# Conducted EMI Analysis and Mitigation in 48V Automotive

## Case Study Based on a 48V-12V DCDC Converter

48V汽车电子传导EMI分析与降噪：以一个
48V-12V DC/DC变换器为例

Speaker: Yiming Li

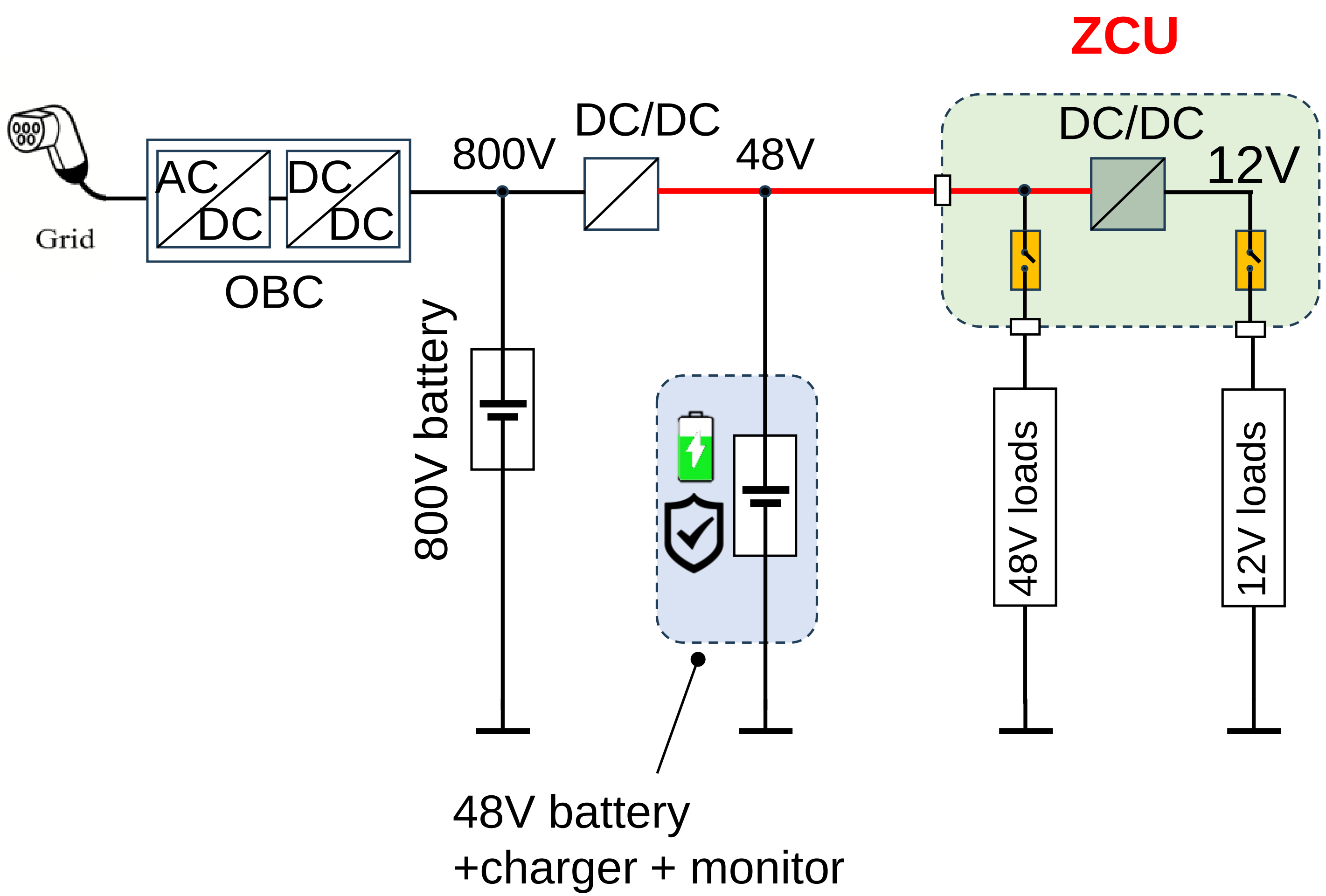
rev 20180504

# Agenda

- EMI challenge for 48V Automotive
- 48V LLC Introduction and Application
- Conducted EMI Noise Analysis for Various Cases
- Summary and Conclusion

# EMI Challenge for 48V Automotive

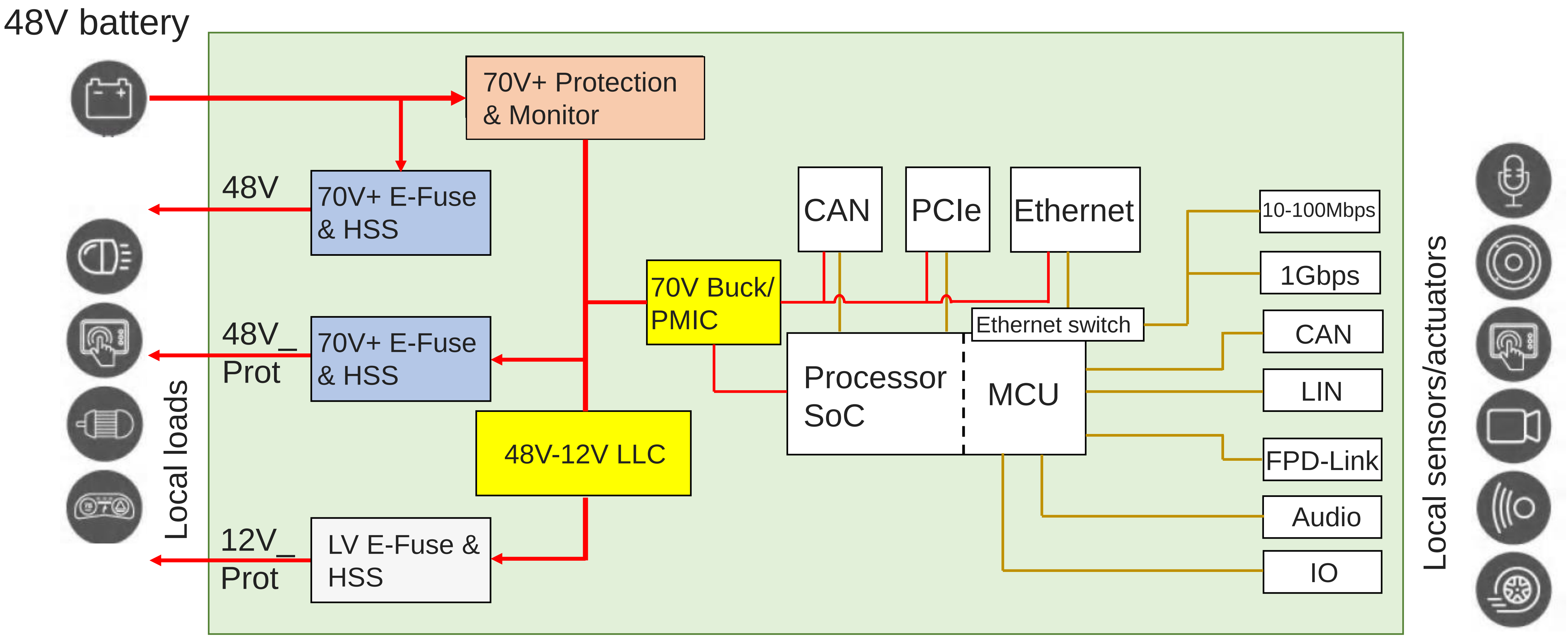
# Power Architecture: 48V Bus + local 48V->12V




Advantage:

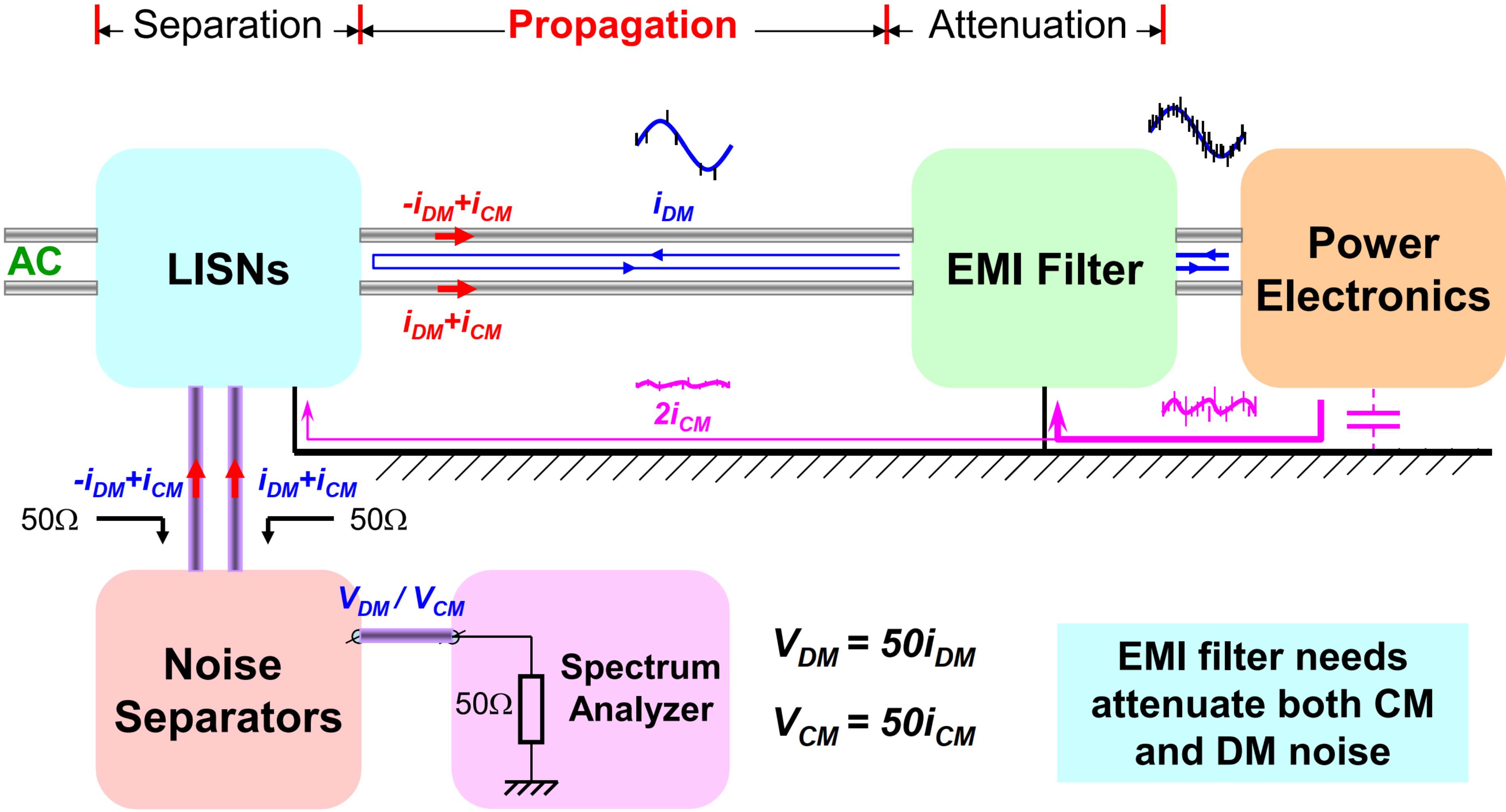
- 48V wire harness has best weight saving
- 12V Battery not required because:
  - 48V battery as a buffer for loads
  - HV battery charges 48V battery
- Easy to upgrade:
  in the future when more load move to 48V, only need to size the local 48V->12V DCDC w/o touching the architecture
- Good total Efficiency
- Low cost

# Architecture of Zonal Control Unit




Notes: 1. DC/DC input voltage increases from 12V to 48V.
2. An additional 48-12V DC-DC is applied for 12V power rail.

