DESIGN, LAYOUT & SIMULATION OF 3-PHASE ACDC FILTERS

Andreas Nadler
Field Application Engineer
WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

DIGITAL DAYS 2025

3-Phase Filter Design

- Sources of interference
- Components
- Calculation and simulation
- Filter Design
- Measurements of interference suppression

3-PHASE FILTER DESIGN


Internal

WÜRTH ELEKTRONIK MORE THAN YOU EXPECT

APPLICATION NOTE

ANP137 | 3-Phasen EMV Filter Design
Messung-Berechnung-Simulation

Andreas Nadler

1. EINLEITUNG

Ziel dieser Application Note ist es, dem Leser einen prägnanten und umfassenden Überblick über die wesentlichen Schritte zur Dimensionierung eines geeigneten Netzfilters für 3-Phasen-Applikationen zu geben. Dabei wird ein diskreter Netzfilter durch Berechnungen und LTSpice-Simulationen ausgelegt und die Ergebnisse werden anschließend im EMV-Labor validiert. Darüber hinaus behandelt diese Application Note die Berechnung von Varistoren und Leckströmen. Grundkenntnisse in der Anwendung passiver Bauelemente, der Filtertechnik sowie der EMV-Messtechnik werden für das Verständnis vorausgesetzt. Für die Auslegung von 1-Phasen Netzfiltern sowie weiterführendes Grundlagenwissen, wird auf die ANP015 verwiesen.

Abbildung 2:: Testaufbau, geleitete Störspannung 9 kHz-30 MHz

Nach den aktuell geltenden Normen ist für diese Produktkategorie keine Messung der Störspannungen unterhalb von 150 kHz erforderlich. Es wird jedoch erwartet, dass in naher Zukunft auch Grenzwerte im Frequenzbereich

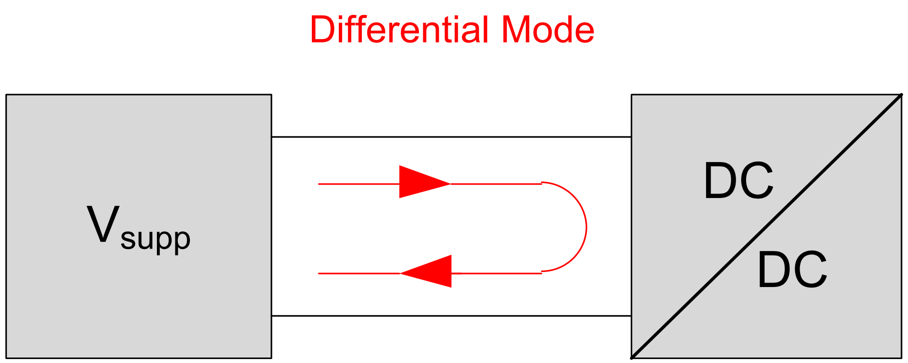
2. MESSAUFBAU

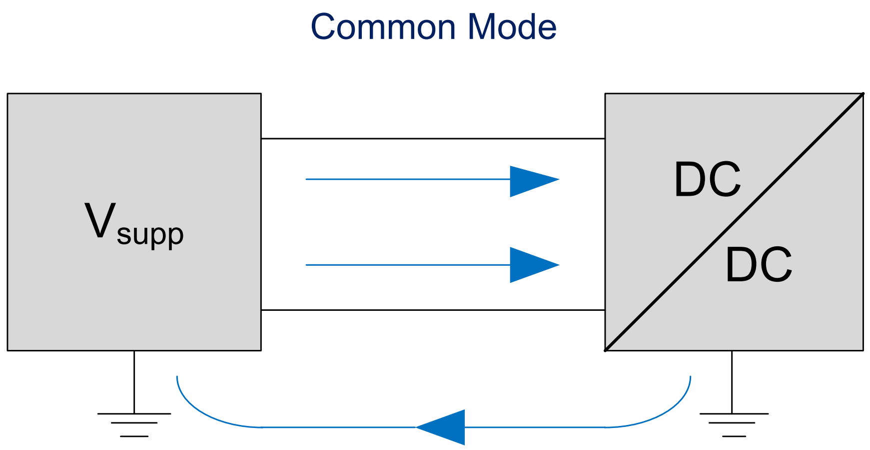
Um die Filterwirkung unter praxisnahen Bedingungen zu

Related Appnote
ANP137

SOURCE OF INTERFERENCE

Differntial Mode & Common Mode





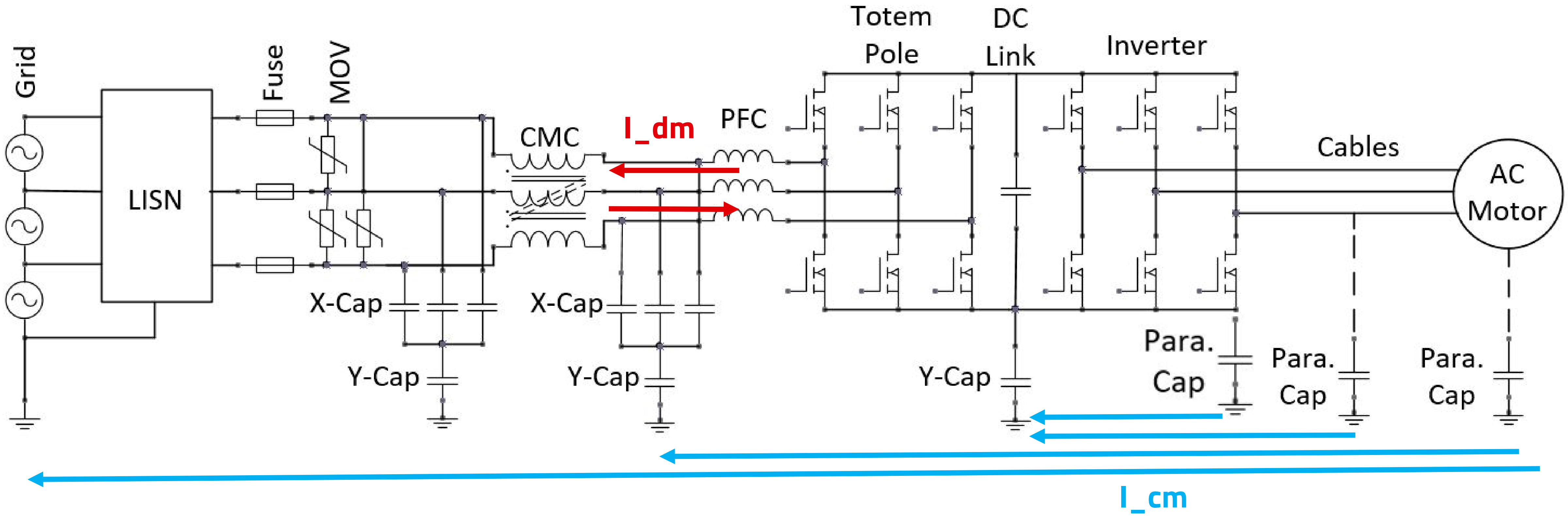
CM & DM comparisson

- **Differential mode currents**
- Current path as in circuit diagram
- Easy to follow paths
- Return current path very close
- Relatively large currents
- Filtering with LC , π , T topologies
- dI / dt is dominant cause
- Conducted EMI problem

- **Common-mode currents**
- Unexpected current path
- Current flows via parasitic paths
- Return current path very large
- Relatively small currents (μA)
- Filtering with CMC and Y-caps
- dU / dt is dominant cause
- Radiated & conducted EMI problem

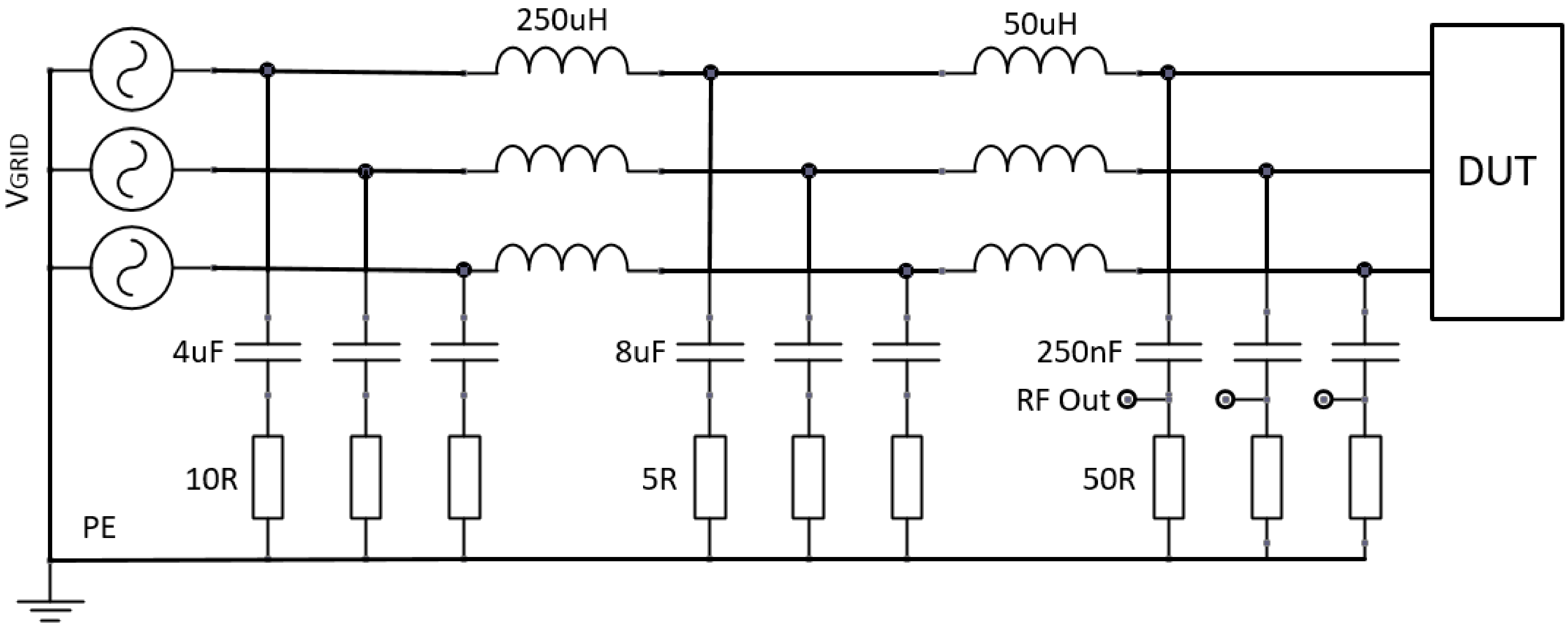
Sources of interference 3 phase system

Typical application: inverter for industrial drives



3-Phase LISN

CISPR 16 LISN



FILTER COMPONENTS

Y2 Caps

MKP Film

- WCAP-FTY2
- Pitch 10 – 37,5mm
- Vr: 330VAC
- 1nF – 1µF
- X1 + Y2 class
- -40°C to +110°C

MLCC X7R / NP0

- WCAP-CSSA
- 1808 – 2220
- Vr: 250VAC
- 33pF – 4.7nF
- X1 + Y2 class
- -55°C to +125°C

Y2 MLCC Characteristics in REDEXPERT TOOL

WCAP-CSSA

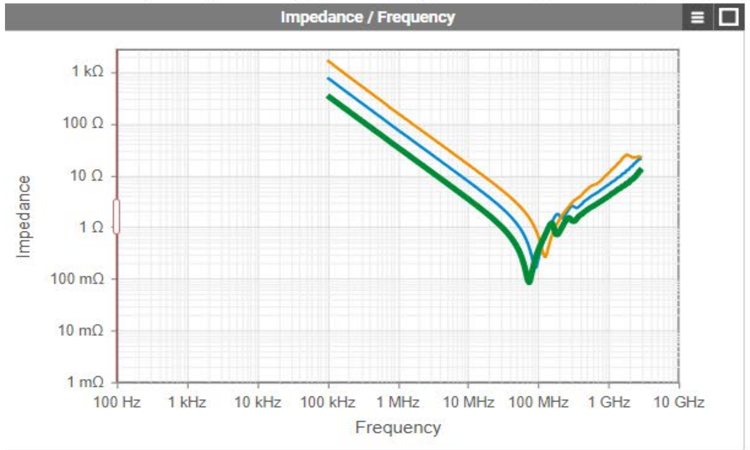
WÜRTH ELEKTRONIK · REDEXPERT · Multilayer Ceramic Chip Capacitors (MLCCs) · Menu

