GaN/SiC Transistors– Fight or Flight?

Getting EMC ready for the next generation of power electronics devices

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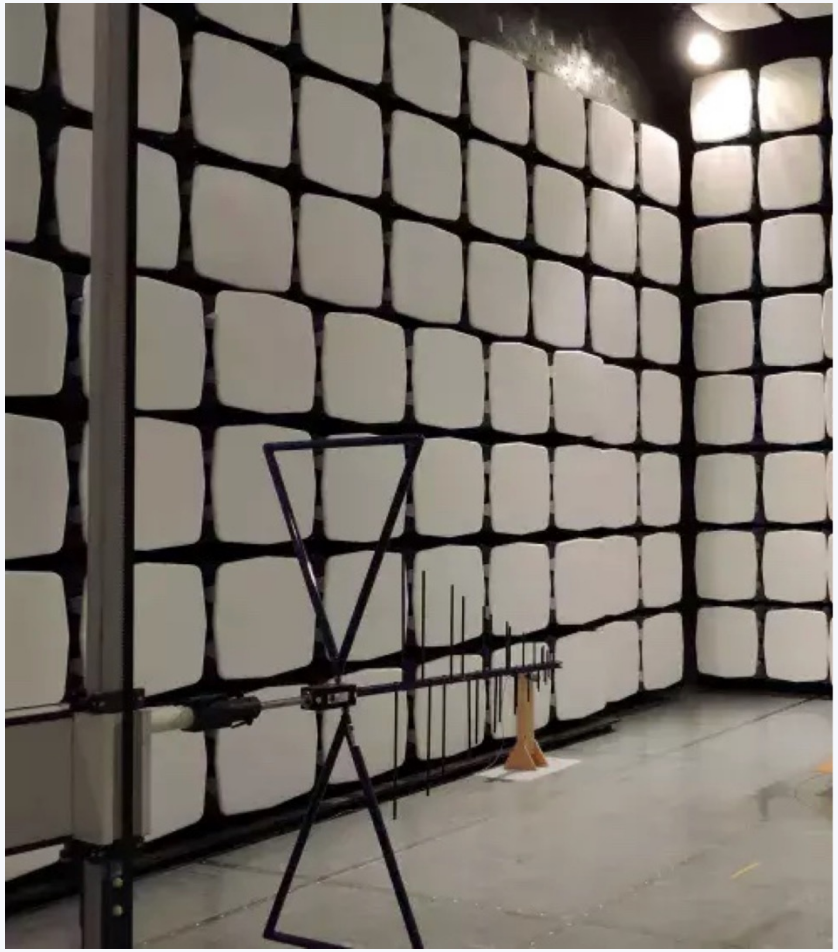
LYRA ELECTRONICS

About Us

Dr. Yegi Bonyadi currently works as Electronics Team Leader at Lyra Electronics Ltd (https://www.lyraelectronics.com), where she focuses on the design of automotive high-power DC-DC converters, on-board chargers and cost-effective EMC design. Her interests include power converter design, automotive power inverters, Hybrid/electric vehicles, power electronics modelling, and Wide-Bandgap semiconductor power devices.

Dr. Min Zhang is the founder and principal EMC consultant of Mach One Design Ltd (www.mach1design.co.uk), a UK-based engineering firm that specializes in EMC consulting, troubleshooting, and training. His in-depth knowledge of power electronics, digital electronics, electric machines, and product design has benefitted companies worldwide. Zhang can be reached at info@mach1design.co.uk

Outline of the Workshop



- EMI Challenges Unveiled
- Demystifying EMC Part 1: Finding Your “Ground”
- Demystifying EMC Part 2: Patristics & Coupling
- Effective EMC Testing Part 1: The Benchtop Approach
- Effective EMC Testing Part 2: The Chamber Approach
- Design Strategies for Achieving EMC Compliance
- A case study
- Q & A Session

GaN & SiC Transistors – Typical Applications

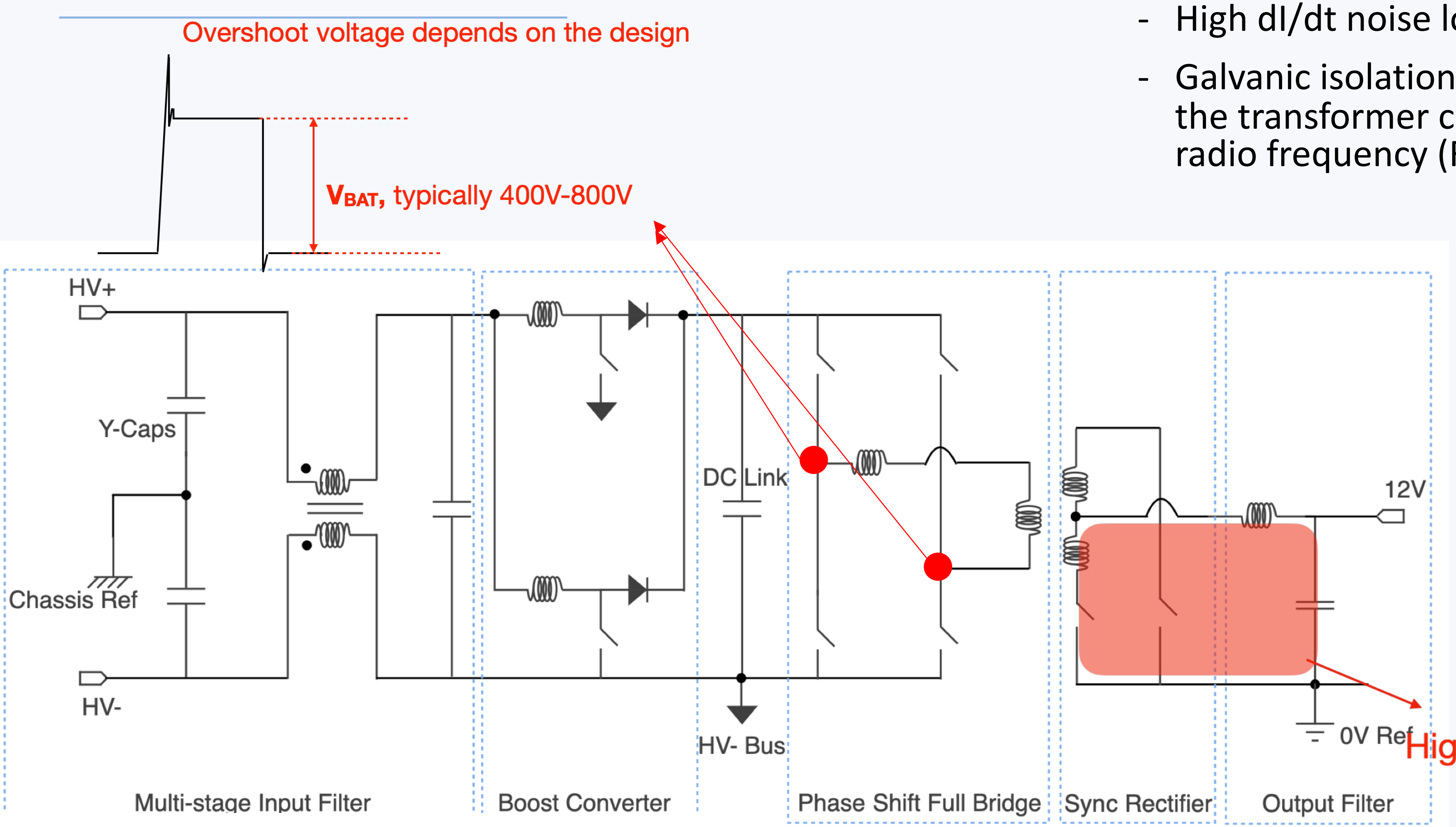
GaN Charger 108W, Belkin, Source: Apple.com

- Mobile phone/Laptop chargers
- Home appliance motor drive applications
- Wireless charging for phones/laptops
- LIDARs
- RF Amplifiers

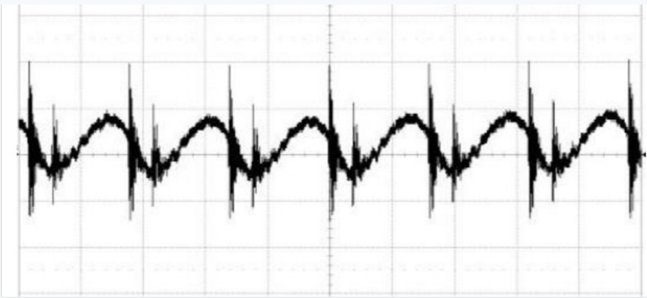
Lyra's 22kW SiC Bi-directional On-board Charger

- Industrial/EV motor drive applications
- Solar inverters
- High power & high-temperature applications
- RF and microwave applications (typically, Military applications)

New Challenges

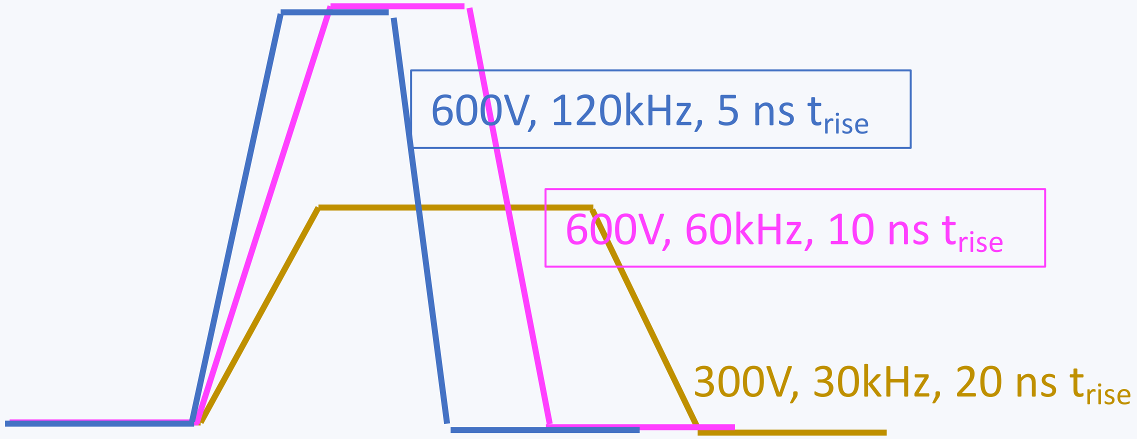


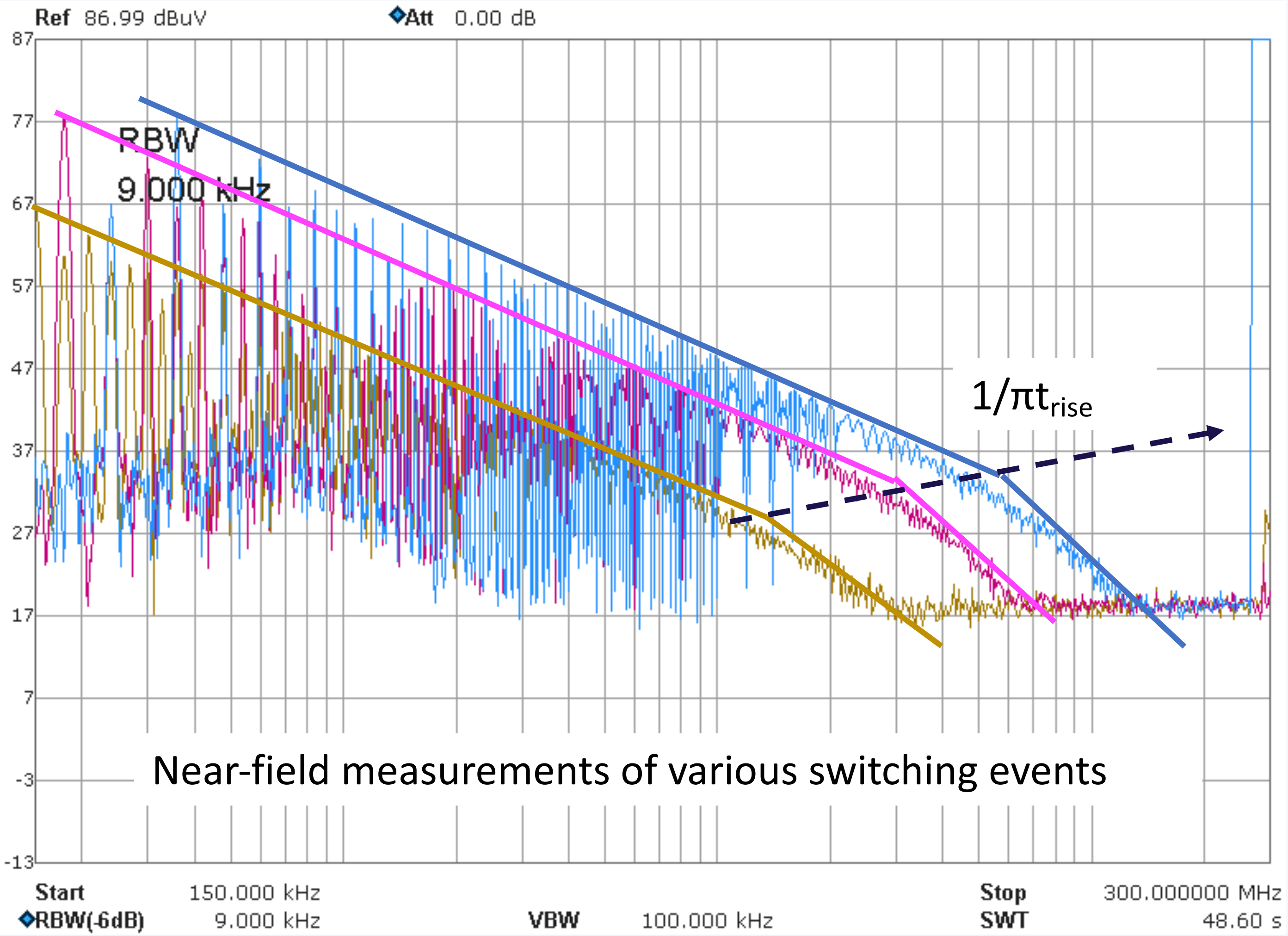
Simplified Schematics of a DC-DC Converter



- High dV/dt noise, for example, motor drives, DC-DCs, and On-board-chargers
- High dI/dt noise loop, e.g. motor drives, DC-DCs
- Galvanic isolation provides a safety feature, but the transformer cannot block high-frequency radio frequency (RF) signals

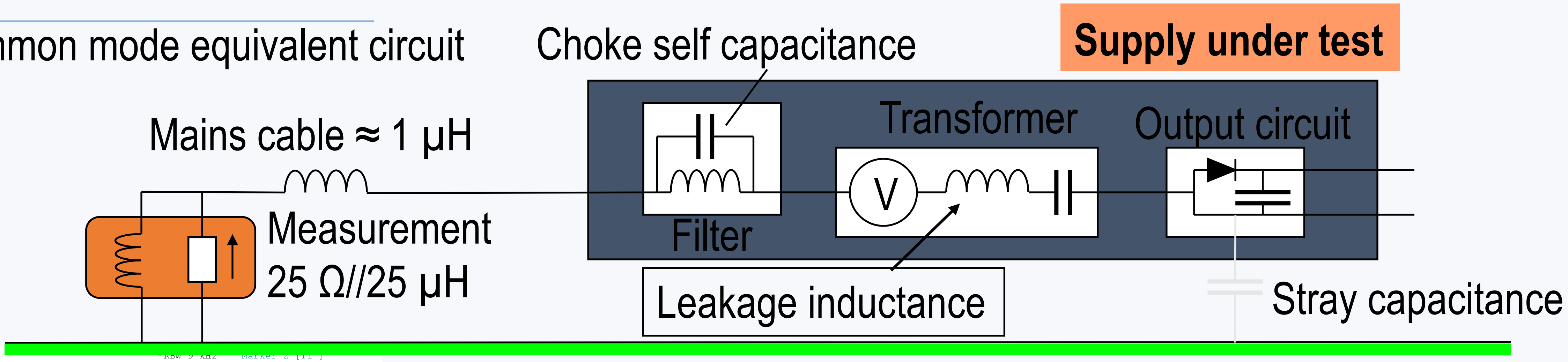
Need for Speed?





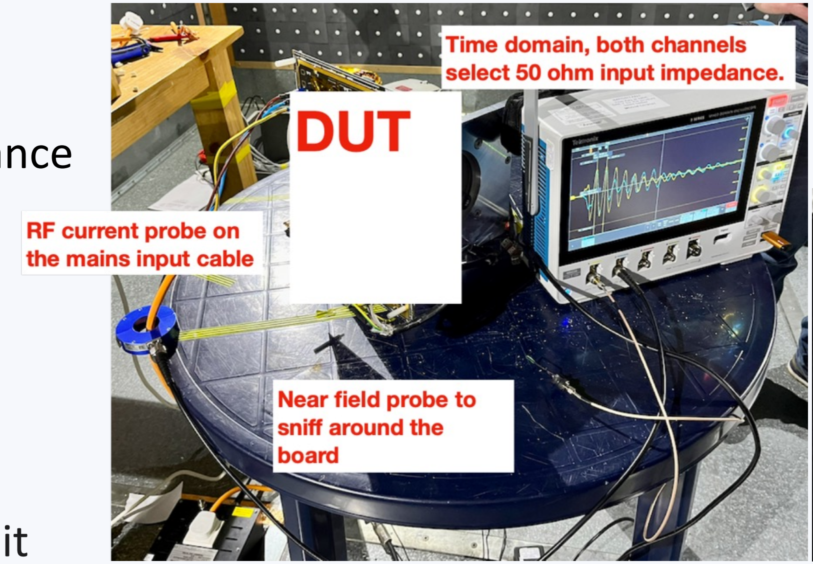
Conducted Emissions - The 10-30 MHz "Hump"

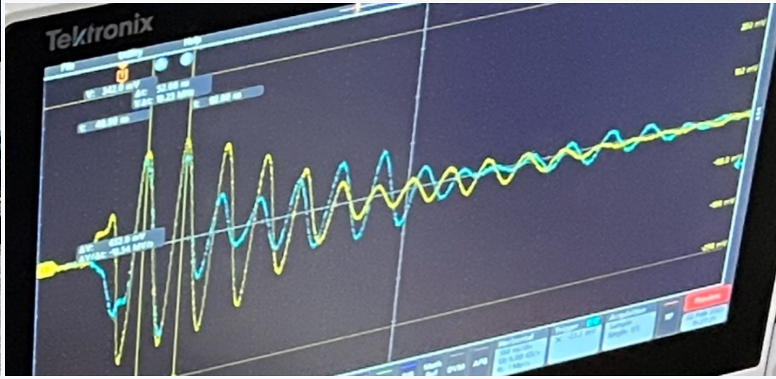
Common mode equivalent circuit



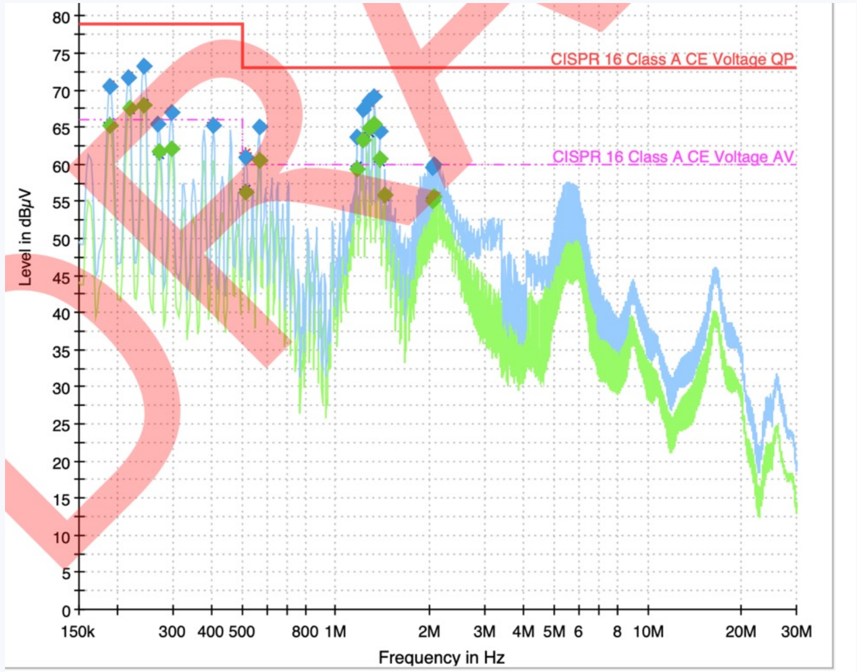
Conducted Emission Test Result of a SiC PFC Crcuit

Resonance

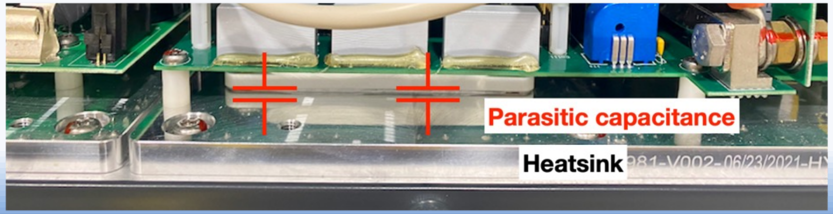




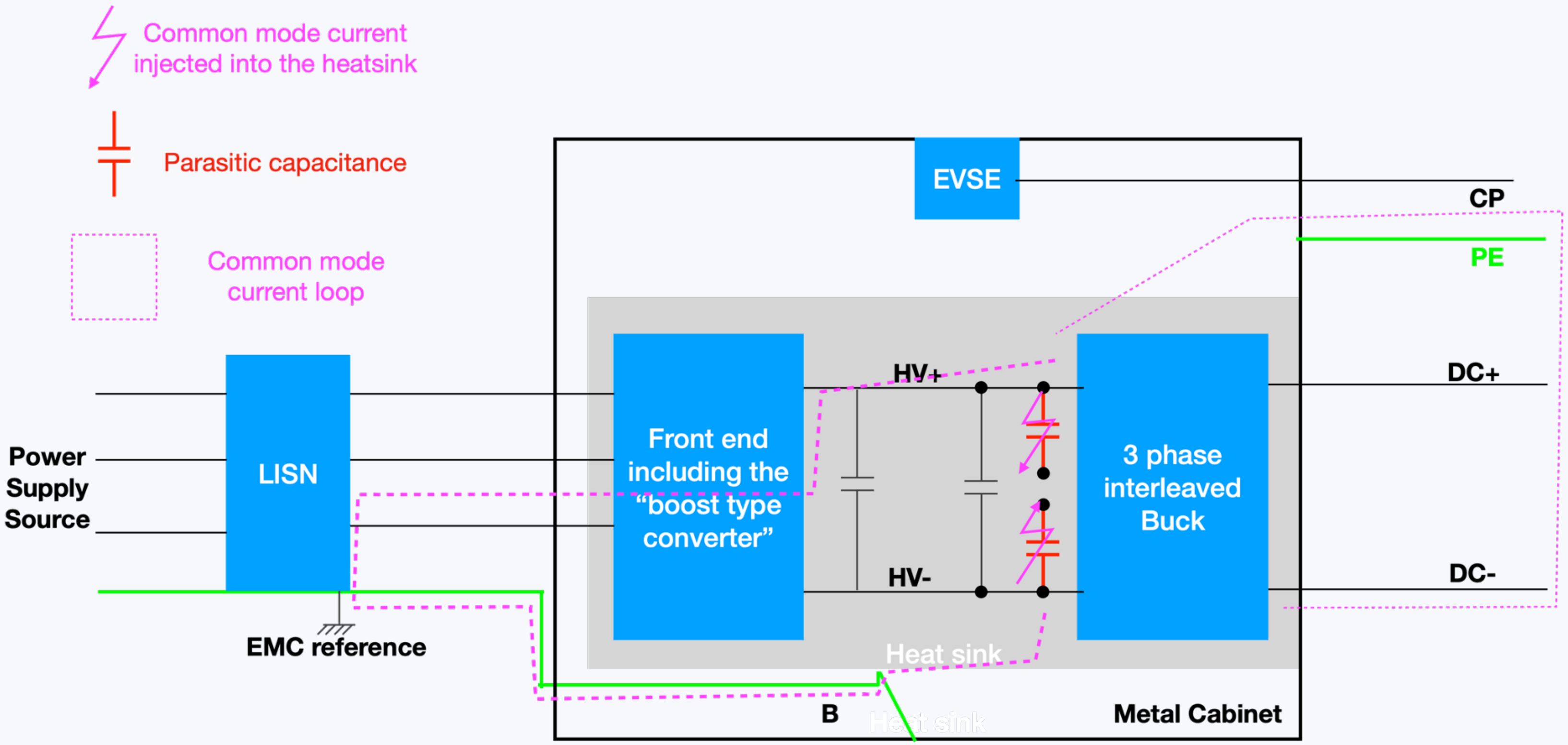
Conducted Emissions - Low-frequency Common Mode Noise



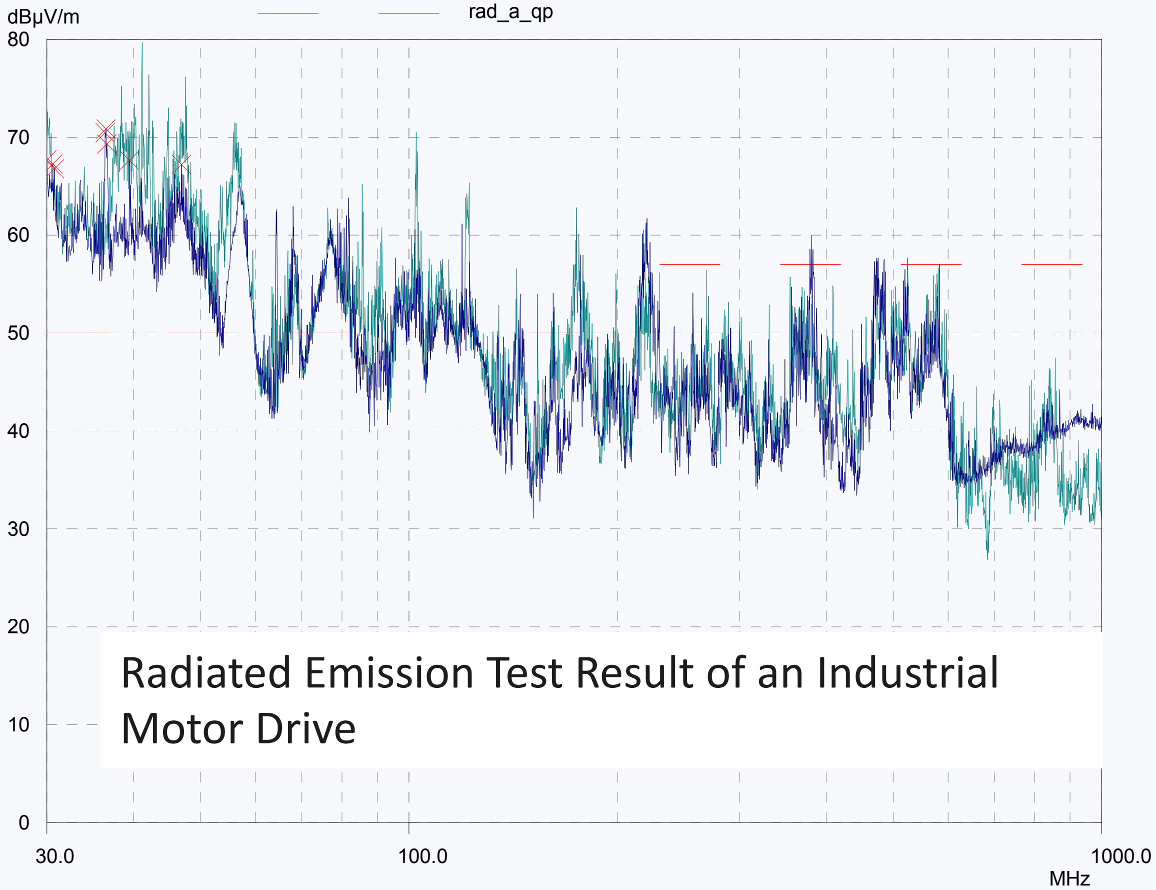
(a) the power converters are bolted to the heat sink which is earthed



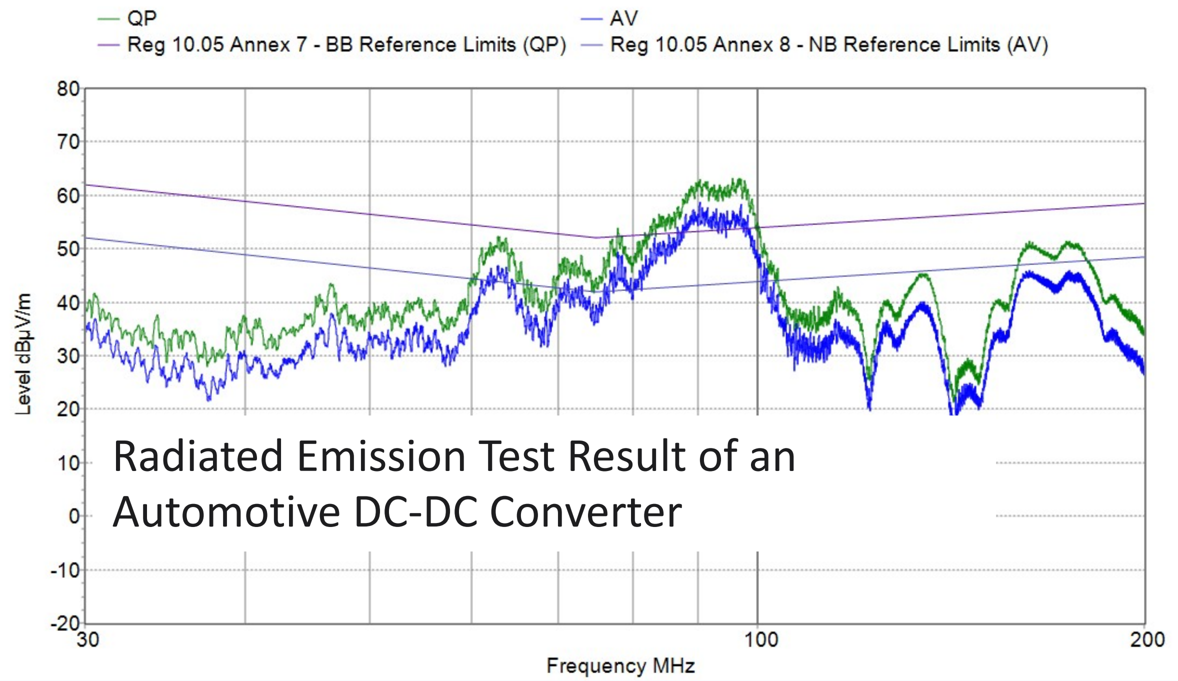
(b) A detailed view between the power switches and the heatsink