# Conducted EMI: Modeling and General Reduction Technique



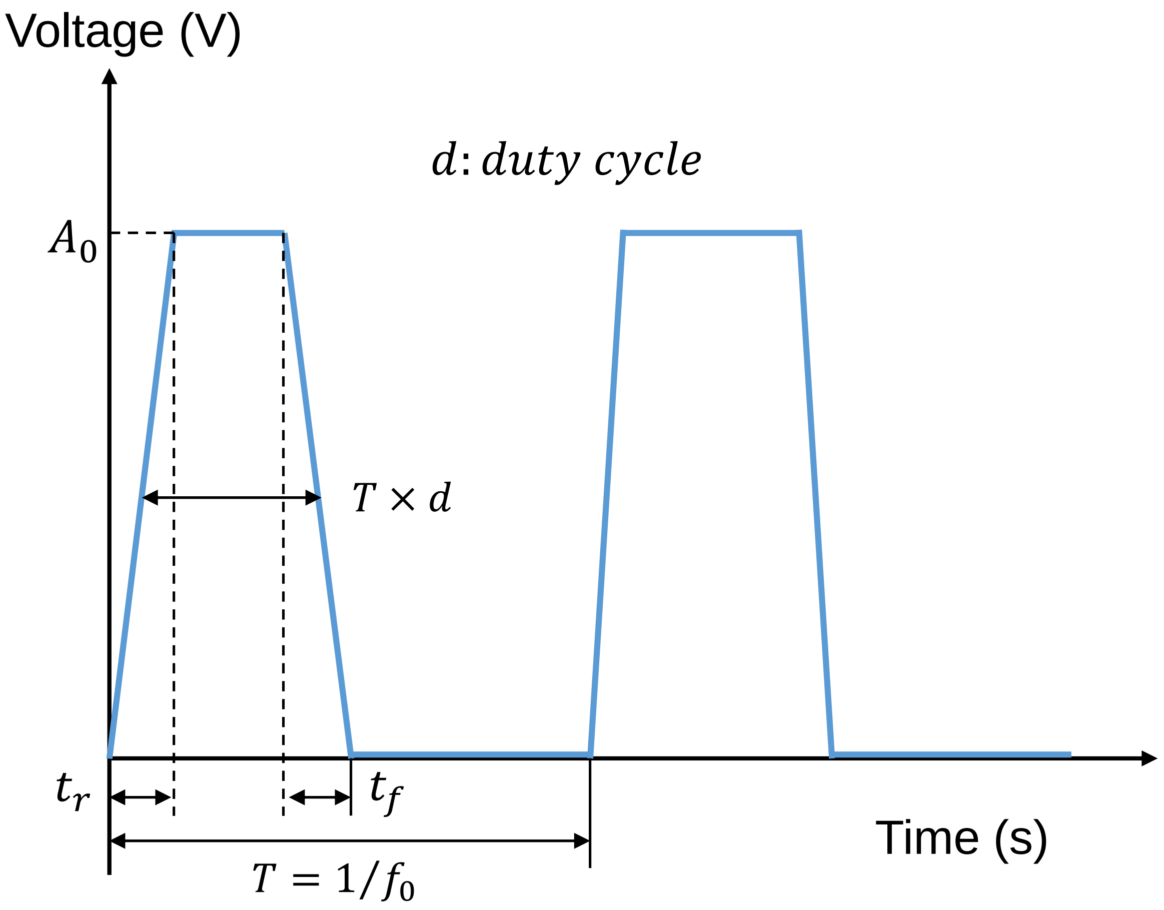

$V_{DM} = 50i_{DM}$

$V_{CM} = 50i_{CM}$

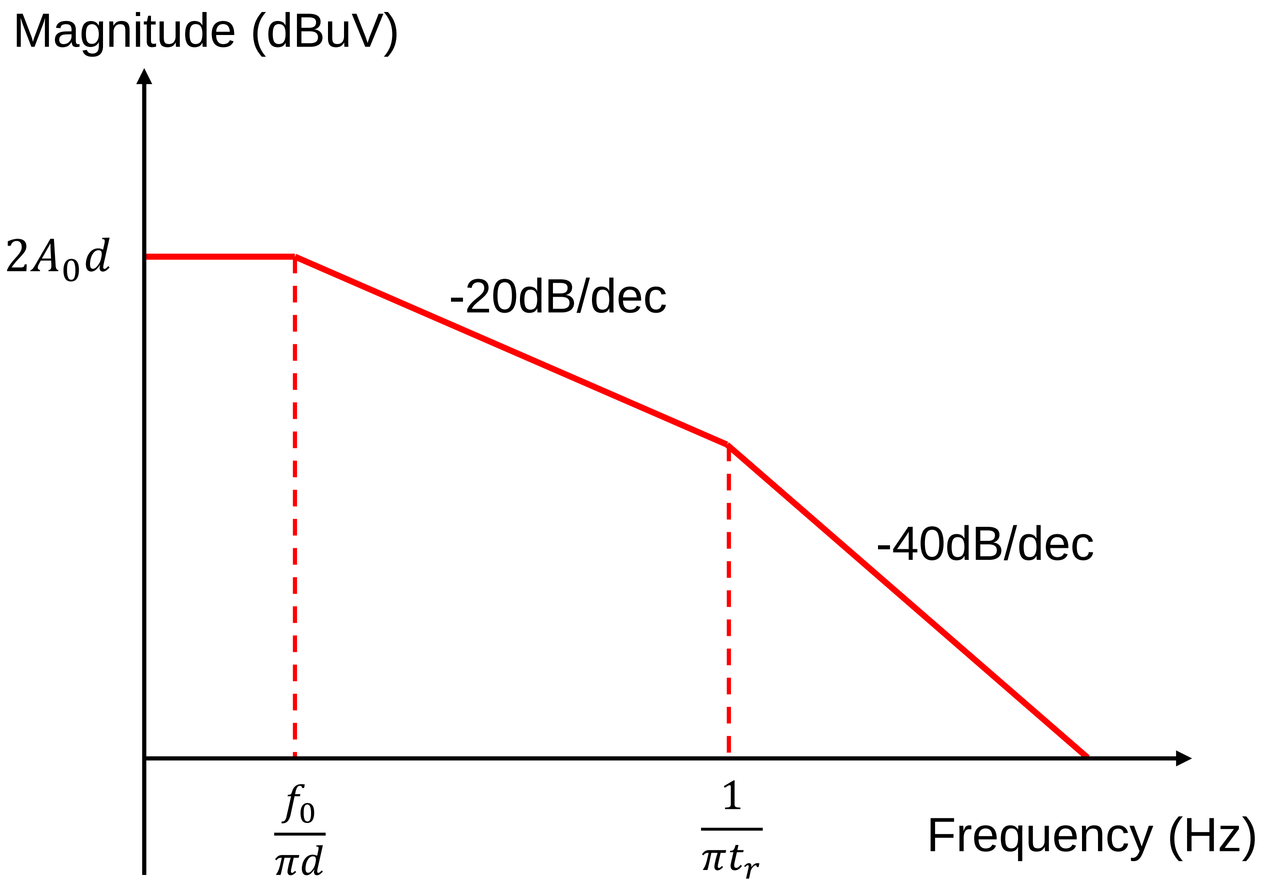
EMI filter needs attenuate both CM and DM noise

# Spectrum of a Trapezoidal Wave

**Time Domain**




**Frequency Domain**




$$f_0 = \frac{1}{T} = fundamental\ frequency$$

# Fourier Expression of a Trapezoidal Waveform

$A_n$ represent the magnitude of the nth order harmonic

$$A_n = 2A_0 \cdot d \cdot \left|\frac{\sin(n\pi d)}{n\pi d}\right| \left|\frac{\sin\left(\frac{n\pi t_r}{T}\right)}{\frac{n\pi t_r}{T}}\right|$$

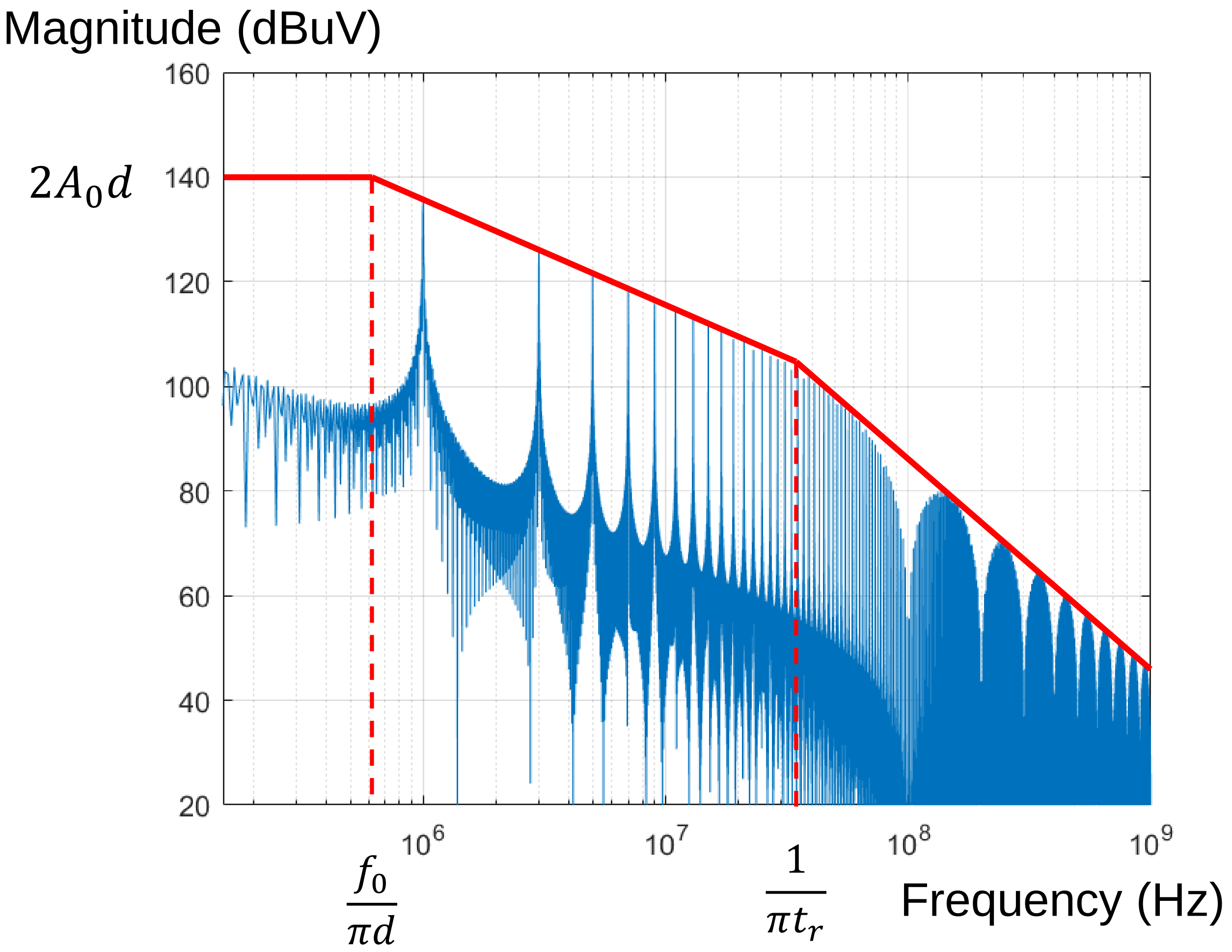
$$\frac{\sin(x)}{x} < 1 \; if \; x < 1$$

$$\frac{\sin(x)}{x} \le \frac{1}{x} \; if \; x \ge 1$$

$$V(f) = \begin{cases} 2A_0 d & f < \frac{f_0}{\pi d} \\ \frac{2A_0}{\pi}\left(\frac{f_0}{\boldsymbol{f}}\right) & \frac{f_0}{\pi d} < f < \frac{1}{\pi t_r} \\ \frac{2A_0}{\pi^2 t_r}\left(\frac{f_0}{\boldsymbol{f^2}}\right) & f > \frac{1}{\pi t_r} \end{cases}$$

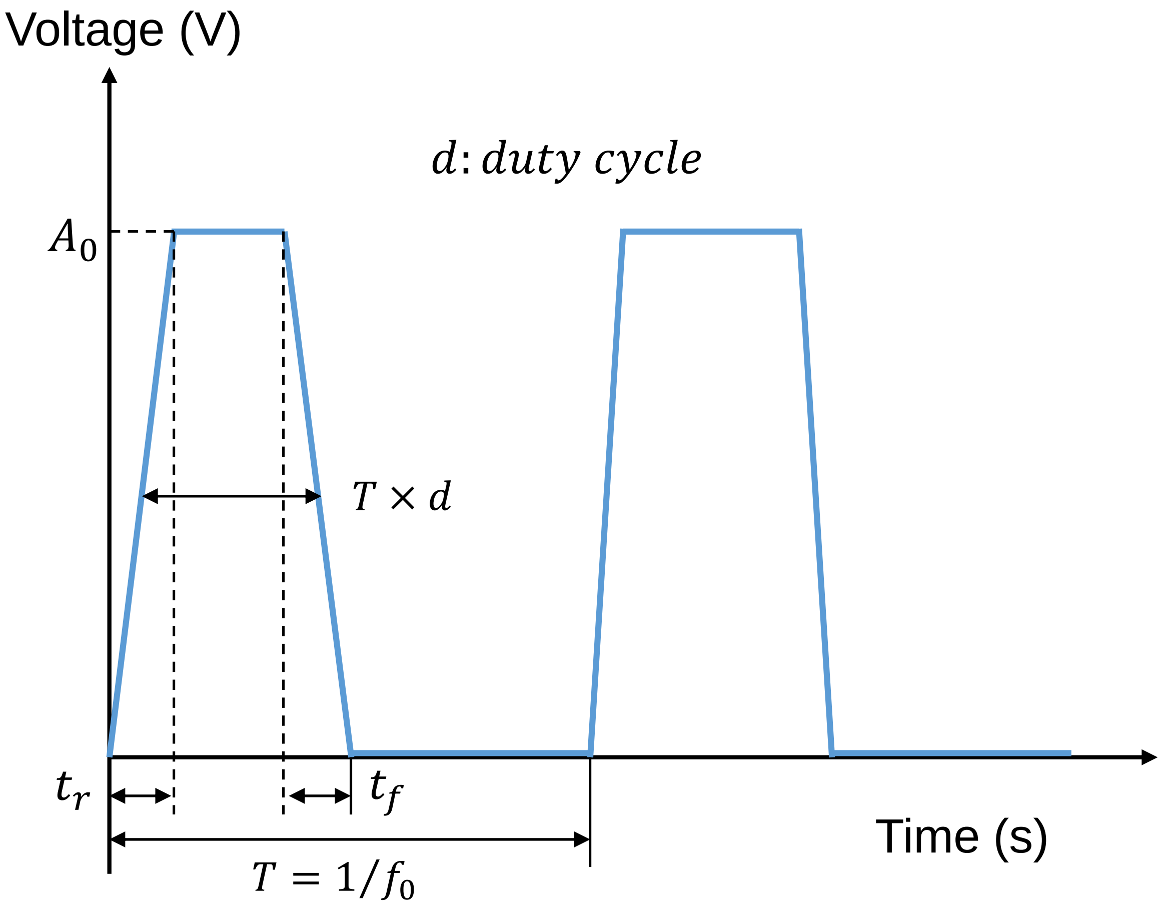
where $V(f)$ is the envelope of the spectrum

