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Equivalent Circuits for Analysis of Common-Mode Behavior in Power Electronic-Based Systems*

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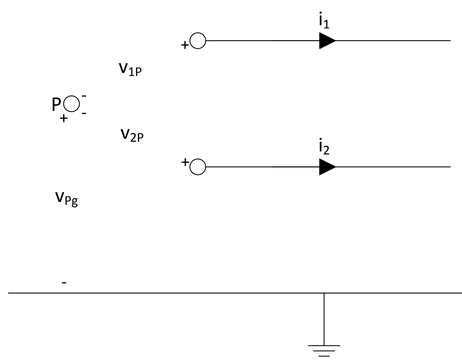
Introduction

- Push toward higher switching frequencies and higher DC bus voltages has introduced challenges in electric vehicle design.
- Common-mode current can yield radiated emissions that couple to other systems, creating electromagnetic compatibility issues.
- Traditional approach to model common-mode behavior adds parasitic elements to differential-mode circuits
- Computational burden significant. Yields limited insight on how to proceed.
- A formalized method to model common-mode behavior has been derived. A key contribution is the definition of a common-mode voltage with respect to arbitrary point P (not ground).
- One can characterize components separately, then connect through selection of the point P.
- Yields simplified model with lower computational burden and capability to provide better insight into problematic resonances, influence of switching frequency, etc.
- Easier to identify effectiveness of mitigation steps.

Defining Common Mode



Two wire definitions

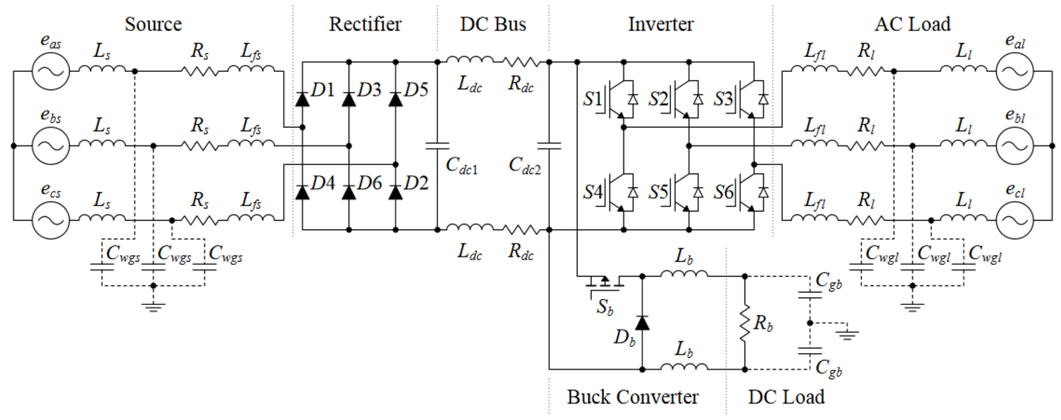
- $v_{DM} \triangleq v_{1P} - v_{2P}$
- $i_{DM} \triangleq \frac{1}{2}(i_1 - i_2)$
- $v_{CM} \triangleq \frac{1}{2}(v_{1P} + v_{2P})$
- $i_{CM} \triangleq i_1 + i_2$

$K \geq 2$ wire definitions

- $v_{CM} \triangleq \frac{1}{K}\sum_{k=1}^{K} v_{kP}$
- $i_{CM} \triangleq \sum_{k=1}^{K} i_k$

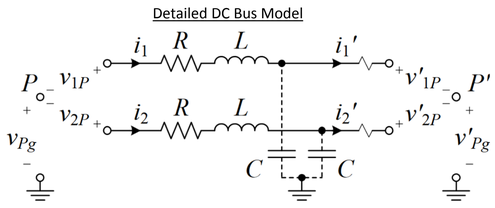
Adding Parasitic Elements

- Types of common-mode problems encountered and desired fidelity of model will affect what parasitic pathways need to be added to form the mixed-mode circuit.

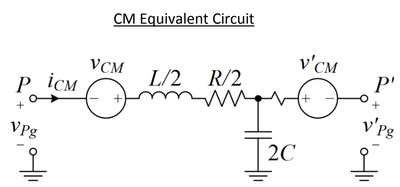


Deriving Common-mode Equivalent Circuit

Detailed DC Bus Model

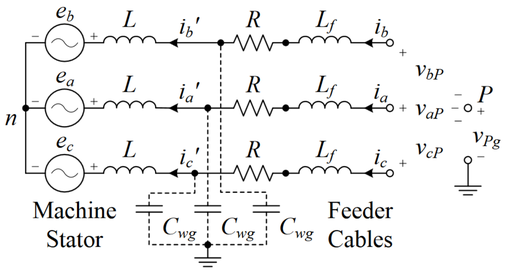


CM Equivalent Circuit

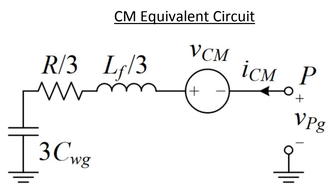


$$v_{PG} = -v_{12P} + Ri_{12} + L\frac{di_{12}}{dt} + \frac{1}{C}\int (i_{12} - i'_{12})dt \quad \rightarrow \quad v_{PG} = -v_{CM} + \frac{R}{2}i_{CM} + \frac{L}{2}\frac{di_{CM}}{dt} + \frac{1}{2C}\int (i_{CM} - i'_{CM})dt$$