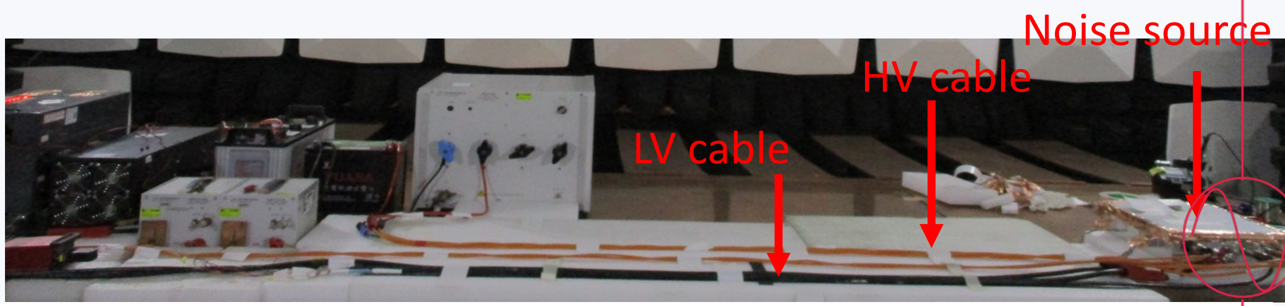
Radiated Emissions – Cables as the Main Radiators



Radiated Emission Test Result of an Industrial Motor Drive

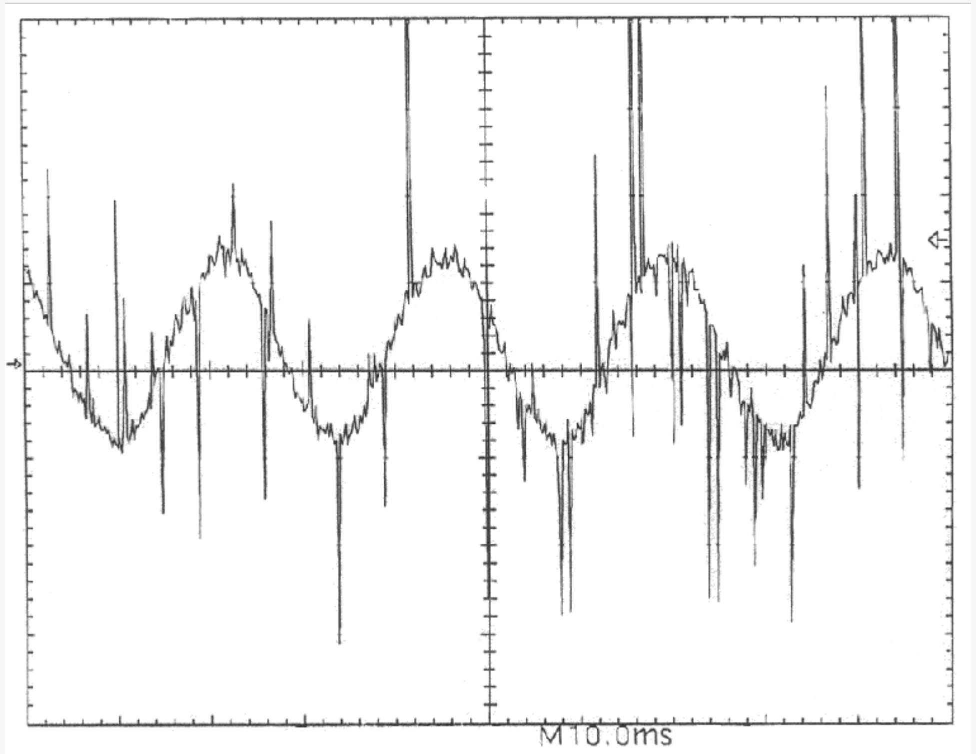


Radiated Emission Test Result of an Automotive DC-DC Converter



A Typical Radiated Emission Set-up for Automotive EMC Testing

Going Beyond Meeting Regulatory Requirements



A highly distorted current waveform of a motor (sources: Rockwell Automation)

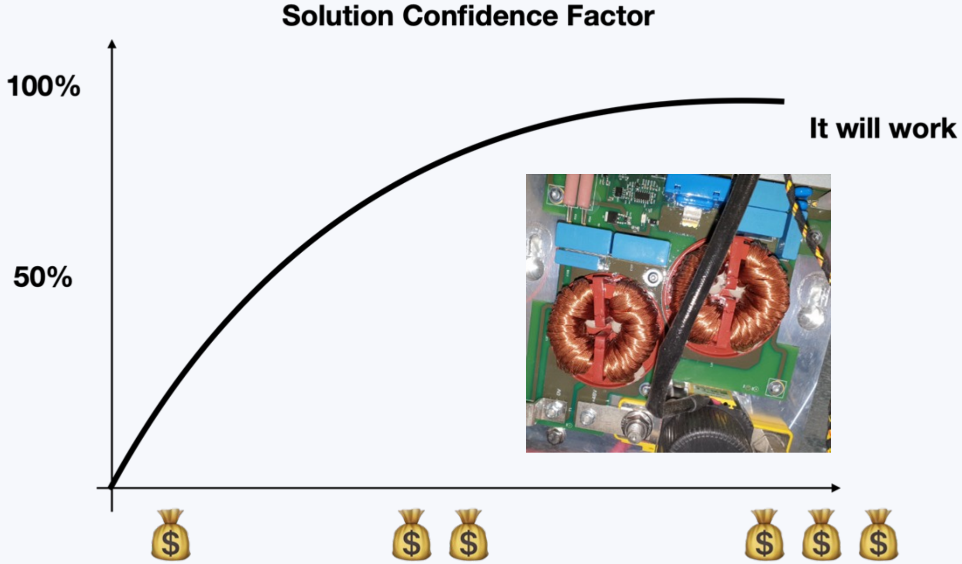
$$I_{\text{ph}} = I_{\text{fundamental}} + I_{harmonics} + I_{\text{switching}} + I_{\text{transient}}$$

- The fundamental content depends on the motor speed.
- Low-frequency noise (kHz - 10s of kHz range) arises from the lower harmonics content of the current waveform.
- Broadband noise (30-300 MHz) is generated due to the fast rise time of the switching devices.
- High-frequency noise (>300 MHz) results from events such as reverse recovery charge of a body diode or occasional electrical breakdown caused by bearing current in an electric motor.

Insulation Breakdown, Bearing Lifetime, Sensor Inaccuracy, etc -> Functional Safety?

What shall we do?

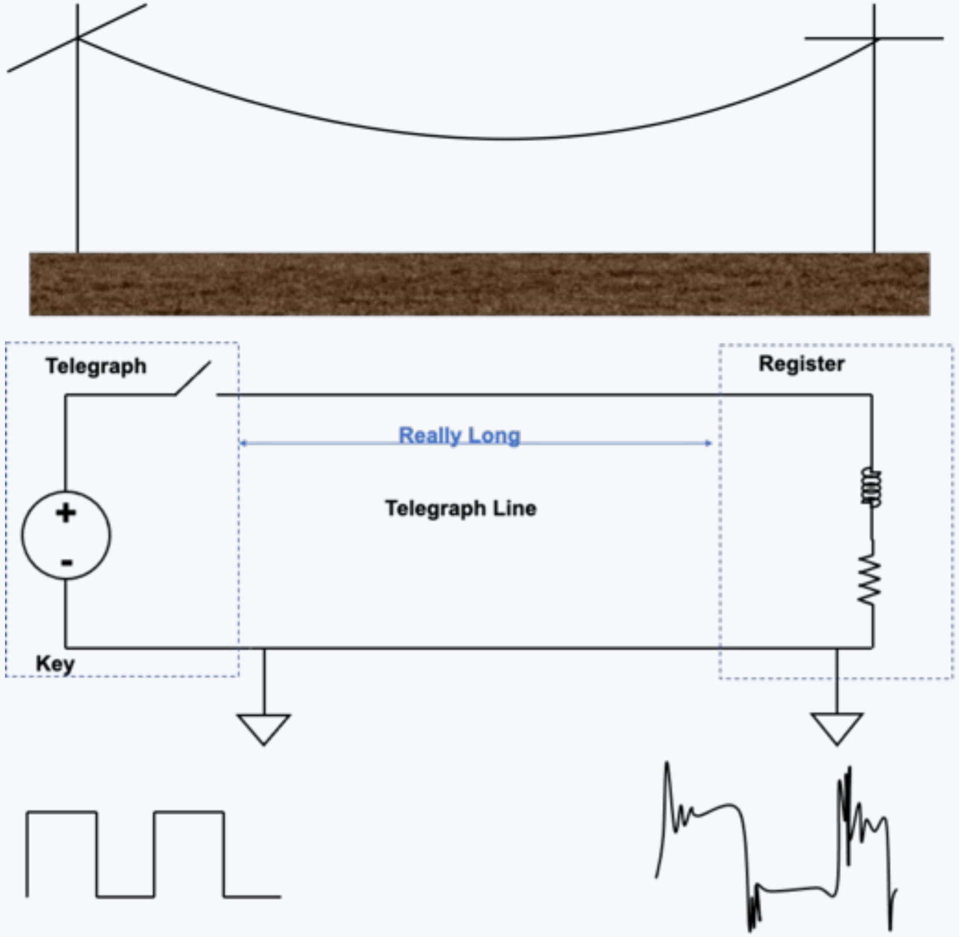
Design, Develop & Pray



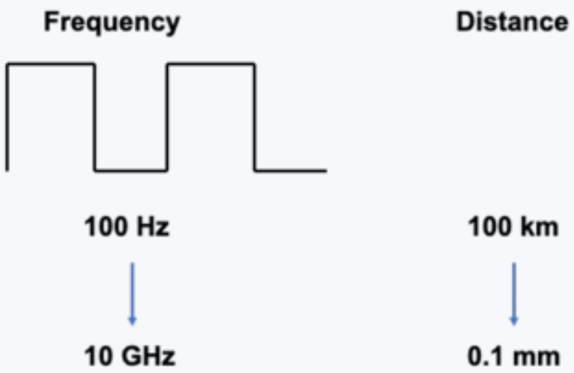
Filtering & Shielding, the More, the Better.

Identify, Locate & Solve

Demystifying “Ground”



A telegraph system that Samuel Morse built



An FPGA chip on the PCB

Sending a GHz signal on a PCB is, electromagnetically speaking, almost like sending a Morse code across the country.

As a rule of thumb, if the device you are transmitting electric signals across is larger than 1/10 of a wave length, then you need to start thinking about transmission line theory.

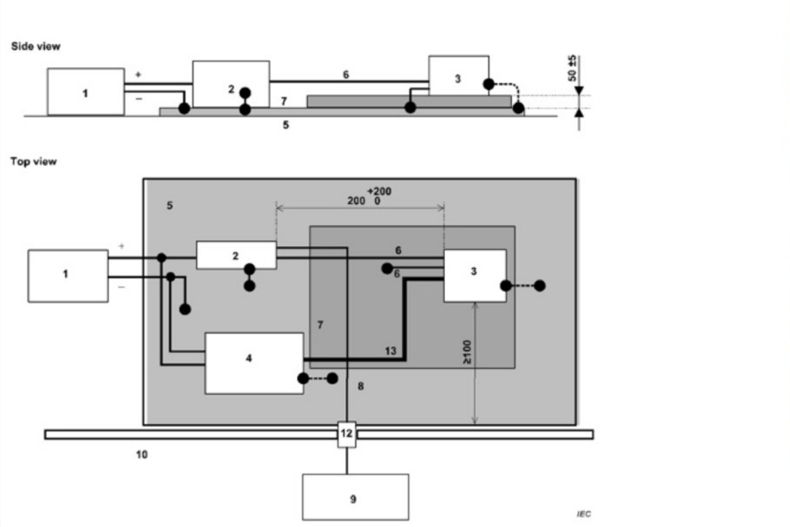
Searching for a “Quiet Ground”

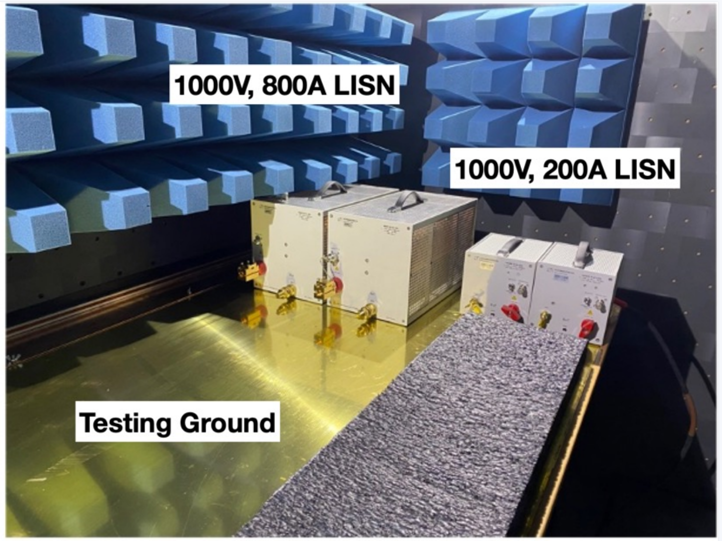
- Often referred to as “Reference Ground Plane”
- Made of copper, brass, bronze or galvanised steel, the ground plane is the top metallic surface on the test bench/table and electrically bonds to the walls or the floor of the shielded enclosure such that its DC resistance does not exceed 2.5 mΩ.
- Conducted emission is to measure the noise with respect to the “reference ground plane” or ”Ground plane”.

Where is the “ground”?

- **The quiet “ground” ?**
- **The RF reference point ?**
- **The earth?**
- **0V, which?**

For automotive applications, the “ground” is the negative end of the 12V battery, which is connected to the vehicle chassis.

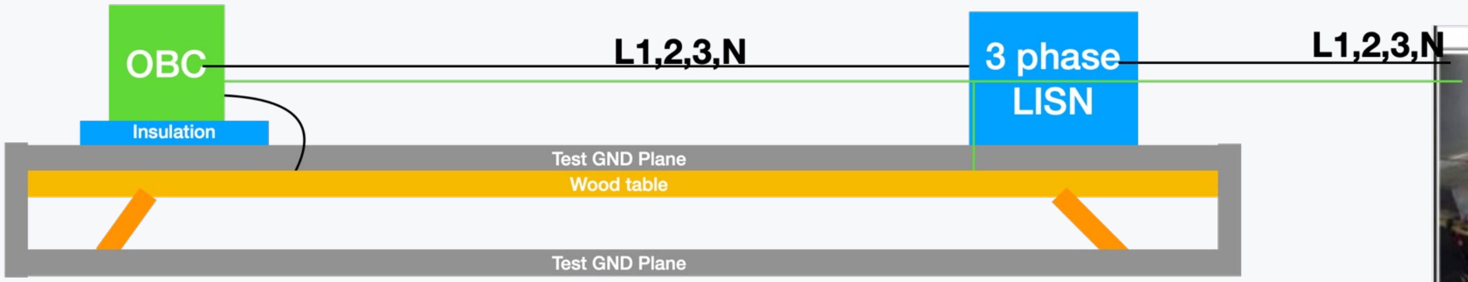


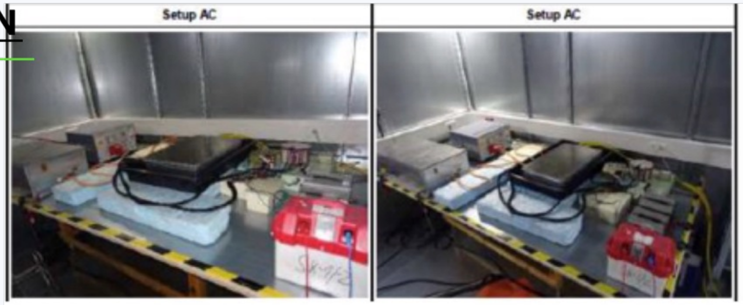


Conducted emissions set-up - CISPR 25

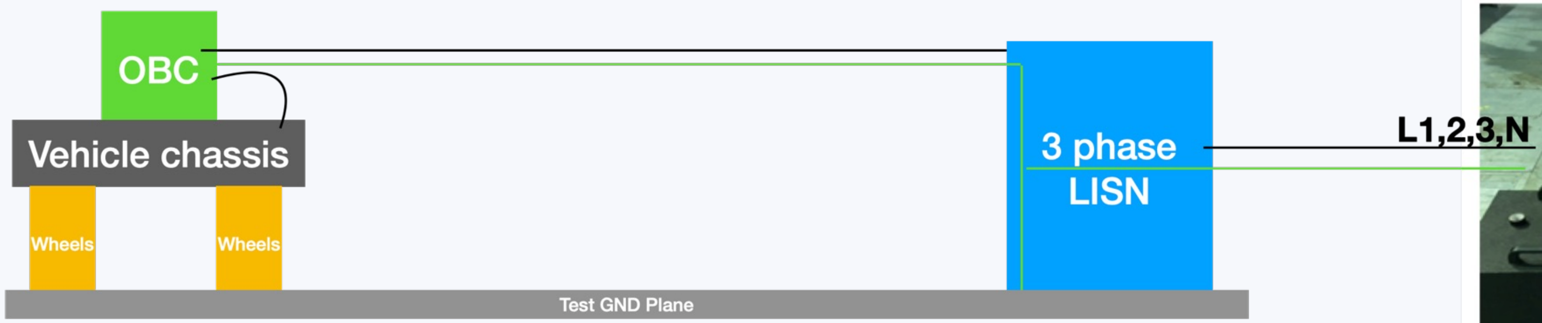
A popular mili-ohmmeter used for checking the continuity of the ground plane and LISN connections

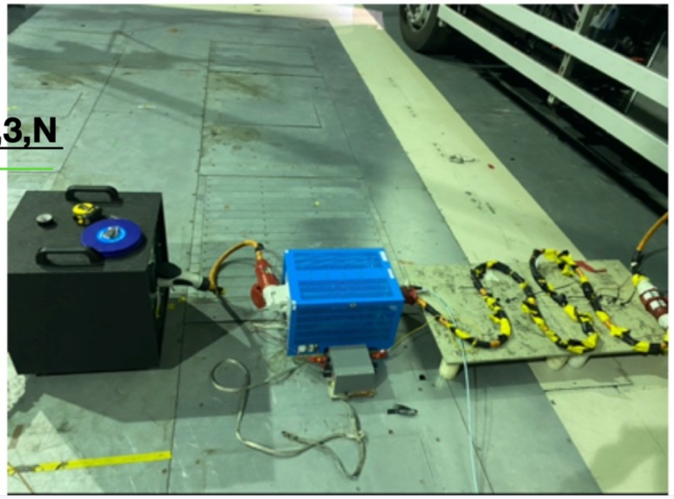
The On-Board Charger “Ground” Puzzle





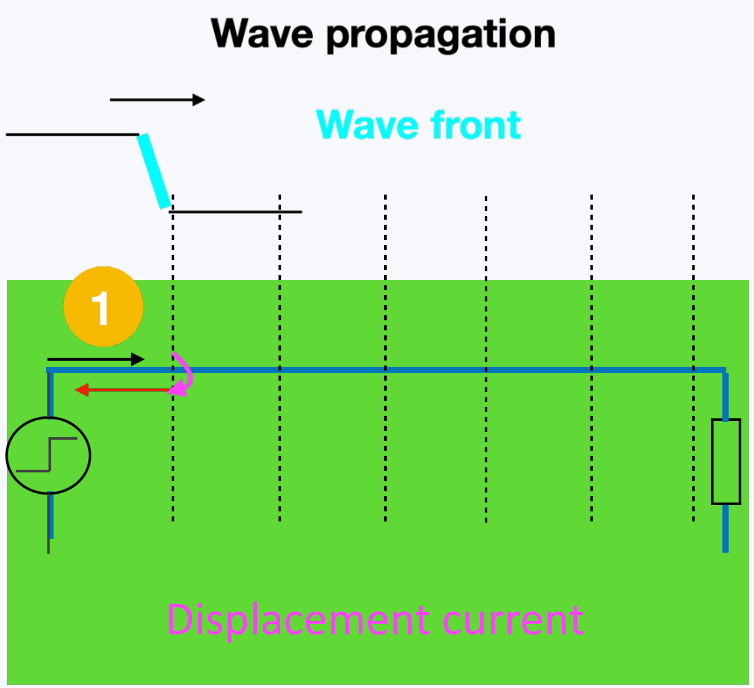
Component test - The test ground plane is connected to the 3-phase LISN, with the PE wire connected; eventually, this ground plane is connected to Earth.

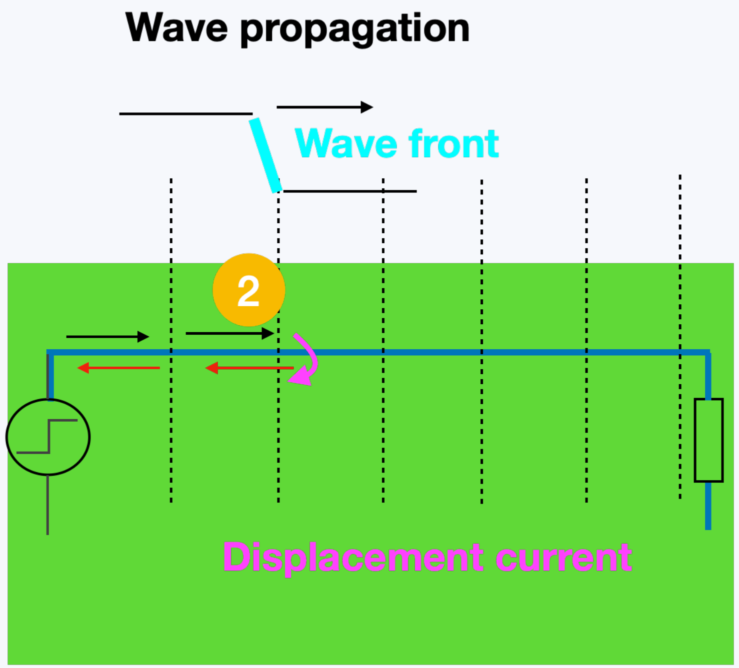


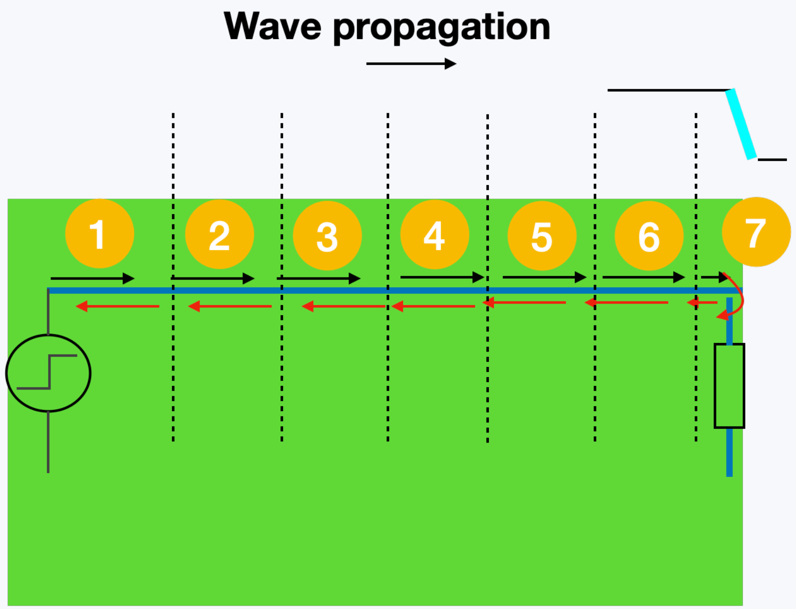


Vehicle test - Very similar to the component test, but there is no electrical connection between the vehicle chassis and the test ground plane.
The vehicle chassis cannot be compared with a test ground plane (in terms of conductivity) either.

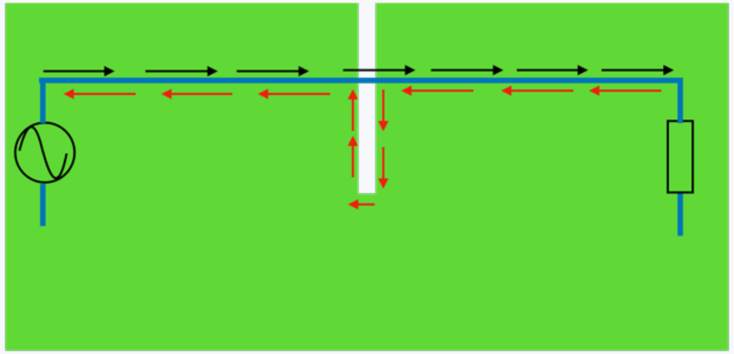
The Return Current Path



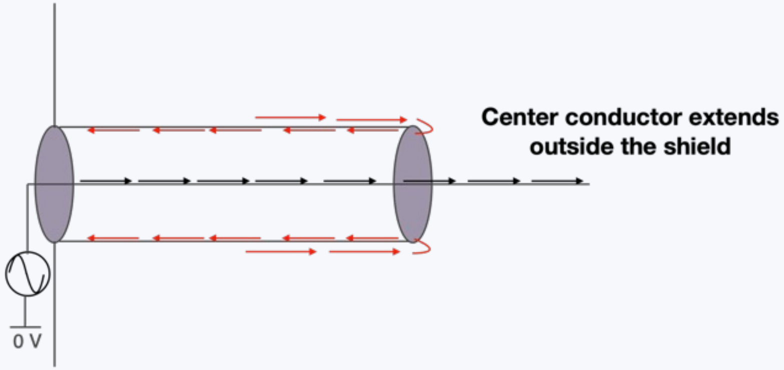




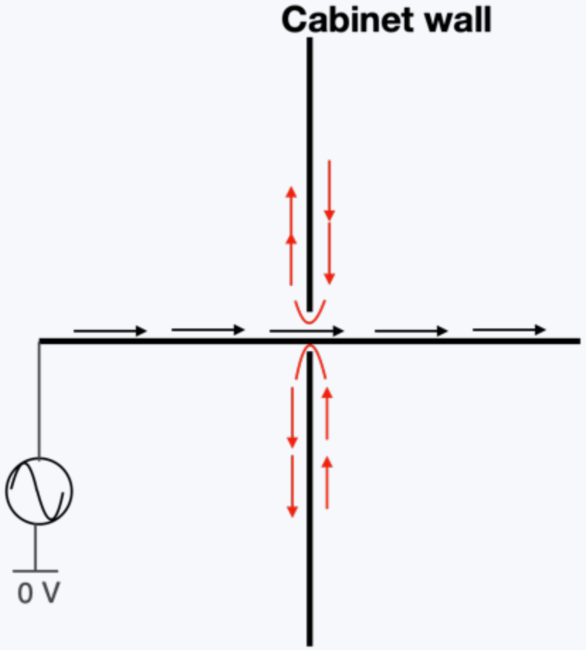
Common "Ground" Issues



Ground plane break



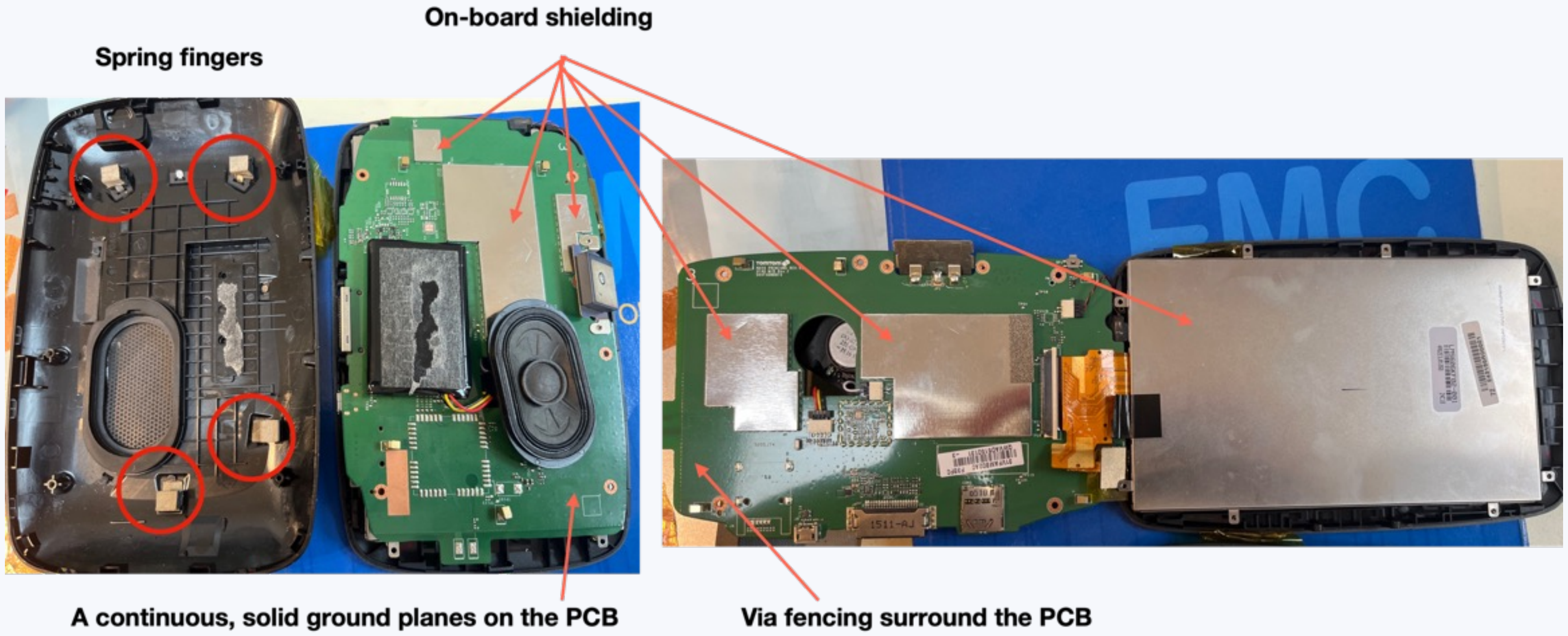
Conductor extends outside the shield

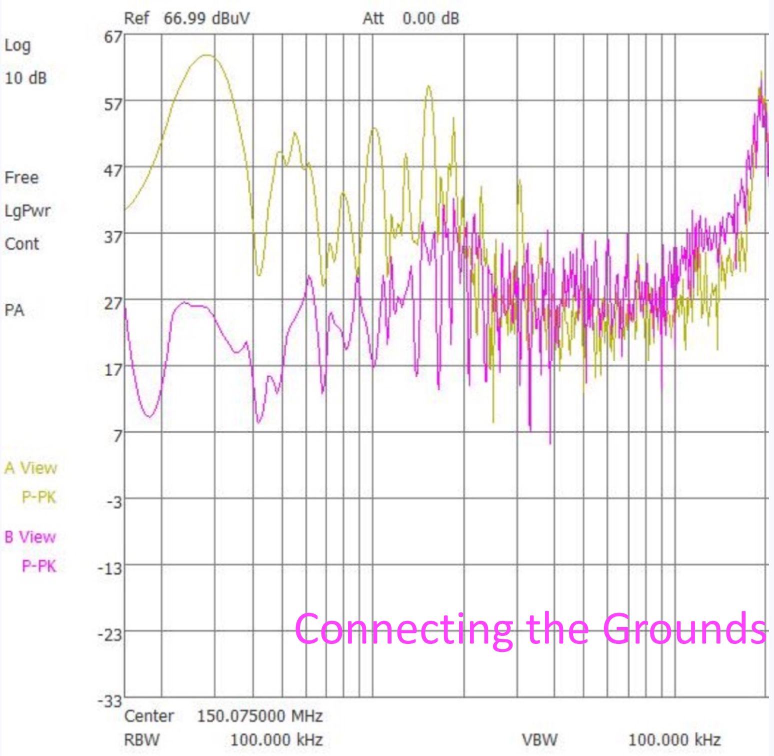


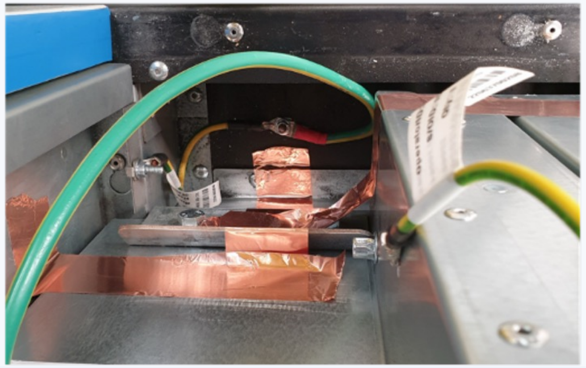
Wires penetrating into an enclosure

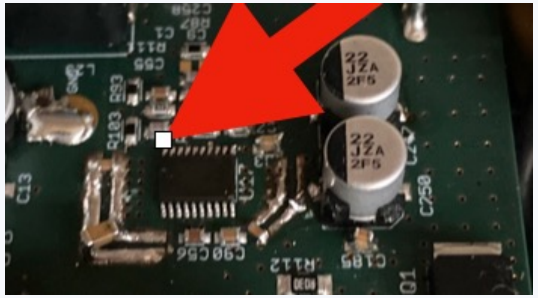
- Ferrite/Magnetic core has no improvement in emissions.
- Capacitors to chassis (common mode caps) make no difference/make things worse.
- "Balloon effect"
- Ineffective shielding
- Susceptible to immunity issues

