EMI Modeling and Analysis of Non-Isolated DC/DC Converters

非隔离DC/DC变换器电磁干扰的分析与建模方法

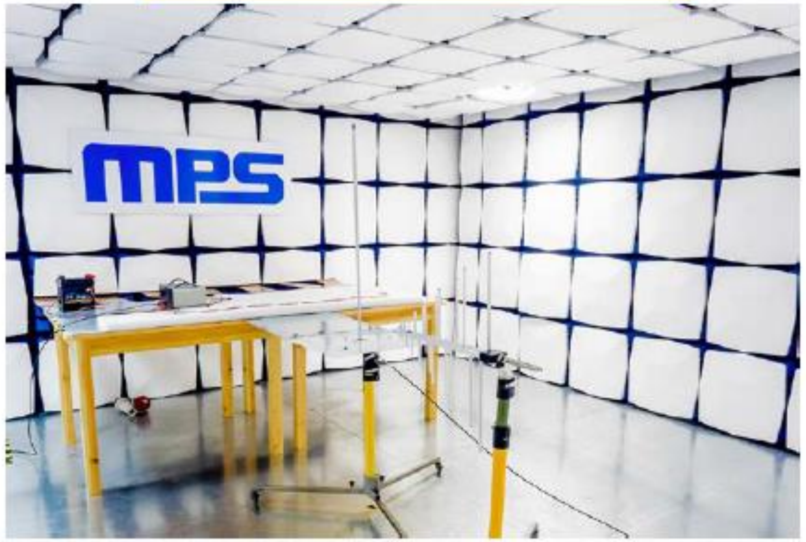
Mar. 2022

Agenda

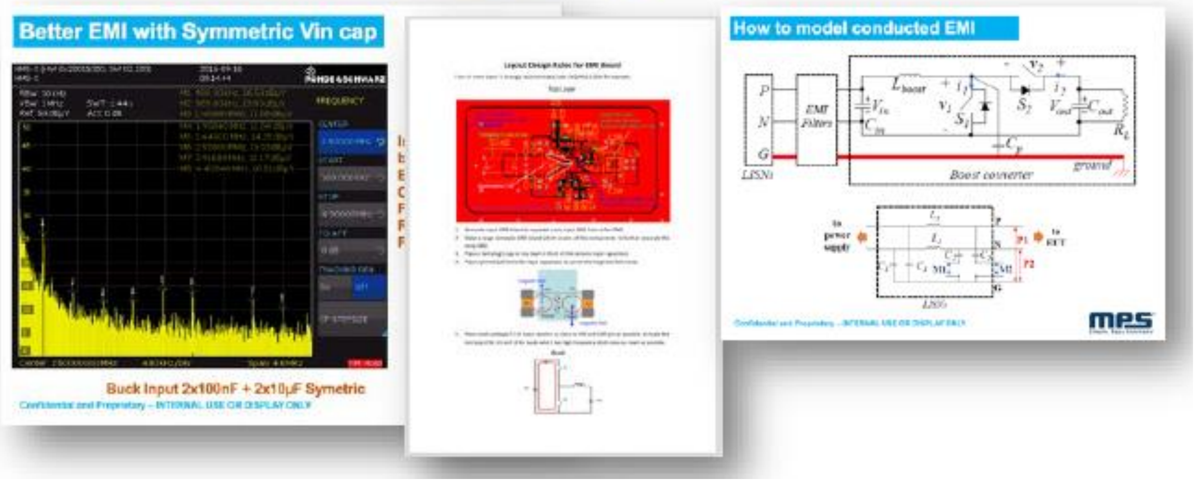
- Background and EMI/EMC Centers in MPS
- Conducted EMI Modeling and Analysis
- Radiated EMI Modeling and Analysis
- Conclusion

MPS EMI Backgrounds

Hangzhou EMI Lab



- $6M investment to build **EMI labs** – help customer to design for EMI in early stage
  - Offenburg – Germany
  - Detroit – USA
  - Hangzhou – China
- **Advanced EMI Model** development for customers
- **University Cooperation** on advanced EMI topics
- Better EMI performance by **IC design** and **system design**



New Detroit Automotive Center

40,000 SF
Conveniently located in Livonia off I-275

Local Technical Experts

Pre-Compliance Testing

Functional Safety

Design Seminars

MPS Livonia

3-Meter Chamber

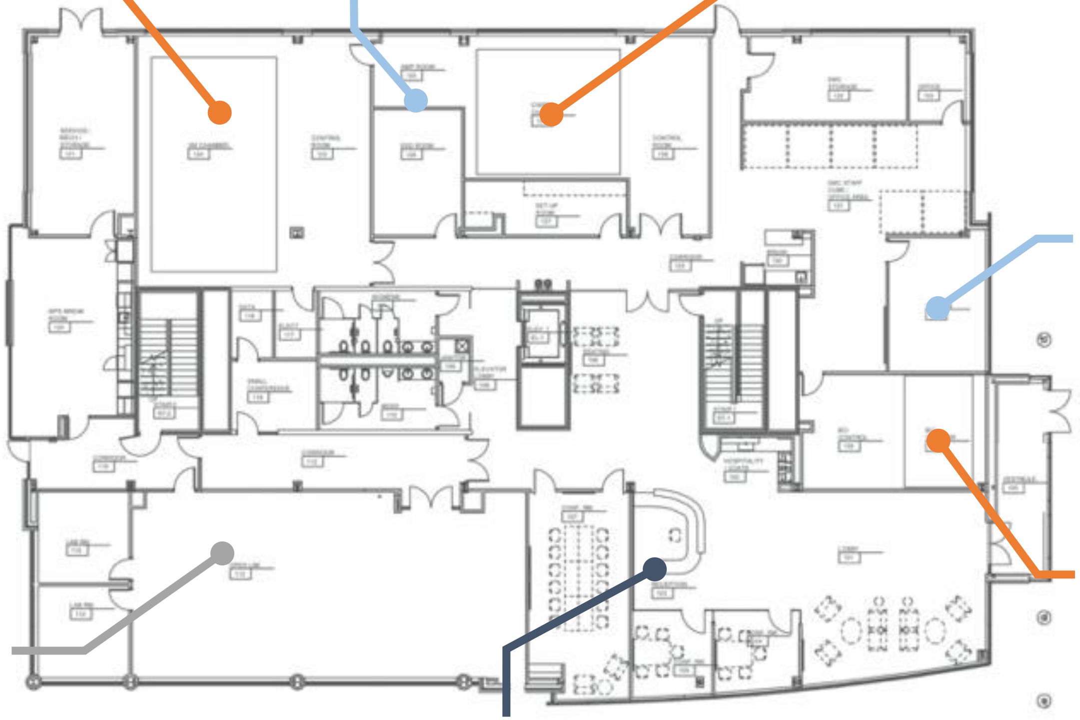
- ✓ Radiated Emissions (RE)
- ✓ Conducted Emissions (CE)
- ✓ Radiated Immunity (RI)
- ✓ CISPR25, CISPR32, ISO11452-2, ISO11452-9, IEC61000-4-3

ESD Testing

- ✓ ISO10605
- ✓ IEC61000-4-2

CISPR Chamber

- ✓ Radiated Emissions (RE)
- ✓ Conducted Emissions (CE)
- ✓ Radiated Immunity (RI)
- ✓ CISPR25, ISO11452-2, ISO11452-9



CI Testing

- ✓ ISO 7637-2/3
- ✓ ISO 16750-4
- ✓ IEC 61000-4-4/5/11 VDI
- ✓ ANSI/IEEE C62.41

Applications Lab

- ✓ Local customer support
- ✓ Reference designs
- ✓ Customer troubleshooting

Shielded Chamber

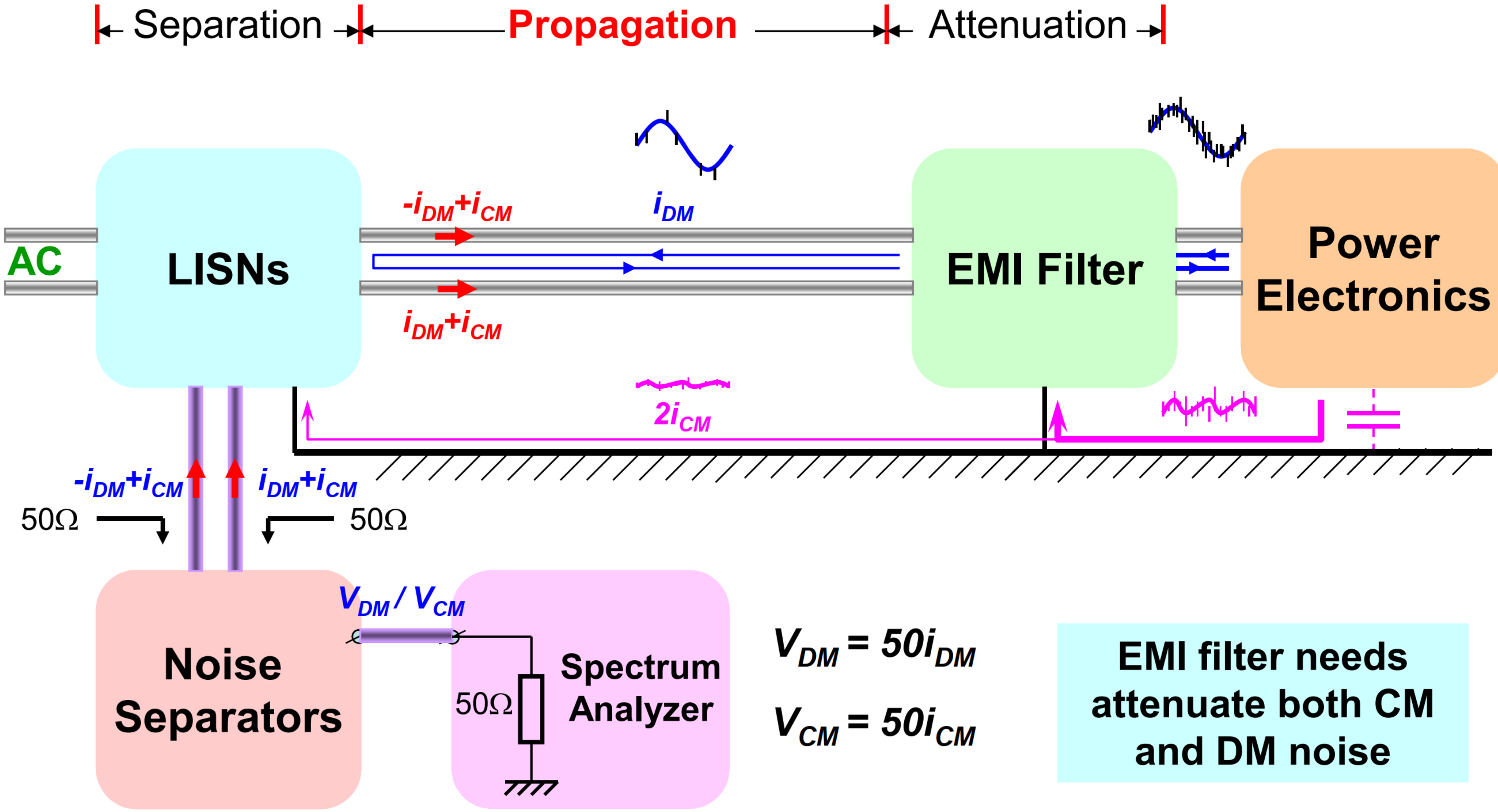
- ✓ Bulk Current Injection (BCI)
- ✓ Magnetic Immunity
- ✓ ISO11452-8, ISO11452-2, IEC61000-4-6

MPS Training Center

- ✓ Design seminars
- ✓ EMI training
- ✓ Lunch ‘n Learns
- ✓ Guest lectures

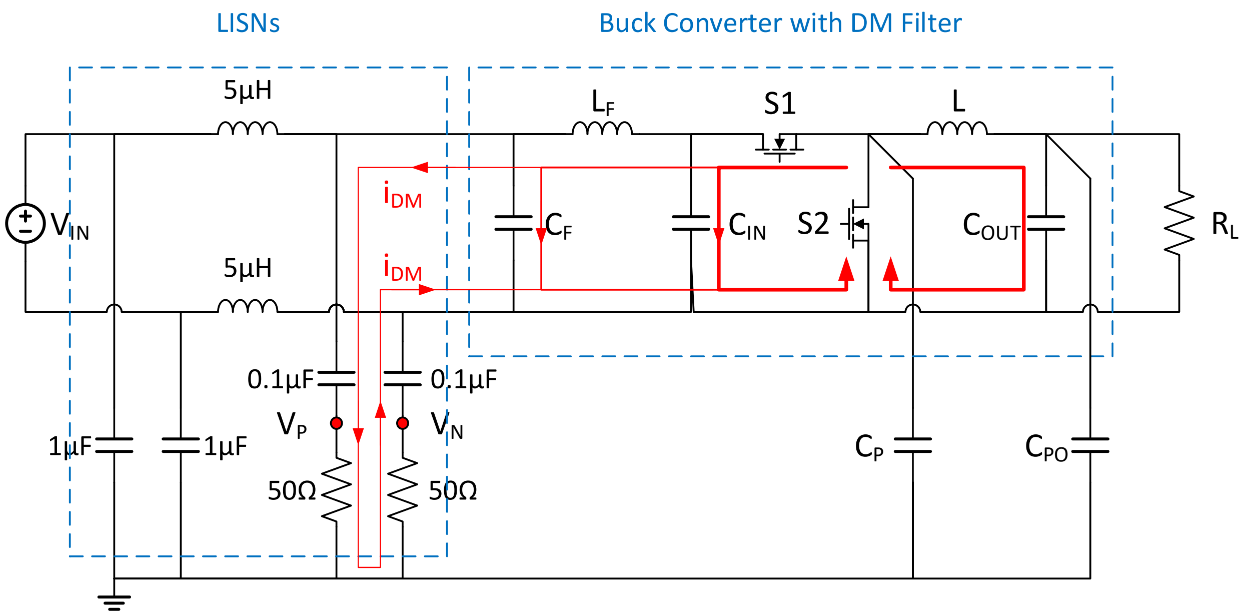
Conducted EMI Modeling and Analysis

Conducted EMI: Modeling and General Reduction Technique



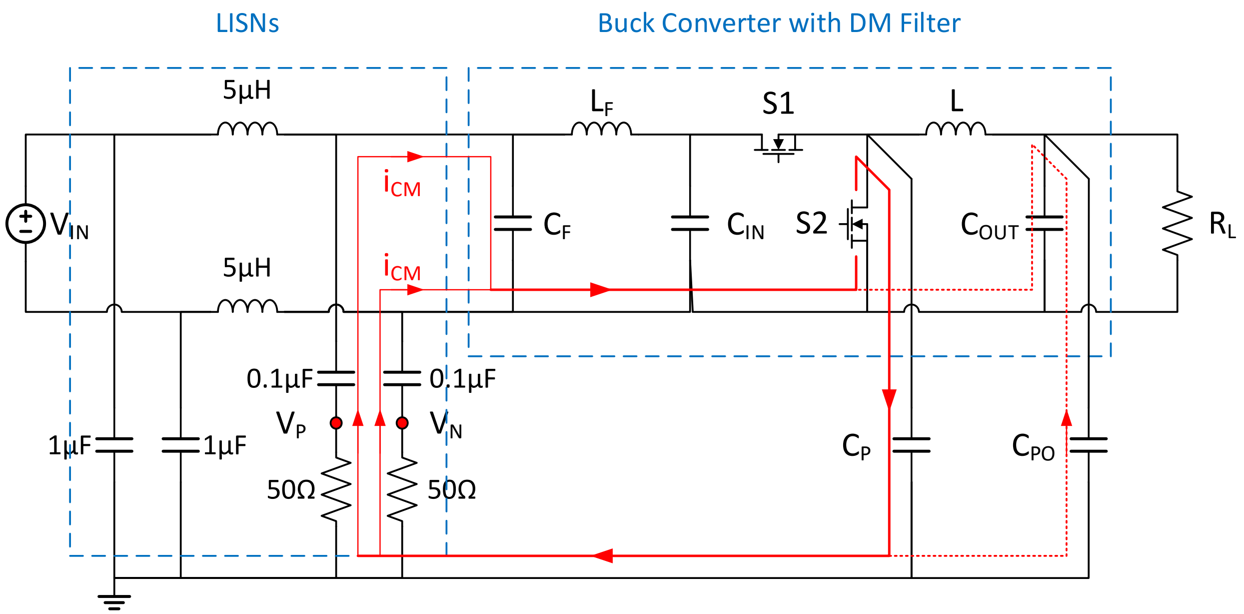
Conducted DM and CM Noise (Low Freq) in a Buck Converter

DM Noise Path



$$V_{DM} = \frac{|V_P - V_N|}{2}$$

CM Noise Path

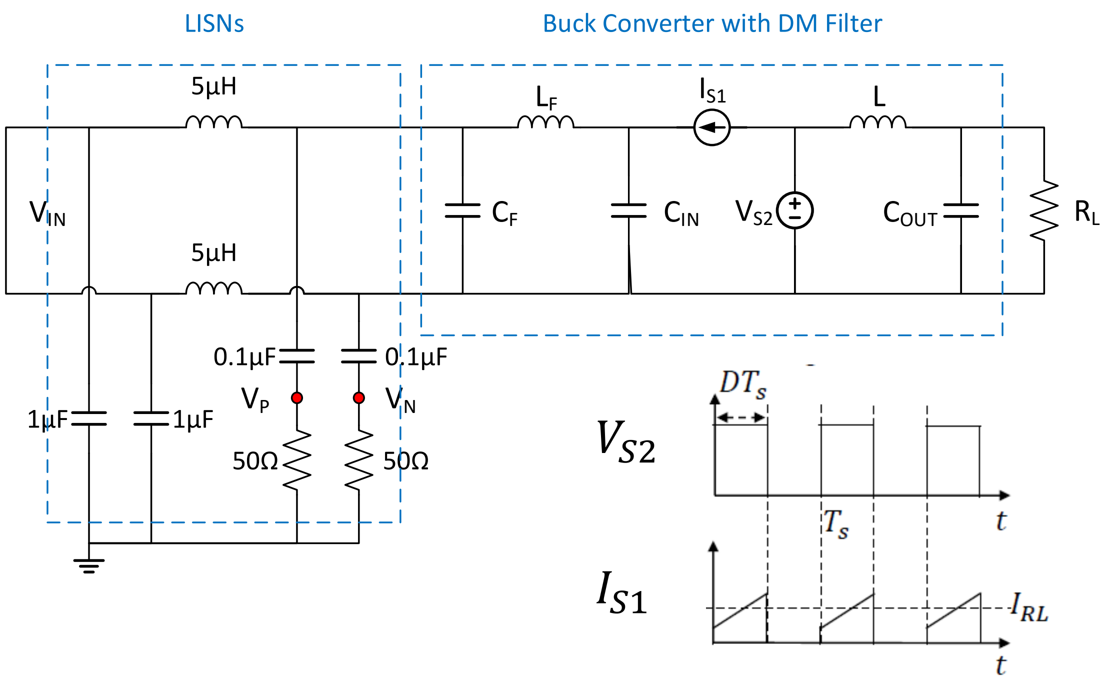


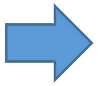
$$V_{CM} = \frac{|V_P + V_N|}{2}$$

Note: High dv/dt nodes and di/dt loops are EMI sources.