$A_0 = 10V, d = 0.5, f_0 = 1MHz, t_r = t_f = 10ns$



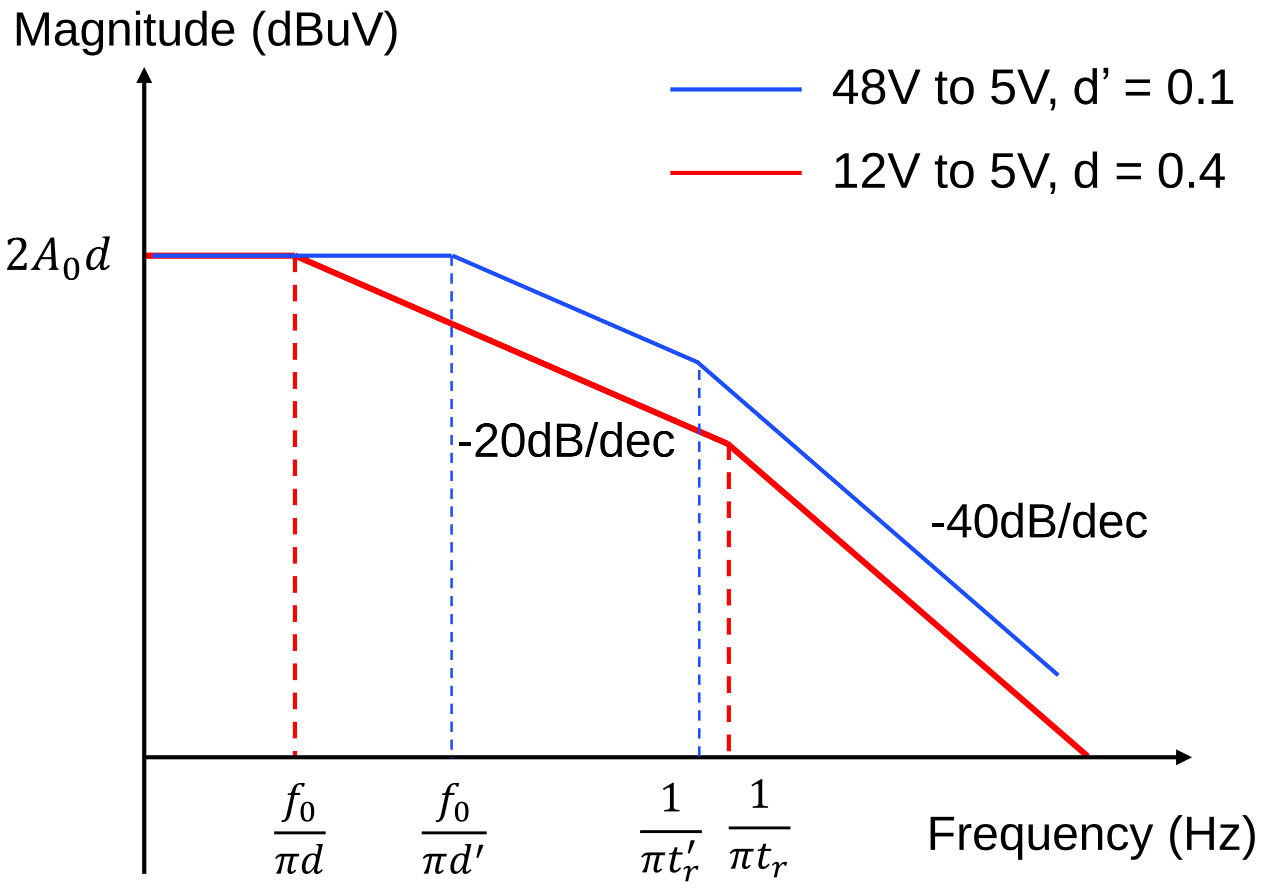
# Spectrum of a Trapezoidal Wave

**Time Domain**




$$f_0 = \frac{1}{T} = fundamental\ frequency$$

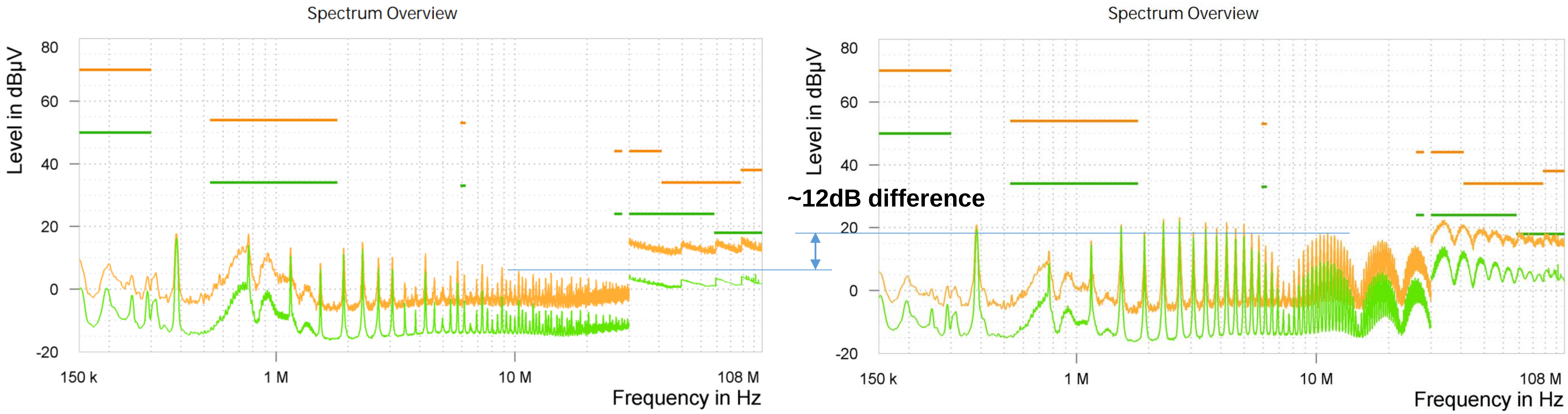
**Frequency Domain**



# EMI Comparison, CE, 150k-30MHz

12V-5V, CE

48V-5V, CE




<u>Note</u>:

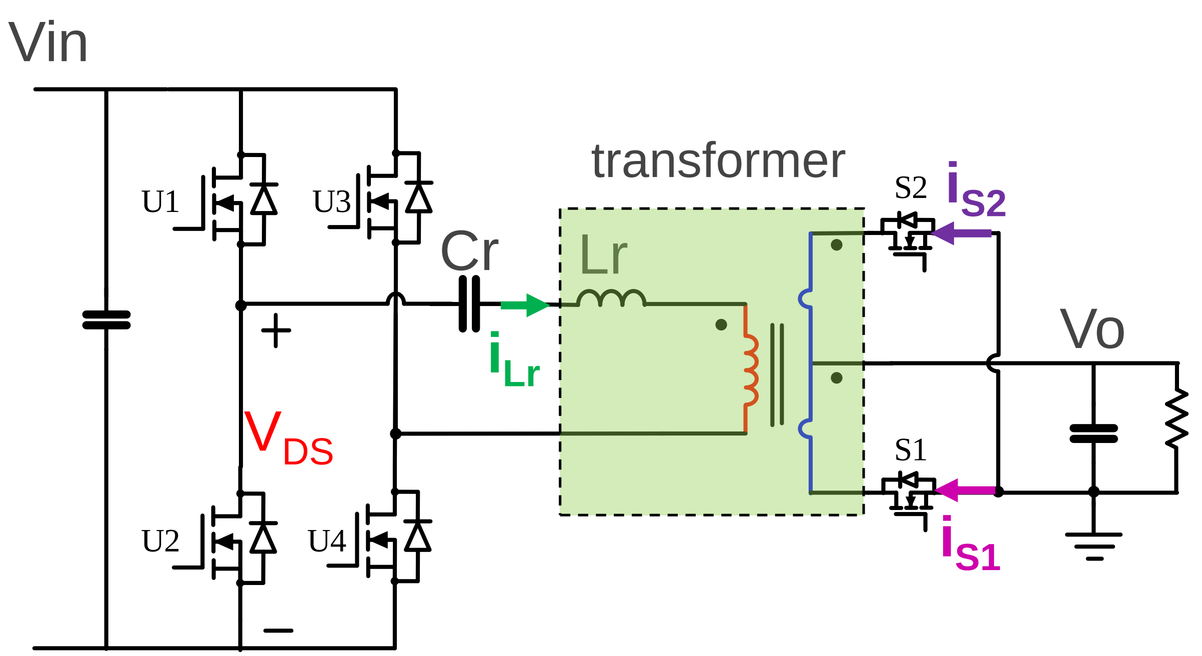
Fundamental Frequency: No too much difference.
After $3^{rd}$ harmonic: There is 12dB difference.

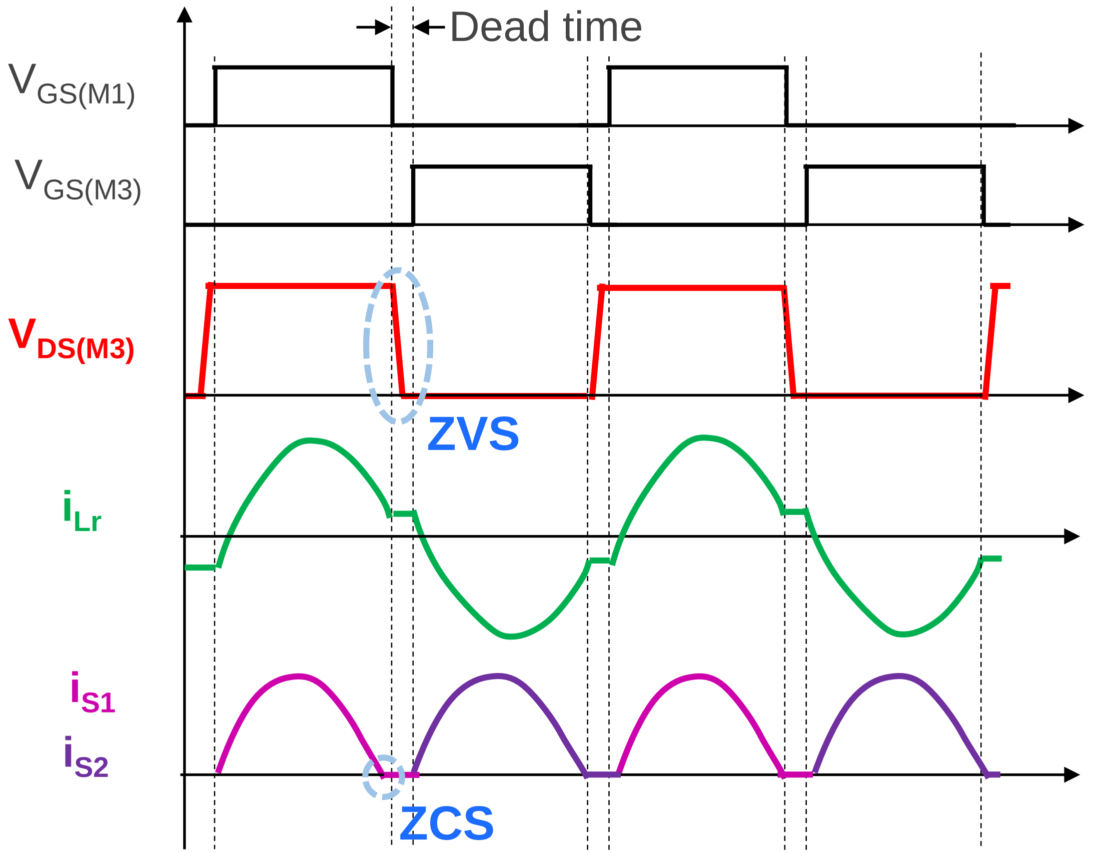
# LLC Introduction and Application

# LLC Benefits for 48V ZCU

- Soft-Switching mitigates EMI source
- Allow Bi-directional Operation
- Support high peak power with small magnetic component size
- Can be fully-isolated

# Soft Switching Characteristics of MPS LLC Topology

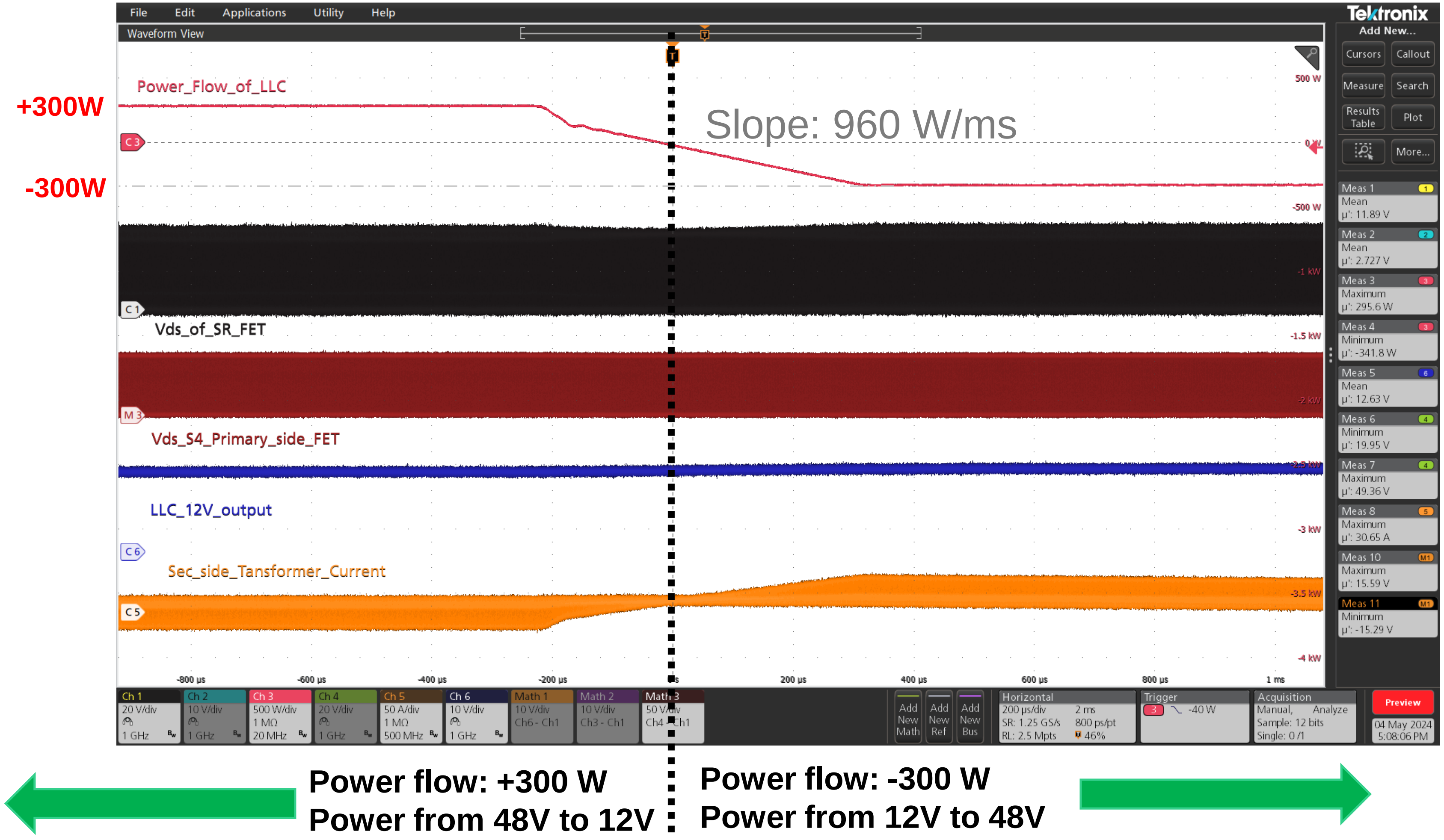



- **ZVS(zero-voltage switching) for all FETs**
  - **Transformer current discharge or charge Coss of FETs**
- **ZCS(zero-current switching) for all secondary FETs**

- **Benefits of soft switching:**
  - High switching frequency
  - High efficiency and high power density
  - Low EMI (No ringings)

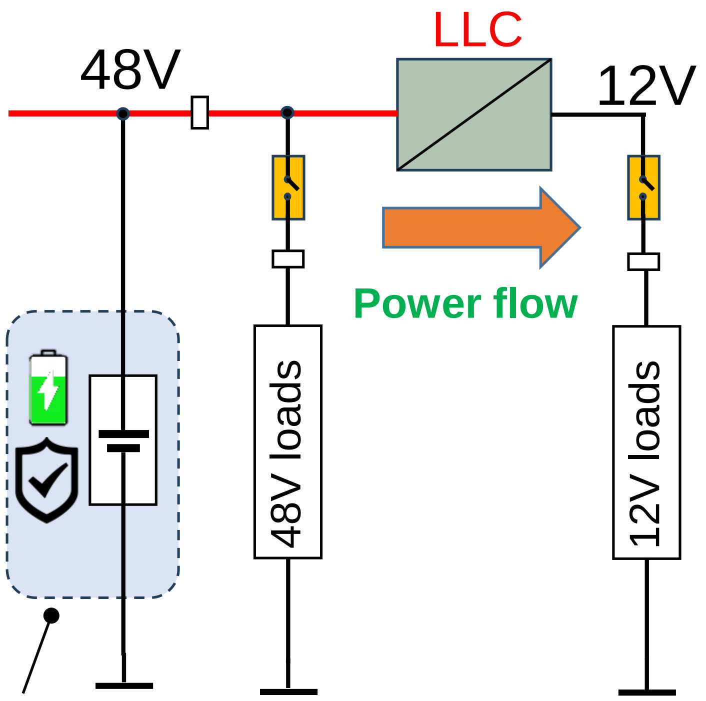
# High-Performance Bidirectional Operation




- Power flow changes from +300 W to -300W. Direction is reversed suddenly.
- 12-V output voltage is stable, and no over-voltage/under-voltage is observed