We Need One Ground and One Ground Only

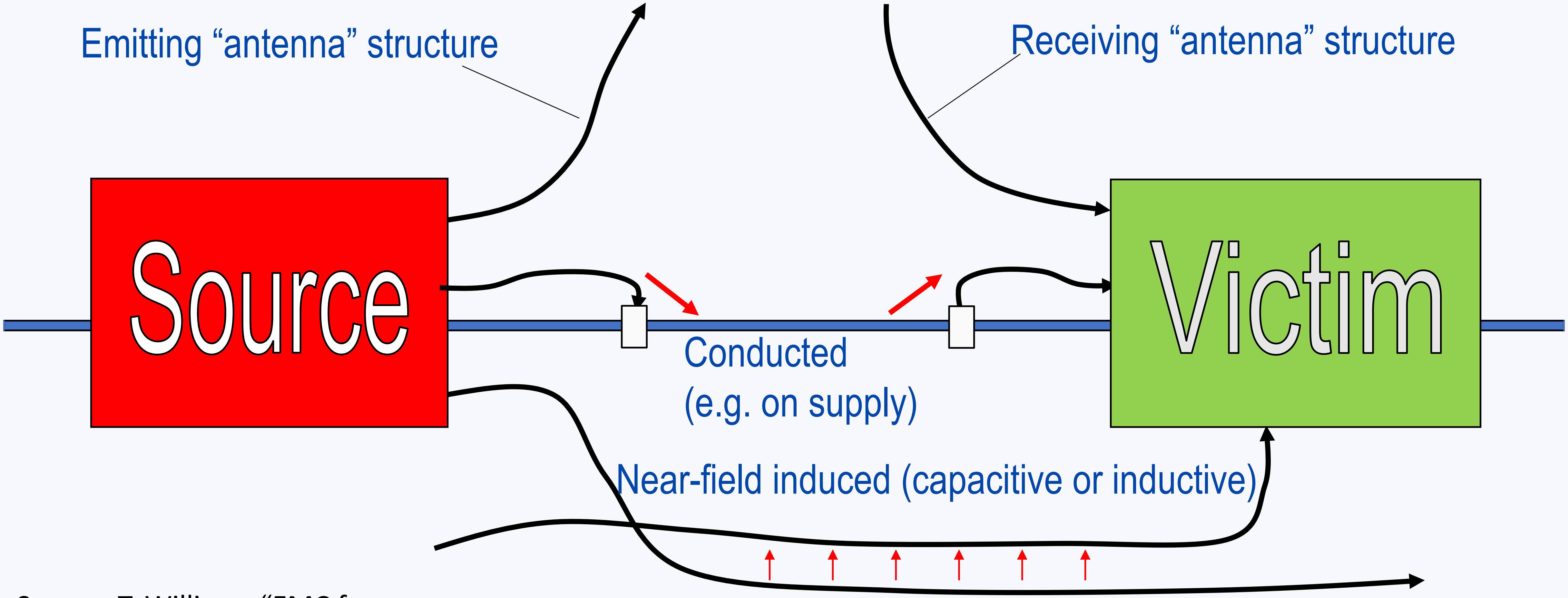






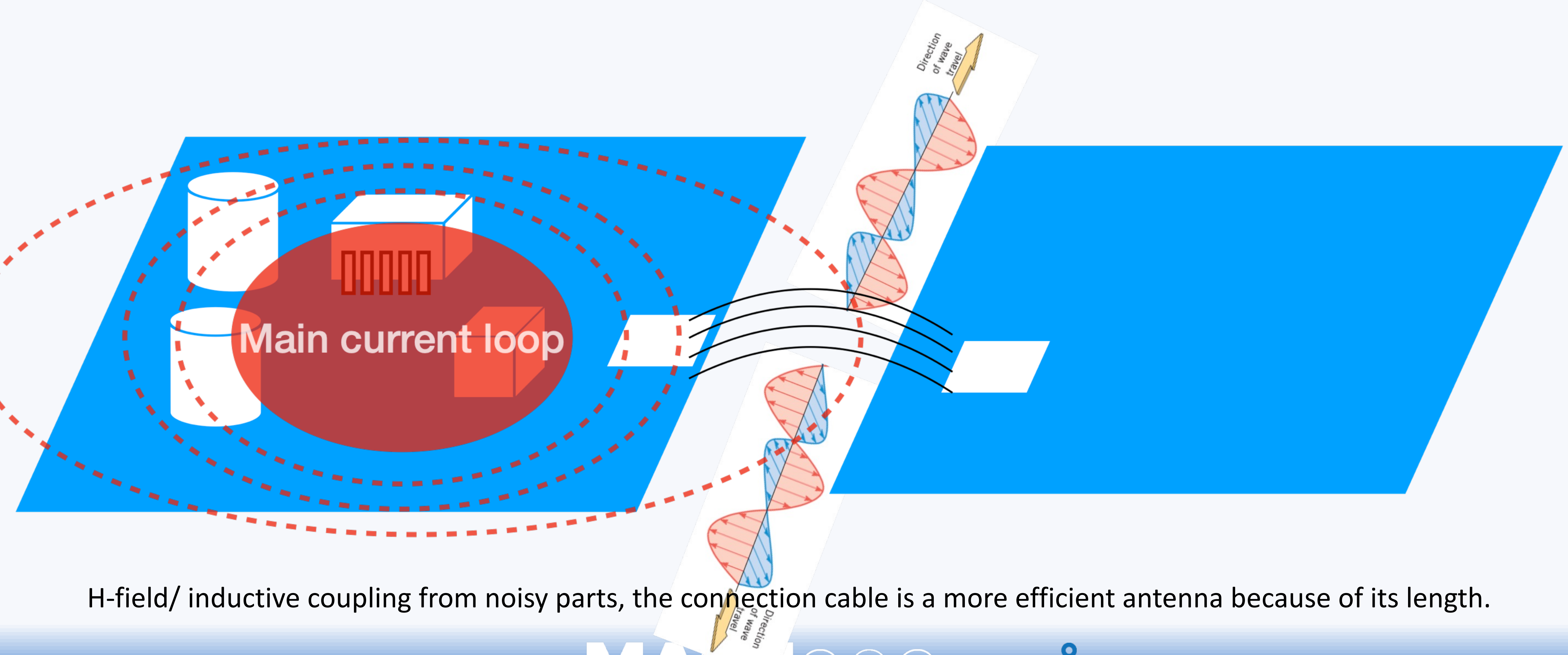


Coupling Mechanism



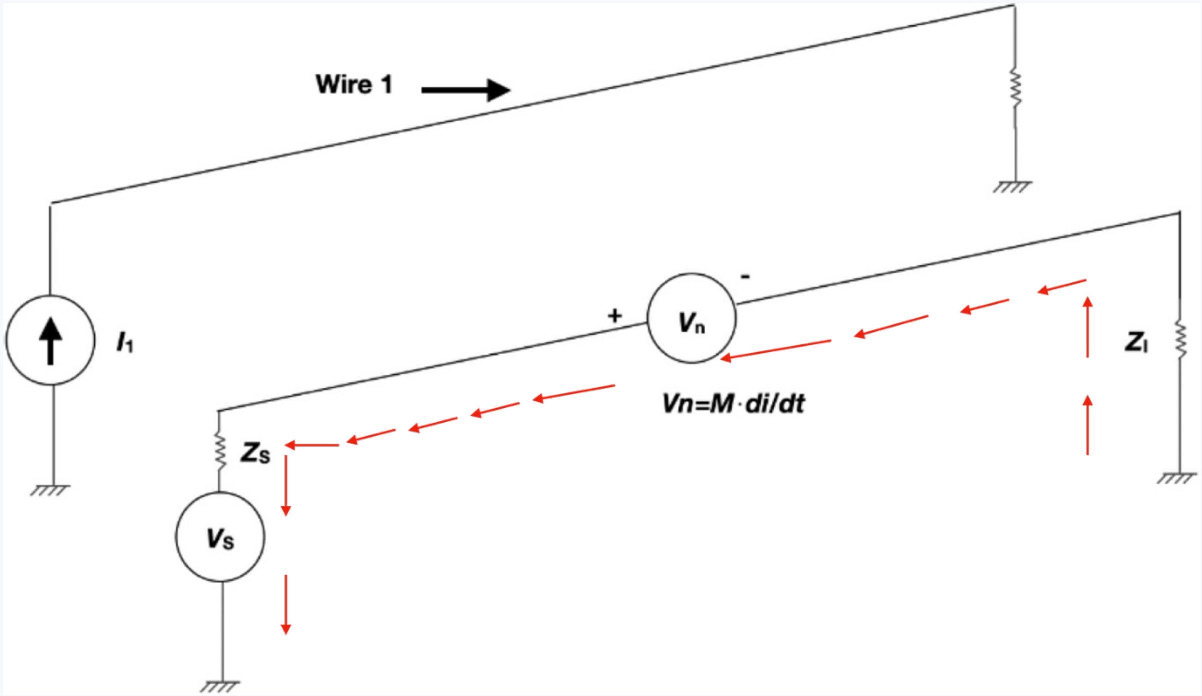
Source: T. Williams "EMC for Product Designers"

Near-field coupling: Magnetic Field/Inductive Coupling



H-field/ inductive coupling from noisy parts, the connection cable is a more efficient antenna because of its length.

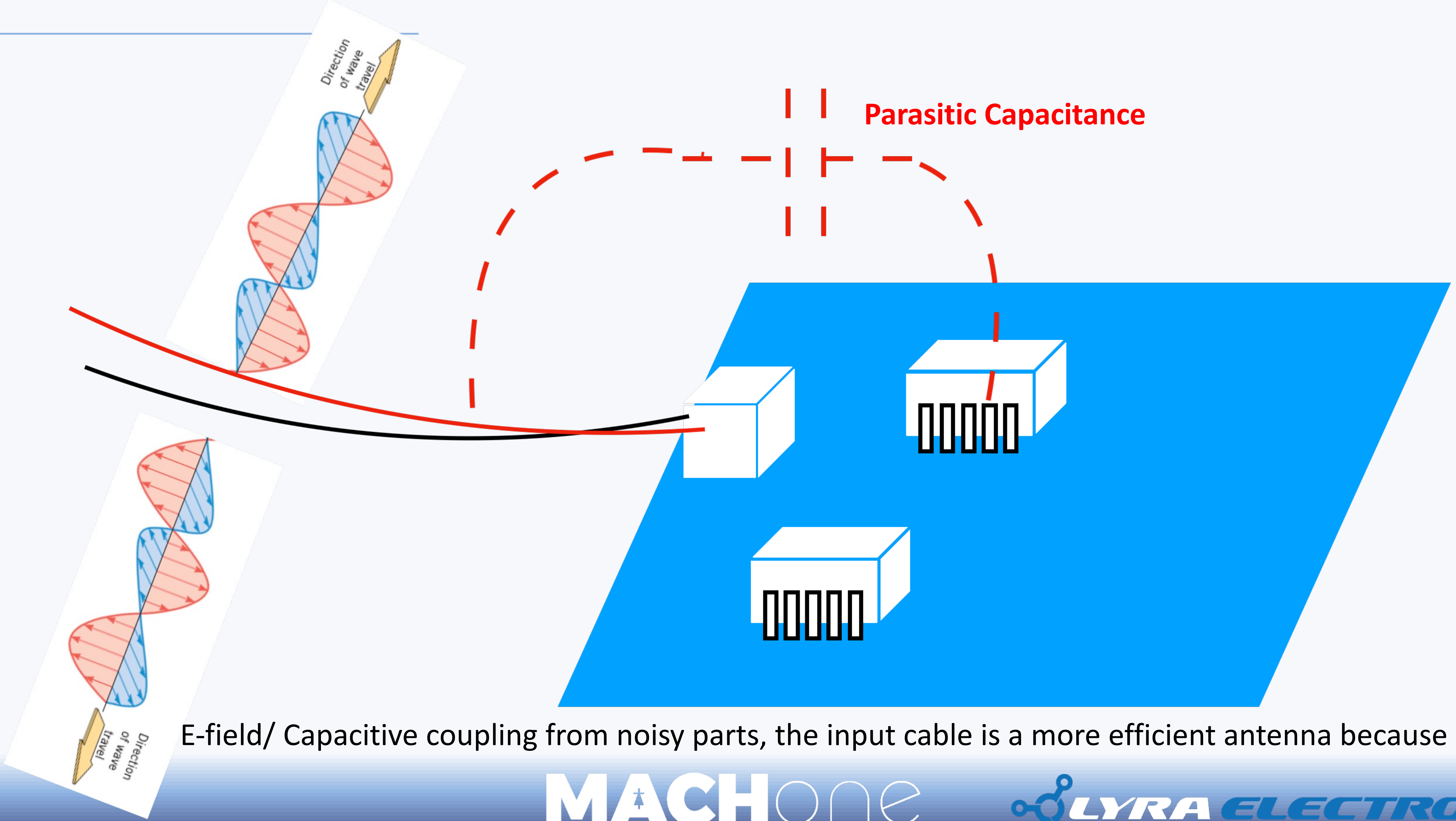
Near-field coupling: Magnetic Field/Inductive Coupling



- Two conductors represent two parallel run wires, traces over a PCB, etc.
- Ignoring the capacitance effect in this example.
- I_1 represents the noise source, in this case, it is a current source.
- What is the induced interference voltage on Z_l ?

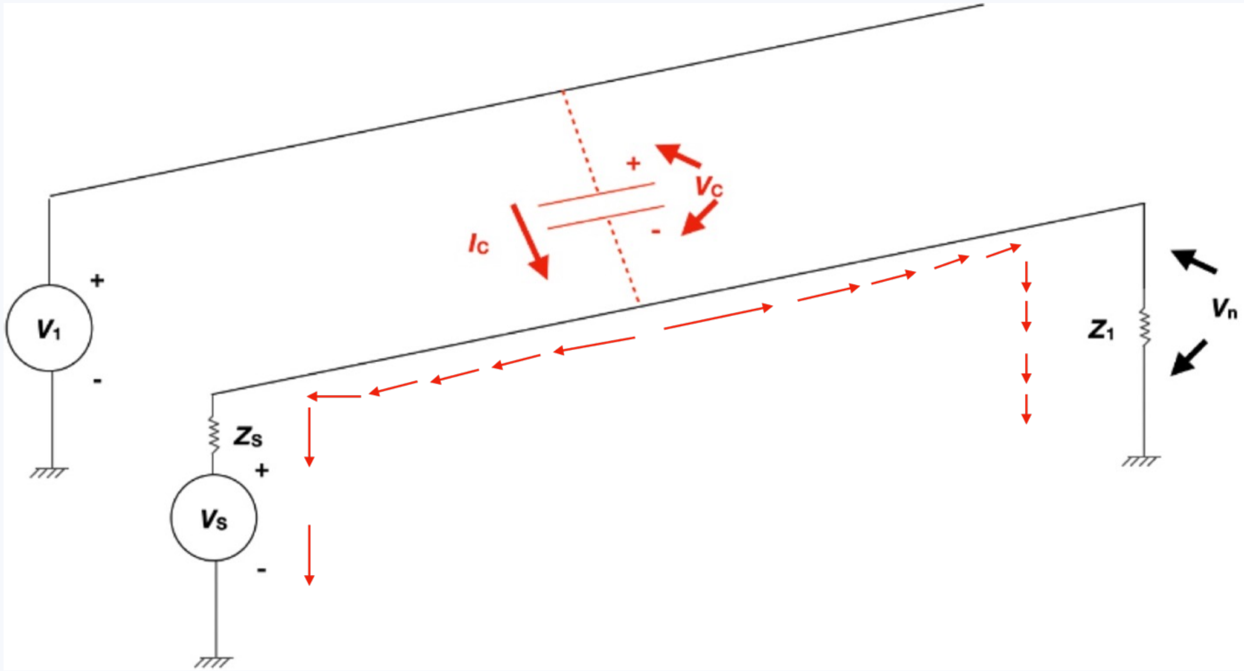
$$V_l = M\frac{dI_1}{dt}\frac{Z_l}{Z_S + Z_l}$$

Near-field coupling: Electric Field/Capacitive Coupling



E-field/ Capacitive coupling from noisy parts, the input cable is a more efficient antenna because of its length.

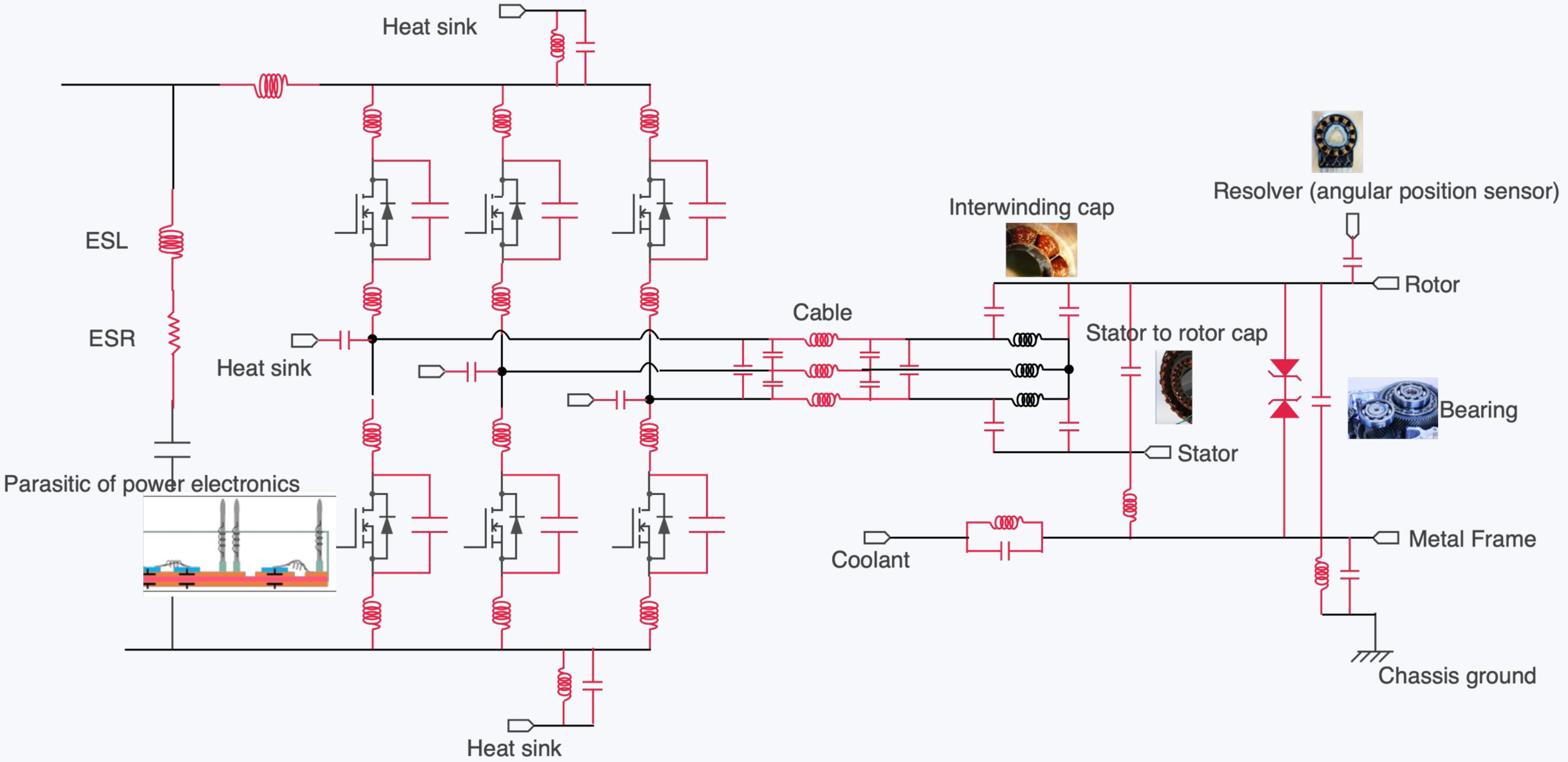
Near-field coupling: Electric Field/Capacitive Coupling



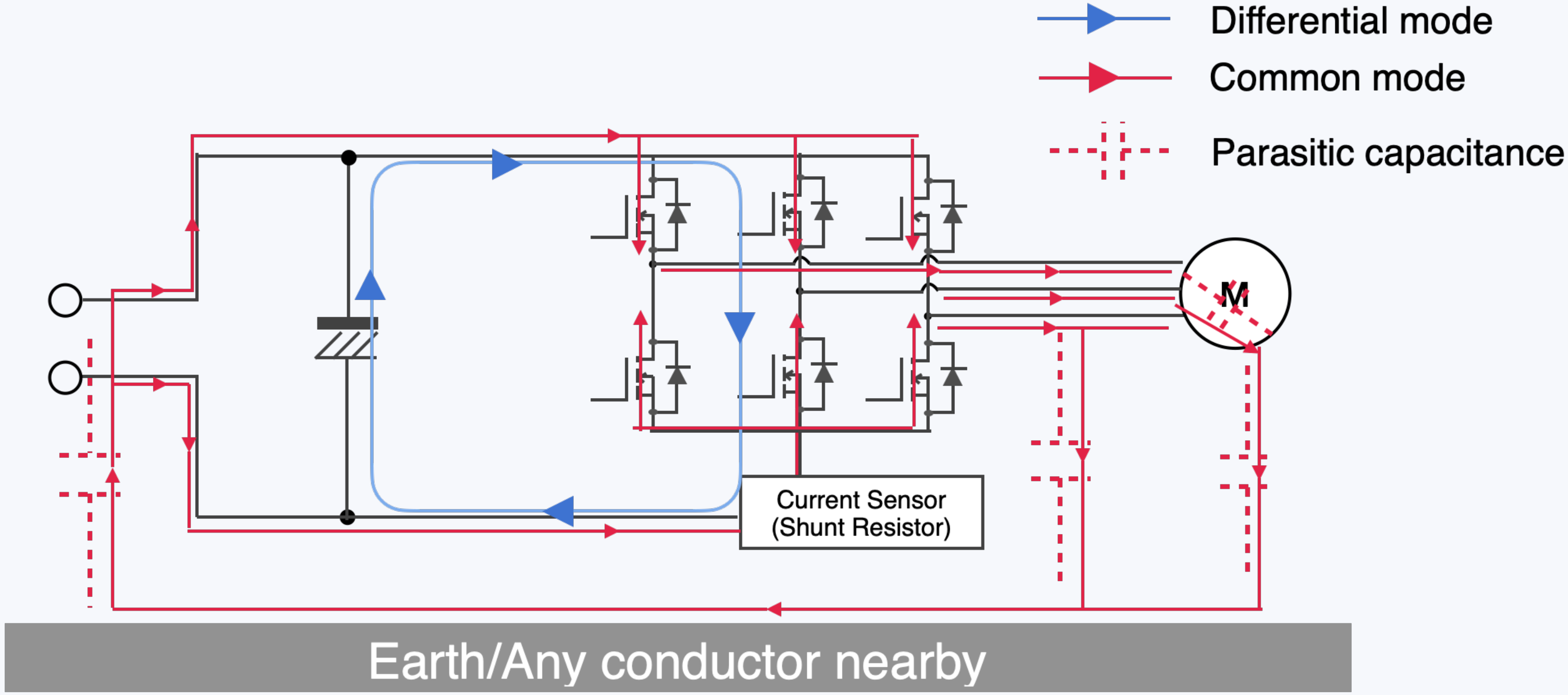
- Two conductors represent two parallel run wires, traces over a PCB, etc.
- Ignoring the inductance effect in this example.
- V_1 represents the noise source.
- What is the induced interference voltage on Z_l?

$$V_n = C\frac{dV_1}{dt}(Z_S||Z_l)$$

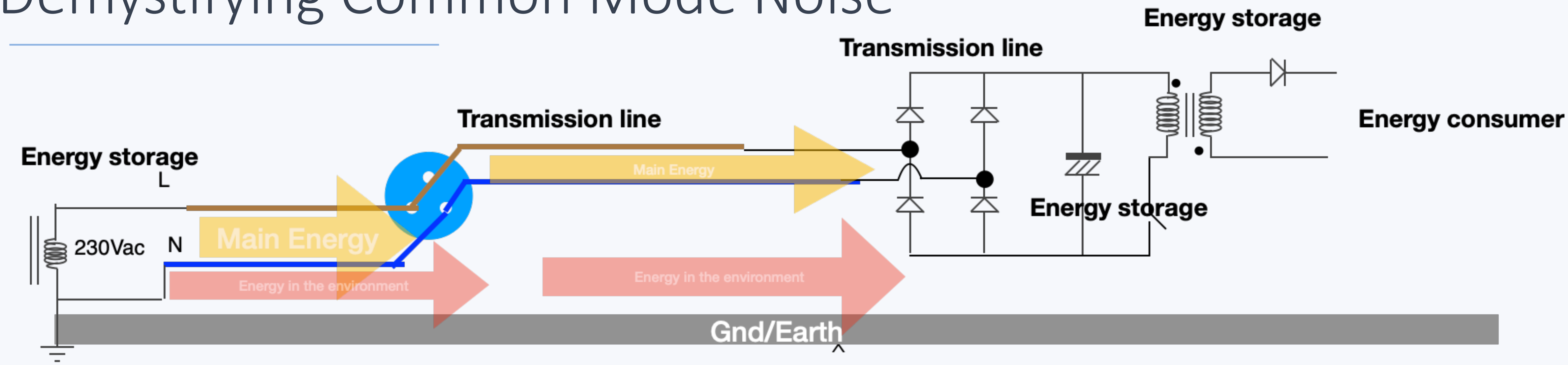
Understanding Coupling and Parasitics

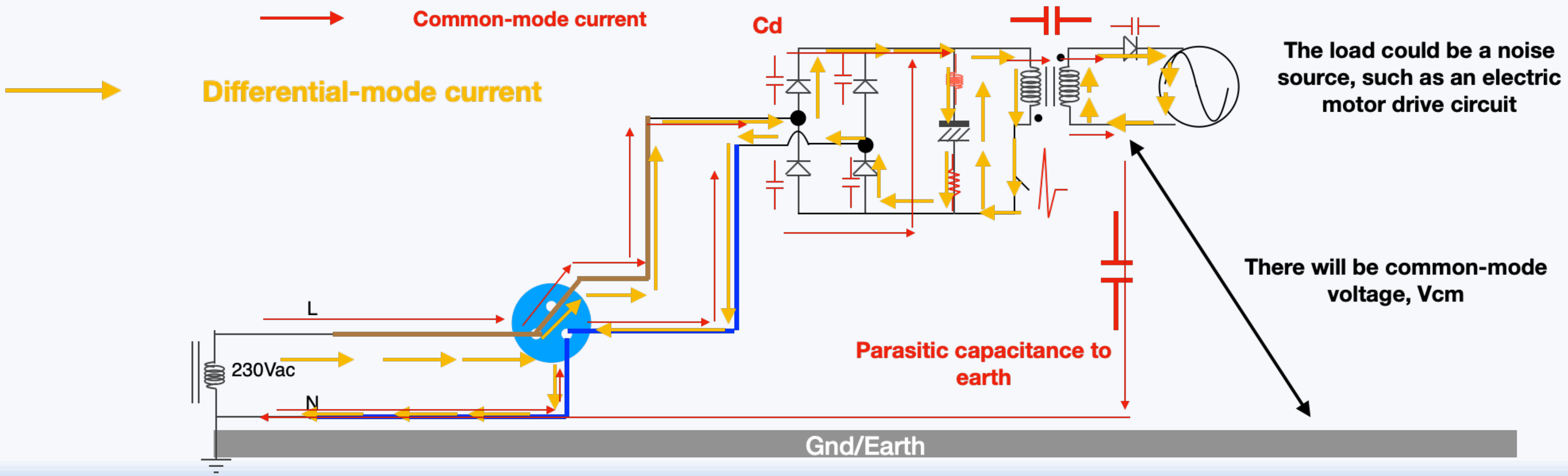


Understanding Coupling and Parasitics:

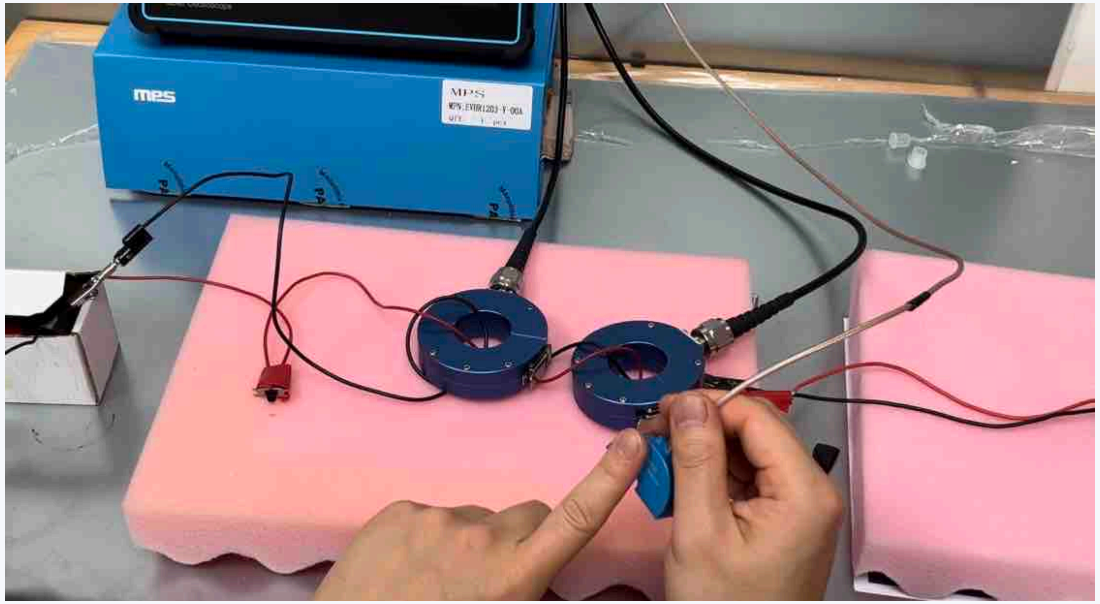


Demystifying Common Mode Noise

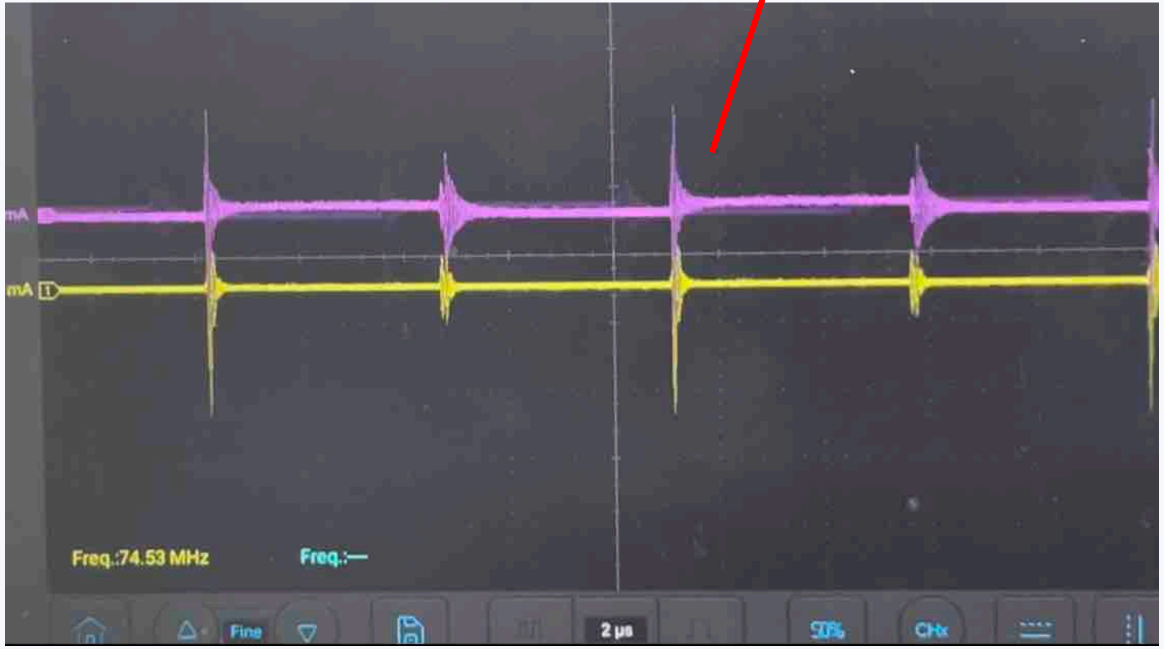




Measuring the Common Mode Noise

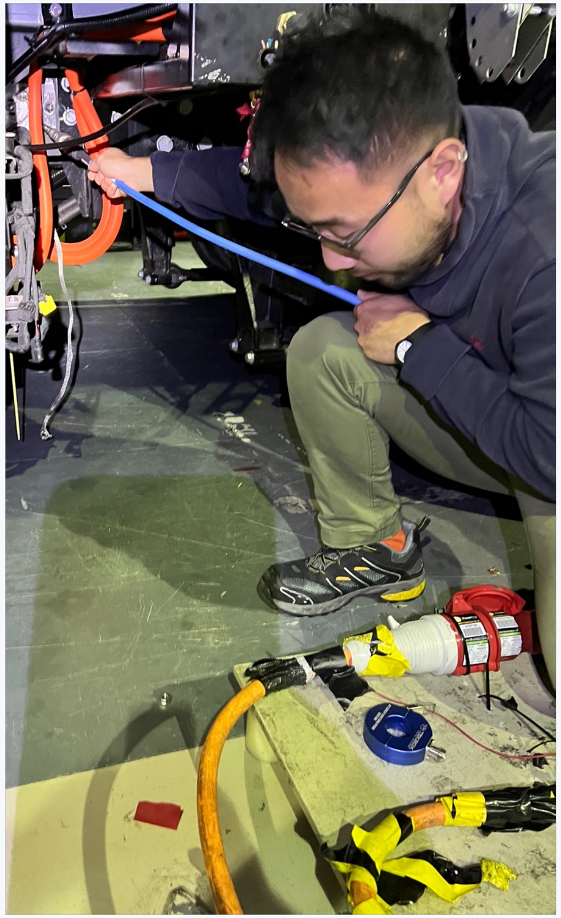


Using RF current probes

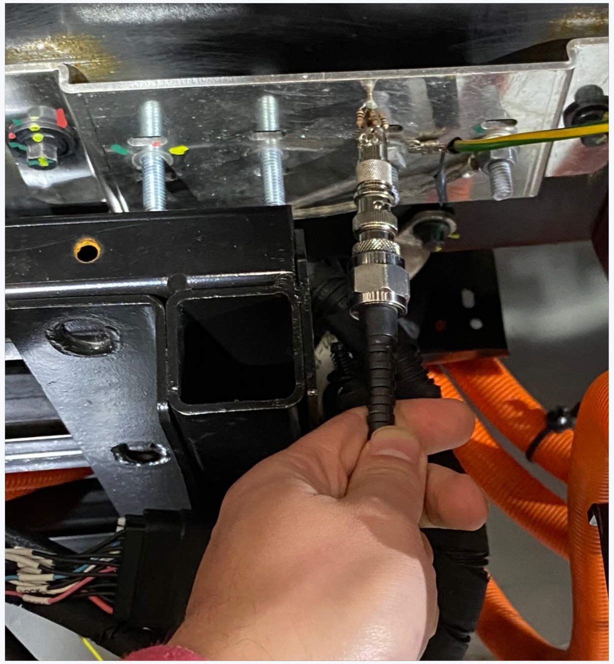


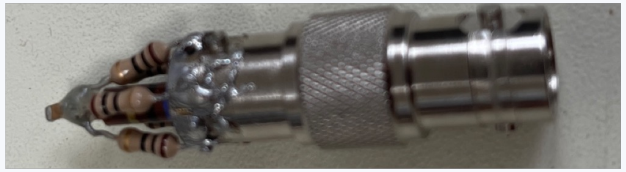
Forward common mode current and return current

Measuring the Common Mode Noise

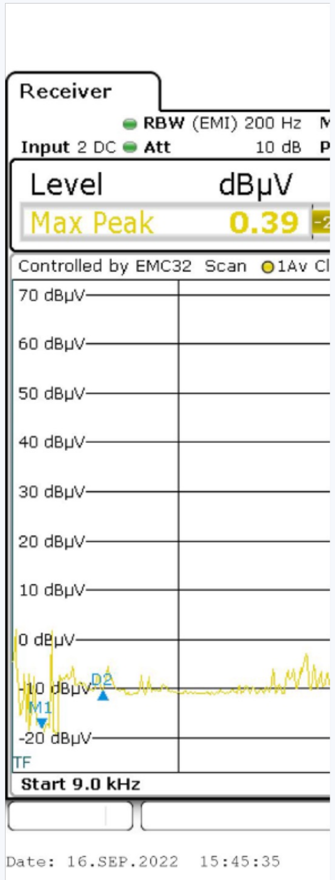


Measuring surface currents on the vehicle chassis

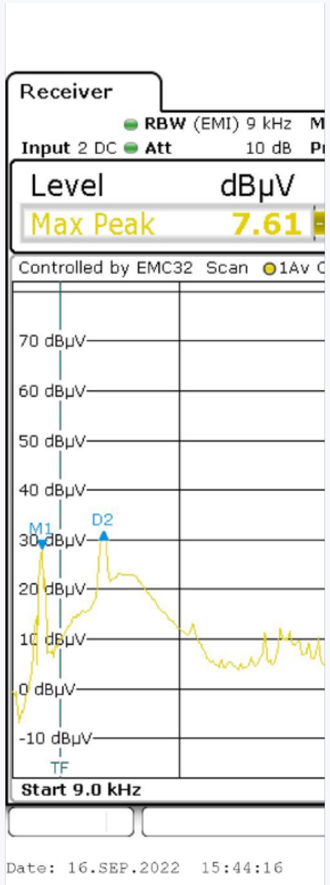




A home-made resistive probe



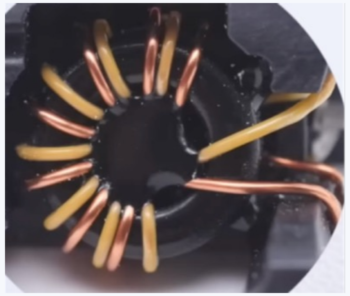
(a) when the OBC was off



(b) when the OBC was on

The surface noise was measured in the low-frequency range

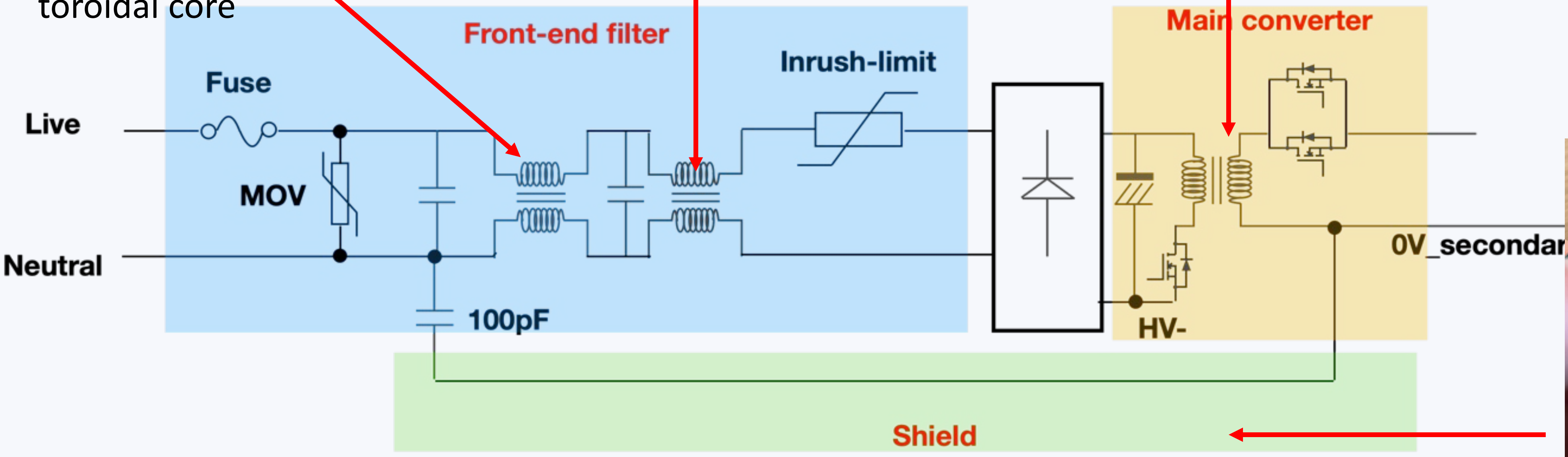
Understanding Coupling and Parasitics: The Key to Designing EMC Filters



Bifilar winding on a toroidal core

Flat-wire winding on a sectional wound CMC

A magnetic flux band around the transformer



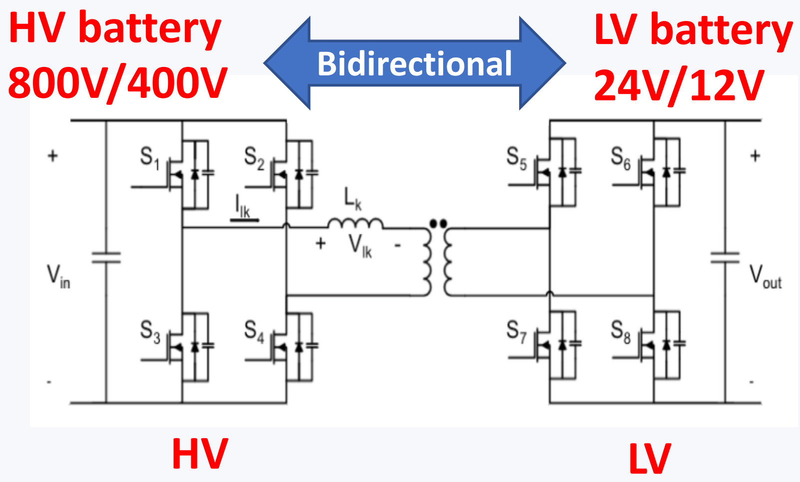
A simplified isolated power supply circuit using GaN devices

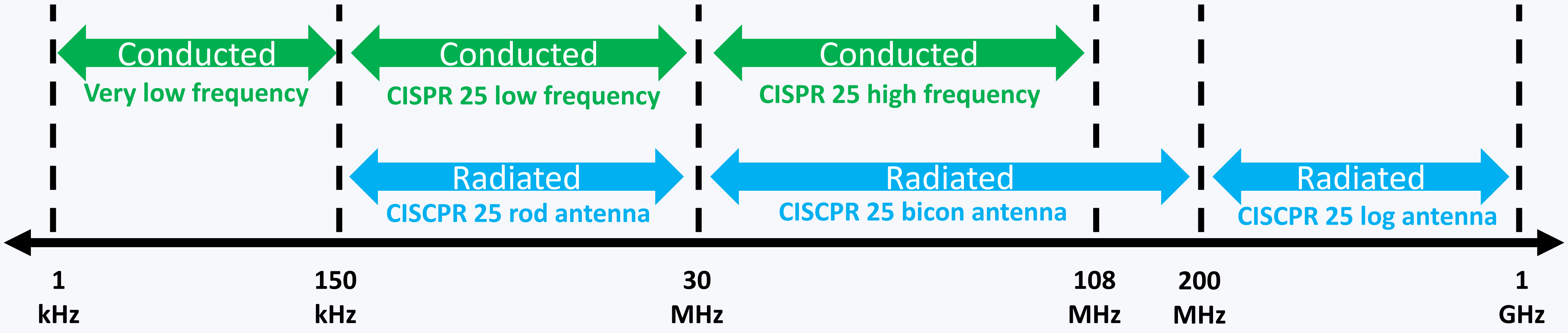
Benchtop EMC Testing

EMI can no longer be an after thought!

- CISPR 25 Automotive EMC standard
  - Conducted Emissions: 150kHz-108MHz
  - Radiated Emissions: 30MHz-2.5GHz

Lyra’s 4kW SiC DC-DC Converter



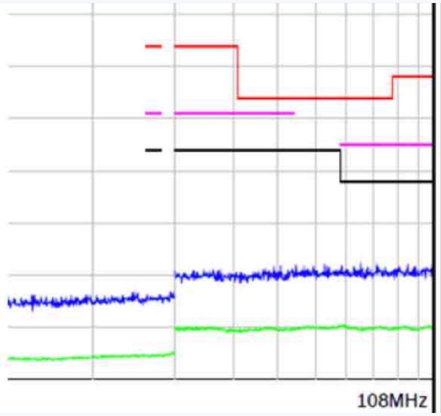


CISPR 25 Testing Methods

- CISPR25 defines two methods for conducted emissions testing:
  - Current probe method
  - Voltage method.
- Both methods can be used to determine if the device under test (DUT) passes or fails the emission test limits.
- Test method is defined by the OEM requirements.

Table 1. CISPR25 Class 5 Peak Limits for Voltage Method and Current Probe Method

Frequency (MHz)	Voltage Method (dBμV)	Current Probe Method (Converted to dBμV)
0.15 to 30	70	84
0.53 to 1.8	54	60
5.9 to 6.2	53	53
76 to 108	38	38
26 to 28	44	44
30 to 54	44	44
68 to 87	38	38

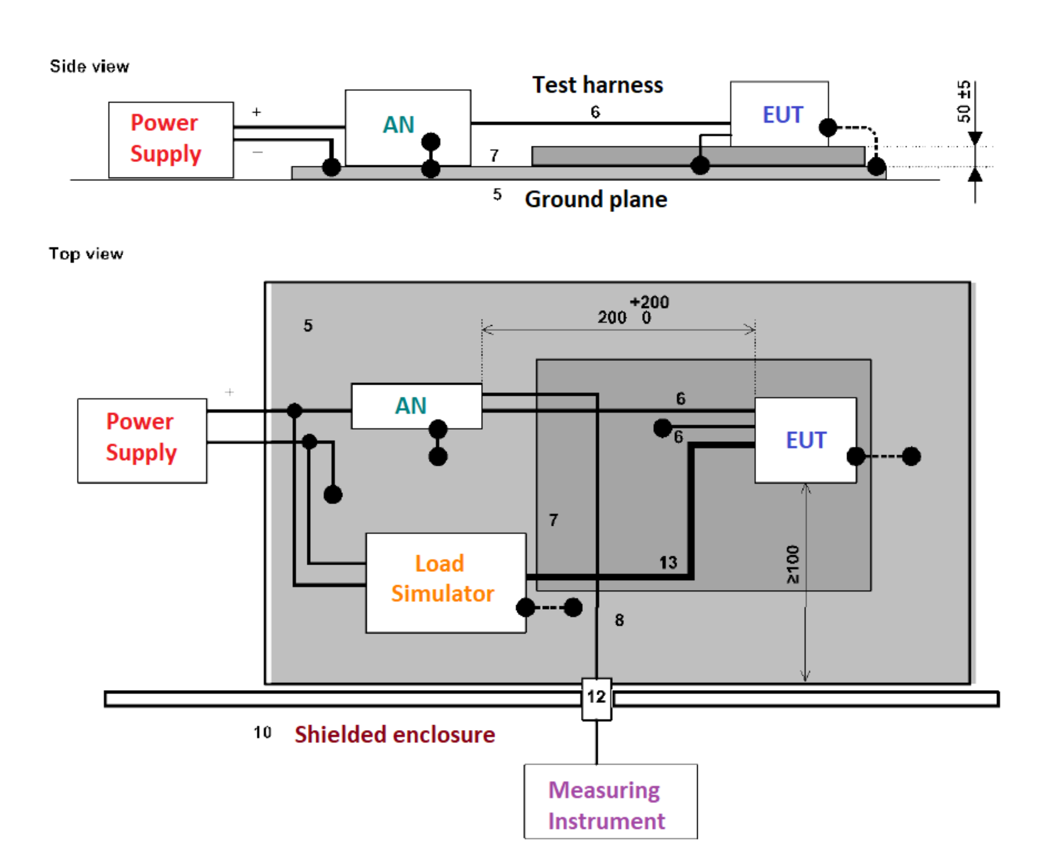


Current measurement across a resistance of 50 Ω

38 dBμV	79.4 μV	1588 nA
25 dBμV	17.8 μV	356 nA
18 dBμV	7.94 μV	159 nA

This is the limit for a 48-12V DC-DC which often has a power of 700W. But it is exactly the same limit for a 600V-12V DC-DC which has a power of 3kW, same limit for an electric motor whose power exceeds 250 kW.

CISPR 25 Conducted Emissions Test Setup

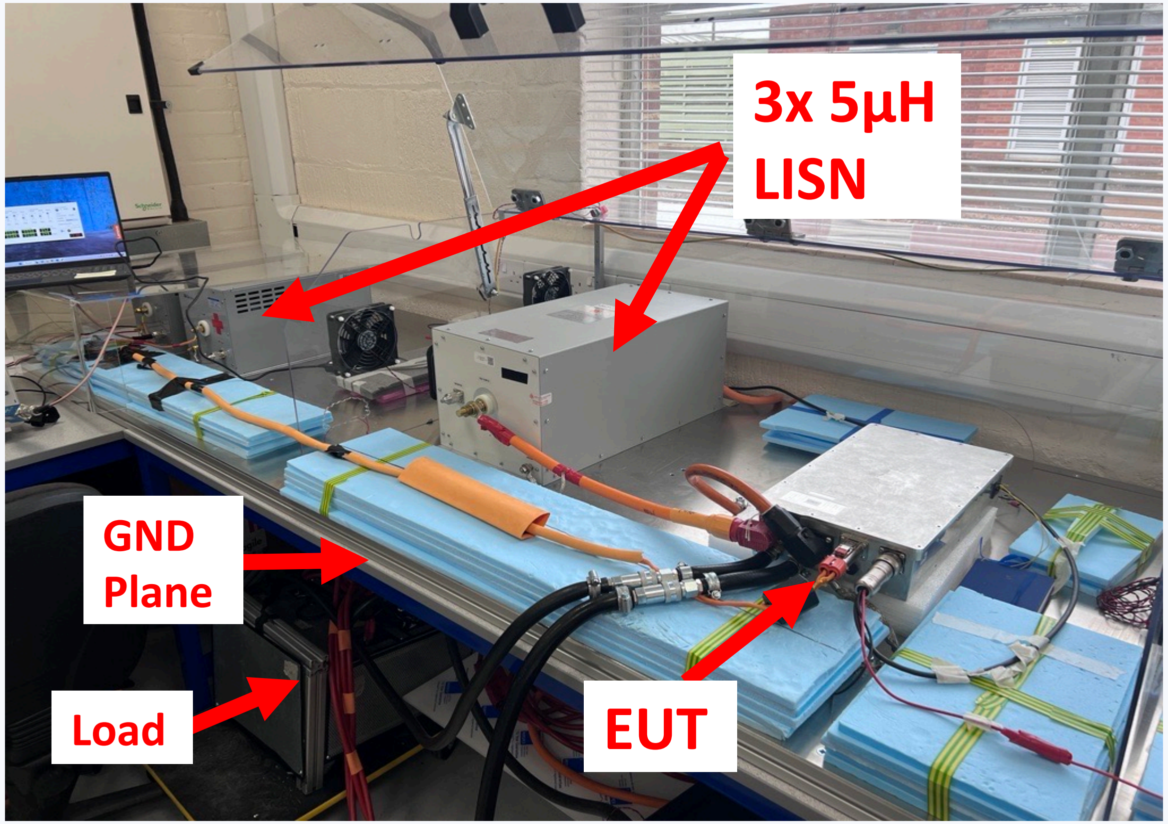


7 Low relative permittivity support ($\varepsilon_r \leq 1,4$)

8 High-quality coaxial cable e.g. double-shielded (50 Ω)

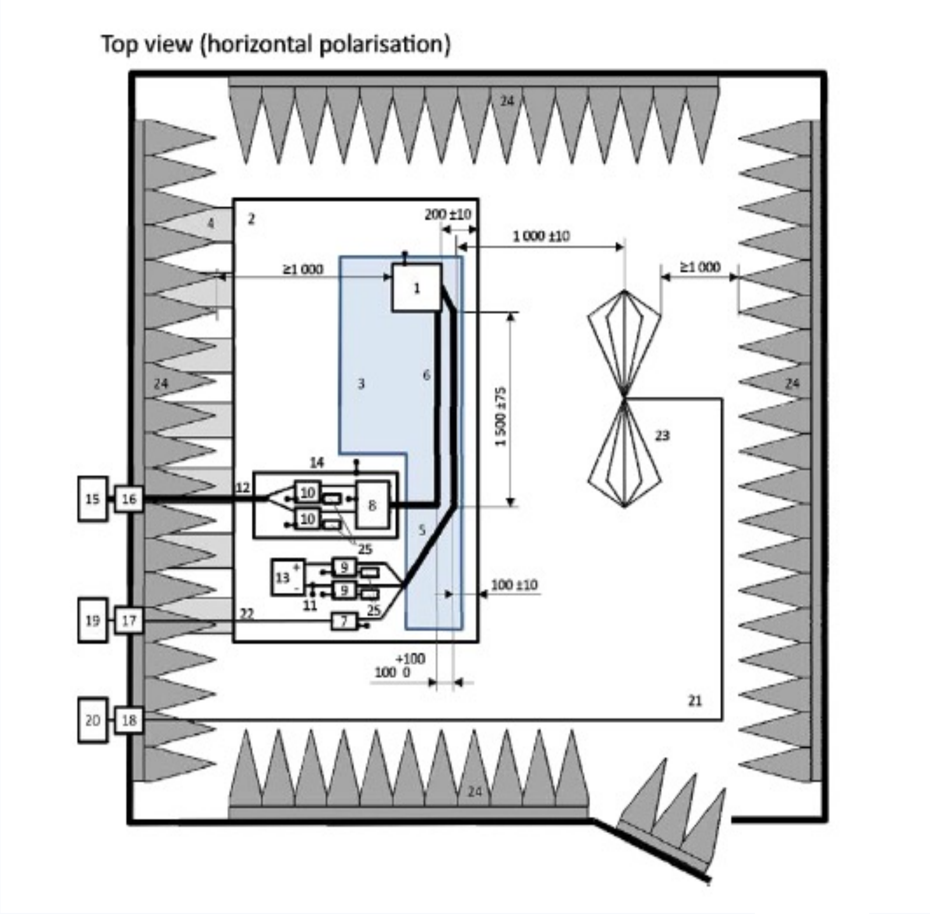
EUT with power return line locally grounded