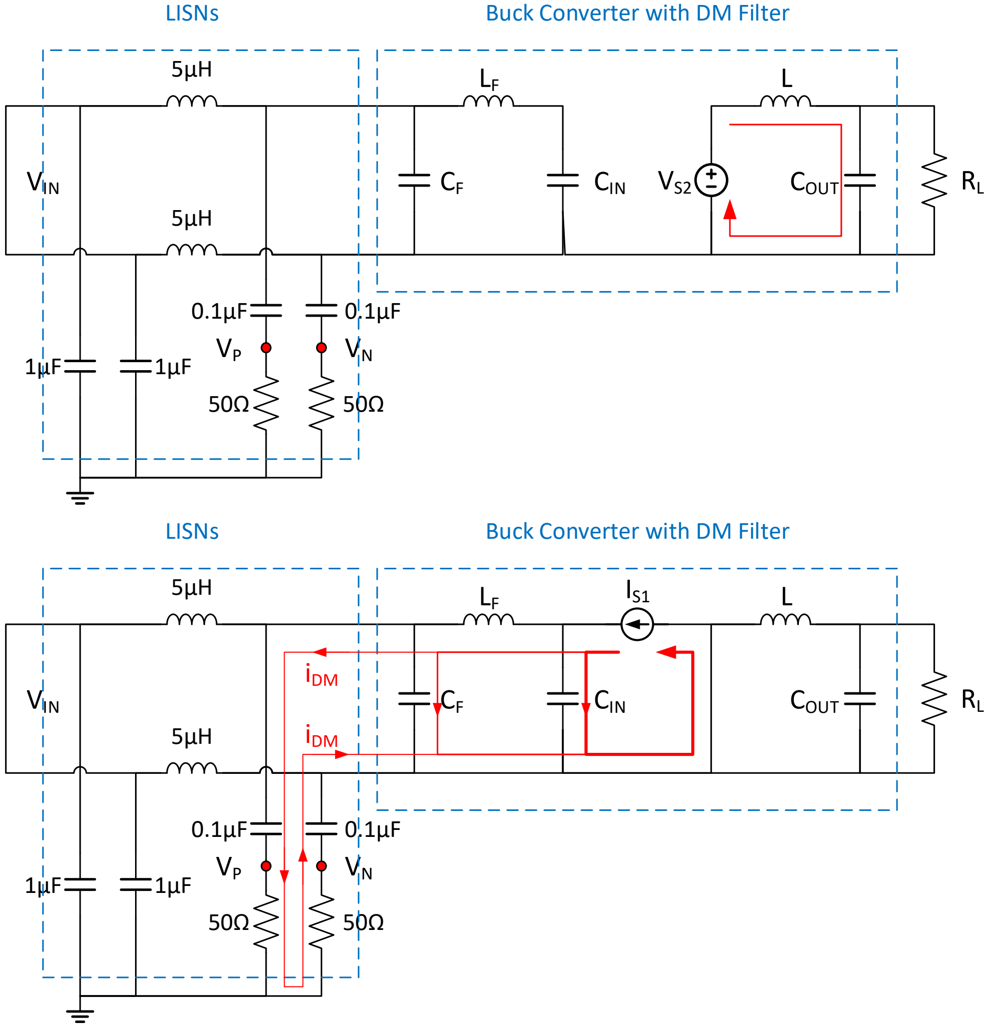
DM Noise Source Analysis

Substitution Theorem





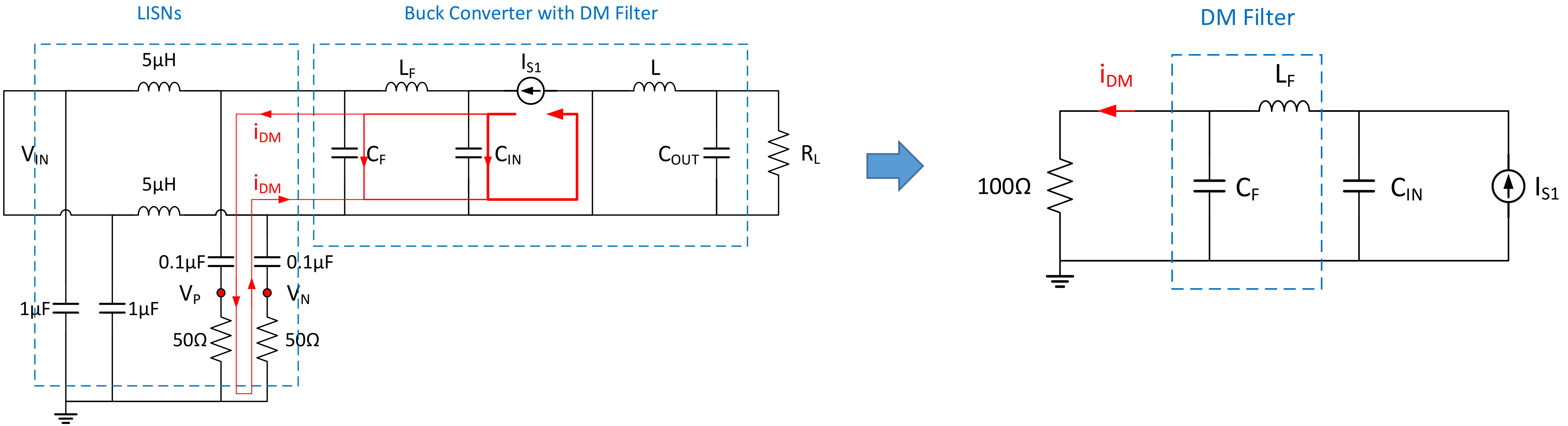
Superposition Theorem



Switches are replaced with voltage or current sources with exact voltage or current of the switches.

Since DM current tends not flow to the ground, the parasitics to ground are ignored.

Basic DM Noise Model

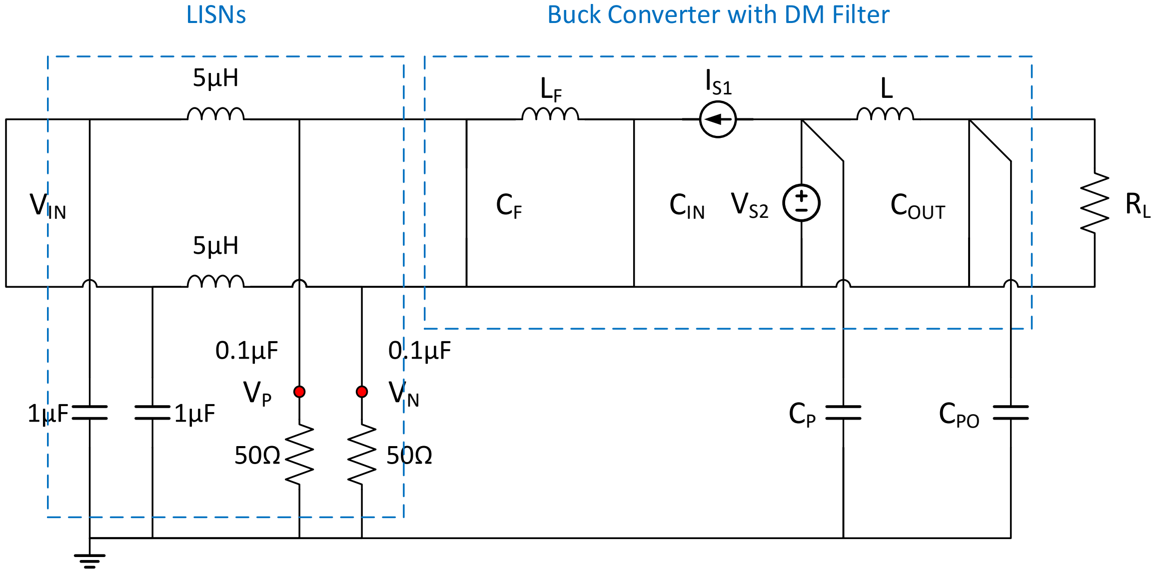


For DM analysis, the LISNs' Impedance can be seen as an 100Ω resistance.

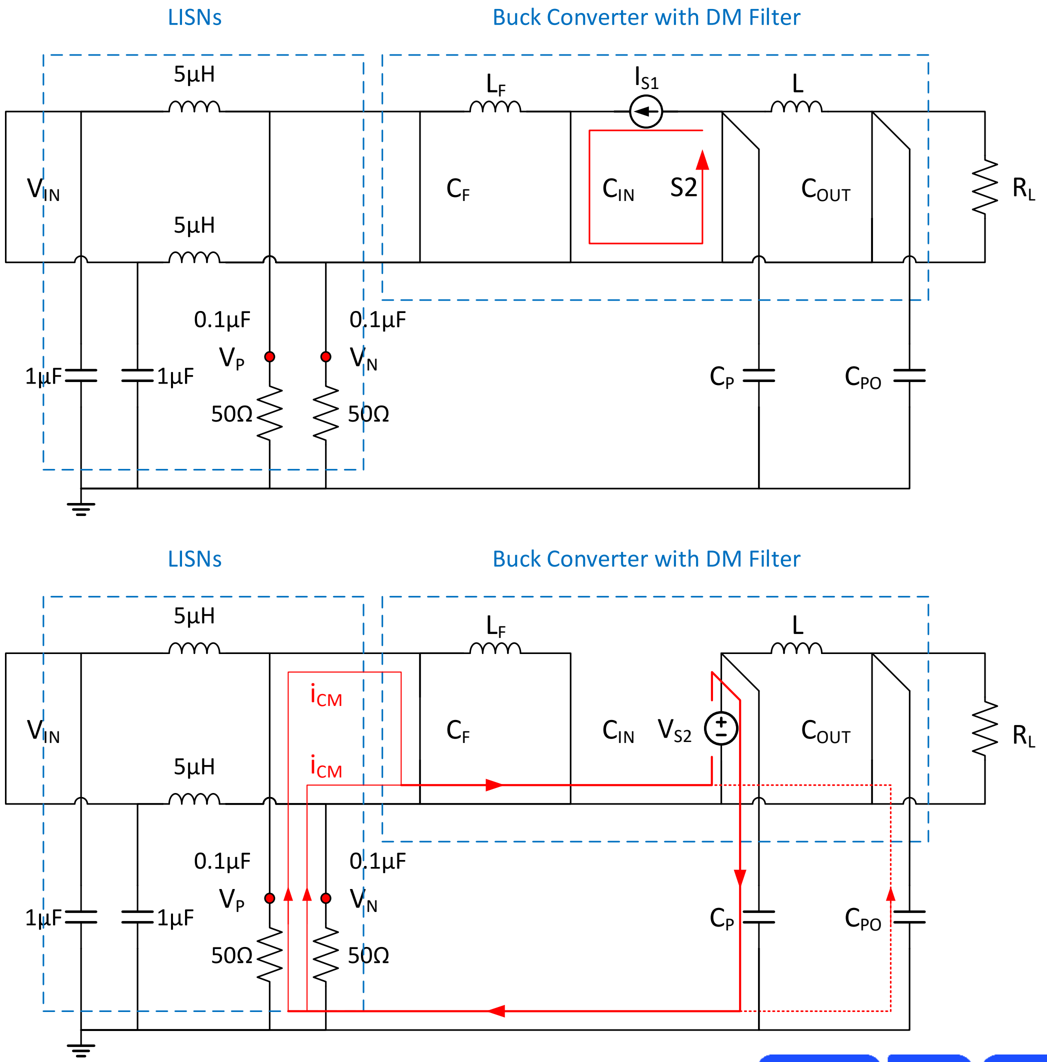
Typically, the DM noise attenuation can be done by **designing a input LC filter properly**.

CM Noise Source Analysis

Substitution Theorem



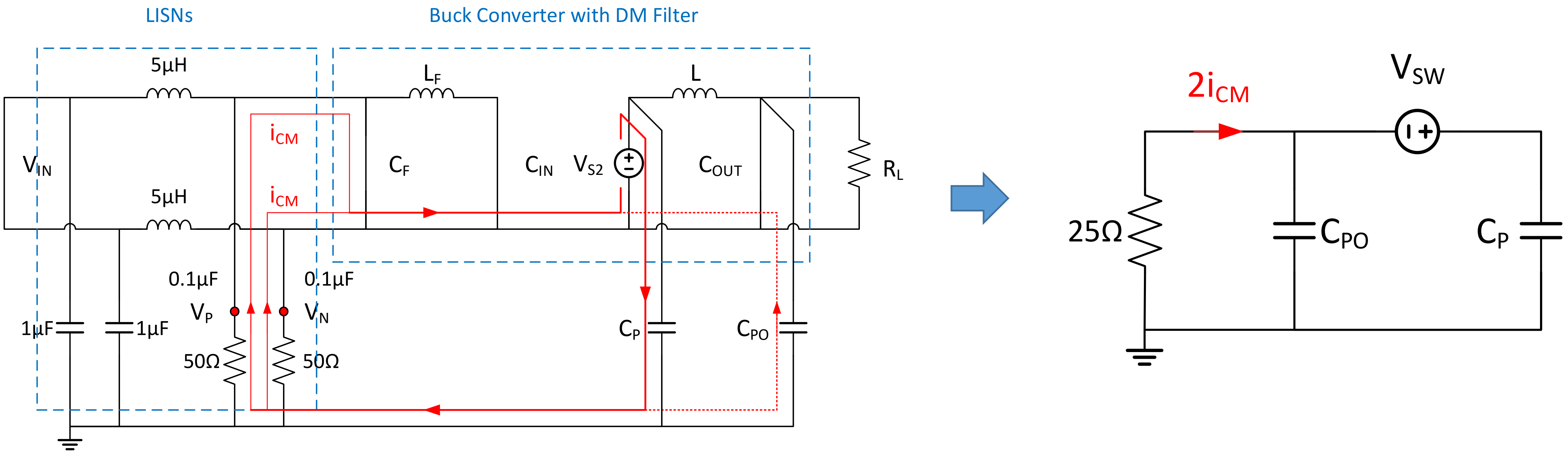
Superposition Theorem



Switches are replaced with voltage or current sources with exact voltage or current of the switches.

Capacitors can be considered as short due to low impedance at EMI low-frequency range.

Basic CM Noise Model



For CM analysis, the LISNs' Impedance can be seen as a 25Ω resistance.

