Supra-EMC

Supraharmonics **E**lectro**M**agnetic **C**ompatibility strategies in power electronic based power grid
(1/5/2023 – 31/10/2027)

EMC Forum 2026

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Innovation Fund Denmark

OUTLINE

- ❑ Introduction to Supraharmonics in Power Electronics
- ❑ Power Grid Characterization
- ❑ Power Converter Noise Propagation Path Modeling
- ❑ EMC Filter Design
- ❑ Outlook for APECS (Newly Developed EMI Prediction Tool)

EMI/EMC in Power Electronics Importance

EMI/EMC Importance and Challenge

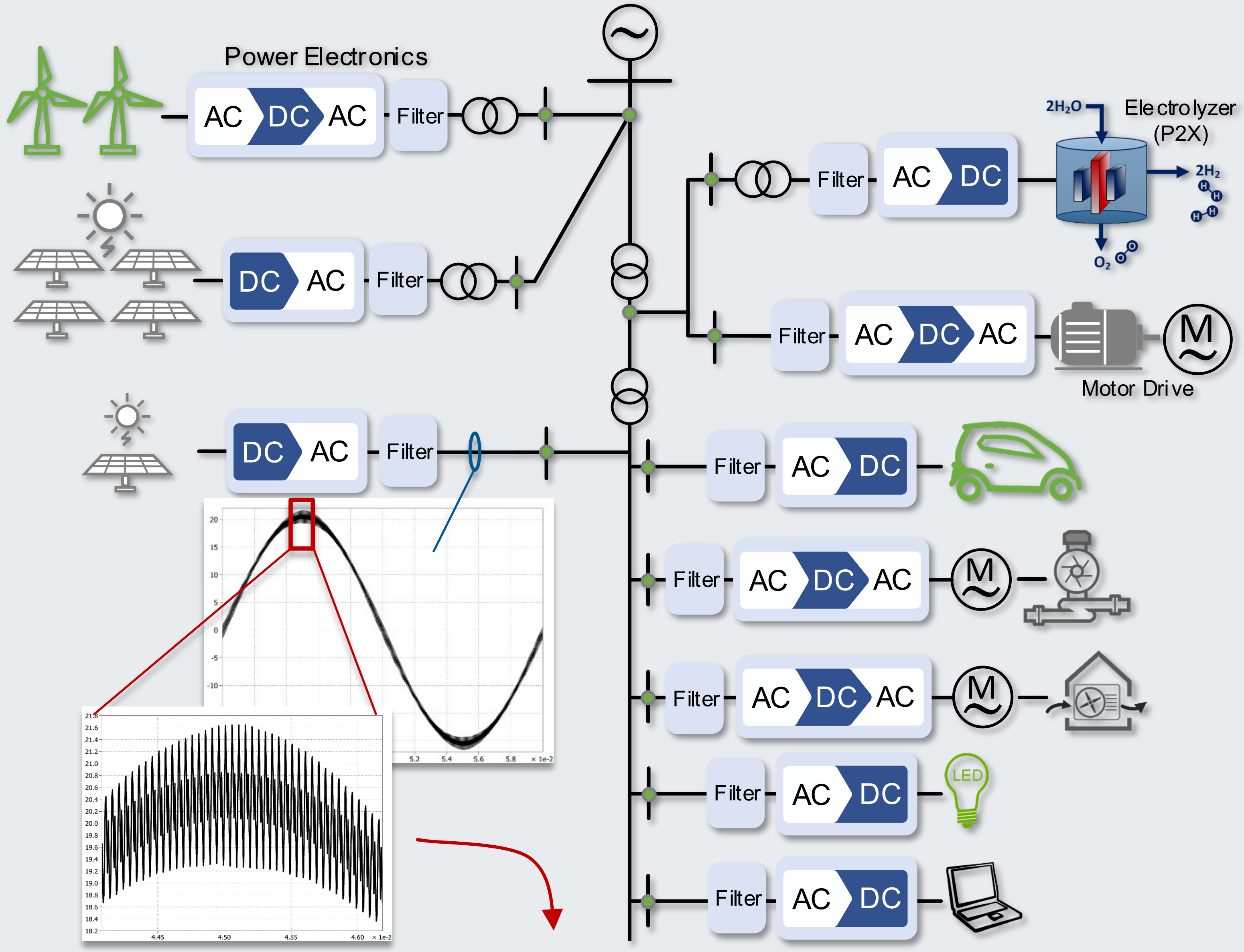
A **new era for electrification** with a growing demand expected to reach 32000 terawatt-hours in 2030 (58 TWh DK)