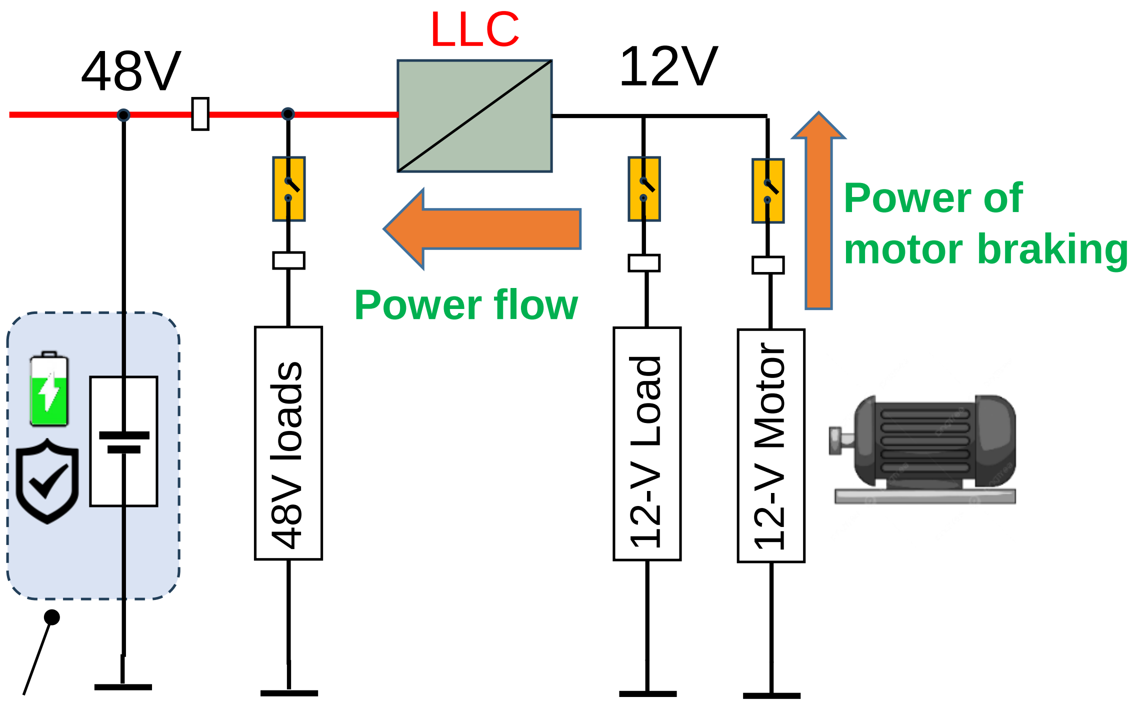
# Occasions for Bidirectional Power Conversion

**Normal Operation:**
Power source: 48-V battery.
Load: 12-V loads




48V battery +charger + monitor

**Occasion 1 of reverse power flow:**
12-V load such as motors return power to 48-V battery



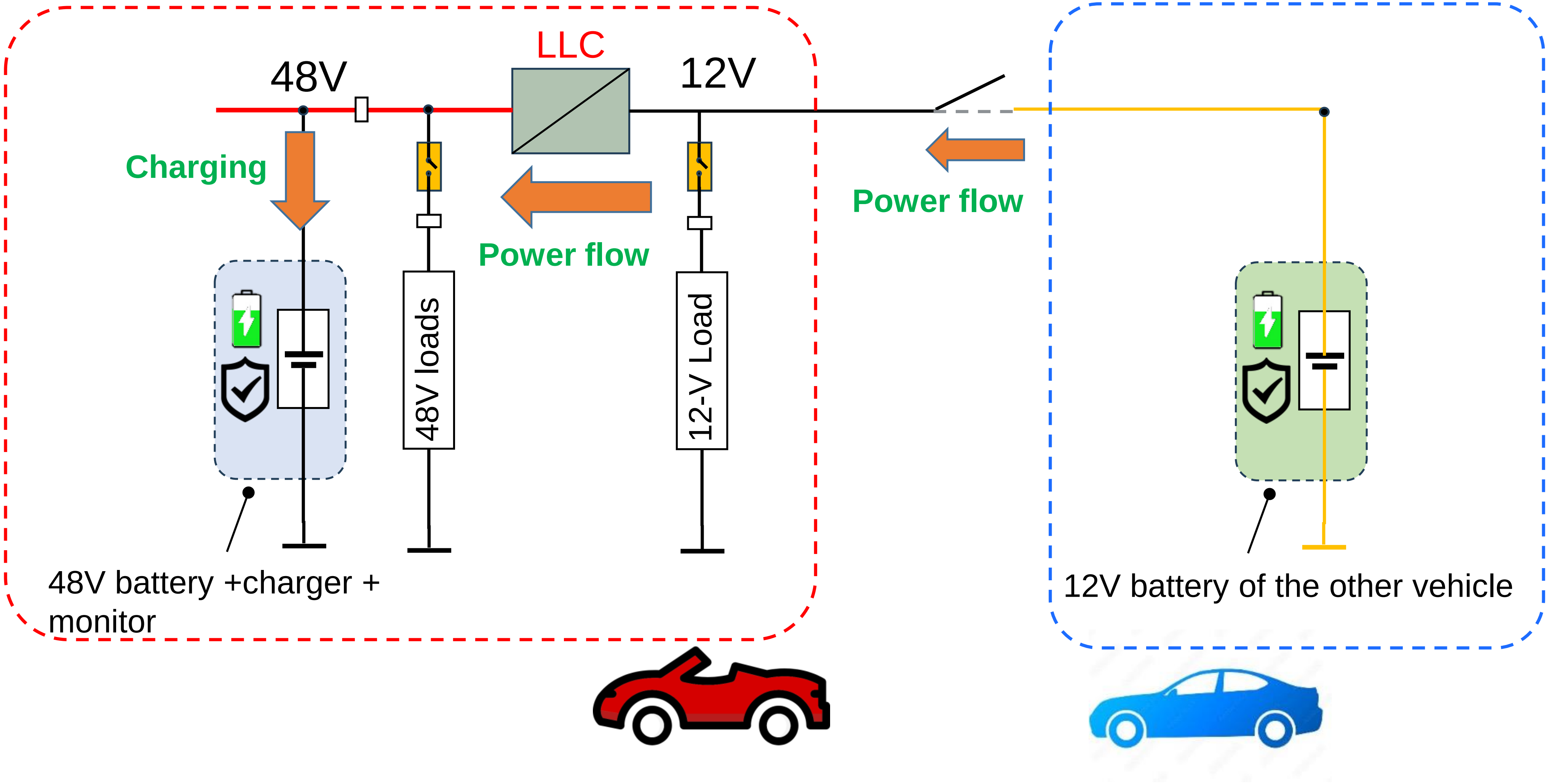

48V battery +charger + monitor

- If LLC cannot sink the power from 12-V loads, 12-V bus is charged, and over-voltage may happen.

# Occasions for Bidirectional Power Conversion

**Occasion 2 of reverse power flow:**

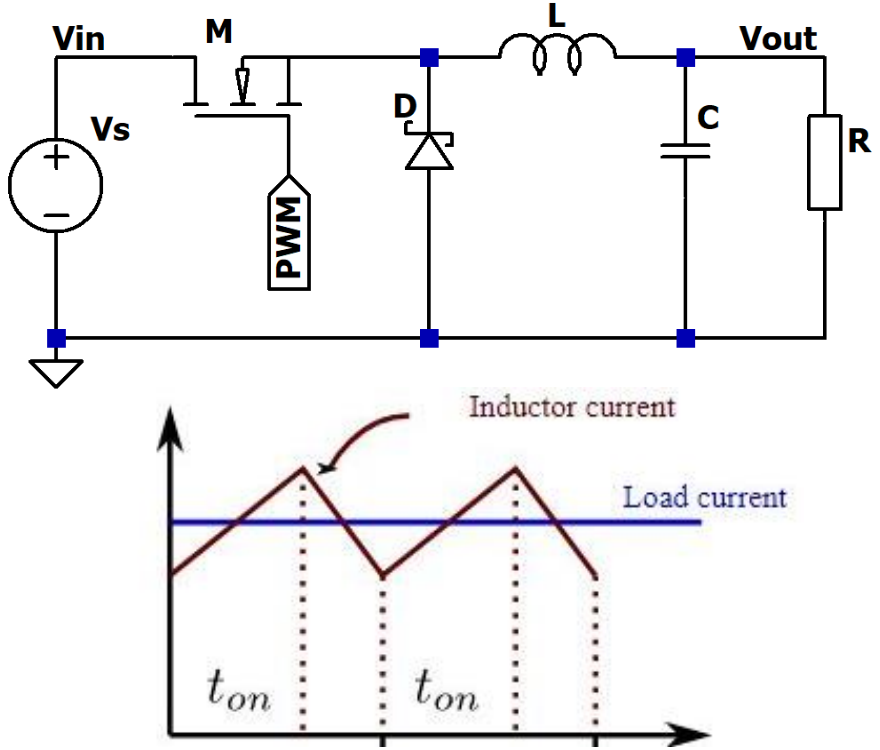
12-V battery of another vehicle used to jump-start 48-V battery



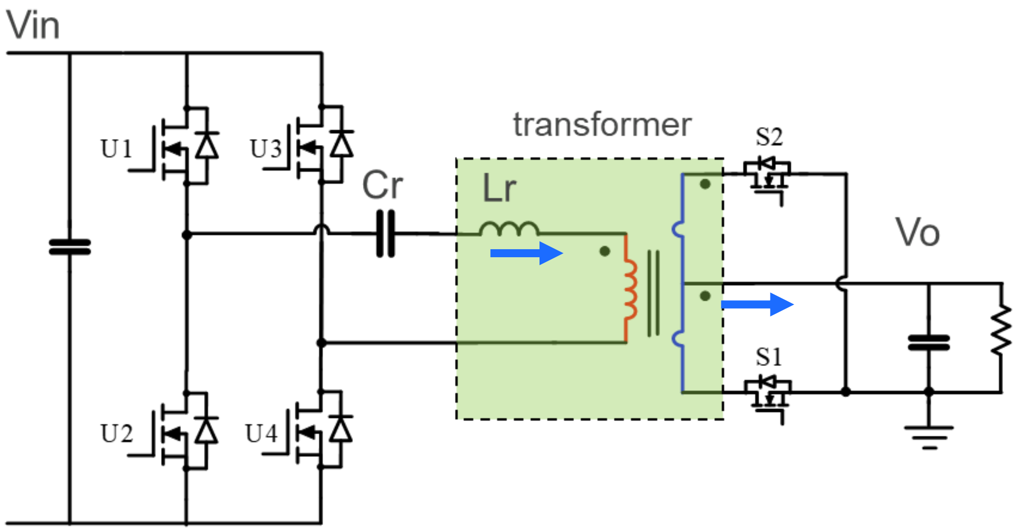

MPS

# Peak Power Capability

## Buck:




## LLC:




- Inductor stores energy
- Larger peak power requires larger magnetic core size to avoid inductor saturation

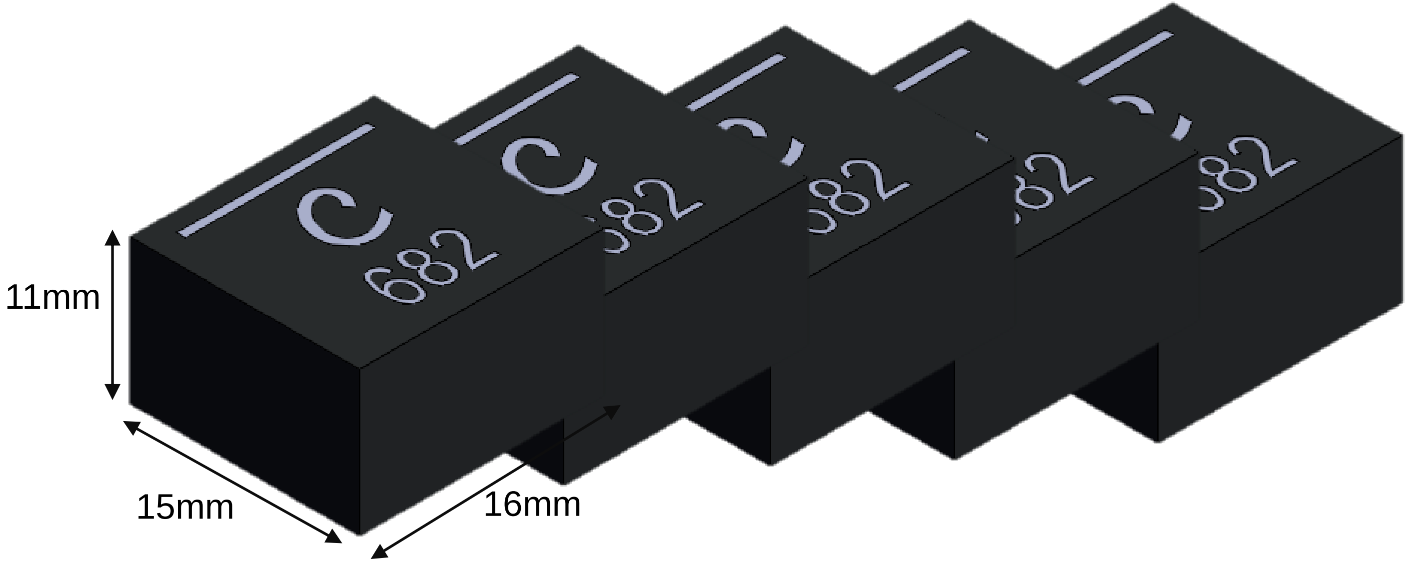
LLC uses transformer rather than inductor:

- Transformer doesn't store energy
- Peak power has no impact on magnetic core size

