Analysis and Suppression of Radiated EMI Due to PCB Ground in Power Converters

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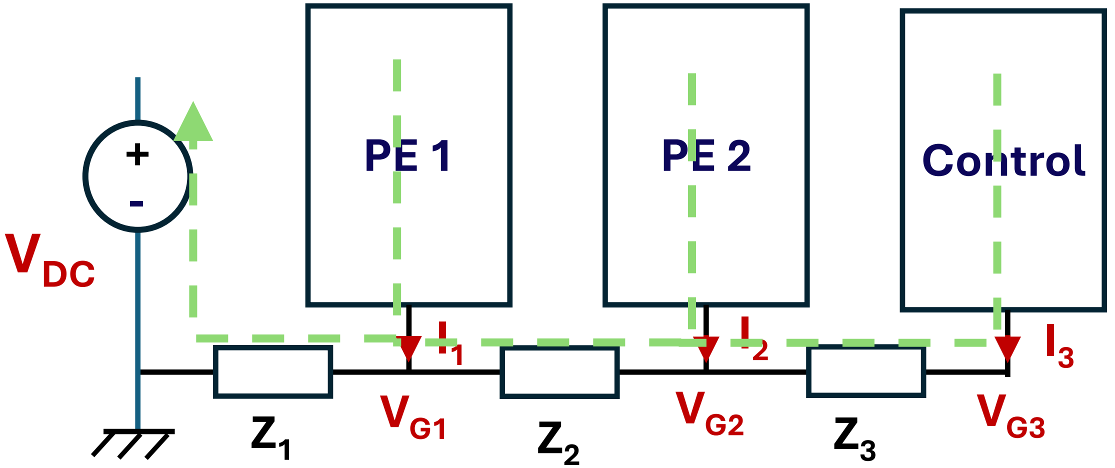
PCB Grounding in Power Electronics

Shared Single-point Grounding



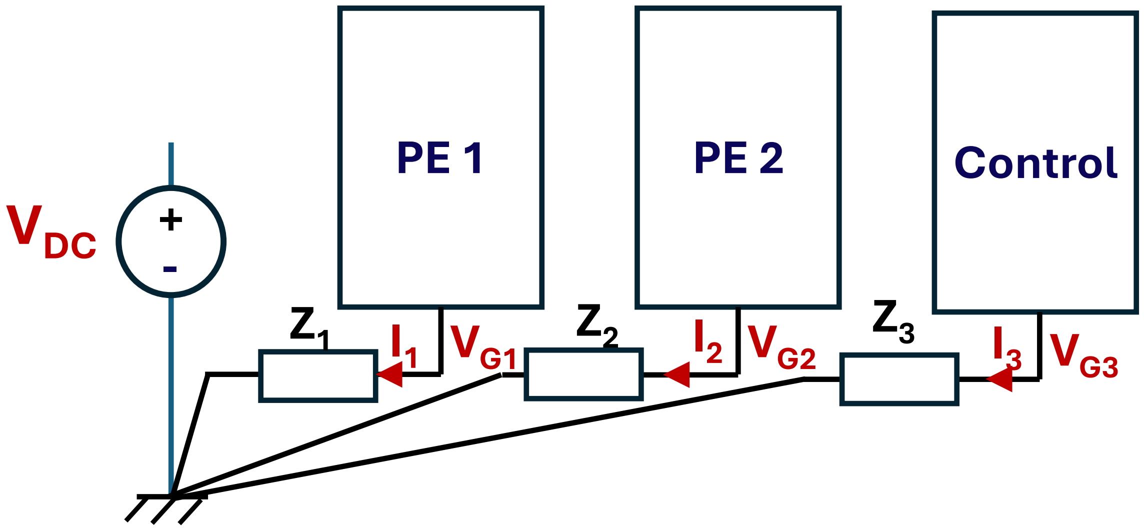
$V_{G1}=(I_1+I_2+I_3)Z_1$

$V_{G2}= (I_1+I_2+I_3)Z_1+ (I_2+I_3)Z_2$

$V_{G3}= (I_1+I_2+I_3)Z_1+ (I_2+I_3)Z_2 +I_3Z_3$

1. Common Ground Impedance Coupling
2. DM power currents transferred to common mode (CM) voltages

Separate Single-point Grounding



$V_{G1}= I_1Z_1$

$V_{G2}= I_2Z_2$

$V_{G3}= I_3Z_3$

No common ground impedance coupling (may still have mutual couplings)

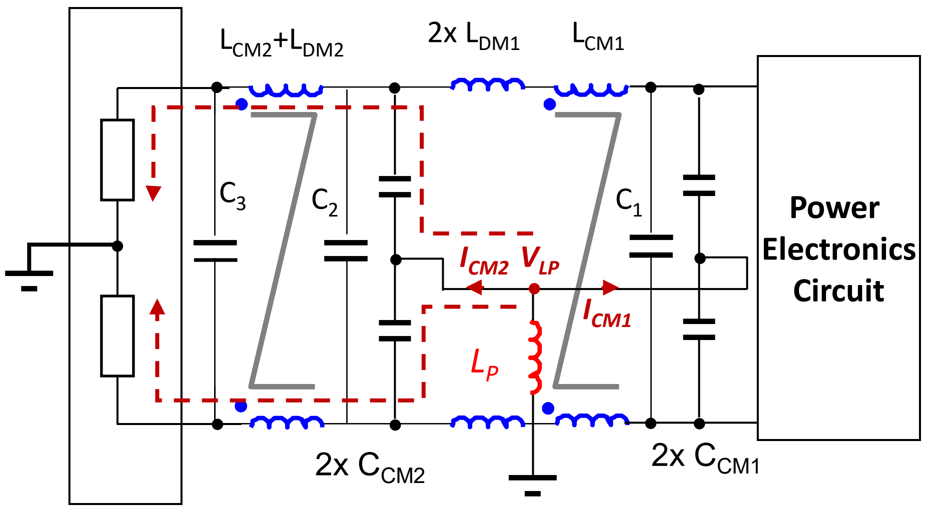
Outlines

1. PCB Ground layout of multi-stage EMI filters
2. Radiated EMI due to PCB ground layouts in non-isolated power converters
3. Radiated EMI due to PCB ground layouts in isolated power converters
4. Radiated EMI due to PCB ground layouts and differential mode EMI noise

PCB Ground Layout of Multi-stage EMI Filters

[1] S. Wang, Y. Y. Maillet, F. Wang, R. Lai, F. Luo and D. Boroyevich, "Parasitic Effects of Grounding Paths on Common-Mode EMI Filter's Performance in Power Electronics Systems," in *IEEE Transactions on Industrial Electronics*, vol. 57, no. 9, pp. 3050-3059, Sept. 2010.

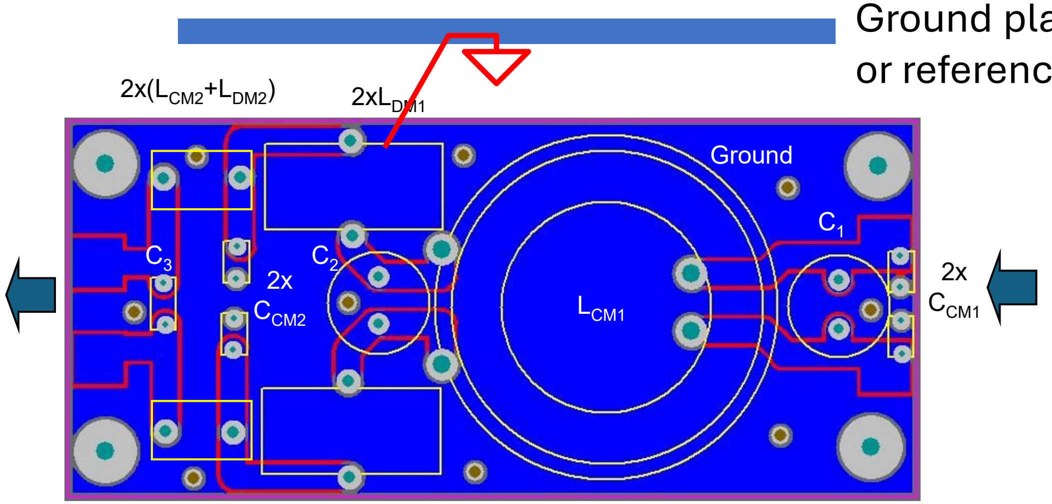
PCB Ground Layout of Muti-stage EMI Filters

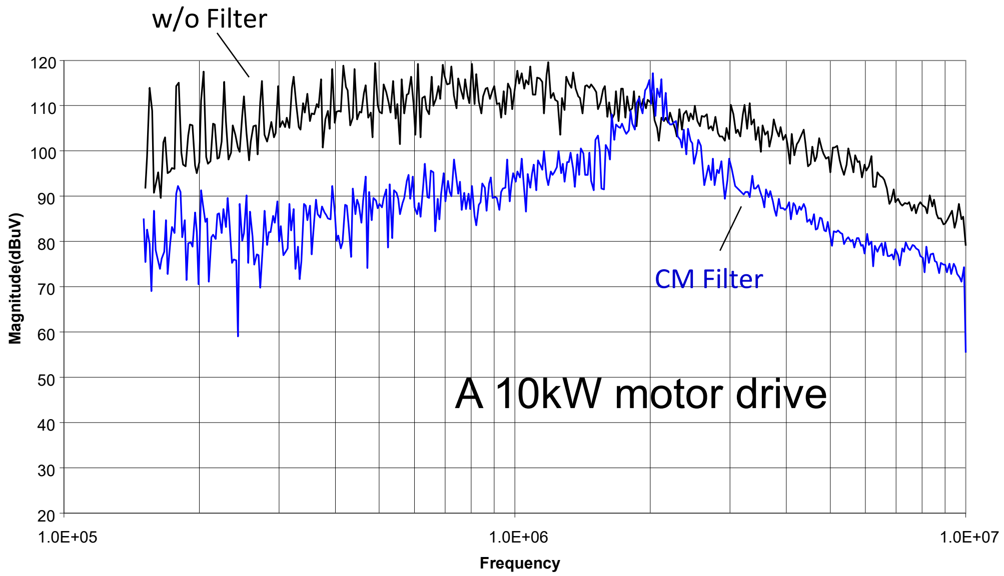


L_P: grounding path inductance

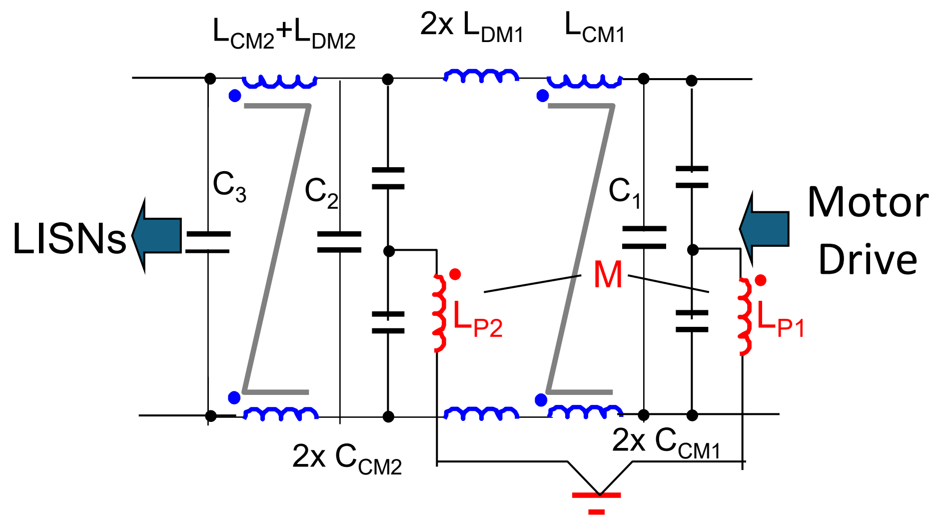
$$\frac{I_{CM1}}{I_{CM2}} = 40\text{dB/dec}$$

I_{CM1}'s voltage drop V_{LP} on L_P increases CM EMI on the input side.

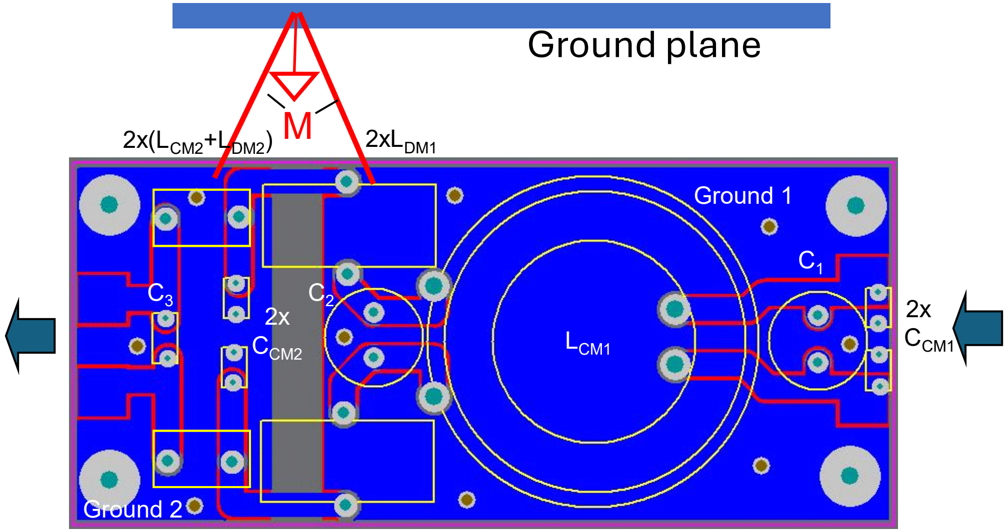


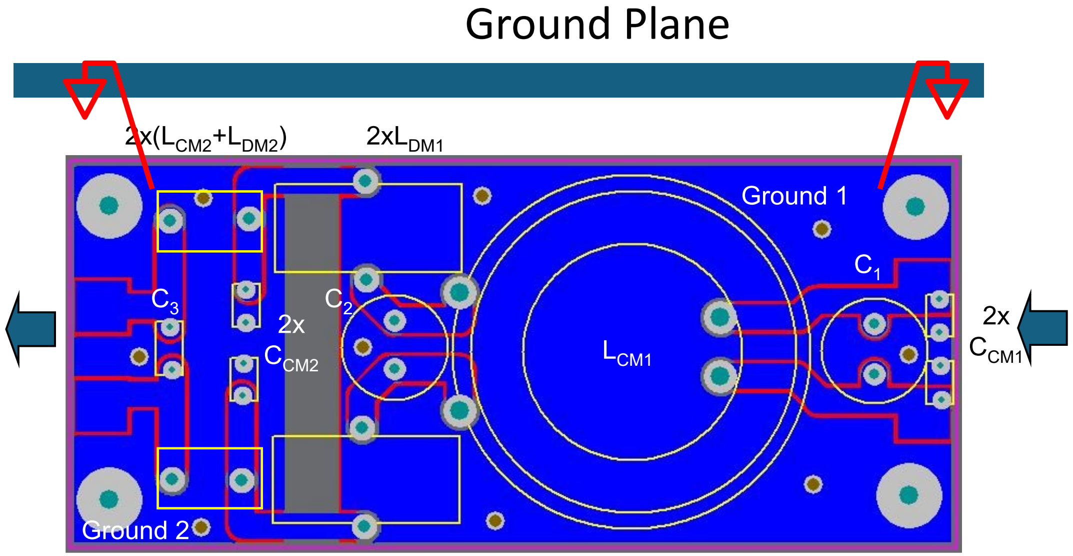


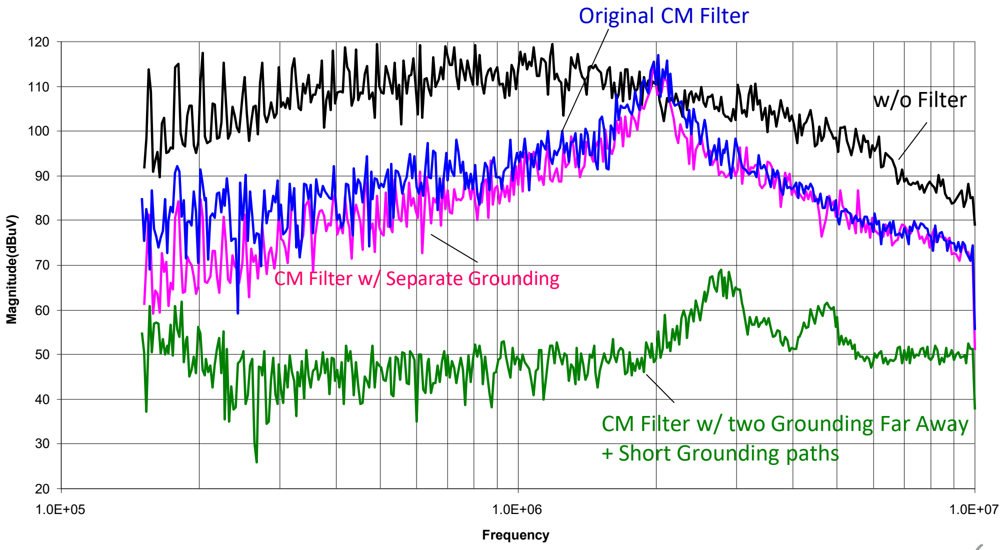
CM Capacitor's Separated Grounding Technique



1. M should be as small as possible
2. L_{P1} and L_{P2} should be as small as possible



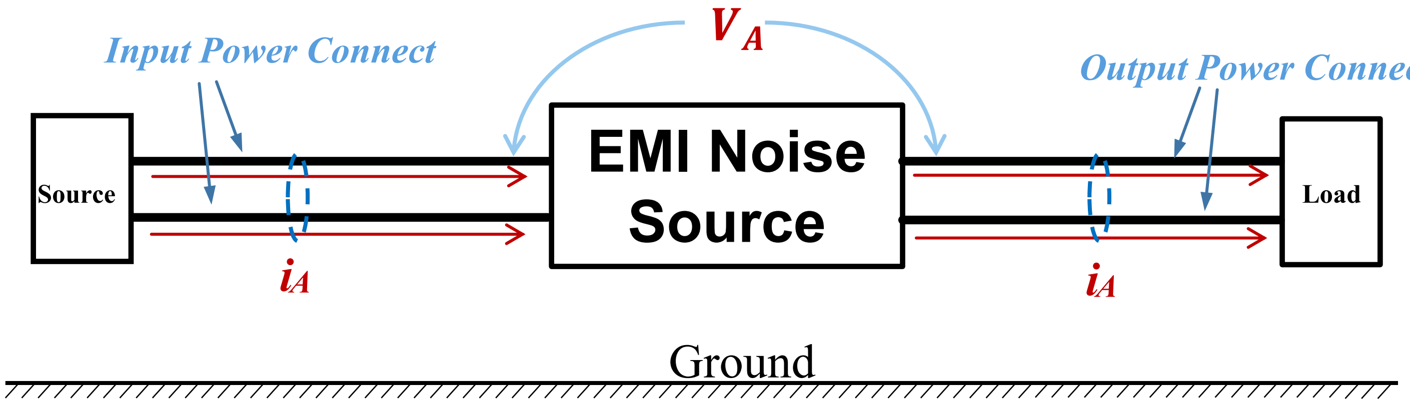




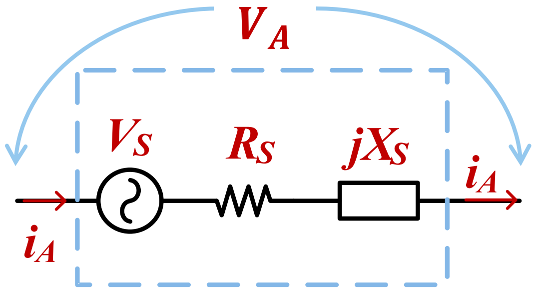
Radiated EMI due to PCB Ground Layouts in Non-isolated Power Converters

[2] J. Yao, S. Wang and Z. Luo, "Modeling, Analysis, and Reduction of Radiated EMI Due to the Voltage Across Input and Output Cables in an Automotive Non-Isolated Power Converter," in *IEEE Transactions on Power Electronics*, vol. 37, no. 5, pp. 5455-5465, May 2022