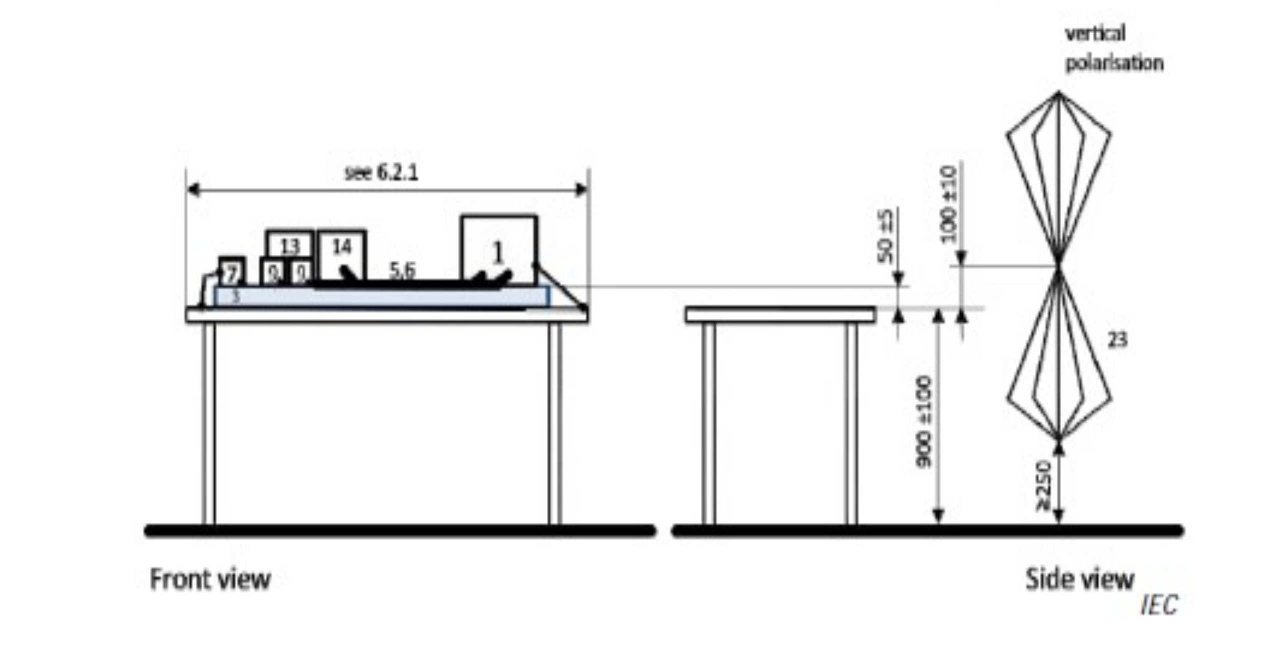
[1]CISPR 25:2016 © IEC 2016



Test setup at Lyra

CISPR 25 Radiated Emissions Test Setup



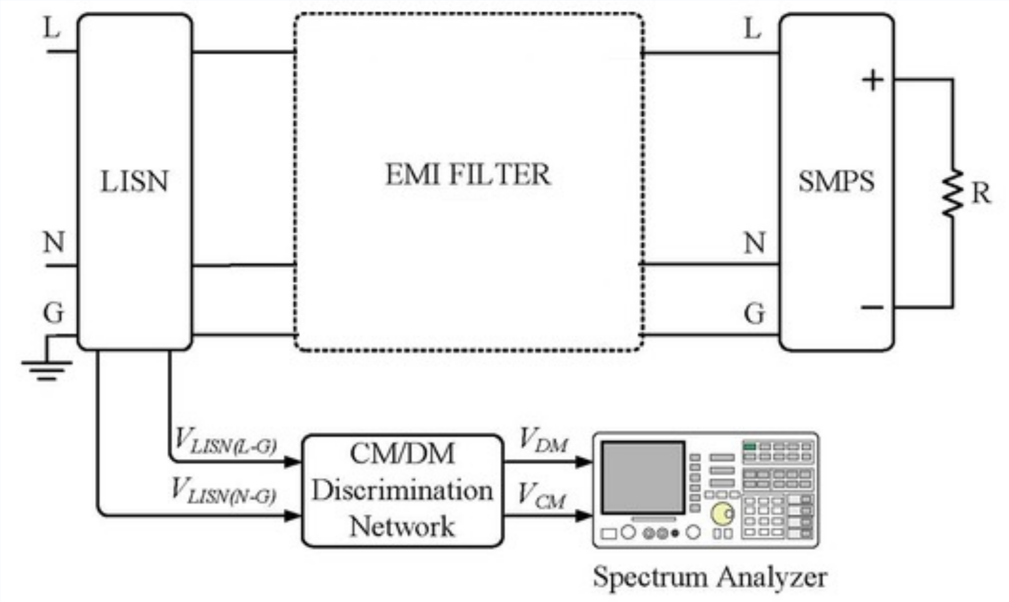


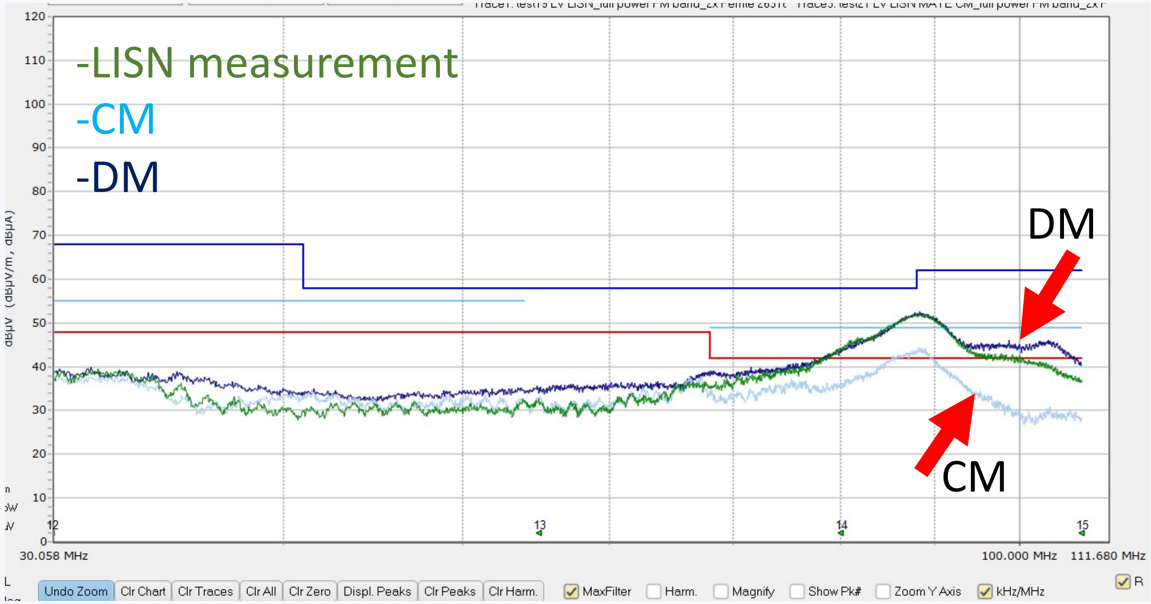
Key

1 EUT
2 Reference ground plane
3 Low relative permittivity support ($\varepsilon_r \le 1{,}4$) thickness 50 mm
4 Ground straps (see 6.2.1)
5 LV harness
6 HV lines (HV+, HV−)
7 LV load simulator
8 Impedance matching network (optional)
9 LV AN
10 HV AN
11 LV supply lines
12 HV supply lines
13 LV power supply 12 V / 24 V / 48 V (should be placed on the reference ground plane)
14 Additional shielded box
15 HV power supply (should be shielded if placed inside ALSE)
16 Power line filter
17 Fibre optic feed through
18 Bulk head connector
19 Stimulating and monitoring system
20 Measuring instrument
21 High quality coaxial cable e.g. double shielded (50 Ω)
22 Optical fibre
23 Biconical antenna
24 RF absorber material
25 50 Ω load

Measurement of Conducted Emissions with LISNs (CM & DM)

- Spectrum analyser cannot distinguish between differential mode and common mode noise.
- CM/DM discrimination network can be placed between the LISN and the spectrum analyser to separate the differential mode voltage and the common mode energy.

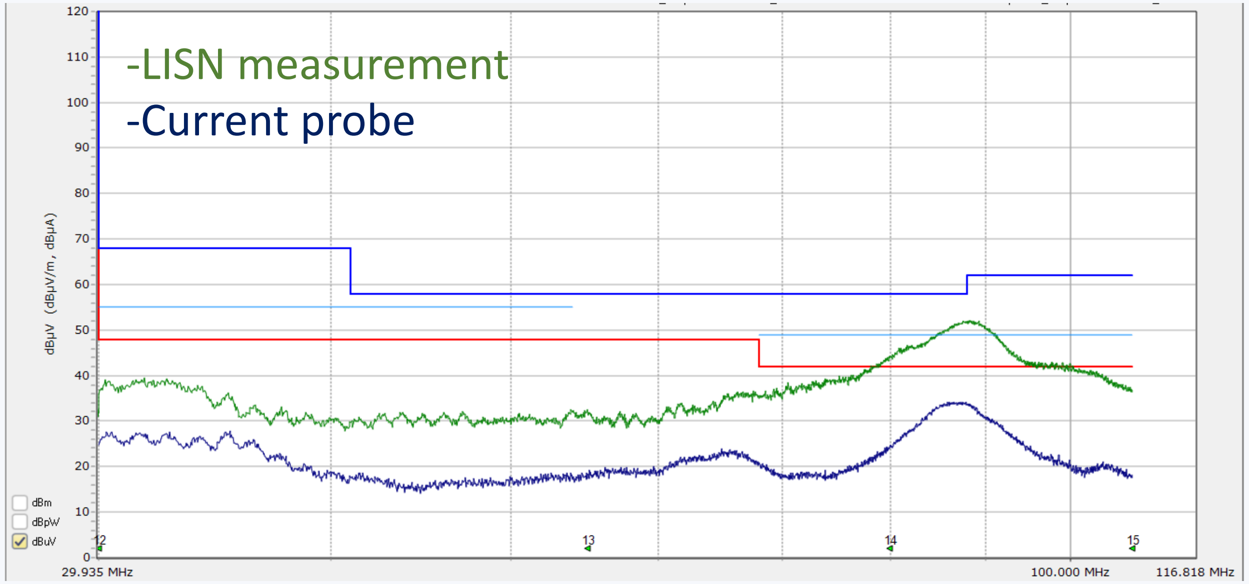




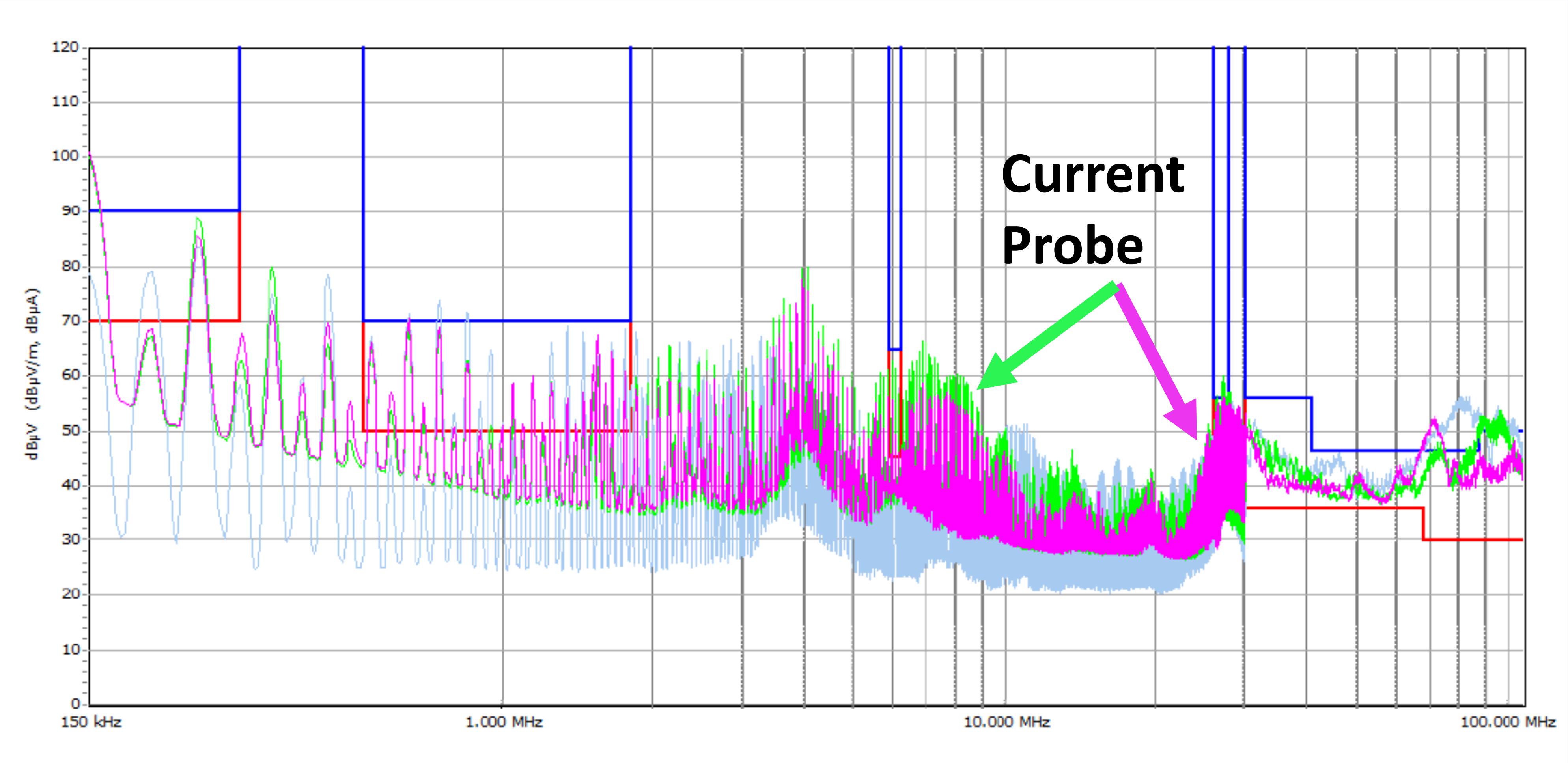
K. Y. See, "Network for conducted EMI diagnosis," IEE Electron. Lett., vol. 35, no. 17, pp. 1446–1447, Aug. 1999.

Current Probe & LISN Measurement

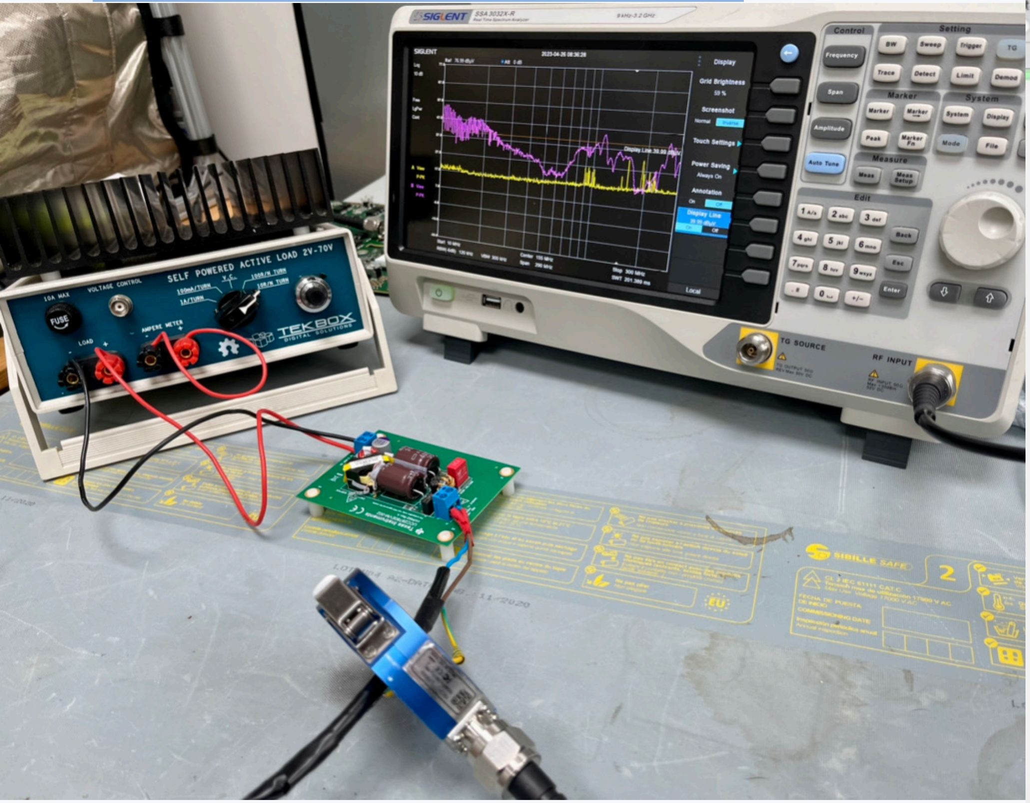
- Current probe method and the voltage method yield very similar results in lower frequencies, below 5 MHz.
- Difference in results in higher frequencies, above 5MHz.

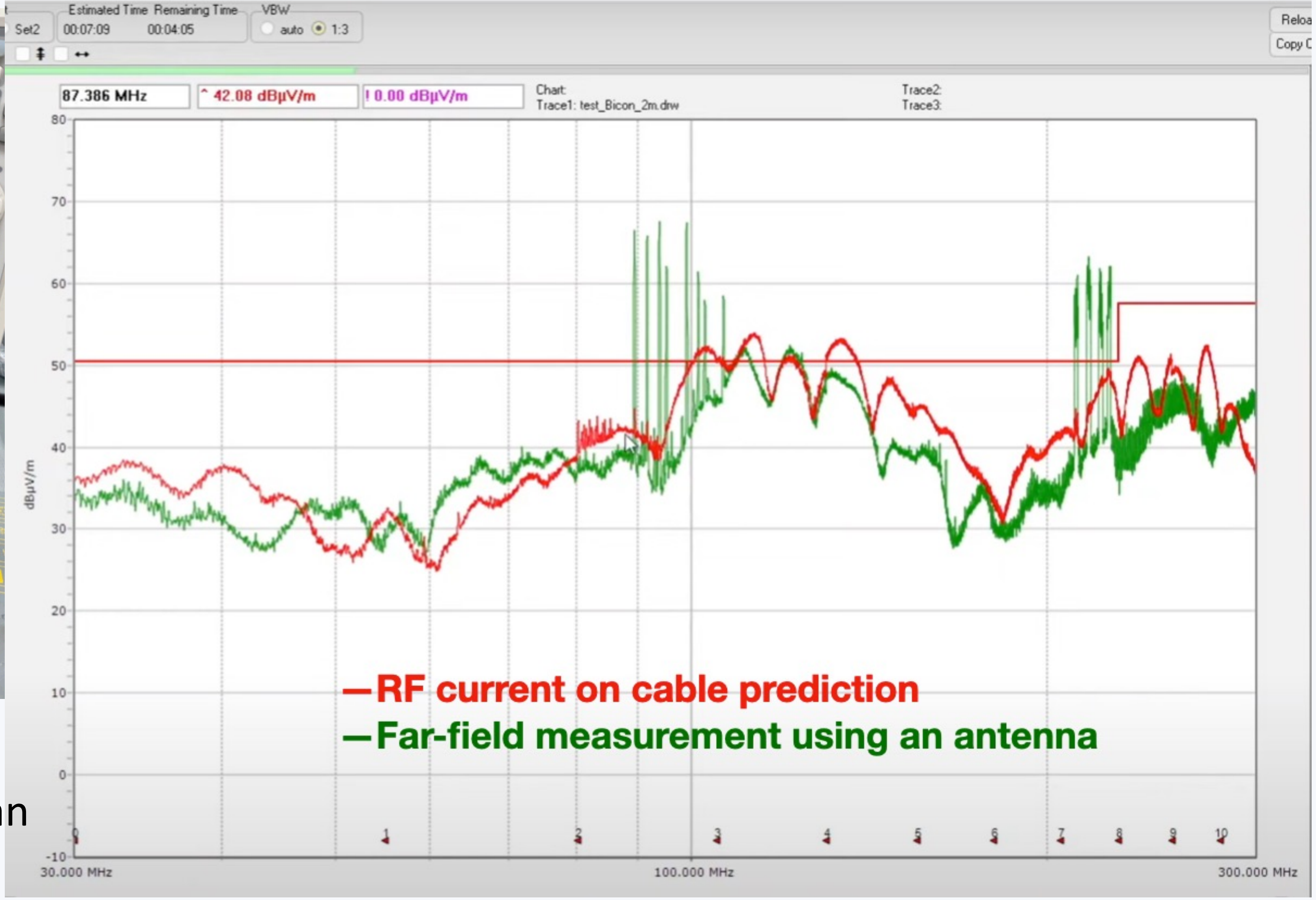


Current Probe vs LISN Measurement



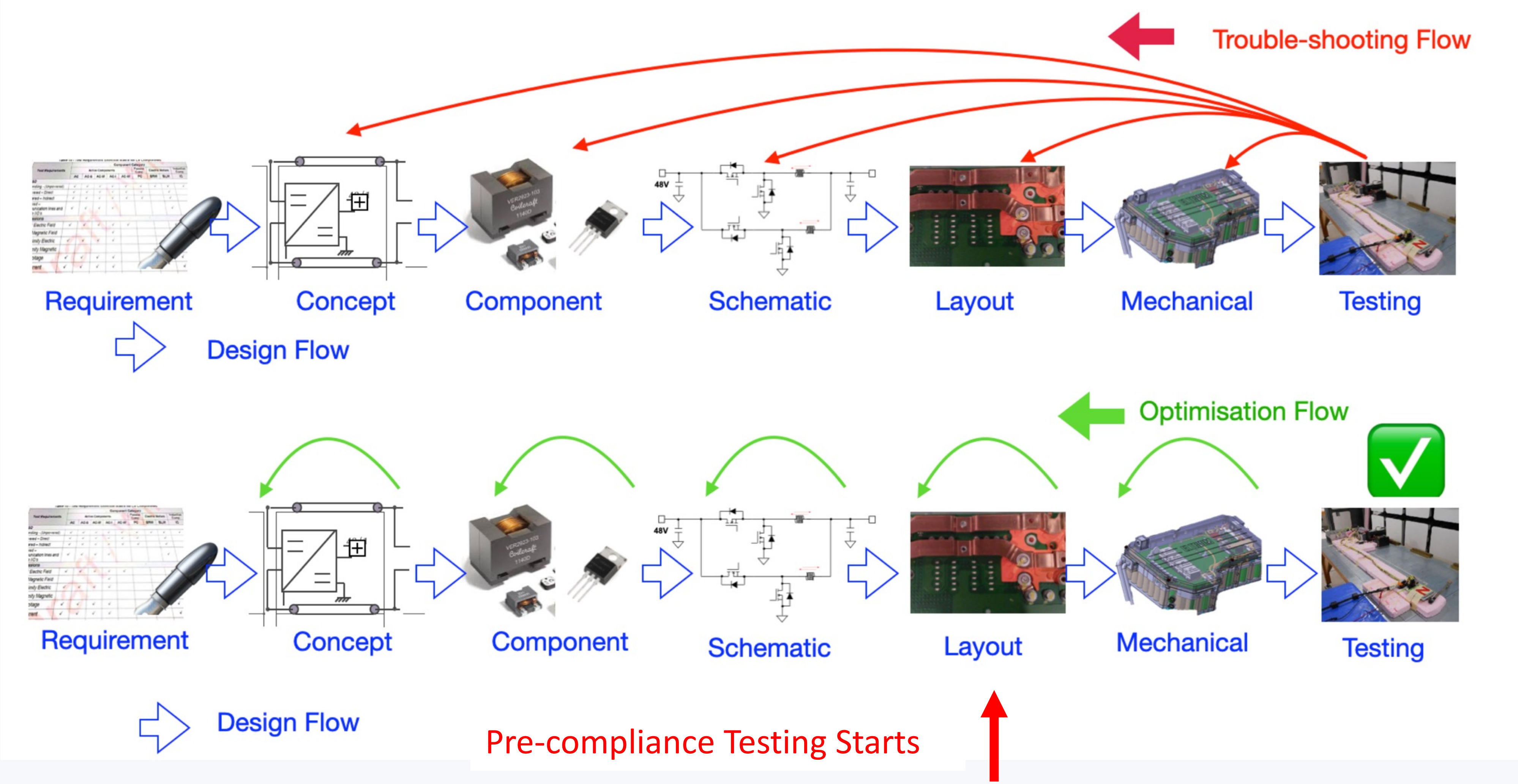
Using Current Probe Results to Predict Far-field Emissions



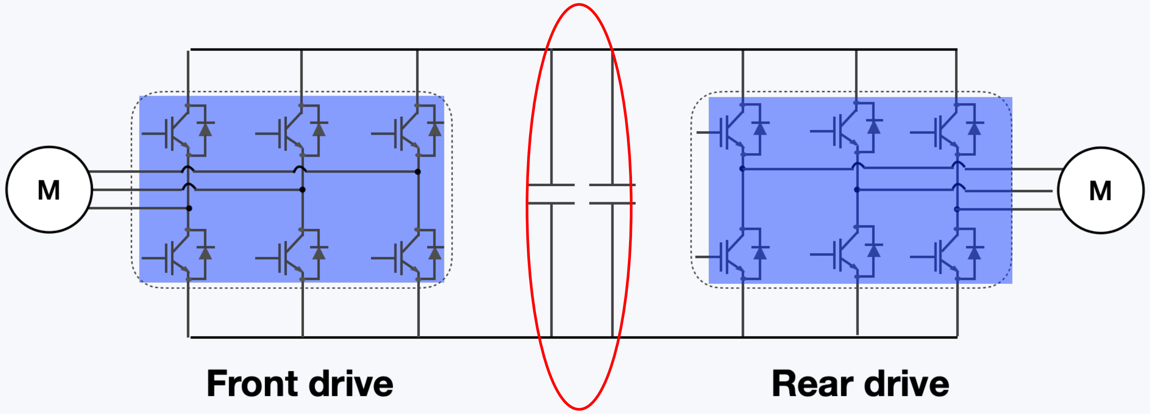


- Using an RF current probe to measure common mode current, far-field emission can therefore be predicted to a good accuracy

Design Strategies – EMC Planning & Management



Design Strategies – DC Link Design

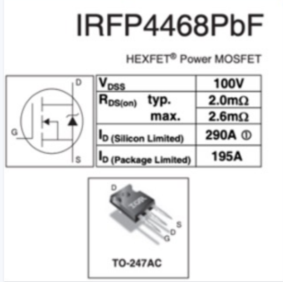


- Does my DC Link has the least impedance (i.e., the smallest loop that I could achieve)?

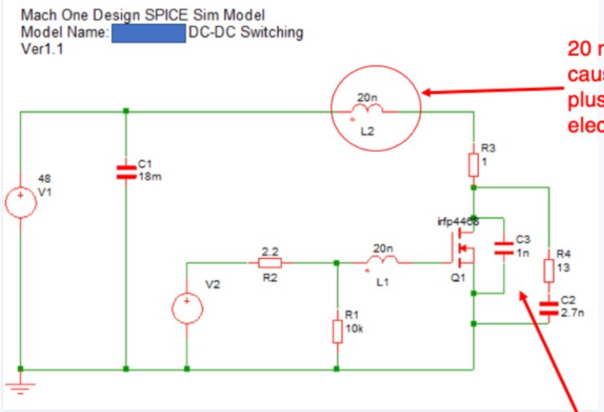
The DC link was on the top side board, and the switches were on the bottom.

Design Strategies – Switching

Estimated 10 nH inductance introduced by the lead of the package.



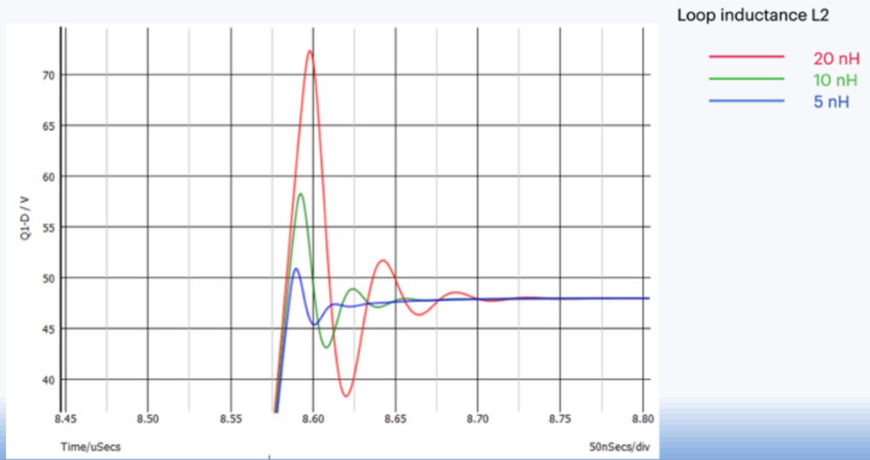
Source: Infineon (International Rectifier)



20 nH loop inductance, including 10 nH caused by the long lead of the device plus 10 nH of PCB tracks to the electrolytic capacitor

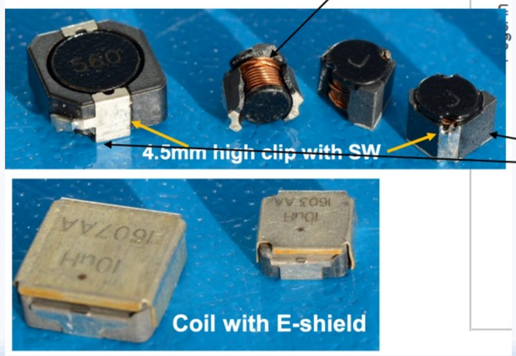
1nF parasitic capacitor of the device based on its packaging and layout

Comments: We often prefer SPICE based simulation as it is quick to build, can run very fast and leads to good understanding of the circuit behavior. This is extremely useful for troubleshooting as can be seen later.

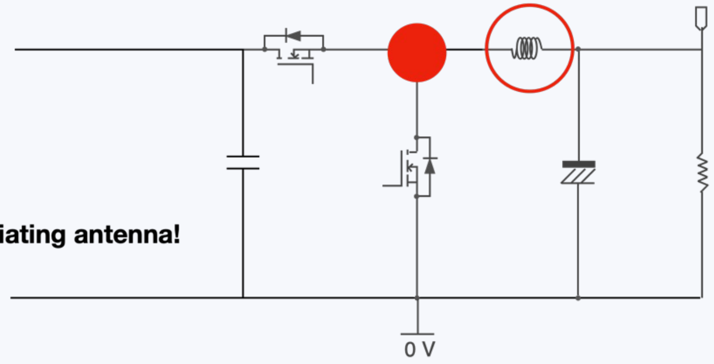


- Through hole or SMD? - That is a question
- Soft switching or hard?
- Snubber?
- ZVS control?
- Spread spectrum or not?
- Covering the switch node with shielded inductor if applicable

Unshielded - Not suitable



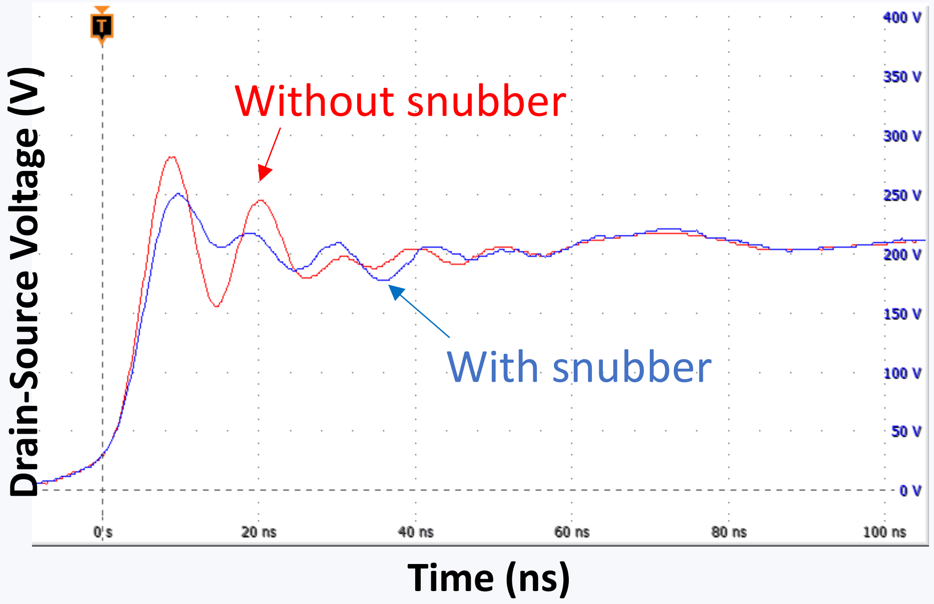
Radiating antenna!