# Magnetic Size Comparison

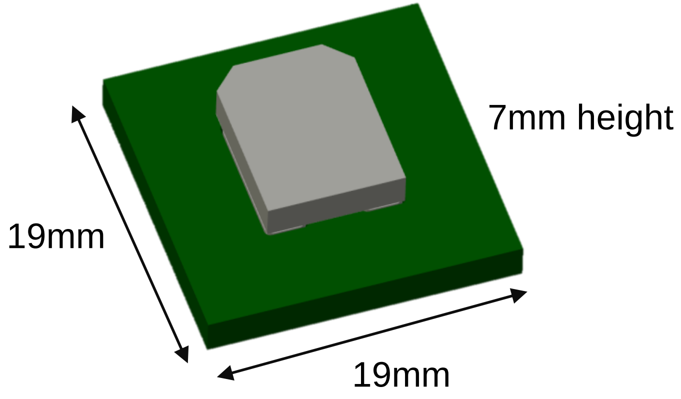
**With 150A peak current capability:**

**Buck:**




**1200mm2**

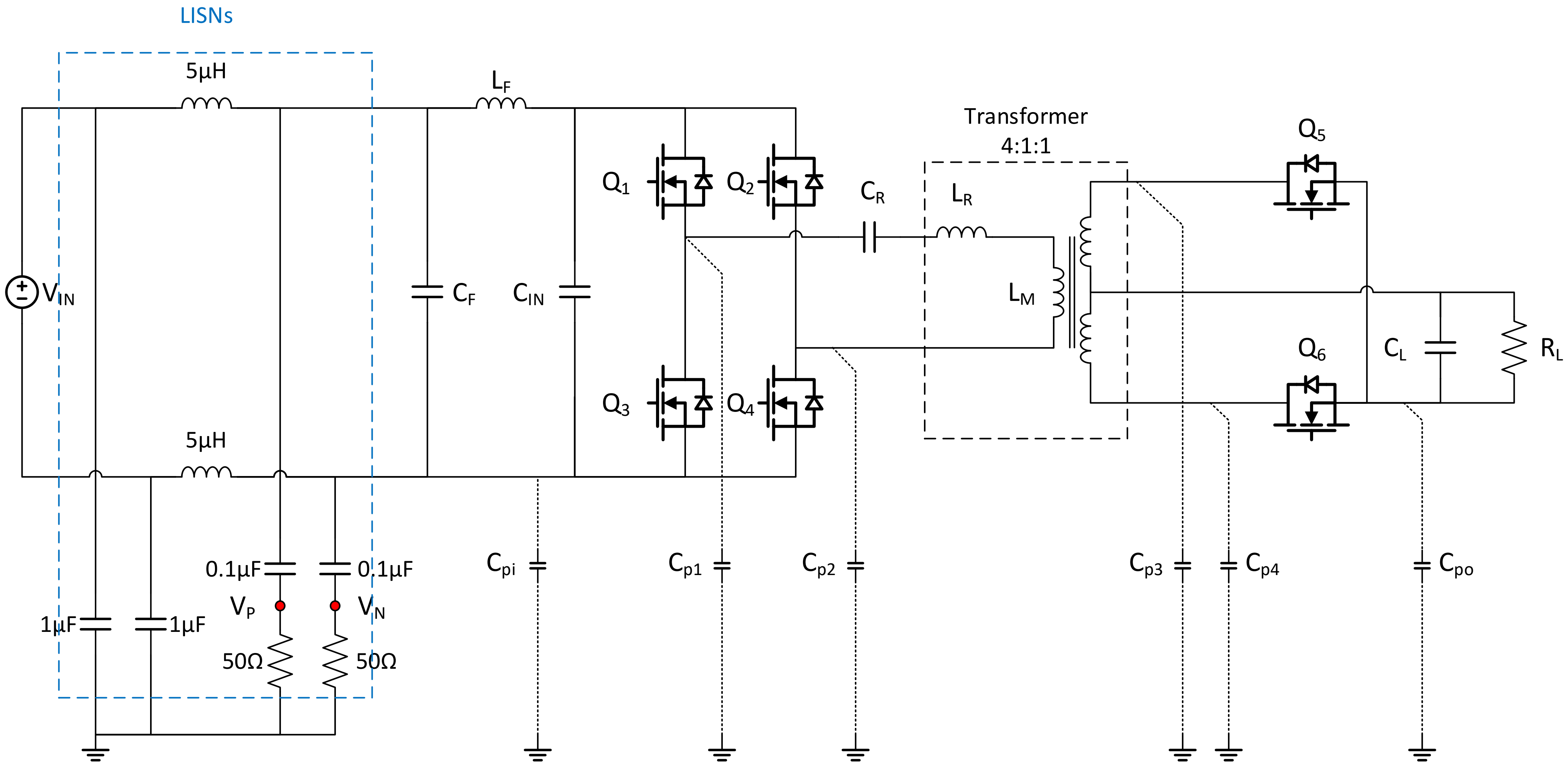
**MPS LLC:**



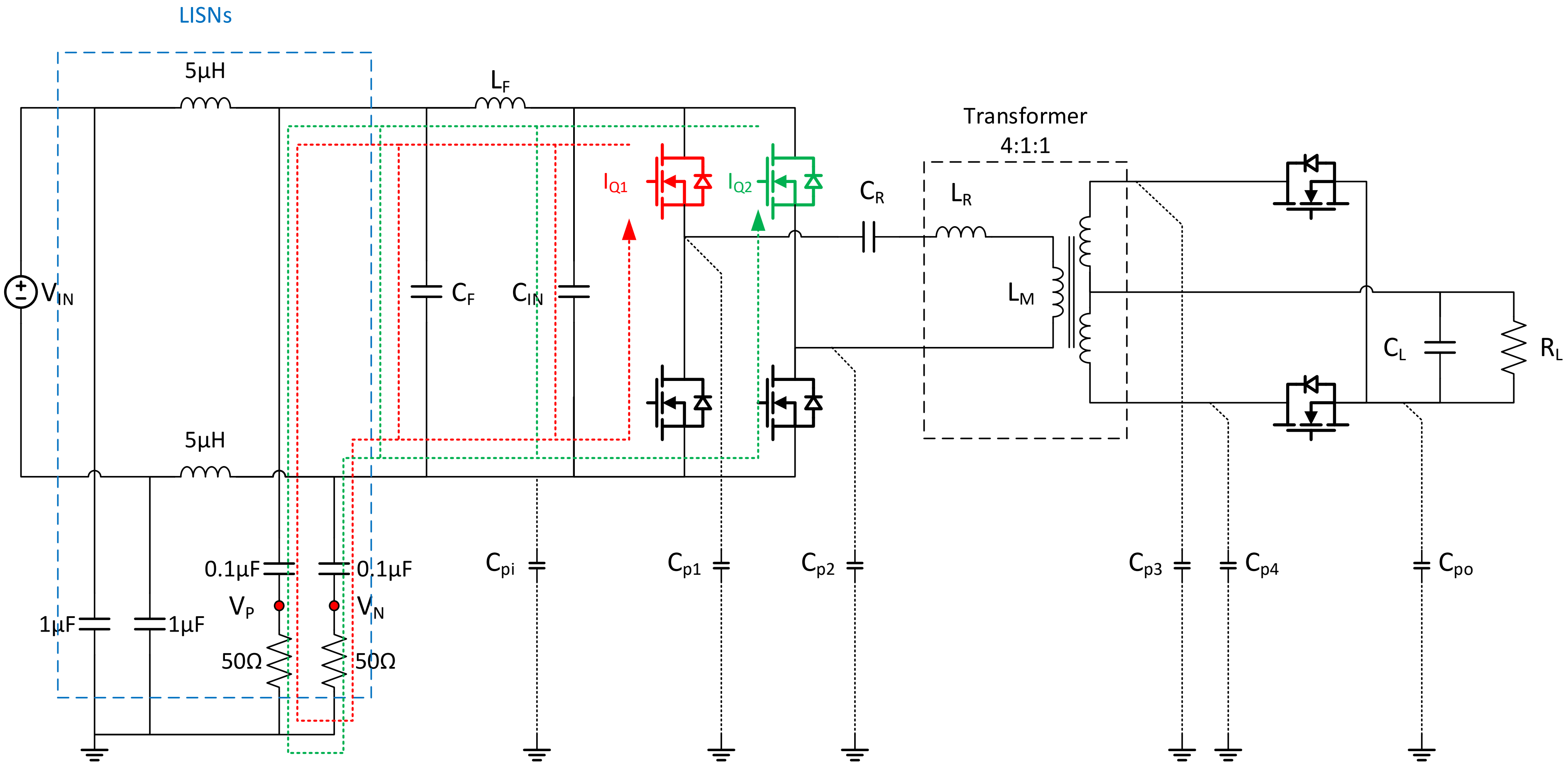

**360mm2**

# LLC EMI Modeling and Reduction

# Traditional LLC Setup

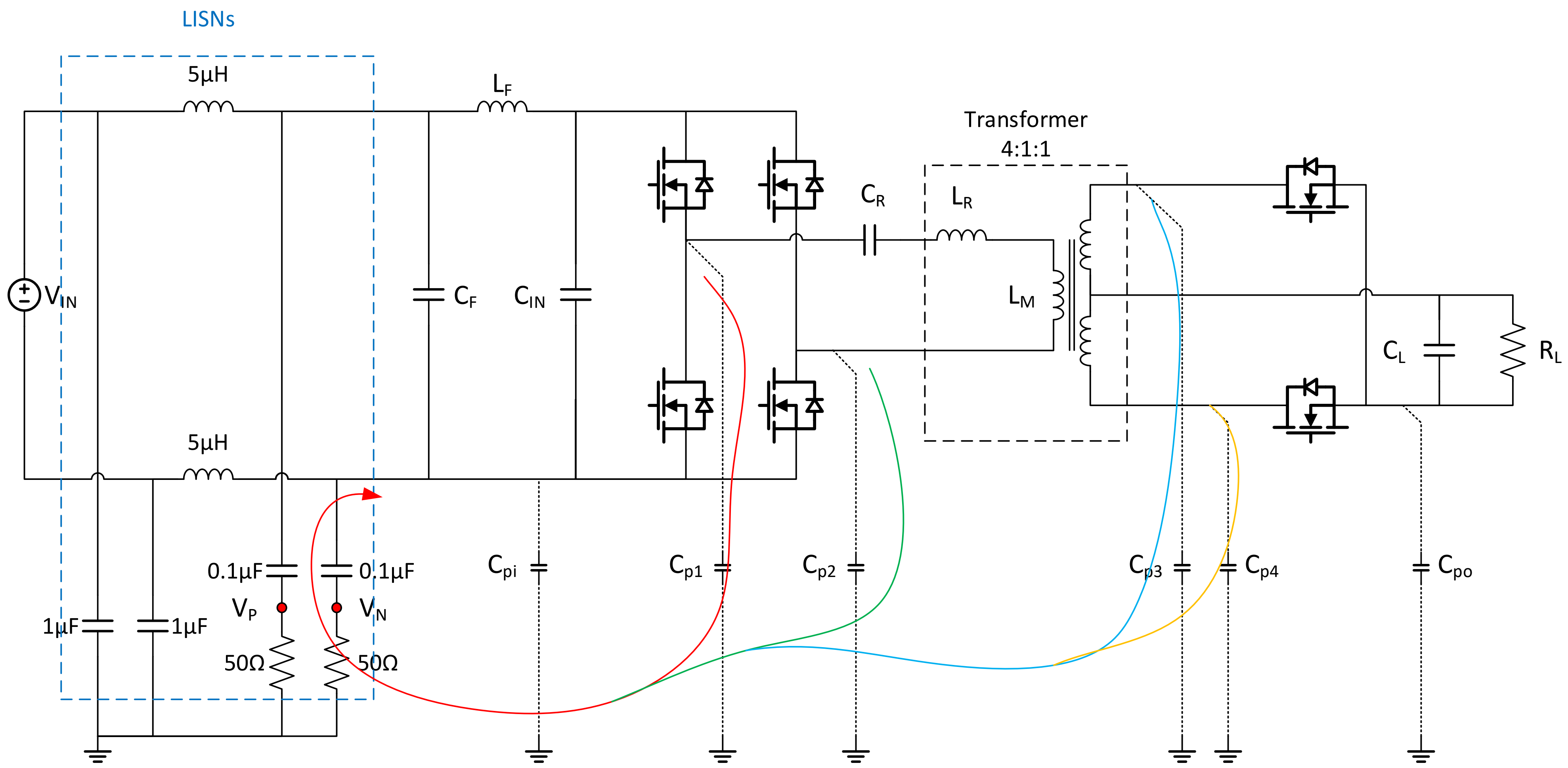


# DM Noise Path Analysis



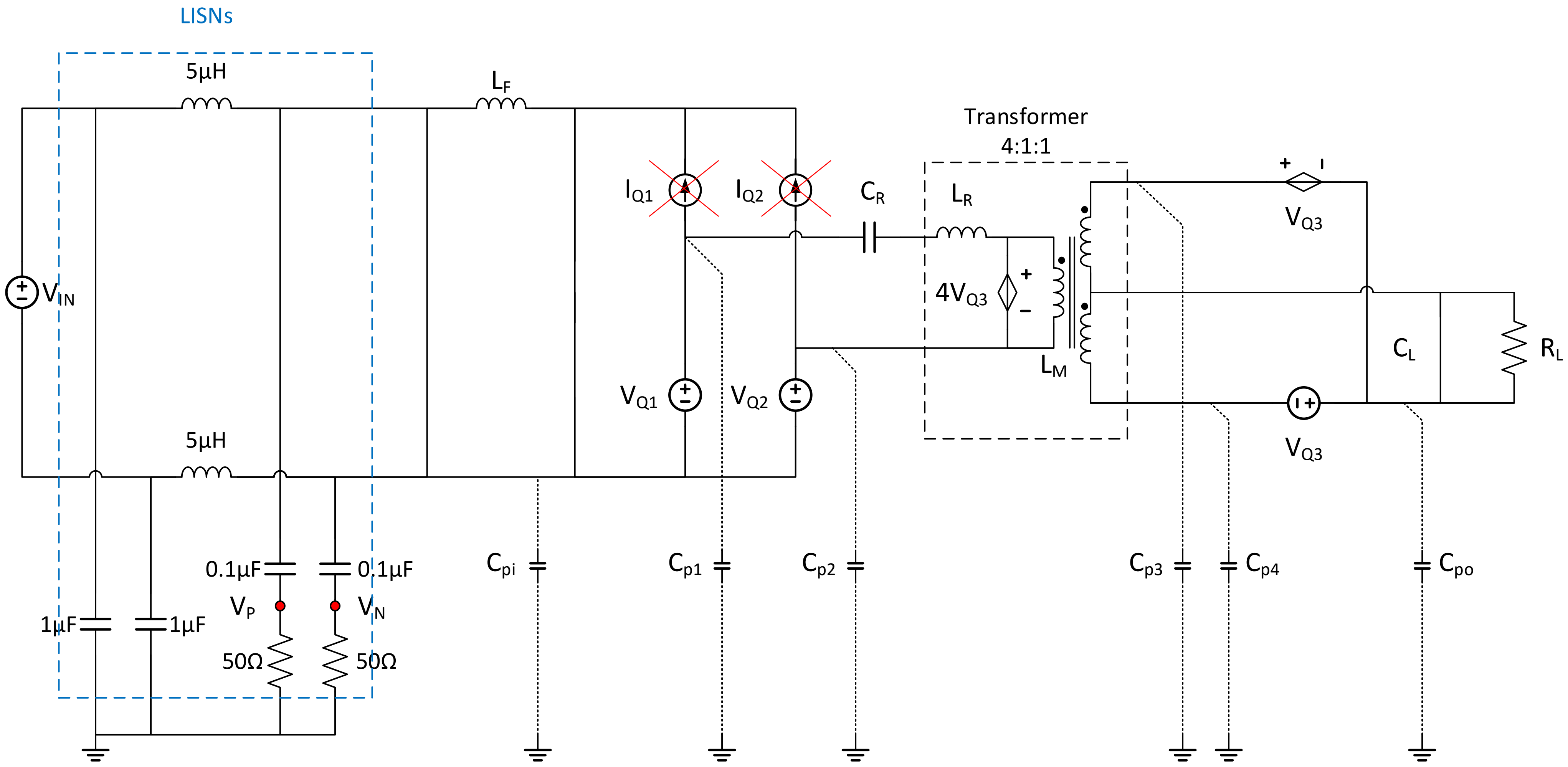

Note: The DM noise source is the sum of Q1 and Q2 current. Input filter helps to reduce DM noise.

