Analysis and Reduction of Conducted EMI with Long Output Cable

输出端带长线负载的传导EMI分析与改善

Jul. 2021

Background

- Sr. Application Engineer at **Monolithic Power Systems** since 2020
- Ph.D. in Electrical Engineering – University of Florida, PEEPRL
- 5 years research experience in EMI modeling and reduction techniques
- Published >20 IEEE Transactions and Conference papers since 2017

- World-wide semiconductor company, $844M revenue in 2020
- Industry-leading proprietary BCD silicon process technology optimized for power management
- Best-in-class power density with 2x or higher benefit in many instances

MPS EMI Backgrounds

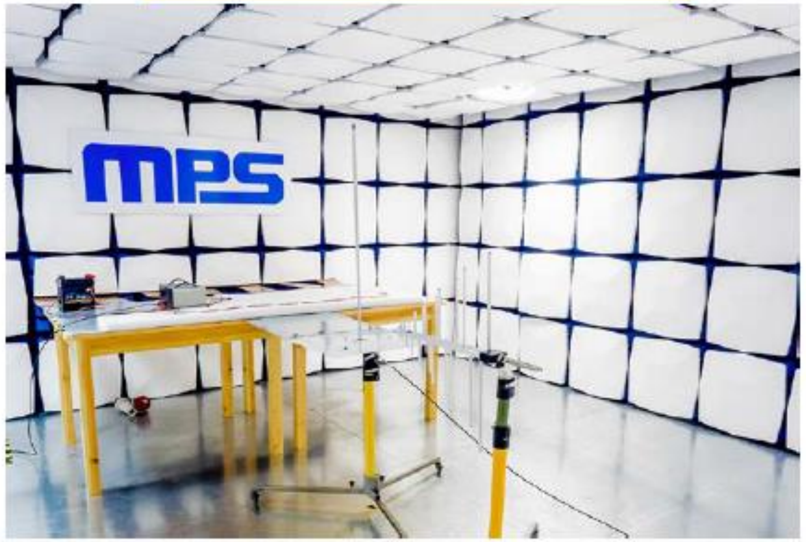
- $6M investment to build **EMI labs** – help customer to design for EMI in early stage
  - ➢ Hangzhou – China
  - ➢ Ettenheim – Germany
  - ➢ Detroit – USA

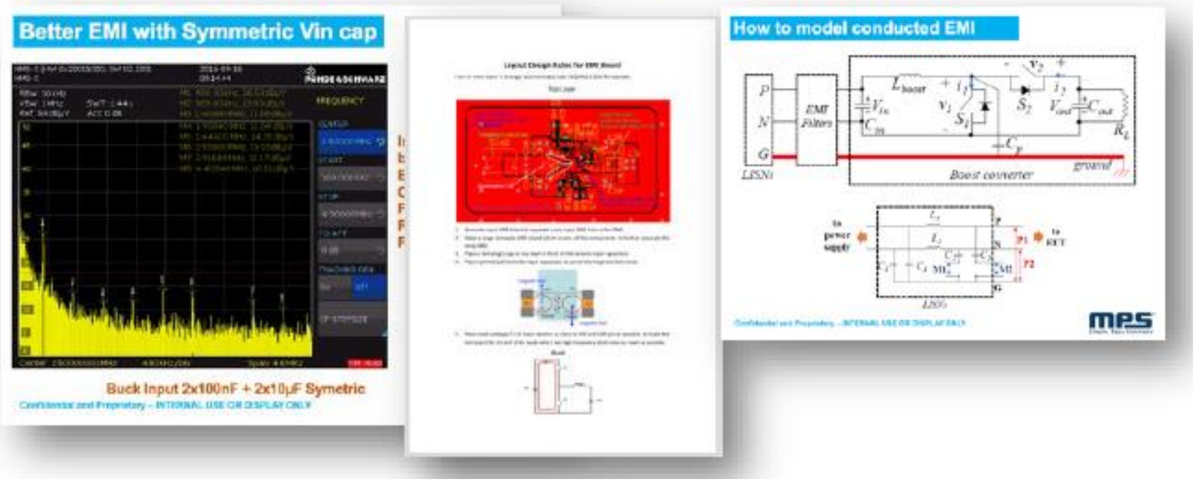
- **Advanced EMI Model** development for customers

- **University Cooperation** on advanced EMI topics

- Better EMI performance by **IC design** and **system design**

Hangzhou EMI Lab





New Detroit Automotive Center

Automotive Applications with Long Output Cable

Class-D

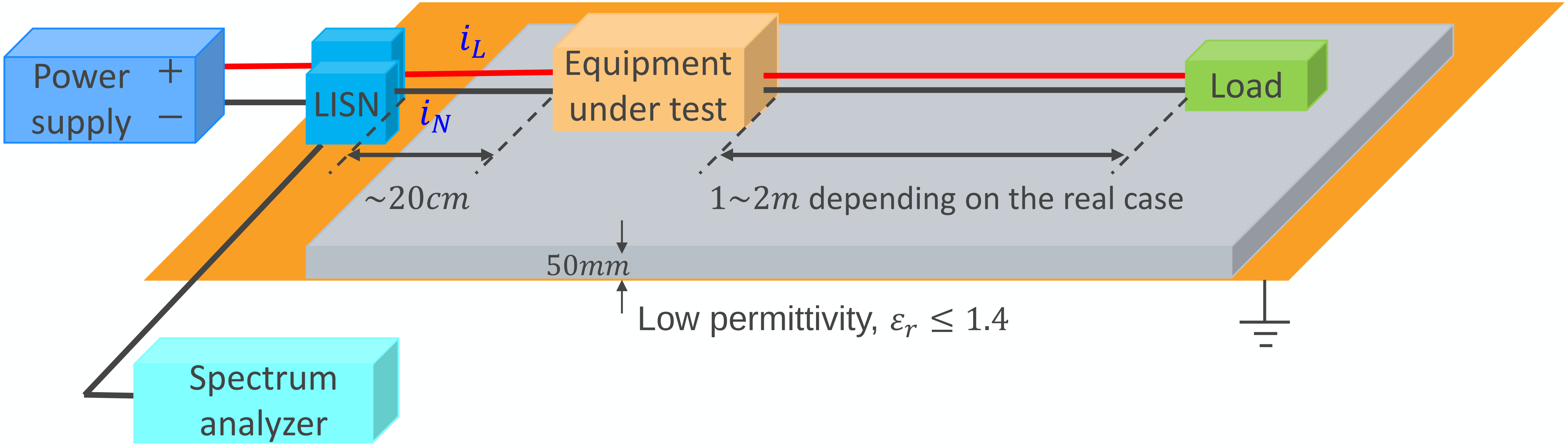
LED

USB Charger

Note: In automotive electronics, there are many loads connected to the board via a long cable.

Conducted EMI Test Setup with a long output cable

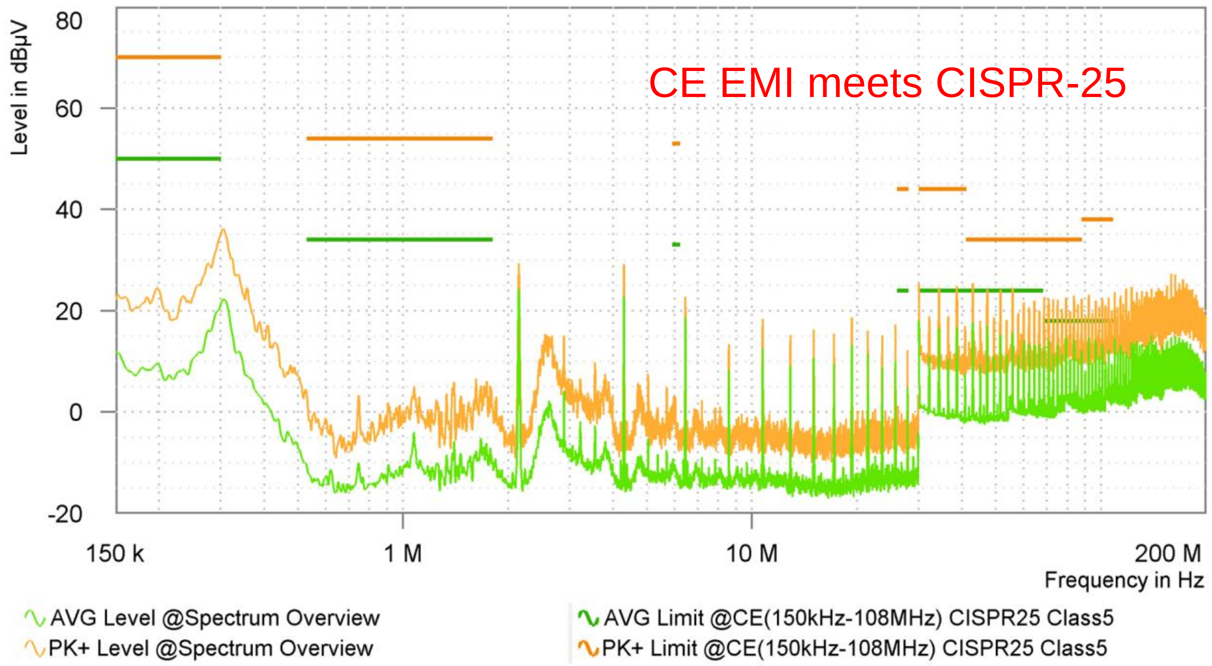
Subject to CISPR25



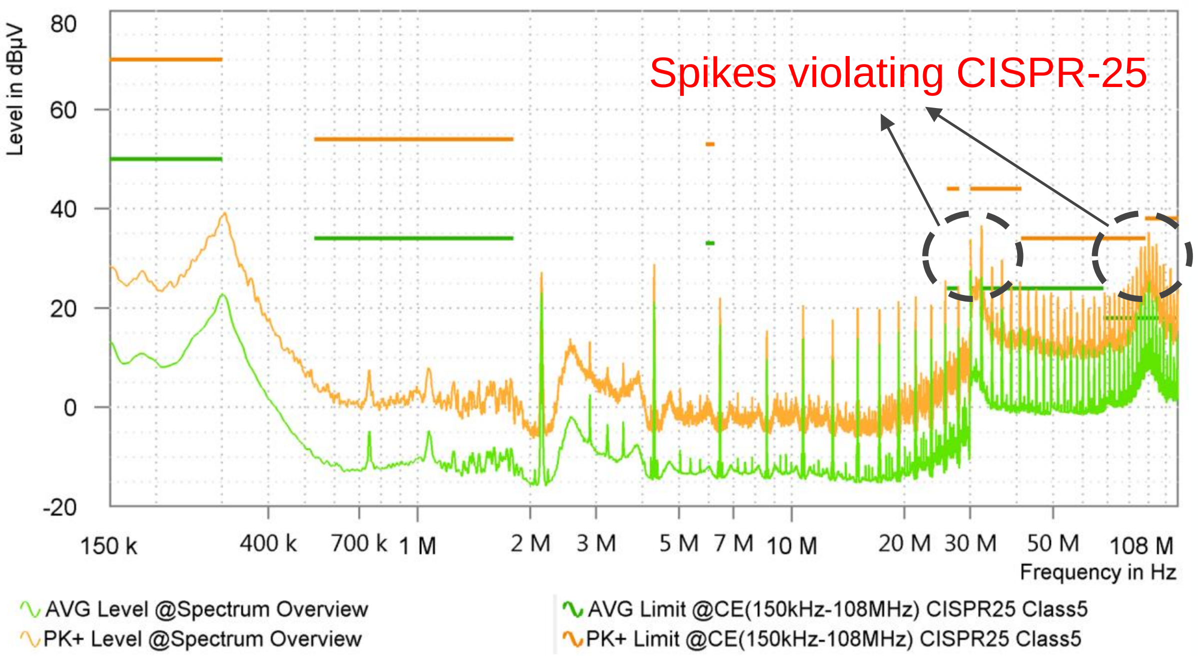
Note: A long output cable is applied in the conducted EMI test. The length depends on the real application, or it is subject to OEM's specification.

Undesired Noises and Spikes with Long Output Cable

2.1MHz Class-D, CE (150kHz to 108MHz)
no output cable



2.1MHz Class-D, CE (150kHz to 108MHz)
with 2m output cable



Note: With a 2-m output cable, the conducted EMI increases, and there are two undesired spikes on the EMI spectrum at ~30MHz and 90MHz. And this is a general phenomenon for various topologies. And this is a common mode (CM) noise, which can be figured out via CM/DM noise separation.