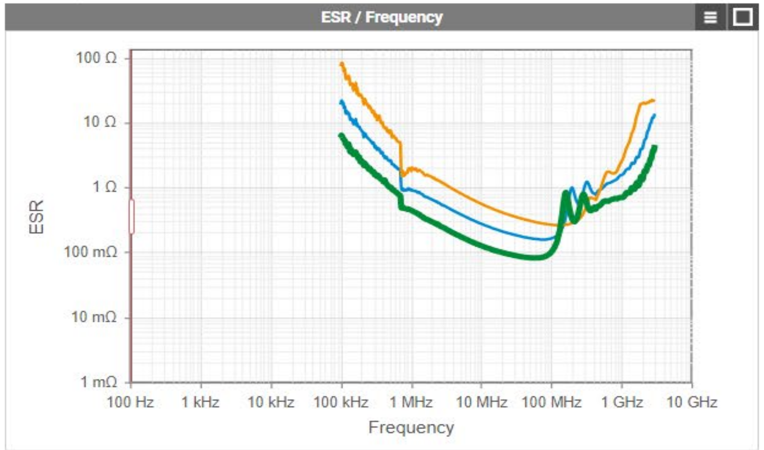
Filters: Series = WCAP-CSSA · Size = 2211, 2220 · 4 items

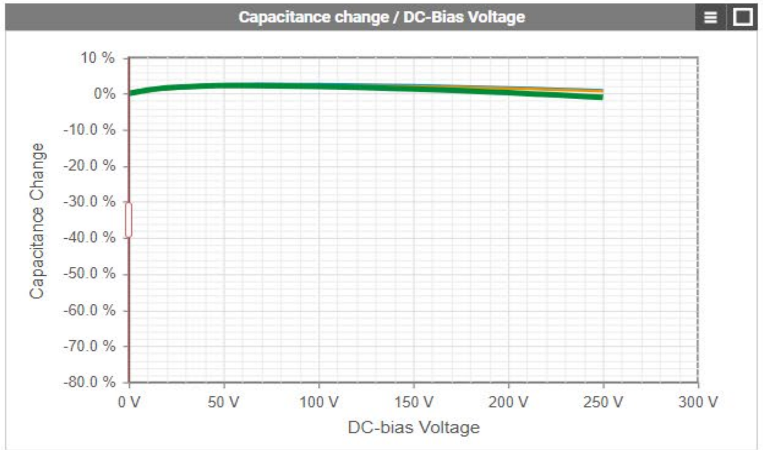
Order Code	Spec		Series	Description	Size	I...	Ce...	C	Tole...	V_R	R_{iso}	DF	Q	T_{min}	T_{max}	TCC	Length	Width	Height
8853522130151			WCAP-CSSA	Safety Class X1/Y2	2211		X7R	2.20 nF	±10 %	250 V	> 10.0 GΩ	2.5 %		-55.0 °C	125 °C	±15%	5.70 mm	5.00 mm	2.50 mr
8853522130111			WCAP-CSSA	Safety Class X1/Y2	2211		X7R	1.00 nF	±10 %	250 V	> 10.0 GΩ	2.5 %		-55.0 °C	125 °C	±15%	5.70 mm	2.80 mm	2.50 mr
8853522140011			WCAP-CSSA	Safety Class X1/Y2	2220		X7R	4.70 nF	±10 %	250 V	> 10.0 GΩ	2.5 %		-55.0 °C	125 °C	±15%	5.70 mm	2.80 mm	2.50 mr
8853522140021			WCAP-CSSA	Safety Class X1/Y2	2220	✔	X7R	1.00 nF	±10 %	250 V	> 10.0 GΩ	2.5 %		-55.0 °C	125 °C	±15%	5.70 mm	2.80 mm	2.50 mr

8853522130151 · WCAP-CSSA · X7R · 2211 · 2.20 nF · 250 V
8853522130111 · WCAP-CSSA · X7R · 2211 · 1.00 nF · 250 V
8853522140011 · WCAP-CSSA · X7R · 2220 · 4.70 nF · 250 V
8853522140021 · WCAP-CSSA · X7R · 2220 · 1.00 nF · 250 V
Click and type or drop an Order Code here
ADD · MORE

Show Panel: Z vs. F · ESR vs. F · ΔC vs. $V_{DC-Bias}$ · C vs. $V_{DC-Bias}$ · ΔC vs. V_{AC} · C vs. T · ΔT vs. $I_{RMS}(F)$



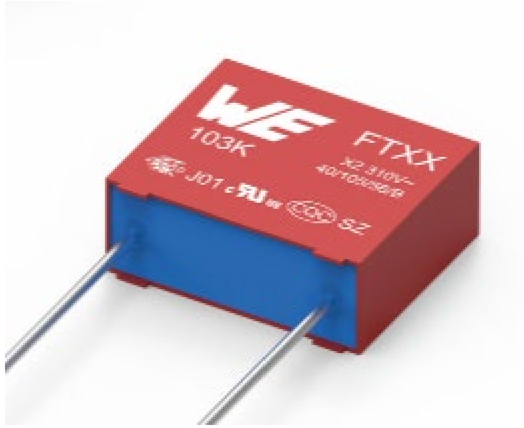




X2 Caps

MKP

- WCAP-FTXX / FTX2
- Pitch: 7.5 – 37.5mm
- Vr: 310VAC / 275VAC
- 5.6nF – 6.8µF
- -40°C to +105°C



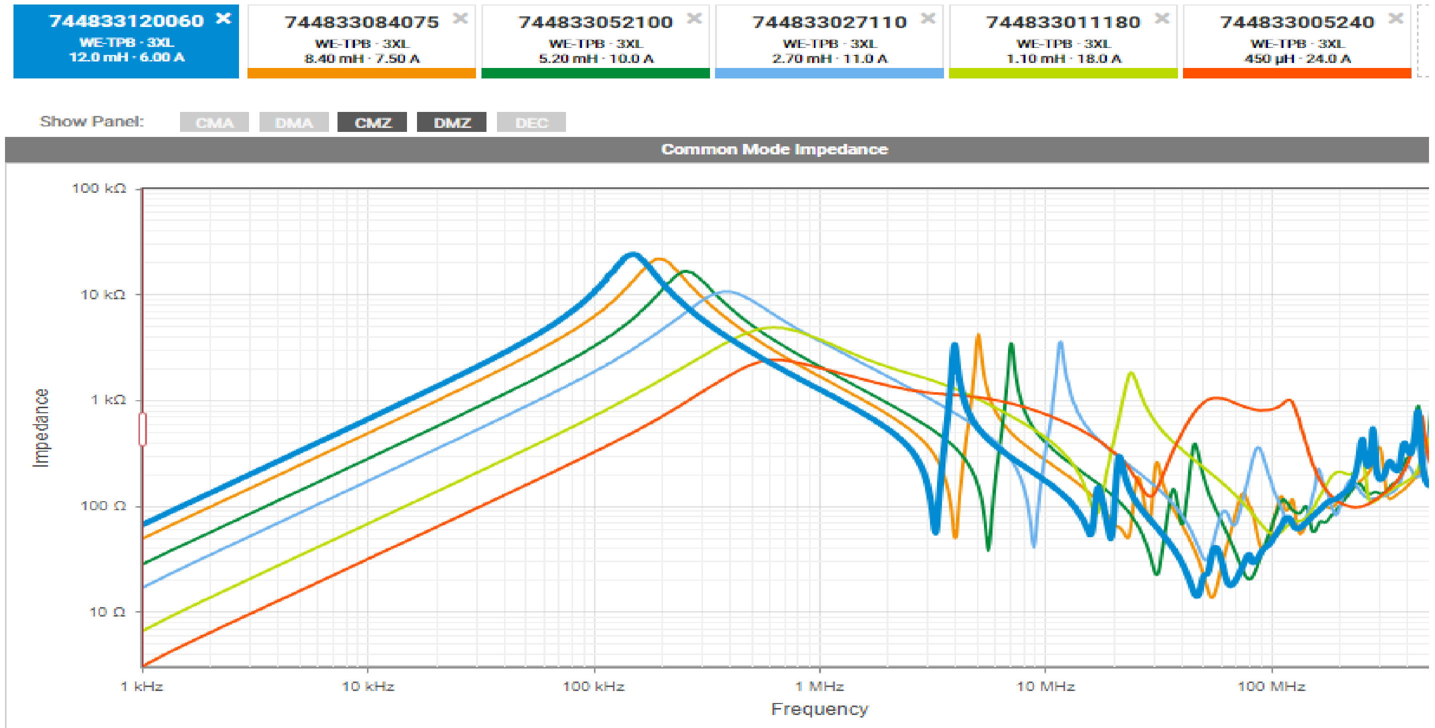
MKP THB

- WCAP-FTXH
- Pitch: 15 – 37.5mm
- Vr: 310VAC
- 33nF – 10µF
- -40°C to +110°C
- THB rated: **1000h @ 85°C + 85% humidity**

CMC´s

3-phase 500V - WE-TPB – Ø47mm

- **MnZn** core material / -40°C to +125°C
- 1kHz to 2MHz effective frequency range
- Up to 24A
- 0,52mH to 12mH

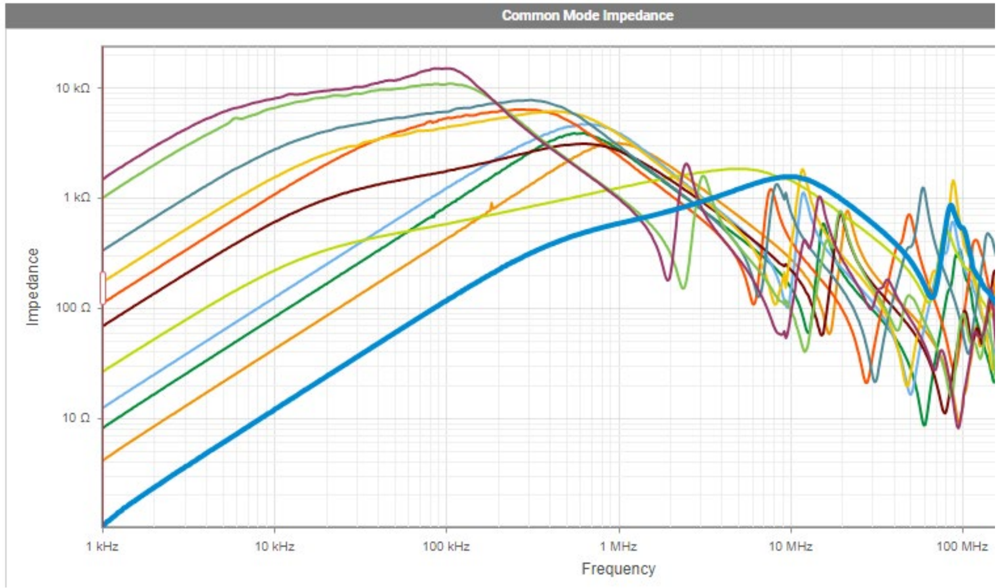


CMC´s

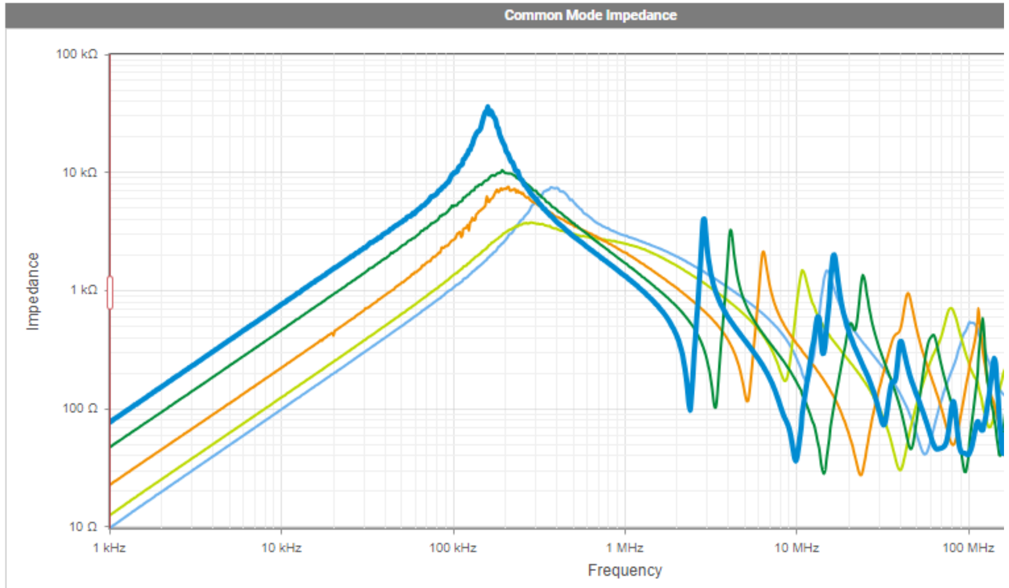
3-phase 760V – WE-TPBHV – Ø70mm

- MnZn & Nanocrystaline core materials / -40°C to +125°C
- 1kHz to 20MHz effective frequency range
- Up to 46A
- 0,2mH to 208mH