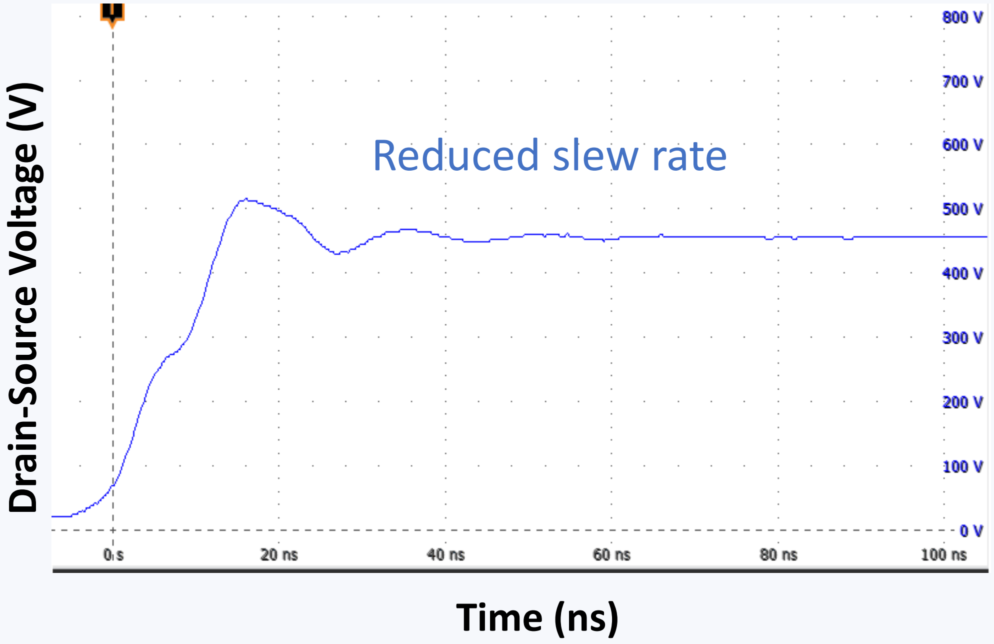


Use shielded inductor to shield the Switch Node

MACHone
Expertise Propels Excellence
LYRA ELECTRONICS

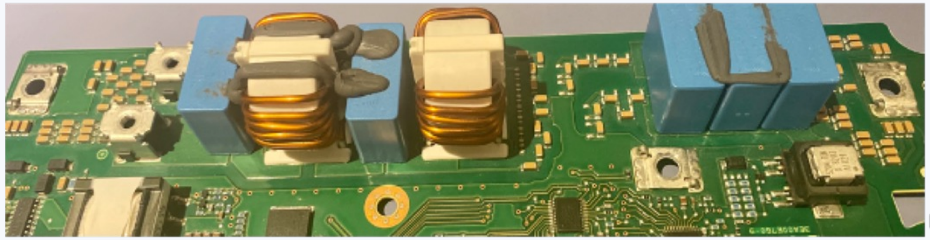
Switching Frequency and Speed

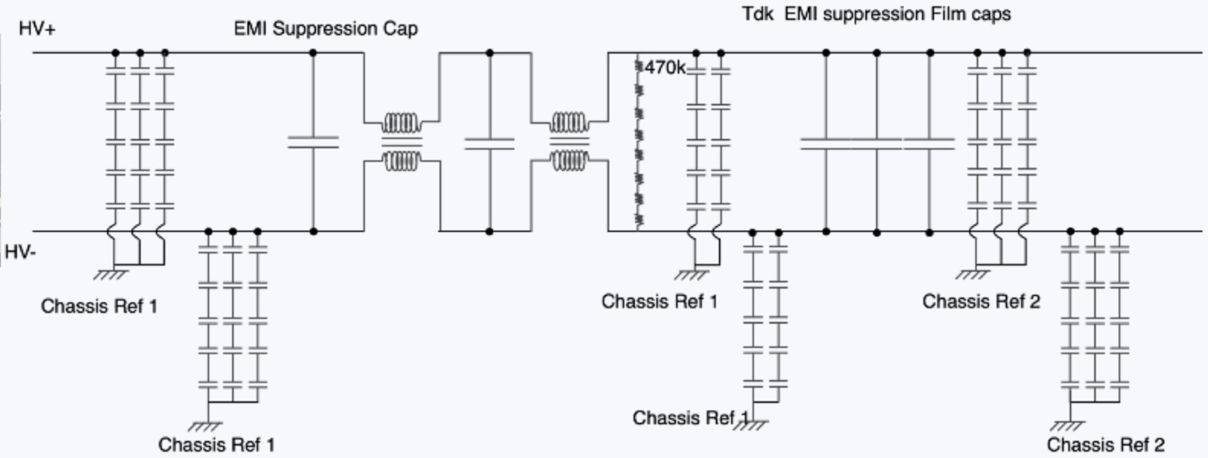




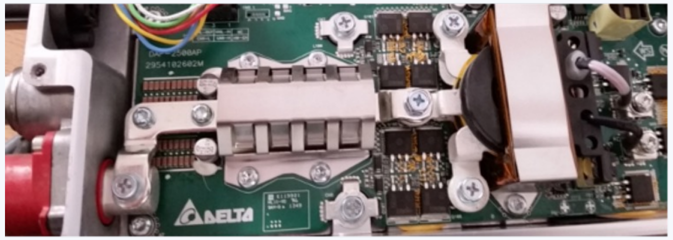
- Snubber damps the resonance of parasitic components
- Reduced ringing impacts EMI at the ringing frequency
- Spike killer noise suppression device (very lossy).
- Reduced slew rates impact EMI roll-off in the 30- to 200MHz band → effects efficiency

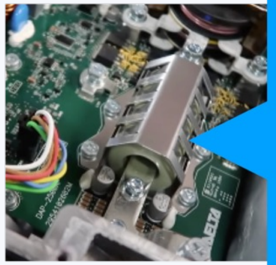
Design Strategies – Filtering





The input filter configuration in a DC-DC module used in Audi Eton - HV, current rating is not high.

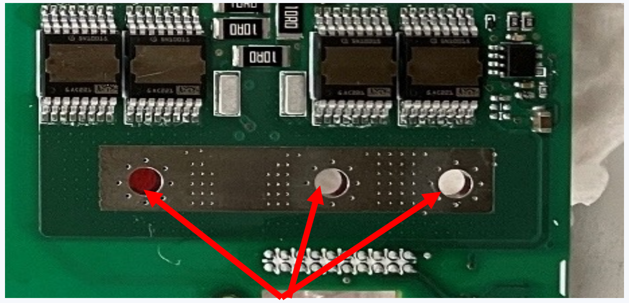


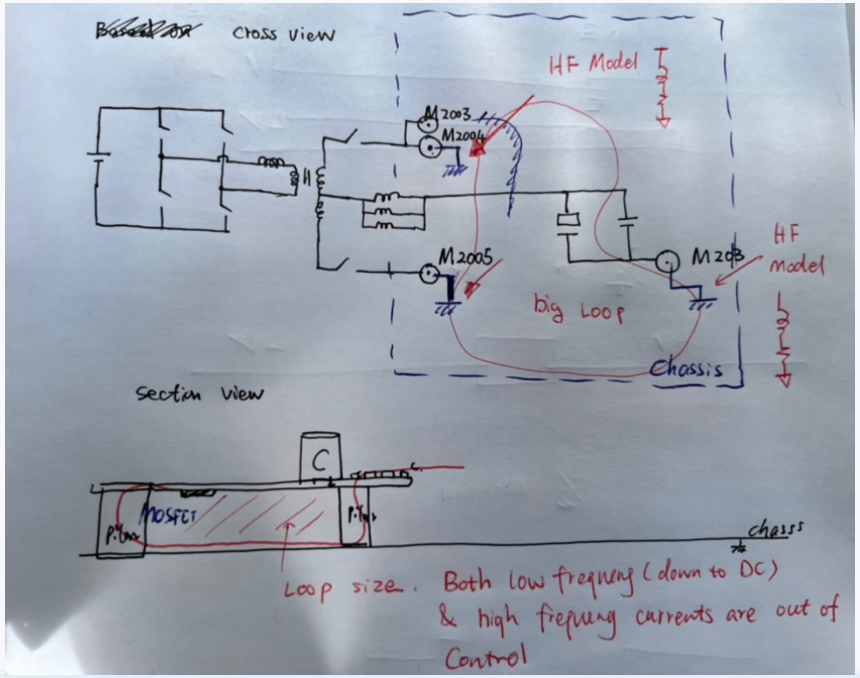


It is easy to make a single-turn two cores (perhaps four cores) configuration. Put positive and negative on adjacent layers on the board, you can use wide track or plane and then it's a bit like winding a bifilar winding, all the magnetic field then flows in the small gap between the two planes and the only remaining flux is the high frequency common mode noise, and all you need to do is to put a core through the board or around the board.

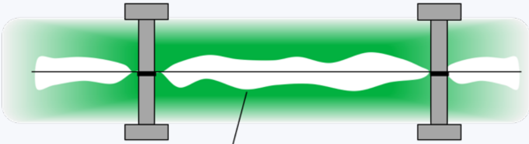
The output filter in a DC-DC module used in Tesla Model S - LV, current is more than 200 Amps

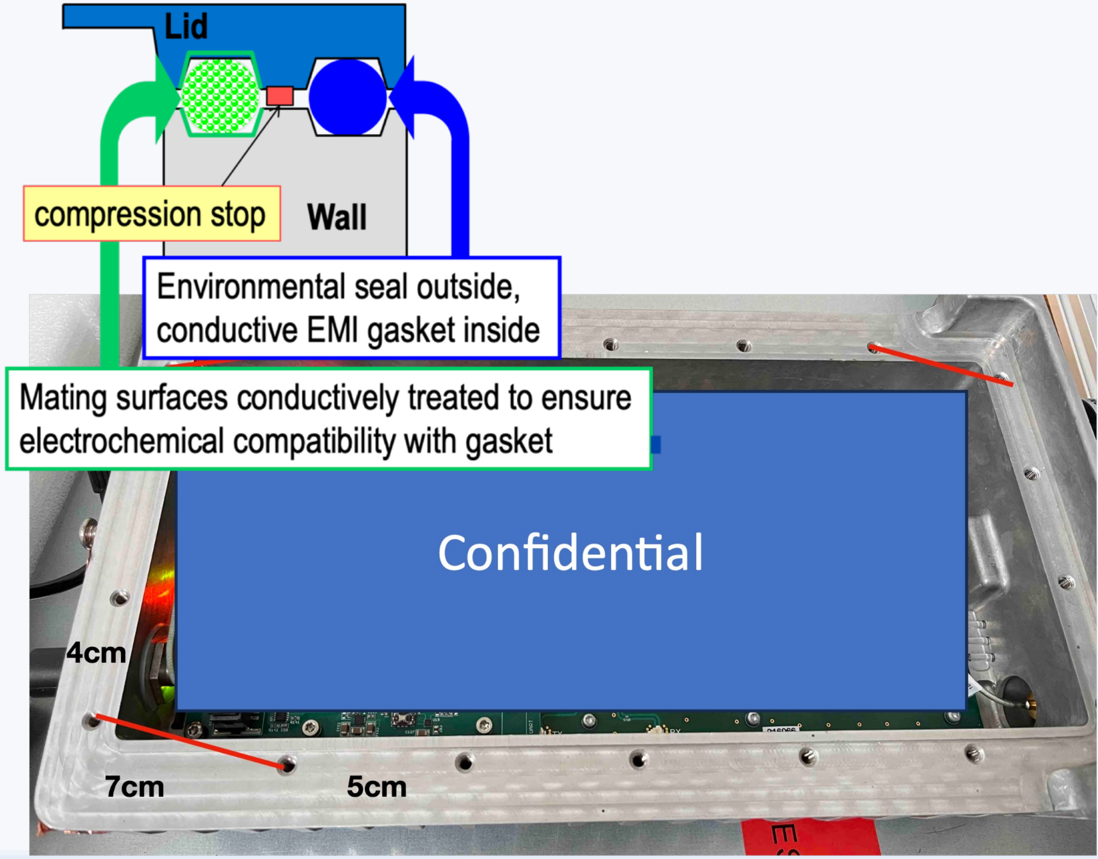
Design Strategies – Grounding and Shielding





A seam is just another aperture





Design Strategies – Active Filtering

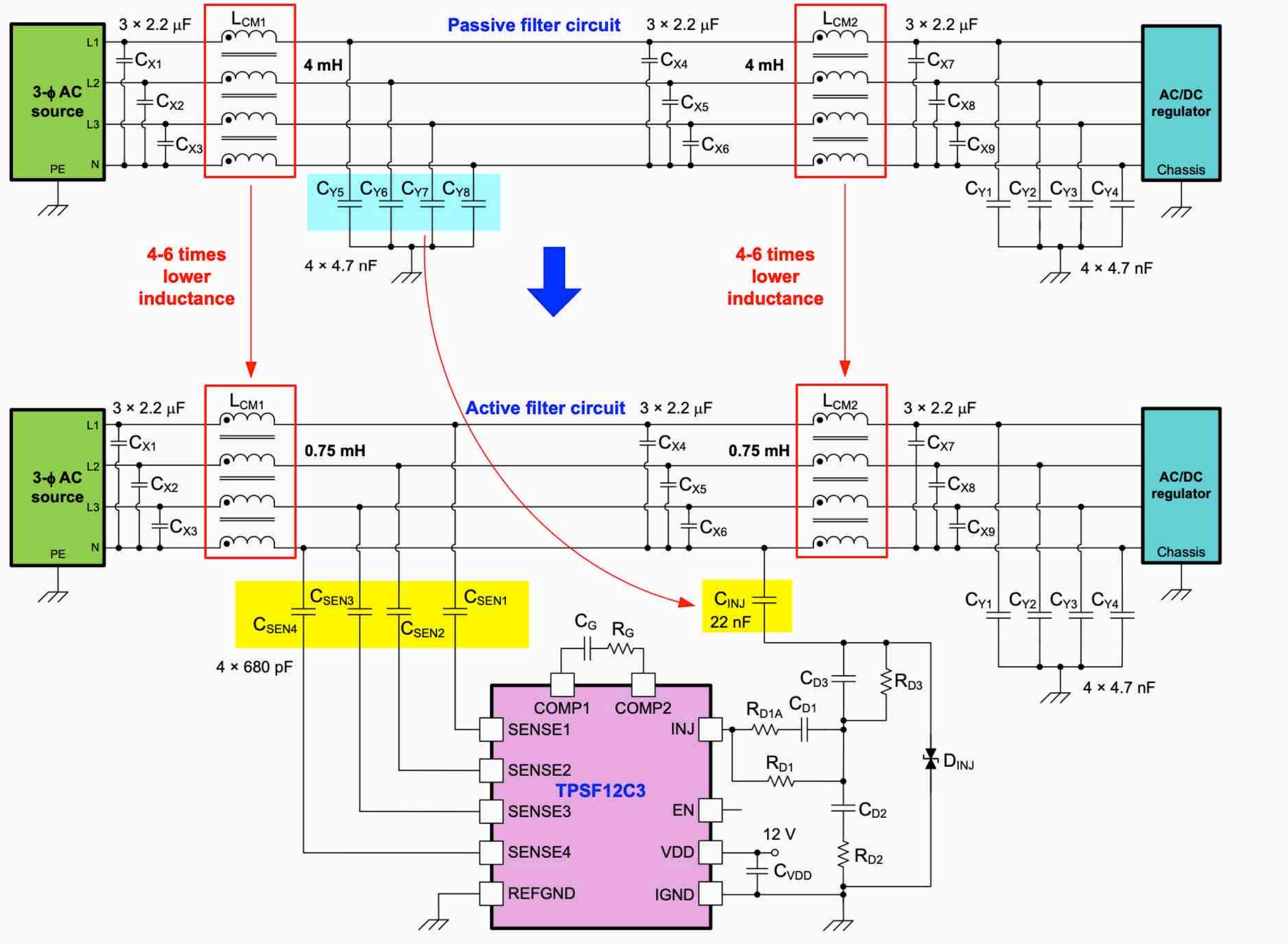
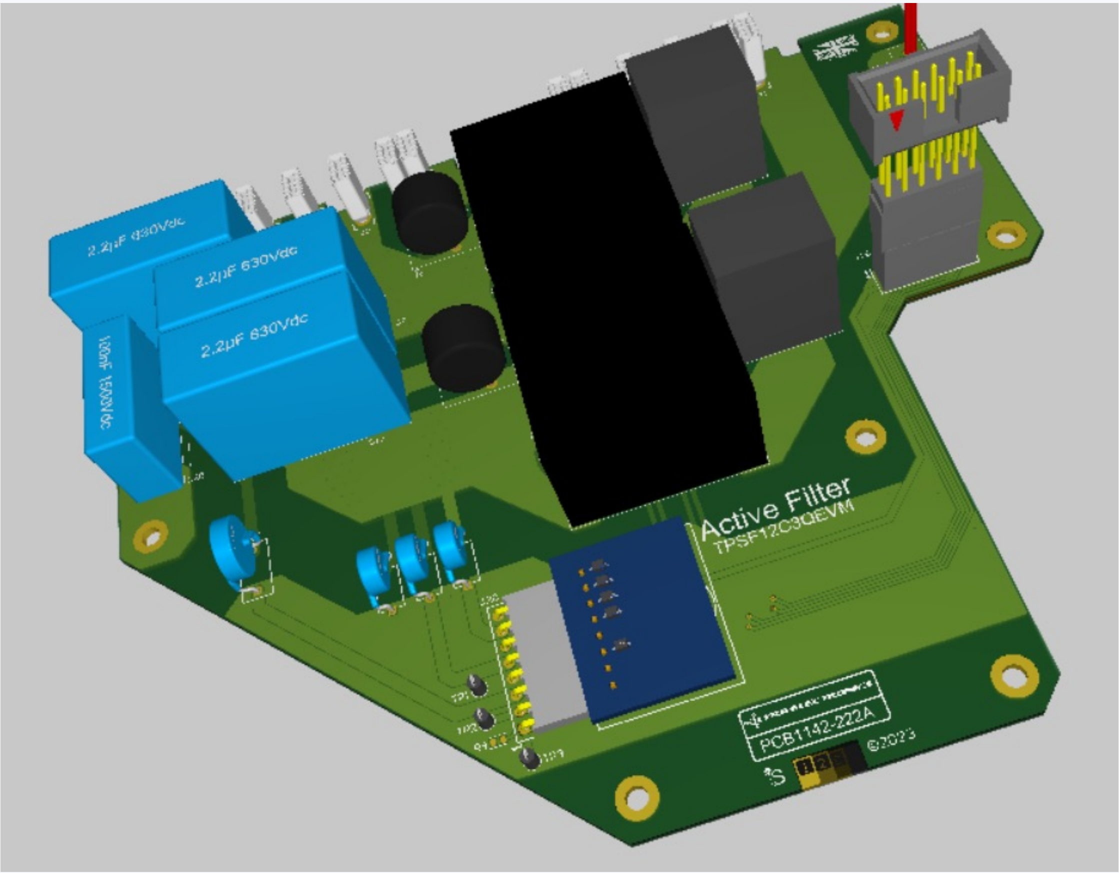


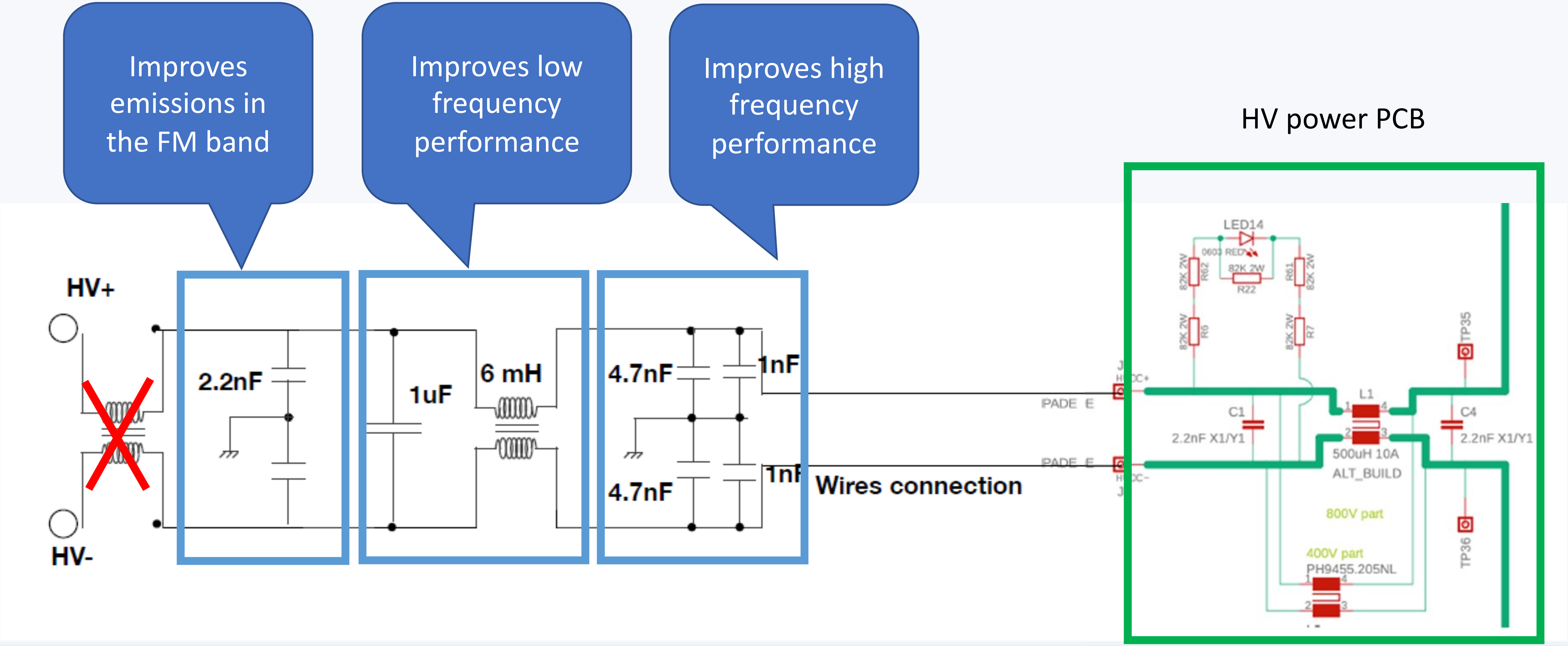
Figure 1-1. Three-Phase, Four-Wire Passive and Active Filter Schematics



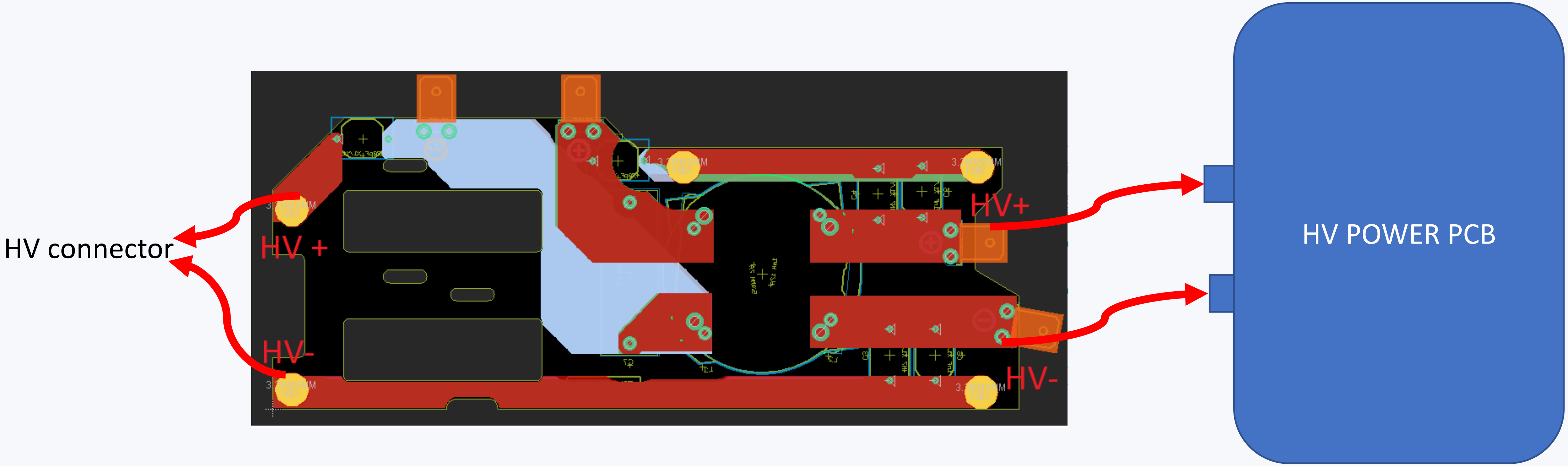
Source: Texas instruments,

Case Study: EMI Reduction on the HV Line

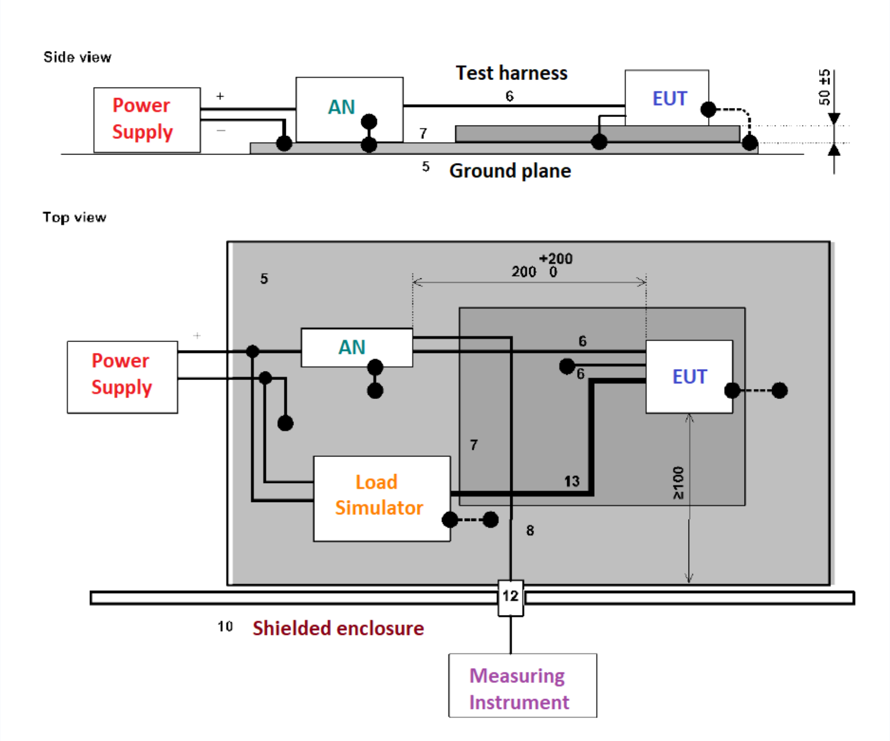
Since unshielded cables were used on the HV line, the focus was to design a multi-stage front end filter