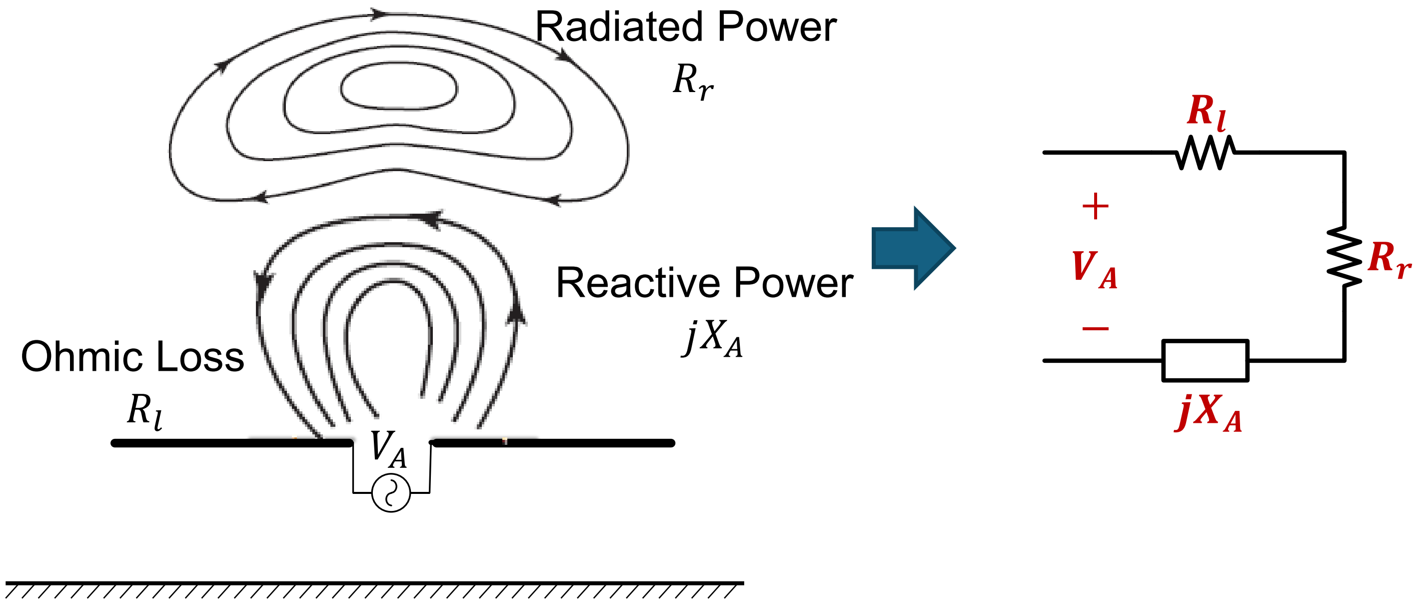
Modeling of Radiated EMI due to Asymmetric Power Interconnects

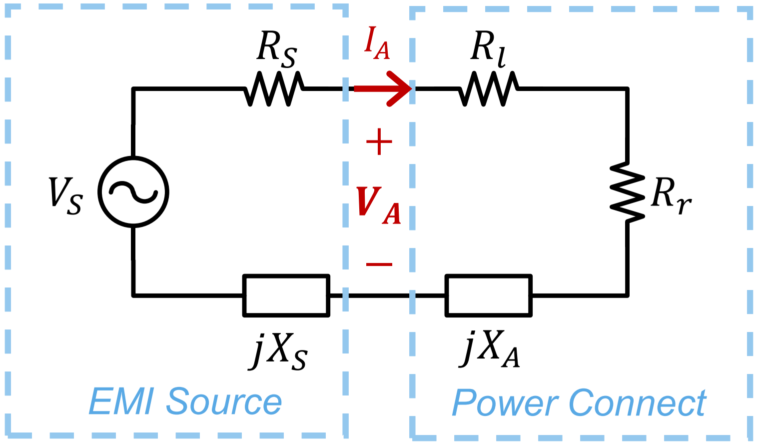


Converter Thevenin Equivalence

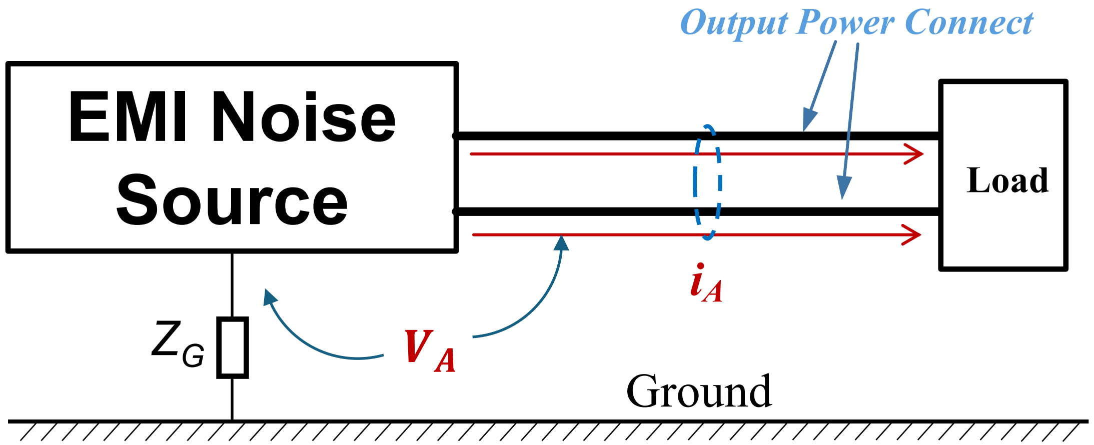


Power interconnect: Asymmetric dipole antenna:





Modeling of Radiated EMI due to One Power Connect

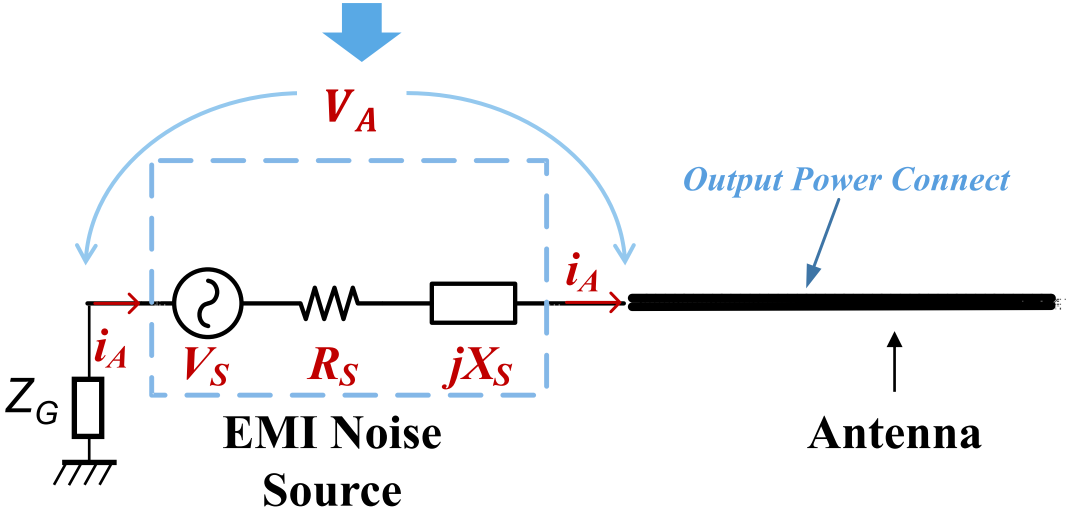


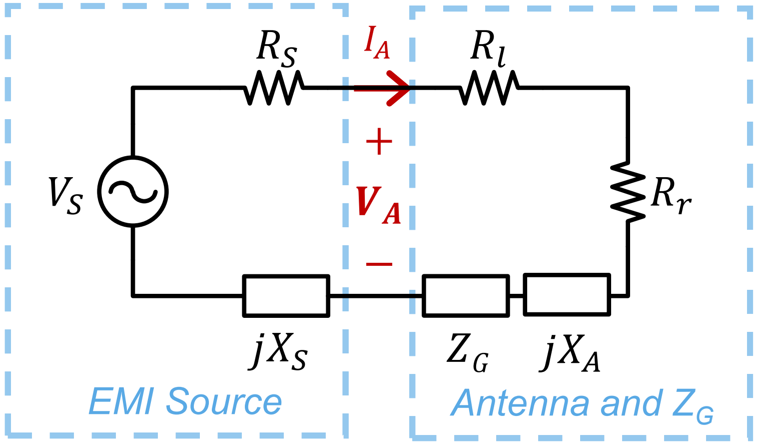
$$E_{max} = \sqrt{\frac{R_r \eta D}{4\pi r^2}} \times |I_A|$$

$$= \sqrt{\frac{\eta D}{4\pi r^2}} \times |V_S| \times \frac{\sqrt{R_r}}{\sqrt{(R_G + R_S + R_r + R_l)^2 + (X_G + X_S + X_A)^2}}$$

Noise source

Due to impedances





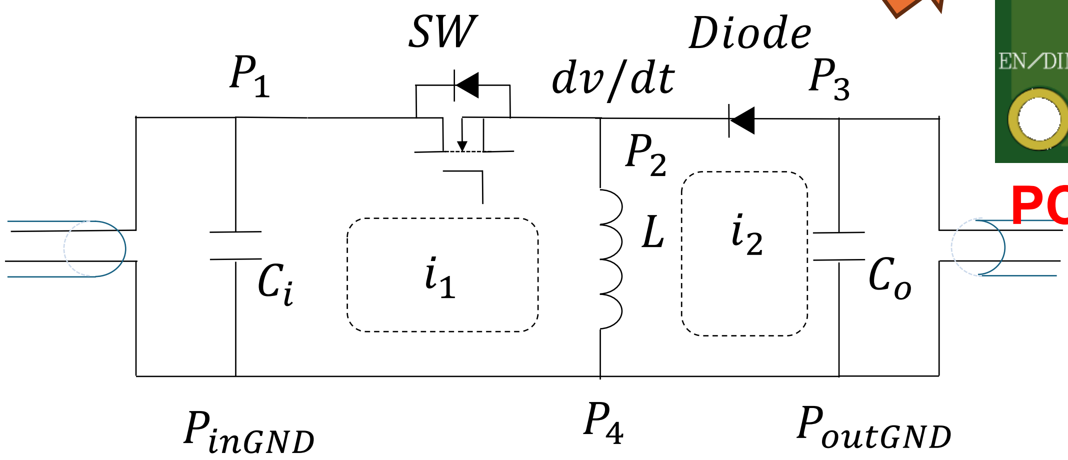
$Z_G = R_G + jX_G$

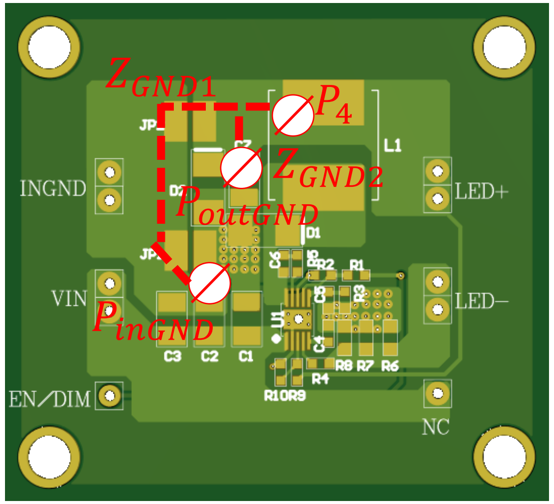
Identify Radiated EMI Noise Source in Non-isolated Power Converters

1. PCB ground impedance between the input and output
2. PCB ground impedance carrying discontinuous switching currents
3. The voltage drops on the PCB ground impedance transfer the DM EMI to CM voltages driving antenna

1. **Z_{GND1} is between the input and output**
2. **i_1 is discontinuous**
3. **Voltage drop drives input and output connections for radiated EMI**