# CM Noise Path Analysis




Note: The CM noise paths are relatively complicated to analyze. There are many switching nodes.

# Substitution & Superposition Theory




Note: $I_{Q1}$ and $I_{Q2}$ does not generate CM noise. $V_{Q1}$, $V_{Q2}$ and $V_{Q3}$ can be CM Noise sources.

# How to Analyze the Transformer?

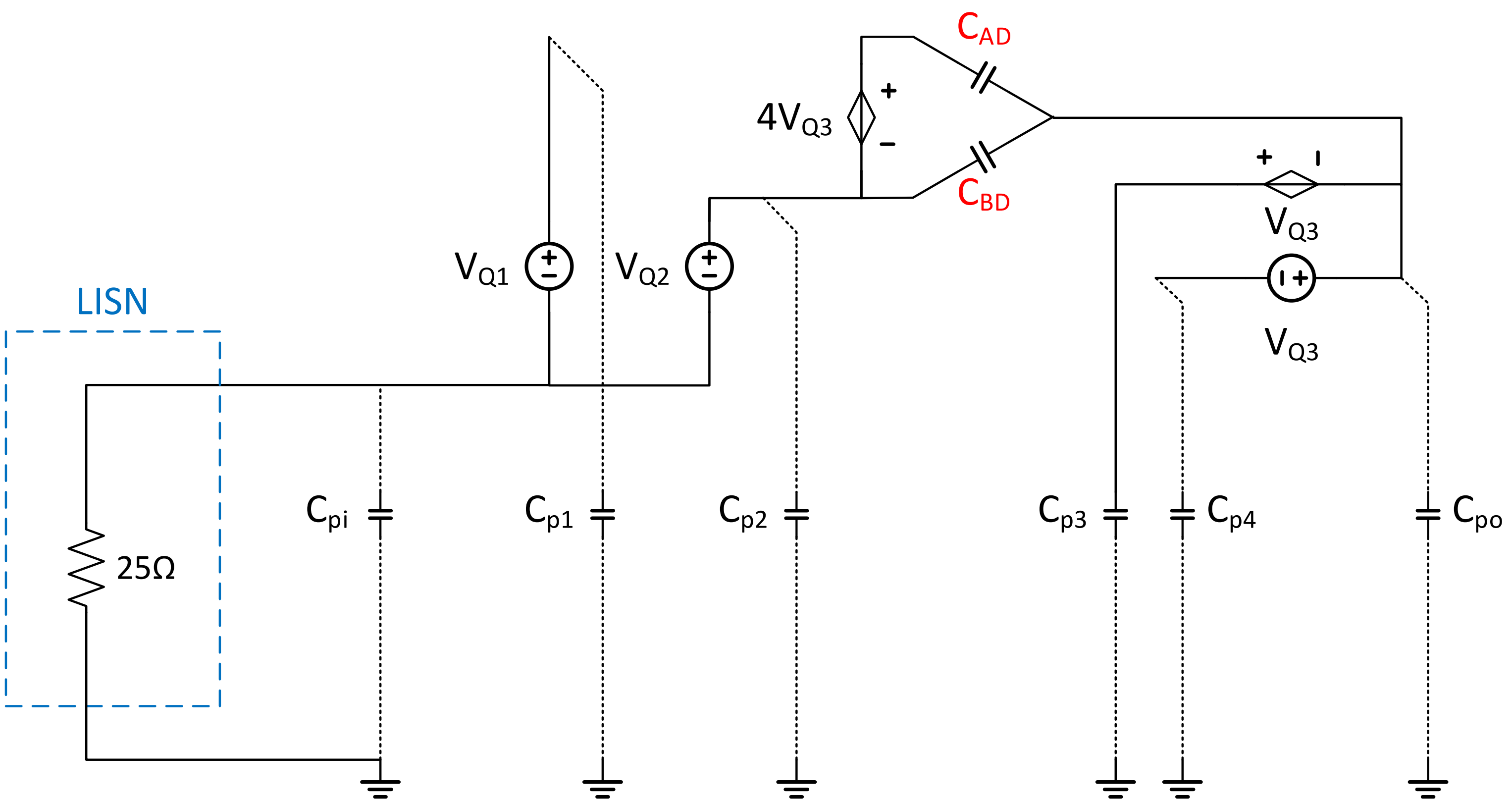
Two-capacitor Transformer Winding Capacitance Model [1]

1) The transformer’s leakage inductance is small so its effect can be ignored.
2) At least one winding of the transformer are connected to an equivalent independent voltage source. This source can be the equivalent voltage source used to substitute nonlinear switches.



[1] H. Zhang, S. Wang, Y. Li, Q. Wang and D. Fu, "Two-Capacitor Transformer Winding Capacitance Models for Common-Mode EMI Noise Analysis in Isolated DC–DC Converters," in *IEEE Transactions on Power Electronics*, vol. 32, no. 11, pp. 8458-8469, Nov. 2017.

# CM Noise Model of LLC



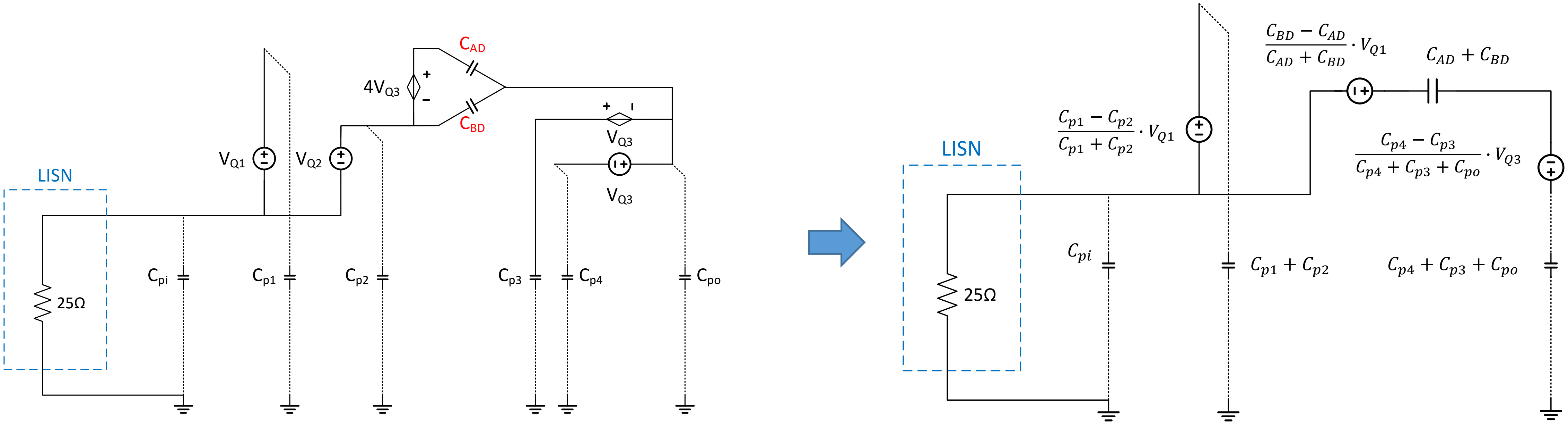

Note: The CM noise model of isolated LLC can be further simplified as above.

# Balance Condition Derivation

$$V_{Q1} \approx -V_{Q2}$$

$$4V_{Q3} \approx V_{Q1} - V_{Q2}$$

Assume that the switching frequency is equal or very close to the resonant frequency.

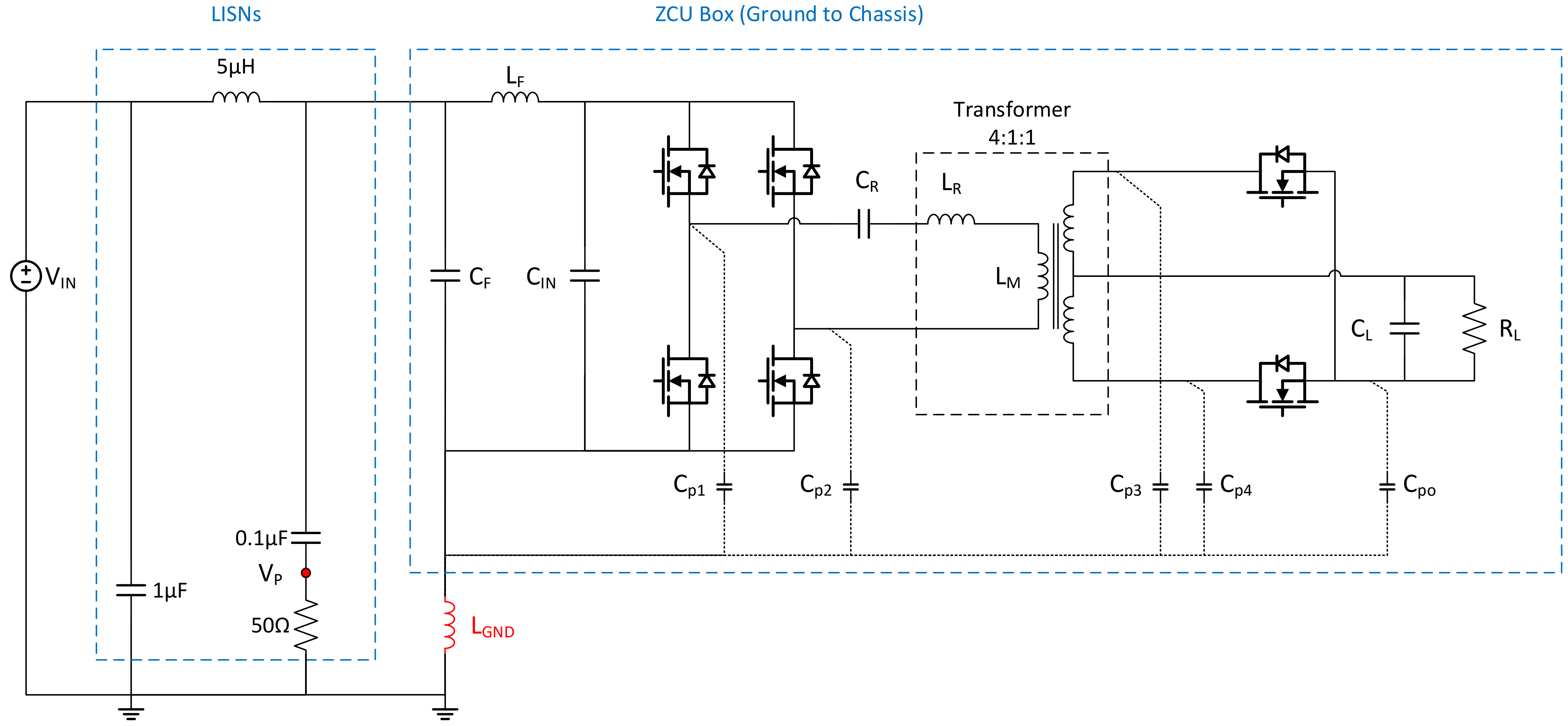



Balance Condition: $C_{p1} = C_{p2}$ $C_{p3} = C_{p4}$ $C_{AD} = C_{BD}$

Note: The isolated LLC CM noise can be cancelled with proper PCB/transformer design to balance the parasitics.