Power Electronics are an essential part of the **green transition**, currently processing **most** of our electricity today

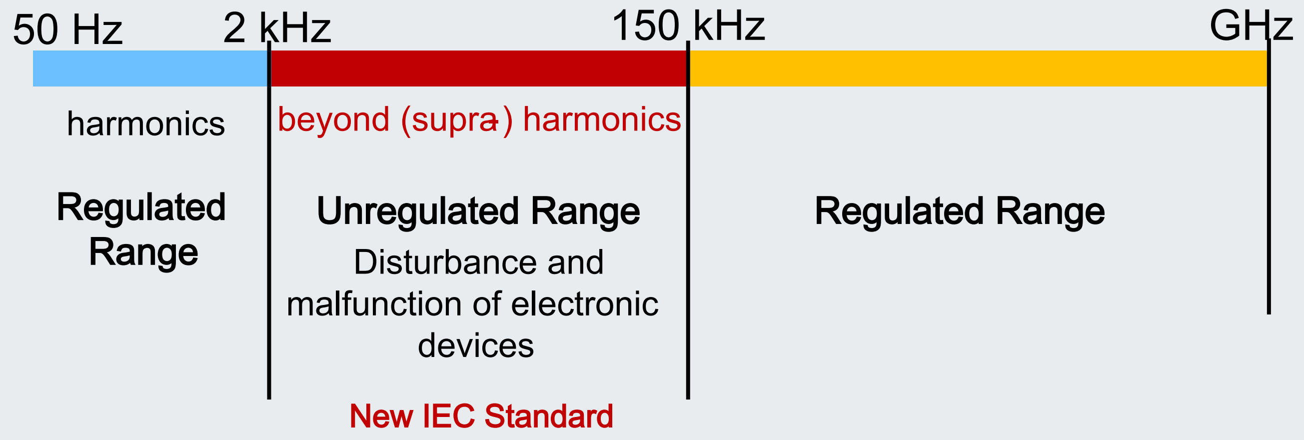
All power electronic converters/systems have the potential to emit **electromagnetic signals** leading to **electromagnetic interference (EMI)**

EMI is a major **road-blocker** for electrification and green transition. Also, **new standards** and **new semiconductors** are on the way

Solution = **Predicting EMI** prior to final prototyping (Develop a Software Tool)



Electromagnetic Interference (EMI),
Cure = Electromagnetic Compatibility (EMC)