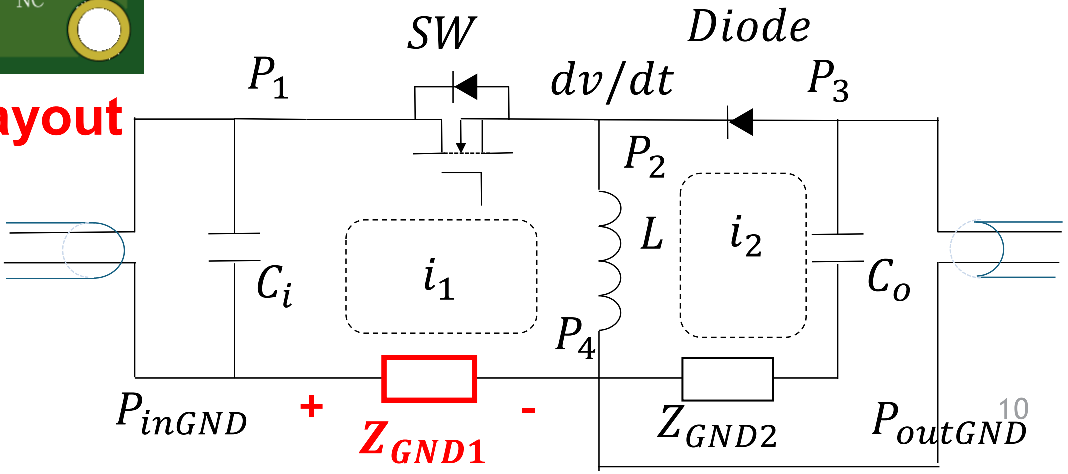
Buck-Boost Converter



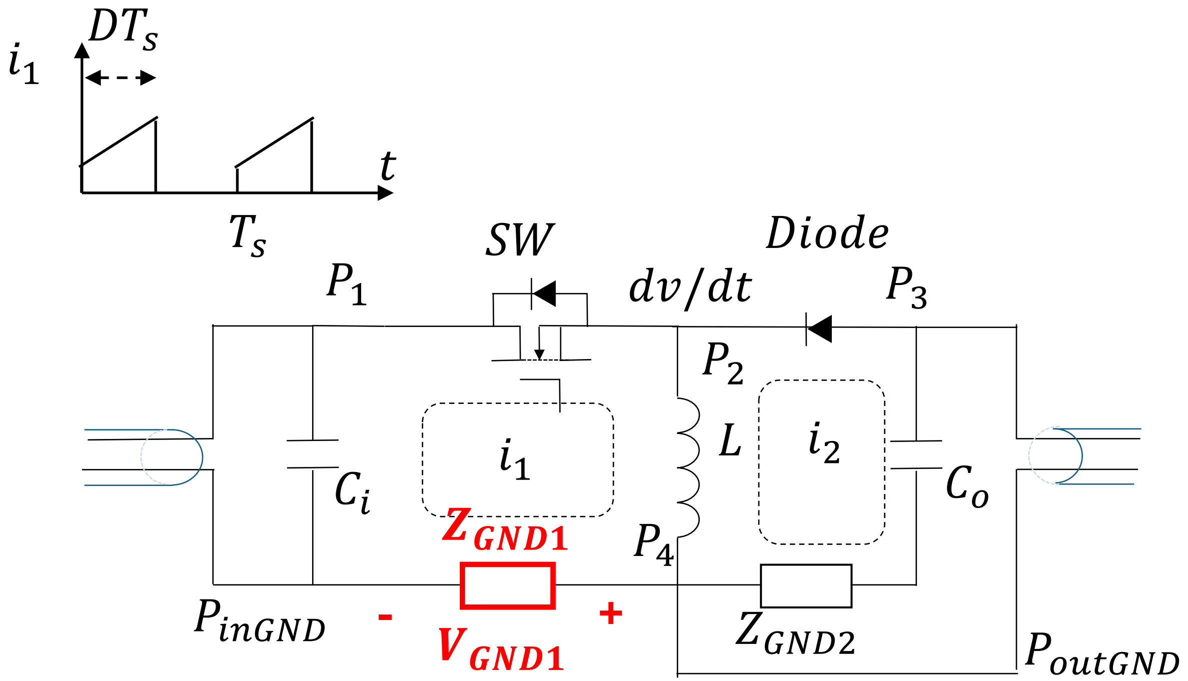


PCB Ground Layout

Identified critical PCB ground layout

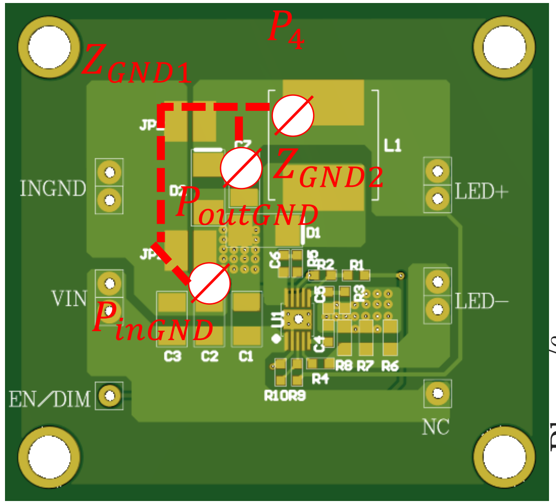


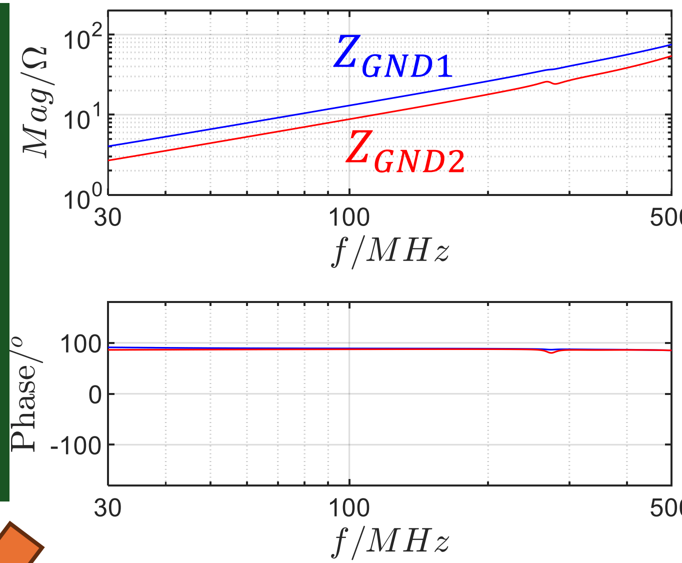
Radiated EMI Model

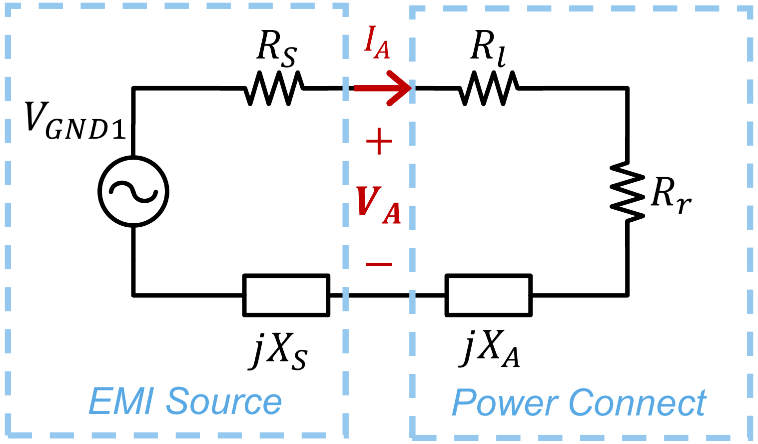


$V_{GND1}=i_1 Z_{GND1}$

Ground layer impedance is significant at HF



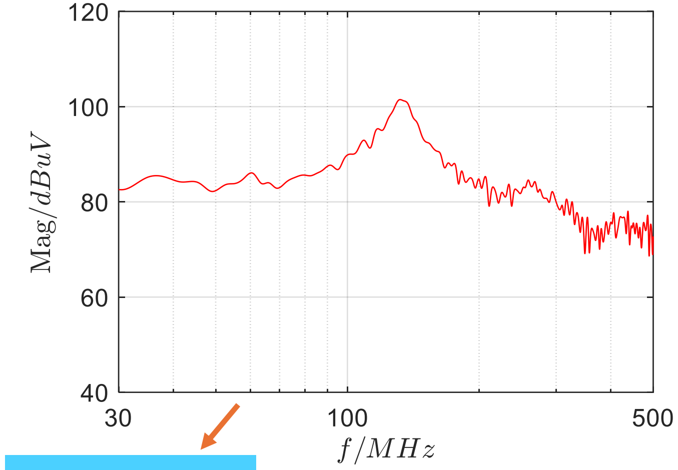


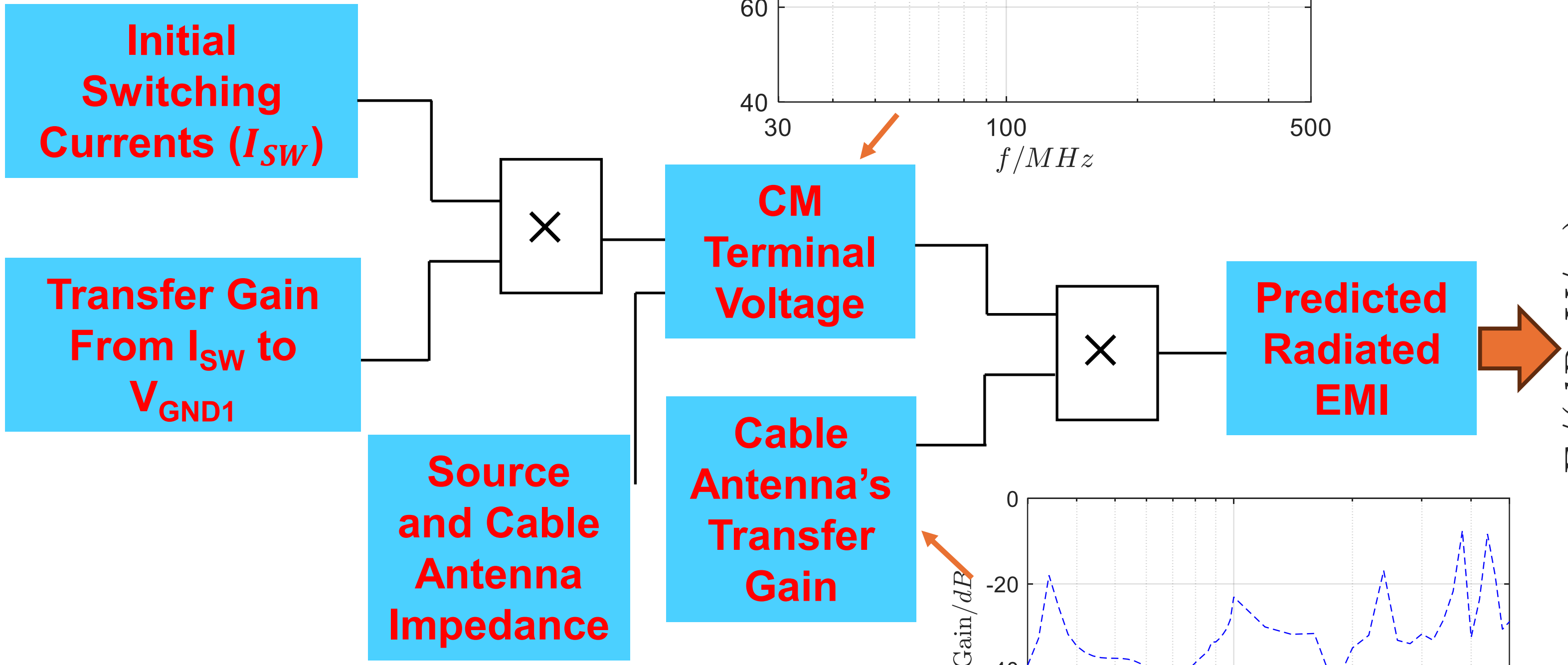


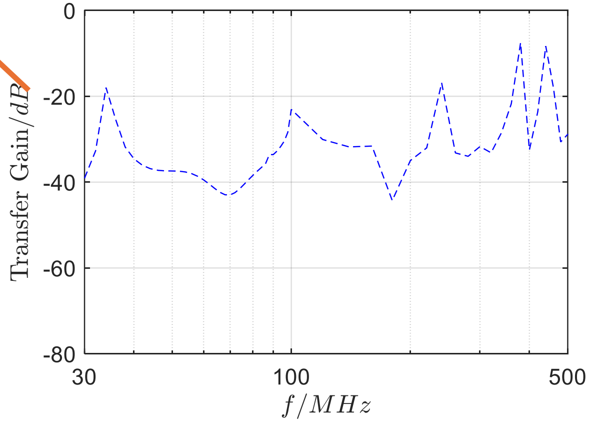
Antenna

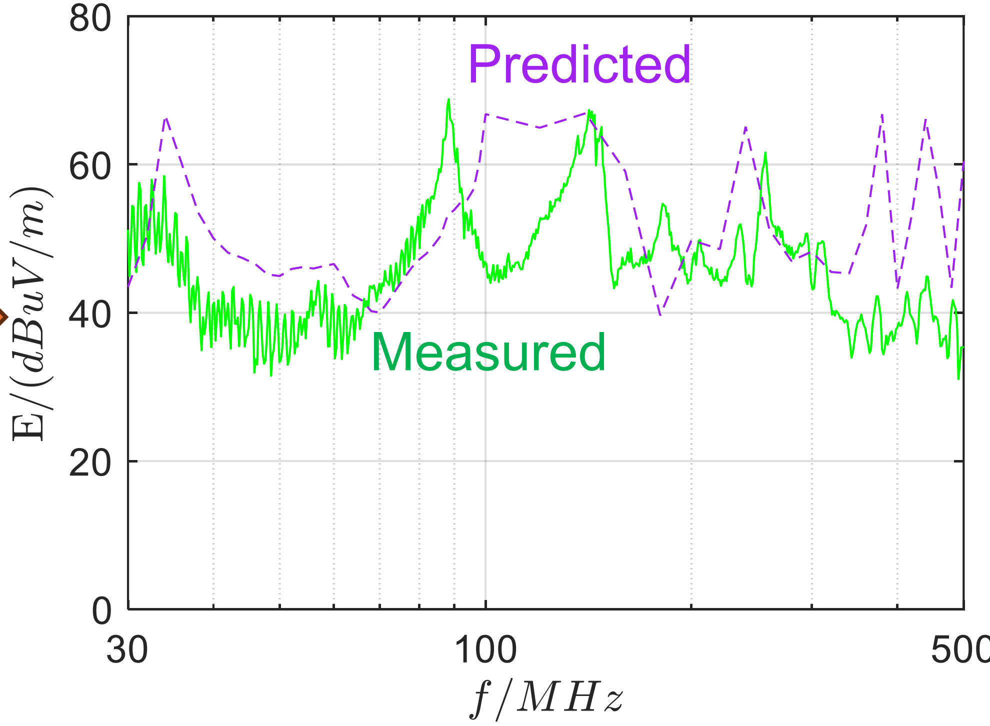
The Predicted Radiated EMI Matches the Measured

Radiated EMI prediction procedure



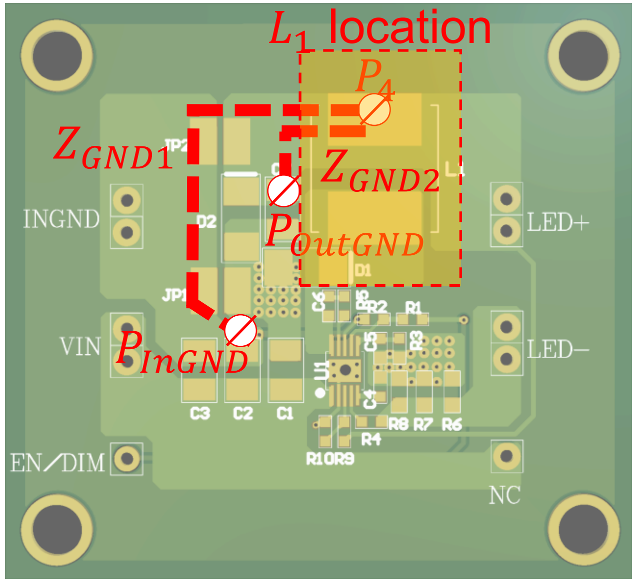




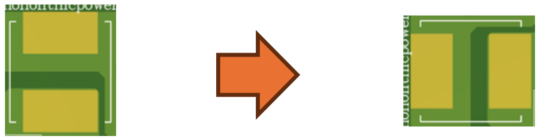


Reduce Radiated EMI by Reducing PCB Ground Impedance

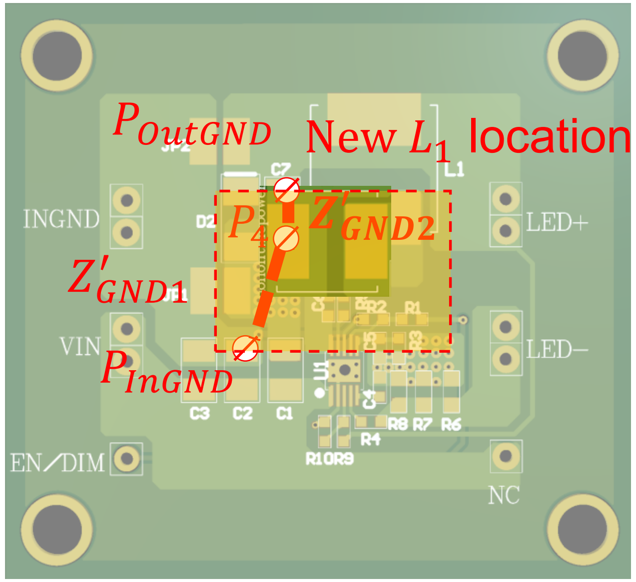
Original layout

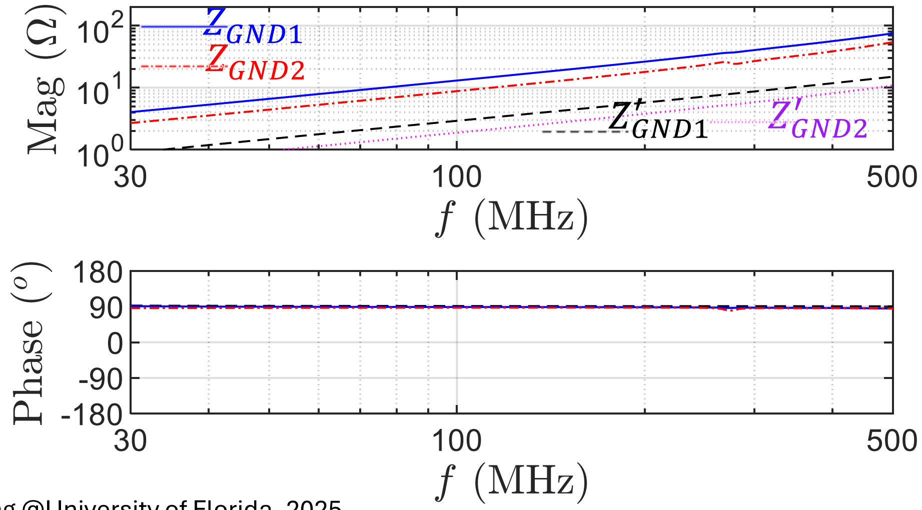


Improving the layout for reducing the ground layer trace length and parasitics

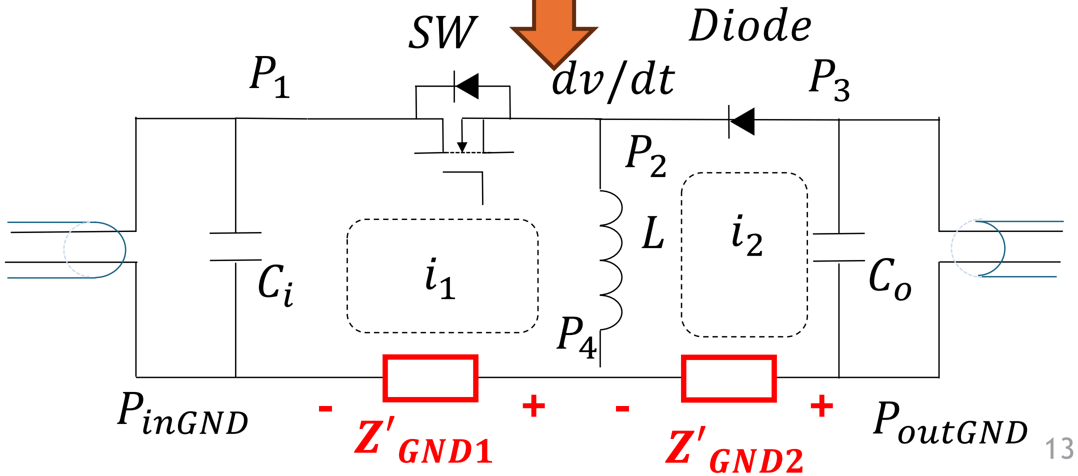


With the inductor arrangement improved to reduce the ground layer impedances



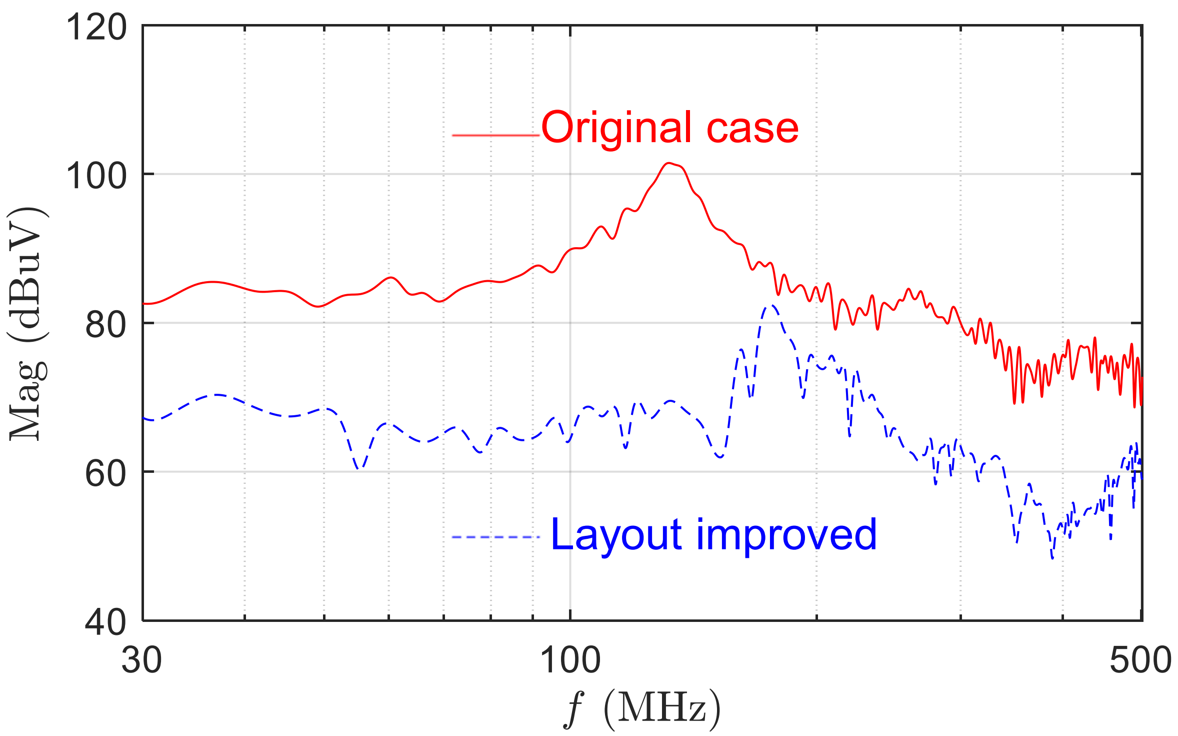


When the length is reduced by 75%, the inductance is reduced by 86.6%.