Nanocrystaline

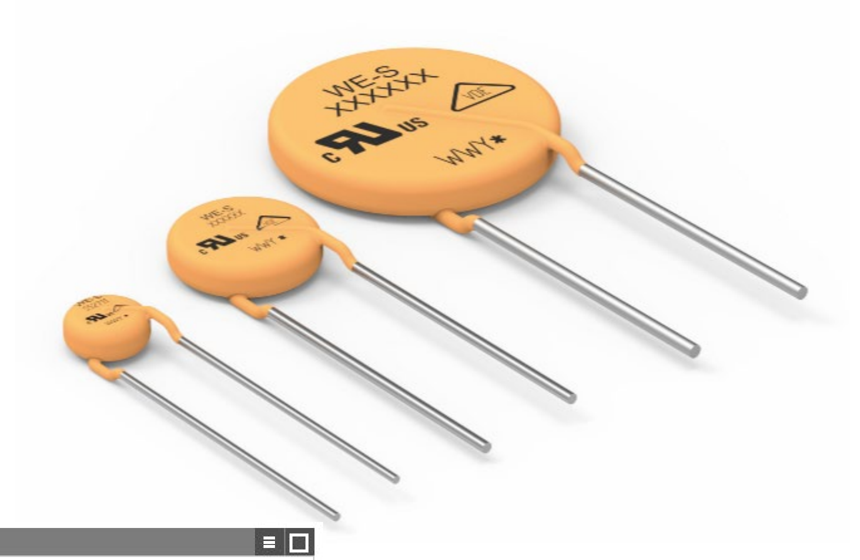


MnZn

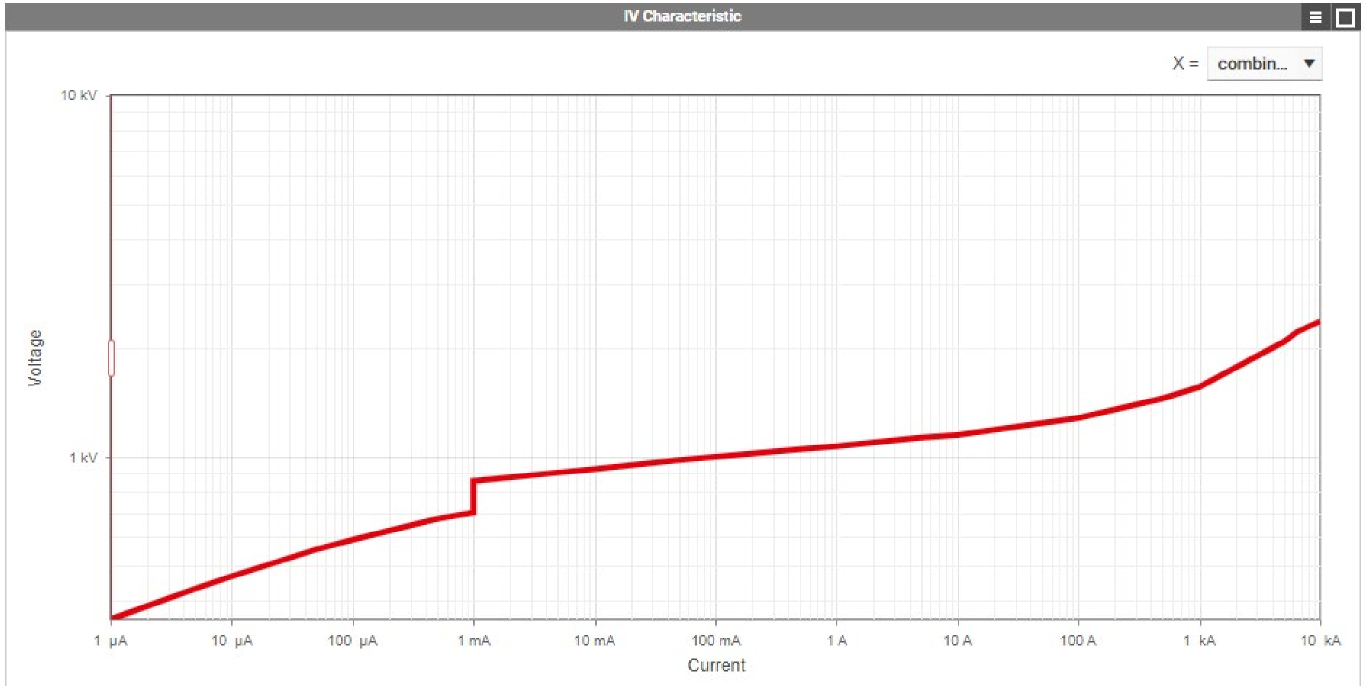


Surge Protection Varistors

WE-VD



- 5 – 20mm Ø THT
- Vrms: 14V – 1000V
- Imax: 100A – 10000A
- -40°C to 105°C
- UL, IEC & VDE certified

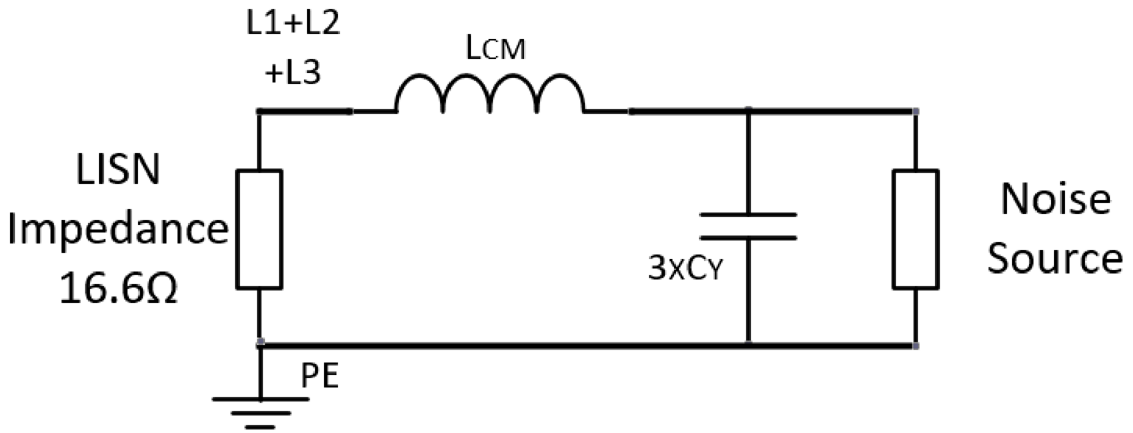


FILTER STRUCTURE

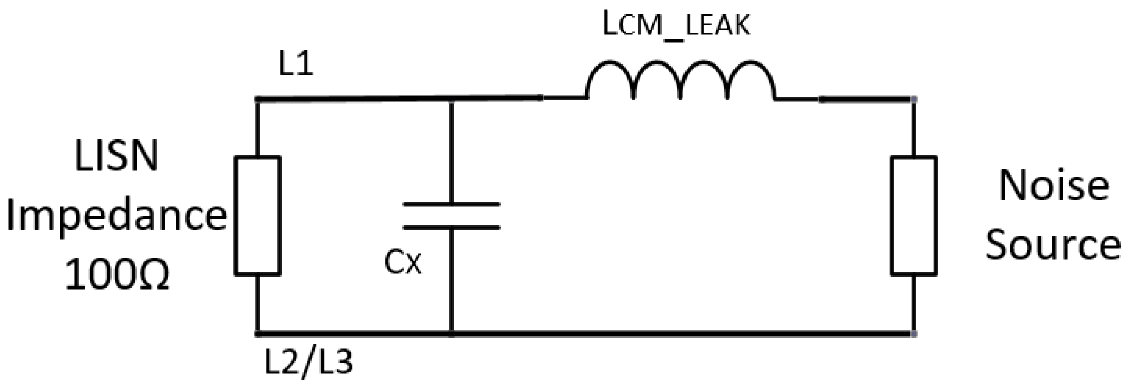
CM & DM Filter Equivalent

Effective LISN Impedance and Component Arrangement

- Common Mode



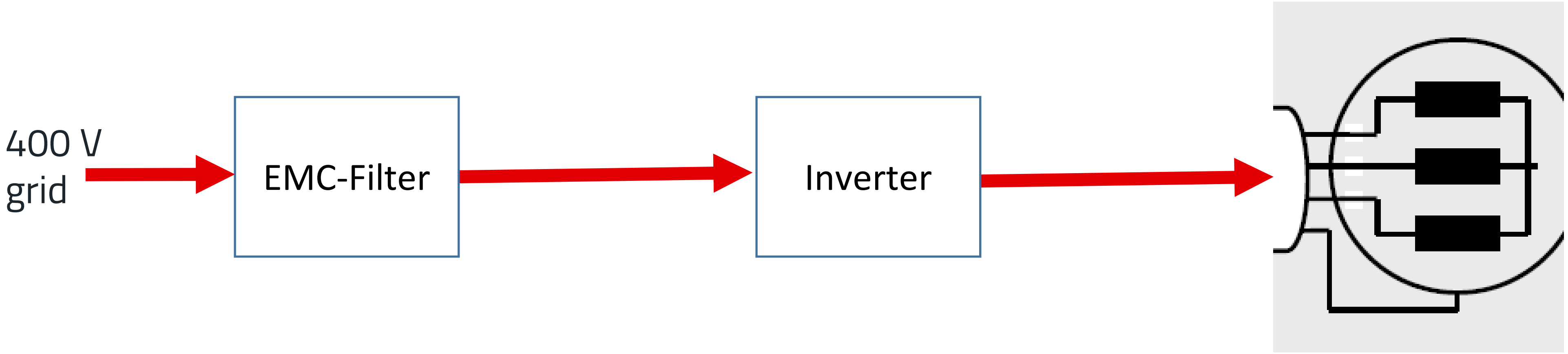
- Differential Mode



DUT SETUP

DUT

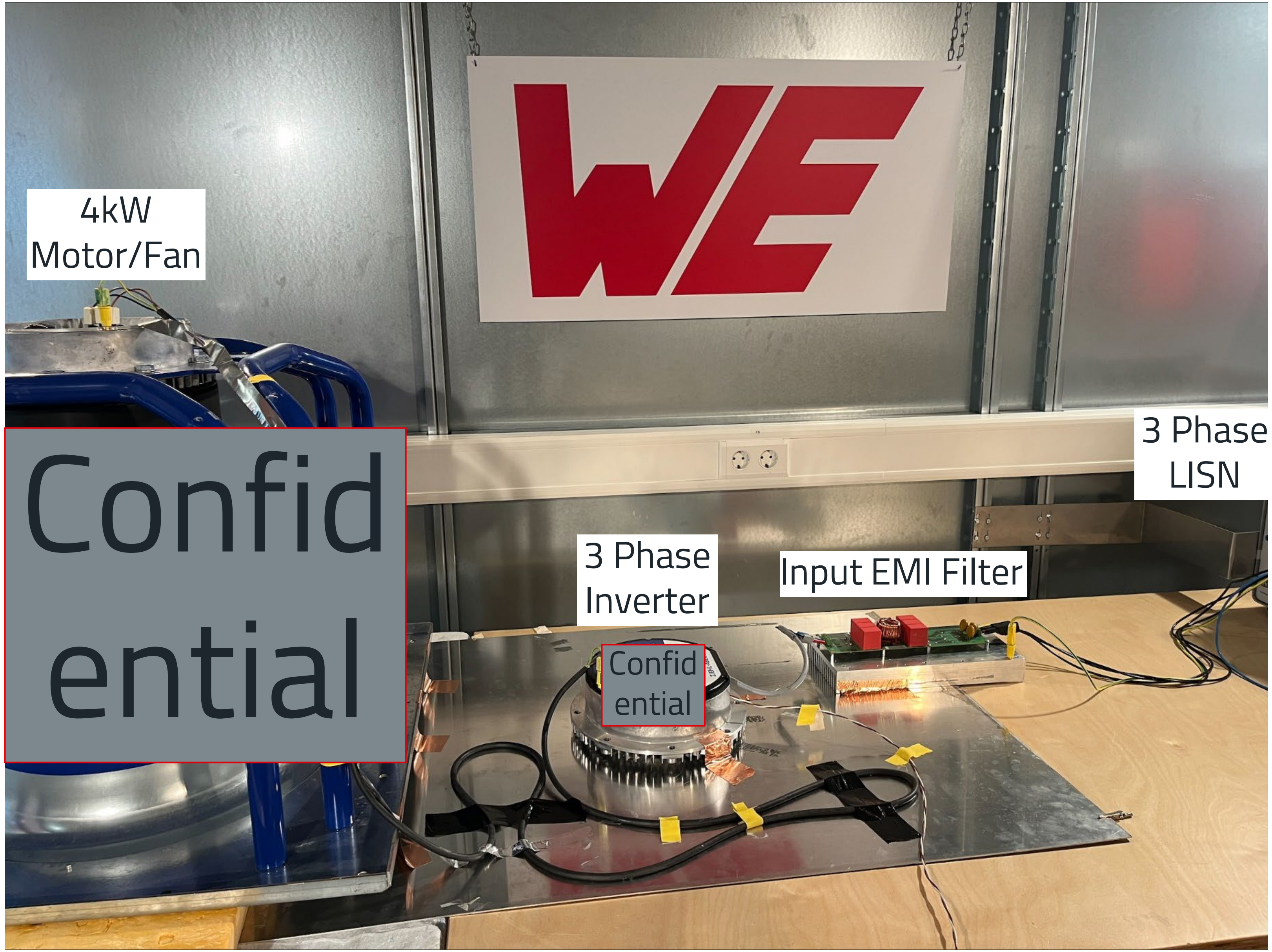
Motor drive system (Fan)



4 kW; 5 A motor current.