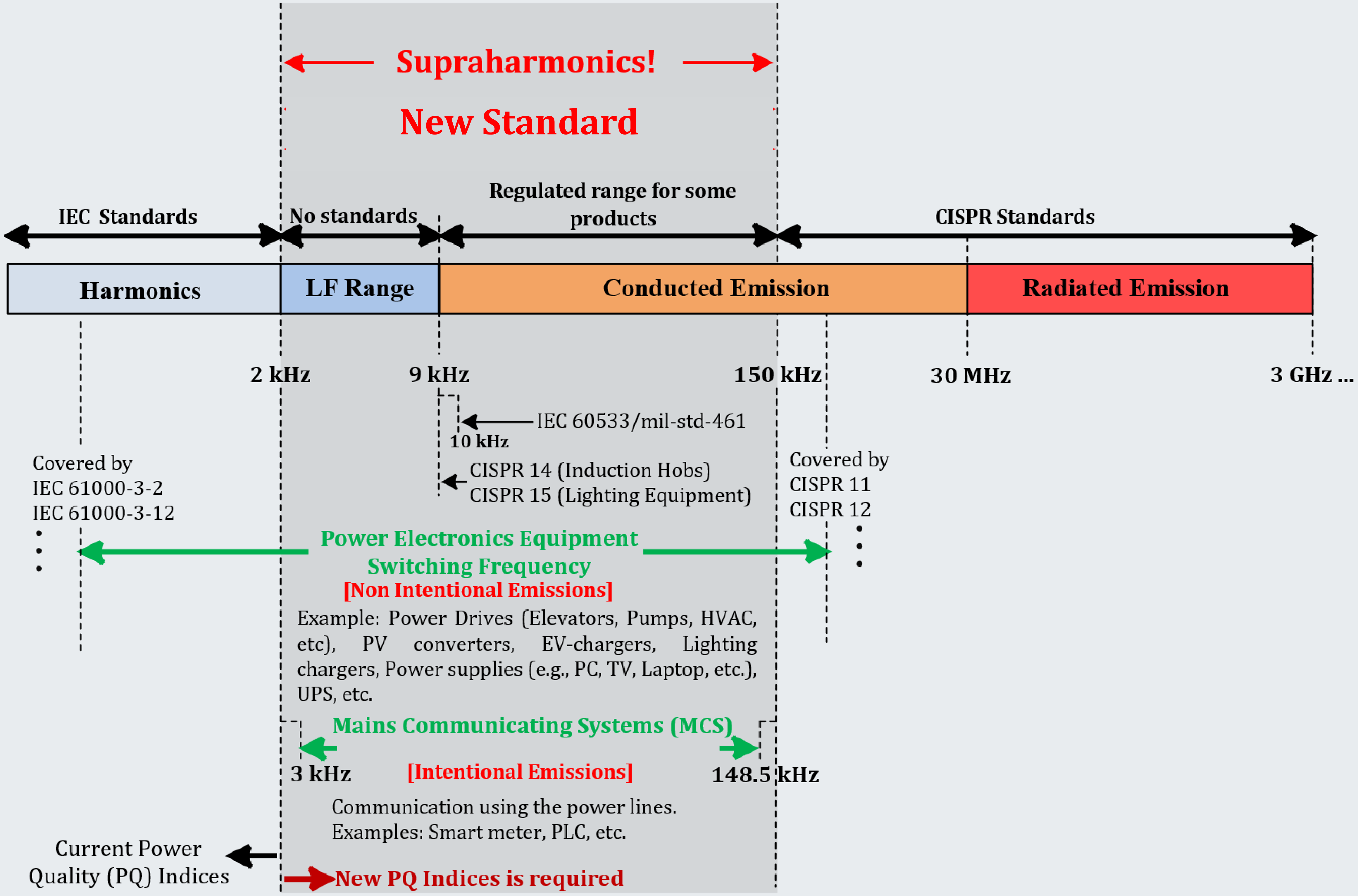


New Challenge

Standardization Gap Between
2 kHz – 150 kHz

Challenges

1. How to cope with **new Supraharmonics standards** while maintaining market competition
2. Further **energy efficiency** boost relies heavily on operation optimization and filter life-cycle improvement
3. New filter design affect **size, cost and stability**
4. Global competition in **time-to-market** (EMC test is a costly and timely trial and error approach!)
5. Lack of **EMC software tool**



IEC Activities…

WG1, JWG6, & WG8 [2 kHz – 150 kHz]

Standard No.	Description	Status
TR 61000-2-15, 2023	Description of the characteristics of networks with high penetration of power electronic converters	Published
TR 50627, 2015	Study report on EMI between electrical equipment/systems in the frequency range below 150 kHz	Published
TS 62578, Ed2, 2015	Power electronic systems and equipment – Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz	Published
IEC 61000-2-2, 2018	Electromagnetic compatibility (EMC) - Environment - Compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems	Published
IEC 61000-2-4, 2024	Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances	Published
IEC 61000-6-3	Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments	Published!
IEC 61000-6-8	Electromagnetic compatibility (EMC) –Part 6-8: Generic standards – Emission standard for professional equipment in commercial and light-industrial locations	Ongoing
IEC 61000-3-10	Emission limits and measurement methods within 2-9 kHz	Limits agreed

Supra-EMC Overview

Supraharmonics **E**lectro**M**agnetic **C**ompatibility strategies in power electronic based power grid