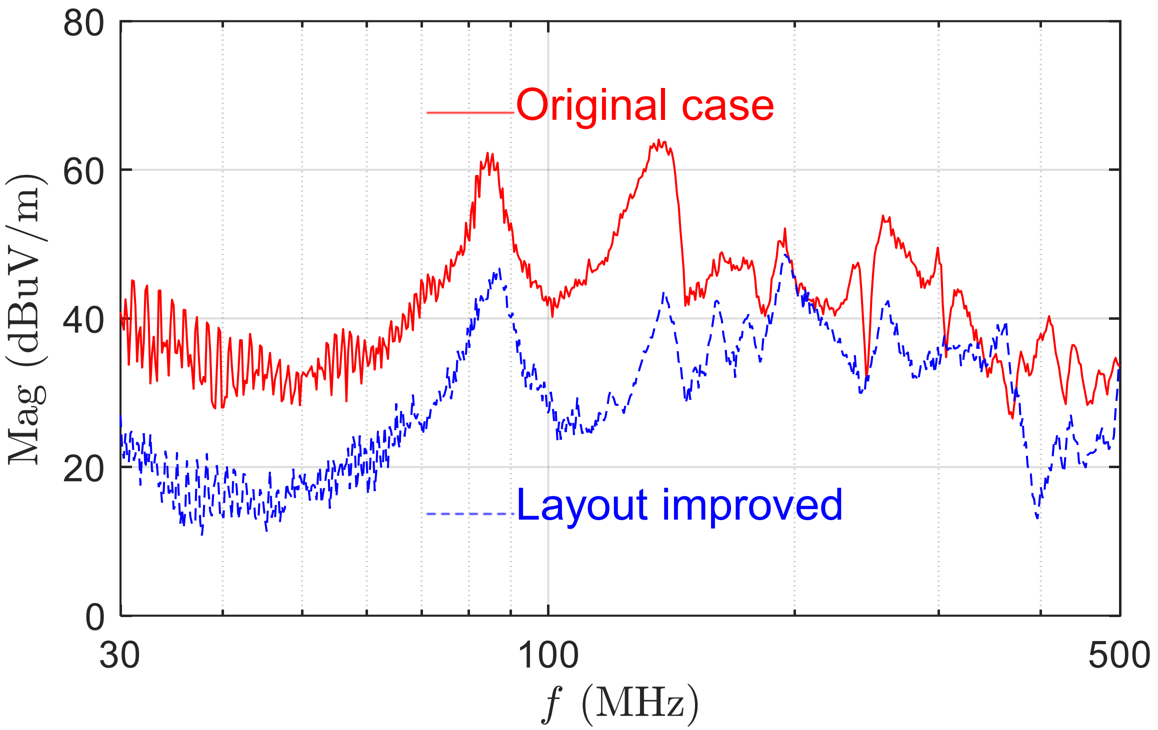


Radiated Noise Reduction with the Improved Layout

Reduction of the radiation excitation voltage

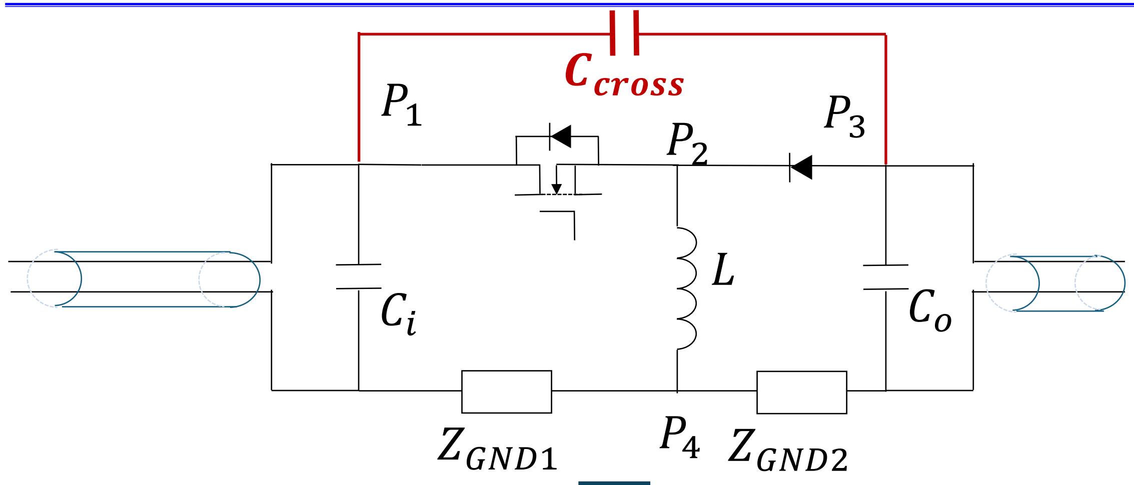


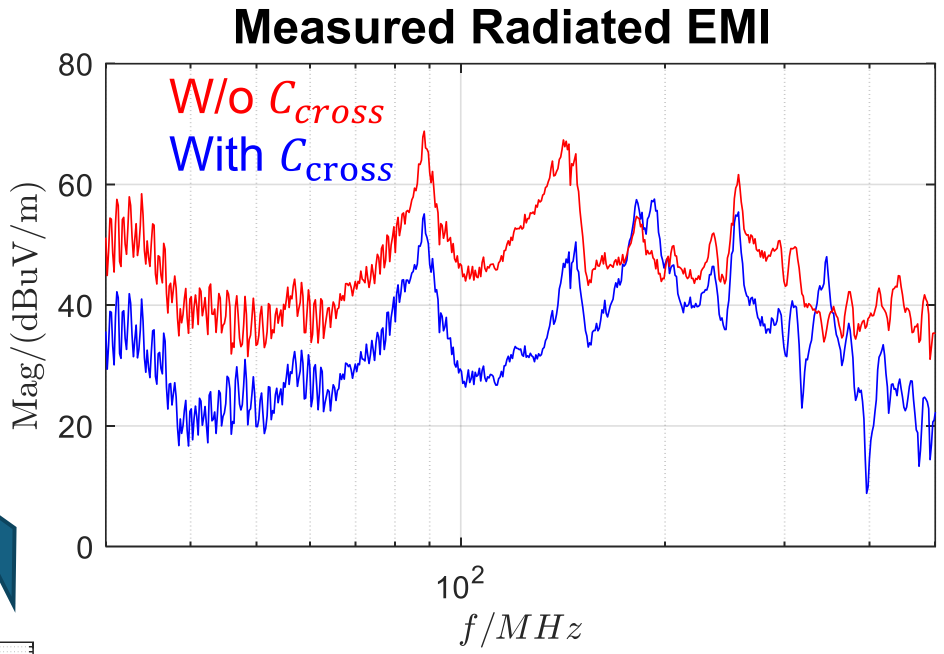
Reduction of the radiated EMI



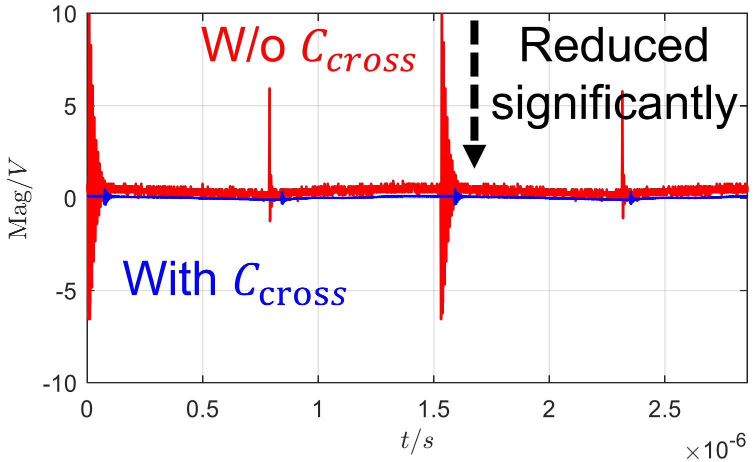
Summary: The radiated EMI is reduced significantly (>15 dB), which verifies the analyses of the ground layer impedance and the inductor arrangement improvement.

Reduce Radiated EMI by Adding a Cross Capacitor

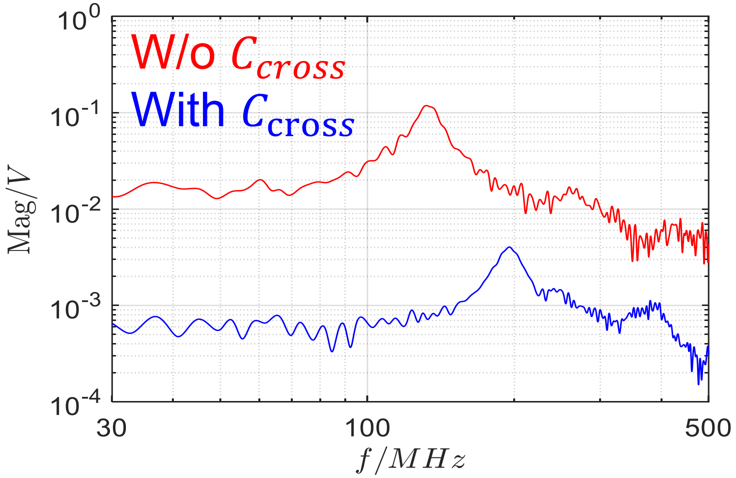




Comparison of CM terminal voltages



Waveform comparison

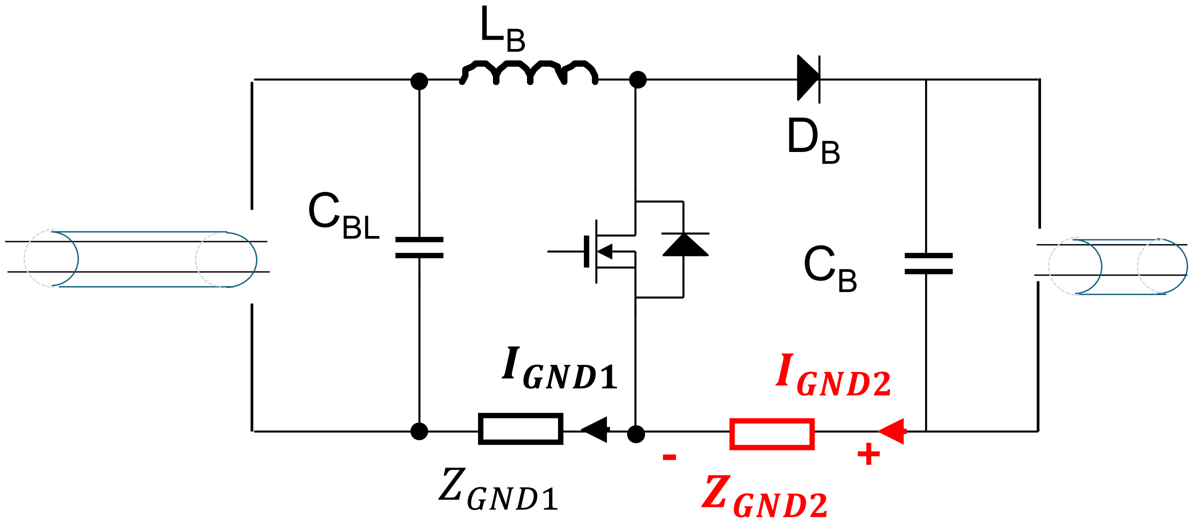


Spectrum comparison

Adding a cross capacitor can equivalently reduce the ground layer impedance and accordingly reduces: 1) the excitation voltage V_A and 2) the radiated EMI.

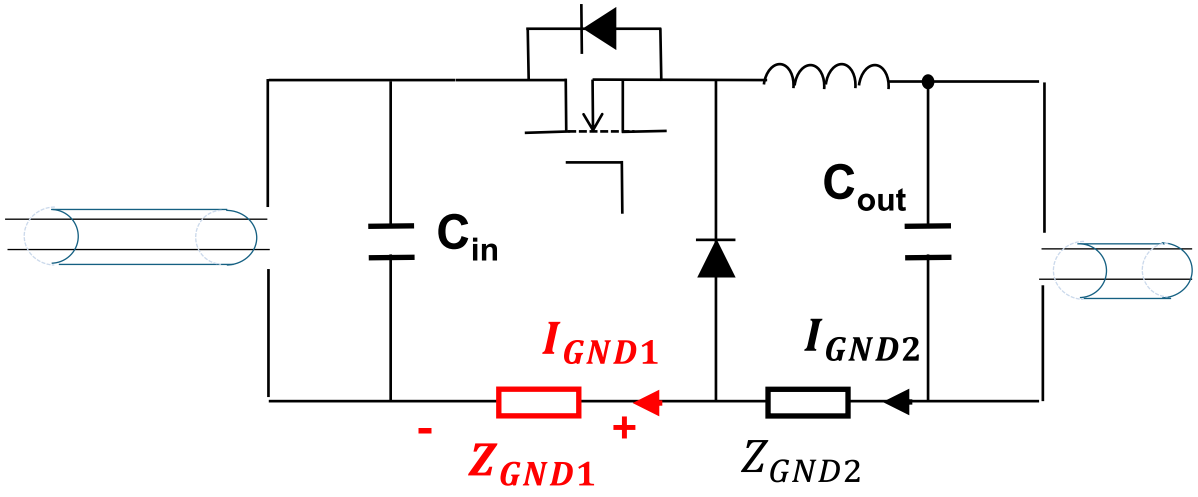
Extending the Techniques to Other Topologies

Boost Converters



1. Z_{GND1} and Z_{GND2} are between the input and output
2. I_{GND1} is continuous (for CCM), I_{GND2} is discontinuous
3. Voltage drop on Z_{GND2} drives input and output connections for radiated EMI
4. PCB layout should reduce Z_{GND2}

Buck Converters

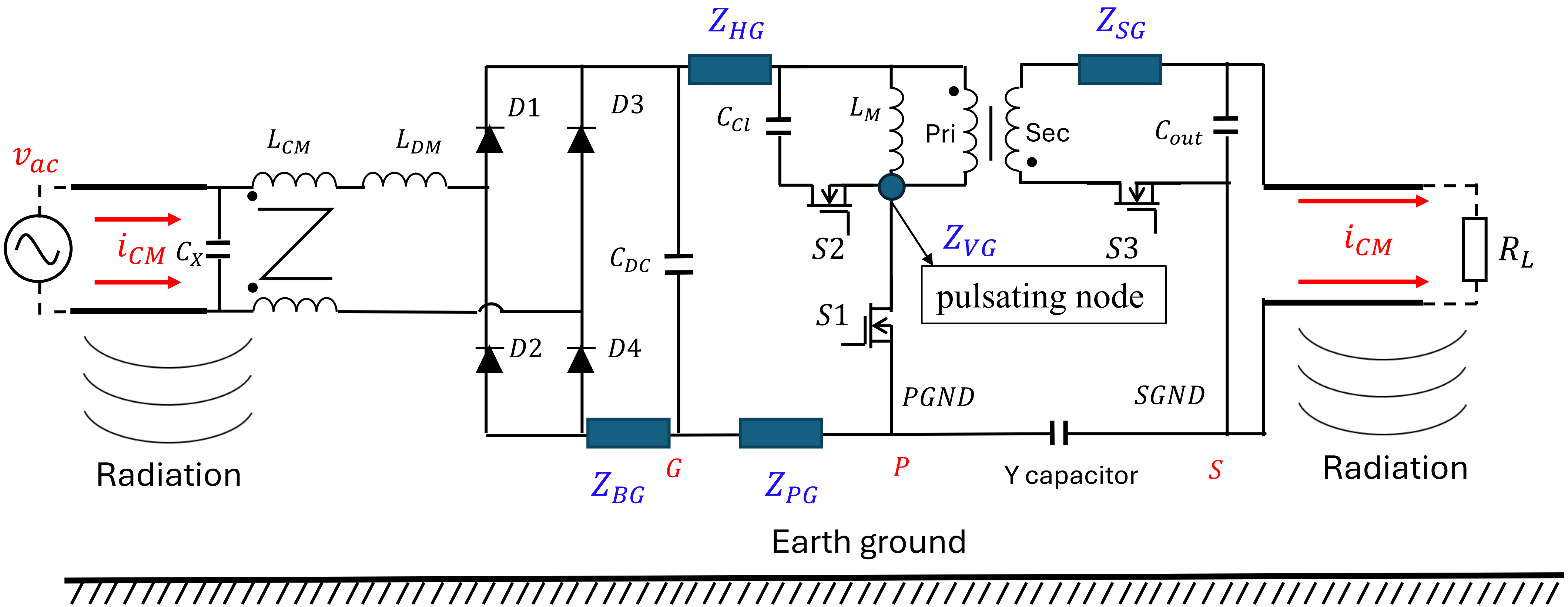


1. Z_{GND1} and Z_{GND2} are between the input and output
2. I_{GND1} is discontinuous, I_{GND2} is continuous (for CCM)
3. Voltage drop on Z_{GND1} drives input and output connections for radiated EMI
4. PCB layout should reduce Z_{GND1}

Radiated EMI due to PCB Ground Layouts in Isolated Power Converters

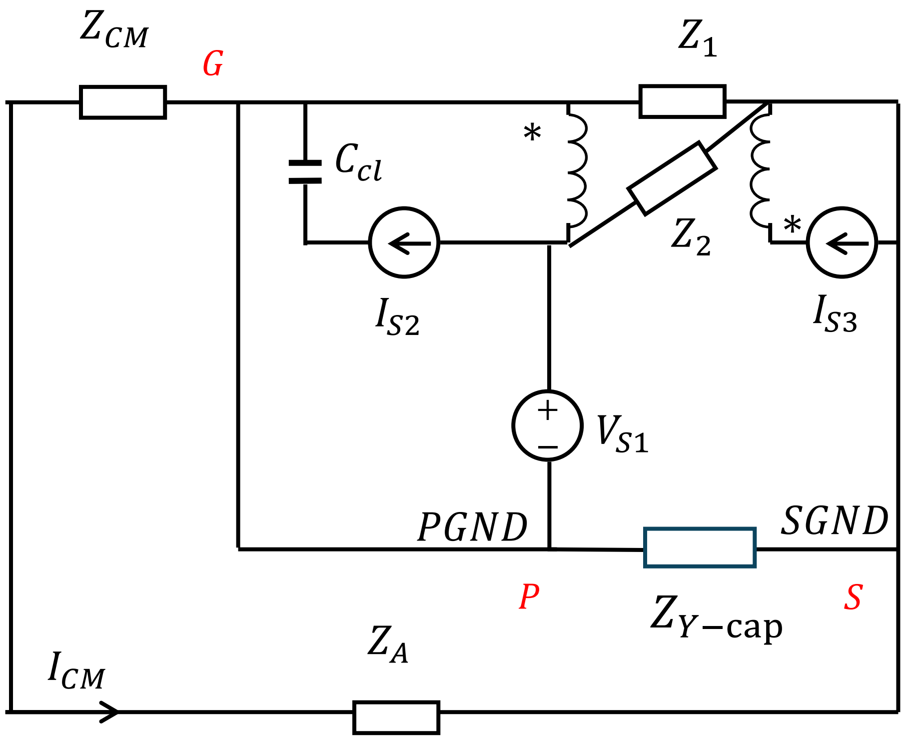
[3] Z. Ma, S. Wang, H. Sheng and S. Lakshmikanthan, "Modeling, Analysis and Mitigation of Radiated EMI Due to PCB Ground Impedance in a 65 W High-Density Active-Clamp Flyback Converter," in *IEEE Transactions on Industrial Electronics*, vol. 70, no. 12, pp. 12267-12277, Dec. 2023, doi: 10.1109/TIE.2023.3239904

Identify Critical PCB Ground Impedances in A Flyback Converter

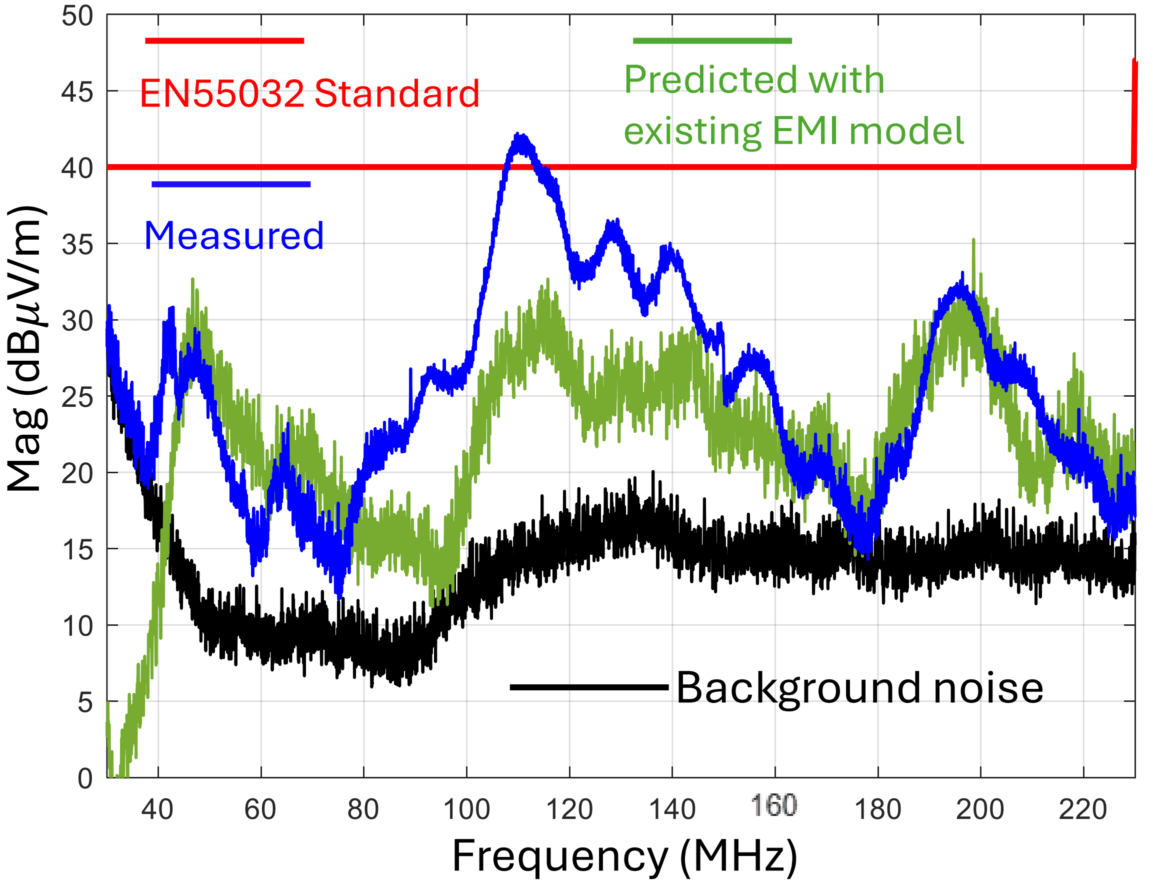


Which PCB layout impedances are important for reducing radiated EMI?