Contents

- Modeling of the Conducted CM EMI
- Impedance of the long output cable
- Noise reduction techniques and experimental verification

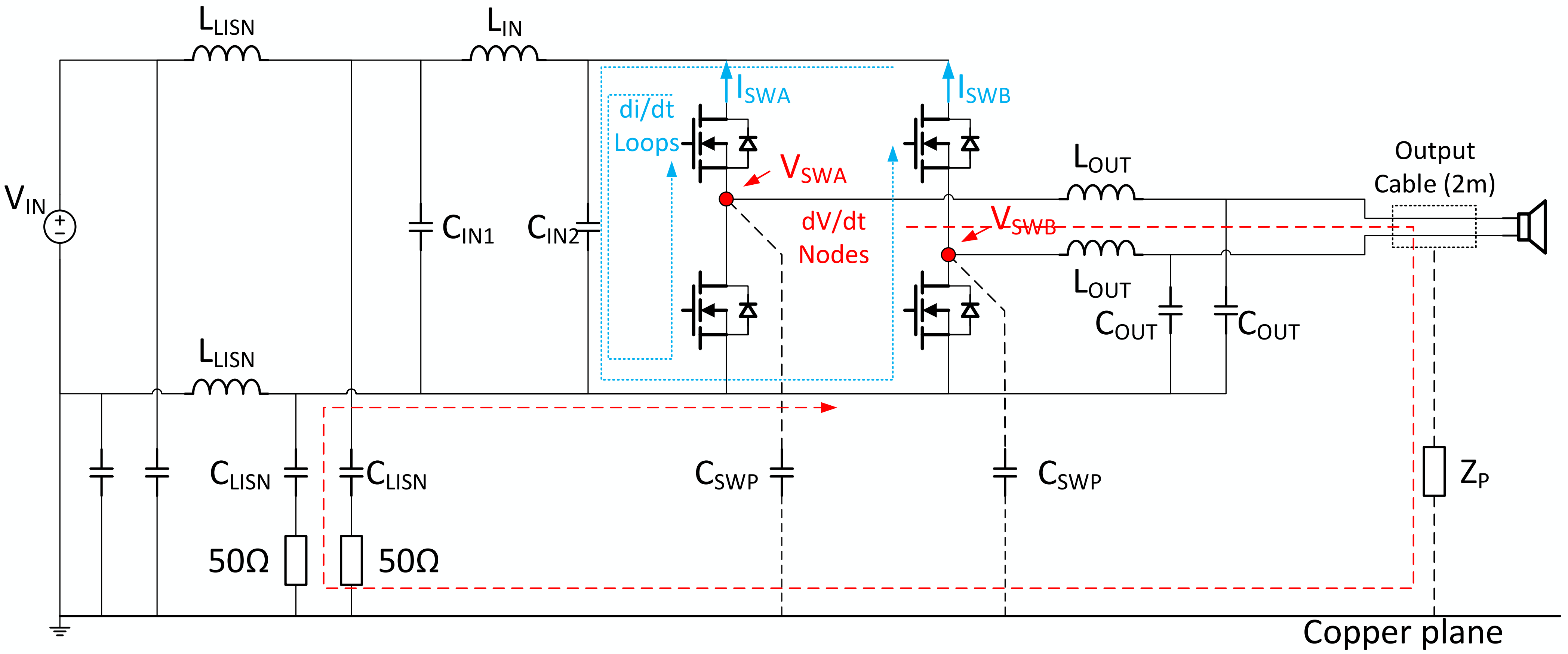
Modeling of CE EMI with long output cable

2.2MHz Class-D, MPQ7795

Example: Class-D Amplifier

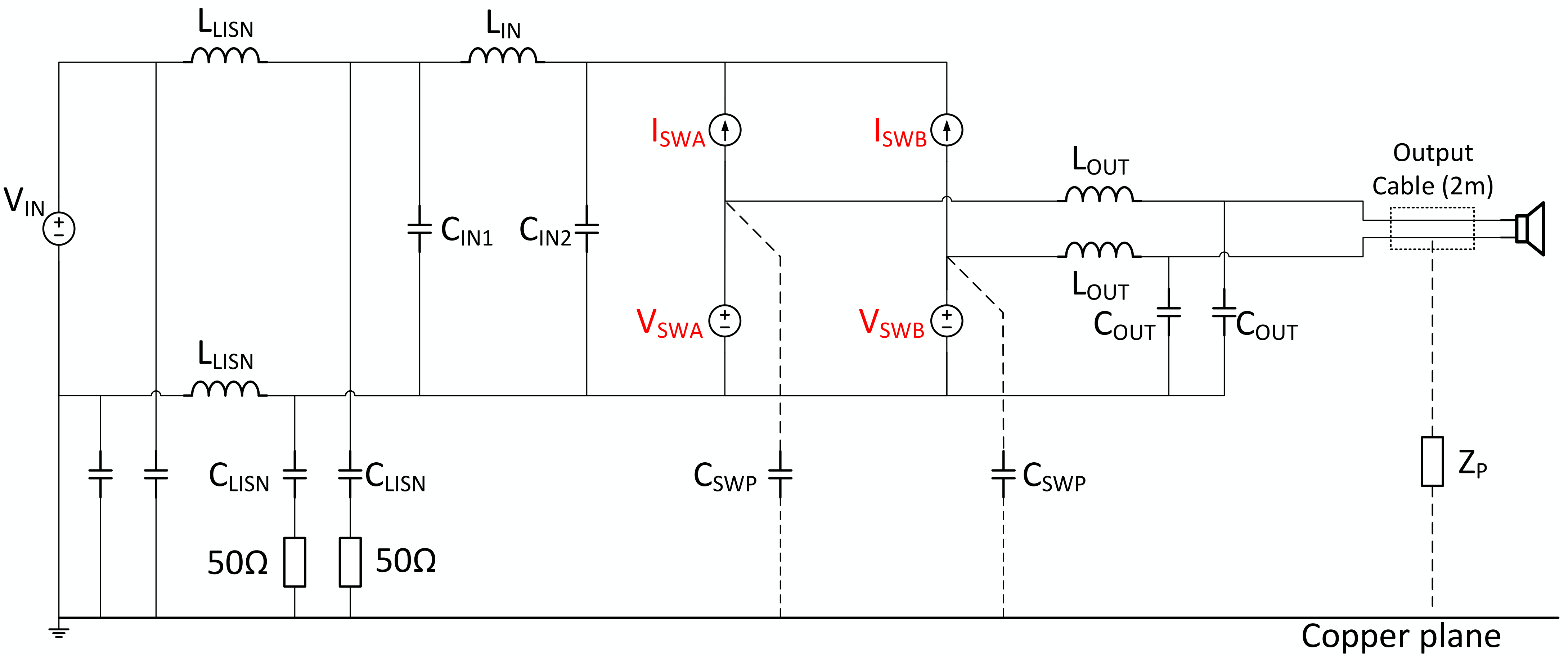
- MPQ7795 is an analog input, bridge tied load (BTL) Class-D audio amplifier for automotive applications.
- MPQ7795 supports both low switching frequency (300kHz/384kHz/470kHz) and high switching frequency (2.2MHz). With higher switching frequency, EMI is more challenging.
- As an audio product, usually a 2-m output cable is required in the EMI test, which makes it more difficult to meet the EMI standard.

Basic EMI Models of BTL Class-D Amplifier



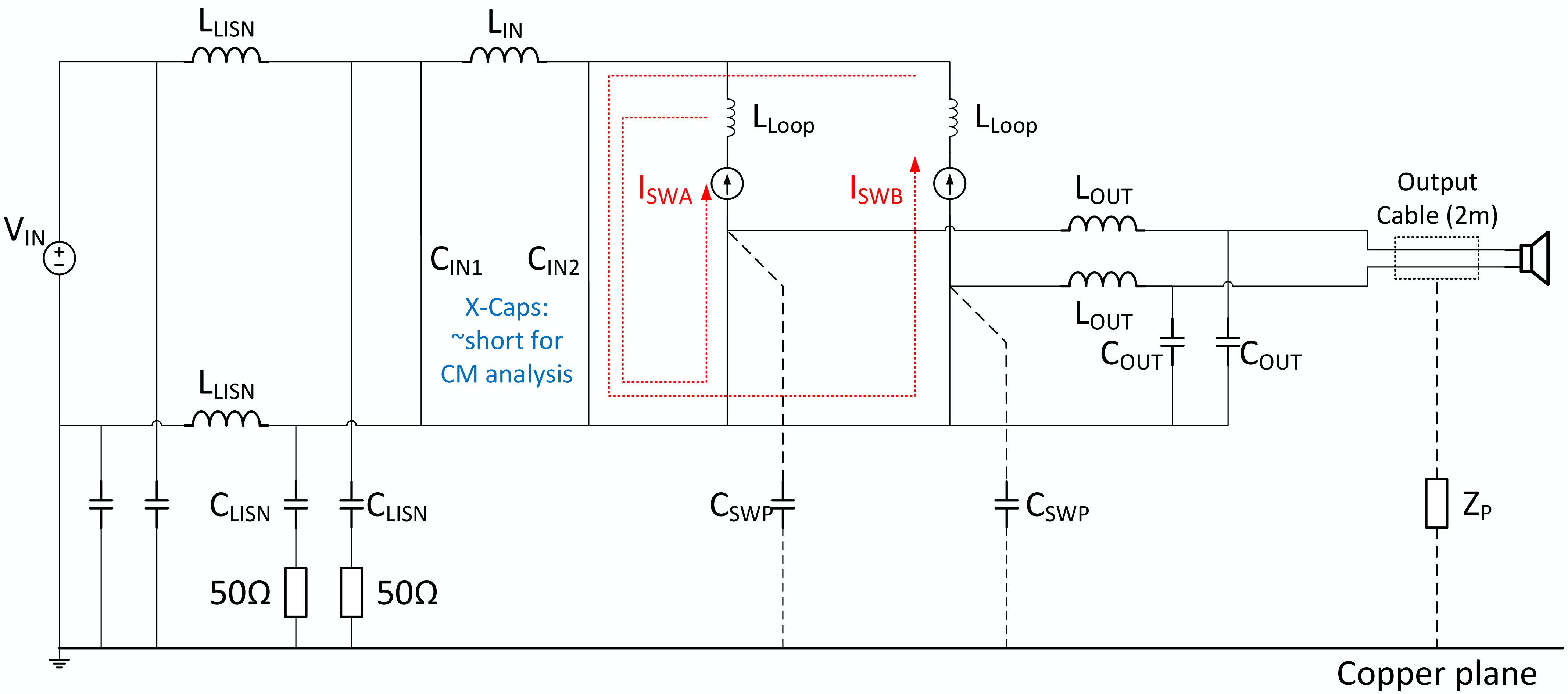
Note: Based on the conducted CM noise path, it is necessary to analyze the output cable to ground impedance.

Basic Common Mode EMI Noise Model: Substitution



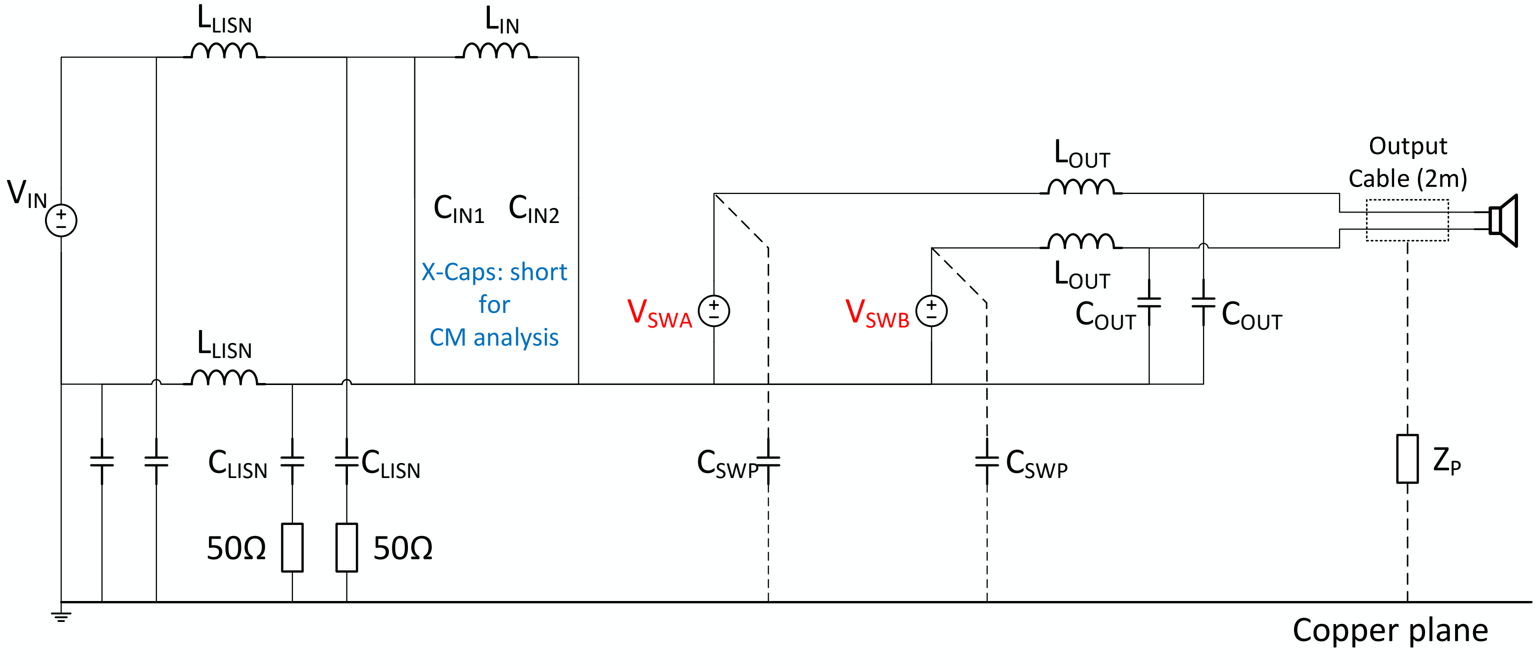
Note: Based on the substitution theorem, the switches are replaced with voltage/current source.

