmatrix} \begin{bmatrix} \frac{1}{2} & 1 \\ -\frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} V^{(d)}_{Cp,12} \\ V^{(c)}_{Cp,12} \end{bmatrix}$$

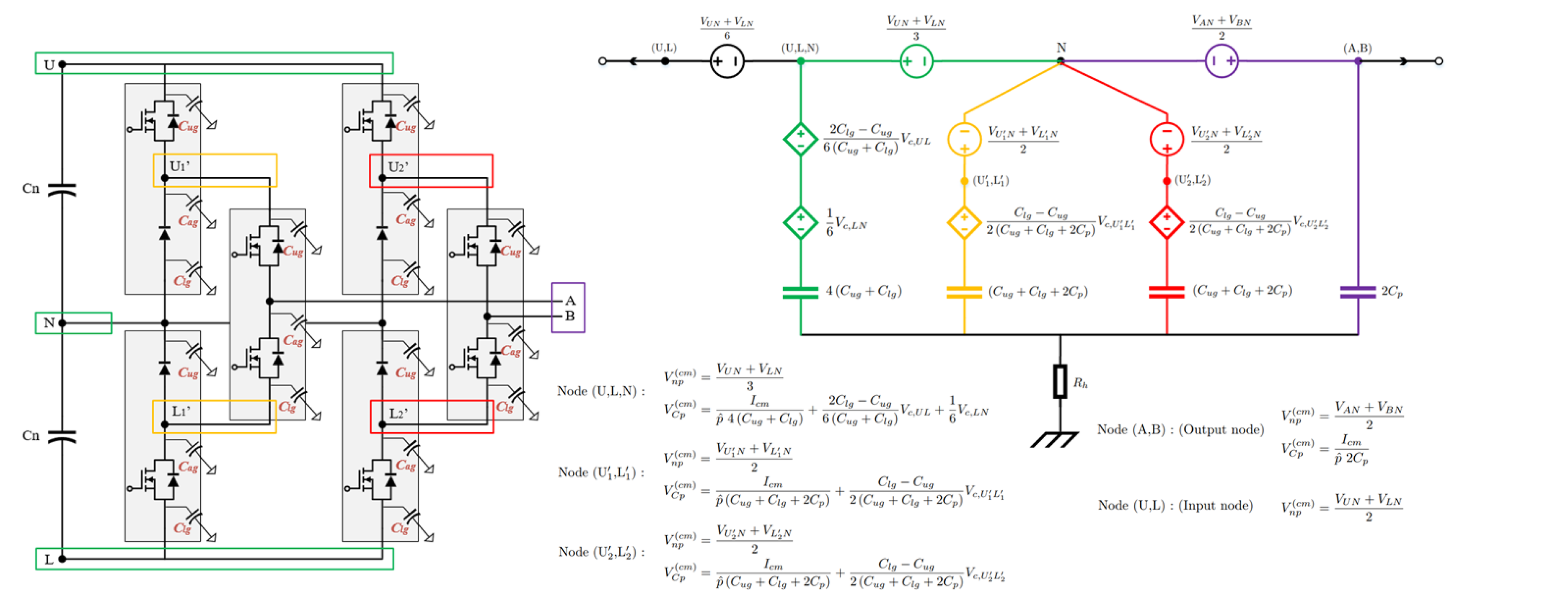
$$\begin{bmatrix} i^{(d)} \\ i^{(c)} \end{bmatrix} = \hat{p} \begin{bmatrix} \frac{C_1 + C_2}{4} & \frac{C_1 - C_2}{2} \\ \frac{C_1 - C_2}{2} & C_1 + C_2 \end{bmatrix} \begin{bmatrix} V^{(d)}_{Cp,12} \\ V^{(c)}_{Cp,12} \end{bmatrix}$$

2 line: $V^{(cm)}_{Cp} = \frac{I_{cm}}{\hat{p}(C_1 + C_2)} + \frac{C_2 - C_1}{2(C_1 + C_2)} V_{c,12}$