Radiation Model w/o Considering Ground Impedances for Flyback Converters

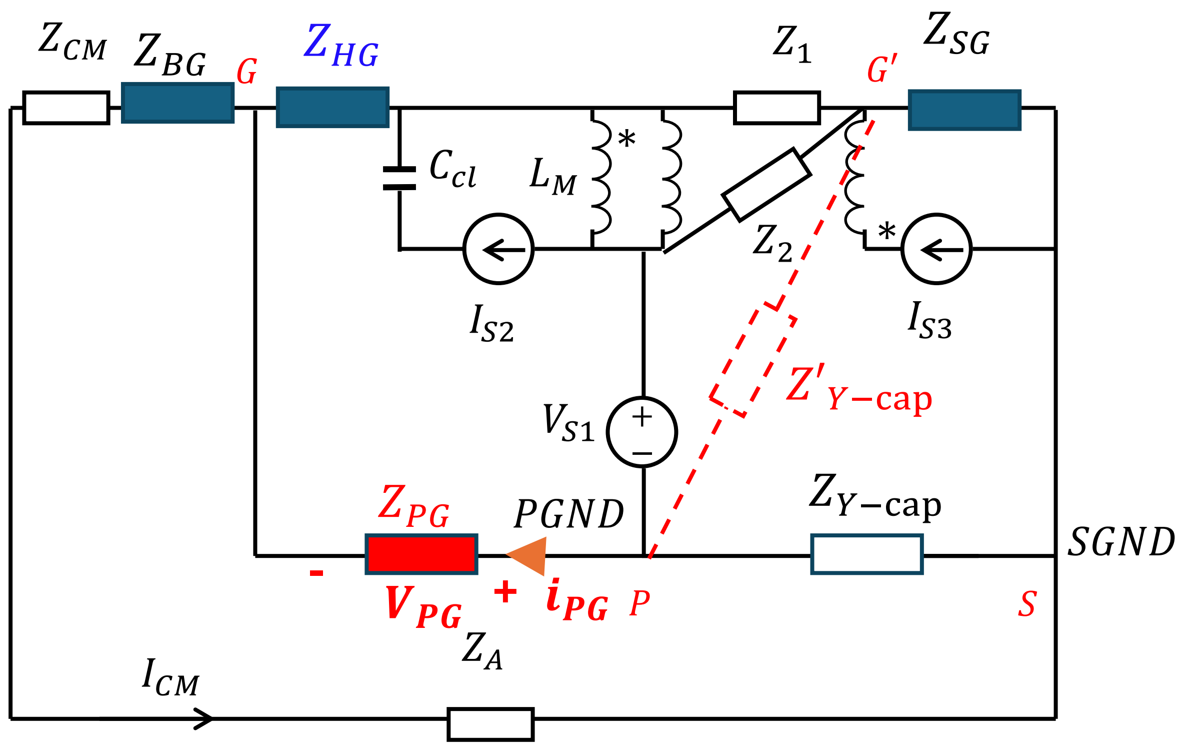


Note: **When analyzing CM EMI noise, the transformer can be represented by a two-impedance model. The substitution theory is applied to simplify the analysis. The model can finally be simplified to the right one.**



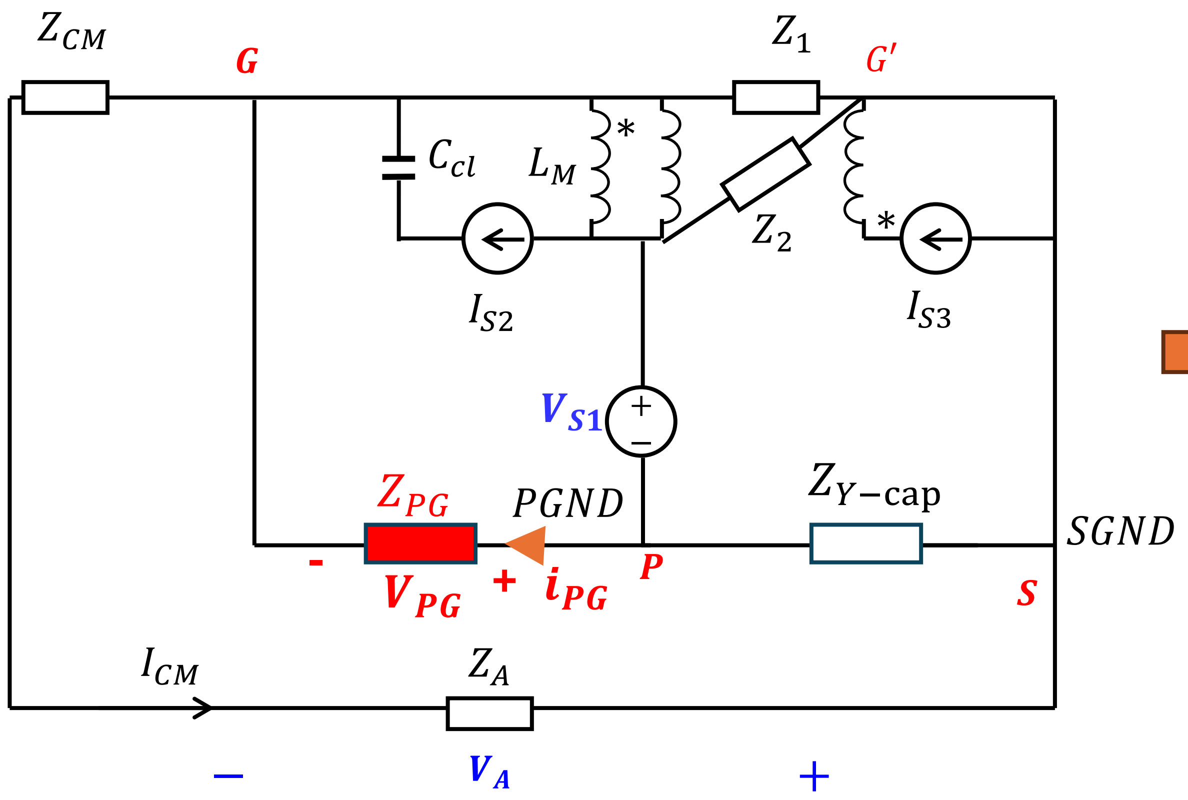
The predicted EMI does not match the measured one, Why?

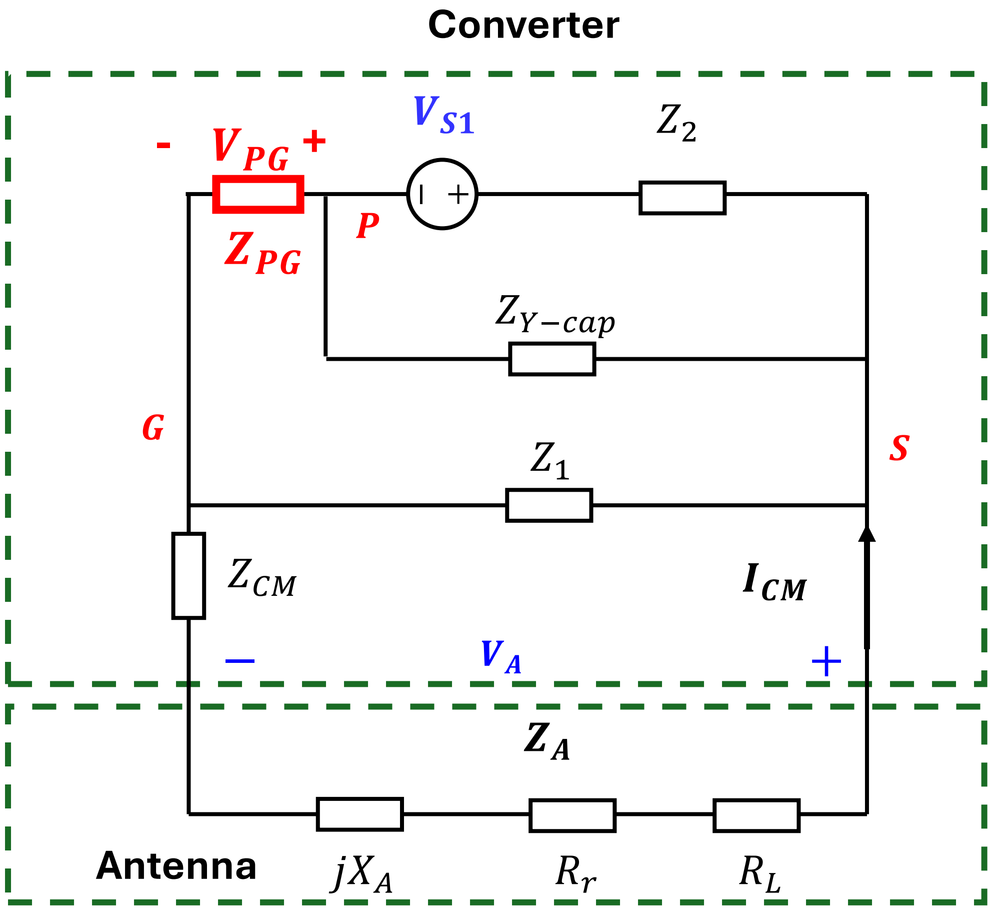
Analysis of PCB Ground Impedances for the Radiated EMI in Flyback Converters



1. Z_{BG} is not important since it is in series with the high impedance of the CM inductor
2. Z_{HG} is not important since it is in series with the transformer's high impedance
3. Z_{SG} is not important since it does not impact V_{SG} due to Y-cap.
4. Z_{PG} is important since i_{PG} is discontinuous and V_{PG} is between the input and output
5. The connection of Y-cap is important to reduce radiated EMI (for the $Z'_{Y\text{-cap}}$ connection, Z_{SG} is important)
6. Connecting Y-cap between the S and G is the BEST

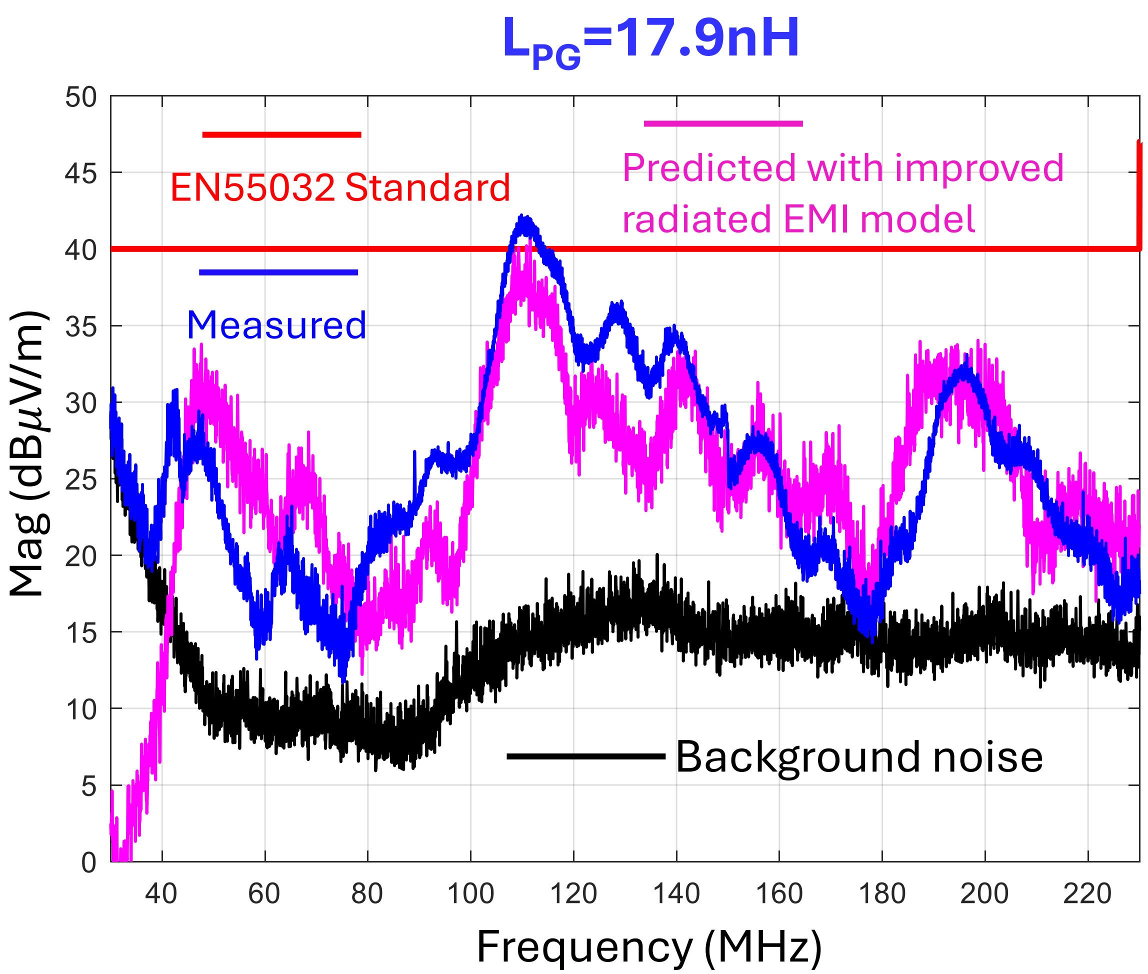
Radiated EMI Model

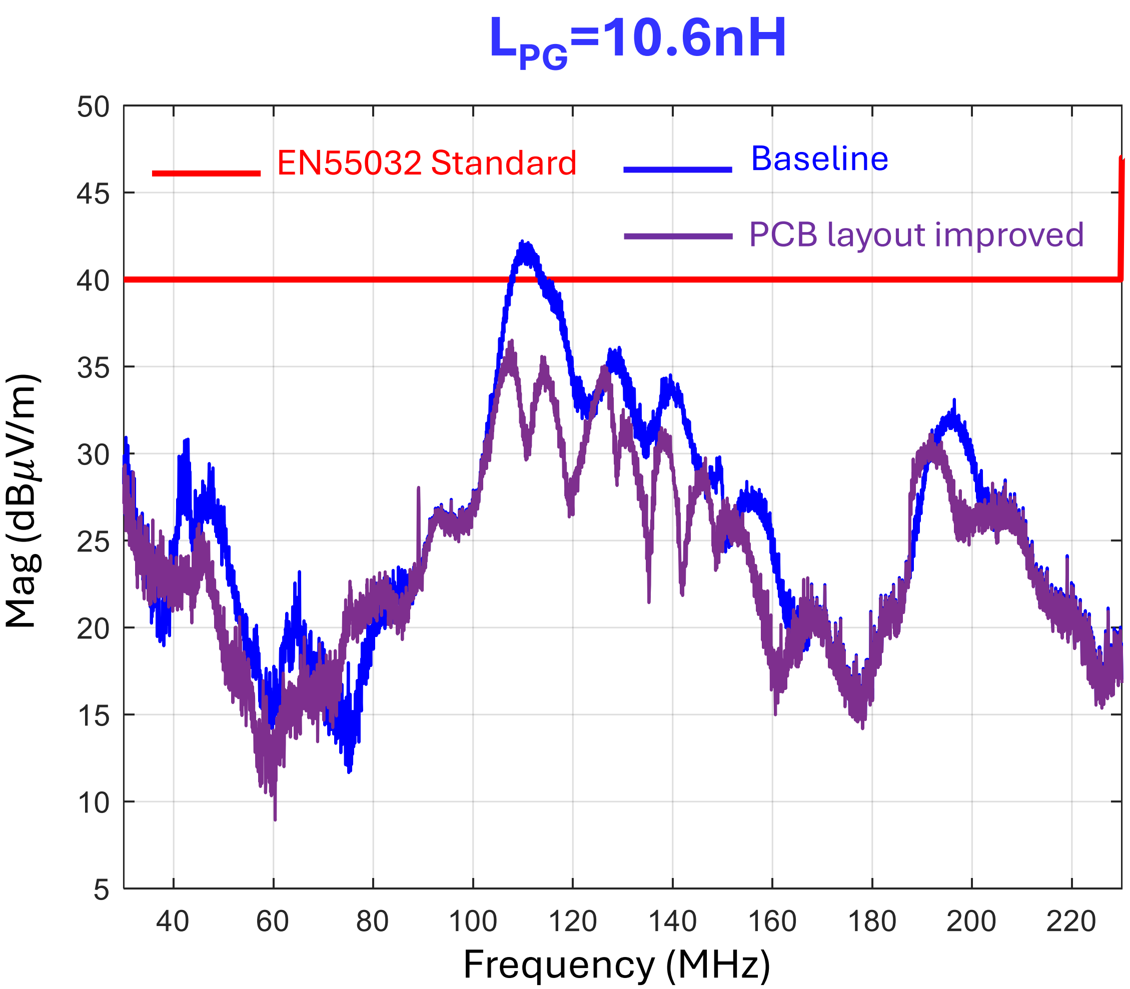




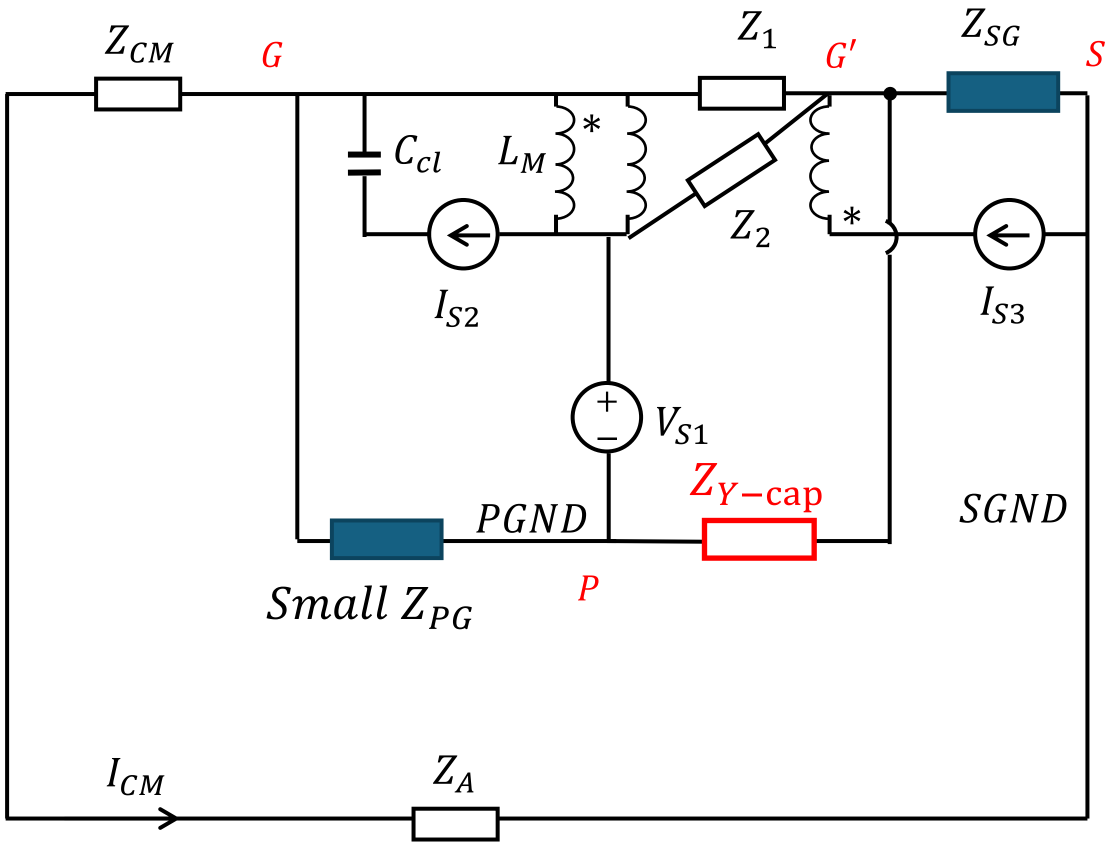
1. Both V_{PG} and V_{S1} can lead to radiated EMI
2. A smaller impedance of Y-cap can help to reduce the radiated EMI due to V_{S1}, but it cannot reduce the radiated EMI due to V_{PG}.