Superposition Theorem: Analysis of Current Sources

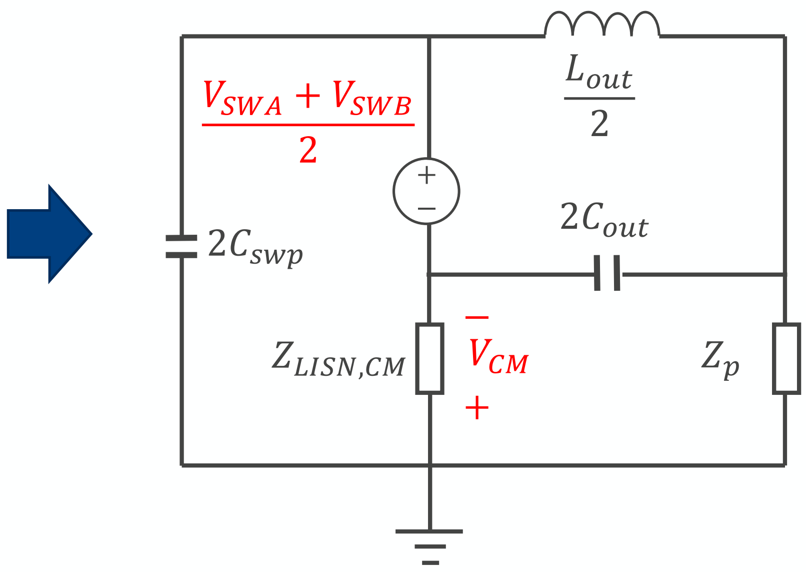


Note: The current sources do not contribute to CM noise.

Superposition Theorem: Analysis of Voltage Sources



Simplified CM Model

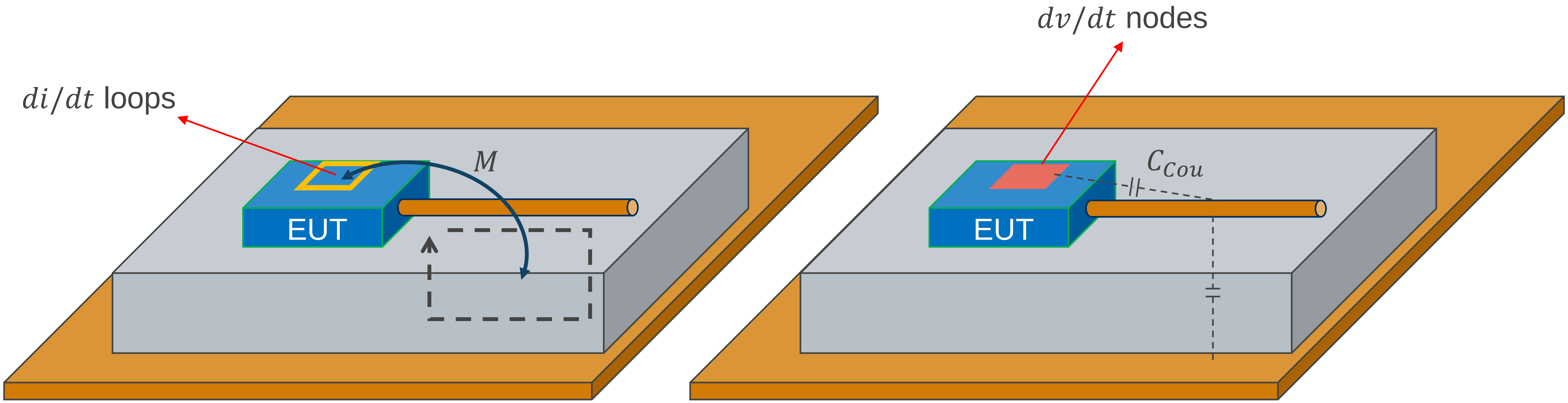


$Z_{LISN,CM}$: 25Ω resistance

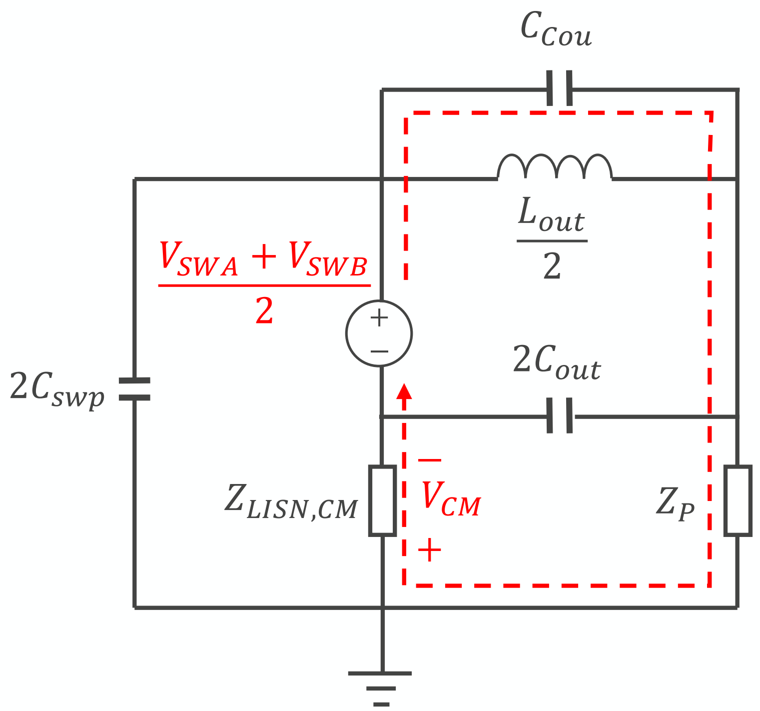
Note: The voltage sources contribute to CM noise.

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.



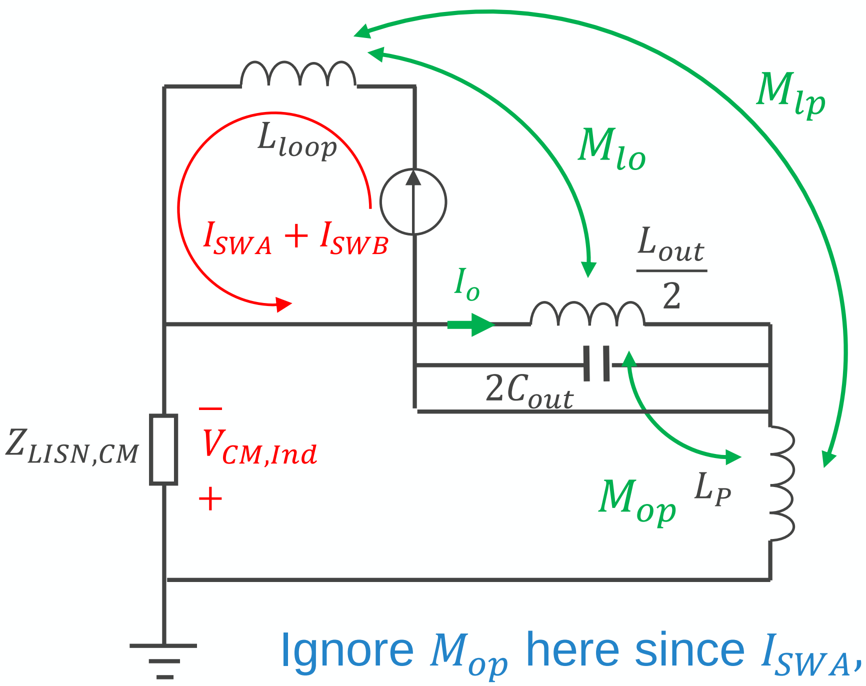
Modeling of the Capacitive Coupling



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

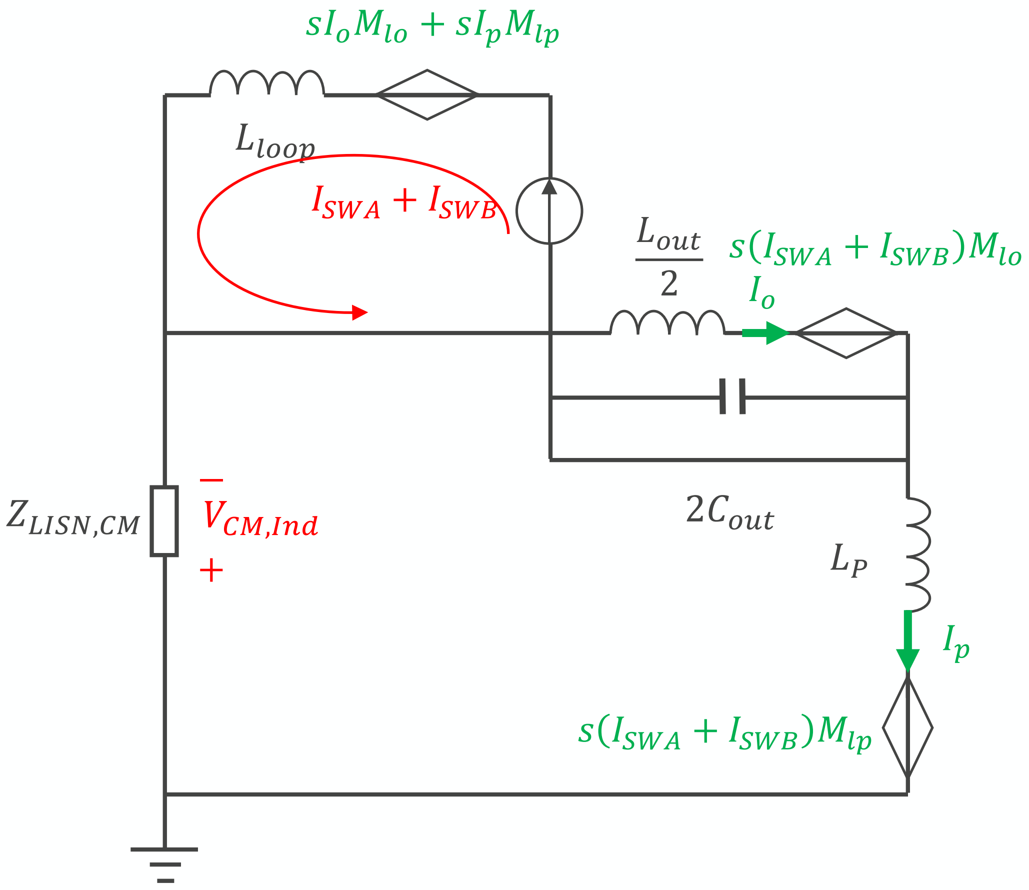
Modeling of the Inductive Coupling

Take input loop as an example



Ignore M_{op} here since I_{SWA}, $I_{SWB} \gg I_o$

Decouple



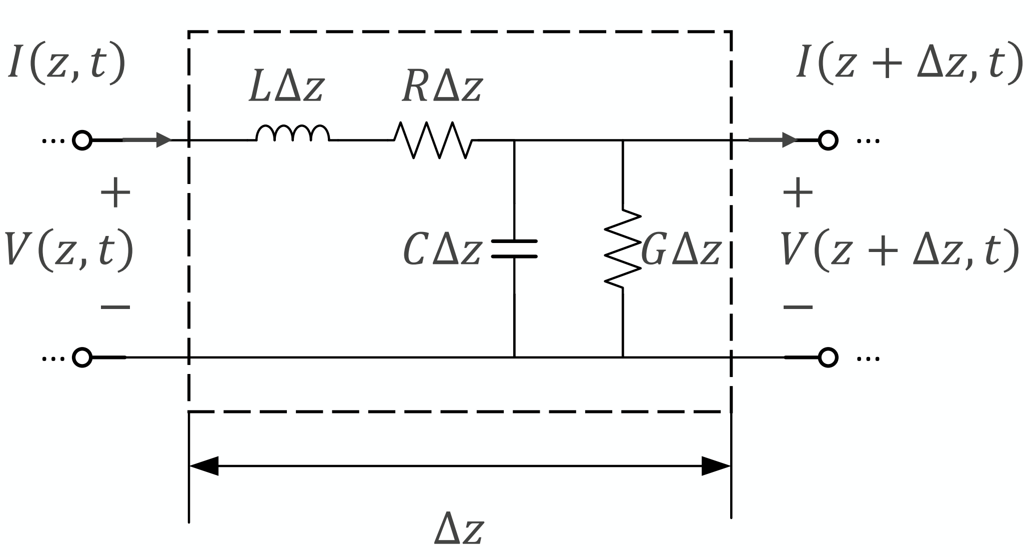
The CM noise induced by the near-field inductive coupling is:

$$V_{CM,Ind} \approx \frac{s(I_{SWA} + I_{SWB})M_{lp}}{Z_{LISN,CM} + sL_p} Z_{LISN,CM} \approx (I_{SWA} + I_{SWB}) Z_{LISN,CM} \frac{M_{lp}}{L_p}$$