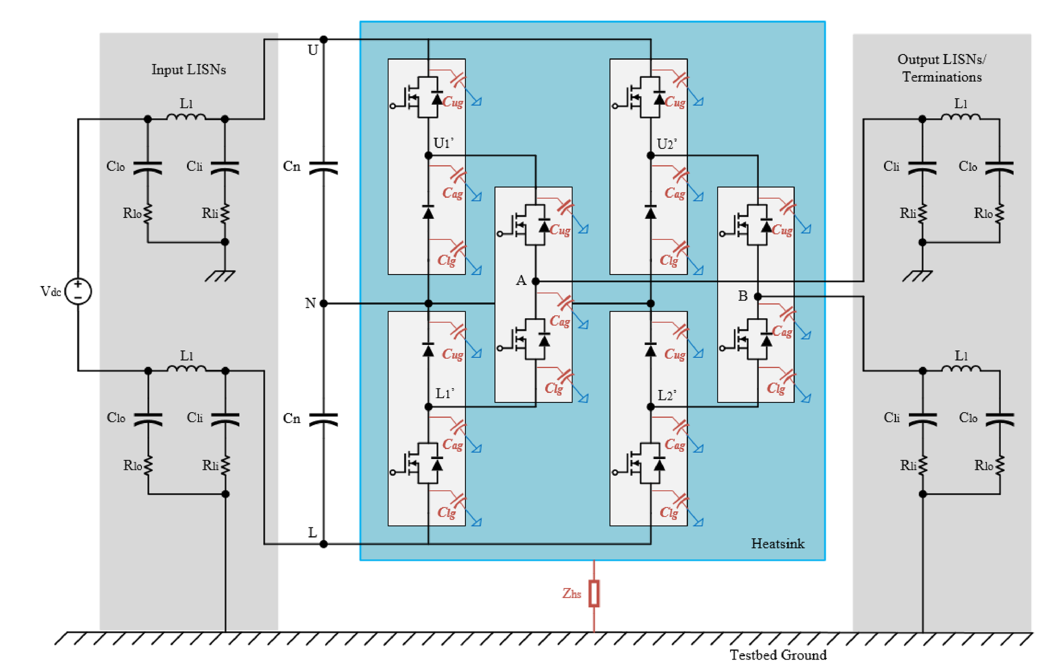
3 line: $V^{(cm)}_{Cp} = \frac{I_{cm}}{\hat{p}(C_1 + C_2 + C_3)} + \frac{C_2 - 2C_1 + C_3}{3(C_1 + C_2 + C_3)} V_{c,12} - \frac{C_1 + C_2 - 2C_3}{3(C_1 + C_2 + C_3)} V_{c,23}$