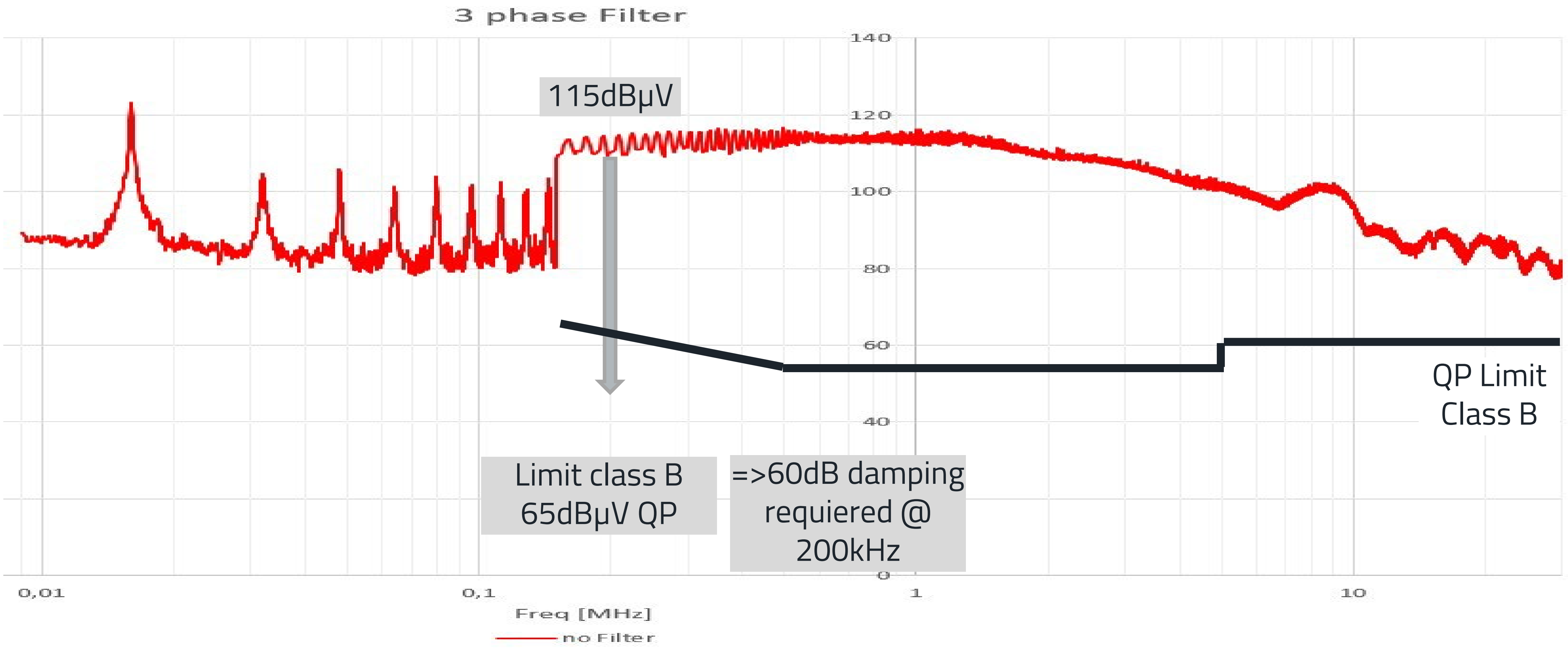
Test Setup

Conducted emission testing

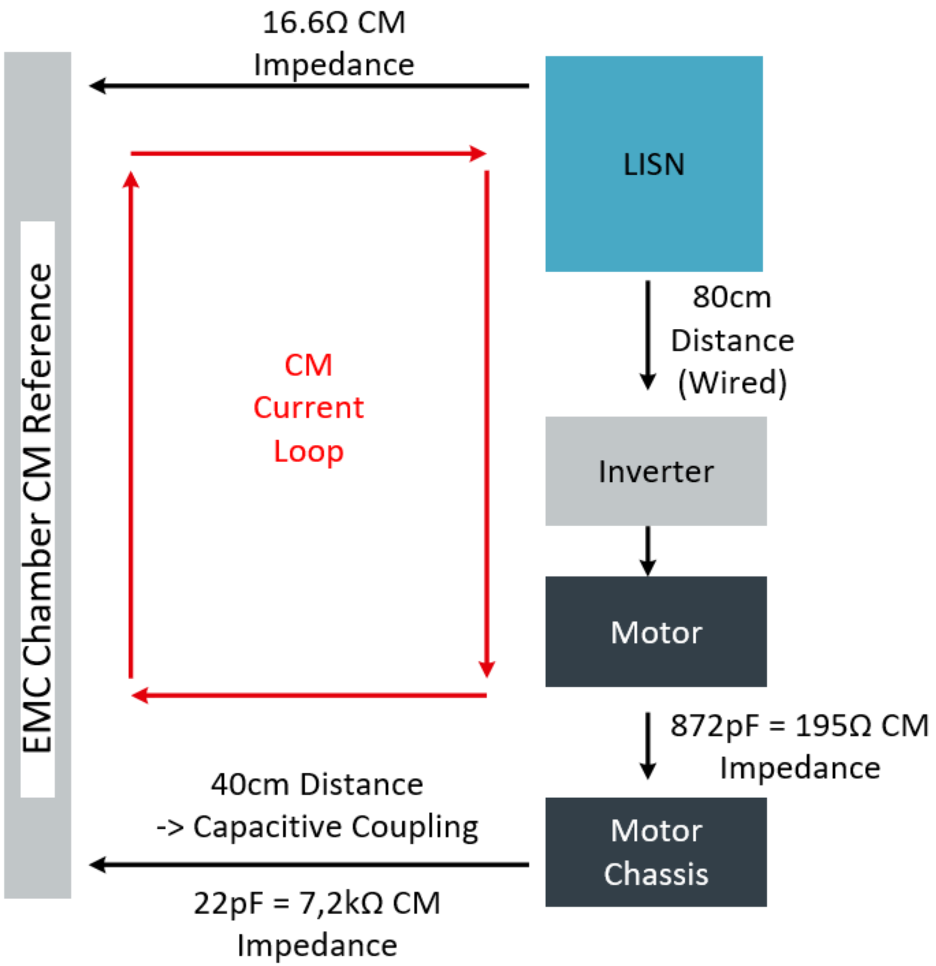


Conducted emissions 150kHz to 30MHz

No filter (PWM fundamental fsw=16kHz)



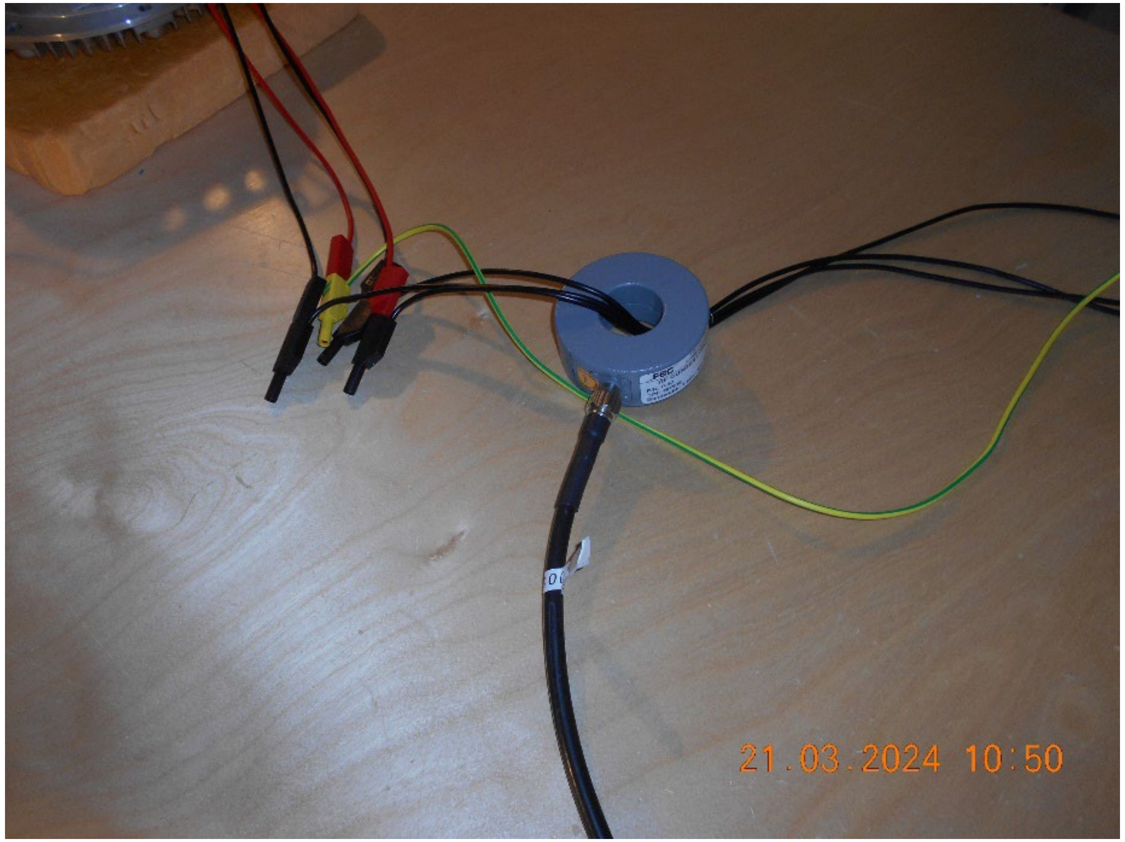
Test Setup


16.6Ω CM
Impedance
LISN
EMC Chamber CM Reference
CM
Current
Loop
80cm
Distance
(Wired)
Inverter
Motor
872pF = 195Ω CM
Impedance
Motor
Chassis
40cm Distance
-> Capacitive Coupling
22pF = 7,2kΩ CM
Impedance

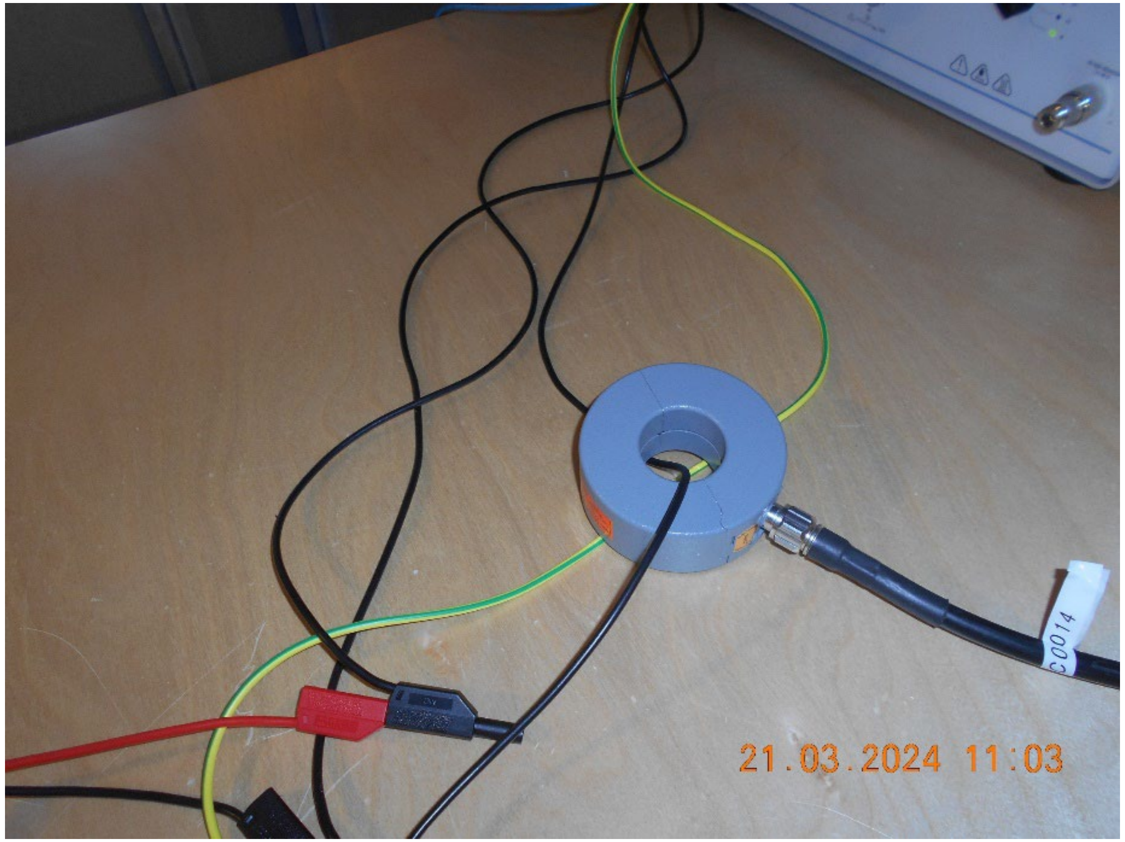
Common Mode vs Differential Mode

Current probe setup

- Common mode on all 3 lines:



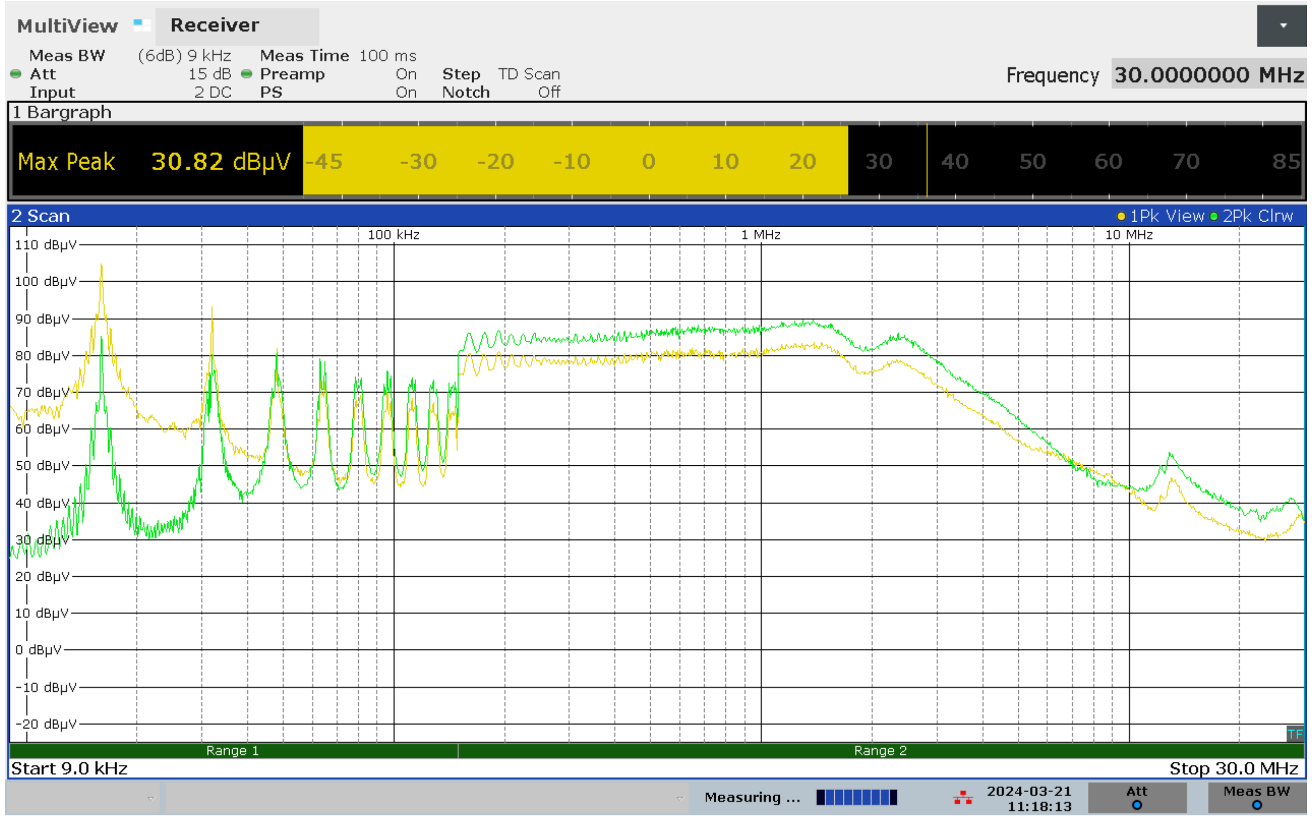
- Differential mode + common mode on single line



Common Mode vs Differential Mode

DUT with PE / Earth connection

- Green = common mode current on all 3 lines
- Yellow = differential mode current + common mode current on a single line



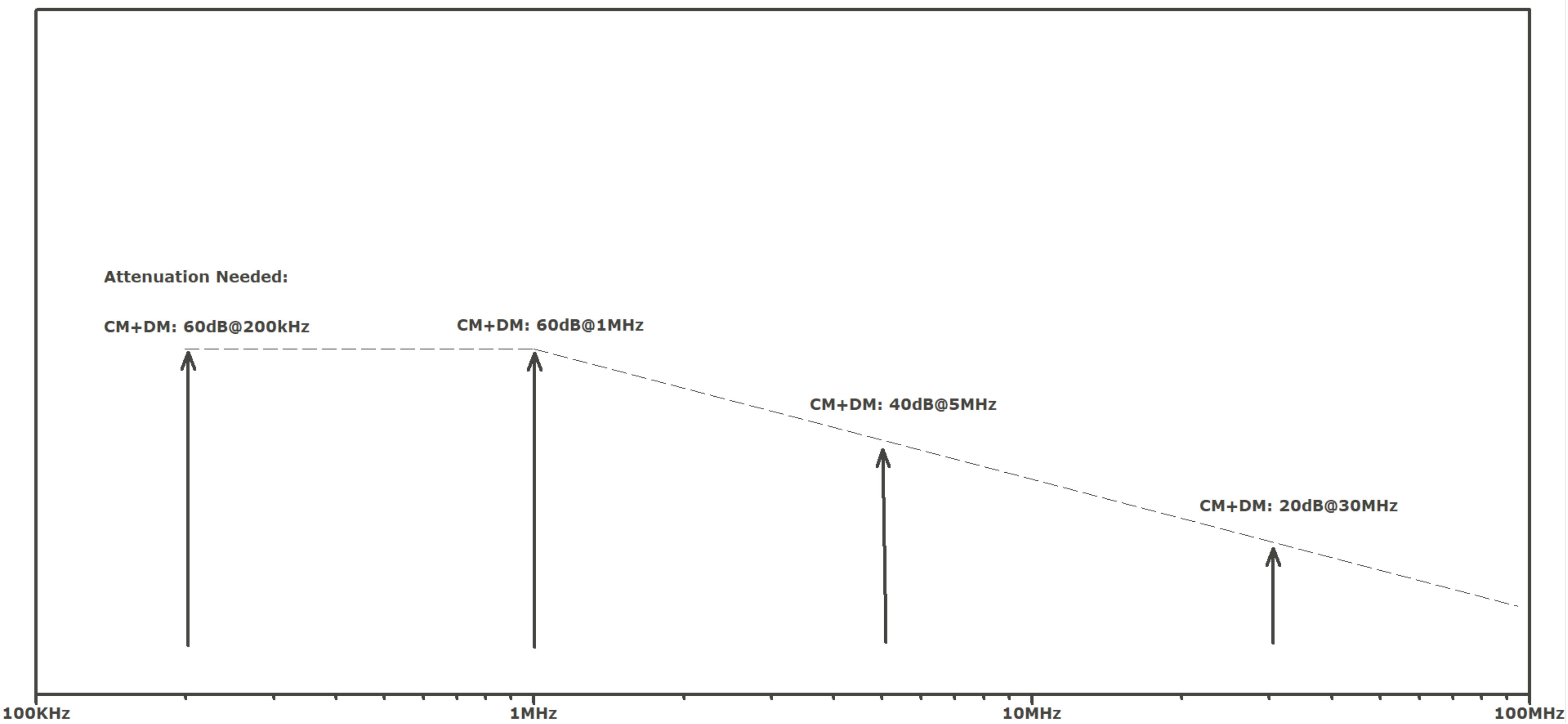
11:18:13 AM 03/21/2024

DM noise dominant below 50 kHz!

CM noise is dominant over 100kHz

Requiered Filter Attenuation

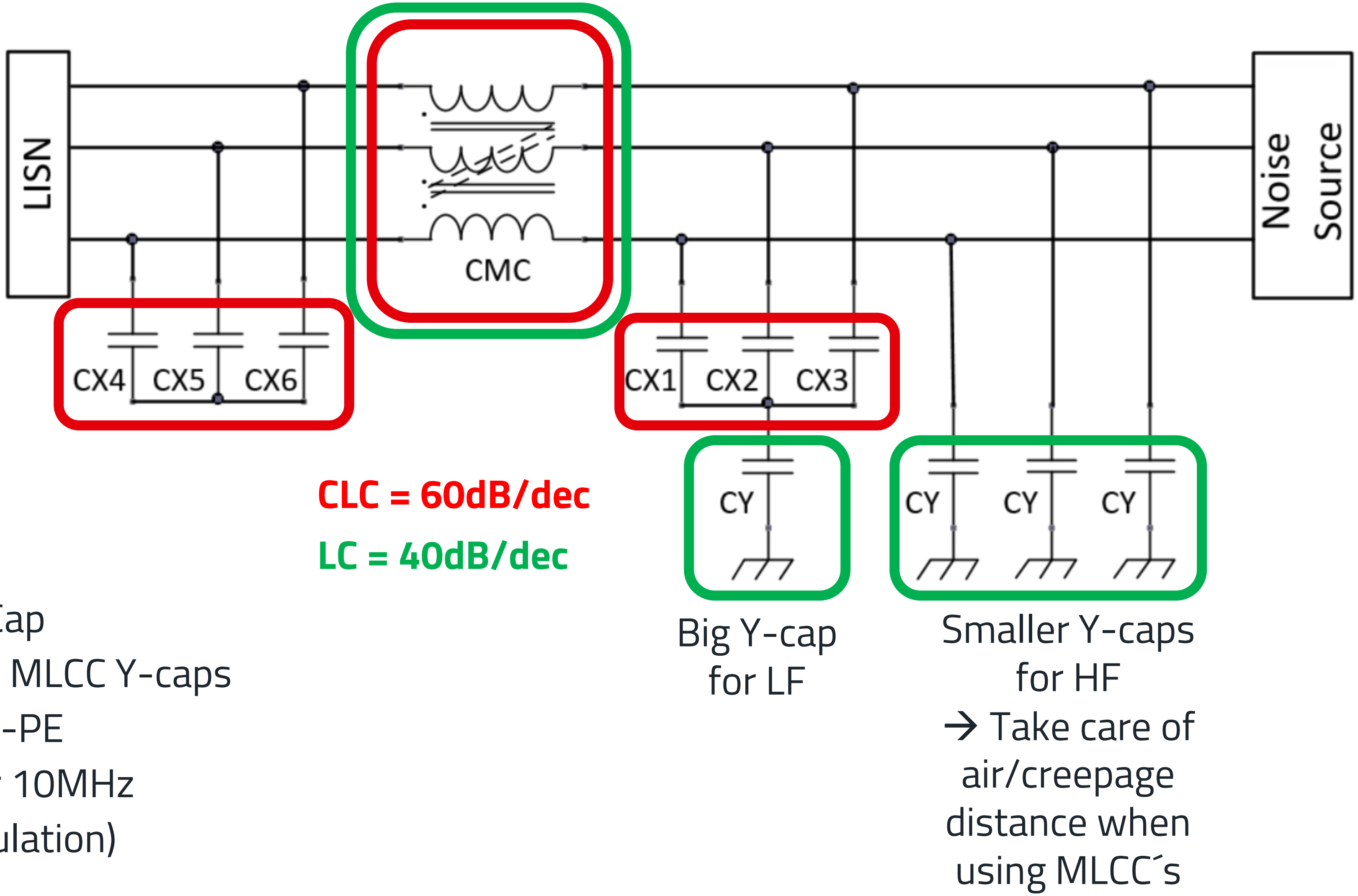
DM & CM



MATH

Chosen Filter Structure for DUT 150kHz to 30MHz

„CLC“ for **DM** and „LC“ for **CM**



- **DM** filter provides 60dB/dec
  - Leakage of CMC + X-Caps

- **CM** filter provides 40dB/dec
  - CMC main inductance + big Y-Cap
  - Additionally 3x small e.g. 2.2nF MLCC Y-caps