MPS

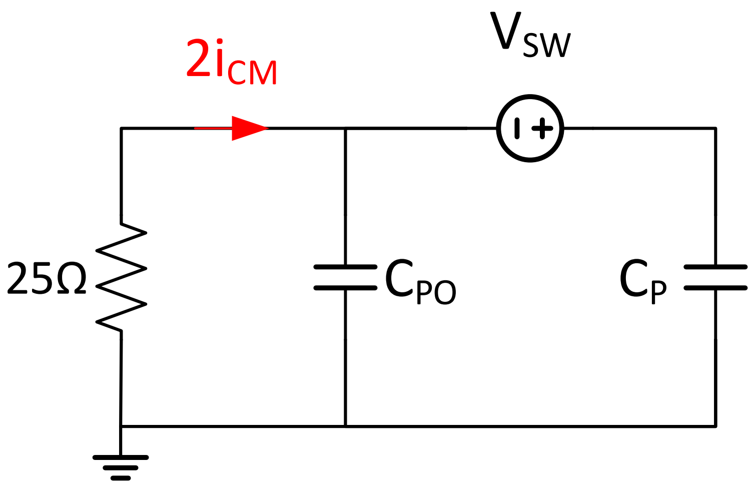
General CM Noise Reduction Techniques based on EMI Model

Reduction from Noise Source:

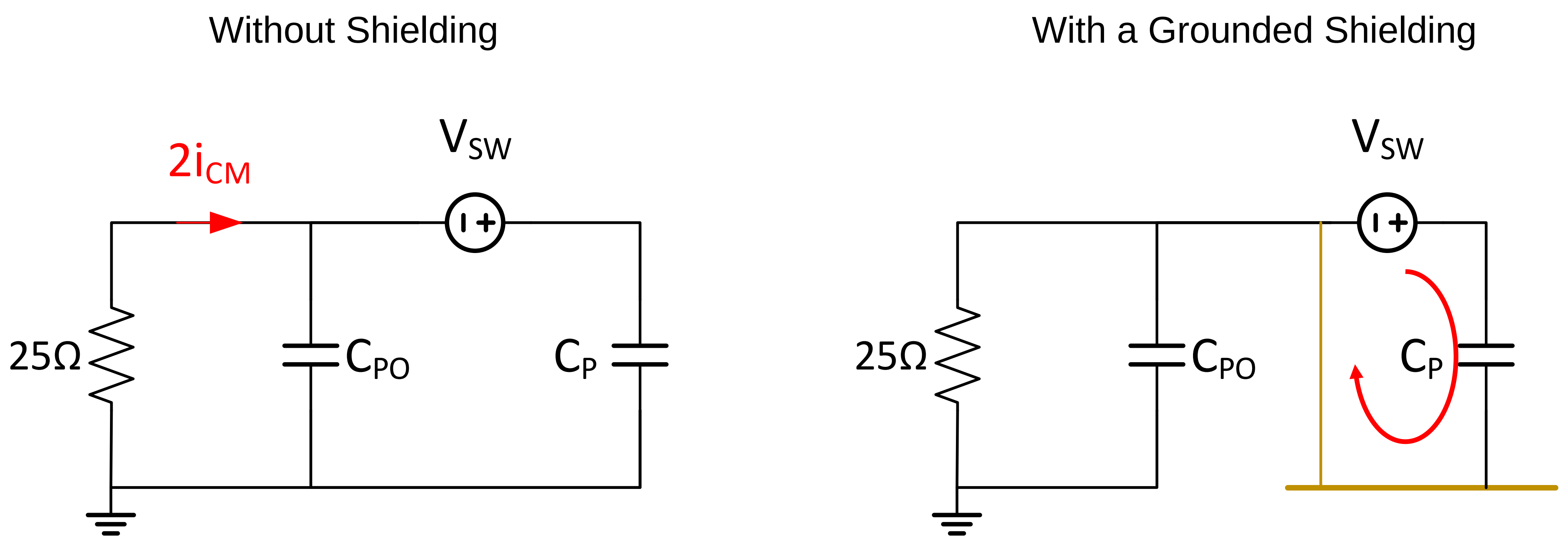
1. Change fsw or reduce slew rate for EMI noise reduction
2. Apply Frequency Spread Spectrum in IC Design

Reduction from Noise Path:

1. Reduce the size of dv/dt node and the inductor to reduce C_p
2. Apply shielding to reduce the influence of the C_p



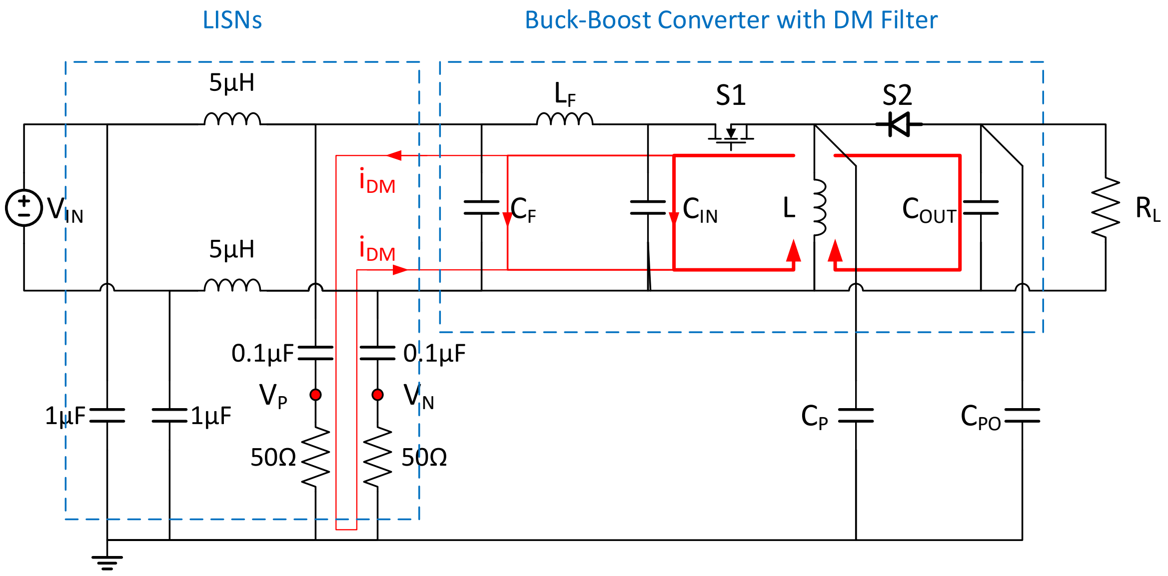
Modeling: Apply Shielding to Reduce EMI Noise



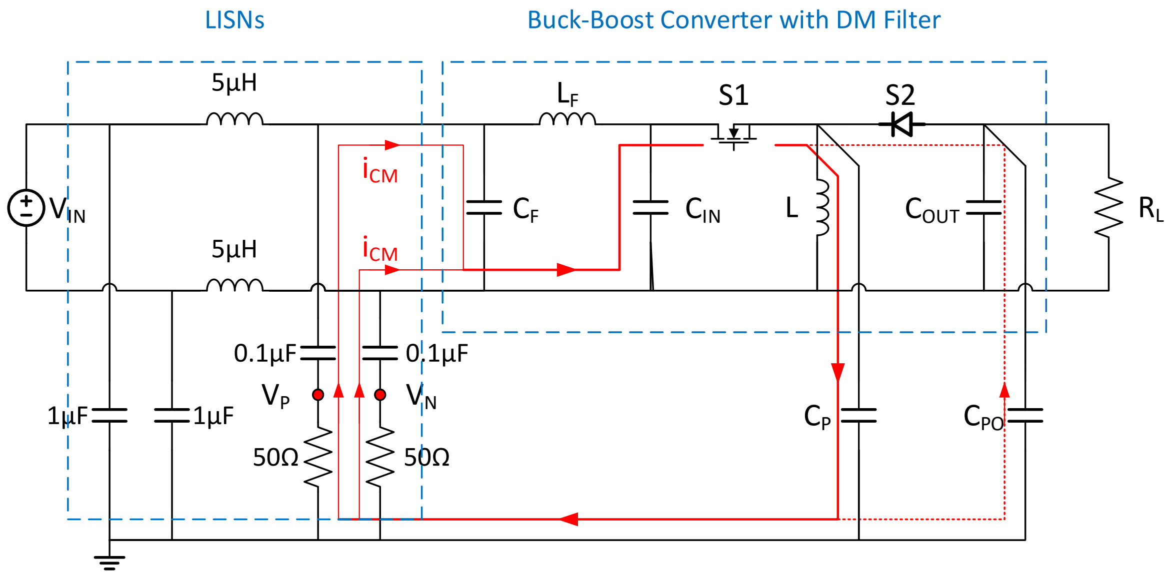
Note: With a grounded shielding, the noise current is confined in the converter, and will not flow through the LISNs. The shielding should be applied to shield the high dv/dt node and the output inductor.

Extend to Other Topology: Noise Paths in Buck-Boost Converter

DM Noise Path



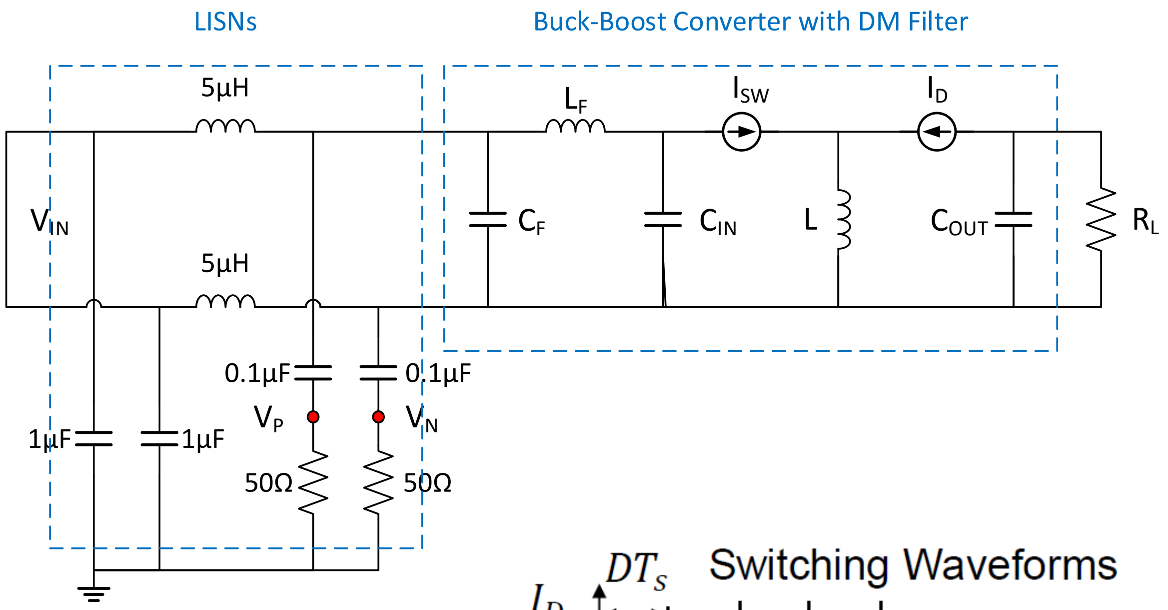
CM Noise Path

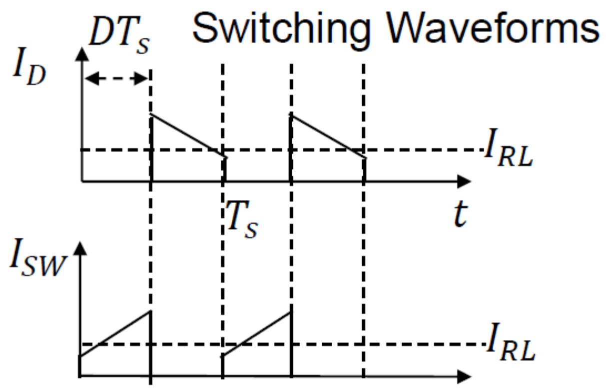


Note: A similar modeling method can be applied for all non-isolated converters.

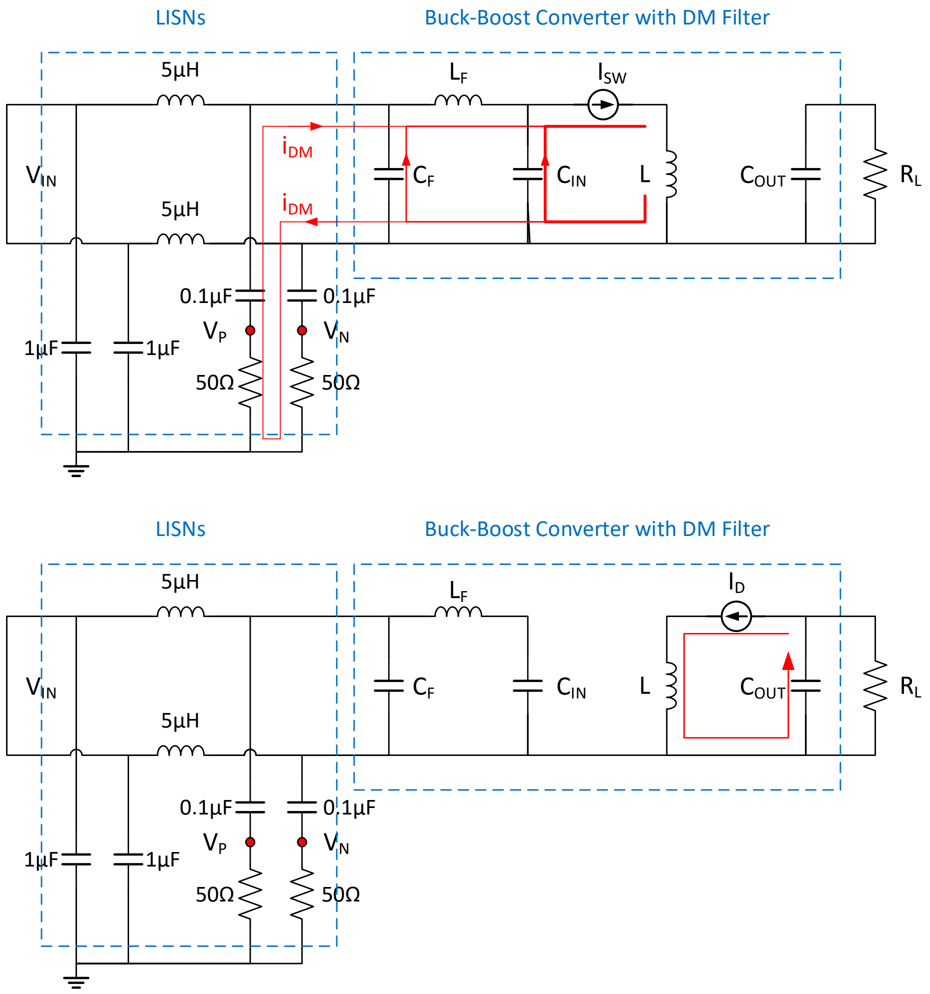
DM Noise Source Analysis and Modeling for Buck-Boost Converter