Impedance of the long output cable

Transmission Line Theory

Transmission Line Theory



$$\begin{cases} V(z+\Delta z,t) - V(z,t) = -R\Delta z \cdot I(z,t) - L\Delta z \dfrac{\partial I(z,t)}{\partial t} \\ I(z+\Delta z,t) - I(z,t) = -G\Delta z \cdot V(z+\Delta z,t) - C\Delta z \dfrac{\partial V(z+\Delta z,t)}{\partial t} \end{cases}$$

$$\begin{cases} \dfrac{\partial V(z,t)}{\partial z} = -\left(R + L\dfrac{\partial}{\partial t}\right) I(z,t) \\ \dfrac{\partial I(z,t)}{\partial z} = -\left(G + C\dfrac{\partial}{\partial t}\right) V(z,t) \end{cases}$$

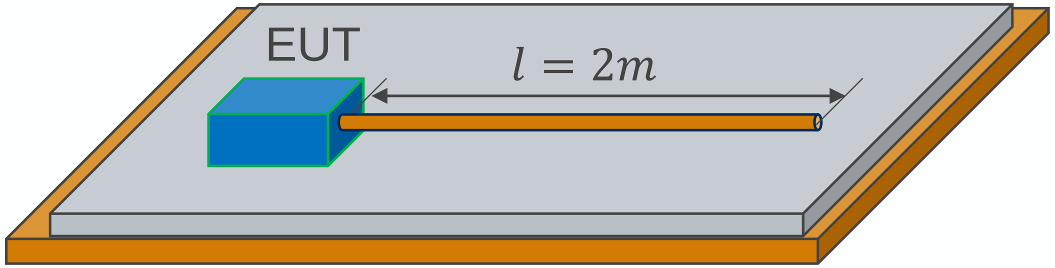
$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$$

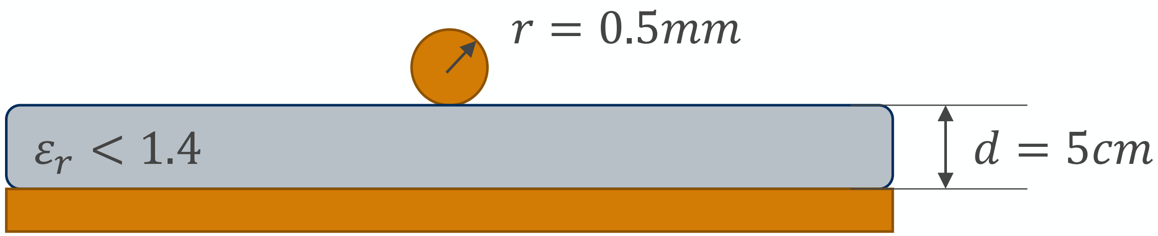
$$Z_0 \equiv \sqrt{\frac{R + j\omega L}{G + j\omega C}} = |Z_0| e^{j\phi_z}$$

$$\begin{cases} V(z) = V^+ e^{-\gamma z} + V^- e^{+\gamma z} \\ I(z) = \dfrac{1}{Z_0}\left(V^+ e^{-\gamma z} - V^- e^{+\gamma z}\right) \end{cases}$$

Note: If R and G are ignorable, $\beta(phase\ constant) = \omega\sqrt{LC}, Z_0(characteristic\ impedance) = \sqrt{L/C}$.

Modeling the Output Cable's Characteristics





$\varepsilon = \varepsilon_0 \varepsilon_r$: Permittivity, $\varepsilon_0 = 8.85 \times 10^{-12}\ \mathrm{F/m}$

$\mu = \mu_0 \mu_r$: Permeability, $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H/m}$

σ: Conductivity, $= 6.0 \times 10^7$ for copper

Note: The parasitic impedance can be seen as the transmission line impedance looking toward the load from the output, terminated at 2m, open load.

$$C = \frac{2\pi\varepsilon}{\cosh^{-1}\left(\frac{d}{r}\right)} \qquad L = \frac{\mu}{2\pi}\cosh^{-1}\left(\frac{d}{r}\right)$$

$$G \approx 0 \qquad R = \frac{1}{2\pi r \sigma \delta} = \frac{1}{2\pi r \sigma \sqrt{\pi f \mu \sigma}}$$

If R and G are ignored:

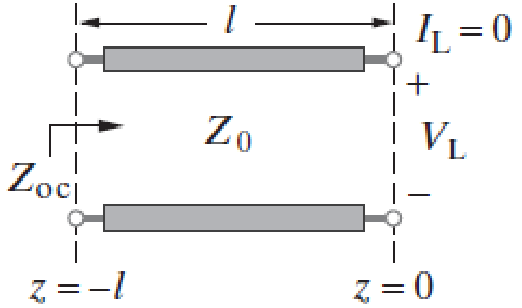
$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\cosh^{-1}\left(\frac{d}{r}\right) \approx \frac{1}{2\pi}\sqrt{\frac{\mu}{\varepsilon}}\ln\left(\frac{2d}{r}\right)\ (r \ll d)$$

Transmission Line with Open-Circuit Termination

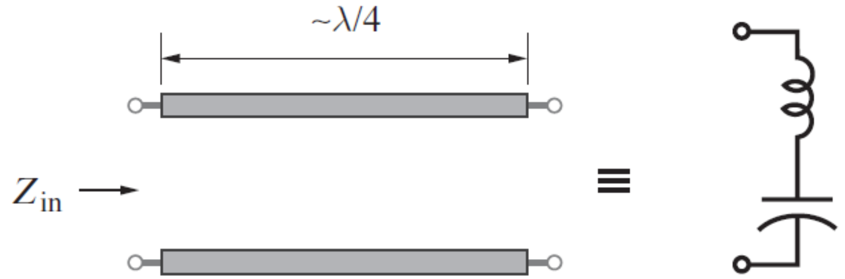
$$\begin{cases} V(z) = V^{+}e^{-j\beta z} + V^{-}e^{+j\beta z} \\ I(z) = \dfrac{1}{Z_0}\left(V^{+}e^{-j\beta z} - V^{-}e^{+j\beta z}\right) \end{cases}$$

$$I\Big|_{z=0} = 0 \quad V^{+} = V^{-}$$

$$\begin{cases} V(z) = 2V^{+}\cos(\beta z) \\ I(z) = \dfrac{2V^{+}}{Z_0}e^{-\frac{j\pi}{2}}\sin(\beta z) \end{cases}$$



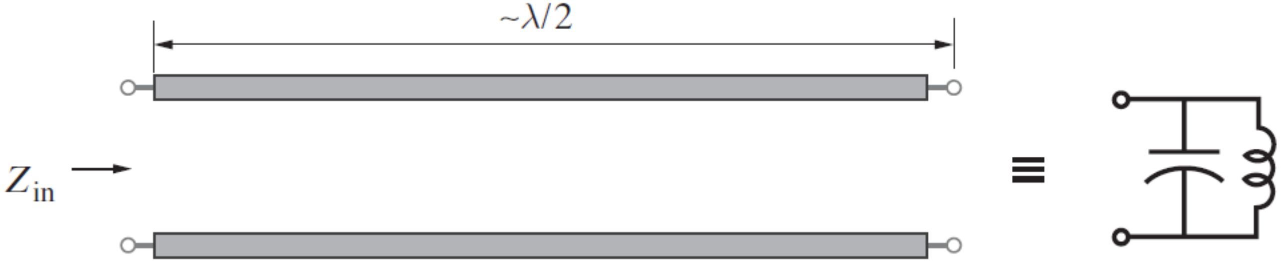
$$Z_{oc} = Z(z = -l) = -jZ_0\cot(\beta l)$$



$$f = \frac{v_p}{\lambda} = \frac{1}{\lambda\sqrt{LC}} = \frac{1}{\lambda\sqrt{\mu_0\varepsilon_0\varepsilon_r}} = \frac{c}{\lambda\sqrt{\varepsilon_r}}$$

$$l_1 = \frac{1}{4}\lambda_1 = 2m \Rightarrow f_1 = \frac{c}{\lambda_1\sqrt{\varepsilon_r}} = 31.6MHz$$

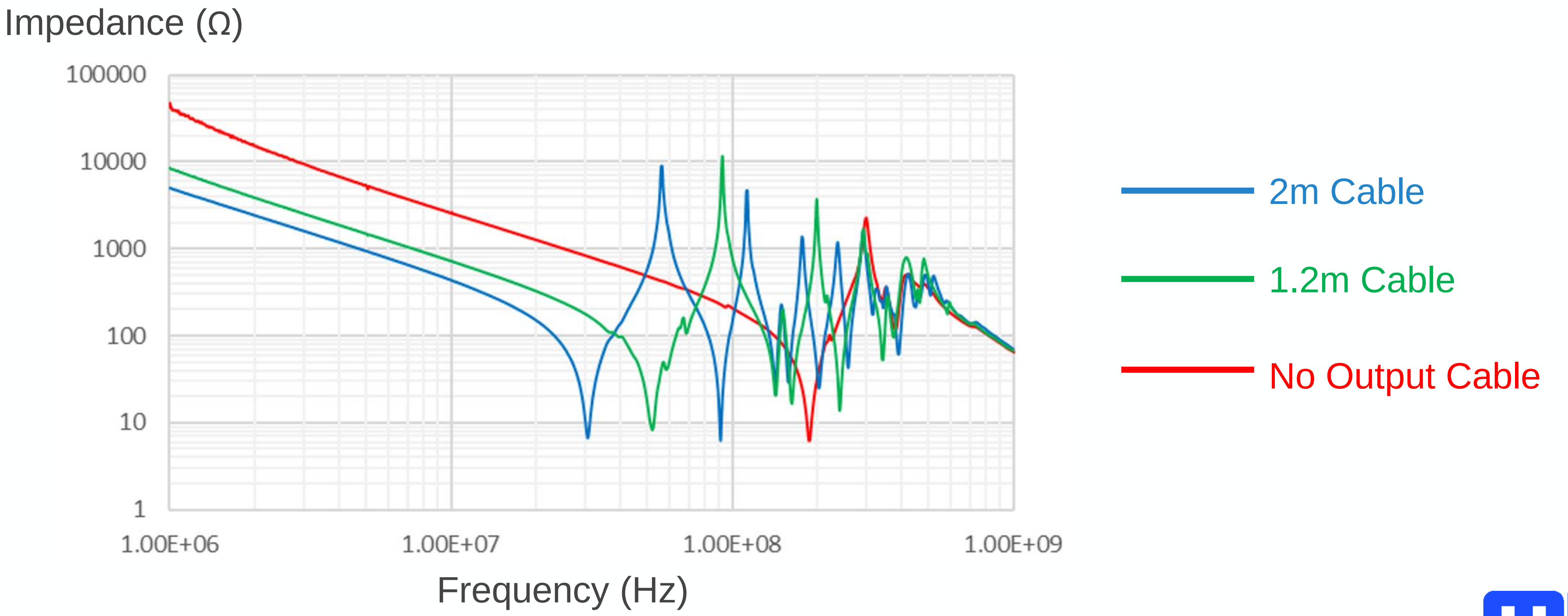
$$l_2 = \frac{3}{4}\lambda_2 = 2m \Rightarrow f_2 = \frac{c}{\lambda_2\sqrt{\varepsilon_r}} = 95.1MHz$$