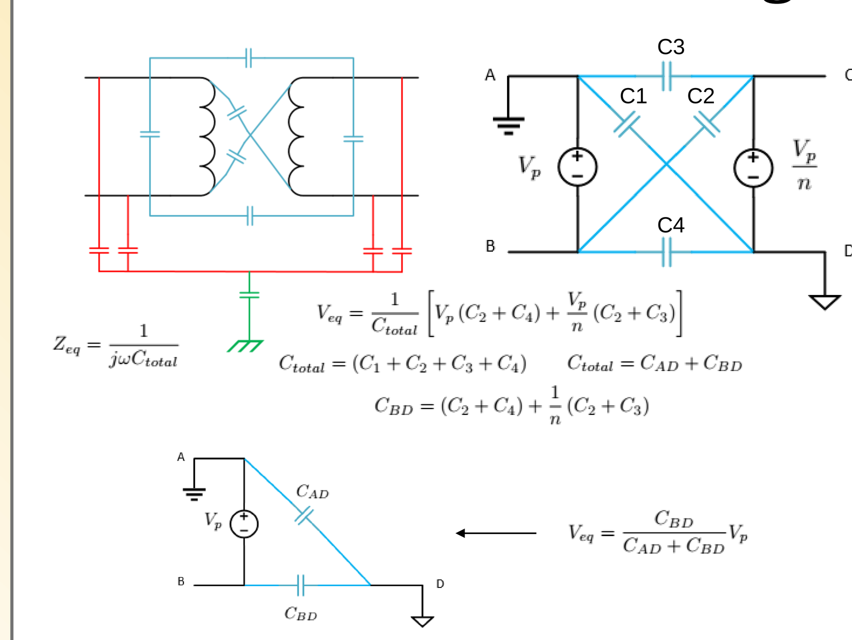
NPC Common-Mode Modeling



EMI Characteristic Testbed

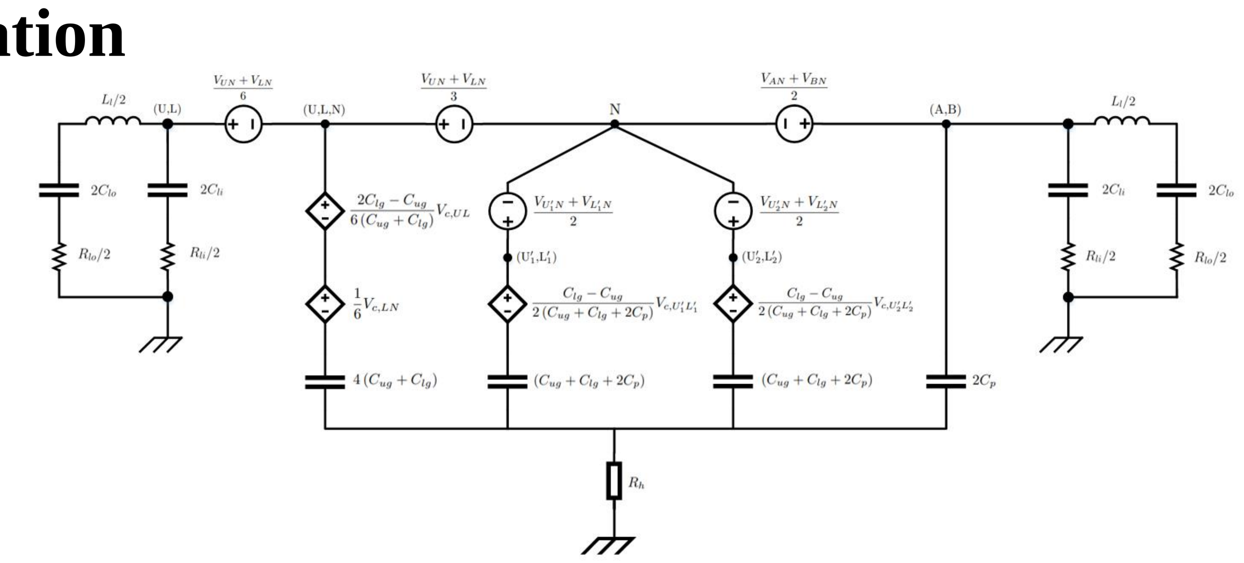


Transformer Modeling



Common-Mode Model Validation

- CM model is validated along side the MM model in the PLECS environment
- The LISNs were designed in accordance with MIL-STD-461 CE-102
- System has LISNs at the input and mirrored at the output to serve as terminating impedances for the Equipment-Under-Test (EUT)
- The CEM is designed to take probed points from the MM circuit and inject them into the CM model in order to replicated the conducted emissions through the modules baseplate into the heatsink



Summary & Purpose

• To model the high frequency common-mode effects of the system

  • Drives conducted EMI at the terminals of the high-frequency transformer

• Understand the switch transition rates (*dV/dt*) and how they drive displacement currents across the power semiconductor module and insulated substrate into the heatsink

  • Understand how that impacts the insulation requirements of the system

• Understand what the high frequency common-mode effects have on the transformer (coupling from primary to secondary sides)