Substitution Theorem

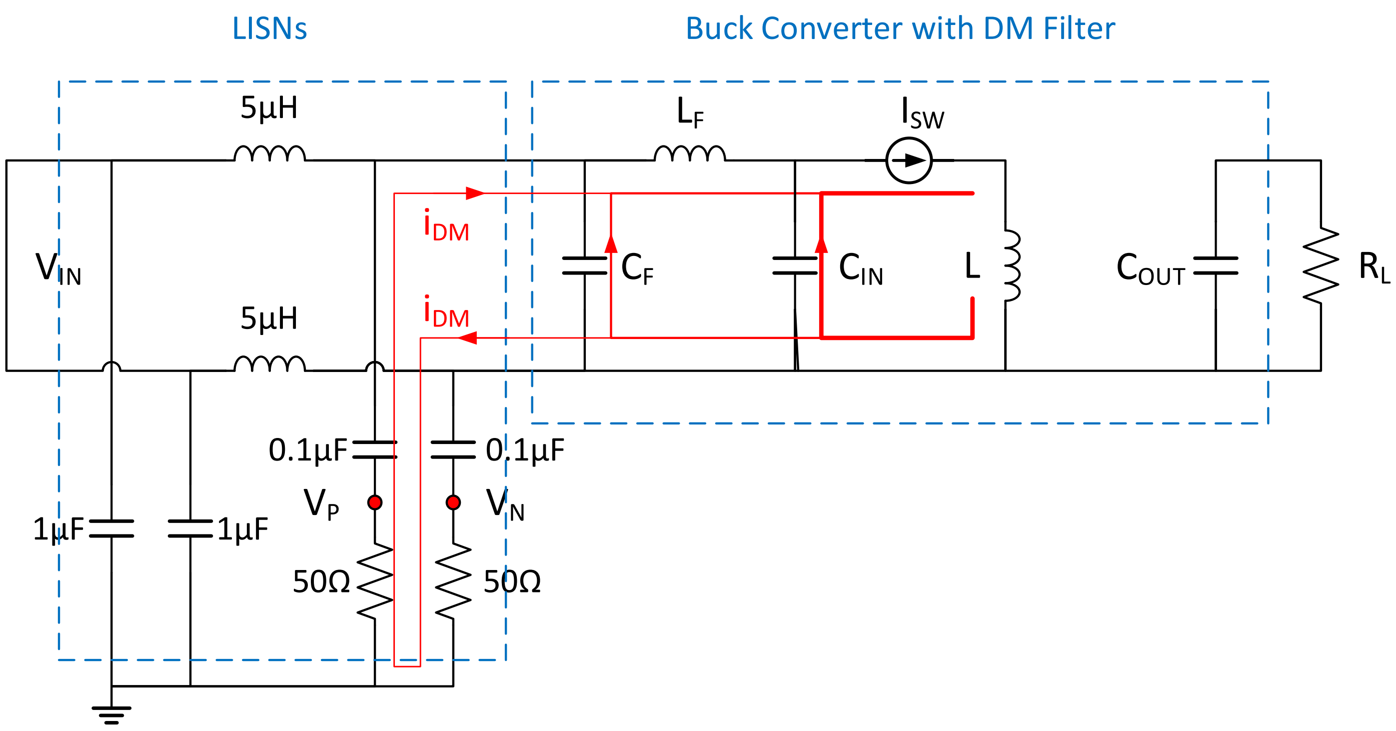


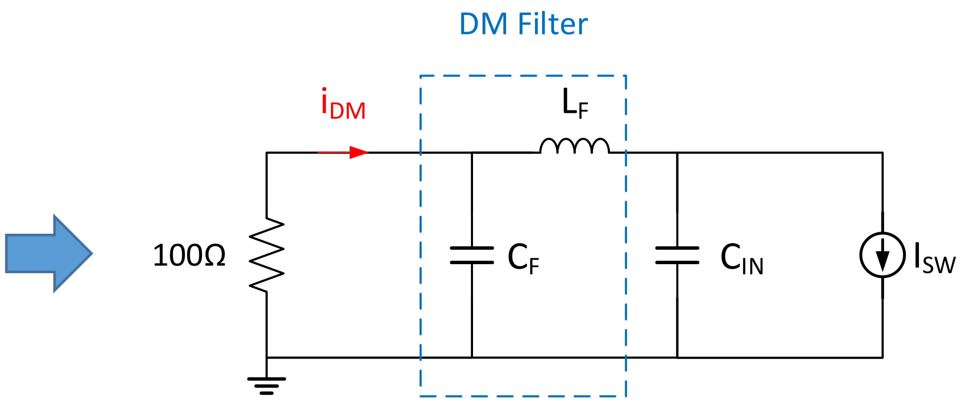


Superposition Theorem



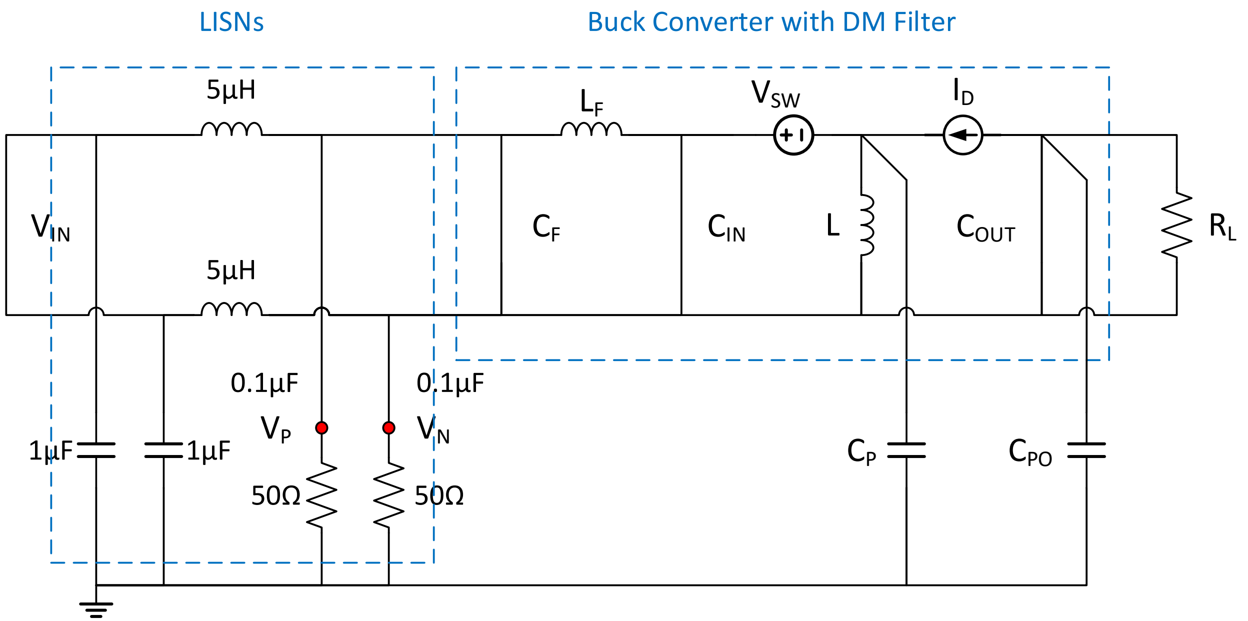
Buck-Boost DM Noise Model

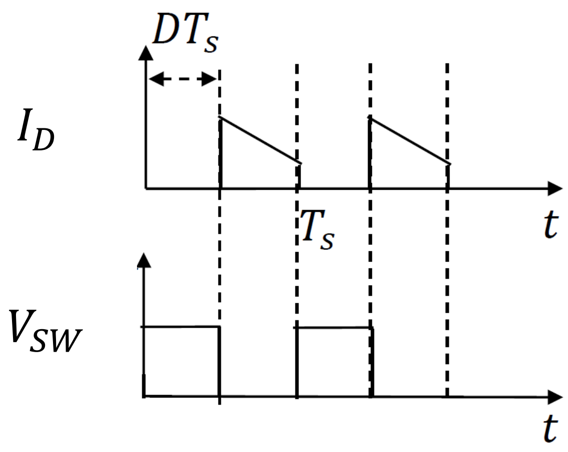


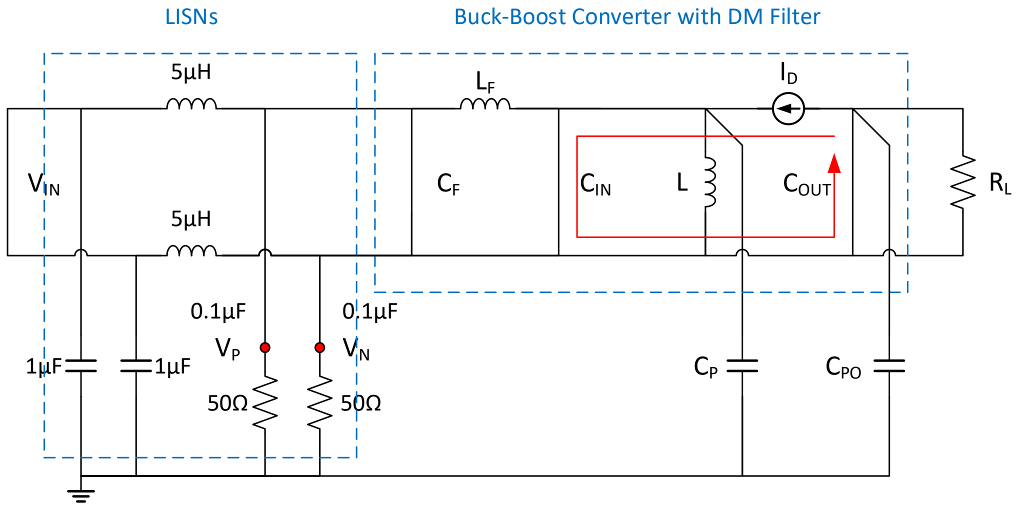


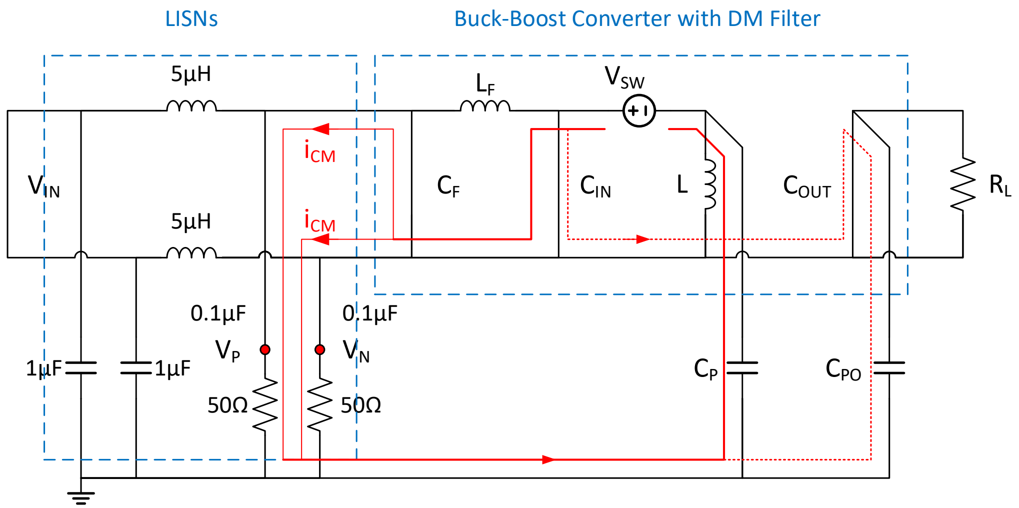
Note: Its DM noise model is just similar to Buck converter.

CM Noise Source Analysis and Modeling for Buck-Boost Converter

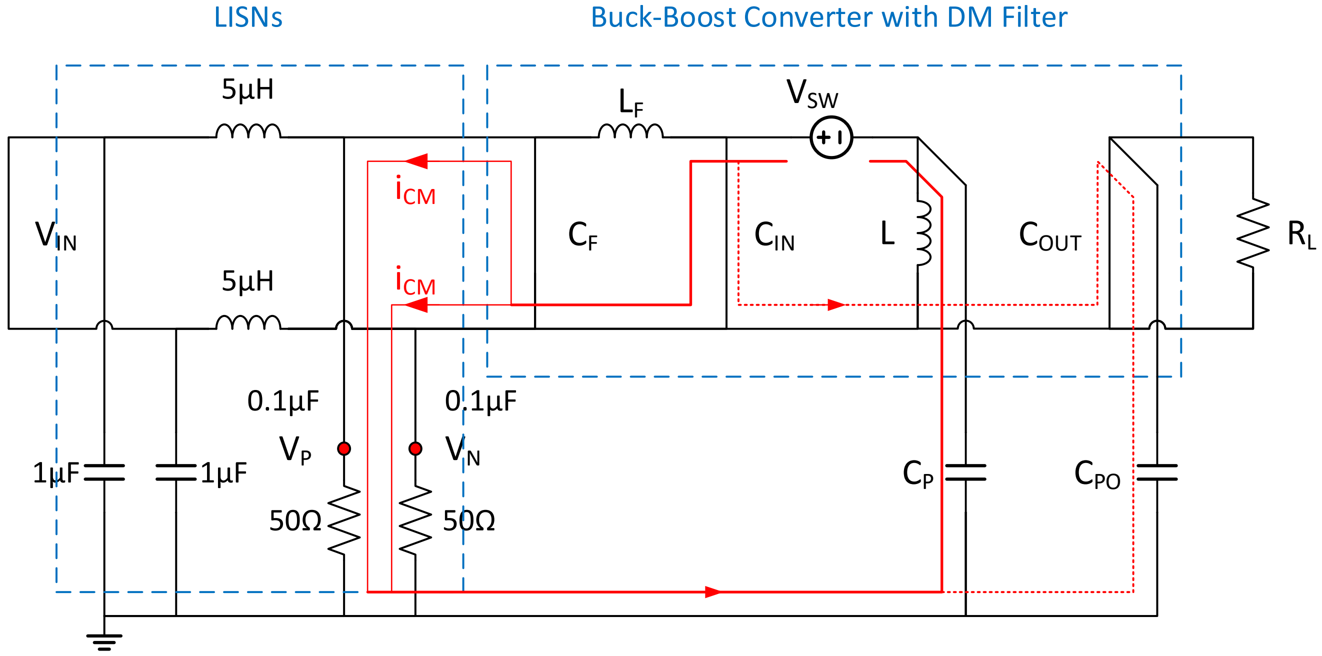


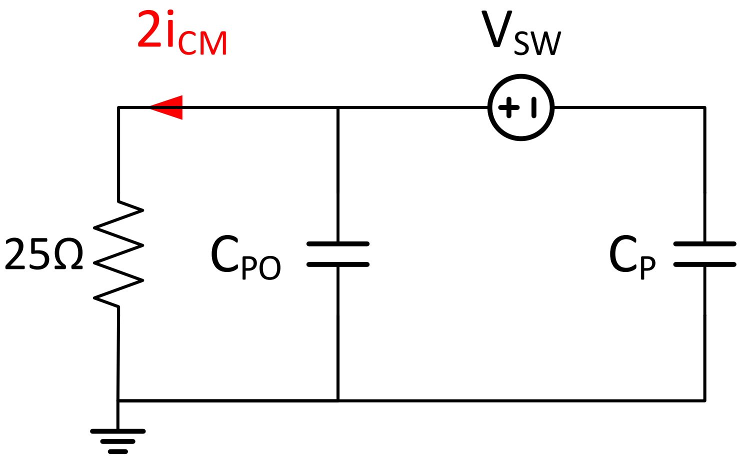






Buck-Boost CM Noise Model



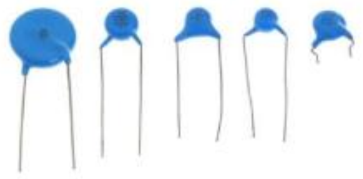


Note: Its CM noise model is also similar to Buck converter.

Refine EMI Model: Parasitic of Passive Components

- Passive Components:
  - Ceramic Capacitor
  - Film Capacitor
  - Electrolytic Capacitor (Bulk Capacitor)
  - Inductors
  - Ferrite Beads

  ……



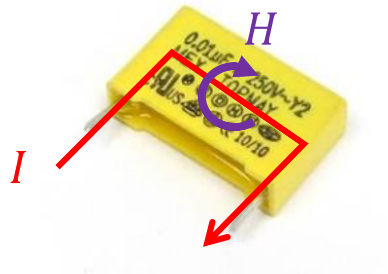
Impedance of a Capacitor

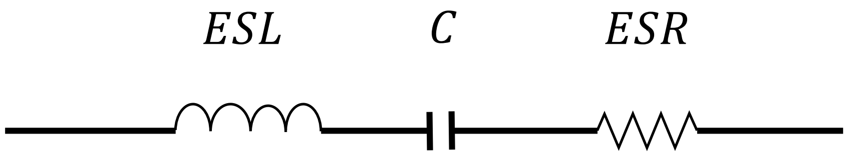
At high frequencies, the capacitors will perform like a resistor or an inductor due to its parasitics.

ESL and ESR are usually used to model the impedance of a capacitor.

Some manufacturers will provide the parameters or SPICE models.

Network Analyzer or Impedance Analyzer can characterize the impedance of EMI components.





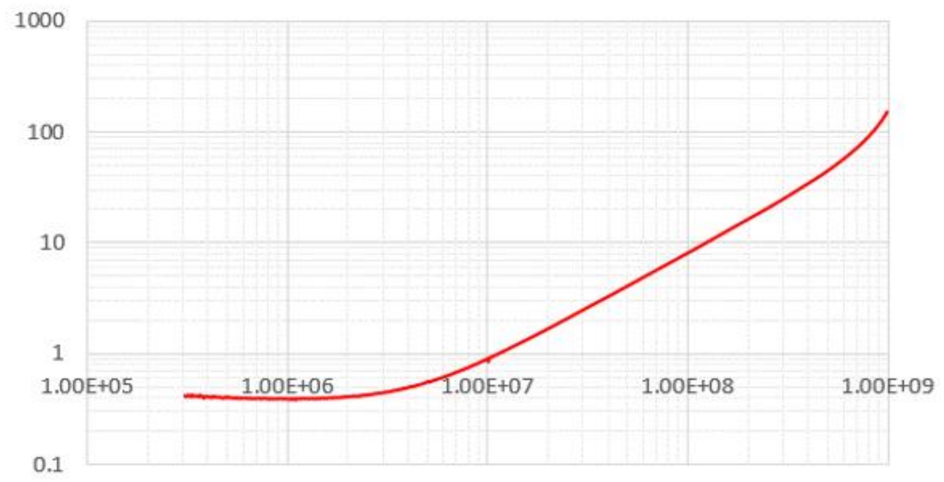
C: Capacitance Value

ESR: Equivalent series resistance

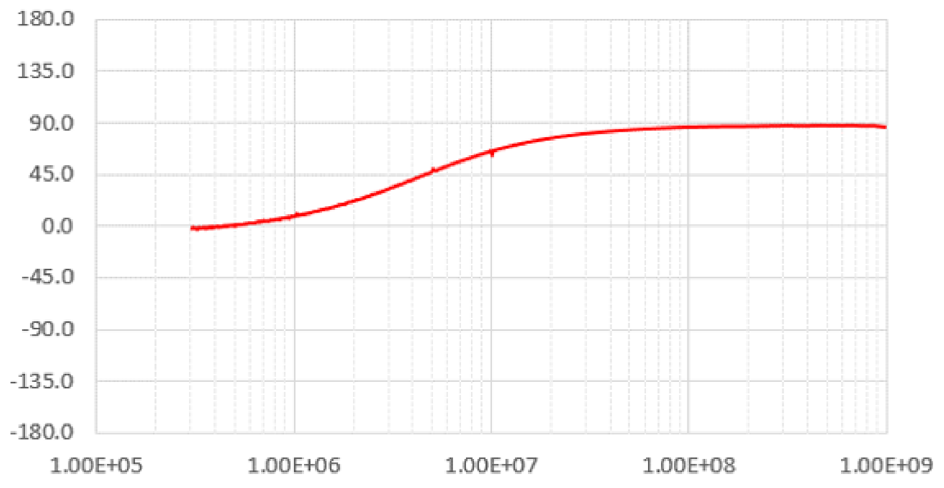
ESL: Equivalent series inductance

Impedance of a Bulk Capacitor (Measured by Network Analyzer)

Imp_mag(ohm)



Imp_ph(deg)



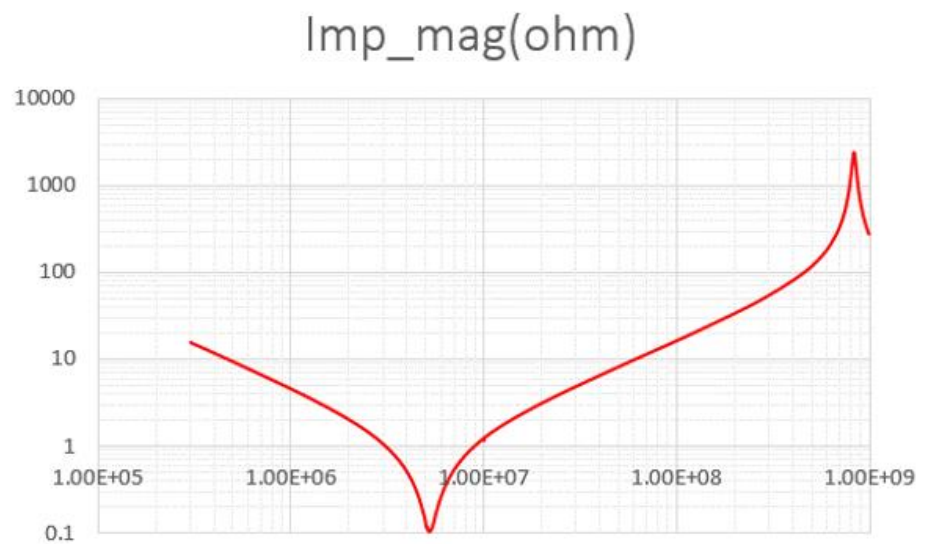
$$ESR \approx 0.4\Omega$$

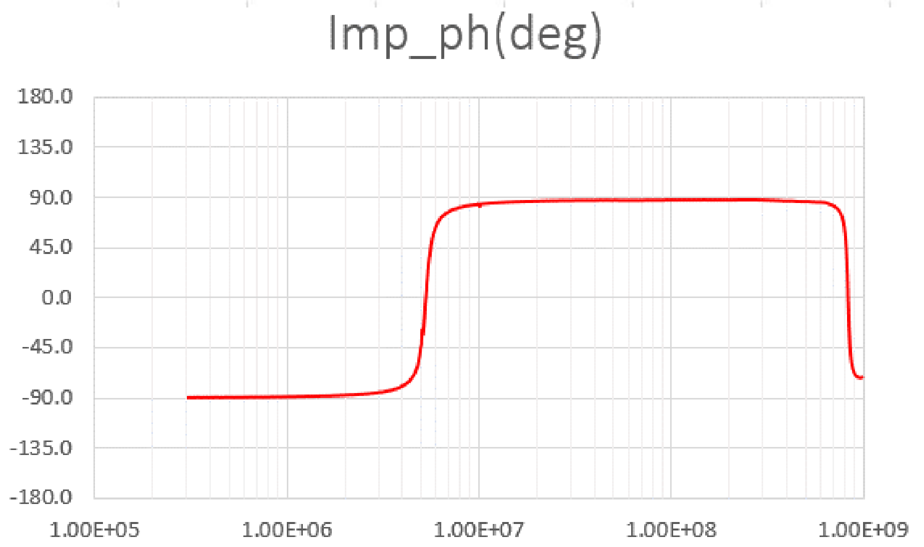
$$ESL \approx \frac{|Z_{HF}|}{2\pi f} = 14nH$$

It should be noted that for conducted EMI range (around 150kHz to 108MHz), the bulk capacitor can be treated its ESR or ESL instead of its capacitance.