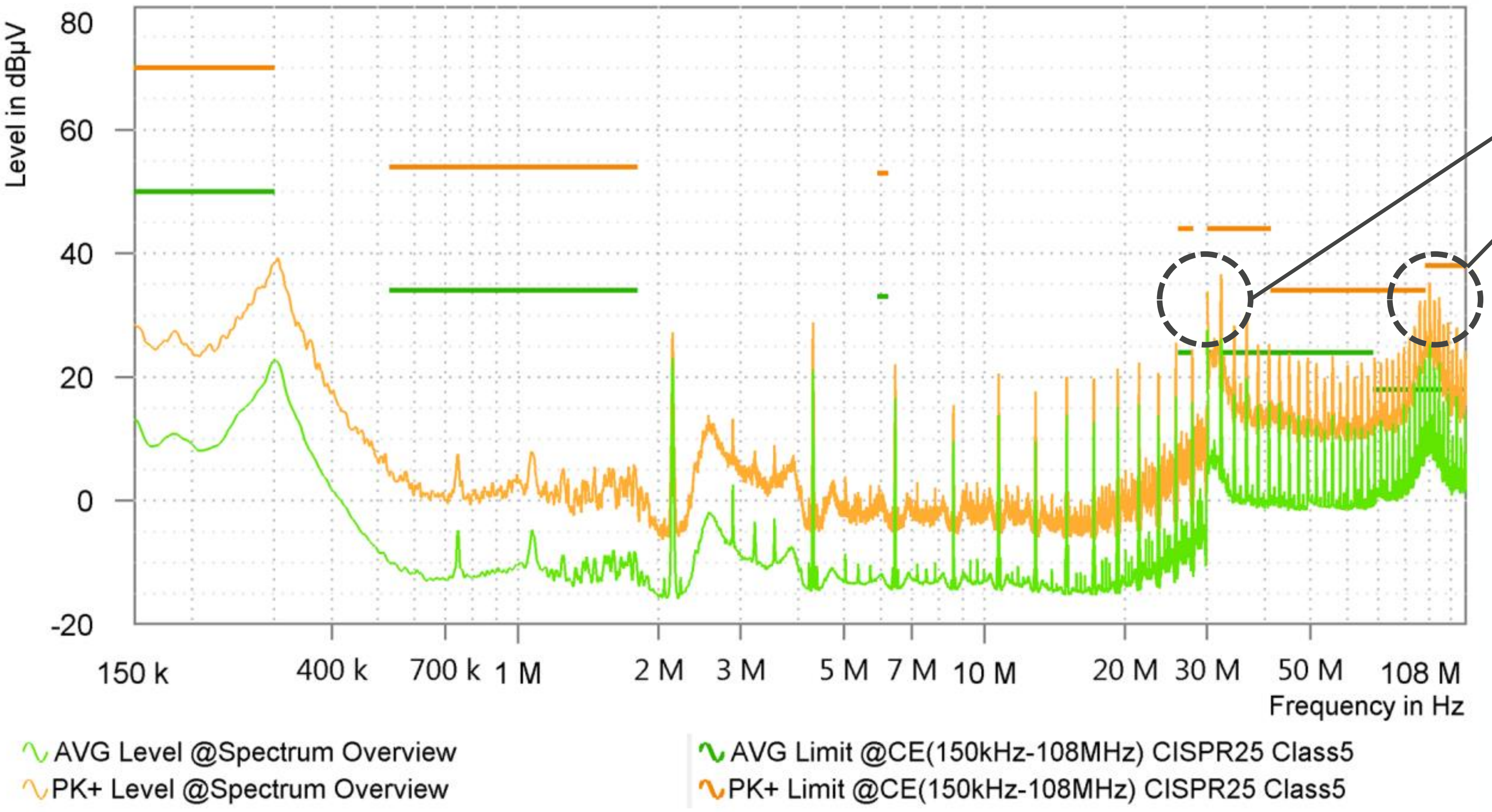
Note: The resonance frequency is not influenced by the wire diameter or distance to the ground.

Measurement of the Output Cable's Impedance

- If the cable length is 2m, there will be two intrinsic series resonance happen at $31.6MHz$ and $95.1MHz$, respectively. Note that the resonance frequency will not influenced by changing the wire size, since λ is constant if ε and μ are fixed.
- If the cable length reduces, the resonance will happen at higher frequency, which helps to improve the EMI.



Phenomenon in the Experiment



Two spikes happen at ~30MHz and ~90MHz

Note: The spikes observed in EMI spectrum can be well explained with the transmission line theory.

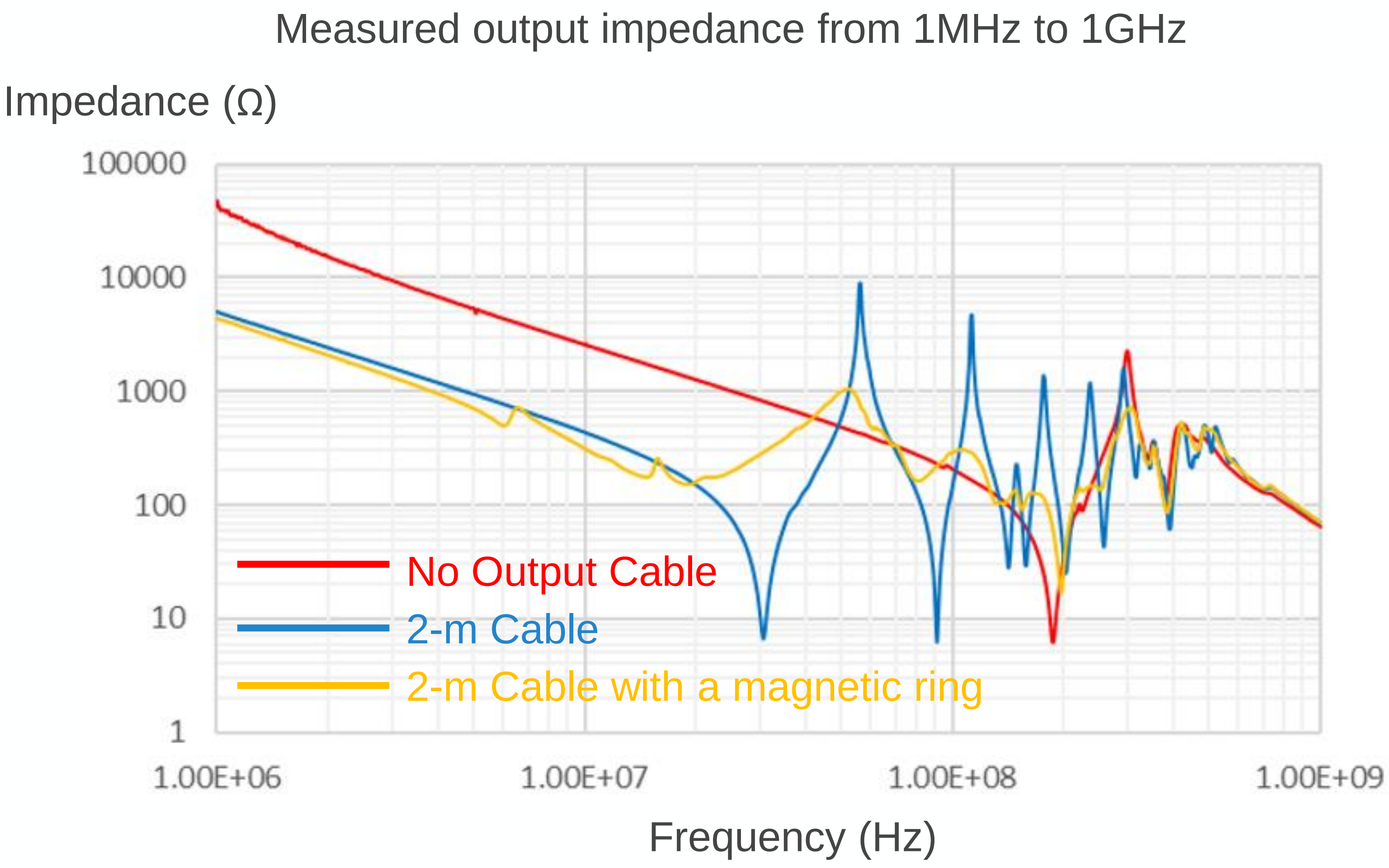
Reduction Techniques and Verification

Shielding, Filtering, and others

General Reduction Methods

- Noise Source Reduction:
  - Reduce the dv/dt slew rate to attenuate high frequency CM noise source.
  - Apply frequency spread spectrum.
- Noise Path Reduction:
  - Reduce the size of the dv/dt nodes and di/dt loops.
  - Add a CM filter or magnetic ring/bead on the output cable to reduce the CM noise.
  - Specify the cable length to avoid the $\frac{1}{4}\lambda$ and $\frac{3}{4}\lambda$ resonance in sensitive frequencies.
    - If the output cable is 1~1.5m, the $\frac{3}{4}\lambda$ resonance is beyond 108MHz and there is no CE issue.
  - Apply a shielding for HF noise reduction

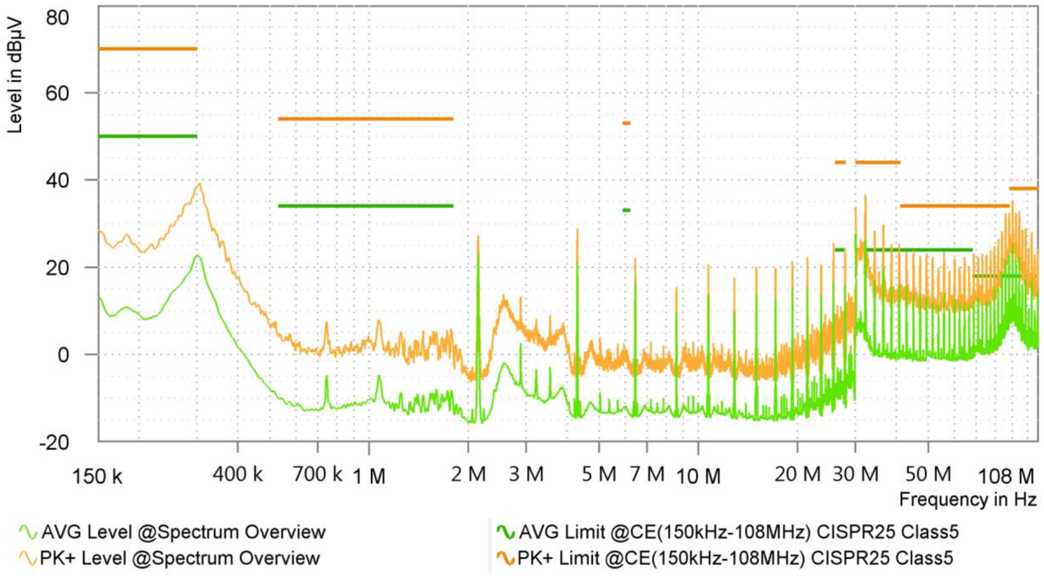
Adding a Magnetic Ring to Increase Z_p



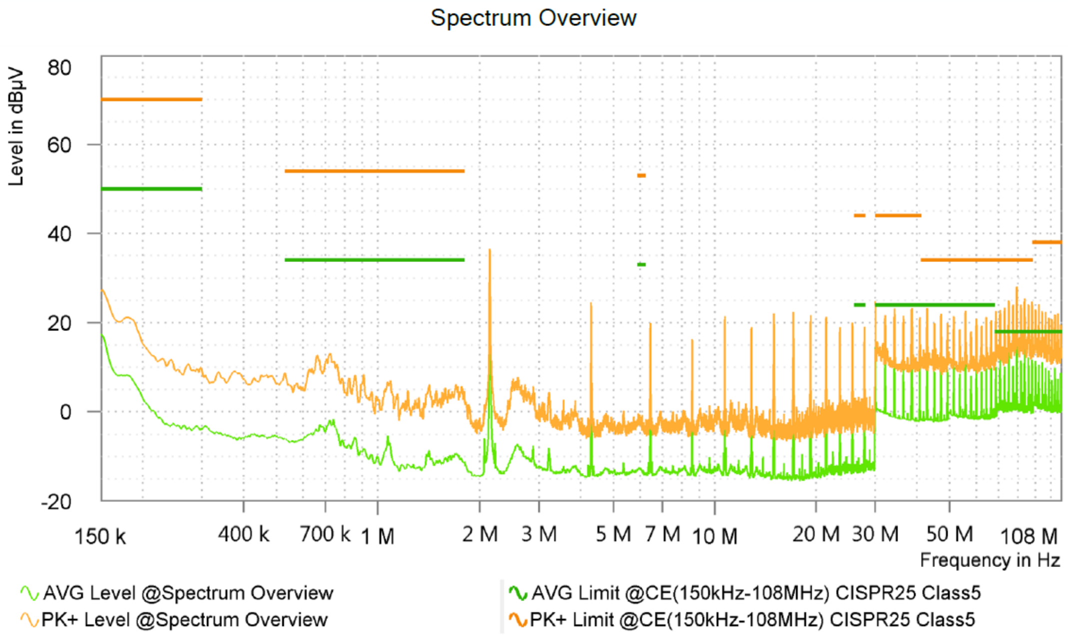
Note: Applying a magnetic ring (ZCAT-3035) helps to increase the output impedance.