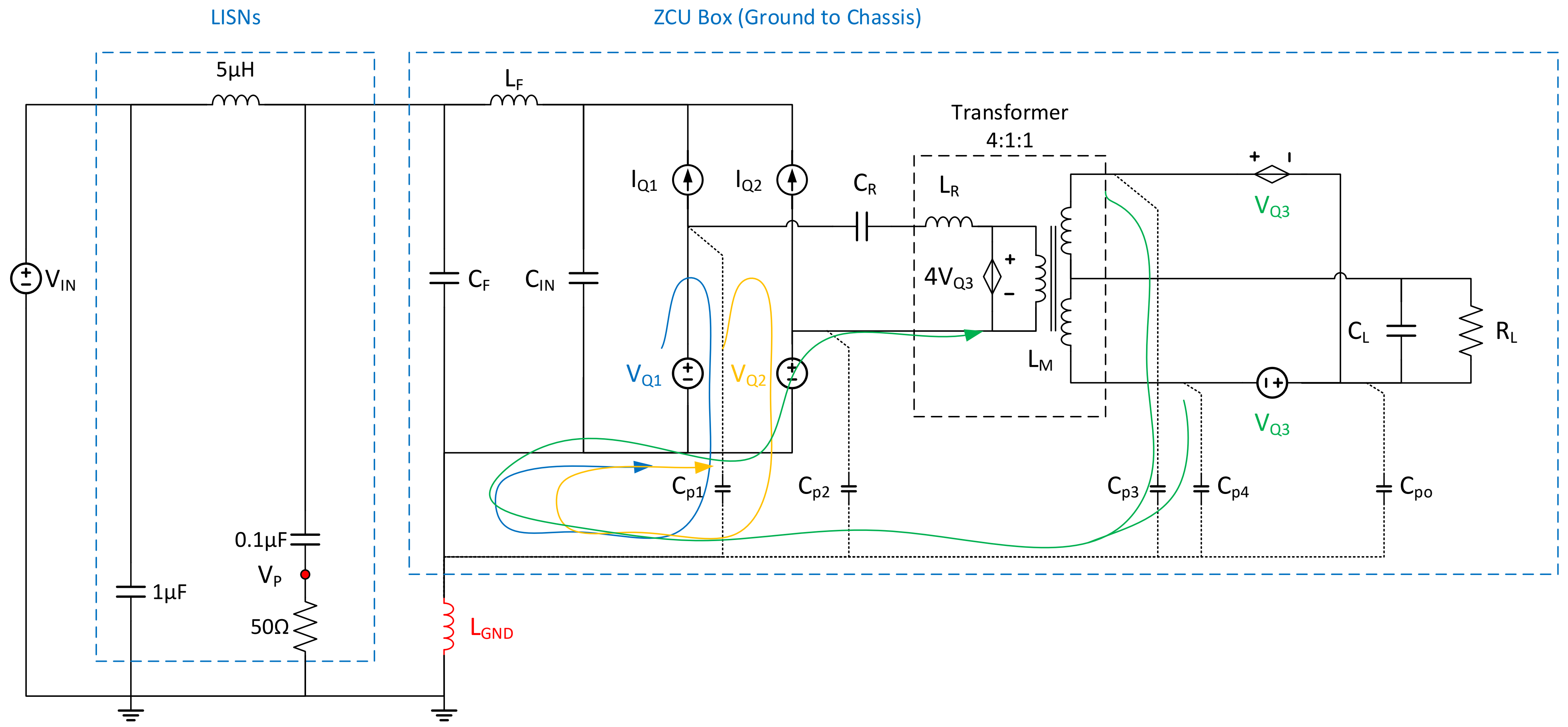
# LLC EMI for a Special Setup

# A Special Setup for Automotive



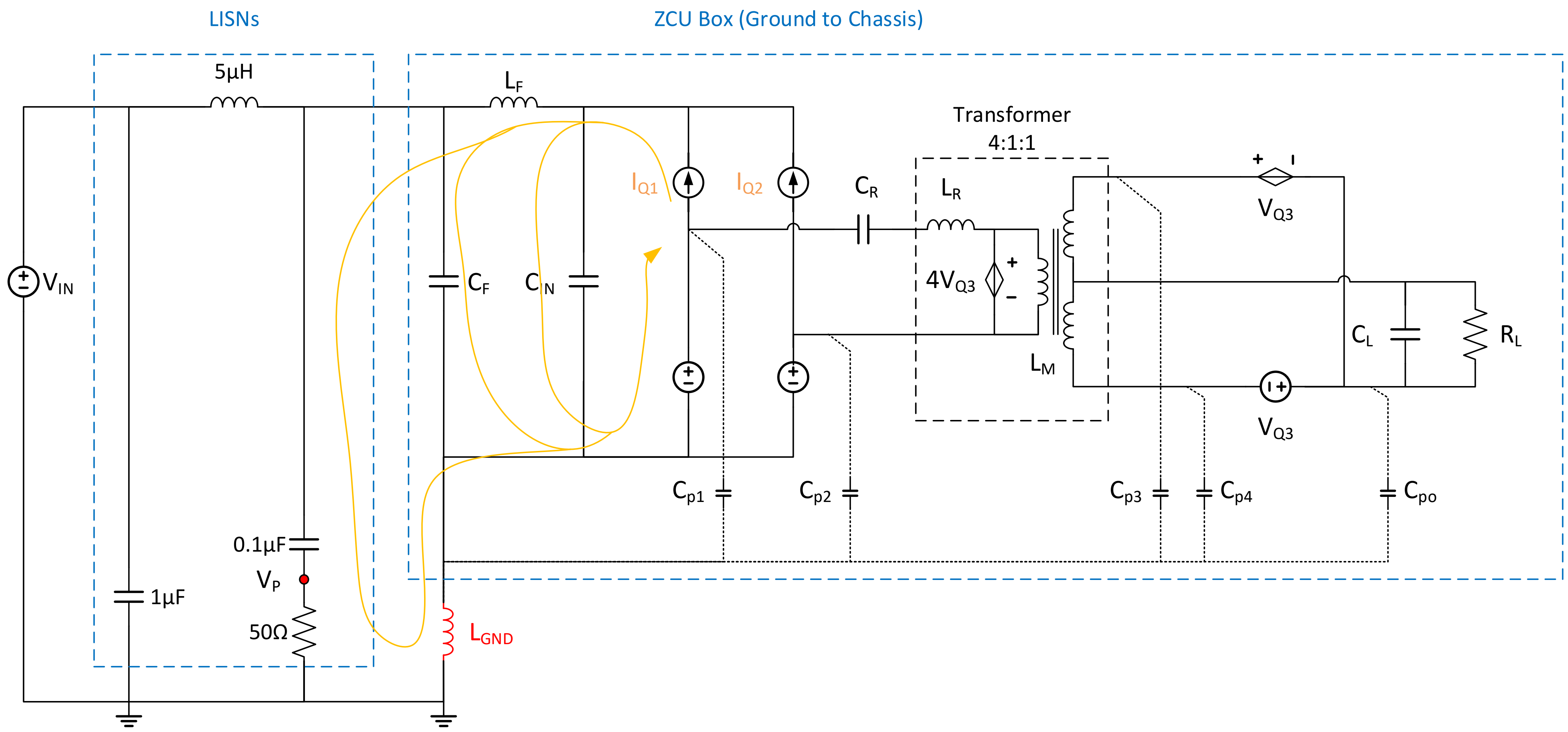

Note: In some applications, there is only positive line as the input. The negative line is grounded to the chassis. In this case, only one LISN noise needs to be measured.

# Noise Path Analysis – V Source



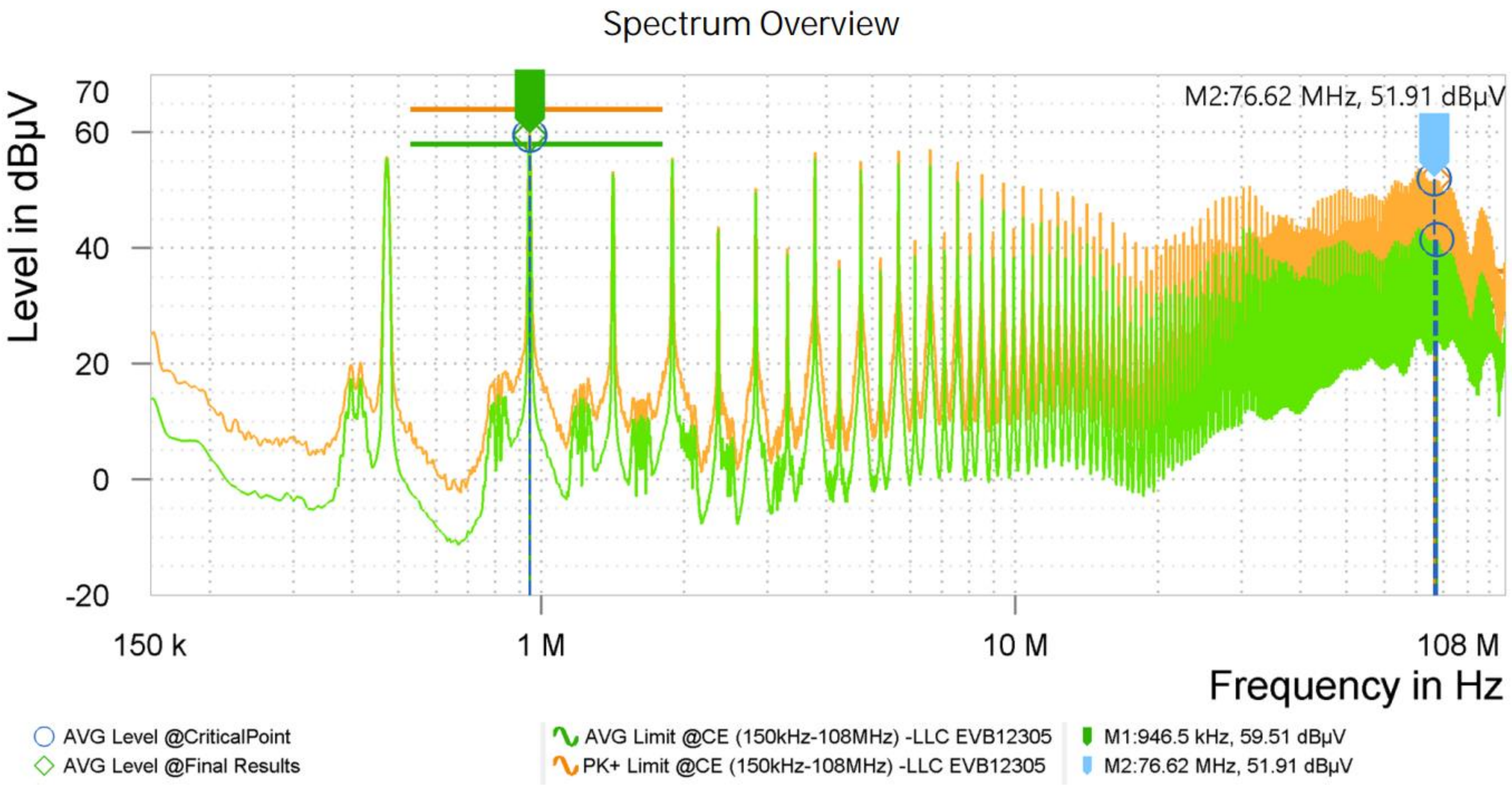

Note: Voltage sources’ noise current does not flow through LISN.

# Noise Path Analysis – I Source



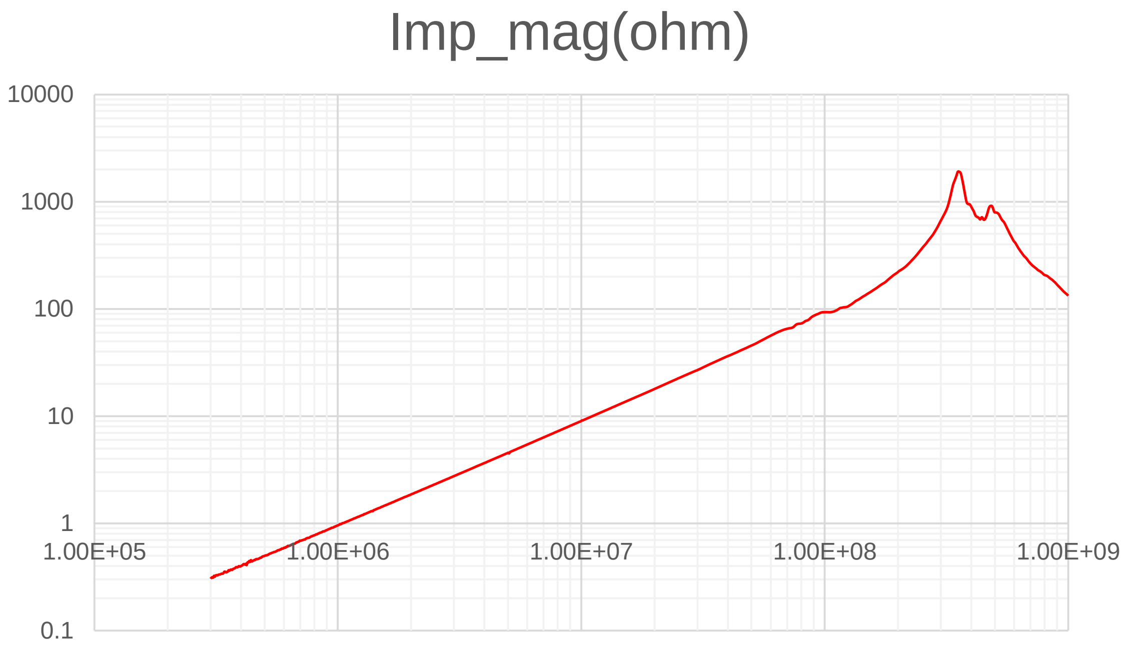

Note: Current sources' noise current flows through LISN. The EMI can be analyzed similar to DM.

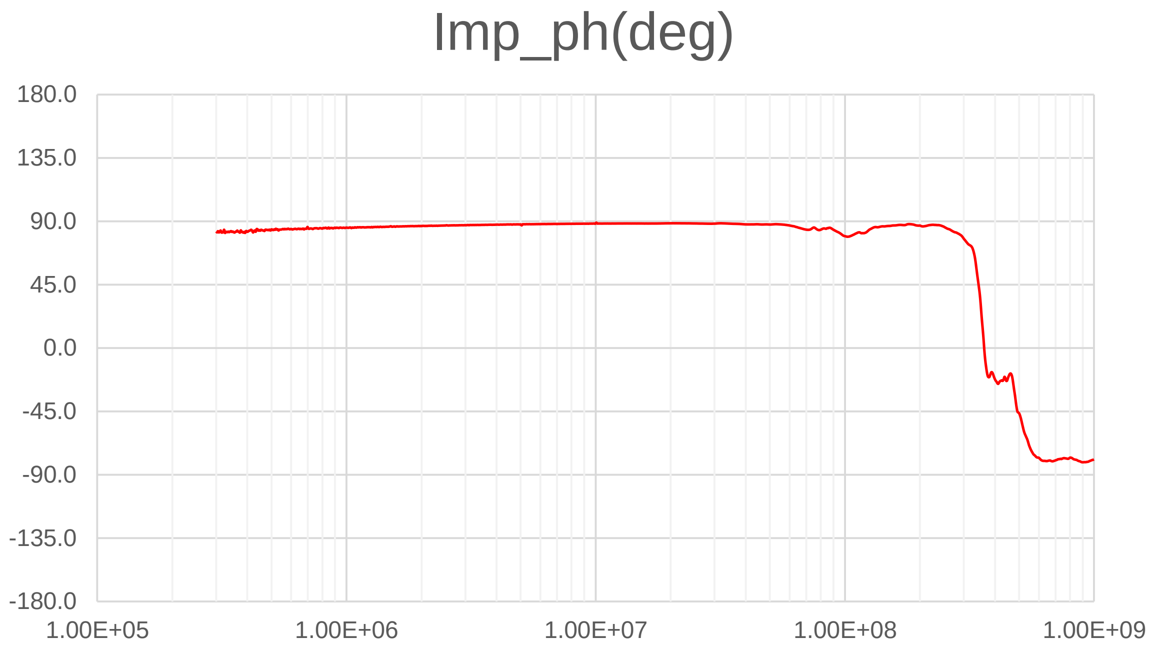
# Baseline EMI Noise




Note: It is found that the EMI is higher than the standard.