For bulk capacitors, there is no resonance observed in the impedance curve since the ESR is relatively large.

Impedance of a Film Capacitor



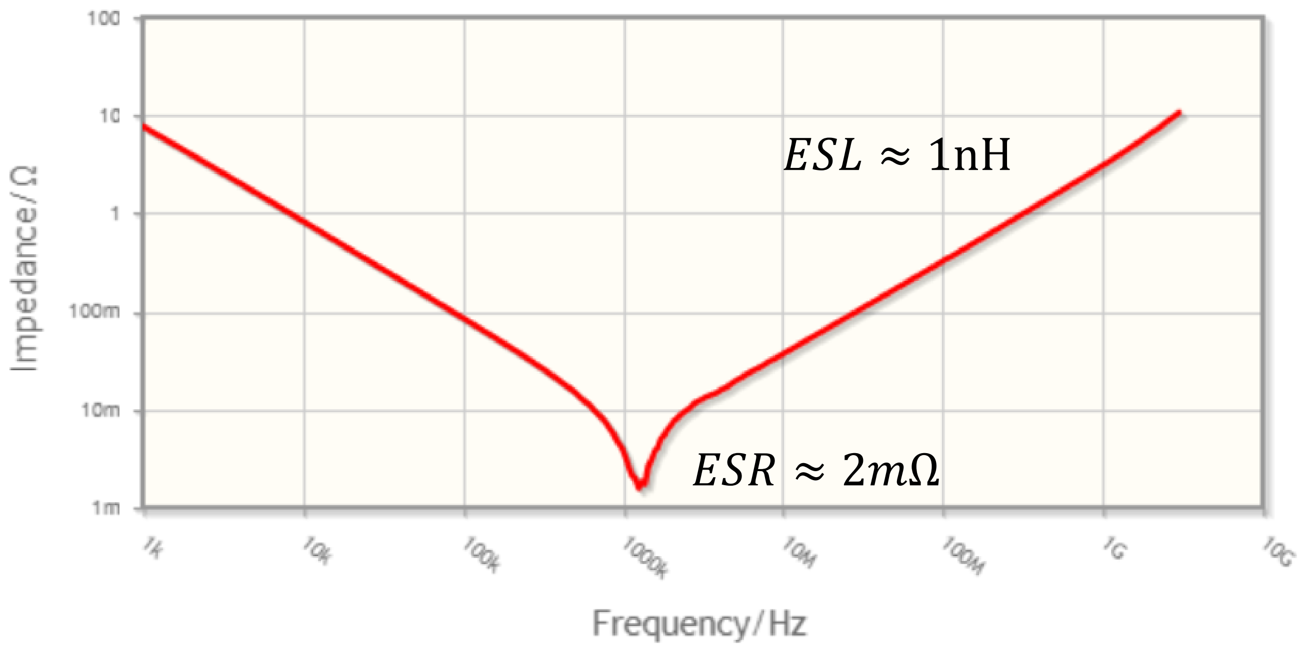


Usually, film capacitor performs as a capacitor up to several MHz.

For film capacitors, there's a high frequency spike due to its small ESR.

Impedance of a Ceramic Capacitor

C2012X5R1E226M125AC, 22uF 0805 25V.



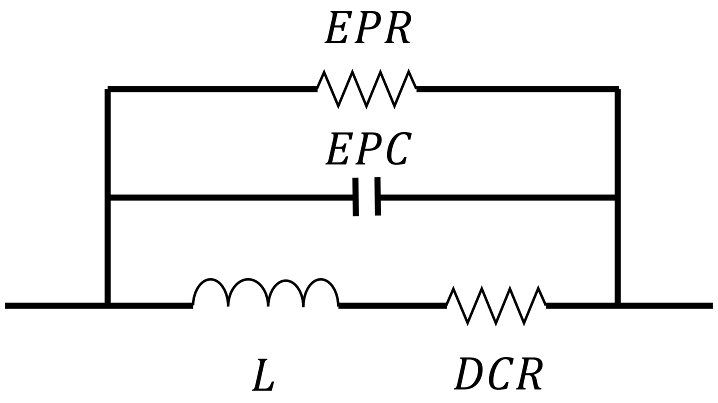
Similarly, ceramic cap performs as a capacitor up to several MHz. And there’s a high frequency spike due to its small ESR.

* Data from the part datasheet

Impedance of an Inductor

- The parasitic capacitance EPC represents the electric energy stored in the inductor: it includes the parasitic capacitances between adjacent winding turns and layers, between winding and the magnetic core, and the energy within the magnetic core.

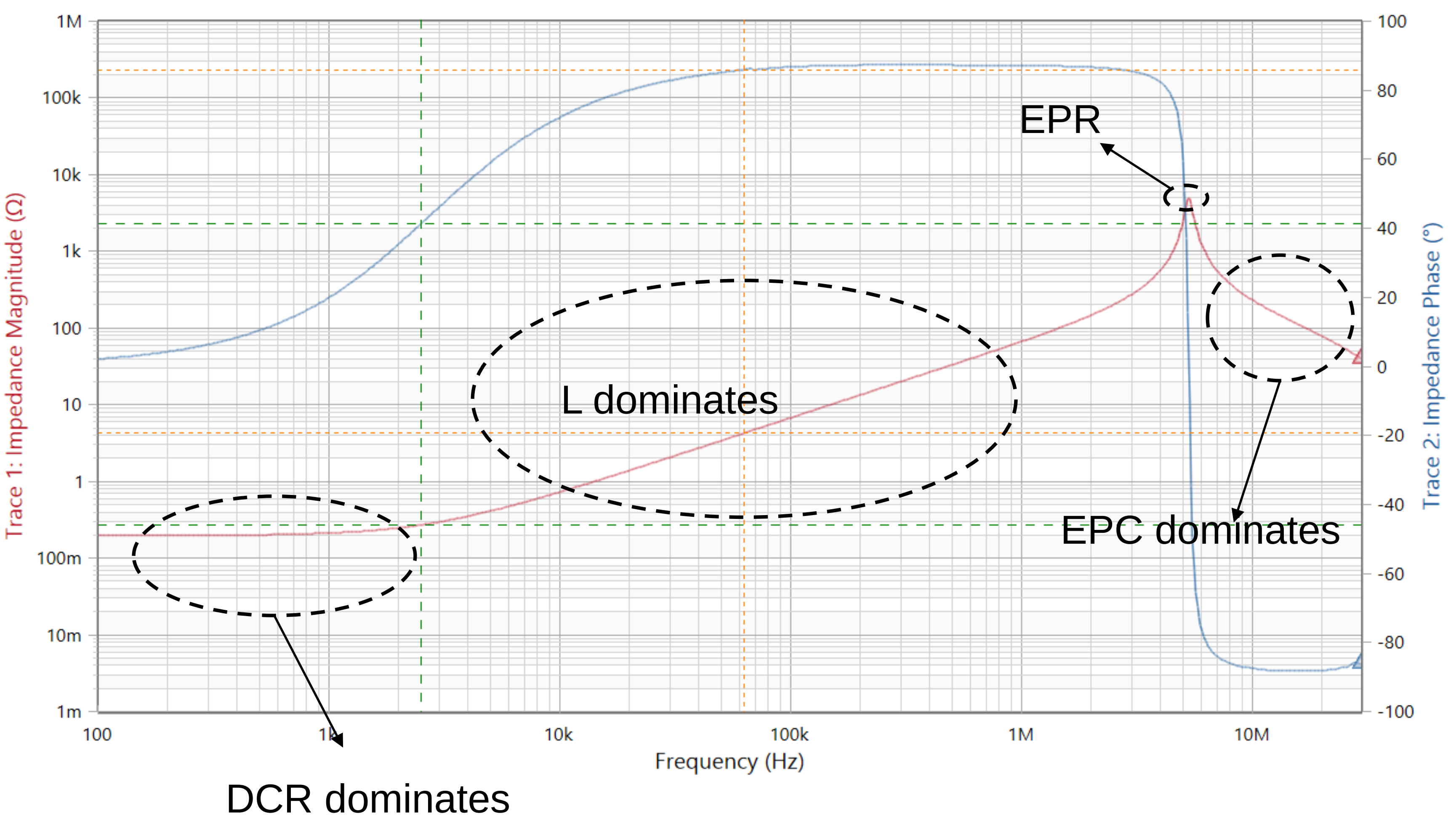
- The series resistor (DCR) represents the winding loss of an inductor; the EPR represents the parasitic resistance (it is dominated by the core loss if there is a magnetic core).



L: Inductance Value
DCR: DC resistance
EPR: Equivalent parallel resistance
EPC: Equivalent parallel capacitance

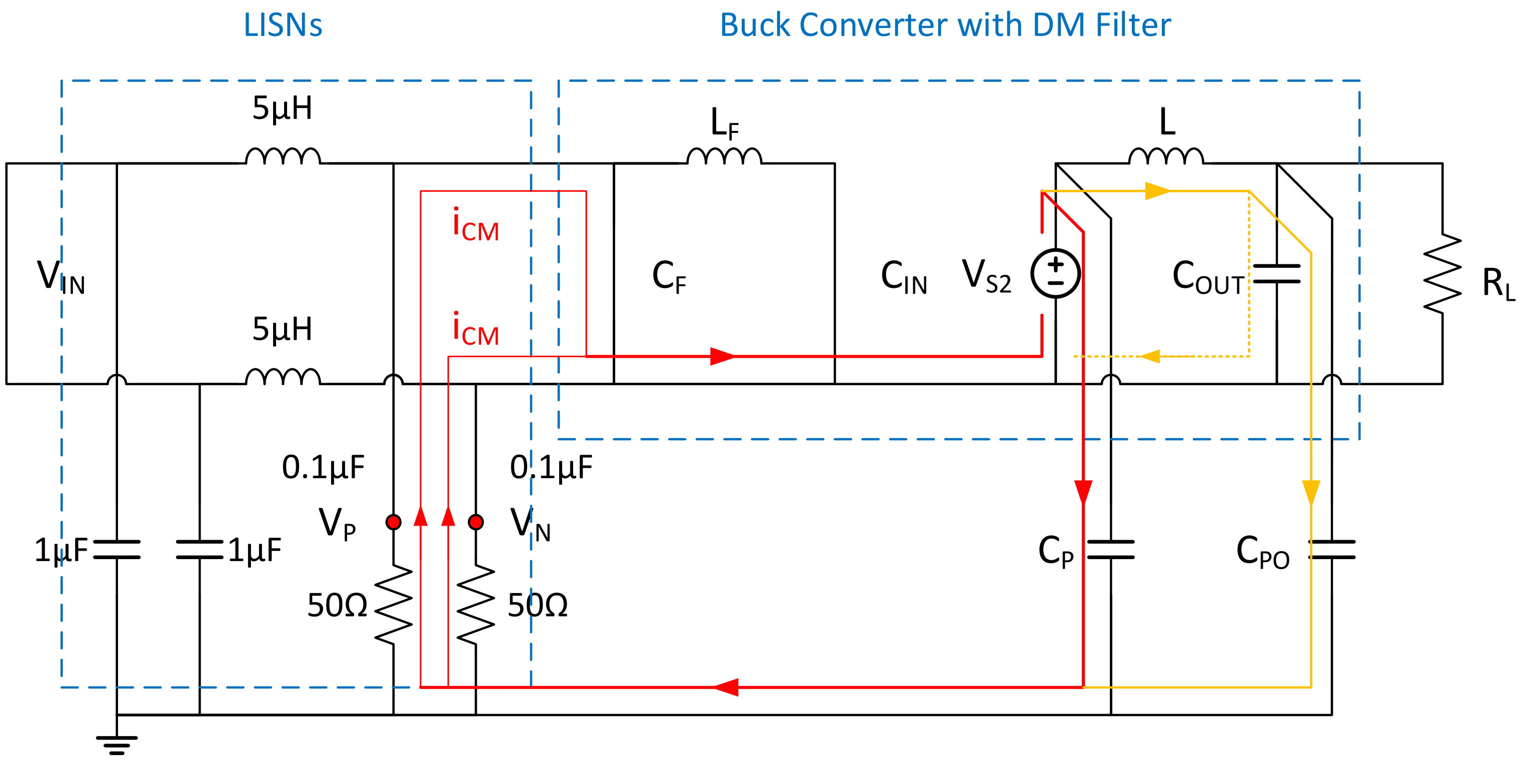
Measurement Result of a Typical Inductor

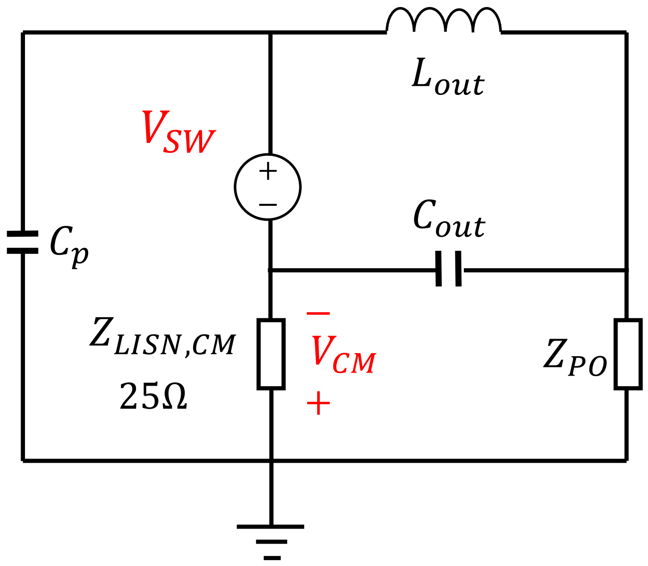
	Frequency	Trace 1	Trace 2
Cursor 1	2.515 kHz	271.291 mΩ	41.344 °
Cursor 2	63.246 kHz	4.267 Ω	85.972 °
Delta C2-C1	60.731 kHz	3.996 Ω	44.628 °



Refine EMI Model: Output Parasitics

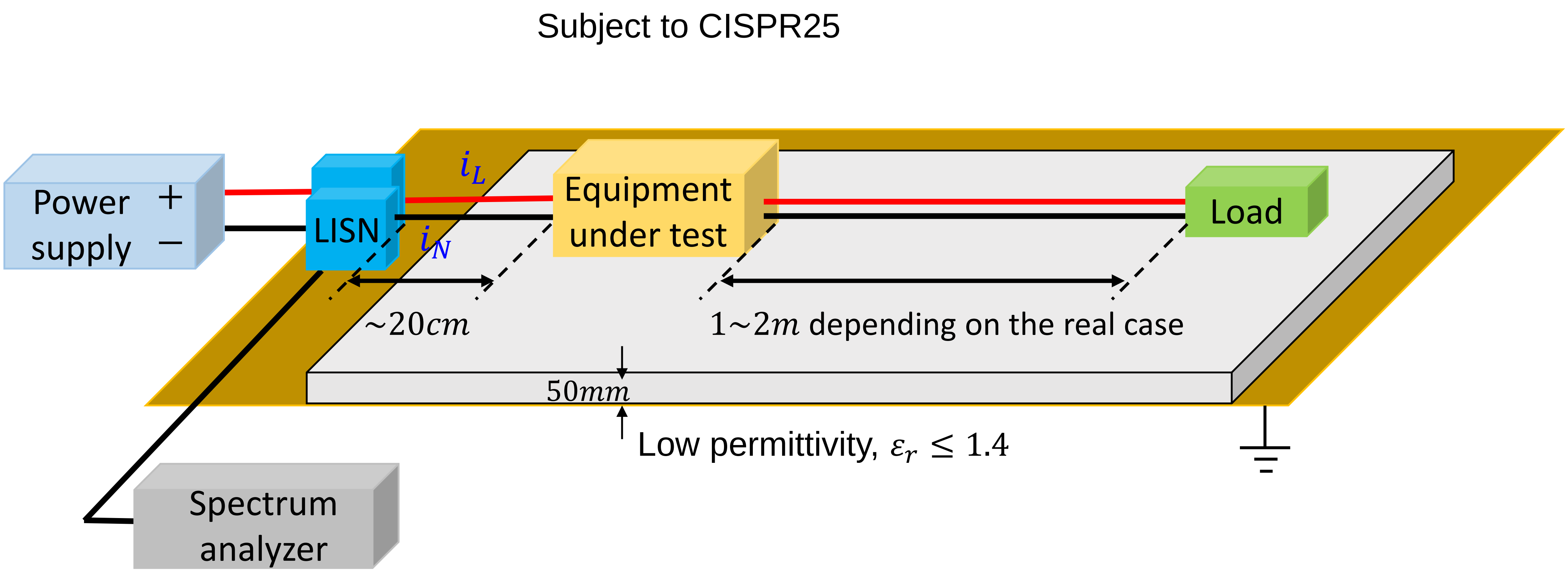
At high frequency, the capacitor impedance may not be ignored.