Experiment Verification: EMI with a Magnetic Ring

CE, Fsw = 2.1MHz, Original

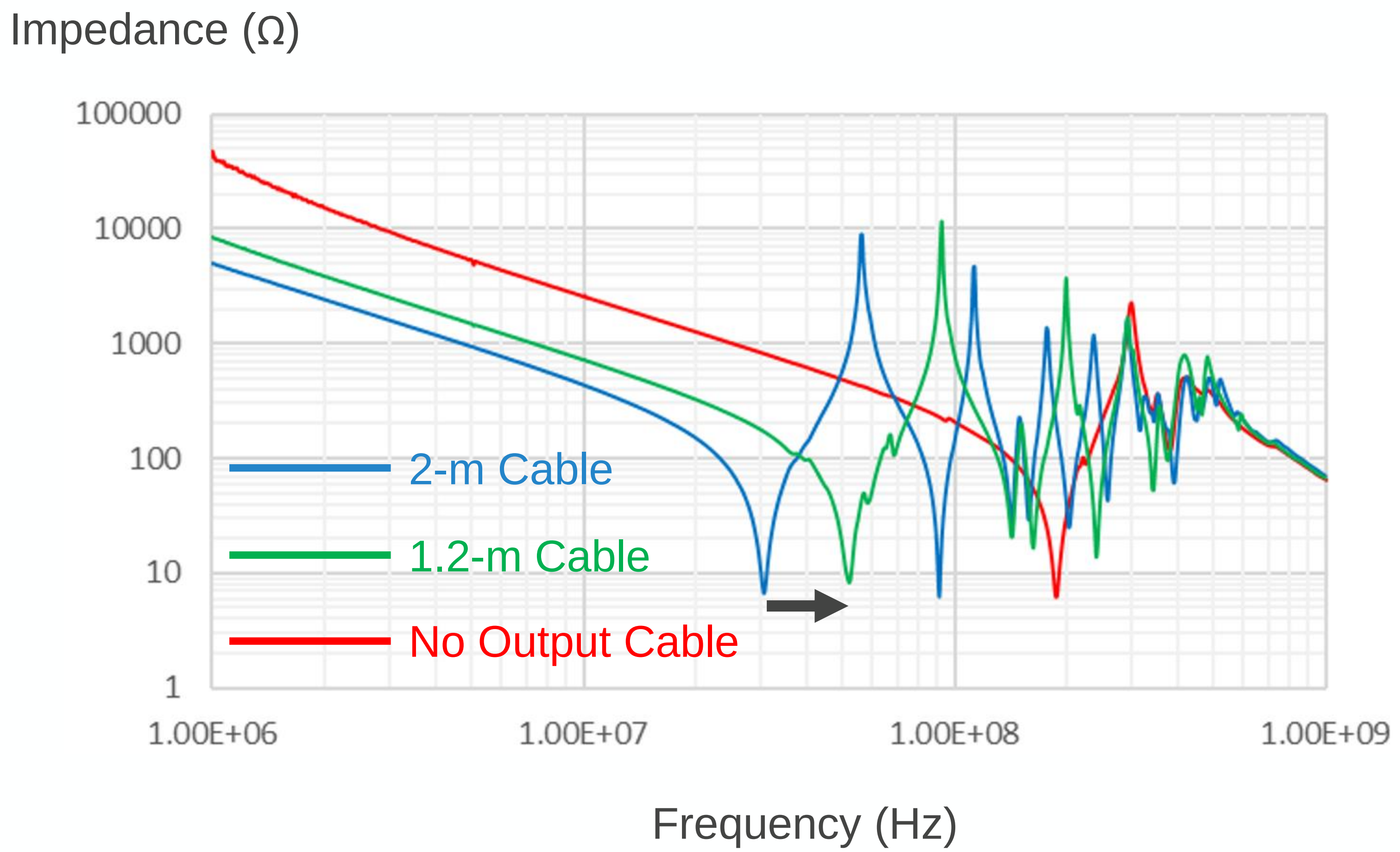


CE, Fsw = 2.1MHz, with magnetic ring



Note: Applying a magnetic ring (ZCAT-3035) helps to change the output impedance, which helps to reduce the spikes. And the CE meets the standard in this case.

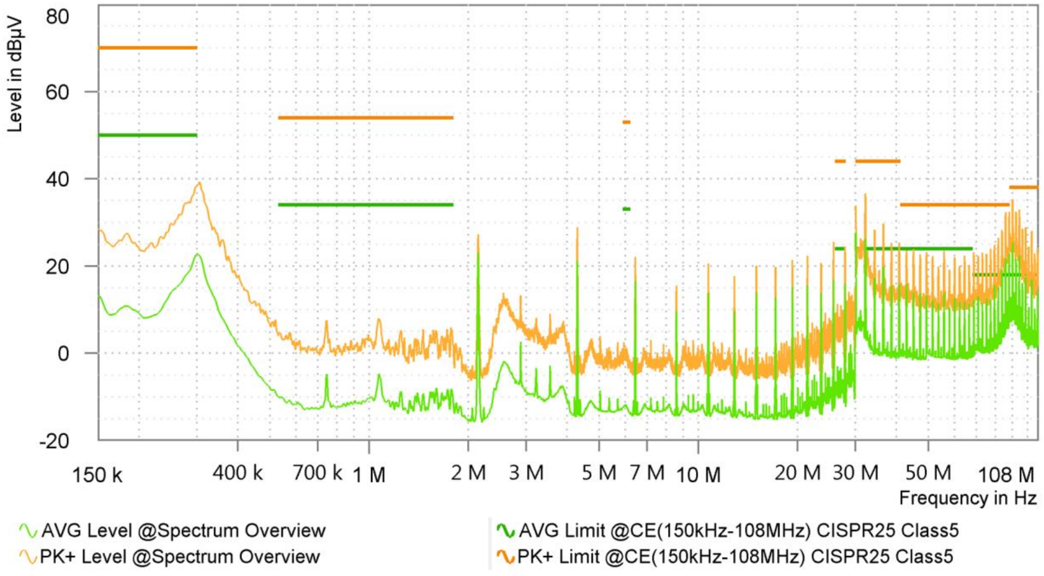
Impedance of Output Cable with Different Length



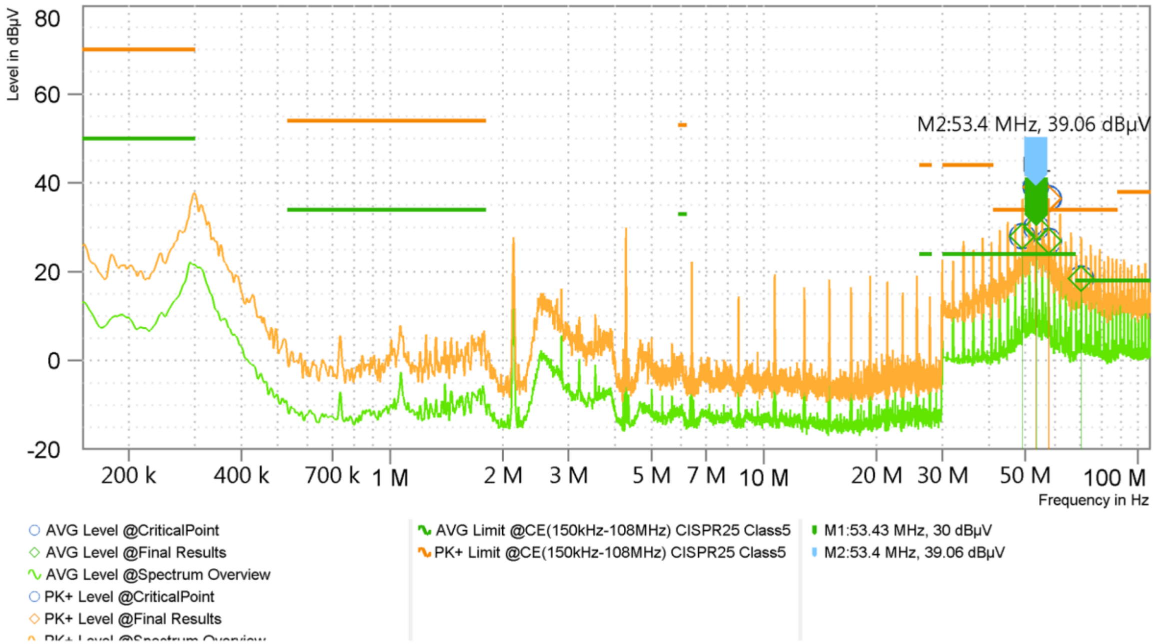
Note: With the 1.2-m cable, the resonance frequency moves to 53MHz, which can be predicted with the above mentioned model. The second resonance is beyond 108MHz, therefore it doesn't show up in the spectrum.

Change the Cable Length to Reduce EMI

CE, Fsw = 2.2MHz, 2m cable



CE, Fsw = 2.2MHz, 1.2m cable

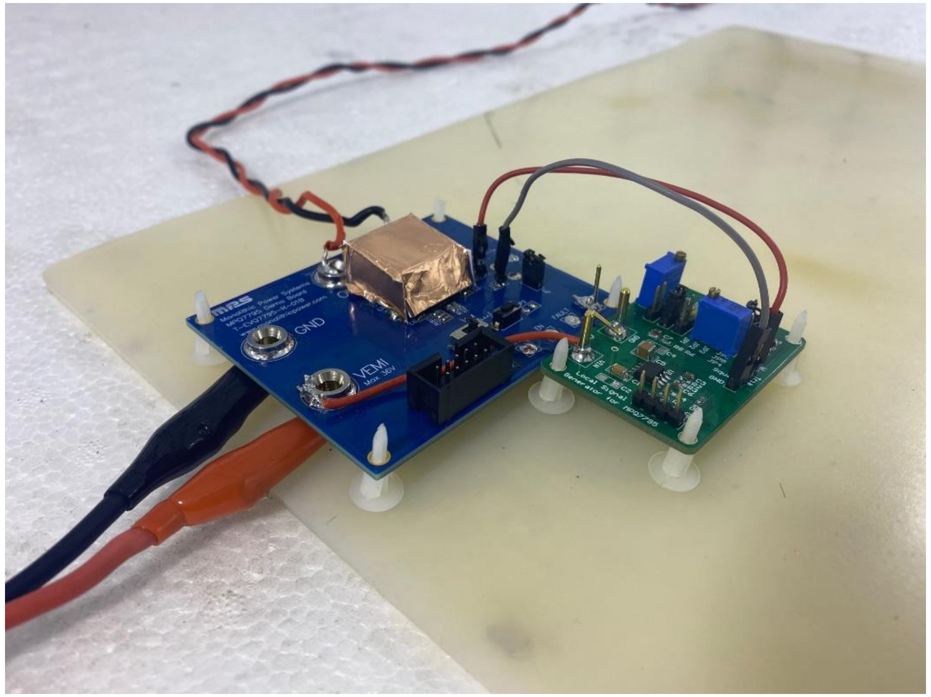


Note: With the 1.2-m cable, the resonance frequency changes to 53MHz, which can be predicted with the above mentioned model. The second resonance is beyond 108MHz, therefore it doesn’t show up in the spectrum.

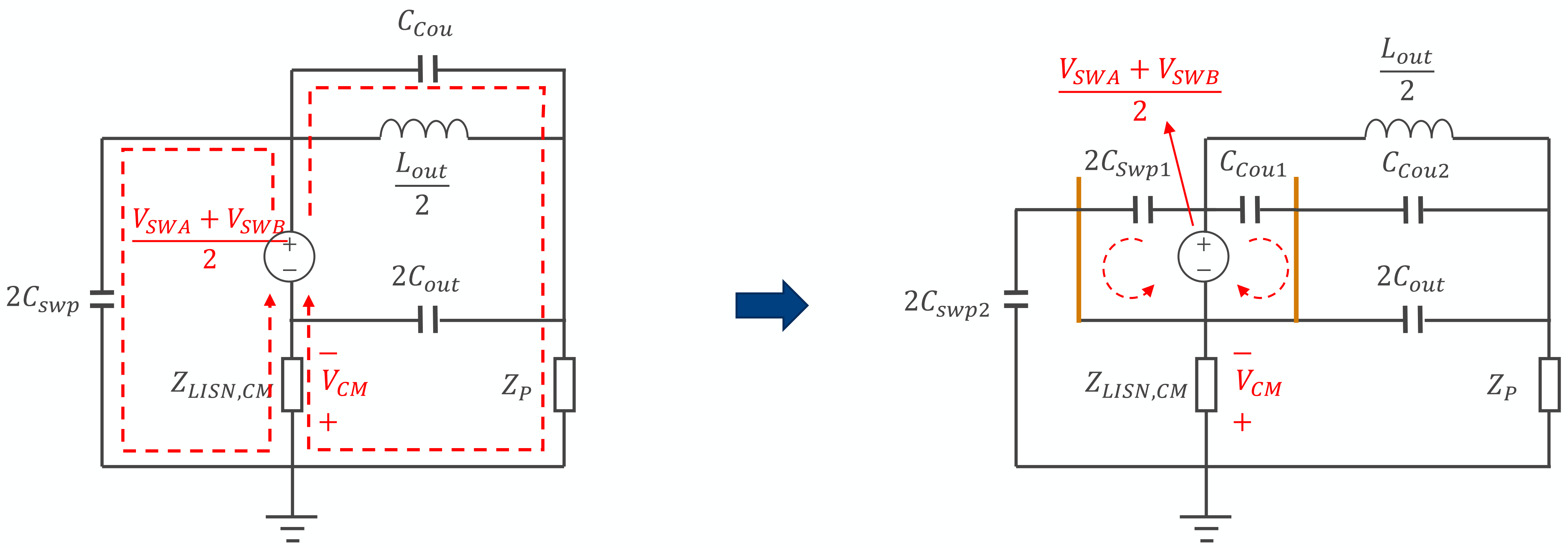
Shielding Technique in HF Noise Reduction

Apply a shielding, grounded to the GND.

Shielding the board helps to reduce the near field couplings from the board to the output cable.