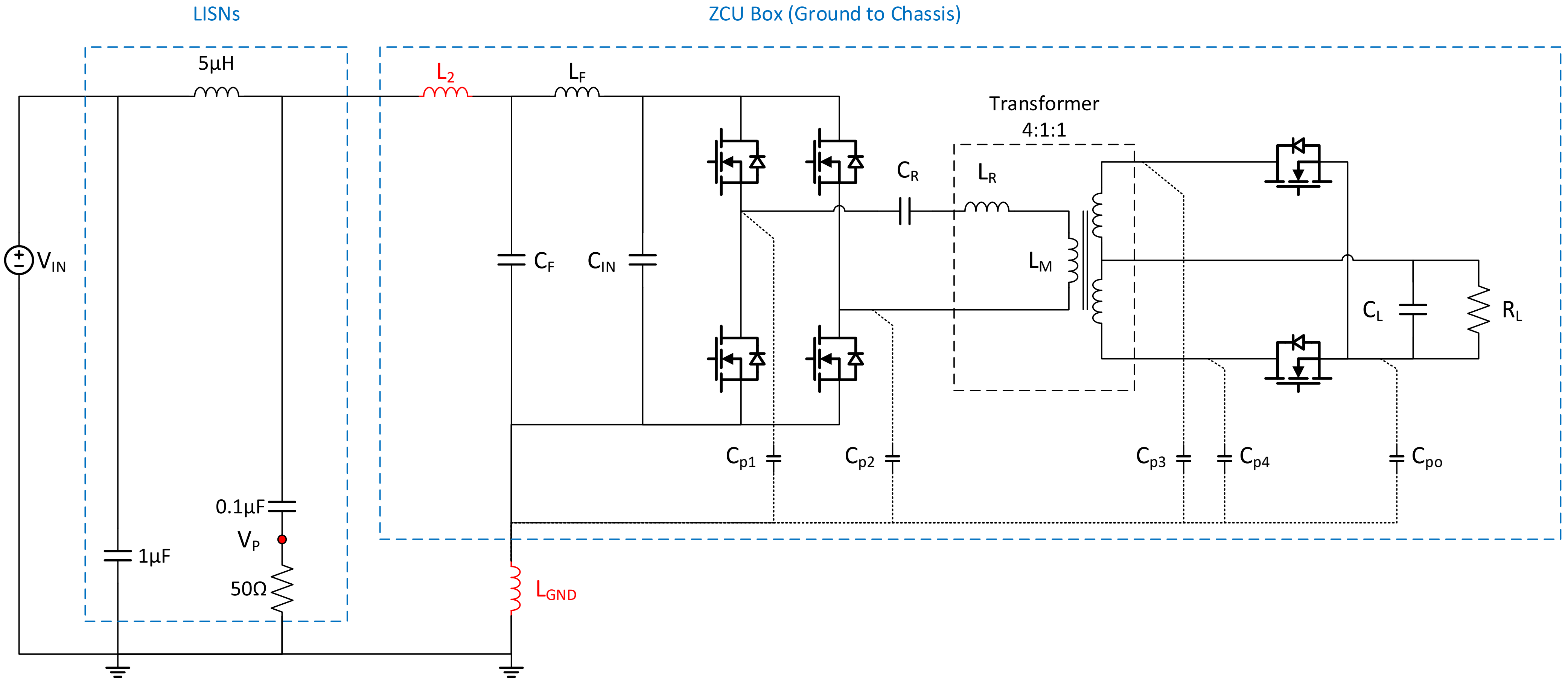
# Measure Impedance of the Grounding Harness $L_{GND}$



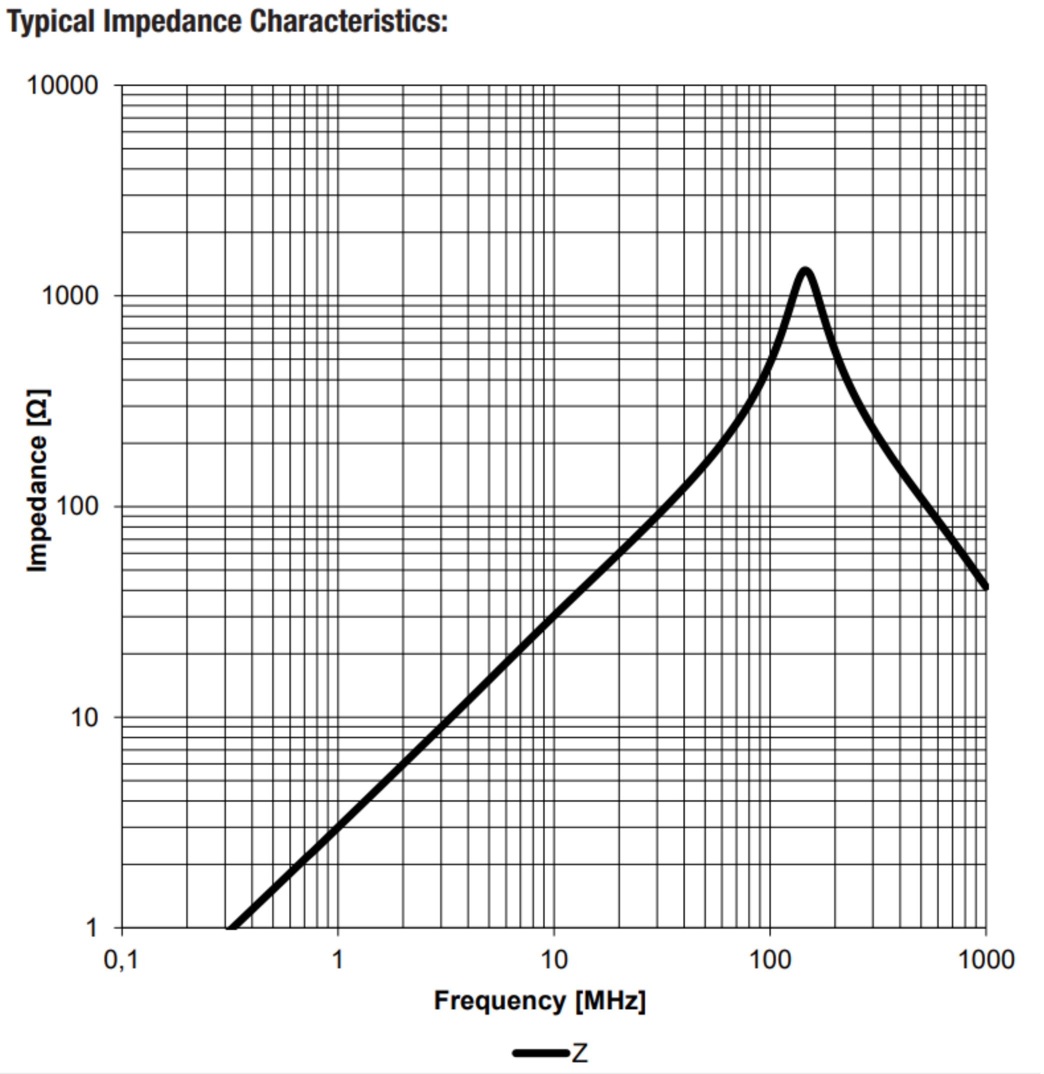

Note: The grounding impedance $L_{GND}$ presents a 0.14uH inductance below 350MHz. And presents as a capacitor between 350MHz and 1GHz. Its impedance is 100ohm at 100MHz.

# Reduction Method




Note: An additional DM inductor L2 can be applied to reduce the EMI noise.

# Find L2 with high Impedance high Frequency

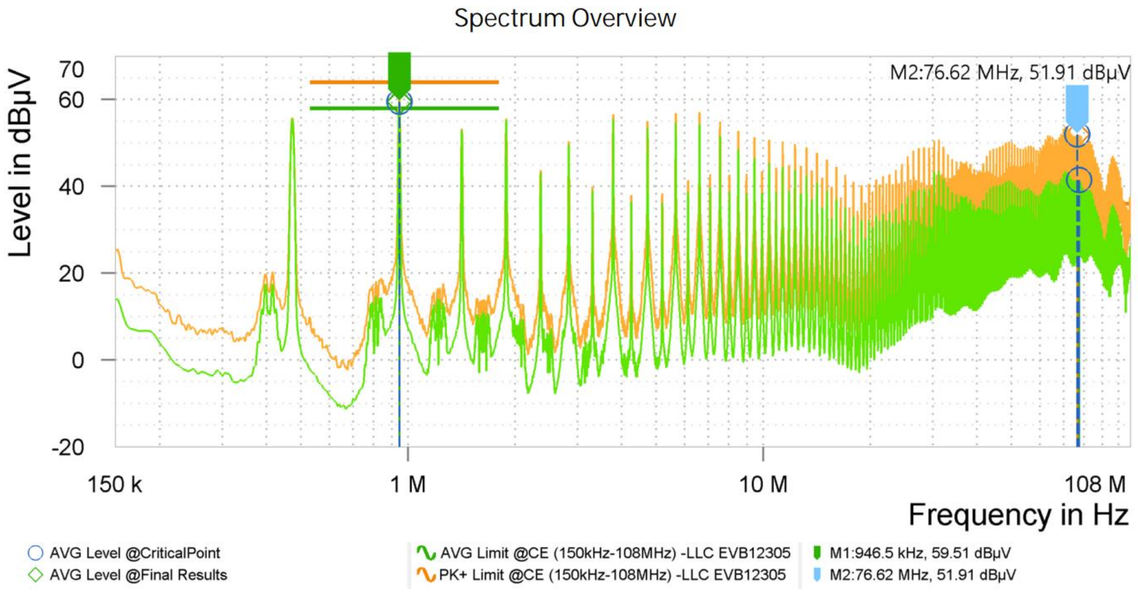



Ni-Zn Core, the Ni-Zn inductor provides high impedance at high frequency range.

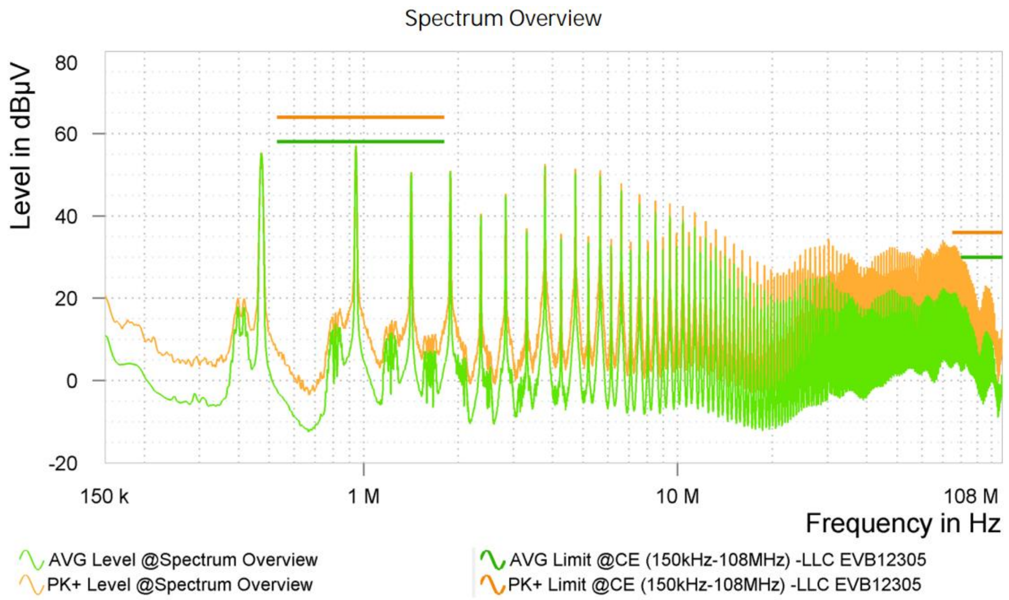
$Z_{L2} = 400\Omega$ at 100MHz

# Result Comparison with L2

CE, VIN = 48V, No Load, No L2



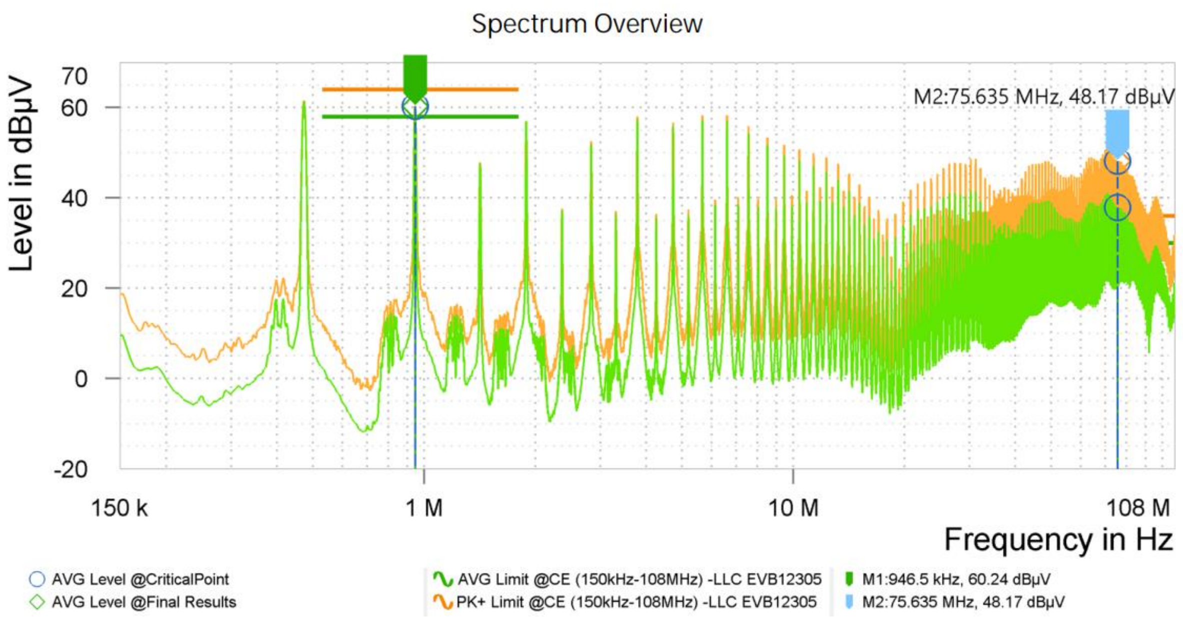

CE, VIN = 48V, No Load, L2 = 2.2uH



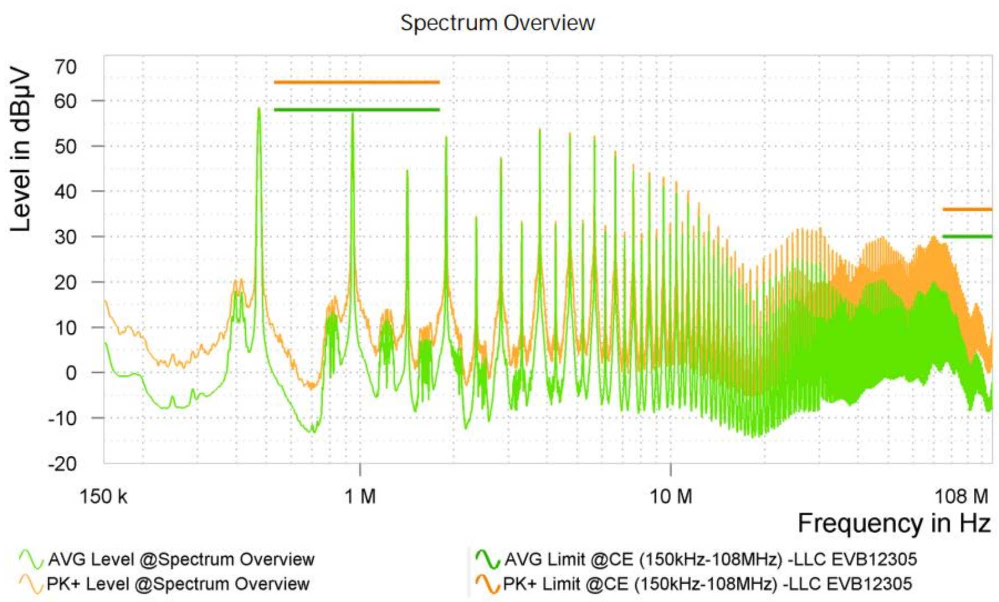

Note: As now the impedance of L2 is 8 times of $L_{GND}$, the high frequency noise reduced further by 5-6dB. The result passed the CE standard with 3dB margin.

# Result Comparison with Load = 12A

CE, VIN = 48V, Load = 12A, No L2




CE, VIN = 48V, Load = 12A, L2 = 2.2uH




Note: With a proper L2 selection, the CE EMI meets with standard with enough margin under 12A.

# Conclusion

- For a DC/DC converter, higher supply voltage will induce worse EMI.
- 48V-12V DC/DC will be a new challenge for 48V system.
- The LLC's operation principle is briefly introduced.
- The Non-Isolated and Isolated LLC is compared.
- The DM/CM LLC Conducted EMI model is introduced.
- LLC CM EMI balance condition is discussed.
- Chassis Grounding LLC EMI test setup in Automotive is introduced.
- CE EMI reduction method for Chassis Grounding LLC is presented.

# Question & Answer

Thank you!