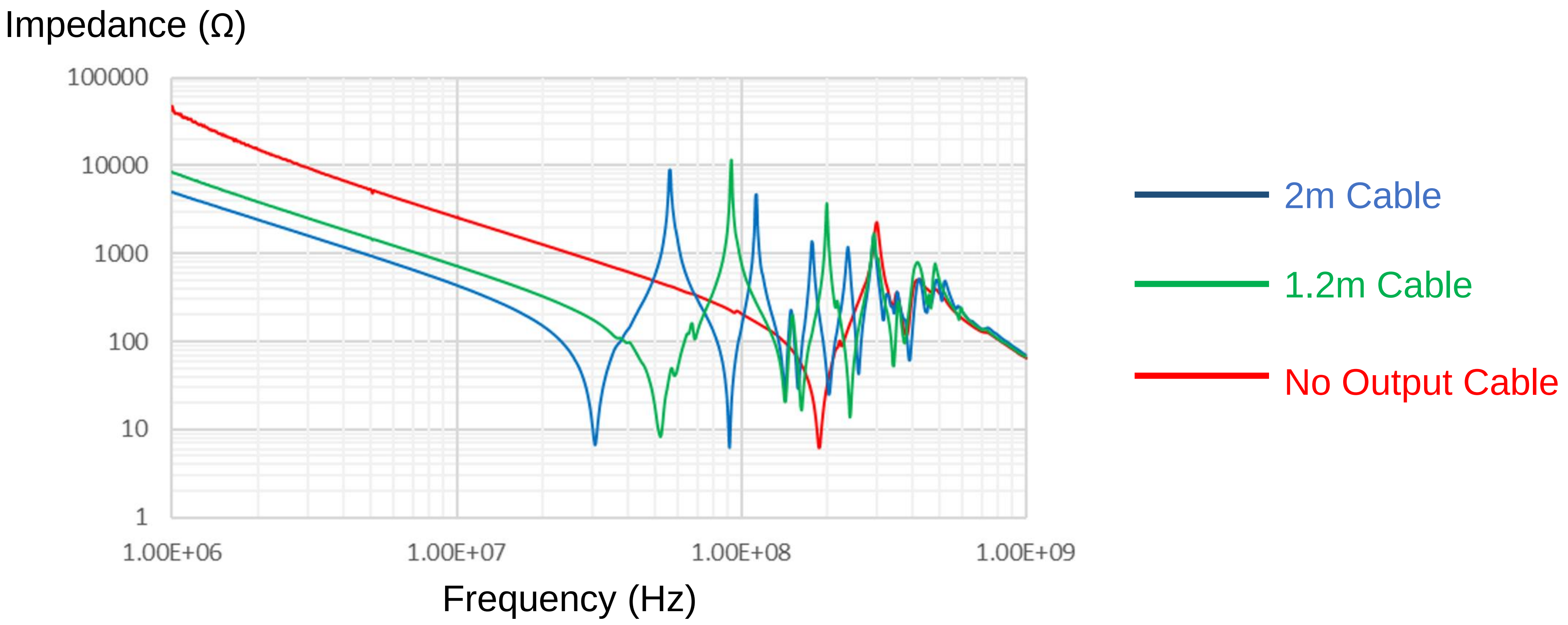
The impedance from output node to the reference ground needs to be considered.

The Case with Long Output Cable



Note: A long output cable is sometimes applied in the conducted EMI test. The length depends on the real application, or it is subject to OEM's specification.

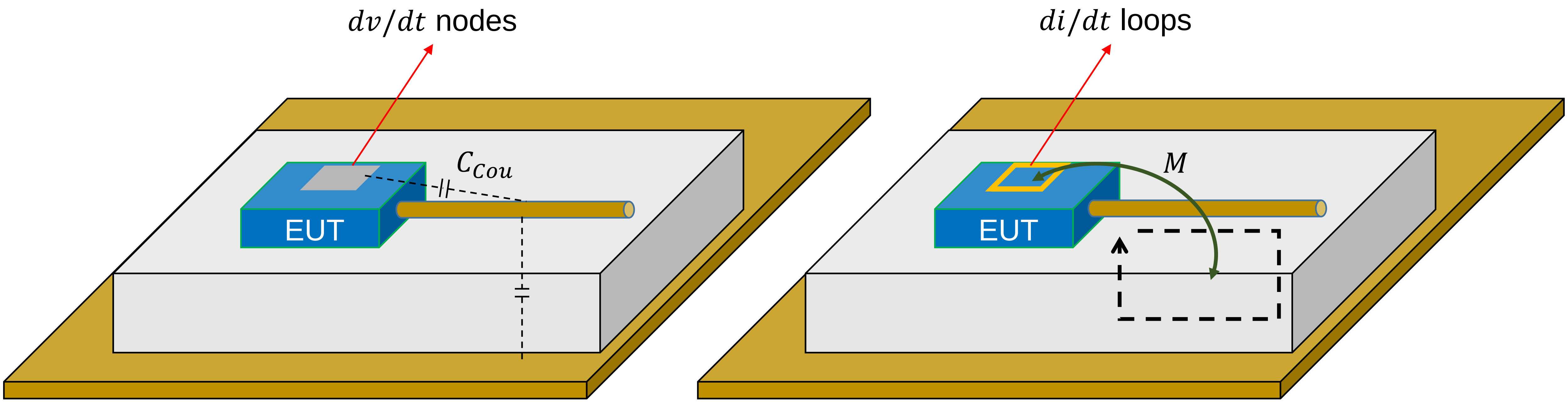
Parasitic Impedance to Ground with and w/o Output Cable



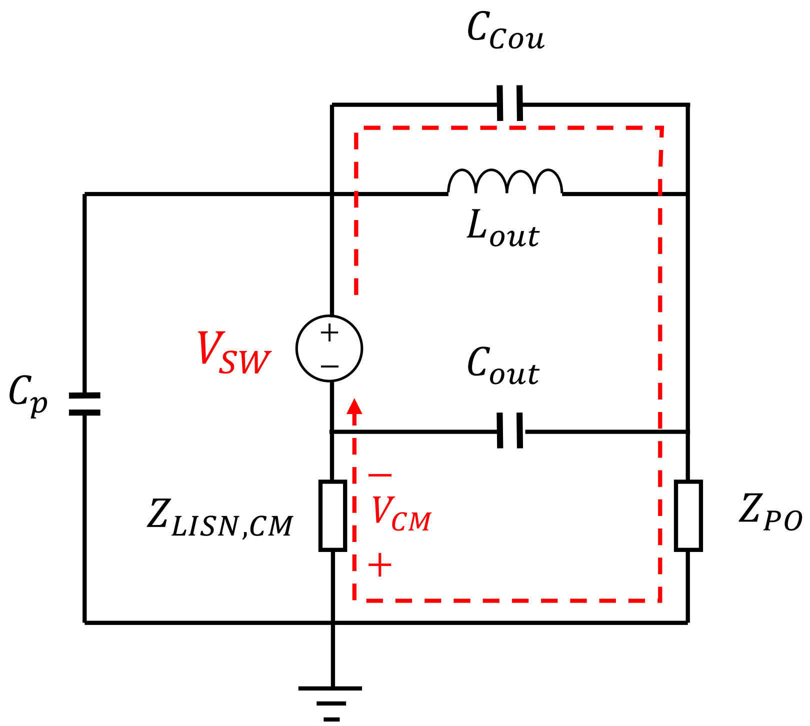
Note: In conducted EMI range (150kHz to 108MHz), with the long output cable, the transmission line effect needs to be considered.

Near Field Couplings with the Long Output Cable

- The capacitive coupling between the dv/dt nodes and the output cable.
- The inductive coupling the di/dt loops and the output cable.



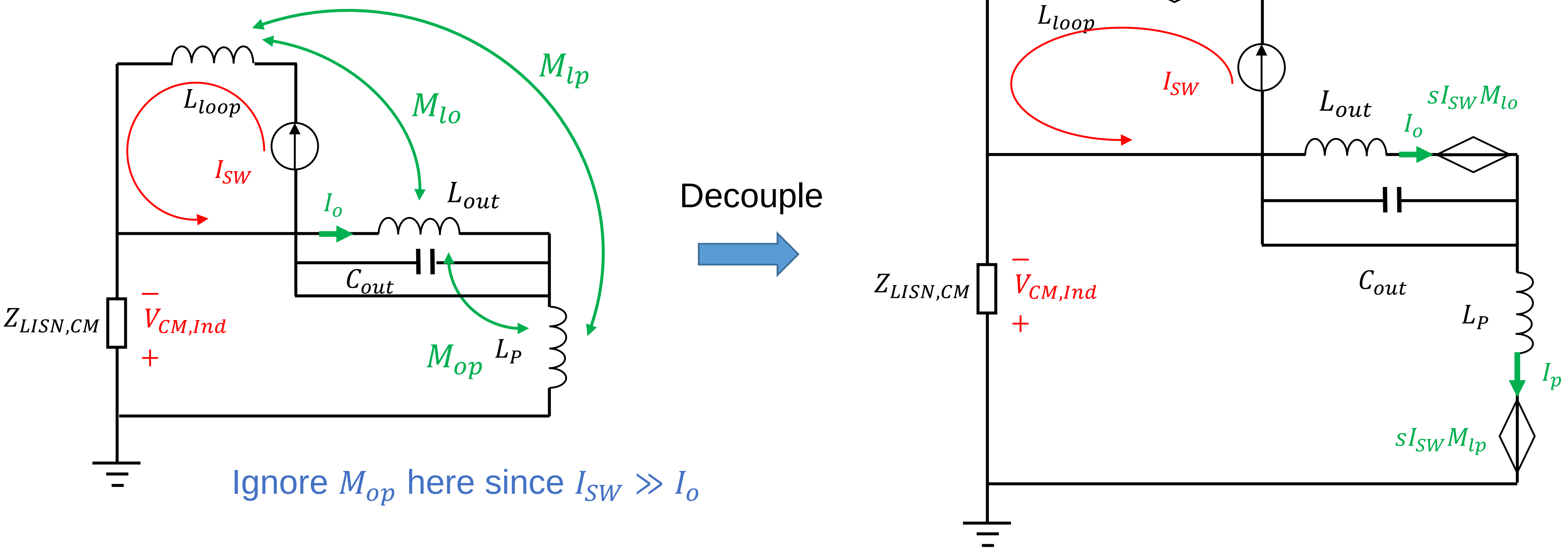
Modeling of the Capacitive Coupling



Note: A near field coupling capacitance C_{Cou} is applied in the model. At high frequency, the influence of C_{Cou} will be significant.

Modeling of the Inductive Coupling

Take input loop as an example

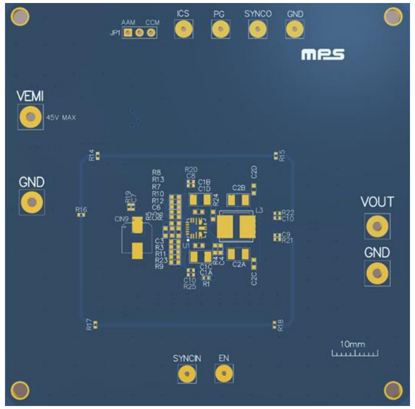


Ignore M_{op} here since $I_{SW} \gg I_o$

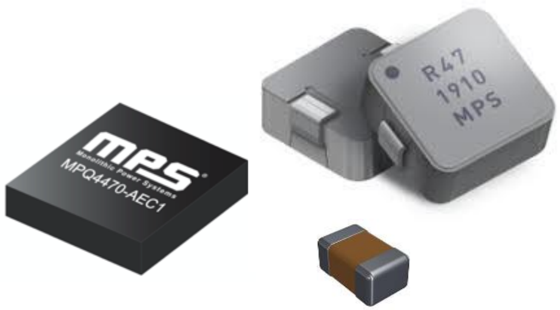
The CM noise induced by the near-field inductive coupling is:

$$V_{CM,Ind} \approx \frac{sI_{SW}M_{lp}}{Z_{LISN,CM} + sL_p} Z_{LISN,CM} \approx I_{SW} Z_{LISN,CM} \frac{M_{lp}}{L_p}$$

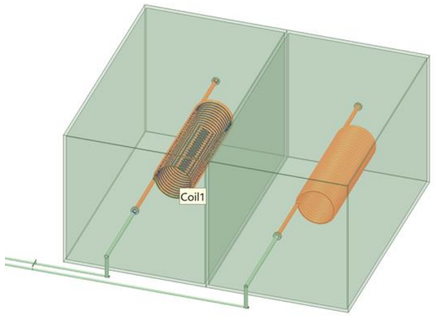
Virtual Lab Environment - Conducted EMI



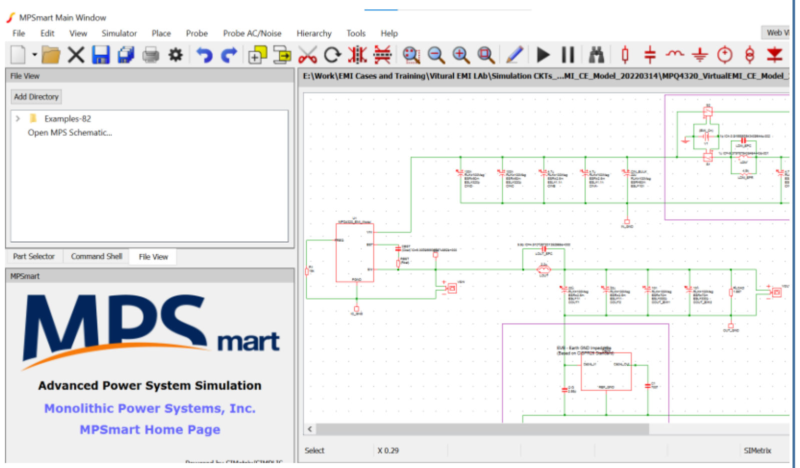
PCB Parasitic extraction



Component SPICE Model



LISN Impedance Extraction



Conducted EMI Reading

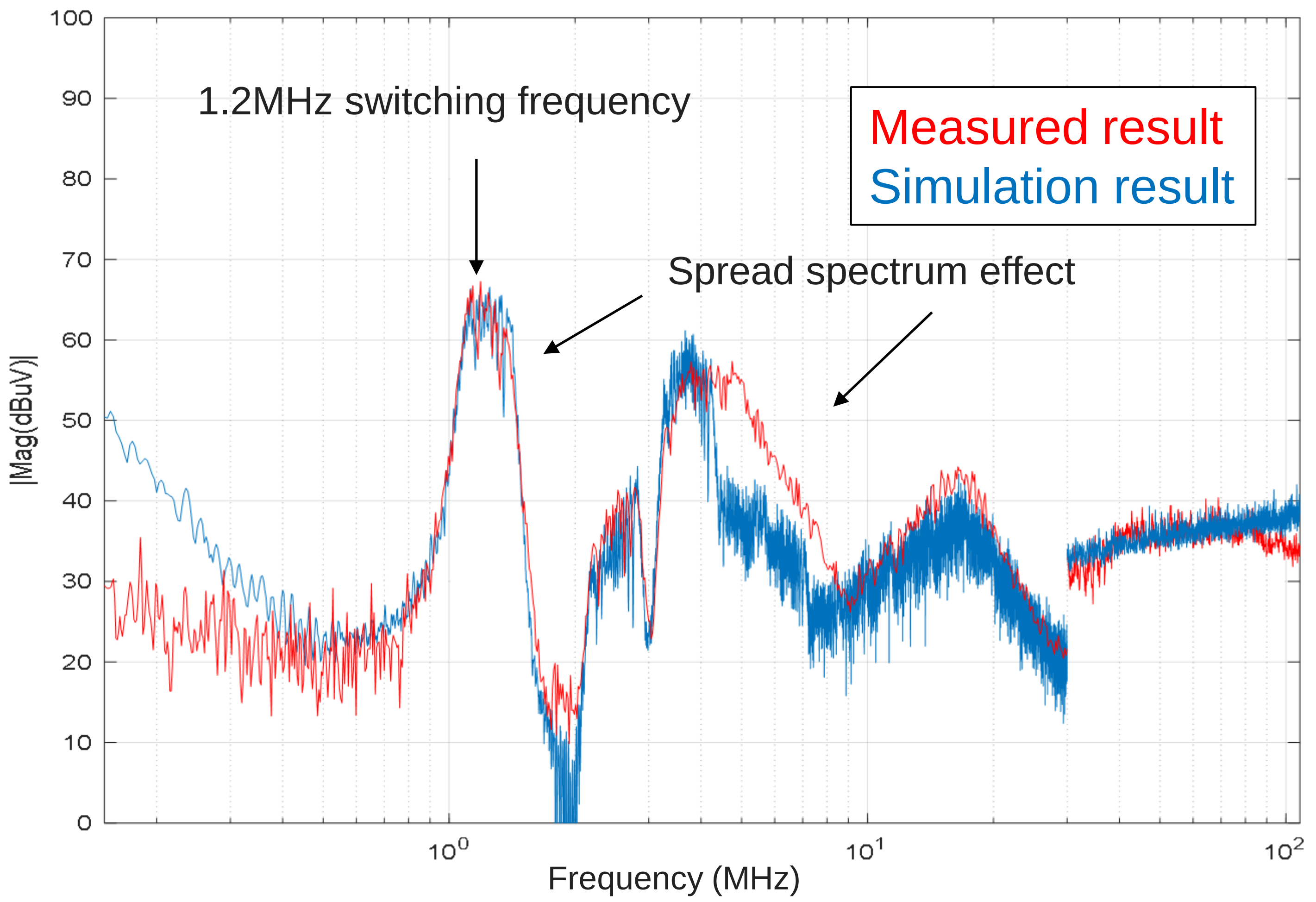
Noise separator

Differential Mode EMI

Common Mode EMI

Noise Transfer Function

Predict EMI in the Simulation



Note: With the EMI model and simulation software, the EMI can be predicted accurately, which greatly benefits the hardware design.