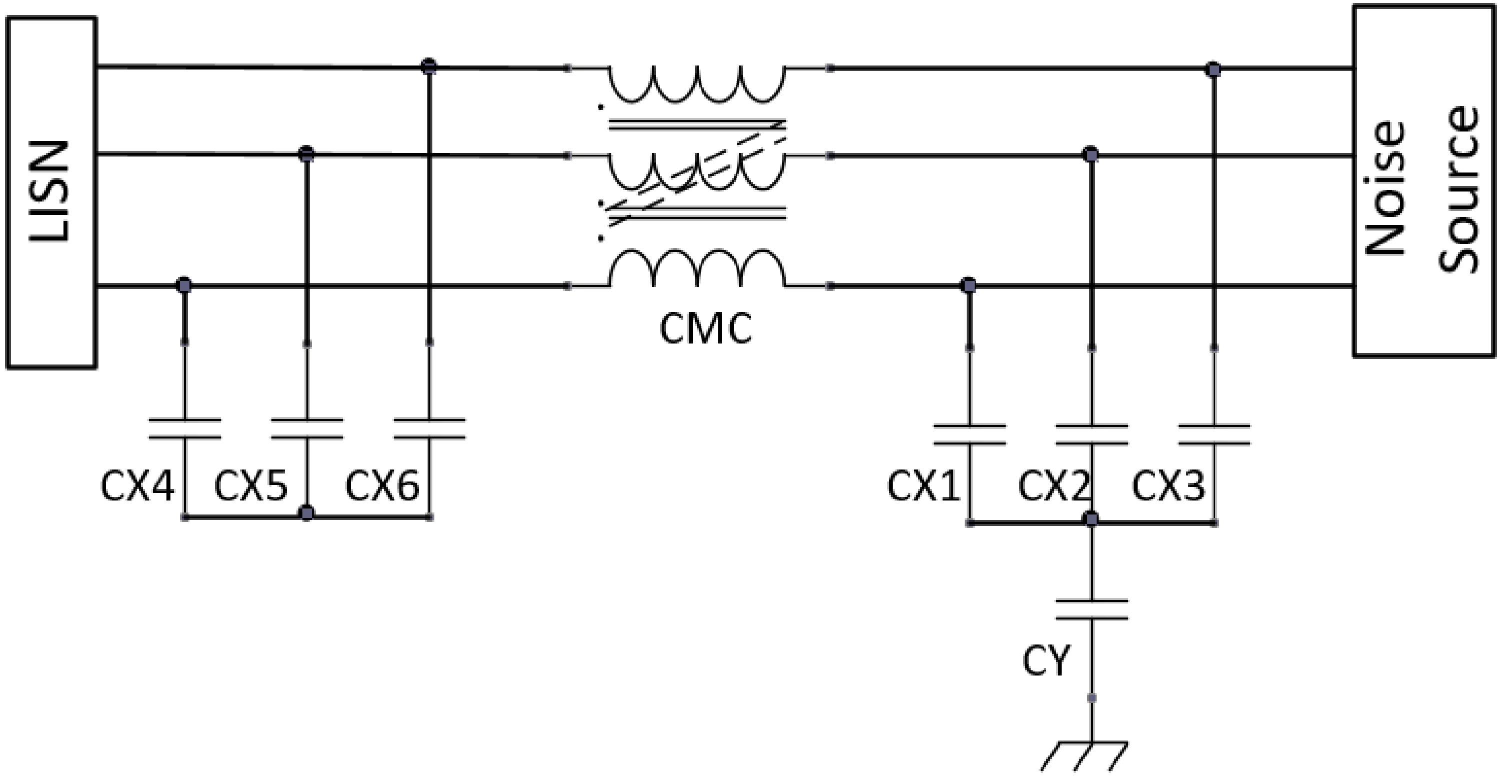
  direct connected between phases-PE
  to increase the insertion loss over 10MHz
  (**not** included in the math but simulation)

CM & DM Filter Equivalent

Effective Cx and Cy in 3 phase systems

- Cx between each phase:
- $Cx_{effective} = \left(\frac{1}{CX1} + \frac{1}{CX2}\right)^{-1}$

- Cy betwenn all 3 phases and PE:
- $Cy_{effective} = \left(\frac{1}{CX1+CX2+CX3} + \frac{1}{CY}\right)^{-1}$



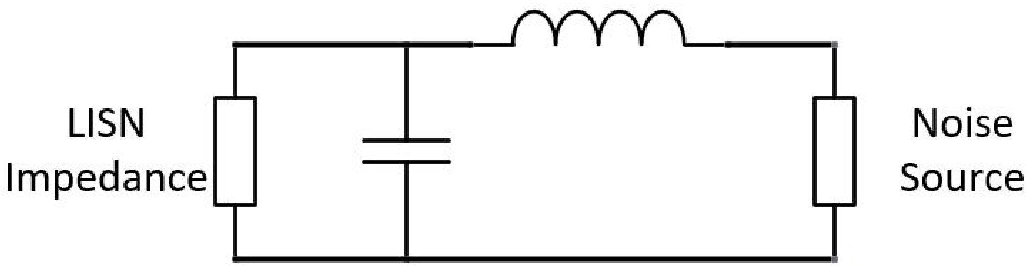
Corner Frequency for desired Attenuation at fsw = A_fsw

Valid for both: CM & DM

1-Stage LC

$$A_{\mathrm{fsw}} = \log\left(\frac{f_{\mathrm{sw}}}{f_{\mathrm{co}}}\right) \cdot 40dB$$

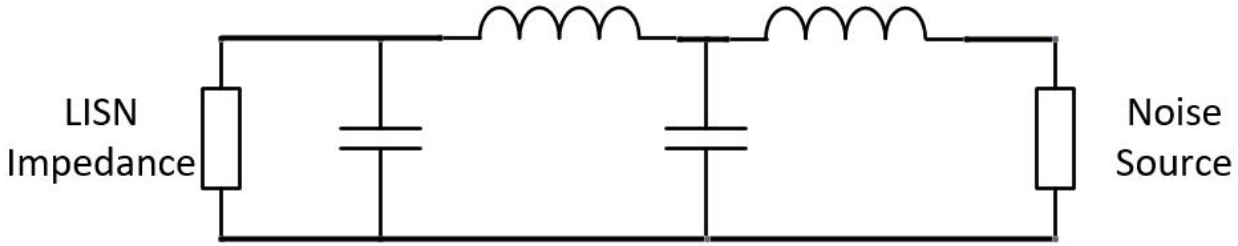
$$f_{co} = \frac{f_{sw}}{10^{\frac{A_{fsw(dB)}}{40dB}}}$$



2-Stage LC

$$A_{\mathrm{fsw}} = \log\left(\frac{f_{\mathrm{sw}}}{f_{\mathrm{co}}}\right) \cdot 80dB$$

$$f_{co} = \frac{f_{sw}}{10^{\frac{A_{fsw(dB)}}{80}dB}}$$



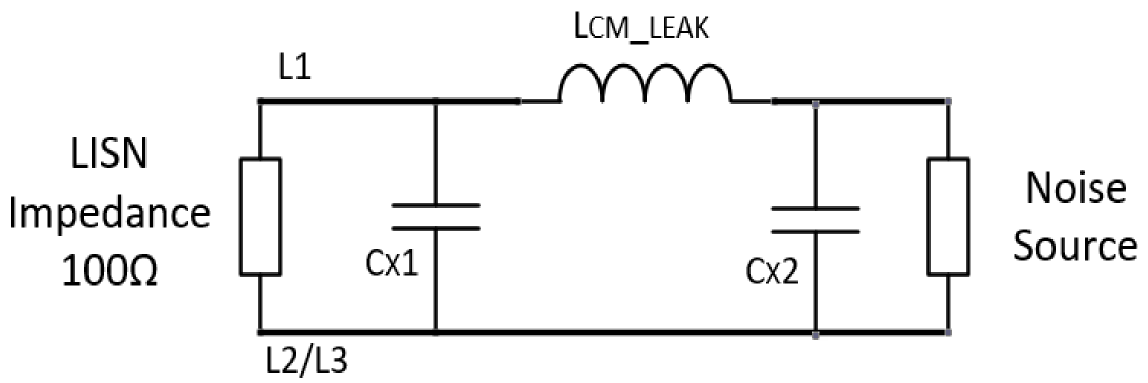
Corner Frequency for desired Attenuation at fsw = A_fsw

DM PI filter

1-Stage CLC = „PI“

$$A_{\mathrm{fsw}} = \log\left(\frac{f_{\mathrm{sw}}}{f_{\mathrm{co}}}\right) \cdot 60dB$$

$$f_{co} = \frac{f_{sw}}{10^{\frac{A_{fsw(dB)}}{60dB}}}$$



Additional Math for „CLC – PI“

$$f_c = \frac{1}{2\pi\sqrt{L_{CMleak} \cdot C_{XG}}}$$

$$C_{XG} = \frac{Cx1 \cdot Cx2}{Cx1 + Cx2}$$

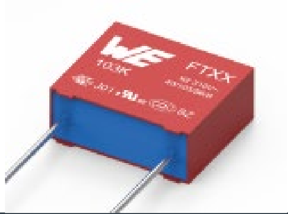
Additionally this result must be divided by „2“ as we have two X2 in a row between the phases!

CLC (DM) & LC (CM) - Stage Calculation (worst case without real CM couping)

Desired damping for CM & DM = 60dB @ 200kHz

1. „CLC PI“ = 60dB/Dec (DM) and „LC“ = 40dB/Dec (CM)
2. DM filter corner frequency: fc_dm = **20kHz** & CM filter corner frequency: fc_cm = **6.3kHz**
3. Define Y-caps → 2x47nF(star/series connected with the X-caps) → $Cy_{effective} = (\frac{1}{CX1+CX2+CX3} + \frac{1}{CY})^{-1} = \mathbf{94nF}$

4. Define L_cm for fc_cm = 6.3kHz → $L_{cm} = \frac{1}{(2\pi fc)^2 C_y} = \frac{1}{(2\pi \cdot 6.3kHz)^2 \cdot 94nF} = 6.8mH$ → **8.4mH** chosen (744833084075)
5. $Actual\ f_{cm} = \frac{1}{2\pi\sqrt{L_{cm}Cy}} = \frac{1}{2\pi\sqrt{8.4mH \cdot 94nF}} = 5.7kHz \longrightarrow A_{fsw_{cm}} = log\left(\frac{200kHz}{5.7kHz}\right) \cdot 40dB = \mathbf{62dB}$
6. Calc. L_dm → XL = 39Ω@100kHz → $L_{dm} = \frac{XL}{2\pi f} = \frac{39\Omega}{2\pi \cdot 100kHz} = \mathbf{62\mu H}$ (use REDEXPERT for help)
7. Define Cx → $C_x = \frac{1}{(2\pi fc)^2 L_{dm}} = \frac{1}{(2\pi \cdot 20kHz)^2 \cdot 62\mu H} = 1.02\mu F$ → 4.7µF chosen → $C_{XG} = \frac{Cx1 \cdot Cx2}{Cx1+Cx2} = \mathbf{2,35\mu F : 2 = 1,18\mu F}$ (6x 890334027030CS)
8. $Actual\ f_{dm} = \frac{1}{2\pi\sqrt{L_{dm}Cx}} = \frac{1}{2\pi\sqrt{62\mu H \cdot 1.18\mu F}} = 18.6kHz \longrightarrow A_{fsw_{dm}} = log\left(\frac{200kHz}{18.6kHz}\right) \cdot 60dB = \mathbf{62dB}$