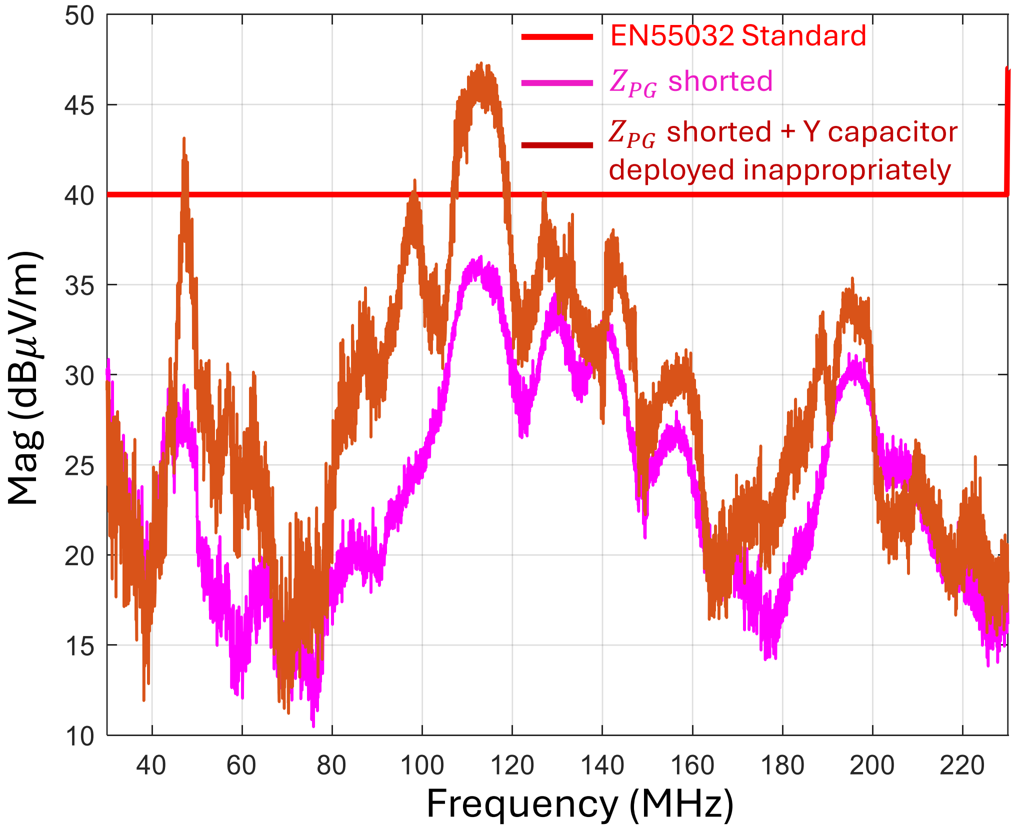
Radiated EMI Reduction by Reducing Z_{PG}





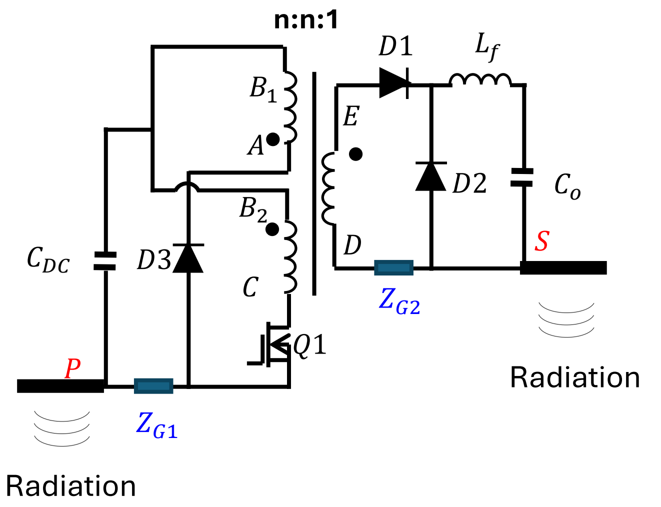
Impact of Y-cap's Layout on the Radiated EMI