Detailed DM/CM Machine Model

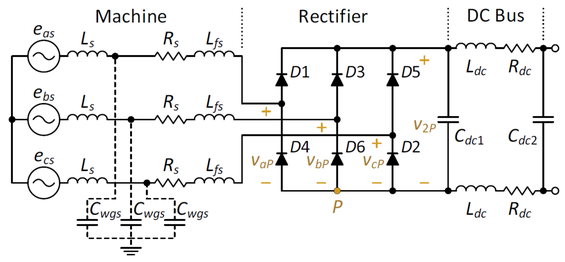


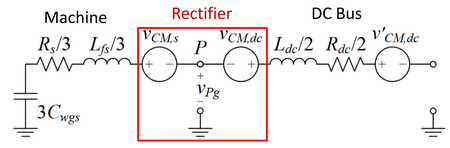
CM Equivalent Circuit



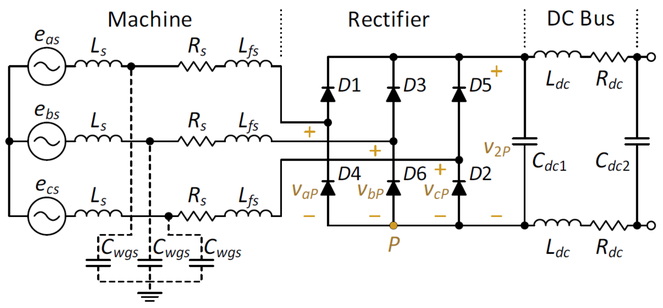
Forming Common-Mode Circuits of Systems

- Select shared reference point and connect CM equivalent circuits.

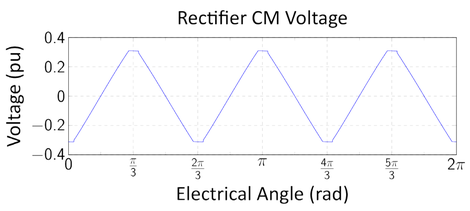




Characterizing Common-mode Sources

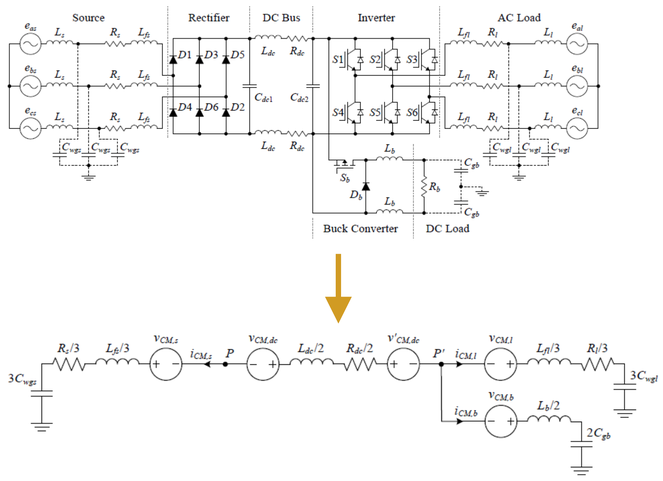


$$v_{CM,s} = \frac{v_{aP} + v_{bP} + v_{cP}}{3} = \frac{v_{D2} + v_{D4} + v_{D6}}{3}$$
$$v_{CM,b} = \frac{v_{1P} + v_{2P}}{2} = \frac{V_{DC}}{2}$$

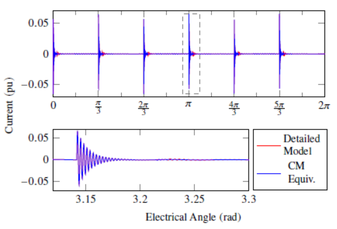


* A. D. Brovont and S. D. Pekarek, "Equivalent circuits for common-mode analysis of naval power systems," *Electric Ship Technologies Symposium (ESTS), 2015 IEEE*, Alexandria, VA, 2015, pp. 245-250.

Validation of Approach



CM Current at Source



CM Current at Buck Converter