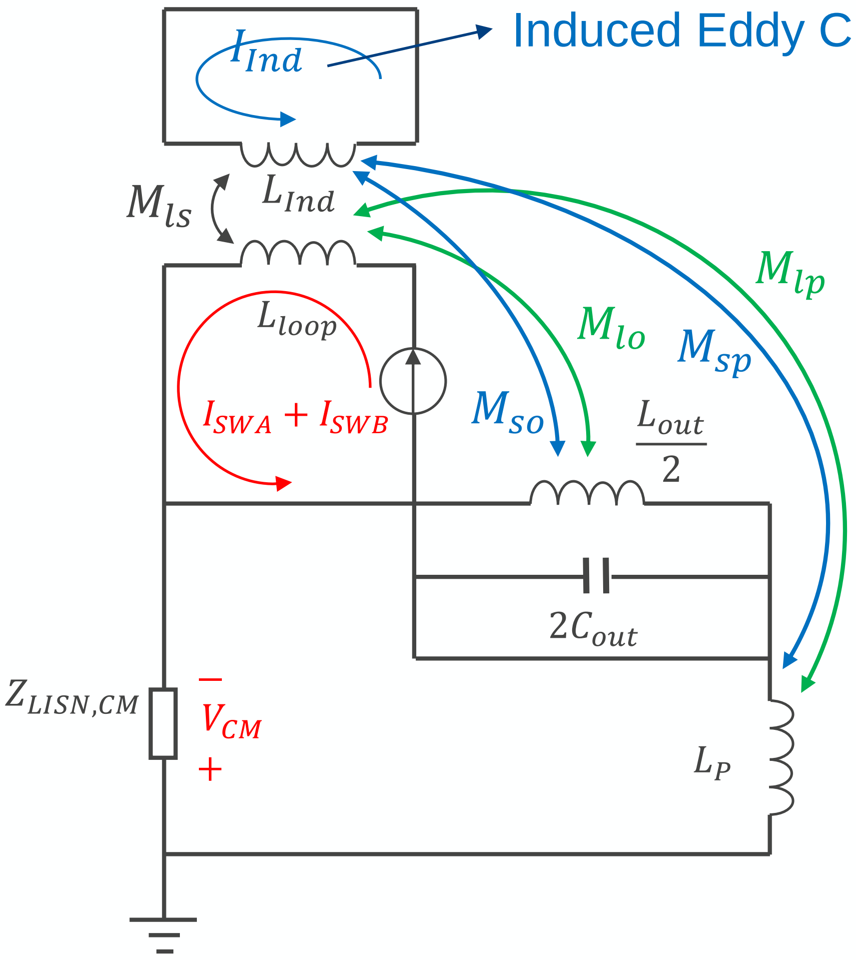


Shielding Model for Capacitive Coupling



Note: With a grounded shielding, the previous C_{Cou} turns into C_{Cou1} and C_{Cou2}. The noise flowing through C_{Cou1} does not contribute the CM noise, while C_{Cou1} can be seen as parallel to C_{out}, which helps to reduce the CM noise. The analysis of C_{swp} is similar.

Shielding Model for Inductive Coupling



Assumptions:

(1) Shielding is well-coupled

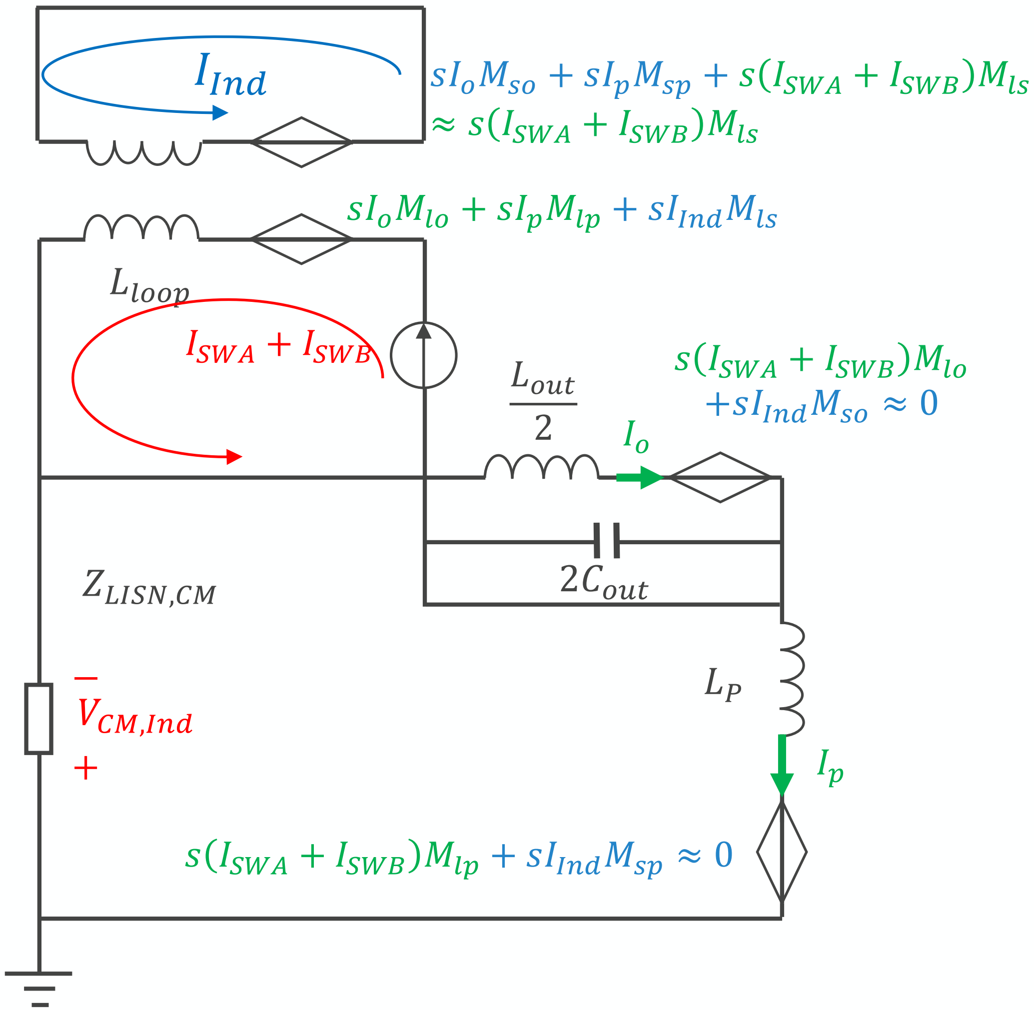
$$M_{ls} \approx L_{Loop} \approx L_{Ind}$$

$$M_{lp} \approx M_{sp}$$

$$M_{lo} \approx M_{so}$$

(2) Shielding's resistance can be ignored (HF)

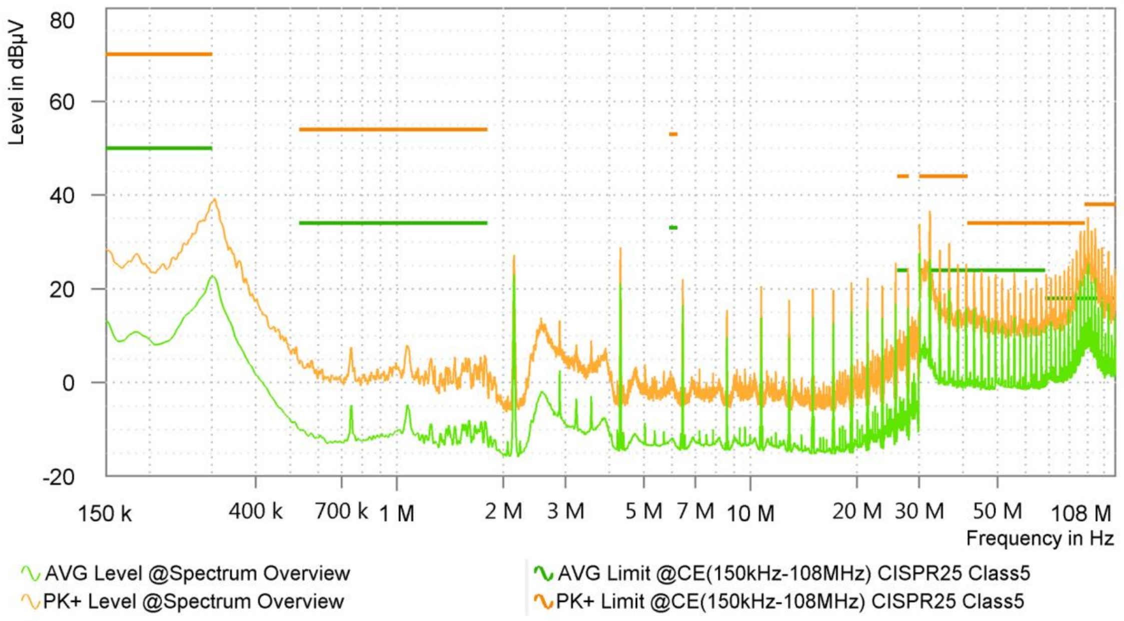
$$I_{Ind} \approx -(I_{SWA} + I_{SWB})$$



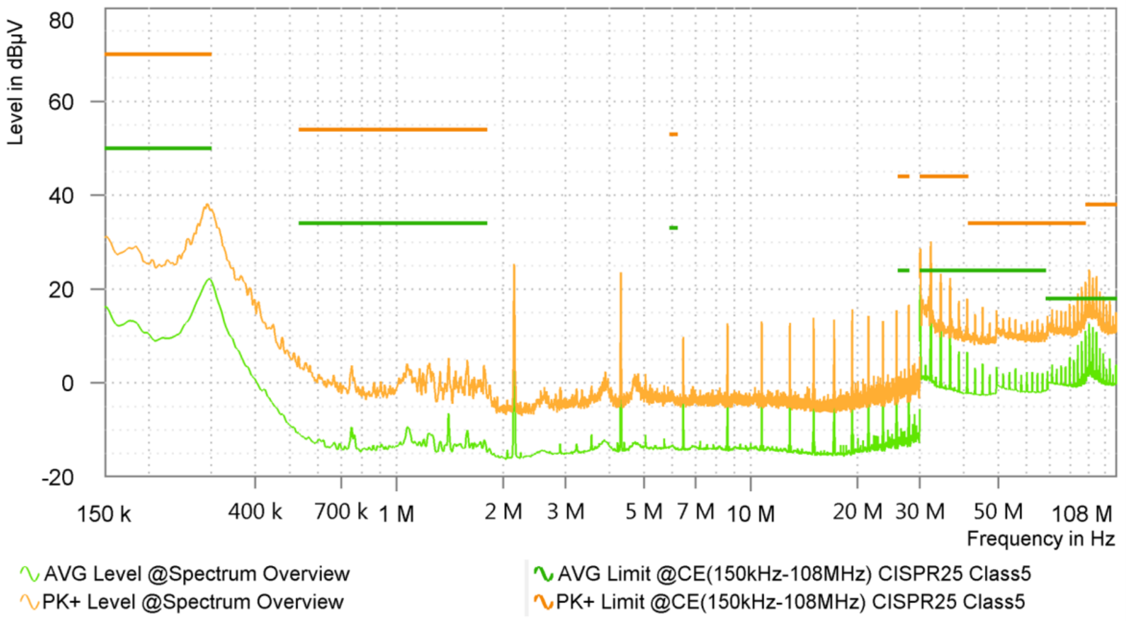
Note: Ideally, the inductive coupling is eliminated with a complete shielding, and there is no induced CM EMI noise.

Experiment Verification on Shielding

CE, Fsw = 2.2MHz, No Shielding



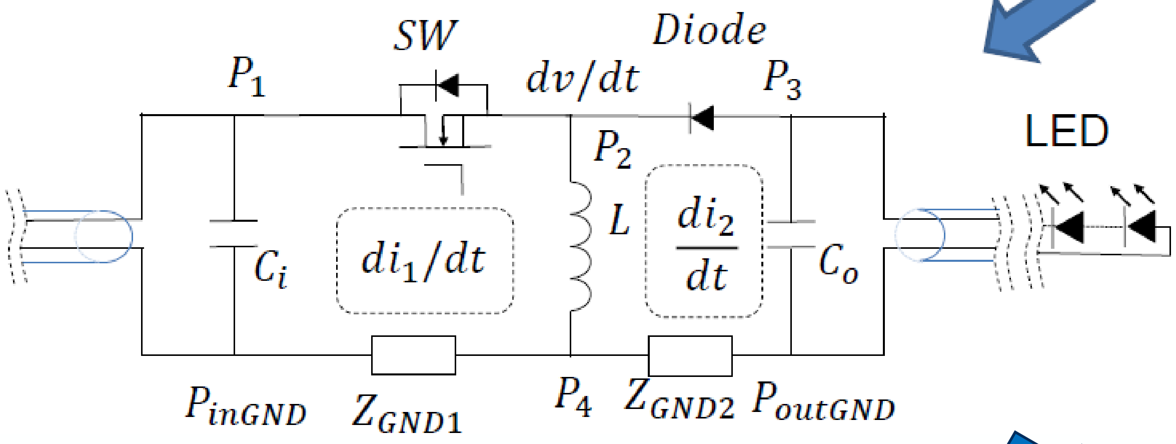
CE, Fsw = 2.2MHz, with Shielding



Note: Applying a shielding also helps to reduce the CE noise, especially at high frequency (76-108MHz). The EMI noise meets CISPR-25 with >6dB margin.

Another Case: MPQ7200

Buck-Boost Topology



Z_{GND} is important in noise analysis.