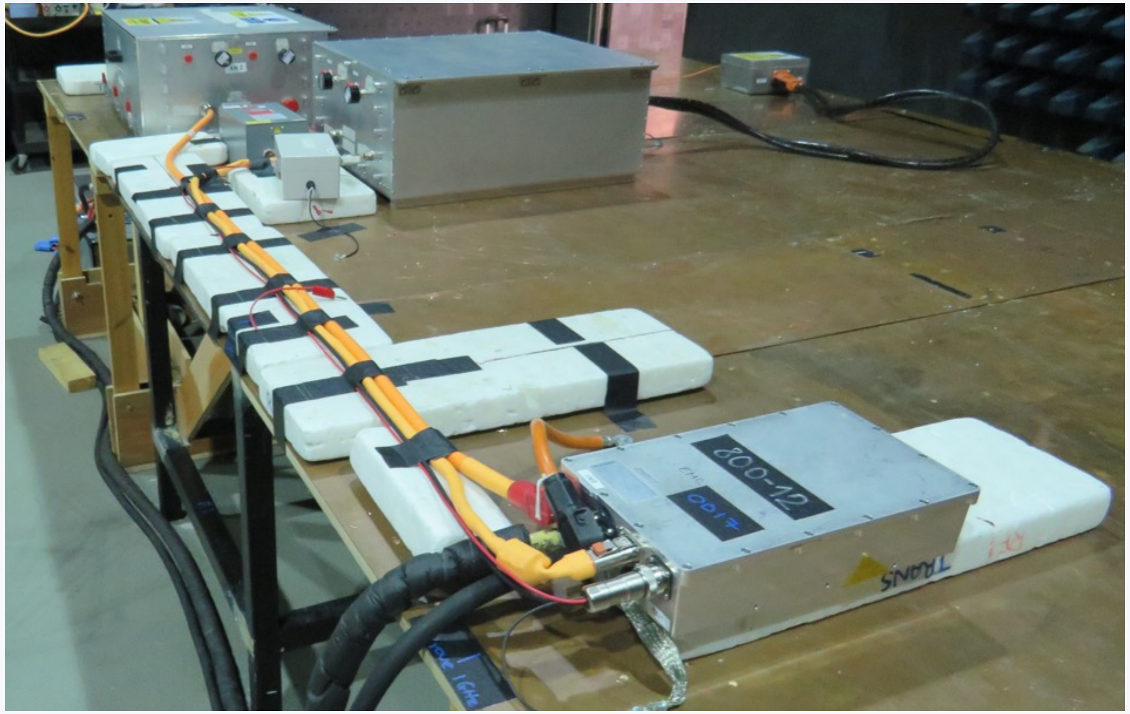


Design a Multi-stage Filter PCB

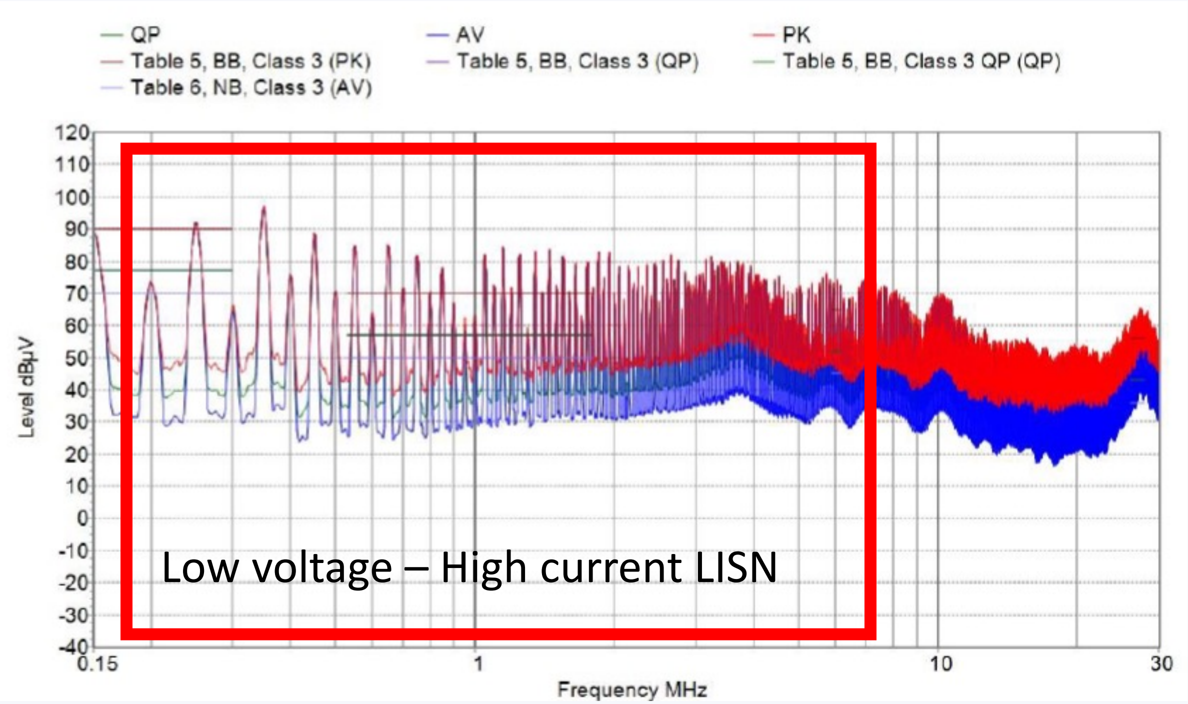


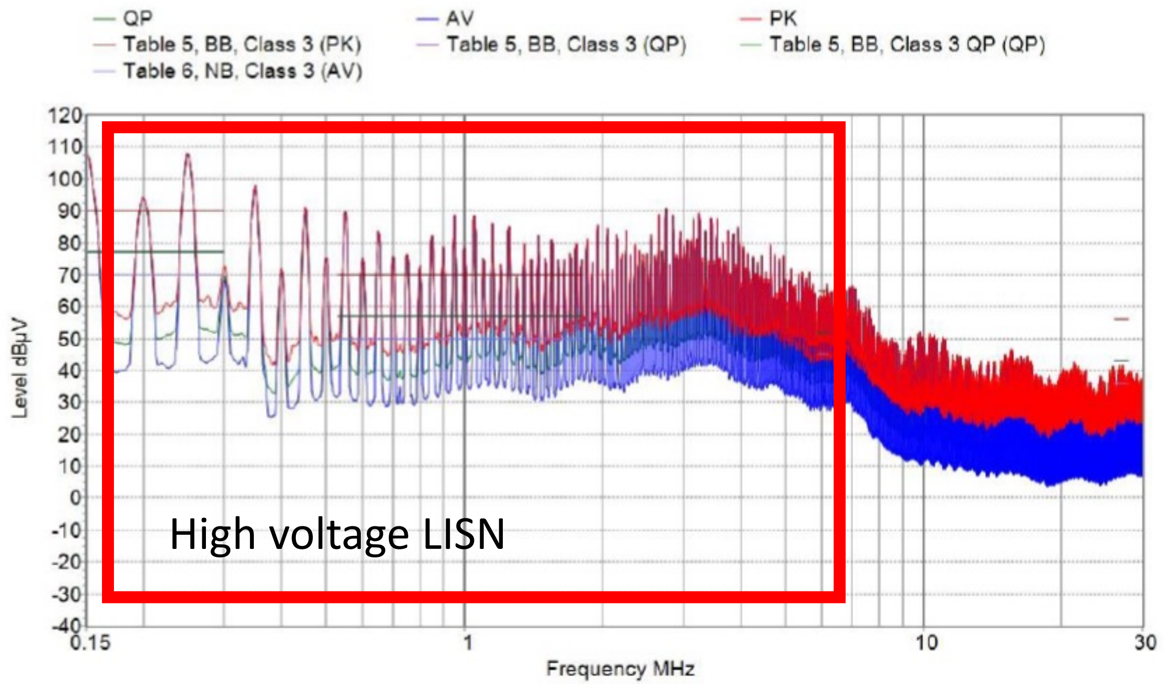
Chamber EMC Testing: Conducted Emissions





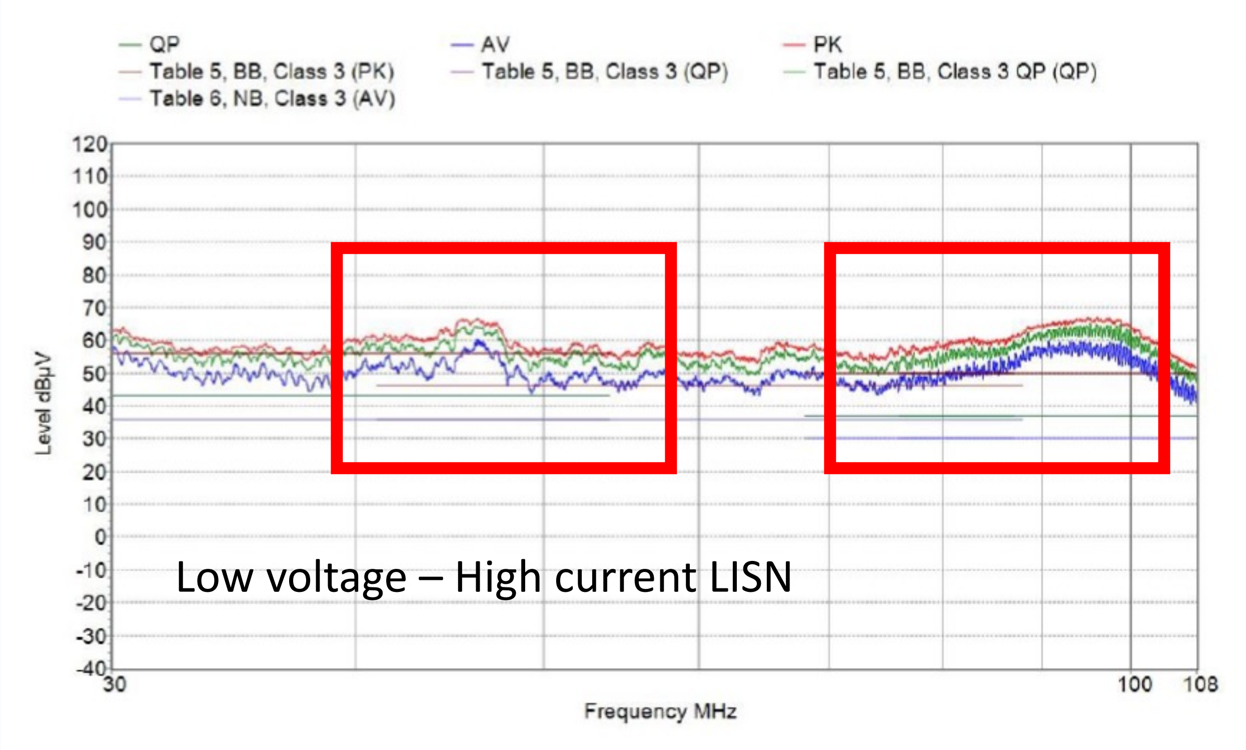
Conducted emissions analysis: the HV Line

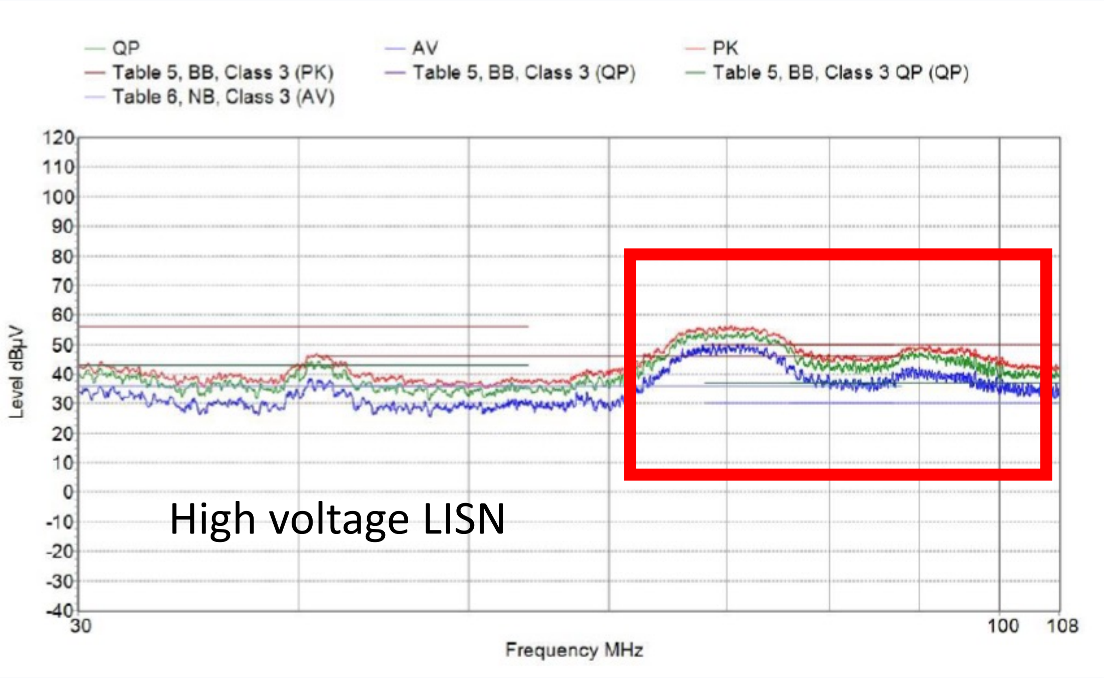




Switching frequency of the converter (50kHz) and its harmonics are the main frequency contents in the low frequency band

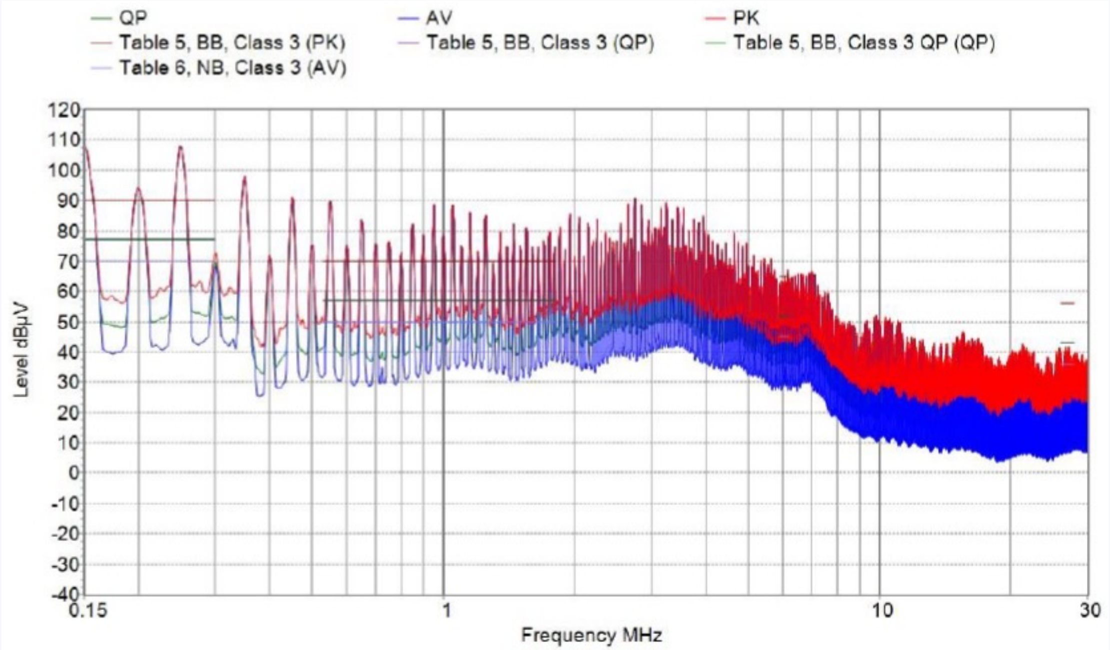
Conducted emissions analysis: the HV Line



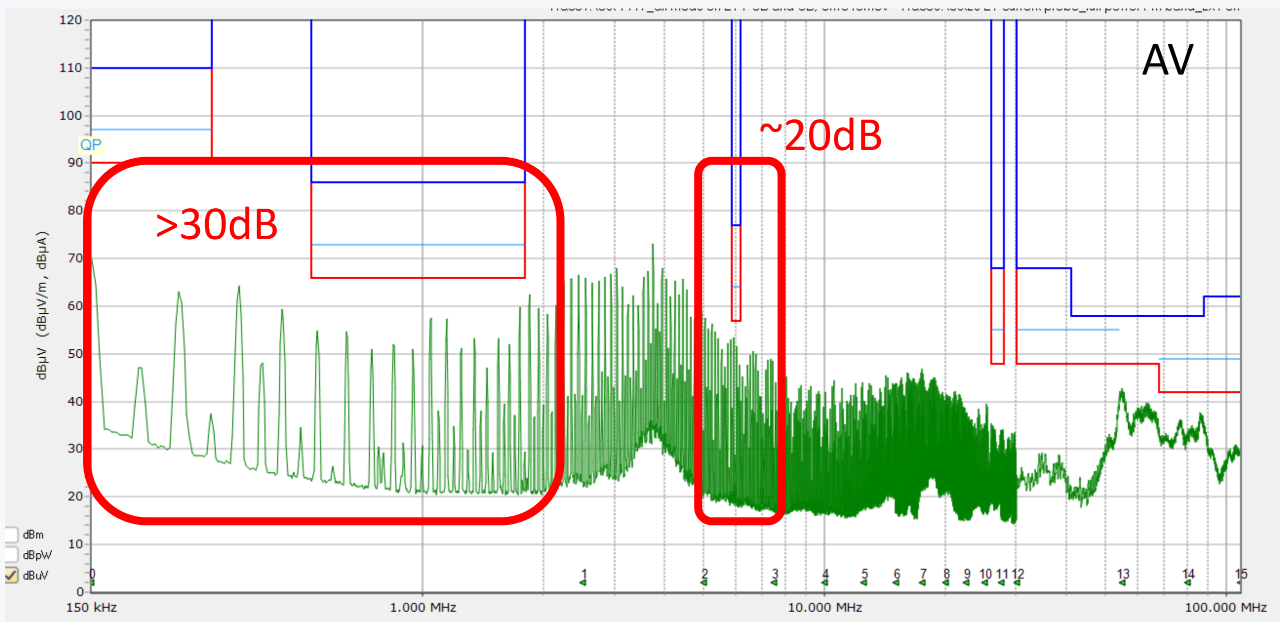


The conducted noise in this region will cause radiated emissions issue as the cables act as antennas.

Improved Result: the HV Line



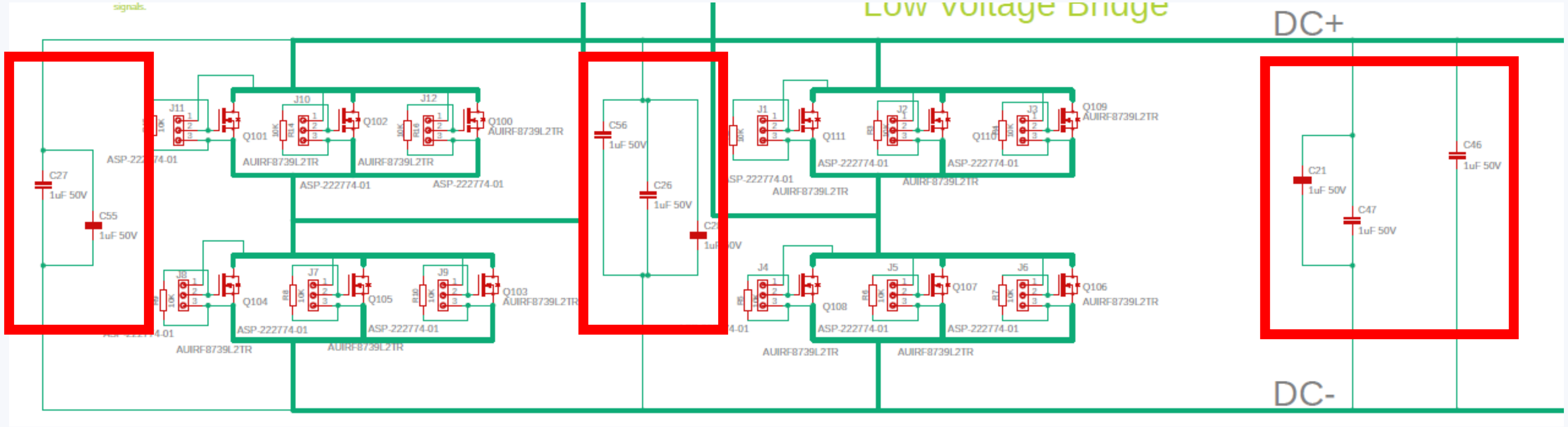
Without HV filter



With HV filter

EMI Reductions on the LV Line

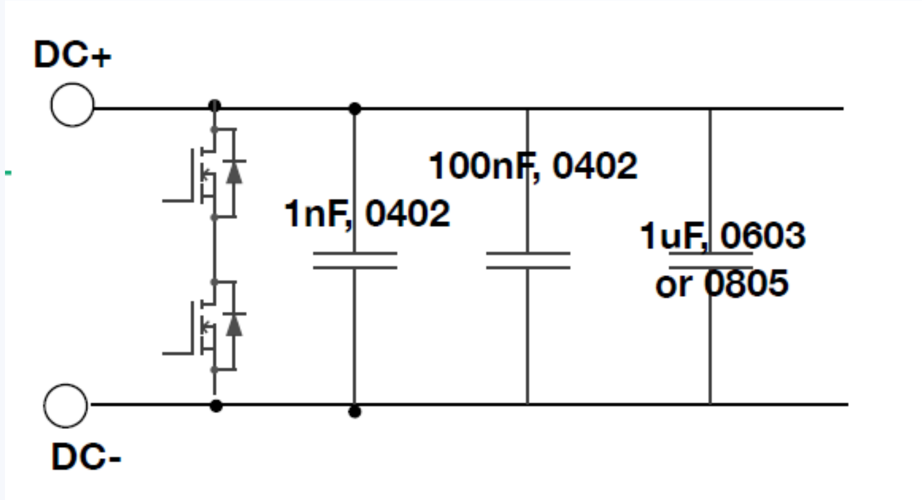
- Due to very high current on the LV line, we could only apply capacitors between the LV rails and the vehicle chassis.
- The key is to limit the impedance caused by the connections.
- Parallel MOSFETs

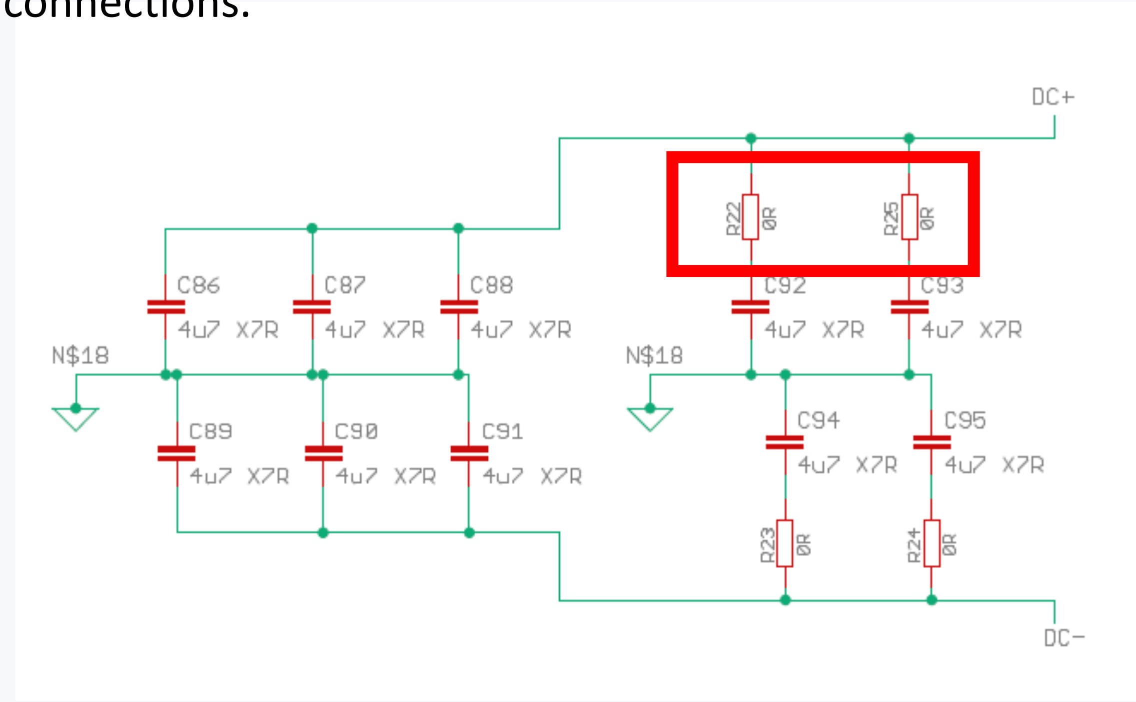


- 3x 1µF capacitors for each half bridge

EMI Reductions on the LV Line

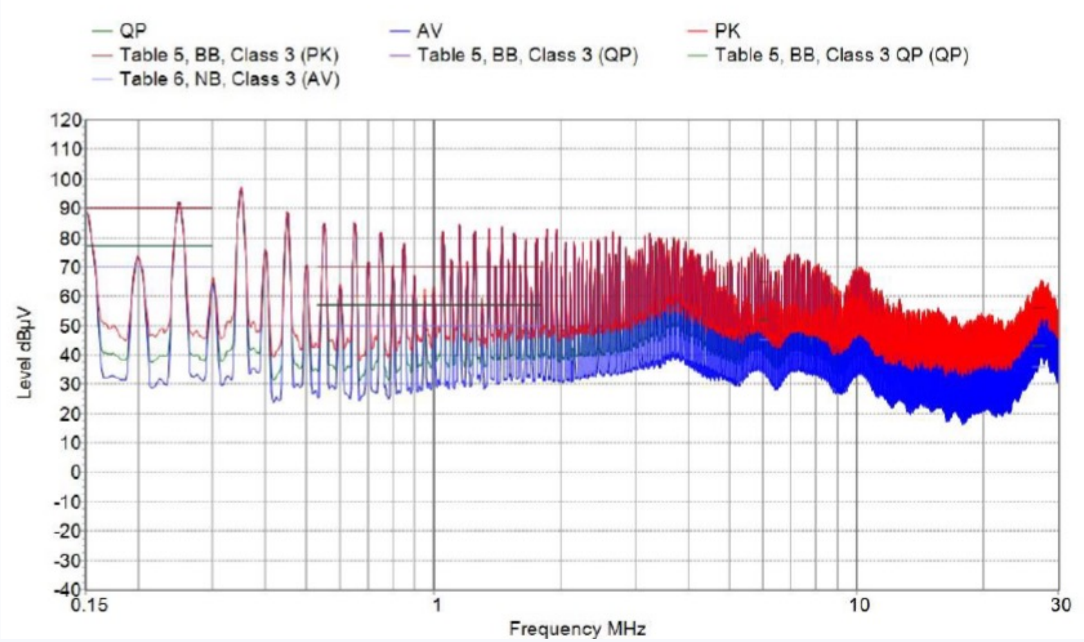
- Due to very high current on the LV line, we could only apply capacitors between the LV rails and the vehicle chassis.
- The key is to limit the impedance caused by the connections.
- Parallel MOSFETs



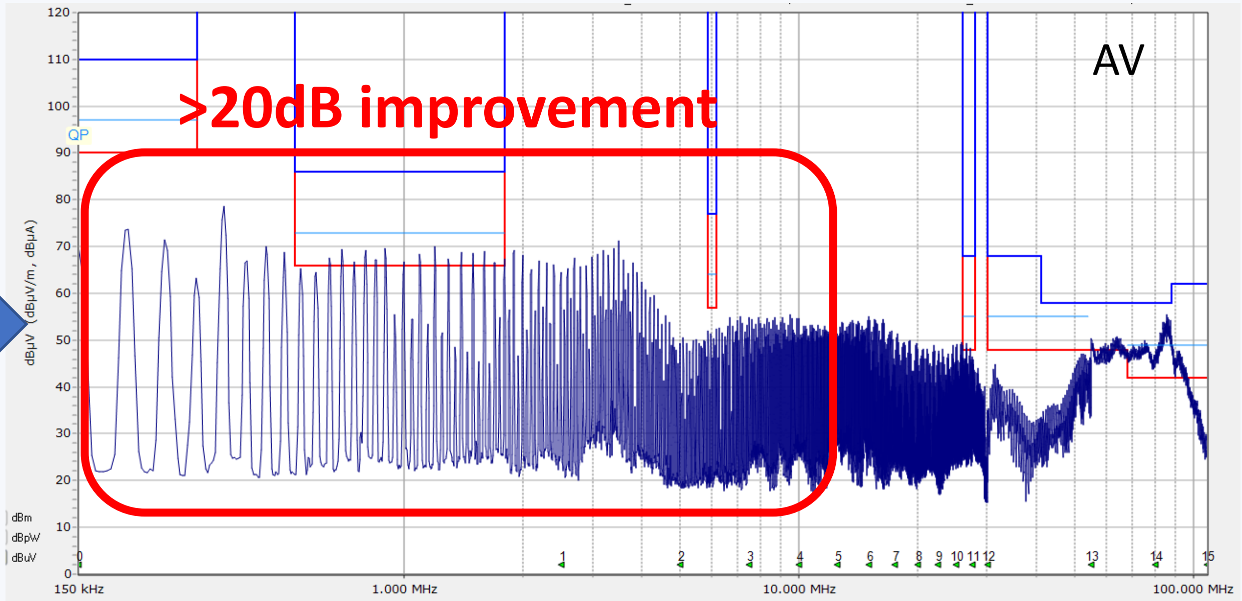


- Use low ESL and ESR capacitors
- MLCC capacitor bank → Cover wide frequency band
- Avoid resonance → Damping
- Parasitic components increase with package size