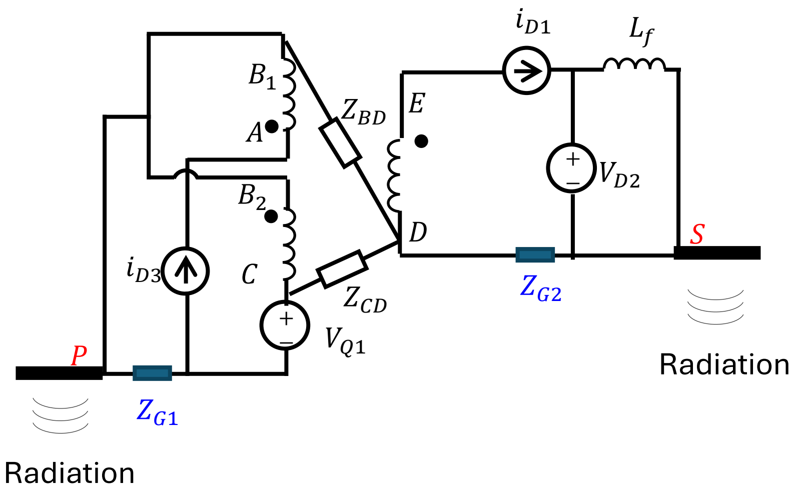


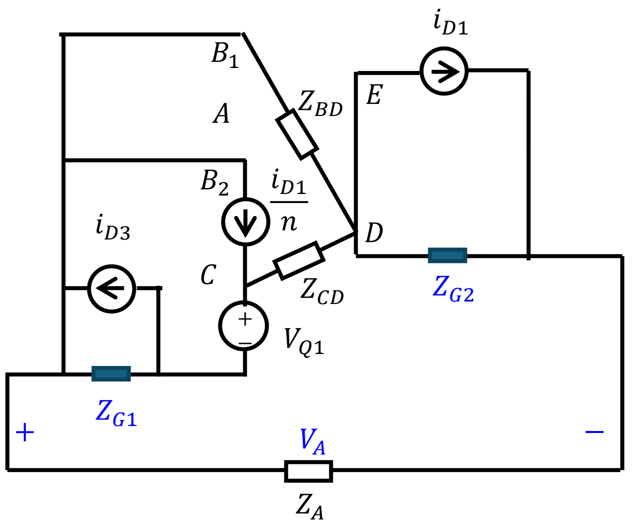


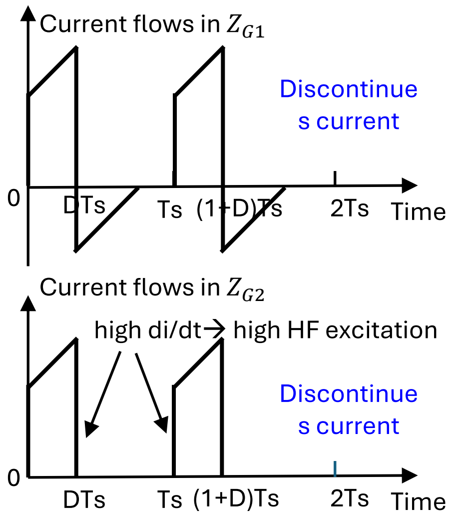
Shuo Wang @University of Florida, 2025

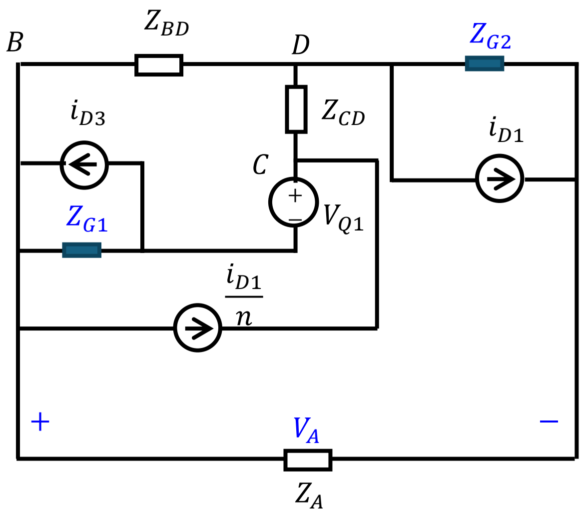
Forward Converters



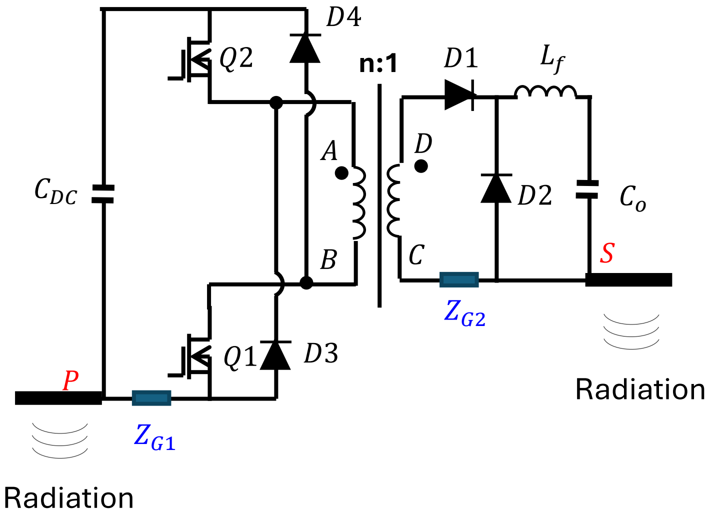


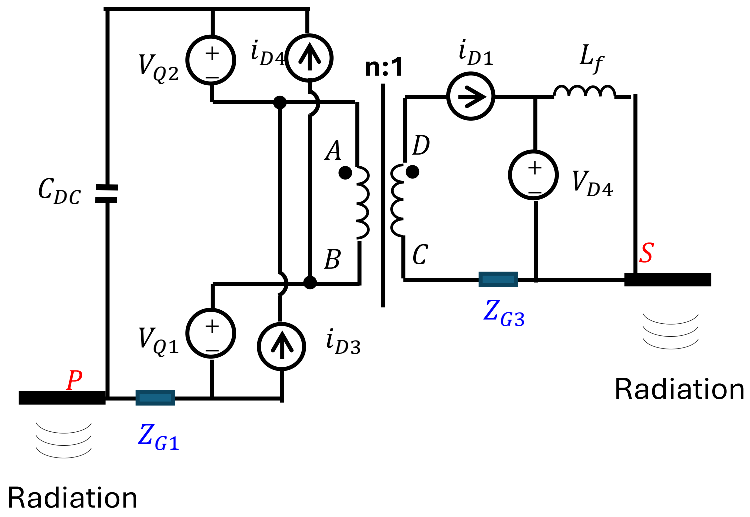


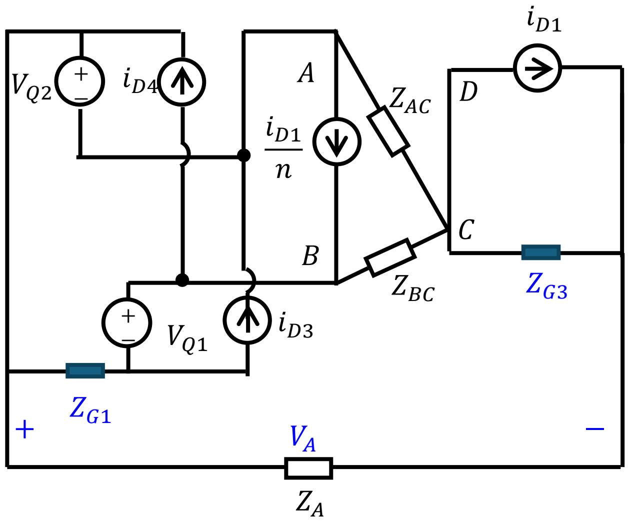


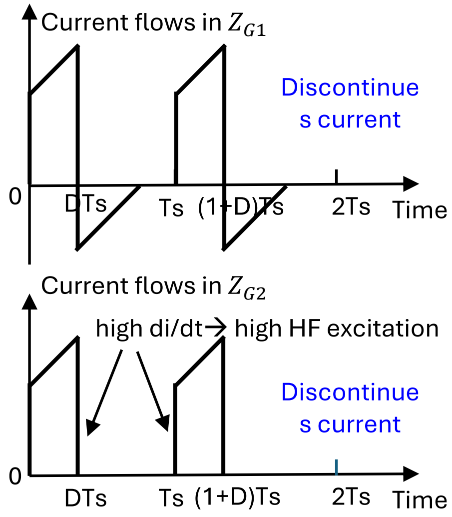


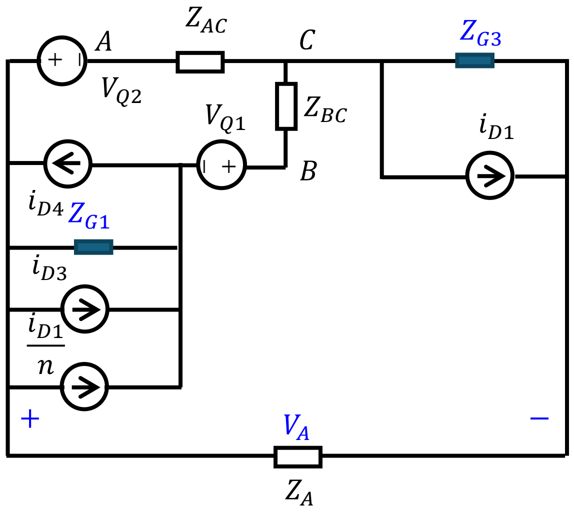
Two-switch Forward Converters



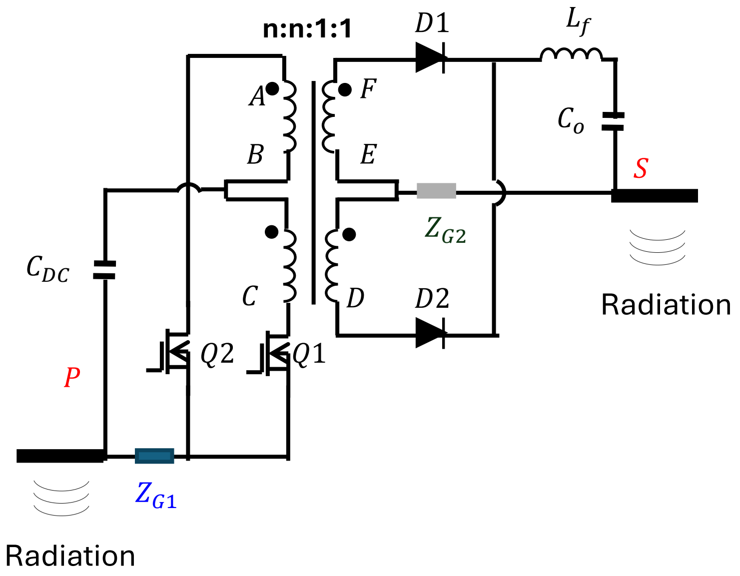


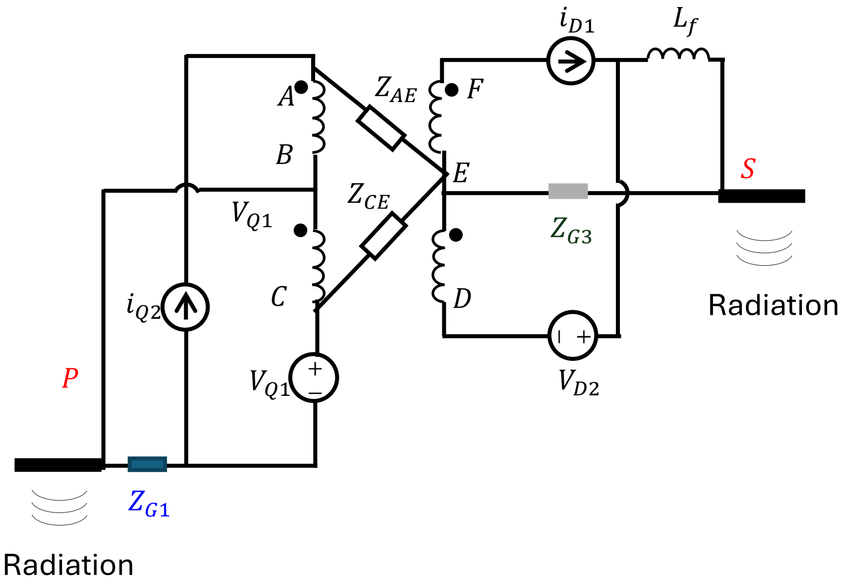


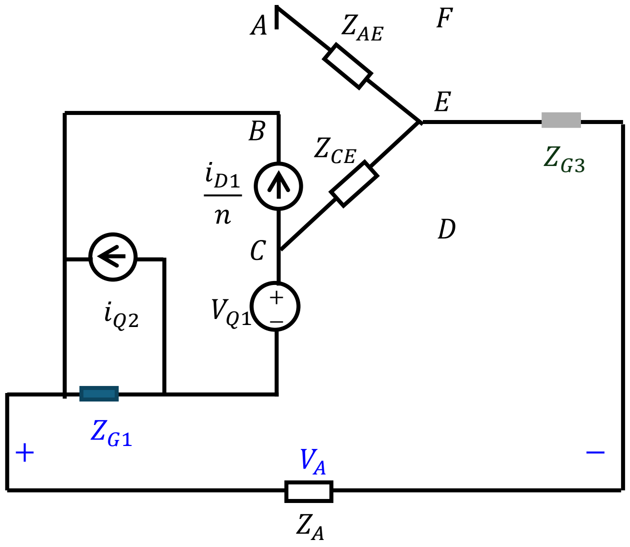


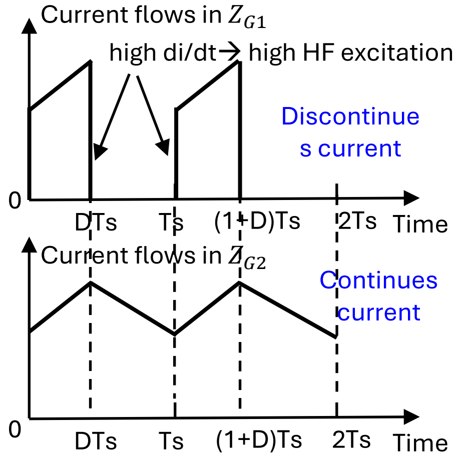


Push-pull Converters

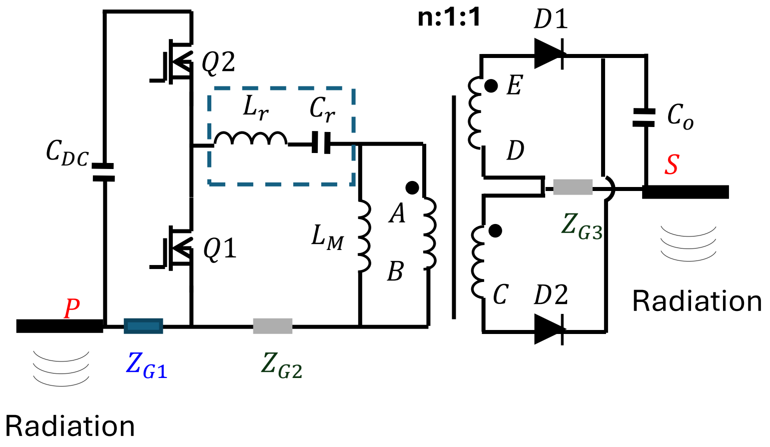


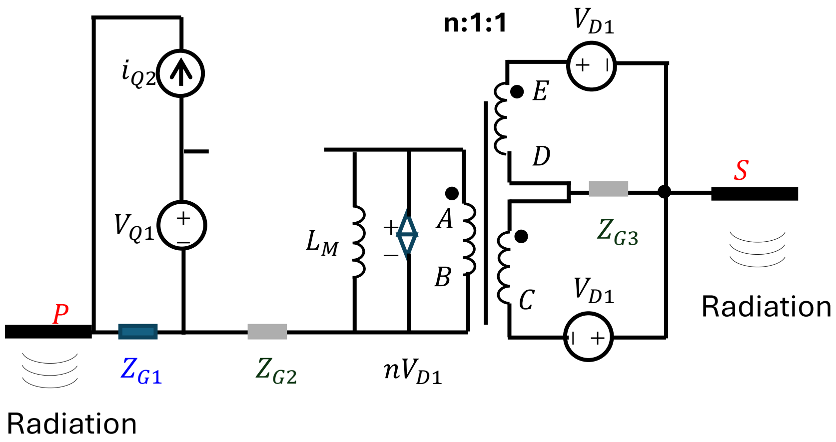


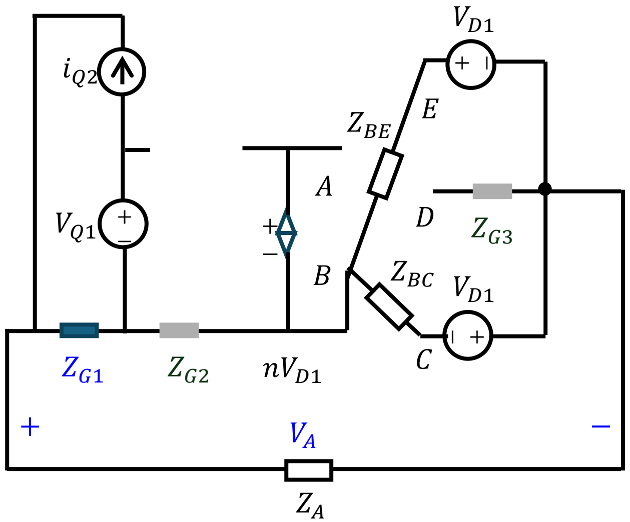


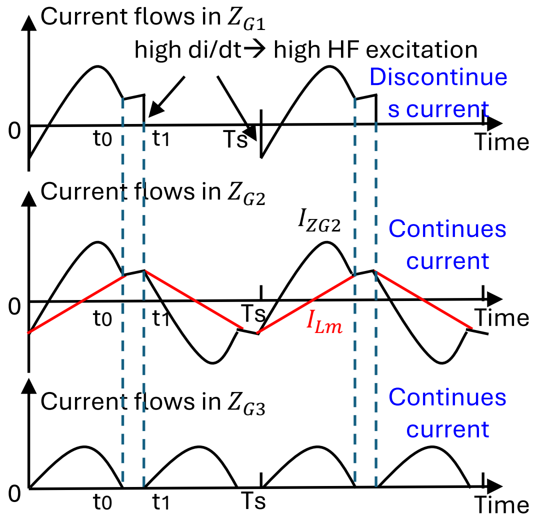


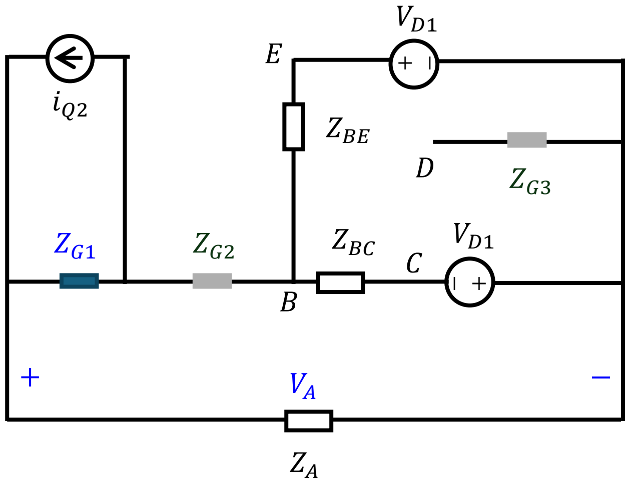
Half-bridge LLC Resonant Converters







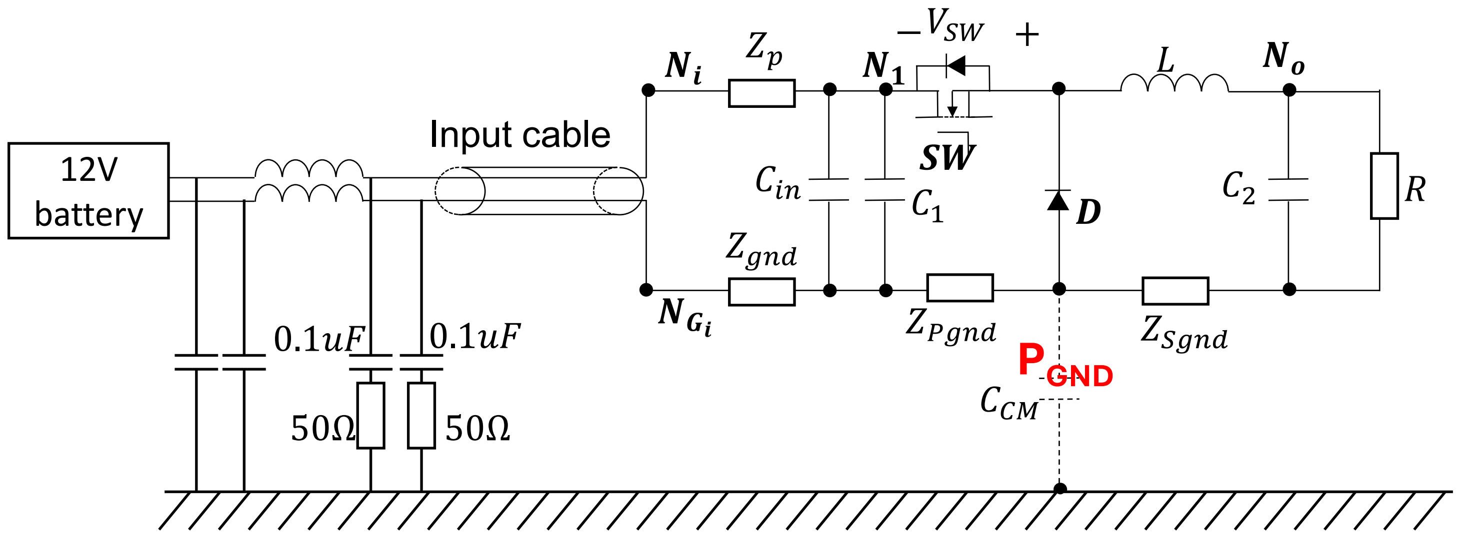


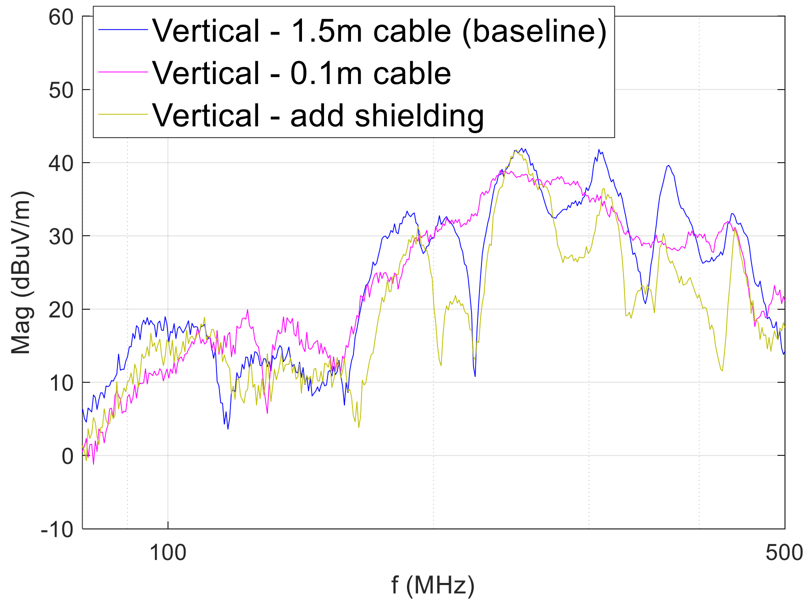


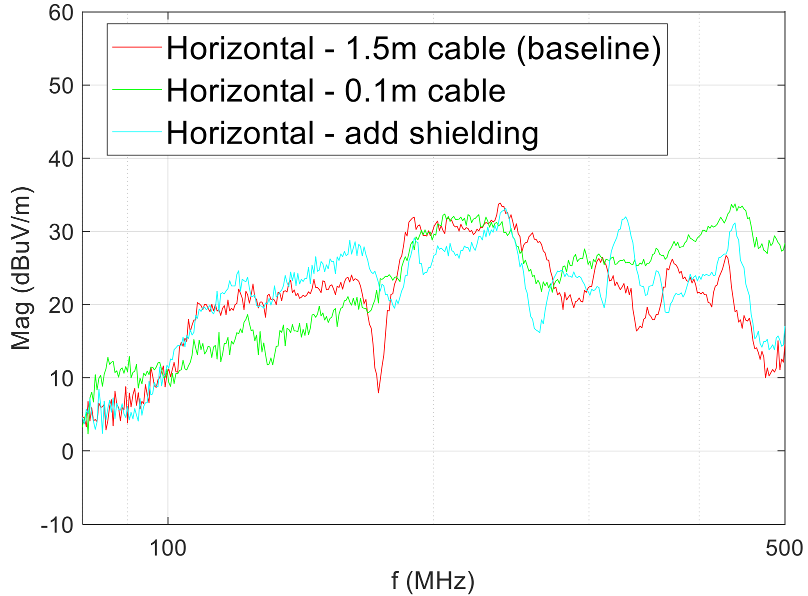
Radiated EMI due to PCB Ground Layouts and Differential Mode EMI Noise

[4] Yanwen Lai, Yirui Yang, Qinghui Huang, Shuo Wang, Zheng Luo, "Modeling, Analysis and Reduction of Radiated EMI Due to the Pulsating Voltage on PCB Ground Plane in a Non-Isolated Power Converter," in *proc. of* 2024 IEEE Energy Conversion Congress and Exposition, Oct. 2024.

A New Radiation Mechanism

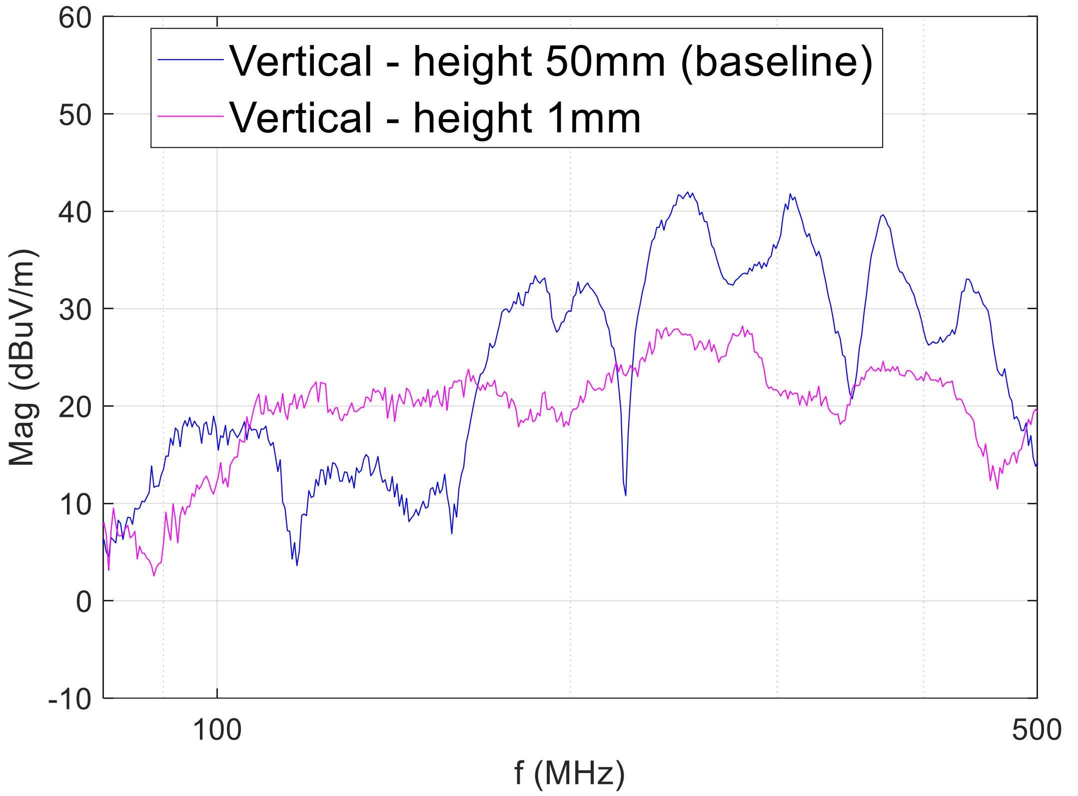


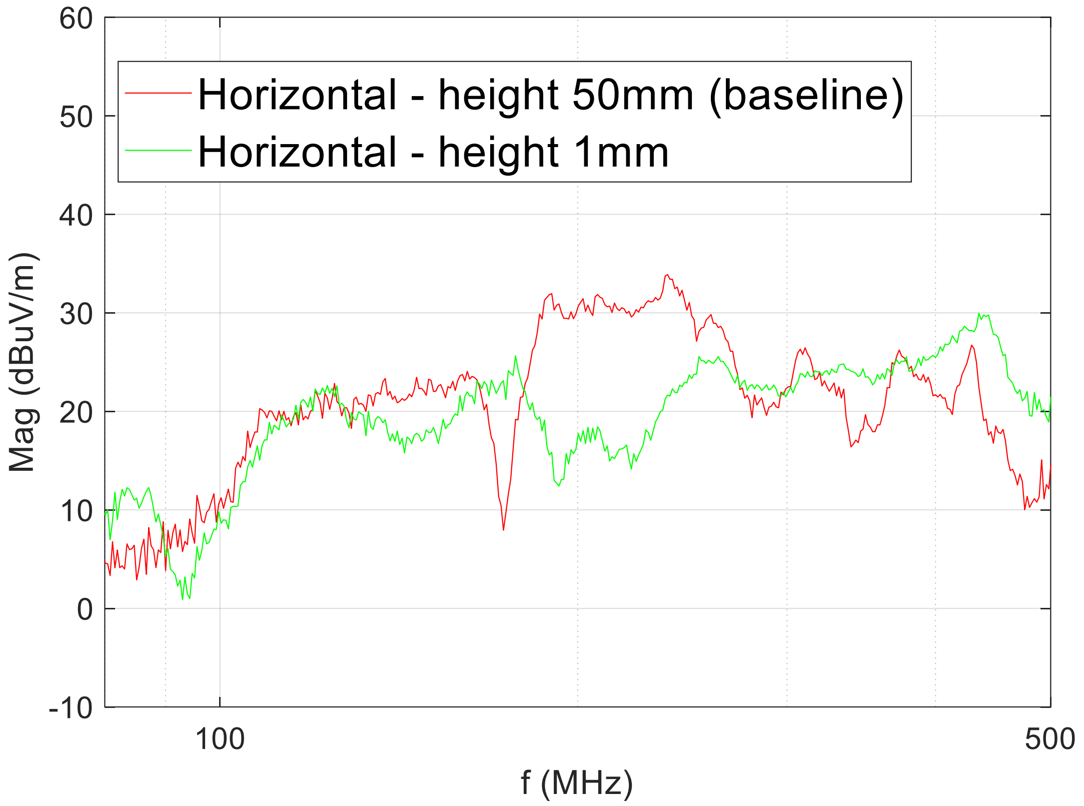




1. **Based on radiated EMI model, with Z_{Pgnd} minimized, reducing cable length l can reduce radiated EMI, when λ>>l.**
2. **Reducing cable length has no impact on radiated EMI for this converter**
3. **Even shielding the converter to the PGND does not help**
4. **Why?**

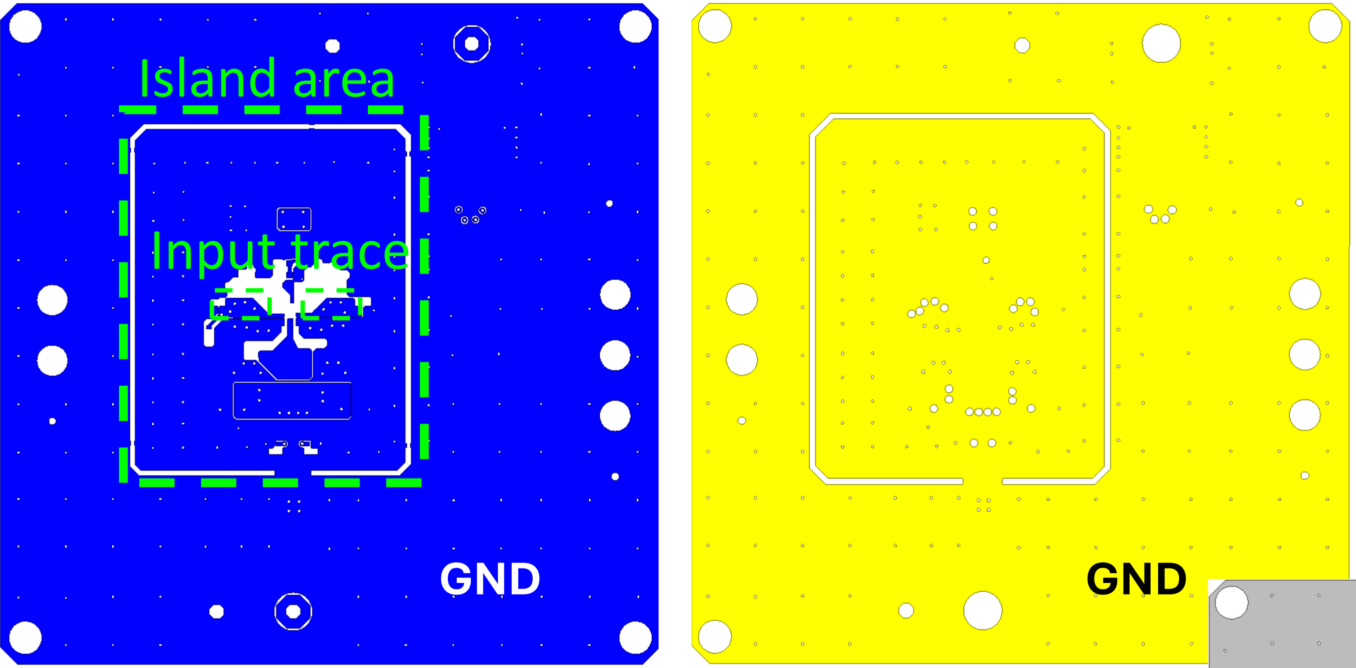
Reducing the Distance between the PCB and the Ground

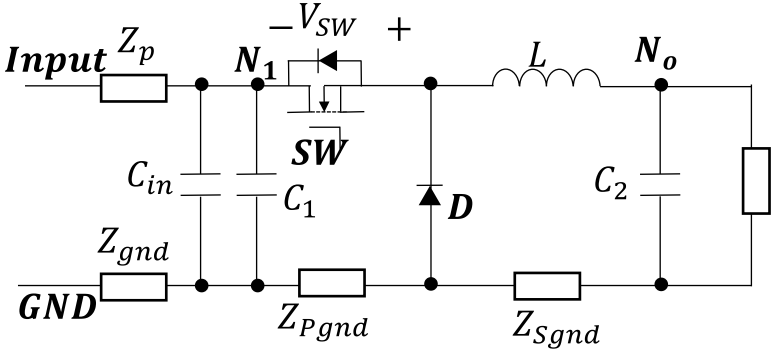




1. **The image under the ground can cancel the radiated EMI**
2. **Reducing distance between the PCB and the ground can reduce radiated EMI**
3. **Something on PCB therefore generates dominant radiated EMI**