Be careful with Nanocrystalline Cores

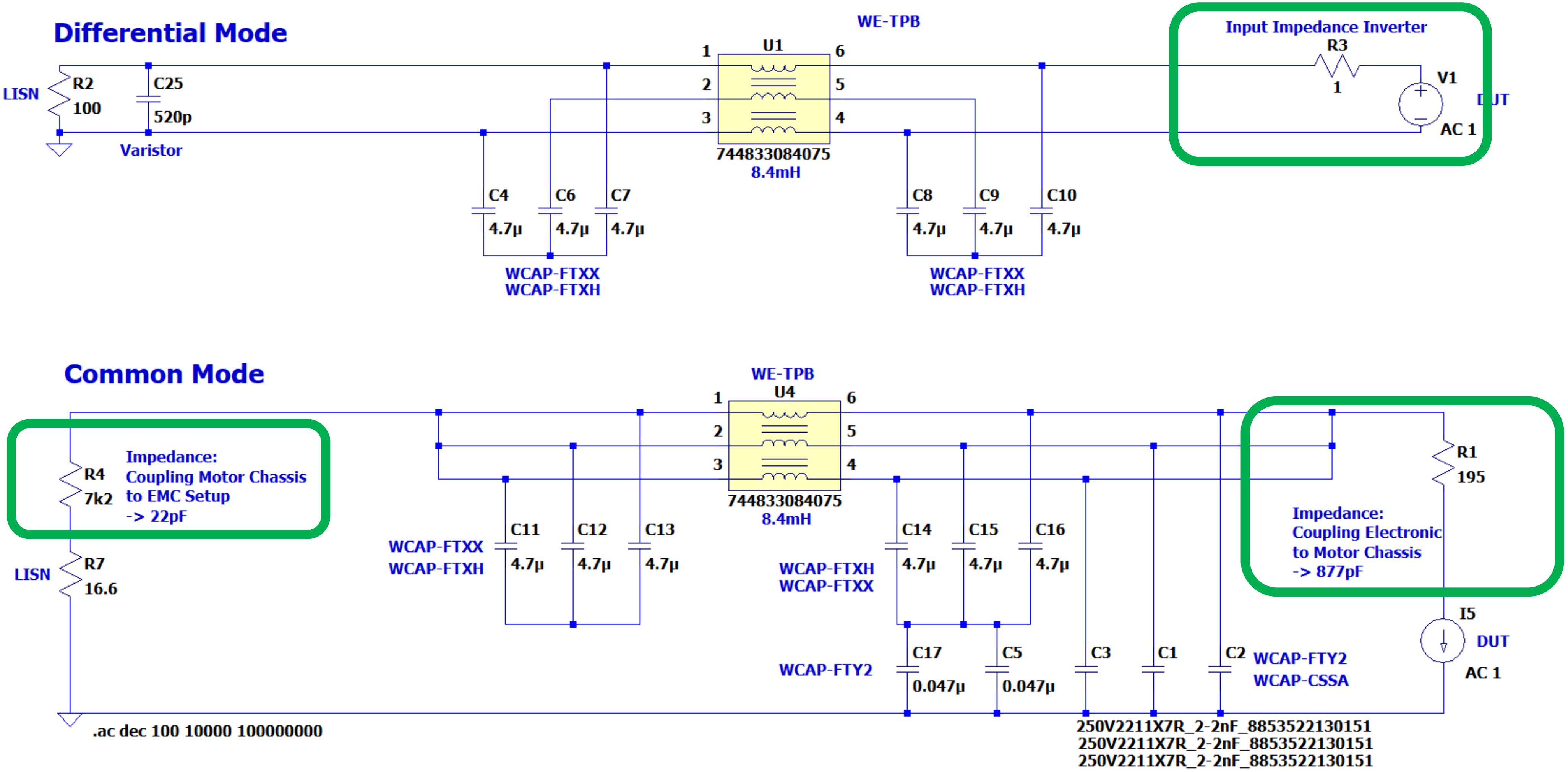
https://we-online.com/re/5tasN741

- E.g. 744838180160 → 18mH (datasheet) meas. at 10kHz
- CM impedance @ 10kHz = 1.06kΩ → 17mH
- CM impedance @ 100kHz = 5.23kΩ → 8mH

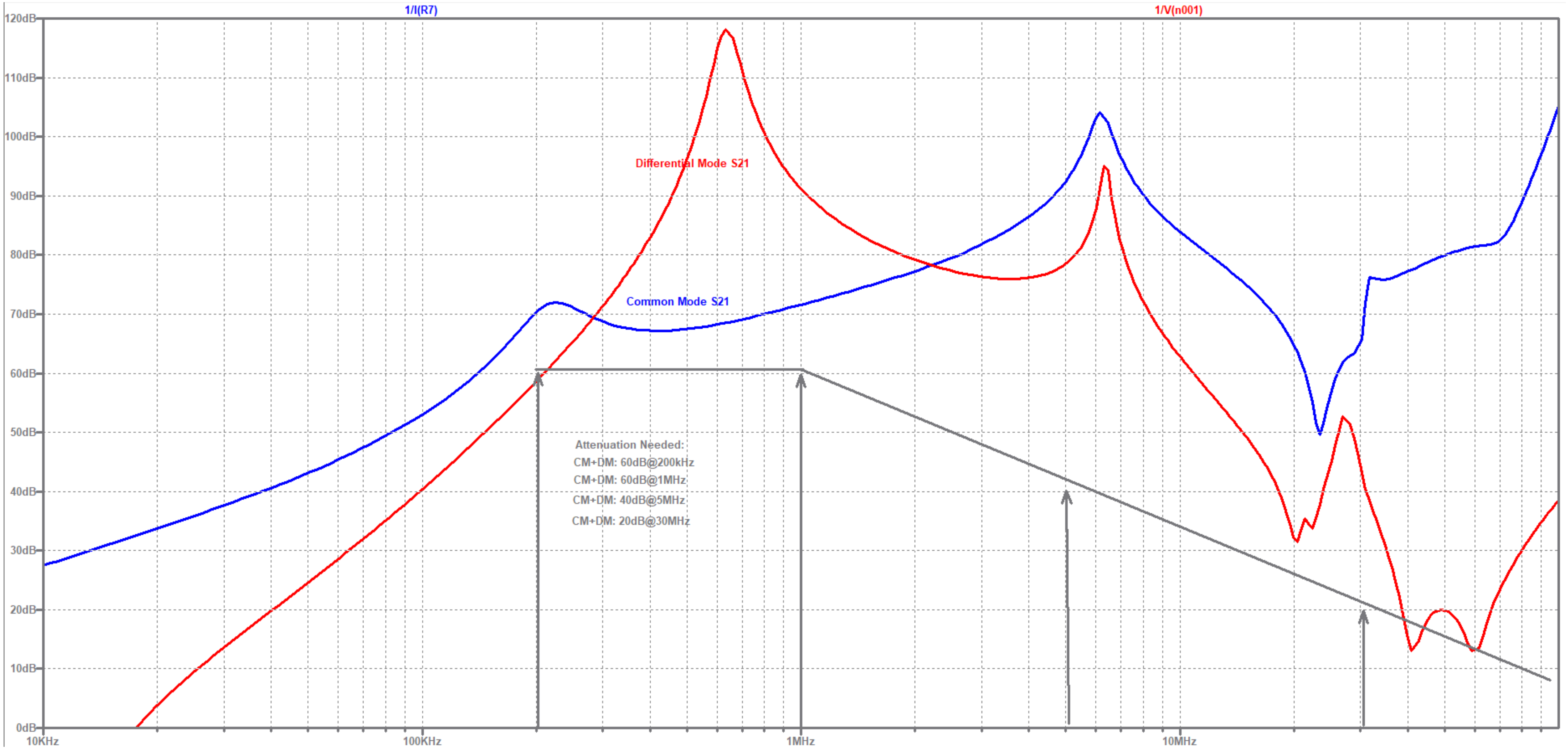
- CM curve is not linear → frequency dependence of the core permeability