Radiated EMI Modeling and Analysis

Radiated EMI Modeling of a Buck-Boost Converter for Lighting

The Future of Analog IC Technology®

MPQ2483

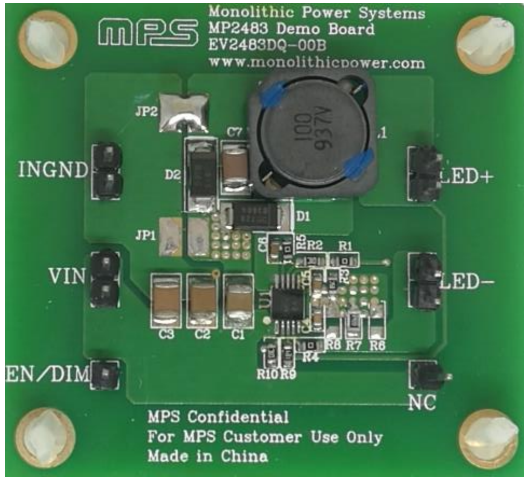
Industrial/Automotive-Grade 55V, 2.5A Programmable Frequency LED Driver Avaiable in AEC-Q100

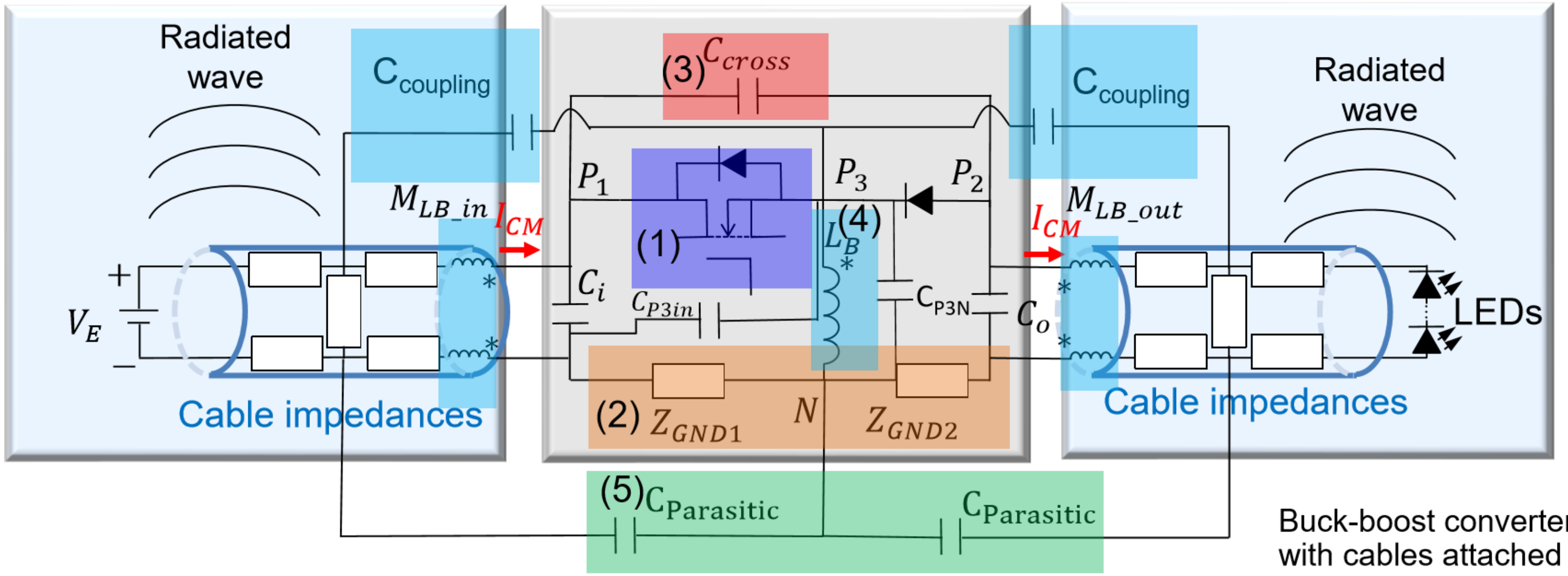
DESCRIPTION

The MPQ2483 is a 55V, LED driver suitable for either step-down or inverting step-up/down applications. It achieves 2.5A peak current over a wide input supply range with excellent load and line regulation. Current mode operation

FEATURES

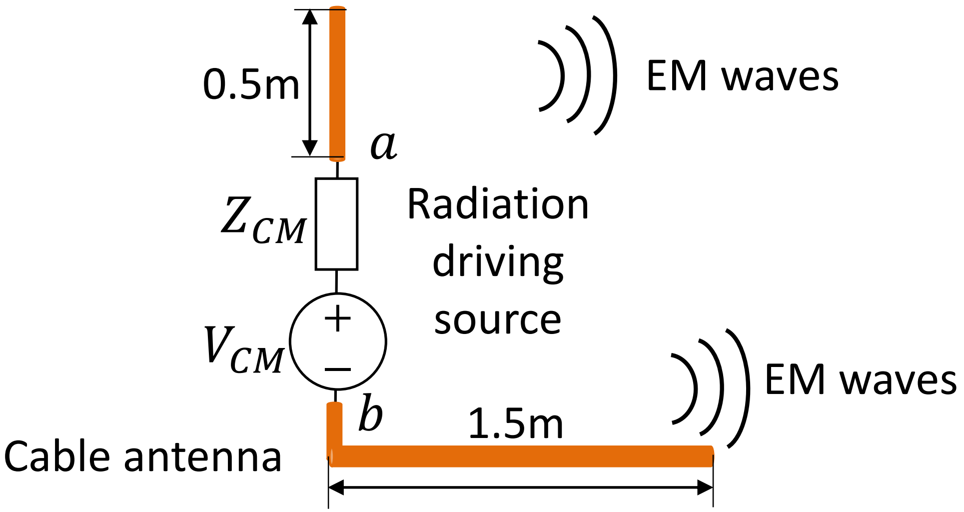
- 2.5A Maximum Peak Current
- Buck or Buck-Boost Modes
- Wide 4.5V to 55V Operating Input Range
- 0.28Ω Internal Power MOSFET Switch
- Analog and PWM Dimming

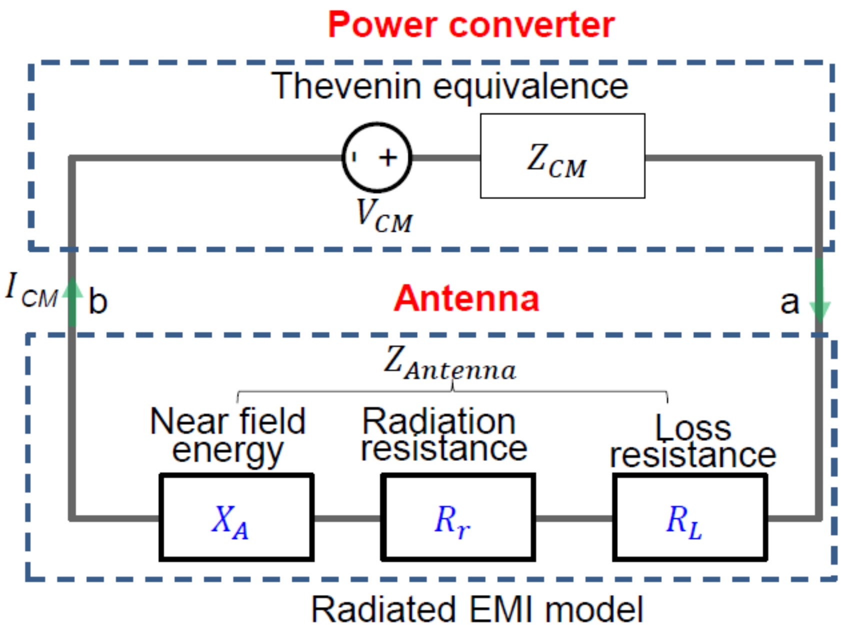




Buck-boost converter with cables attached

Radiated EMI Modeling





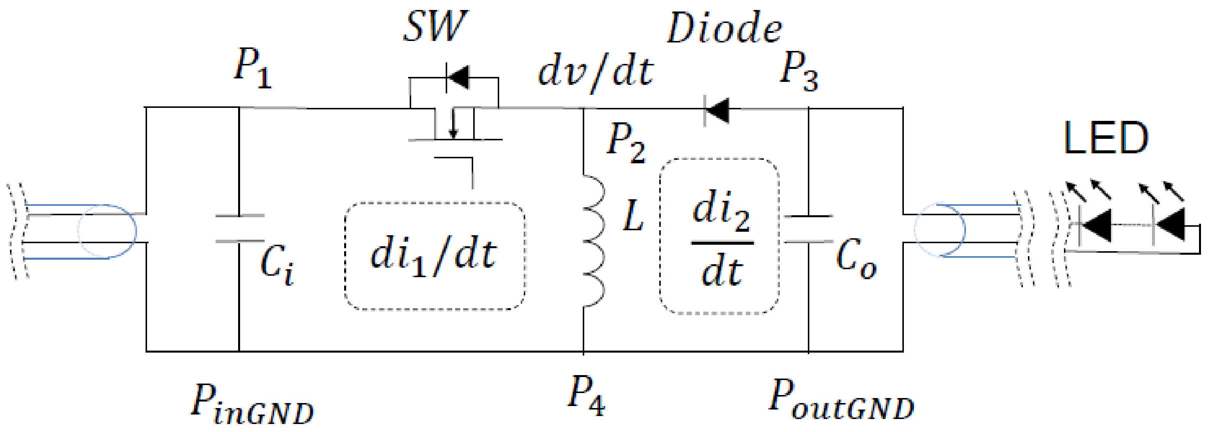
In the far field region, in the isotropic and uniform radiation case, electric field E is,

$$E = \sqrt{P_r \eta / 2\pi r^2}$$

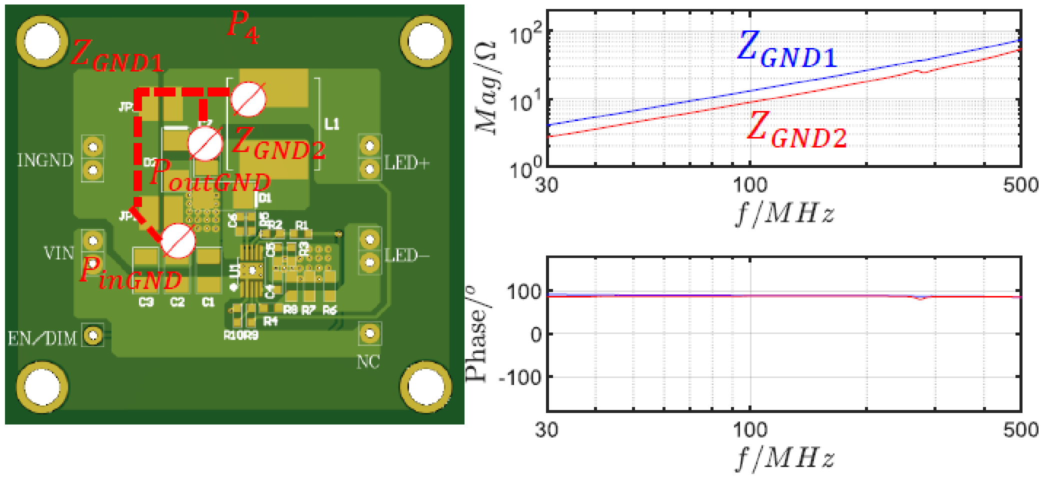
where, $P_r = \frac{1}{2}|I_{CM}|^2 R_r = \frac{|V_{CM}|^2}{2}\left[\frac{R_r}{|Z_{CM}+R_L+R_r+jX_A|^2}\right]$

Buck-boost Converter with Parasitic Impedances

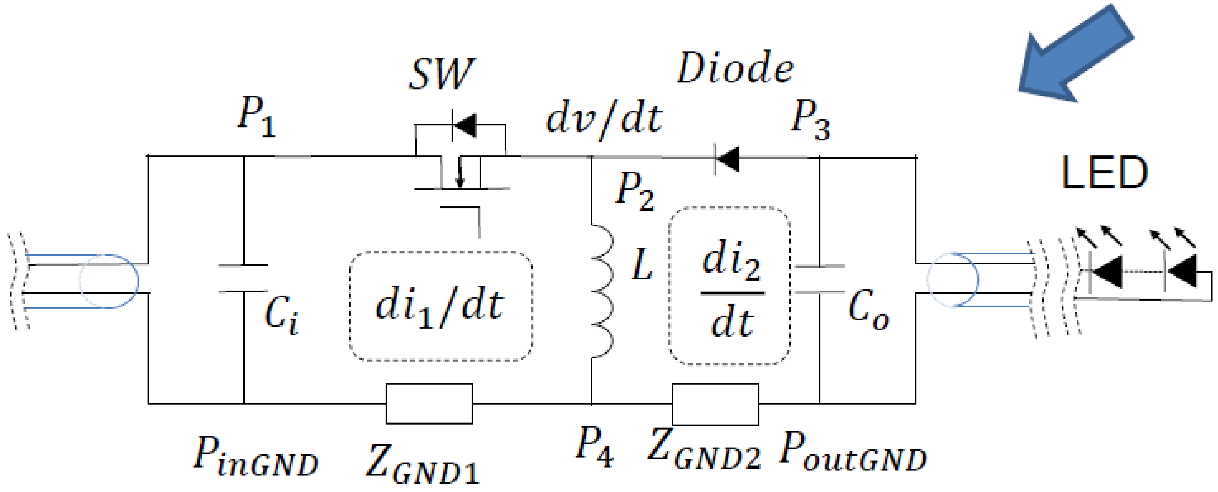
Ideally, the ground layer has zero impedance.



Ground layer impedance is significant at HF

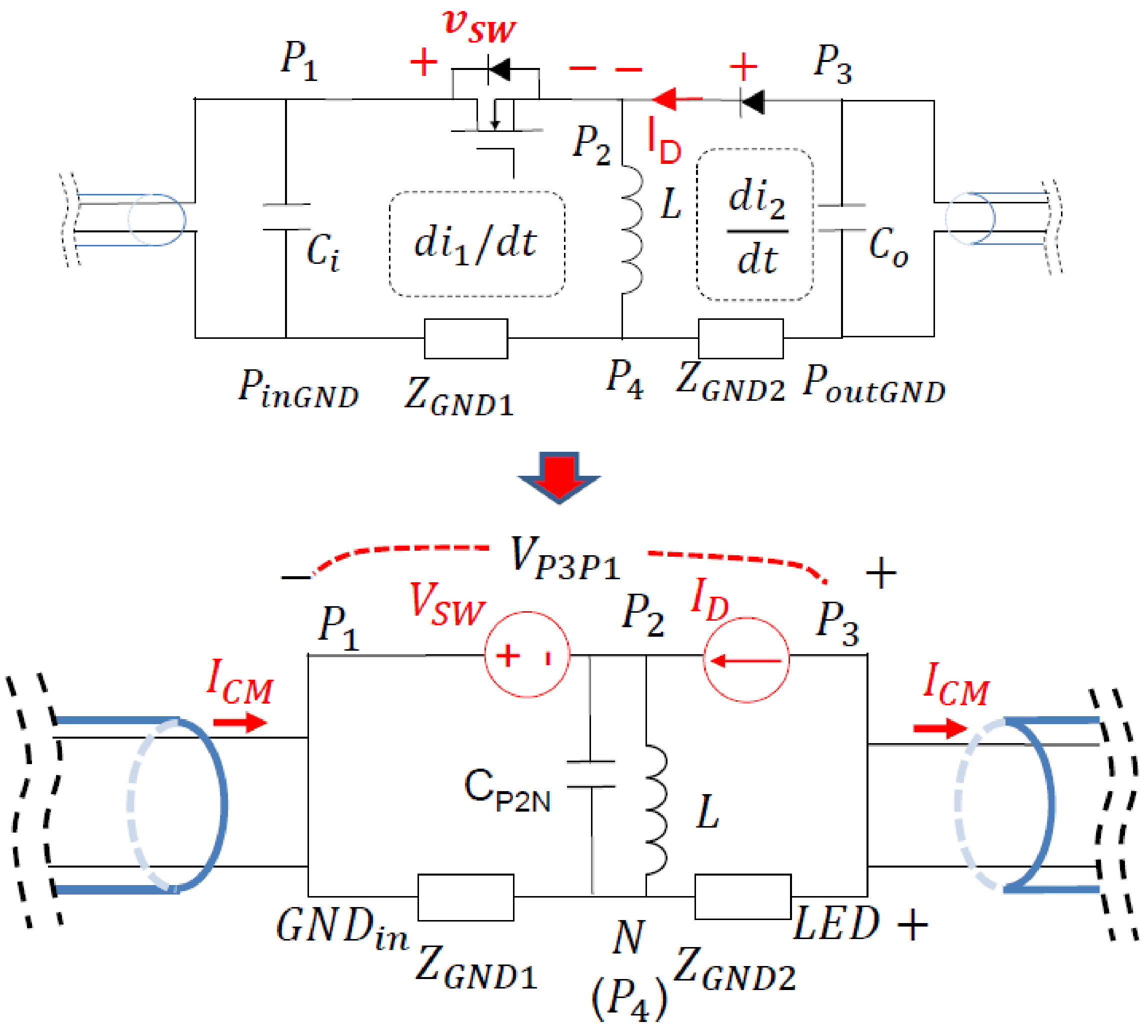


Extracted impedances

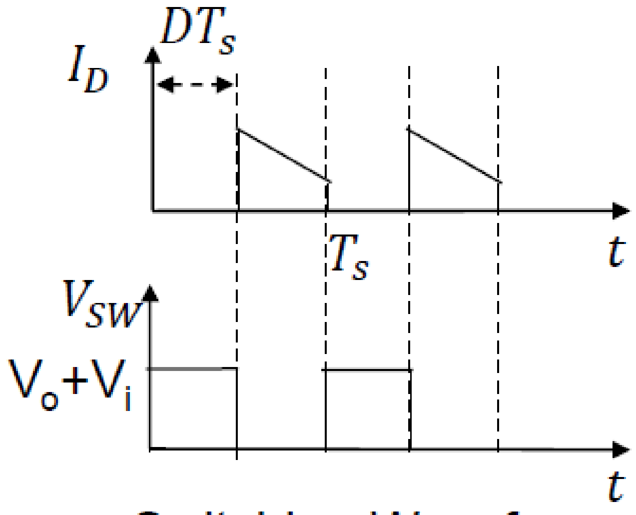


In fact, the ground layer has parasitic impedance.