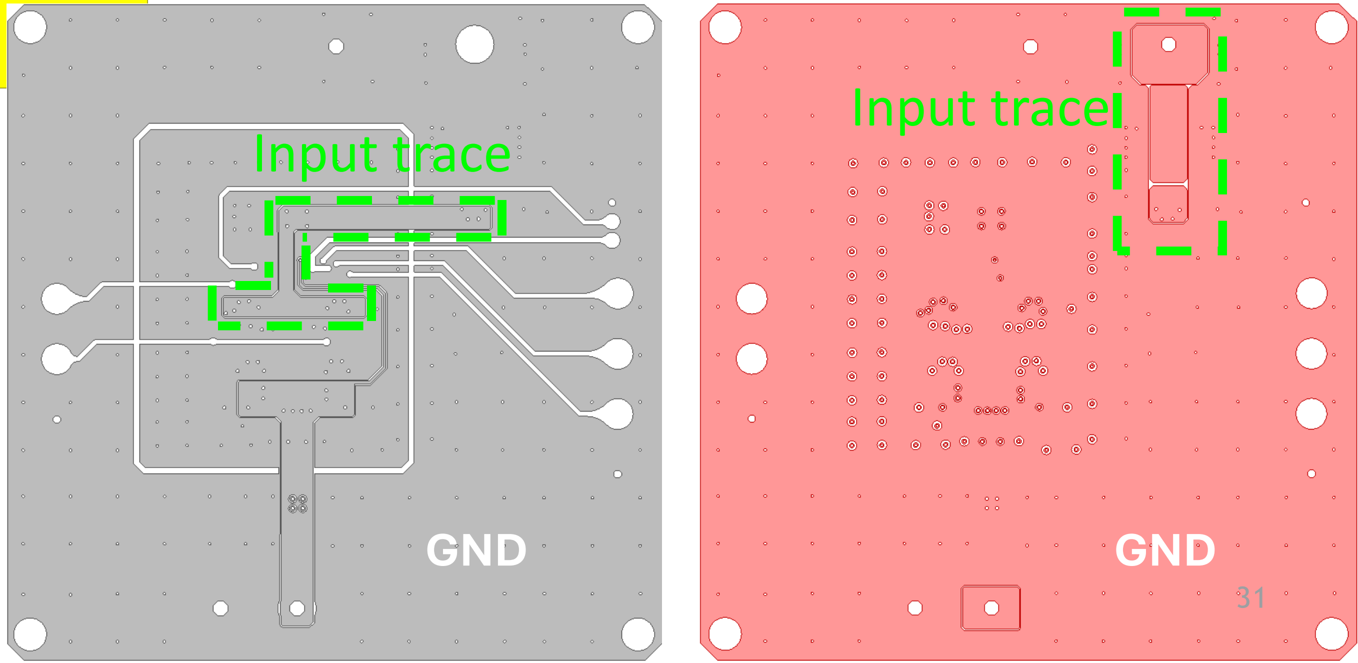
PCB Ground and Input Power Trace Layout



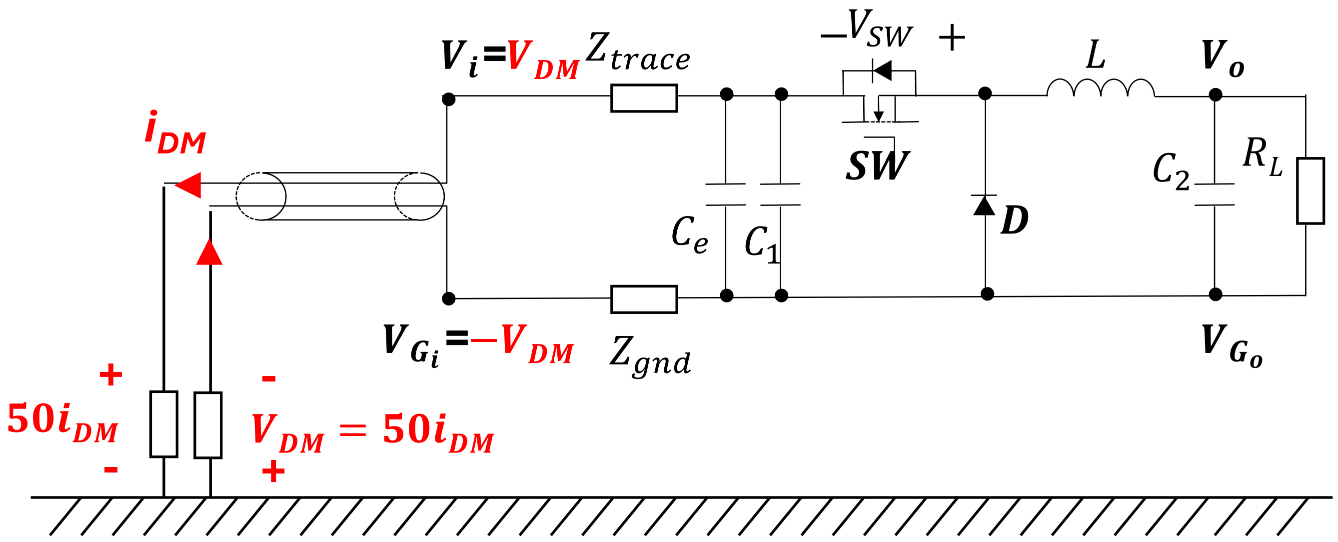


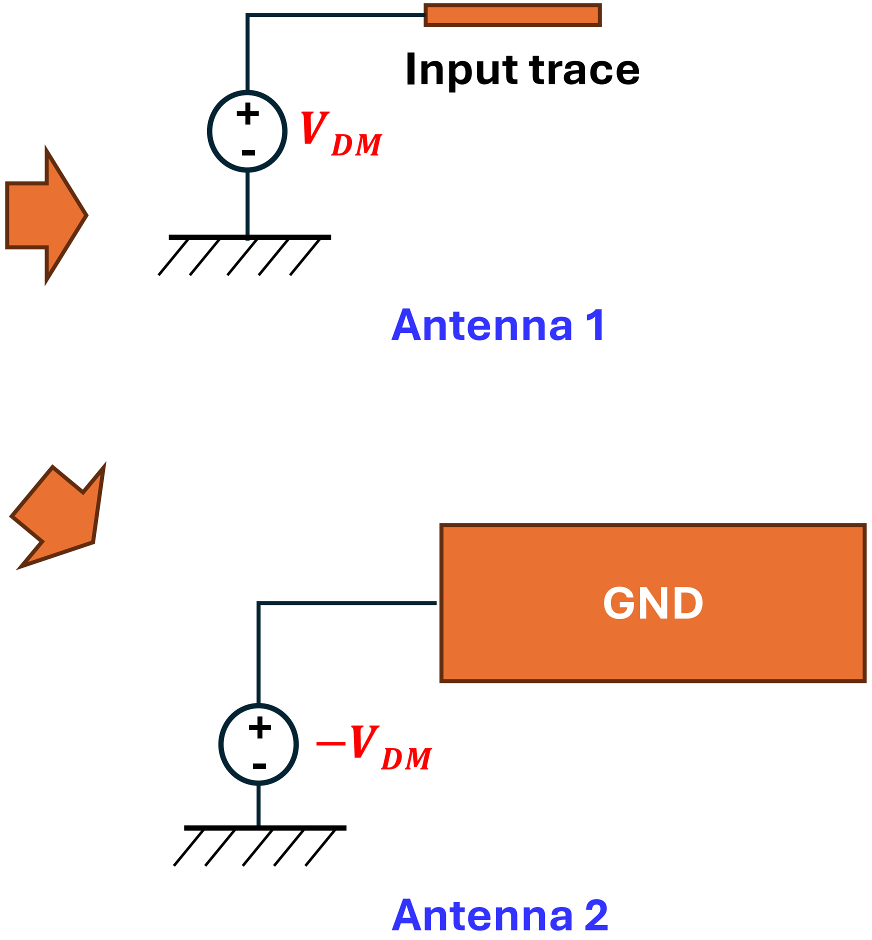
Observation:

1. **Input trace and GND layouts are asymmetric**
2. **Voltage pulsating PCB trace or GND plane can generate radiated EMI**



We have Identified A New Radiation Mechanism Recently

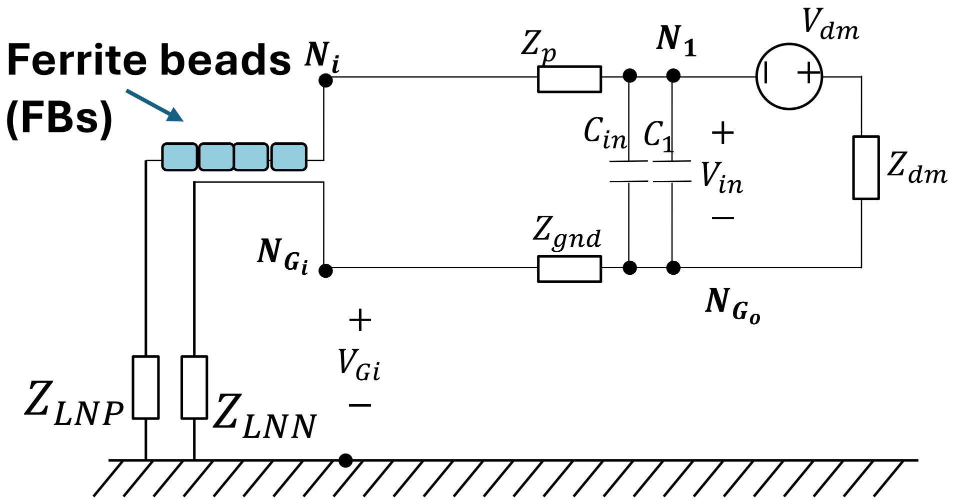


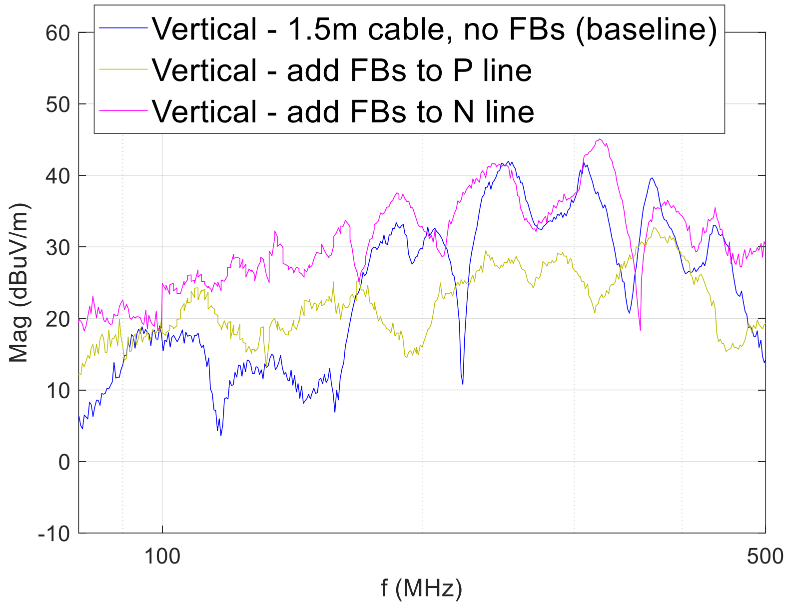


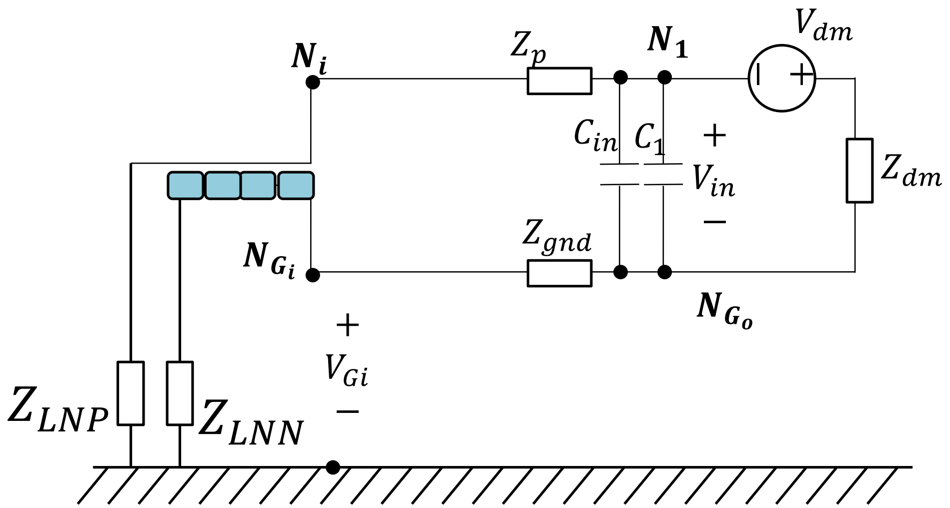
Theory:

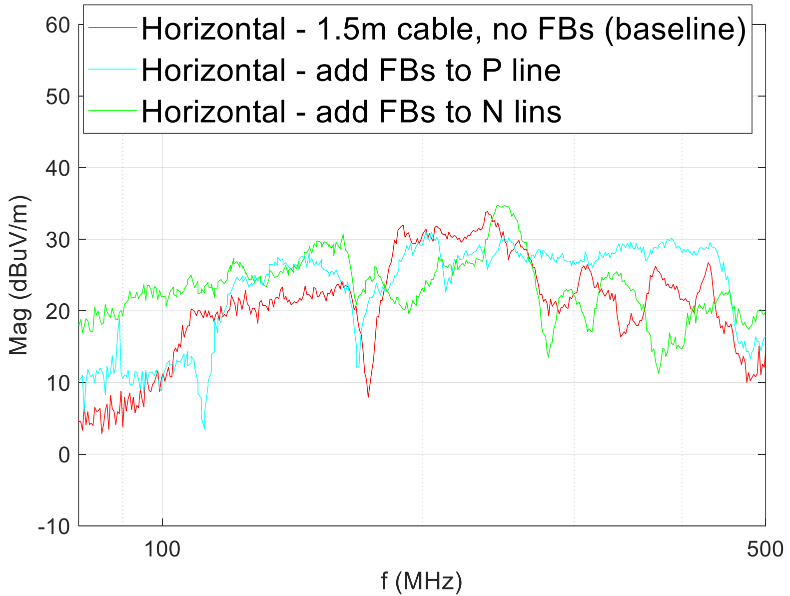
1. Input trace and GND both are antenna
2. The radiation due to single wires in the cable is canceled since the two wires carrying inverse voltages and at the same location
3. The radiation due to Input trace only cancel very small amount of the radiation due to GND
4. The radiation from GND PCB plane is dominant

Validation of the Developed Theory

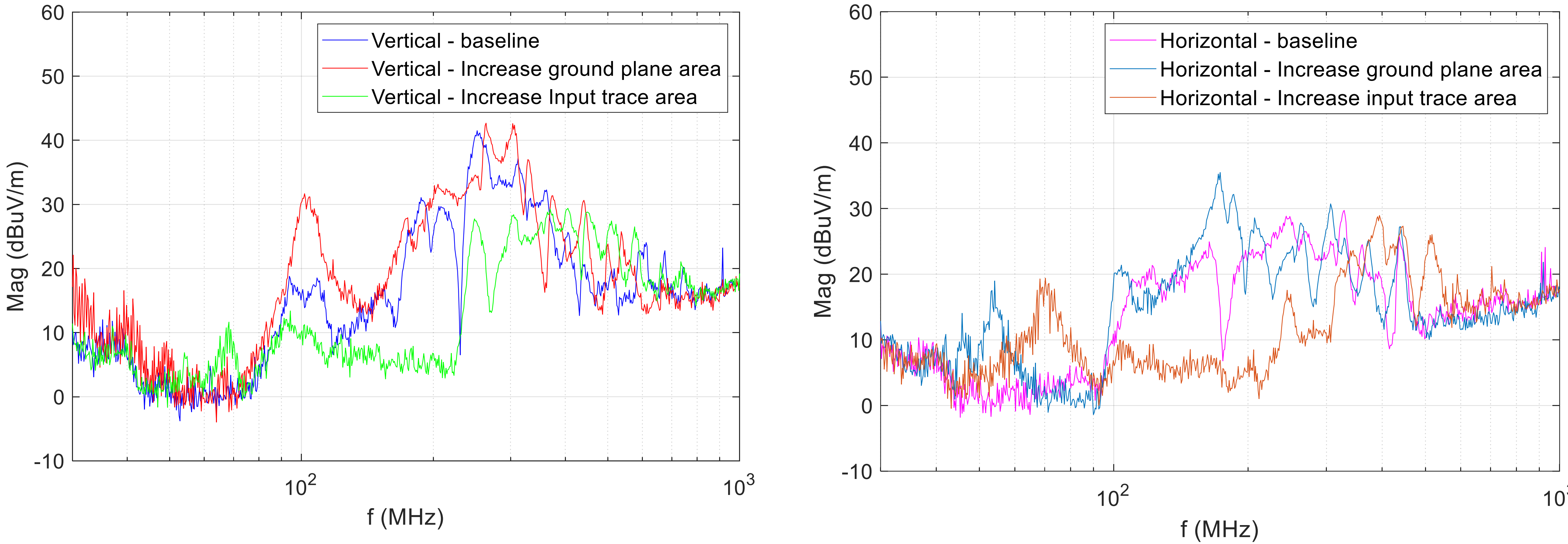








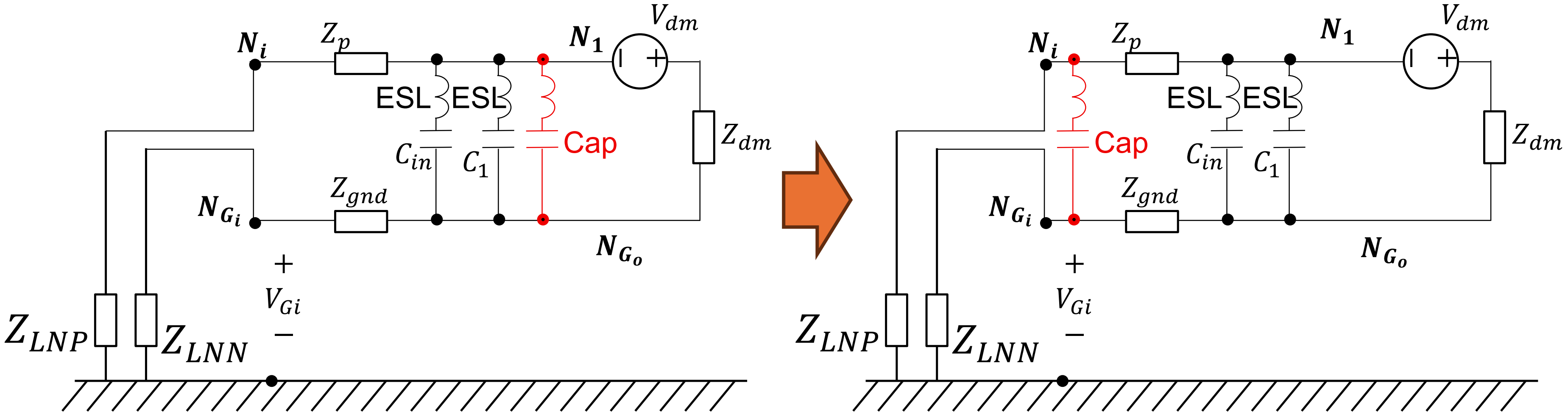
Reduce Radiated EMI by Increasing Input Trace Area

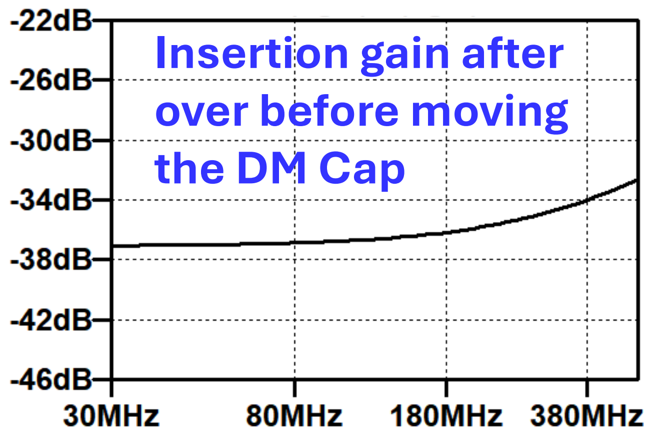


Reasoning:

Bigger input trace can better cancel the radiated EMI due to PCB GND plane

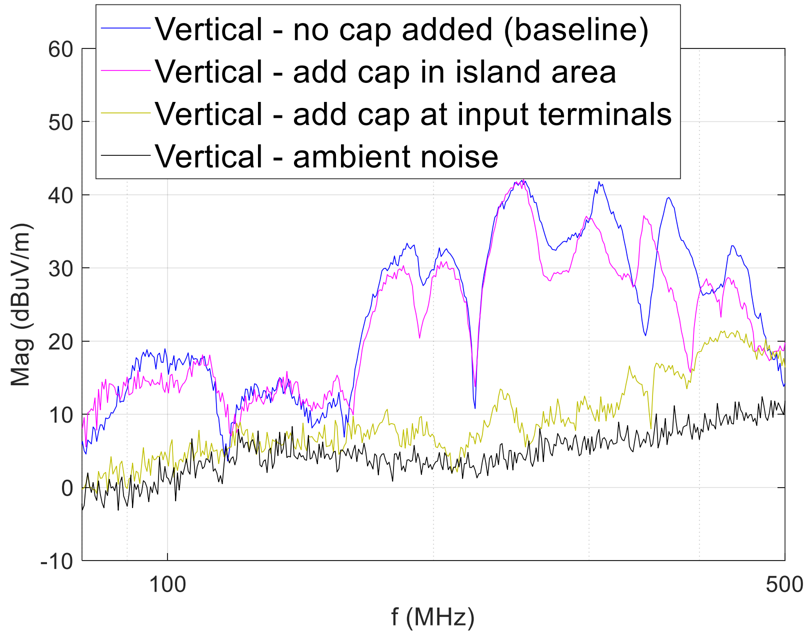
Reduce Radiated EMI by Moving a DM Capacitor to the Input

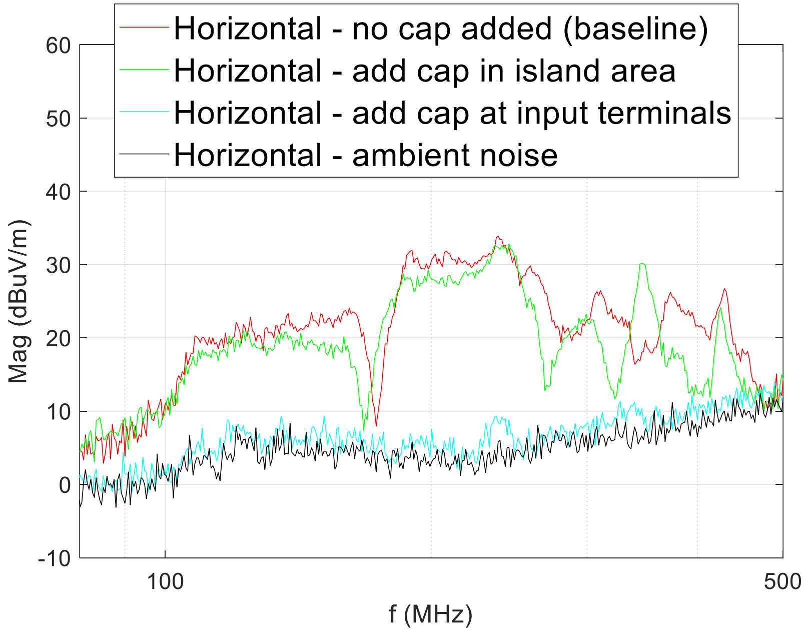




Reasoning:

1. **The new π-type filter reduces DM voltage on GND PCB plane**
2. **Radiated EMI due to GND is thus reduced**





Q & A

Note: **Please cite our work/papers when you publish or share the related work, it is very important to us as it means respect to our contributions**