SIMULATION OF THE CALCULATED CLC FILTER

LT Spice Schematic CLC EMI Filter



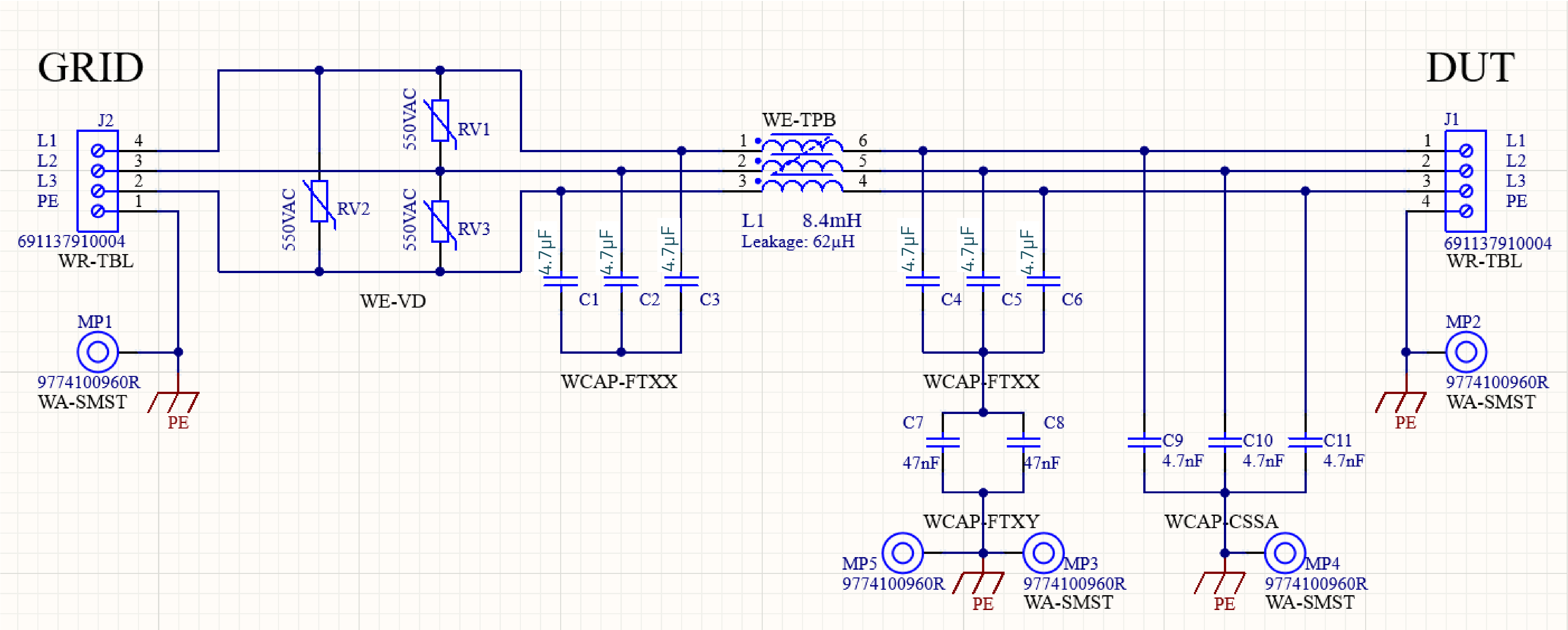
LT Spice Simulation CLC



FILTER PCB

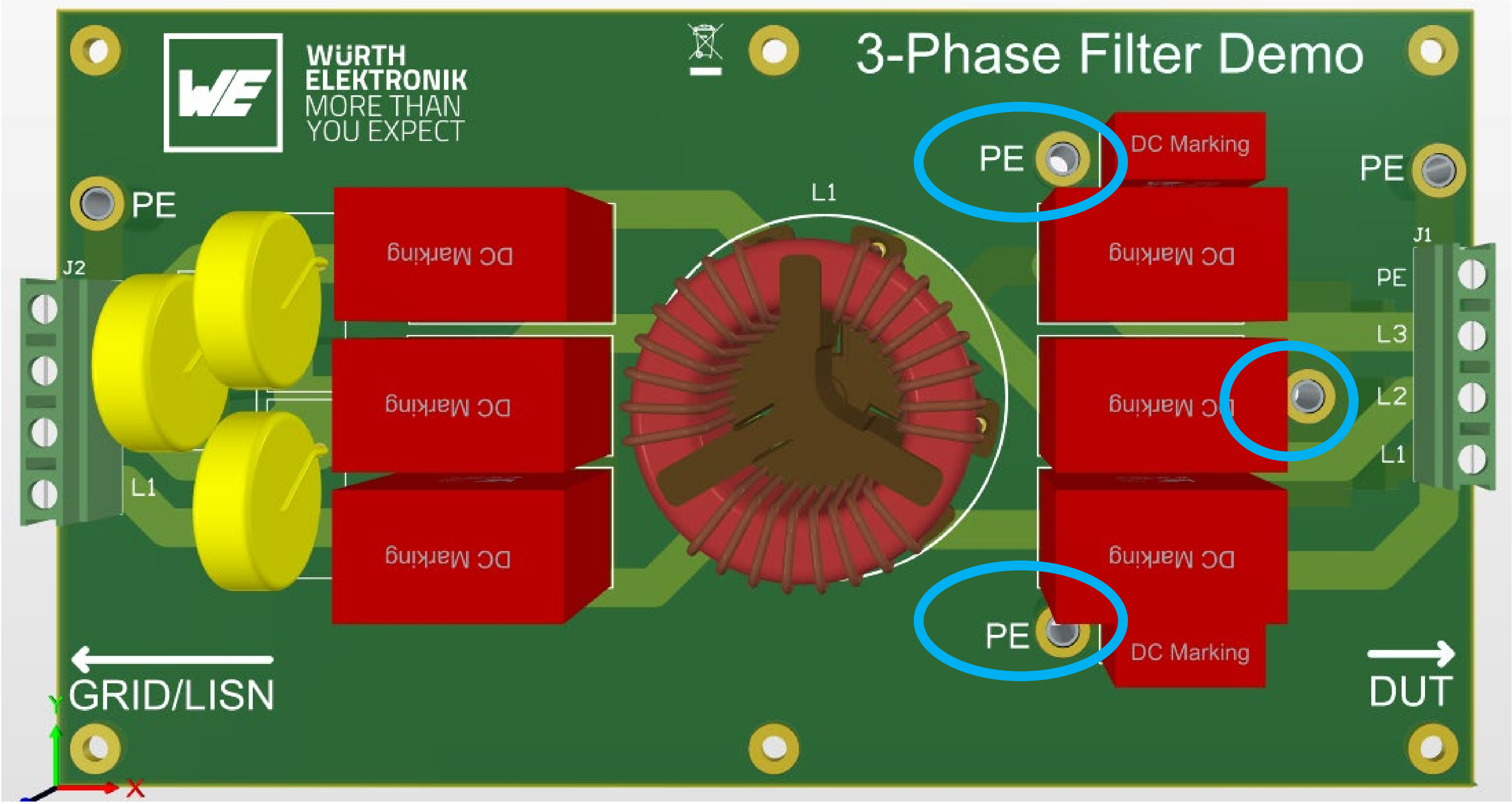
New Filter PCB Schematic

Altium Schematic



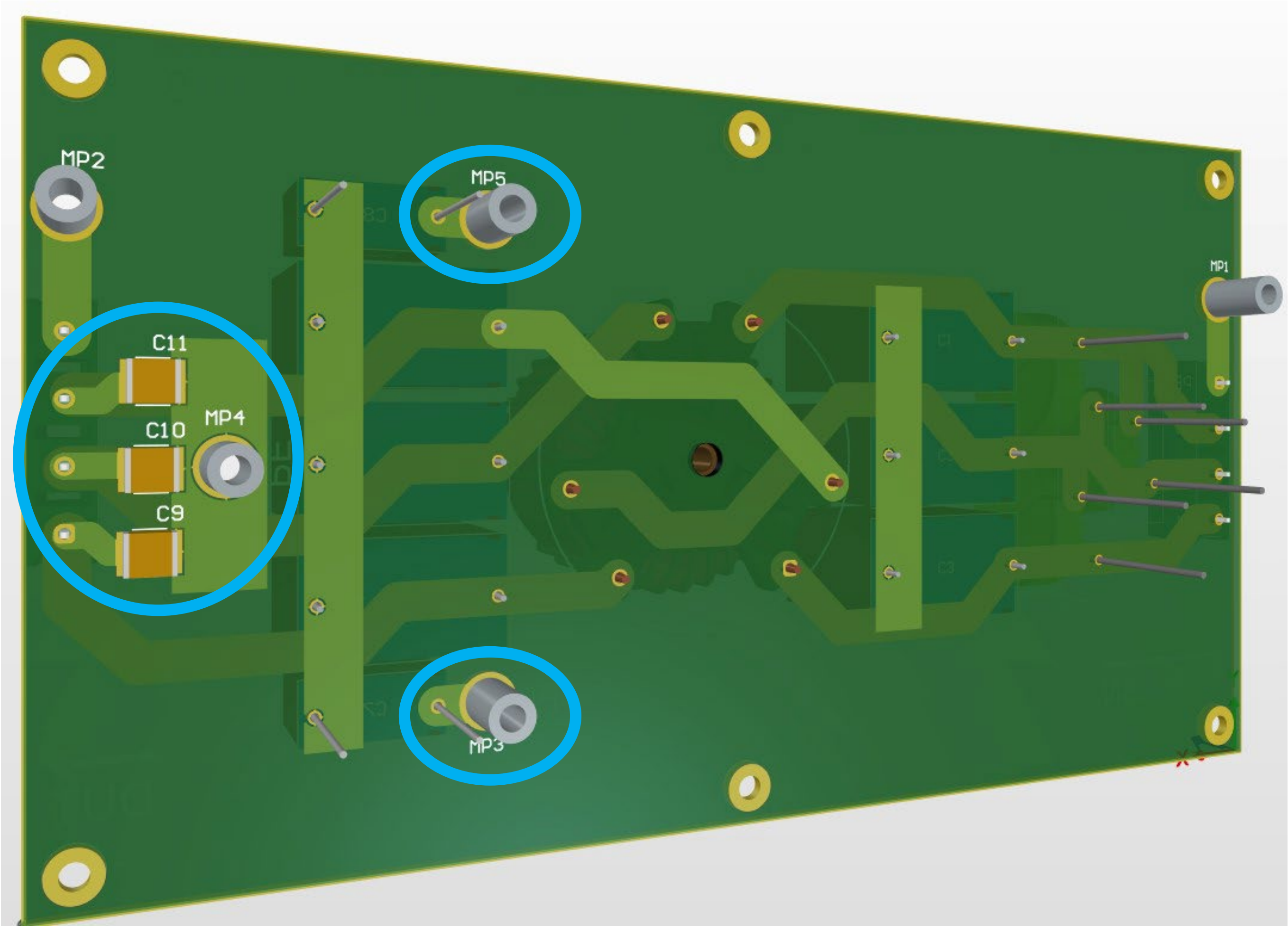
New Filter PCB 3D TOP View

Improved PE connection to chassis



New Filter PCB 3D BOT View

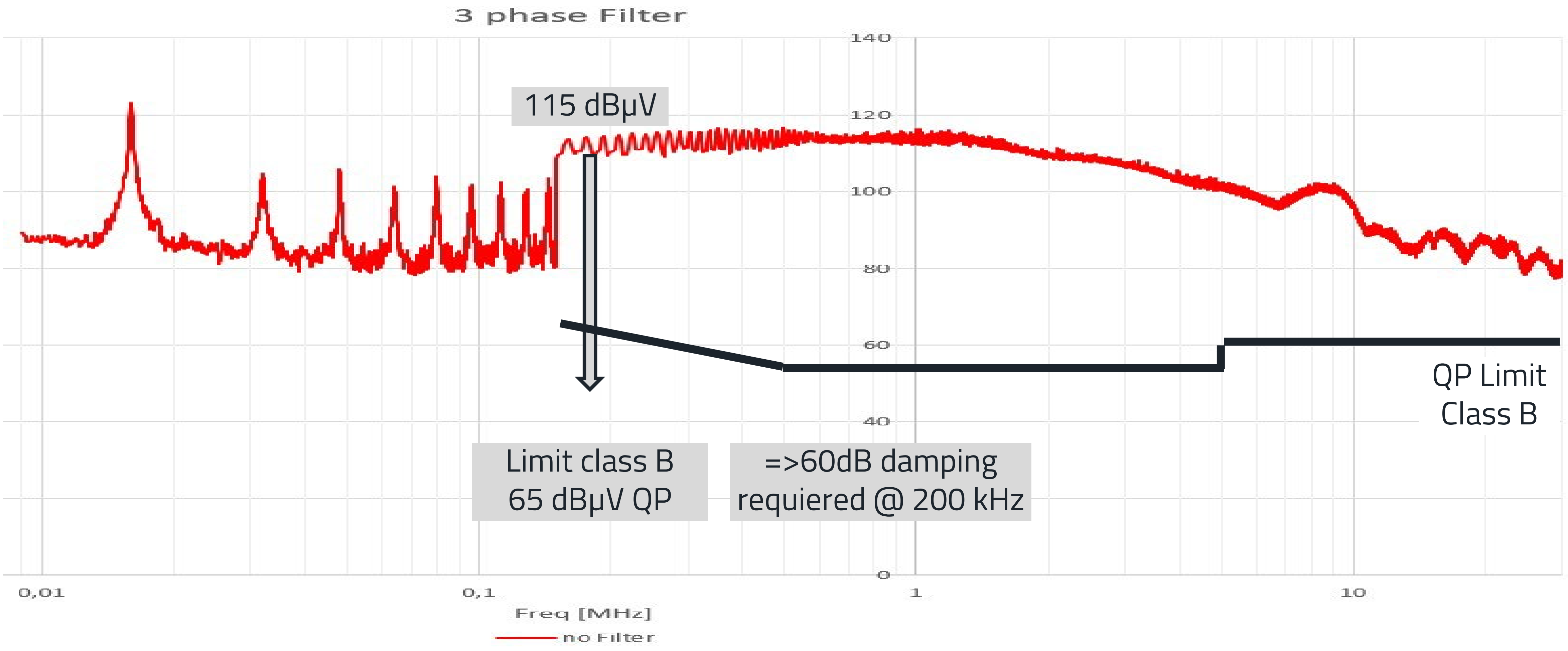
Improved PE connection to chassis



MEASUREMENTS WITH CALCULATED & SIMULATED FILTER

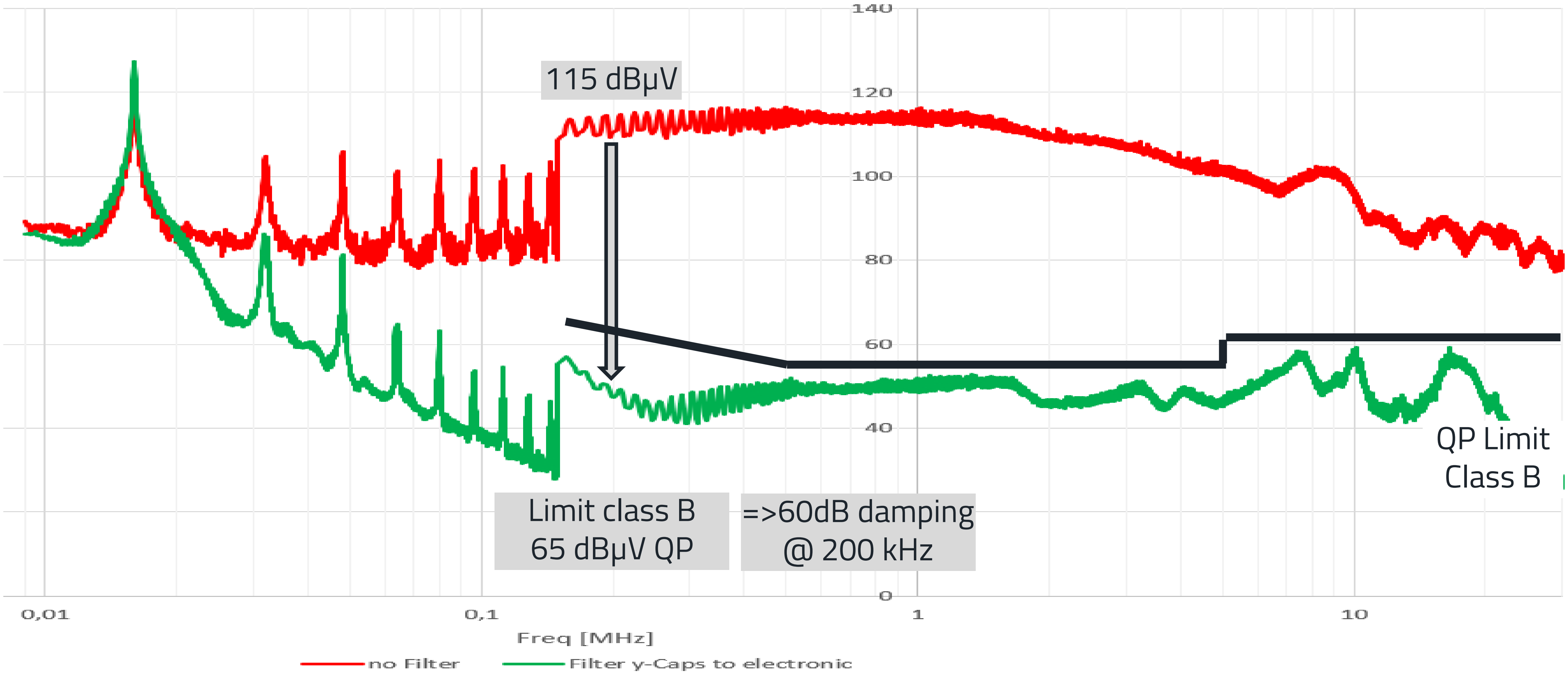
Measurements in the Lab

No Filter



Measurements in the Lab

CLC Filter for 60dB @ 200kHz



What happens if you place the Y-Caps on the wrong side? (=LISN direction, not DUT)

9kHz to 30MHz conducted EMI