Noise Source Modeling with Substitution Theorem

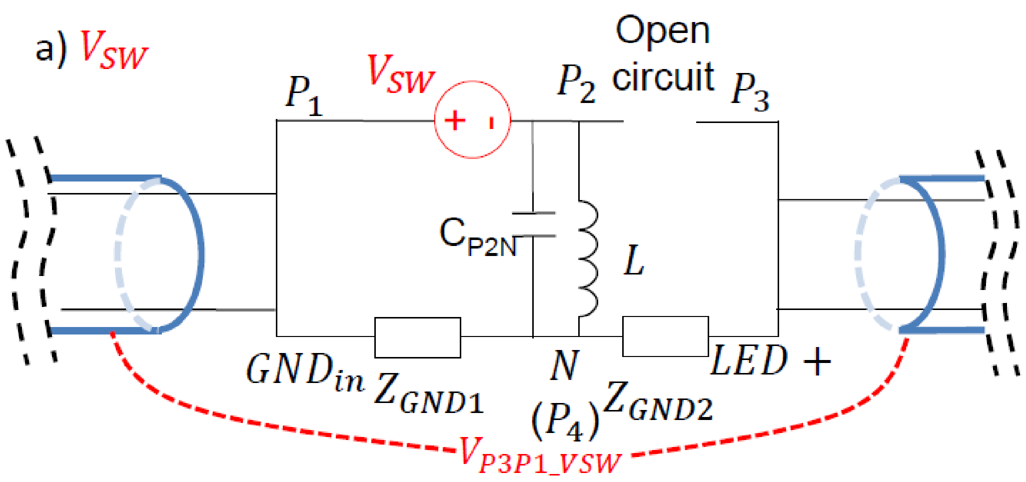


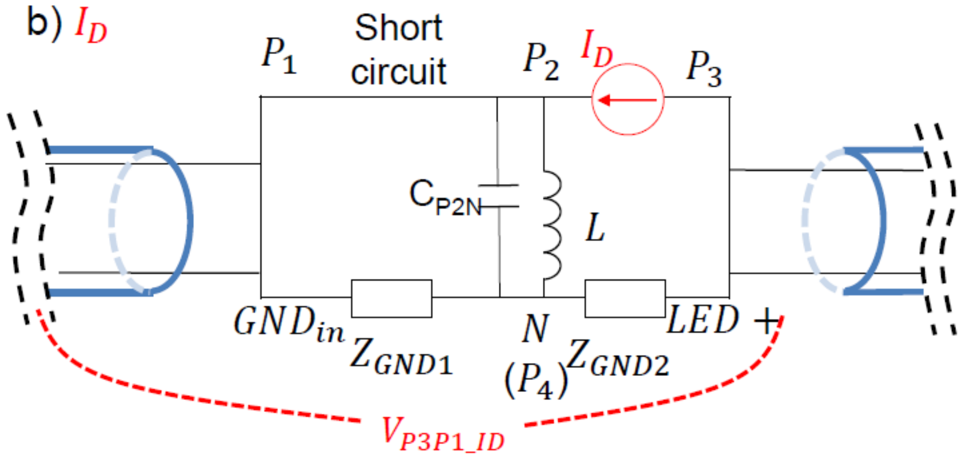
Switching devices replaced by voltage/current sources



Switching Waveforms

Transfer Gain of Noise Transformation with Superposition Theorem





$$V_{P3P1,V_{SW}} = -V_{SW} \cdot \frac{Z_{GND1}}{Z_{GND1} + Z_L}$$

$$G_{V_{SW}}(s) = \frac{V_{P3P1,V_{SW}}}{V_{SW}} = -\frac{Z_{GND1}}{Z_{GND1} + Z_L}$$

$$V_{P3P1} = V_{SW} \cdot G_{V_{SW}}(s) + I_D \cdot G_{I_D}(s)$$

$$V_{P3P1,I_D} = -I_D \cdot [(Z_{GND1}||Z_L) + Z_{GND2}]$$

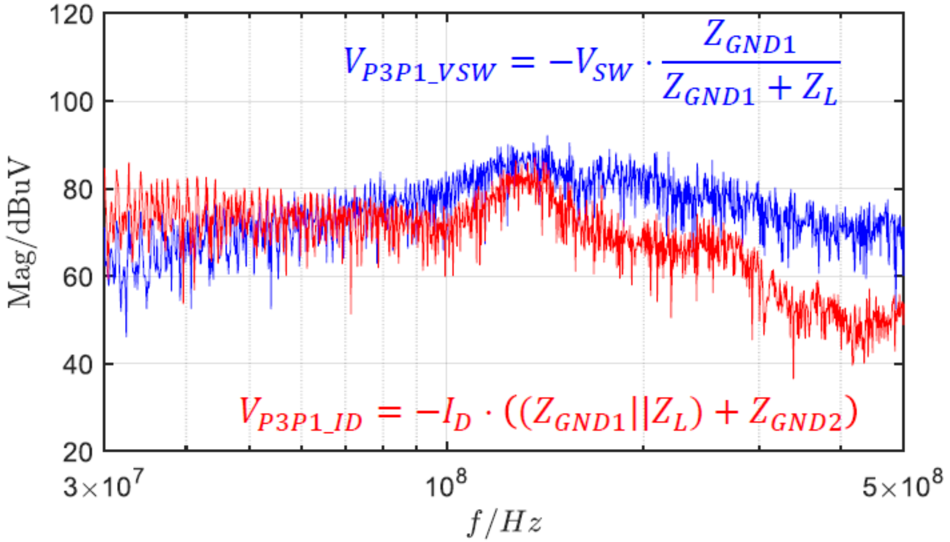
$$G_{I_D}(s) = \frac{V_{P3P1,V_{SW}}}{I_D} = -[(Z_{GND1}||Z_L) + Z_{GND2}]$$

The terminal CM voltage V_{P3P1} can be obtained.

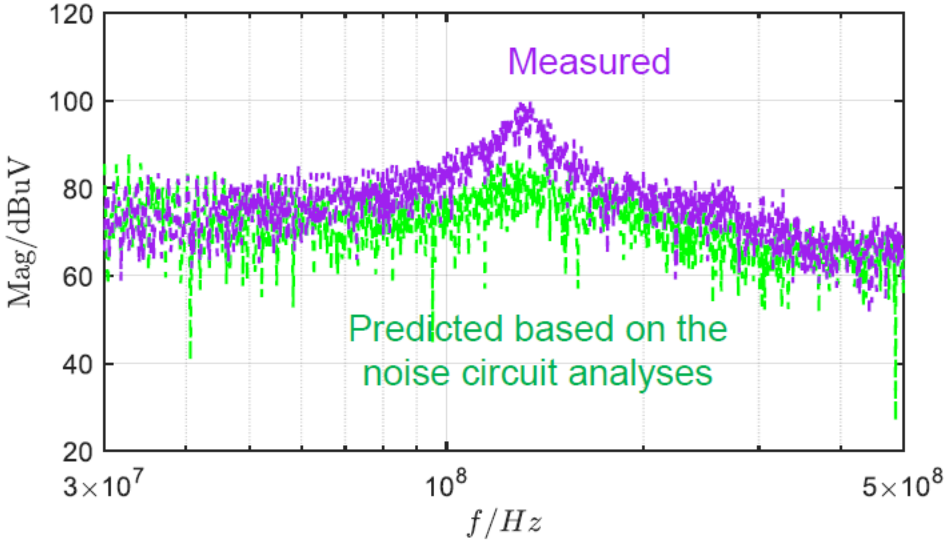
Validation of Noise Circuit

V_{SW} and I_D can be measured and the spectrum can be achieved.
Parasitic impedances can also be measured.

Based on the calculated noise transfer gains, the V_{P3P1} can be predicted.



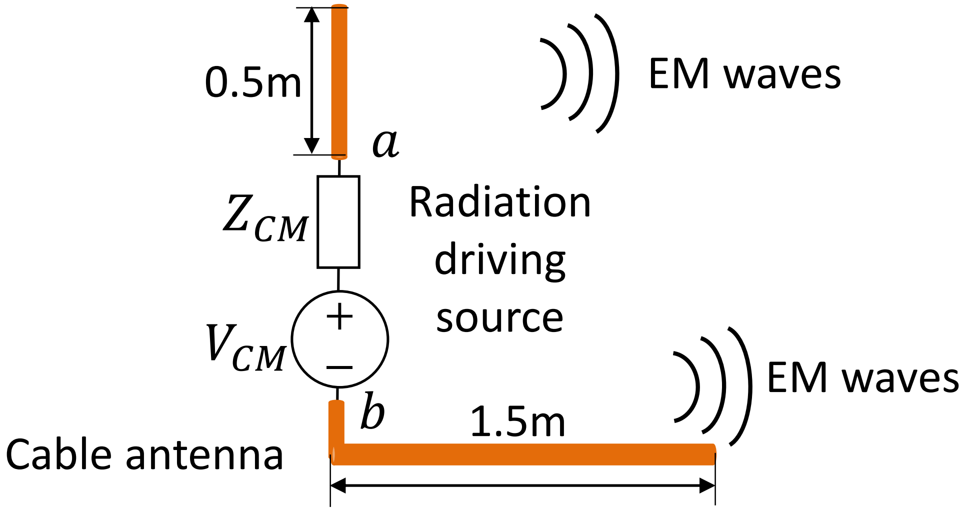
Total contribution from two noise sources to the CM terminal voltage

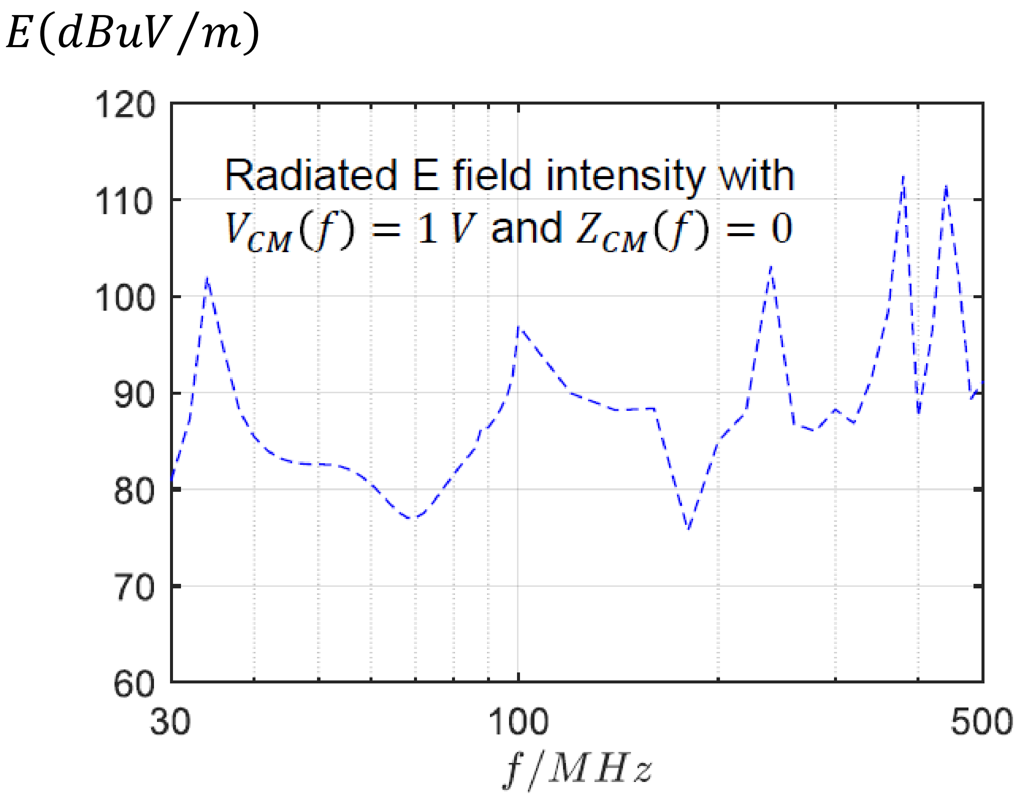


Measured and predicted CM terminal voltage V_{P3P1}

The V_{P3P1} can also be directly measured and compared with the predicted value.

Cable antenna's transfer gain

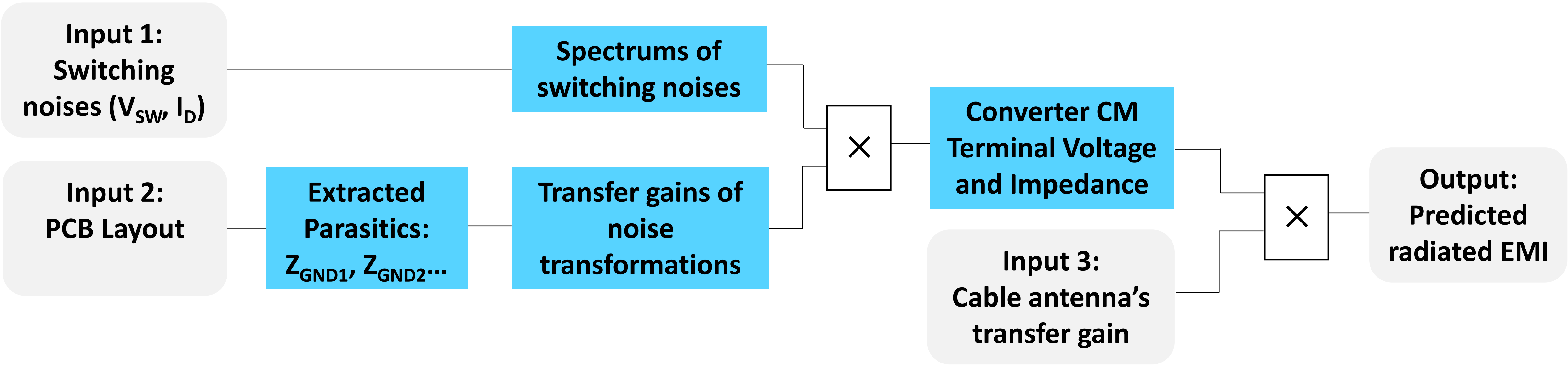


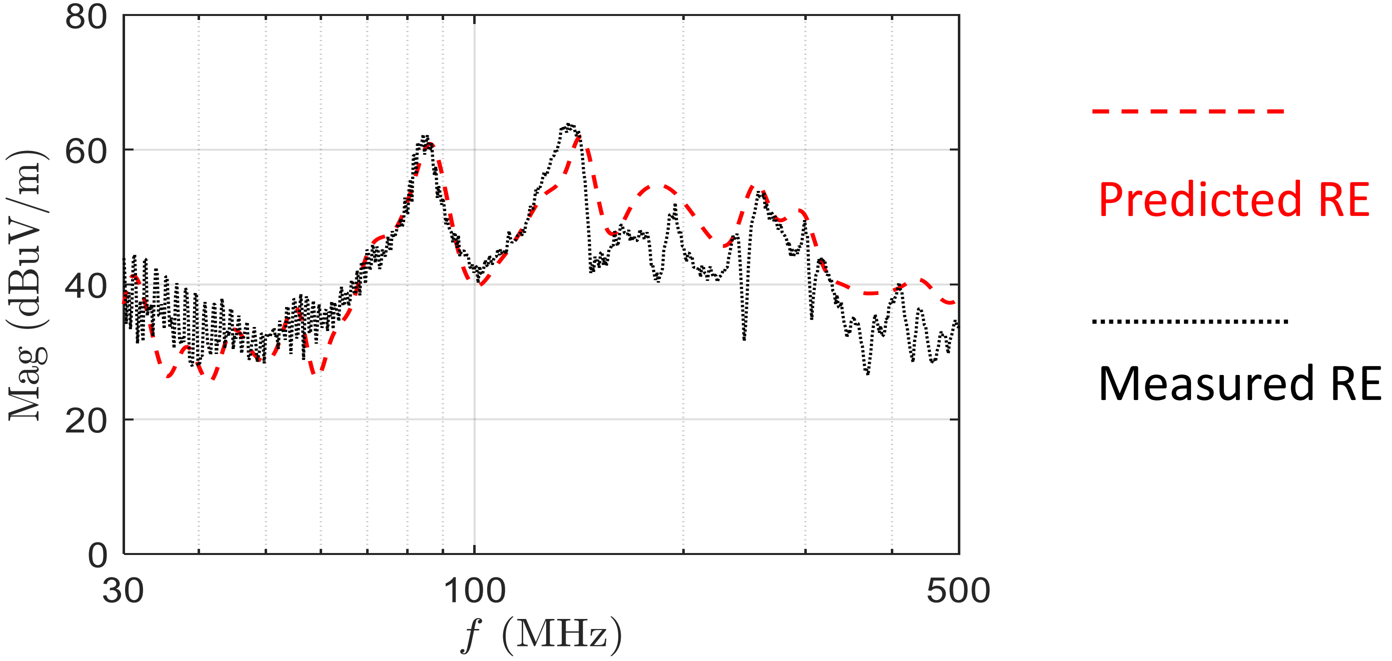


By exciting a unit voltage as the CM terminal voltage for the radiation excitation ($V_{CM} = 1V, Z_{CM} = 0$), the antenna's transfer gain can be measured.

The radiated EMI generated by the power cables can further bumps due to the characteristics of the cable antenna.

Radiated EMI Modeling Top Level





Conclusion

- MPS has strong capability to diagnose and solve EMI issues.
- Conducted CM and DM EMI models are introduced. EMI can be reduced based on source and path.
- The CM and DM models for various non-isolated DC/DC converters are introduced.
- Component Parasitics and Near-Field Coupling Effect are included to refine the EMI model.
- With circuit and LISN model, simulation helps to predict the conducted EMI performance.
- Radiated EMI model and Antenna model are introduced.
- GND impedance is important for radiated EMI modeling and analysis.
- With circuit and antenna model, simulation helps to predict the radiated EMI performance.

Question & Answer

Thank you!