MPQ7200

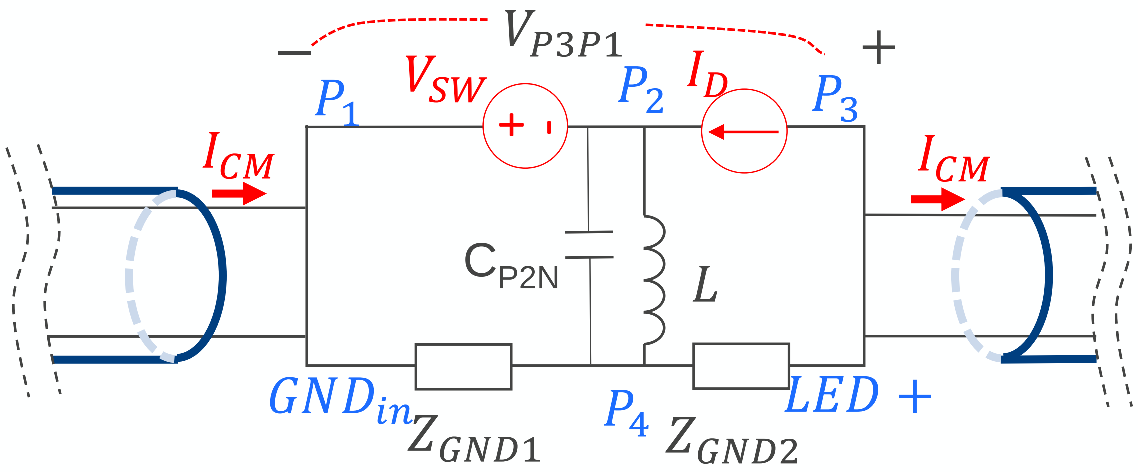
42V, 1.2A Buck-boost or 3A Buck Synchronous LED Driver AEC-Q100 Qualified

DESCRIPTION

The MPQ7200 is a high-frequency, constant current buck-boost LED driver with integrated power MOSFETs. It offers a very compact solution to achieve a 1.2A continuous output current with excellent load and line regulation over a wide input supply range. The MPQ7200 can also be configured to buck mode to provide up to 3A constant load current.

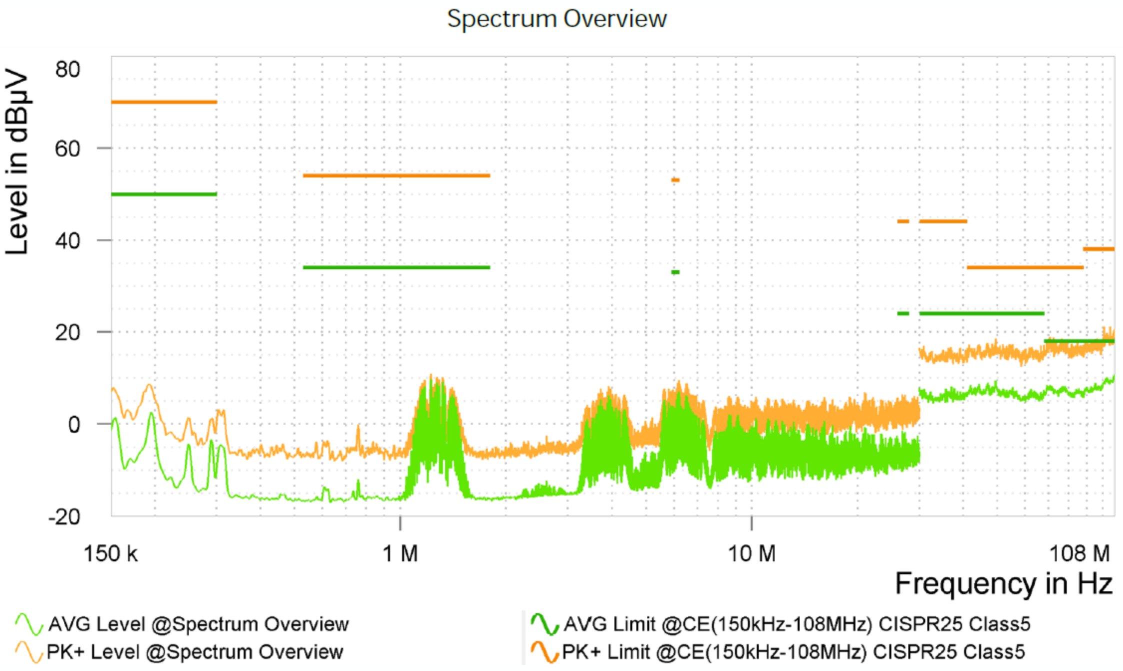
FEATURES

- Wide 6V-to-42V Operating Input Range
- 44mΩ/40mΩ Low $R_{DS(ON)}$ Internal Power MOSFETs
- High-Efficiency Synchronous Mode Operation
- Configurable 1.2A buck-boost or 3A buck
- Programmable LED current
- Default 2.3MHz Switching Frequency for

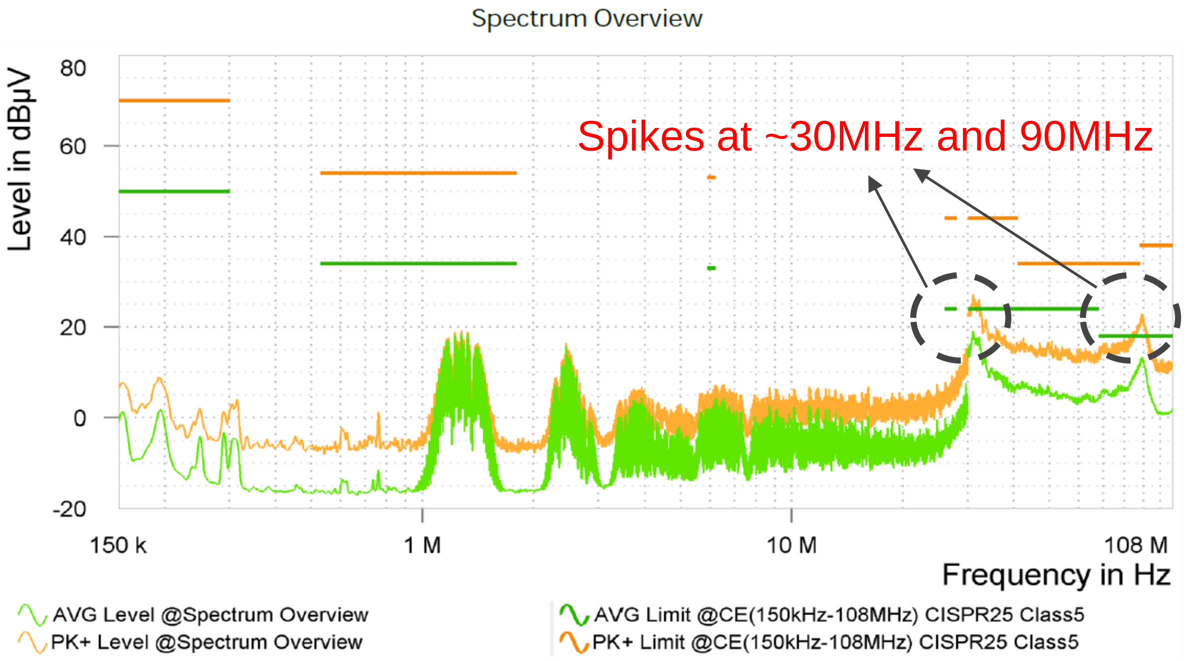


CE EMI with and without 2-m Output Cable

No output cable



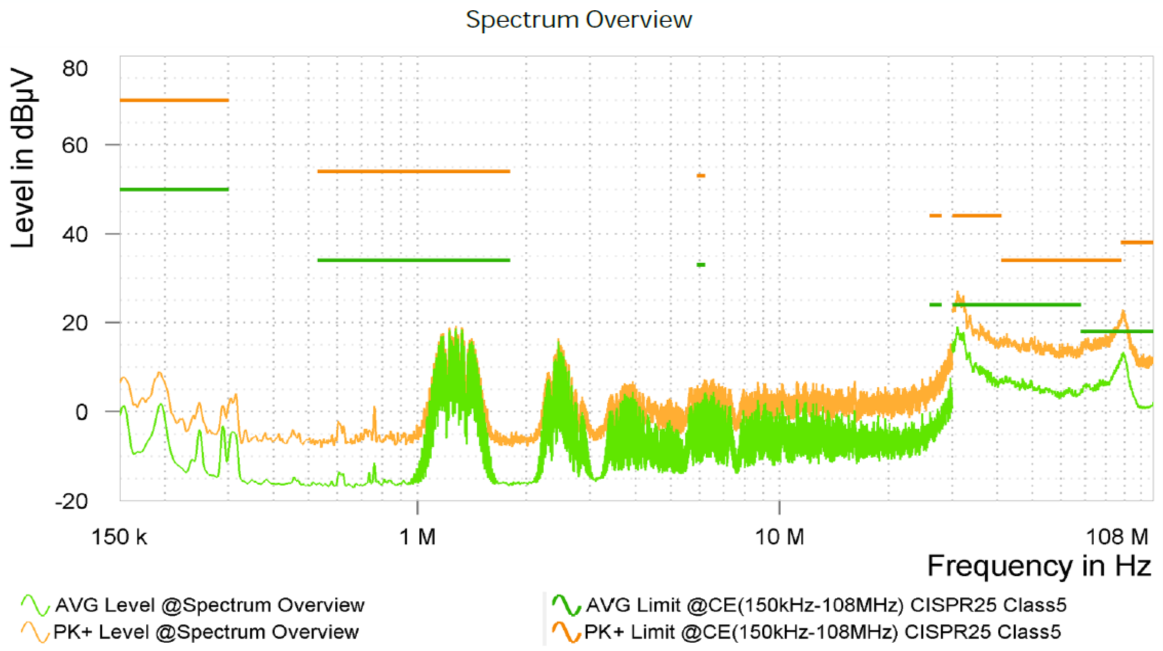
2m output cable



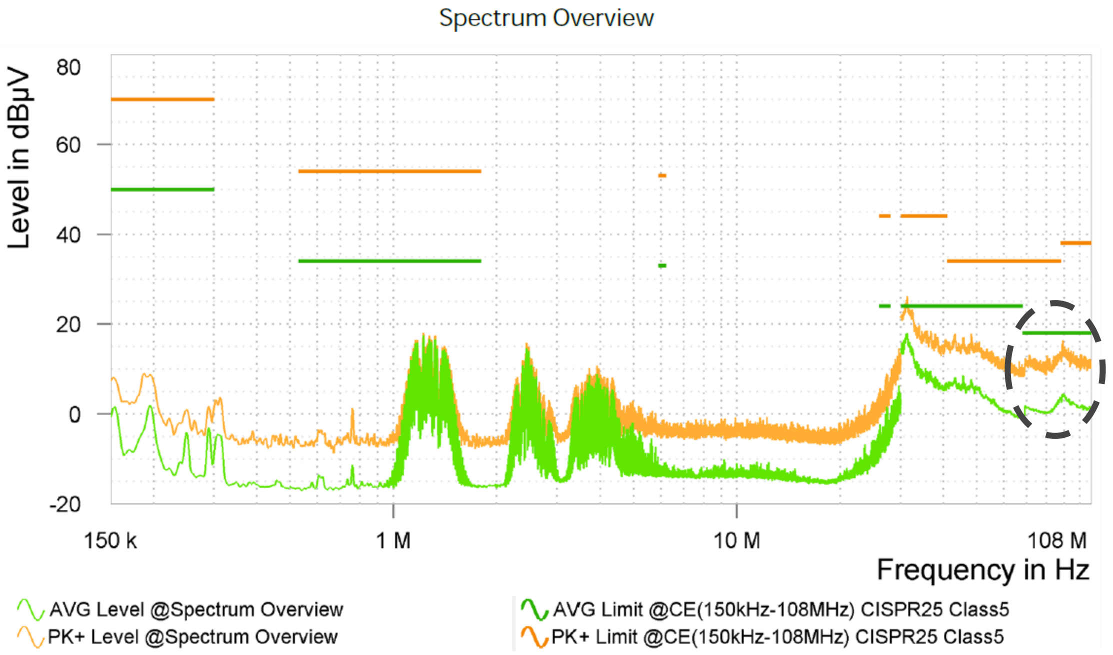
Note: With 2-m output cable, the spike occurs at ~30MHz and 90MHz, identical to the previous results.

Verify Shielding on MPQ7200

2m output cable, no shielding



2m output cable, with shielding



Note: With an additional shielding, the EMI noise at 90MHz reduces by 10dB.

Conclusion

- 1. When measuring the conducted EMI with a long output cable, a CM EMI noise with undesired spikes occurs.
- 2. A CM noise model with near field coupling is proposed to analyze the noise.
- 3. The impedance of the output cable can be modelled with transmission line theory. The spikes occurs at frequencies where the corresponding $\frac{1}{4}\lambda$ or $\frac{3}{4}\lambda$ equals to the cable length.
- 4. Shielding and filtering helps to reduce the EMI noise. Changing the cable length also helps to improve the EMI by moving the spike to bands with higher limit.
- 5. The noise mechanism and reduction methods are applicable to general topologies.

Feedback

Thank you!

For more information:

[1] J. Yao, M. El-Sharkh, Y. Li, Z. Ma, S. Wang and Z. Luo, "Investigation of Radiated EMI in Non-isolated Power Converters with Power Cables in Automotive Applications," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 6957-6964.

[2] J. Yao, S. Wang and Z. Luo, "Near Field Coupling's Impact on Radiated EMI and Mitigation Techniques for Power Converters in Automotive Applications," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020, pp. 5882-5889.