Improved Result: LV Line/High current



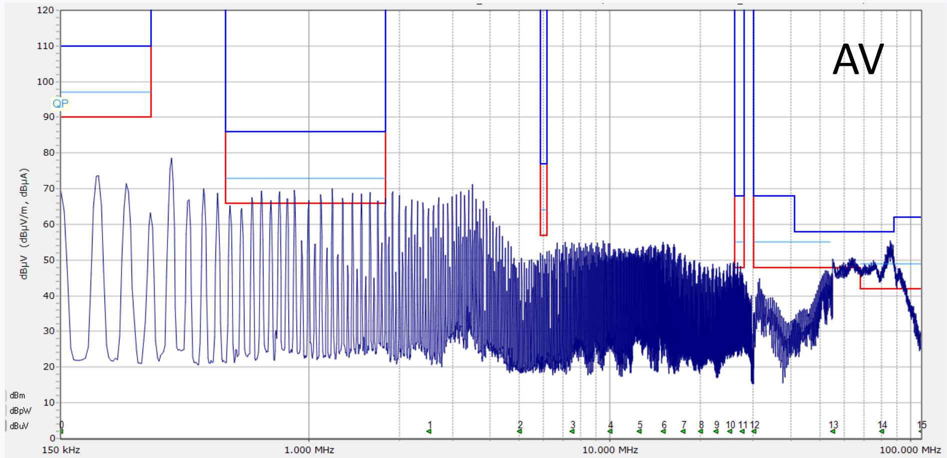
Before

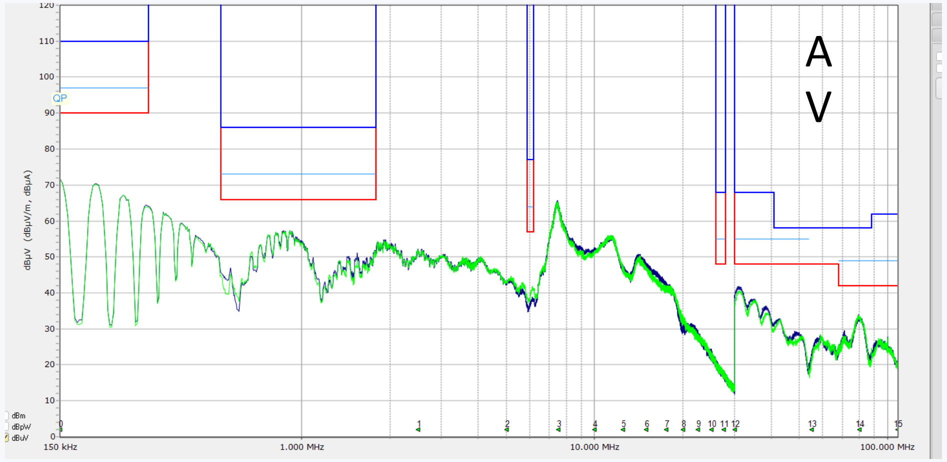


After

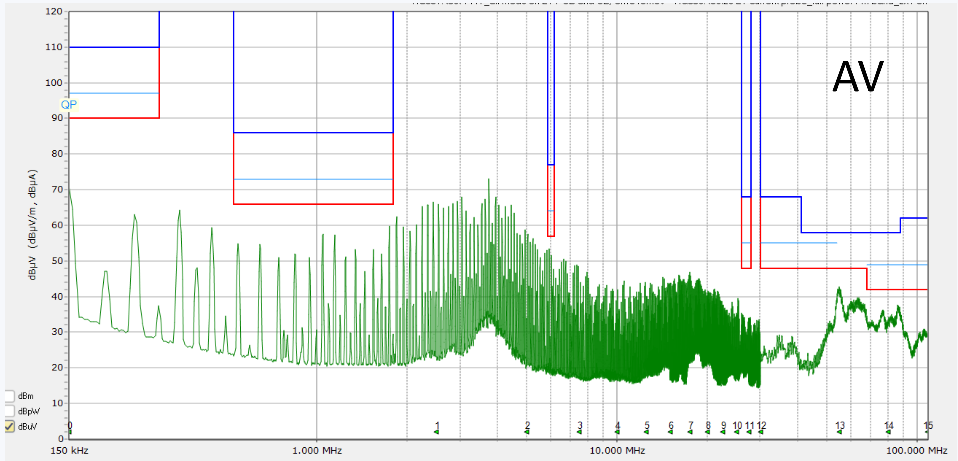
Software Switching Techniques: HV & LV Lines

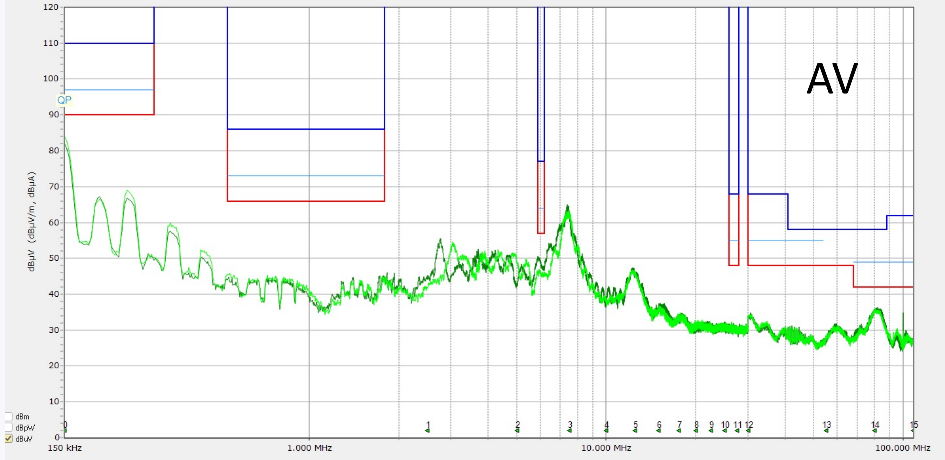
LV





HV



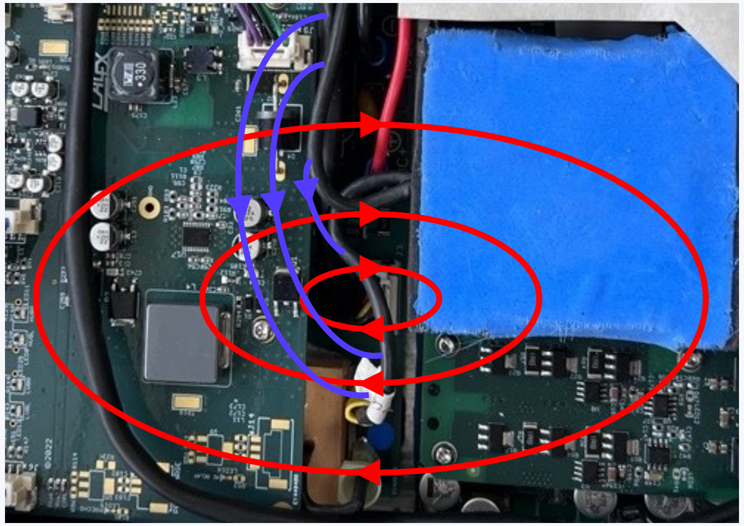


Before

After

PCB design considerations

1. PCB design
   - Select components and circuits with EMI in mind
   - Design and enforce the ground system at the product definition stage
   - Identify and label high di/dt circuits
   - Component placement
   - Careful PCB layout
   - Minimise surface areas of nodes with high dv/dt

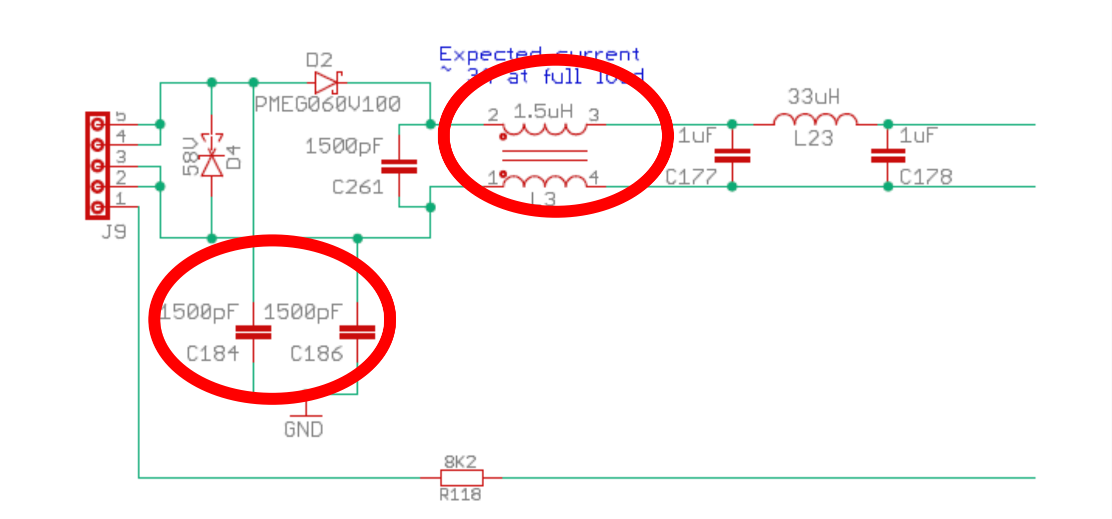


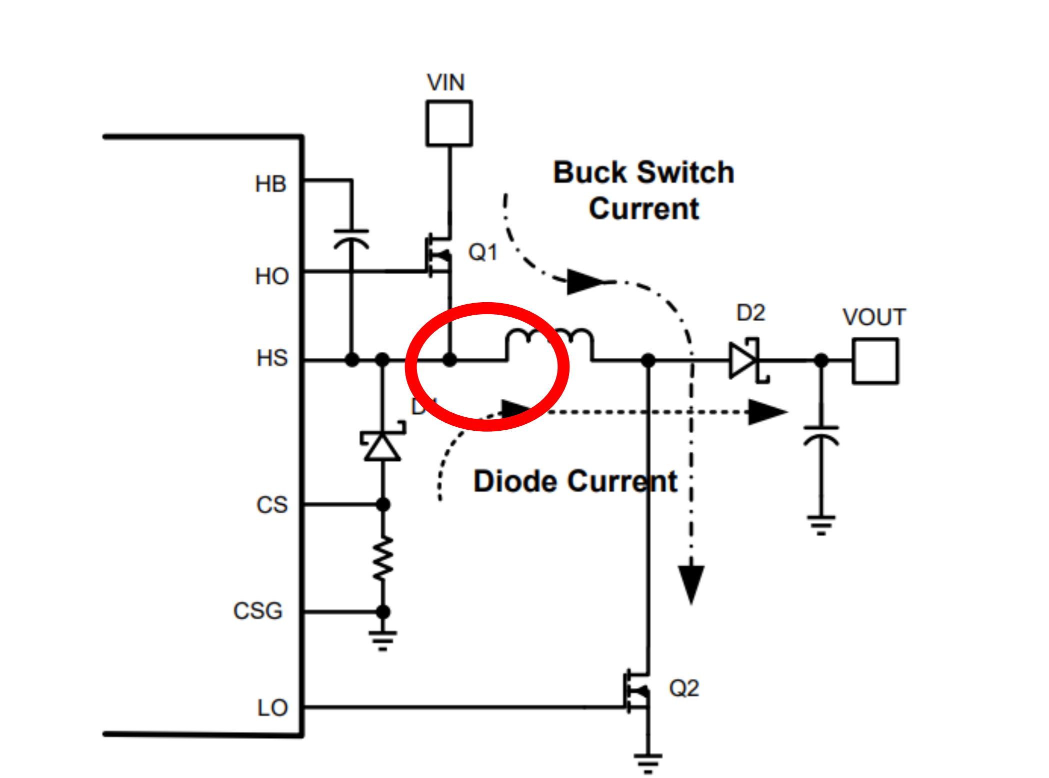
2. Cables
   - Conducted path through cabling
   - Cables can radiate

3. Filters

Pigtails here are a bad idea

Identify Critical Loops with High di/dt Currents

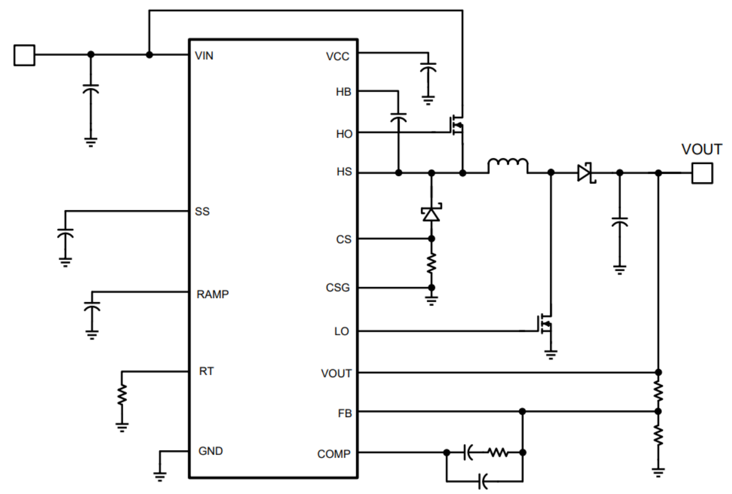


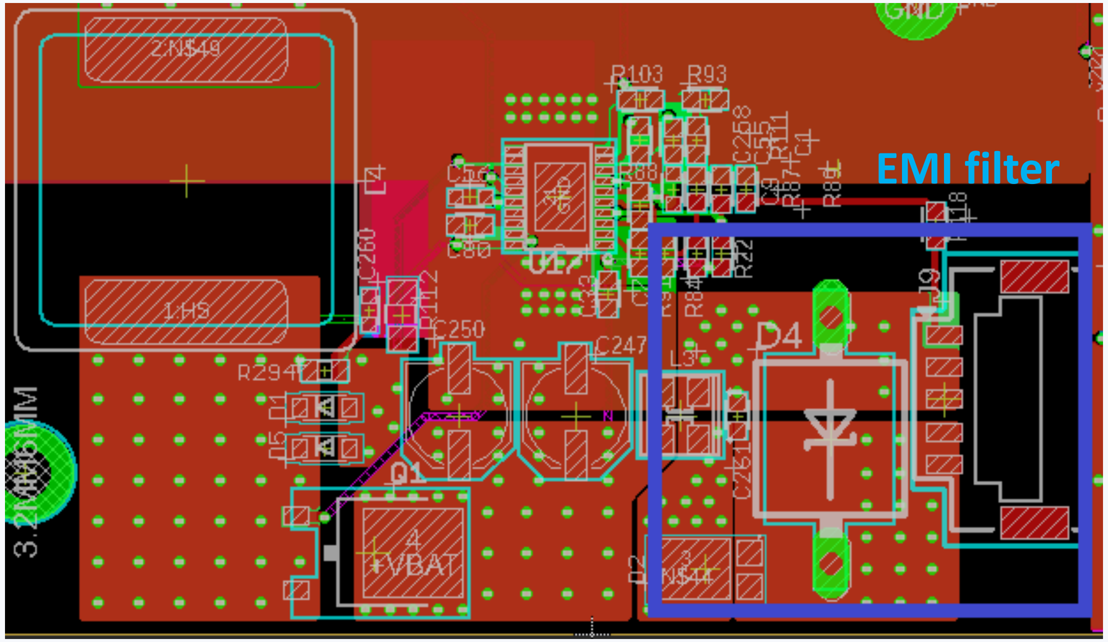


- Pinpoint high slew rate current (high di/dt) loops
- Identify layout-induced parasitic inductance that cause **noise, overshoot, ringing and ground bounce**
- “Shielded” inductor still emits significant EMI!
- Long connections from capacitors to chassis GND
- Improve buck-boost converter layout
- Replace common mode choke

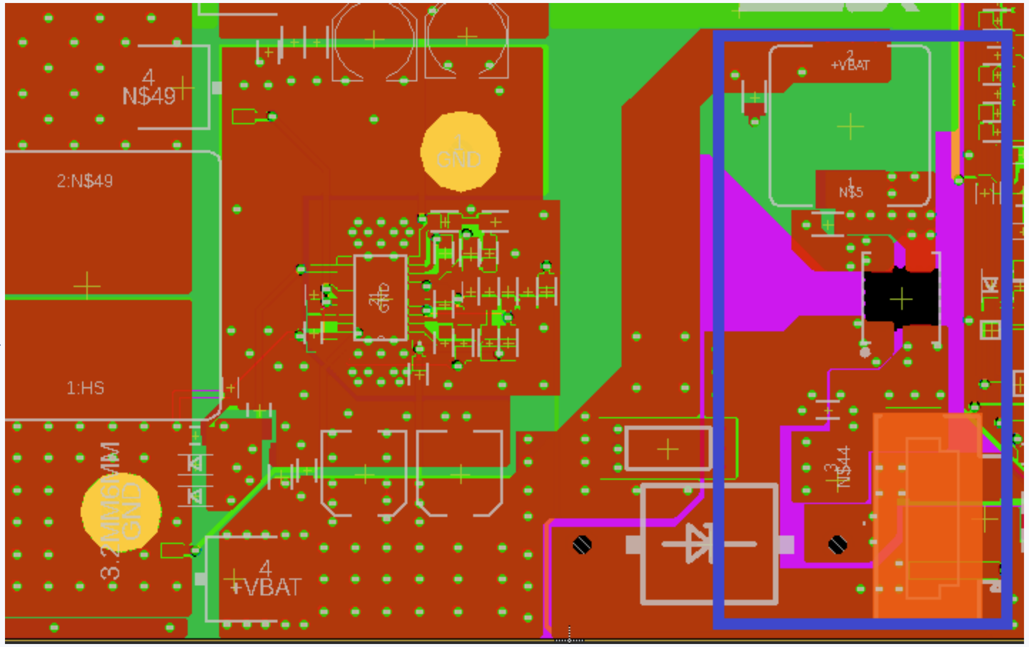
High di/dt Loop

- Power stage shall be placed away from connectors and cables
- Power stage shall be placed away from filters
- Low ESR and ESL input and output capacitors
- EMI filter shall be close to the connector
- Ground plane shall not be broken

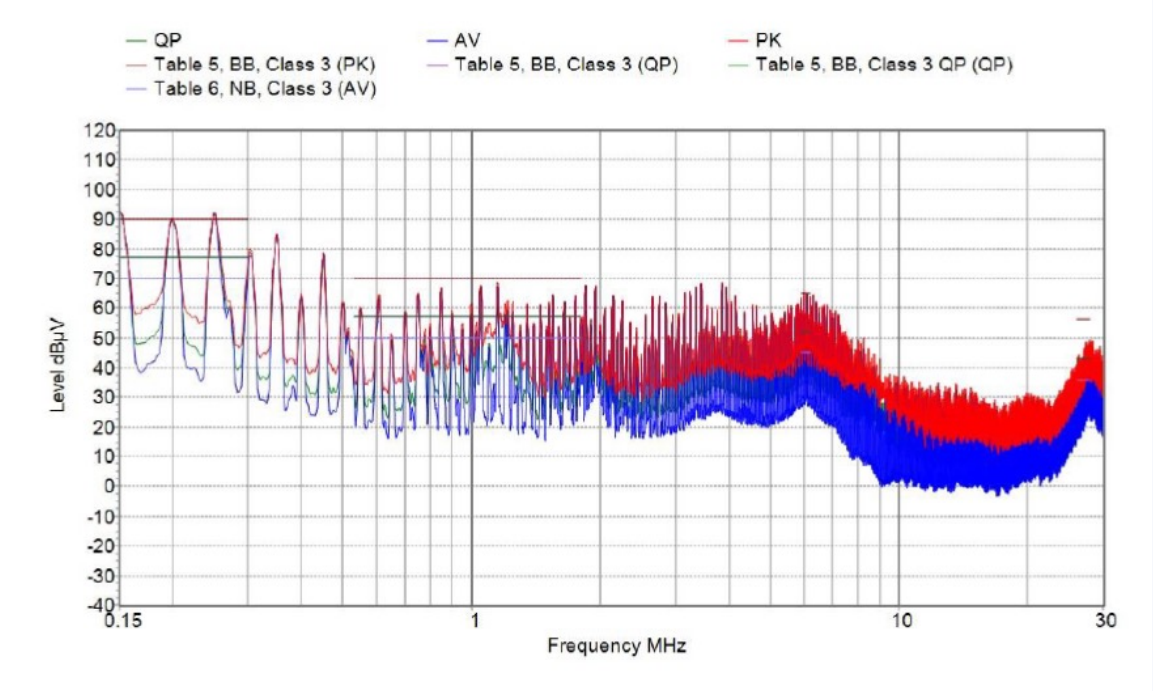




EMI filter



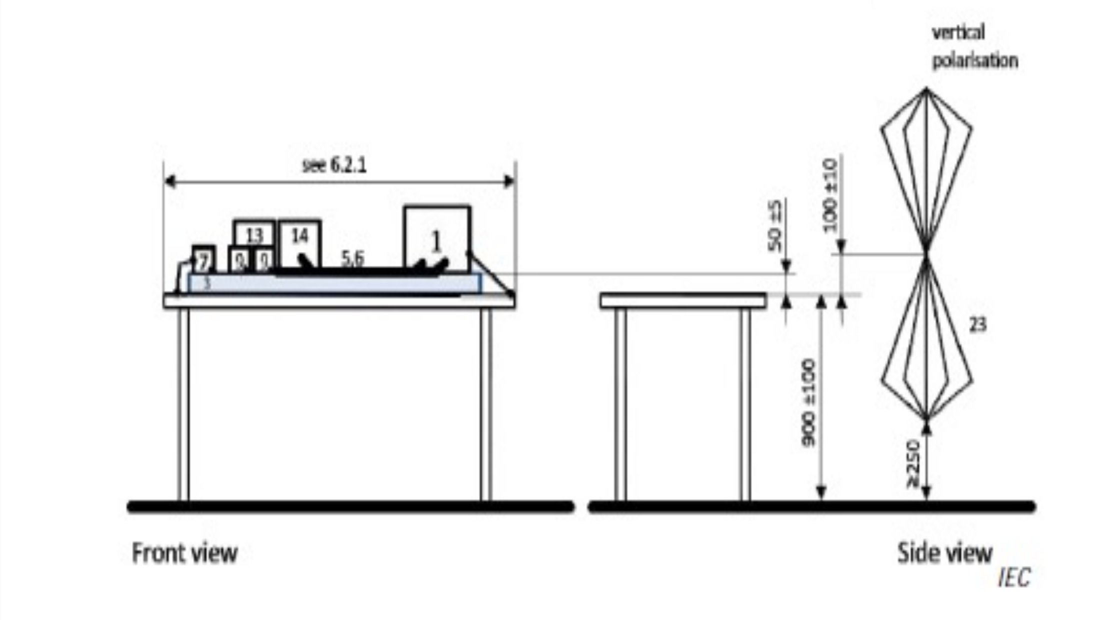
Improved Result: Low Voltage/Low Current Line

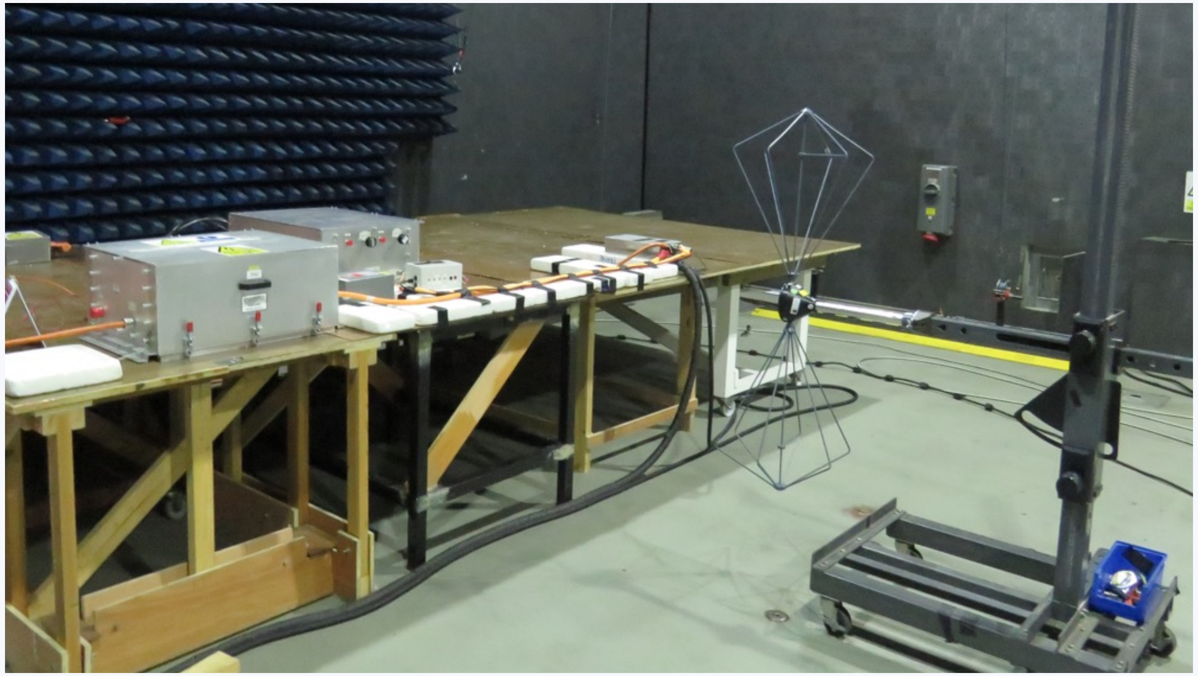


Before

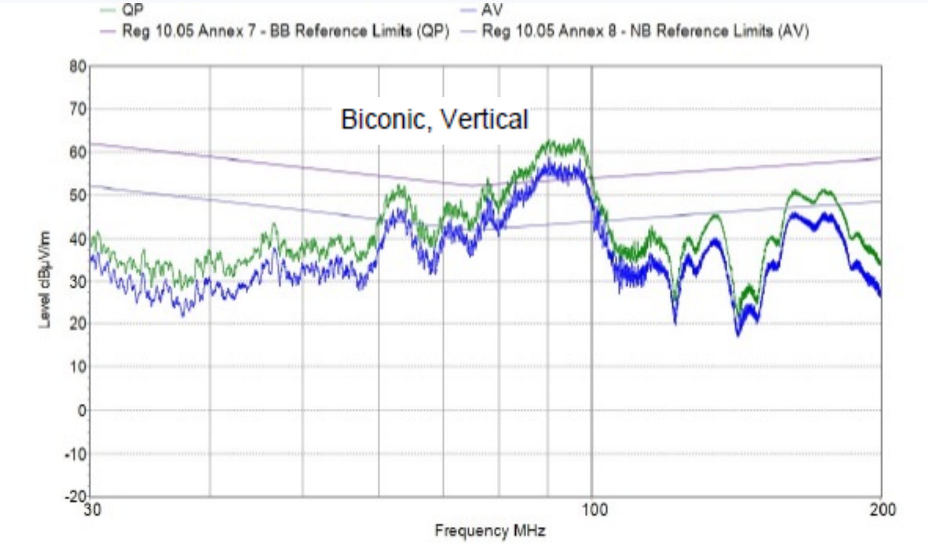
After

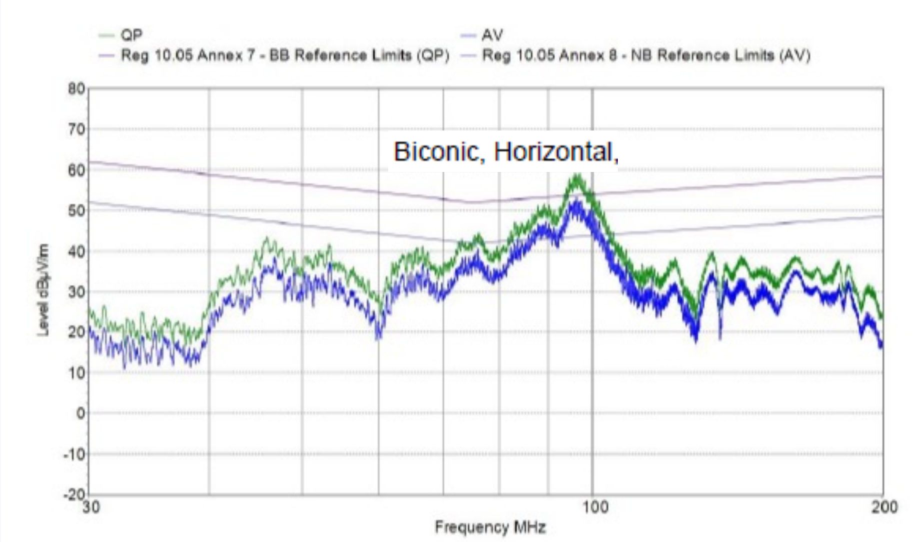
Chamber EMC Testing: Radiated Emissions



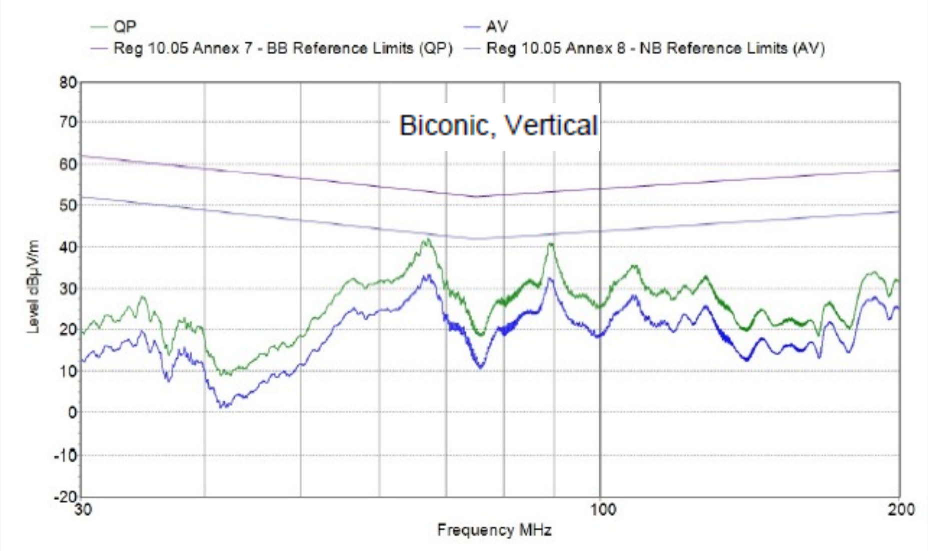


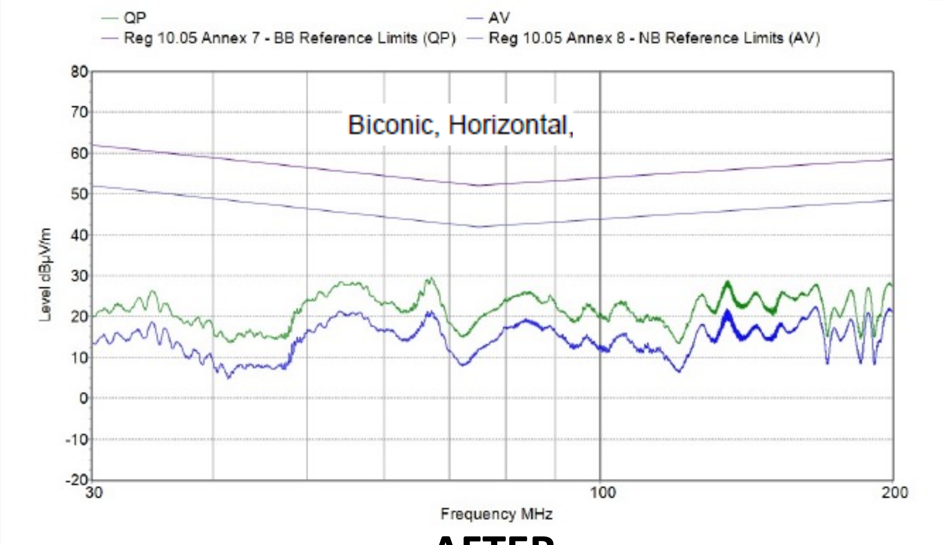
Radiated Emissions Test Results





BEFORE





AFTER

MACHone
Expertise Propels Excellence
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Thank you!

Any questions?

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