Innovation Fund Grand Solutions

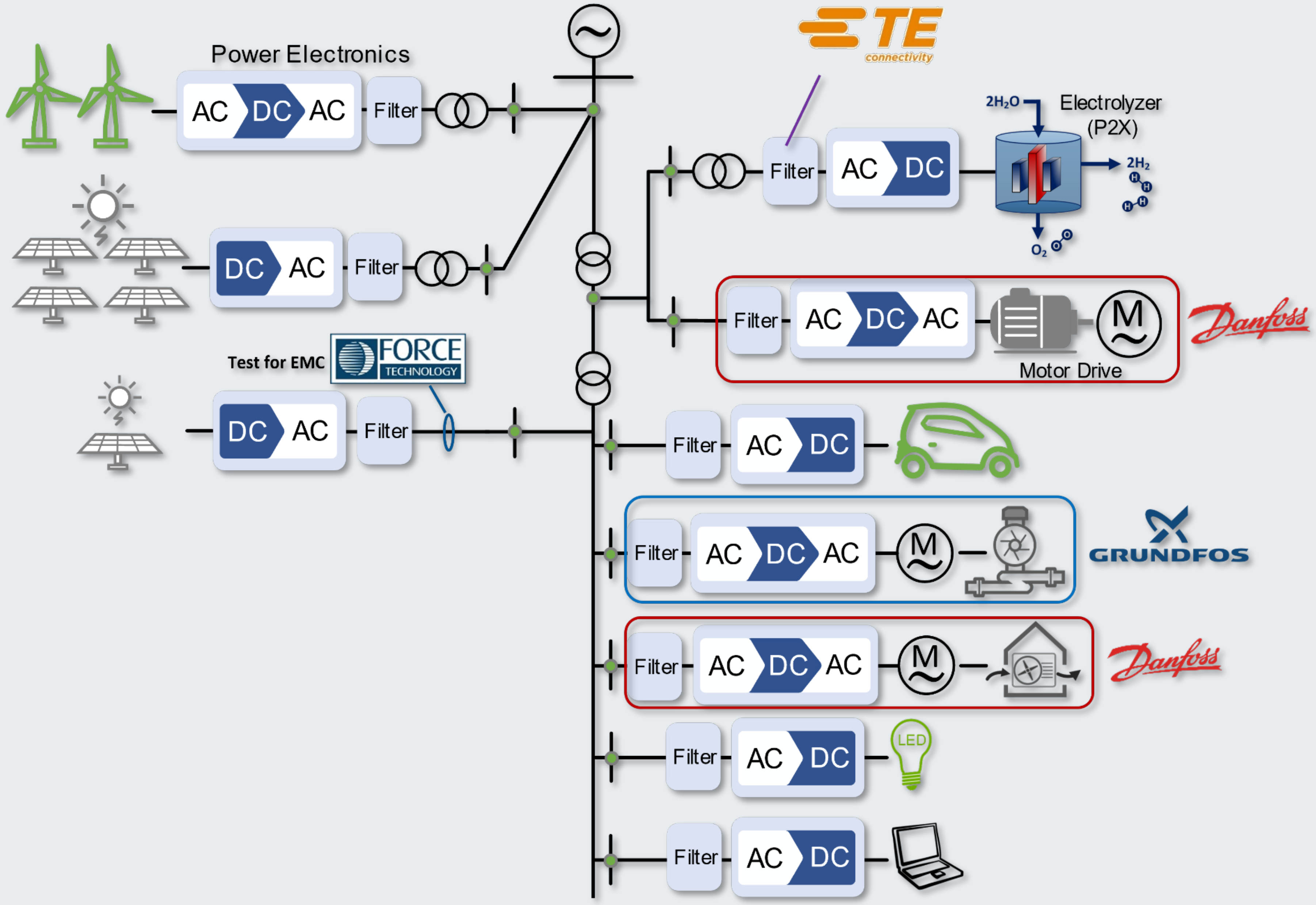
Innovation Fund Denmark

(1/5/2023 – 31/10/2027, total budget: 3.2 million €)

Vision: To bridge the gap between power grid compatibility and Power Electronics (PE) EMC to develop and demonstrate EMC tools and device for PE applications. To exploit new energy and cost-effective solutions for sustainable business opportunities and develop new EMC tools and devices for commercialization.

Six Partners

Danfoss
GRUNDFOS
TE connectivity
FORCE TECHNOLOGY
AAU ENERGY – AALBORG UNIVERSITY
APECS – ADVANCED POWER ELECTRONIC SOLUTIONS



Supra-EMC Overview

Project Objectives

New energy and cost-effective solutions for new business potential and develop new EMC tools and devices for commercialization.

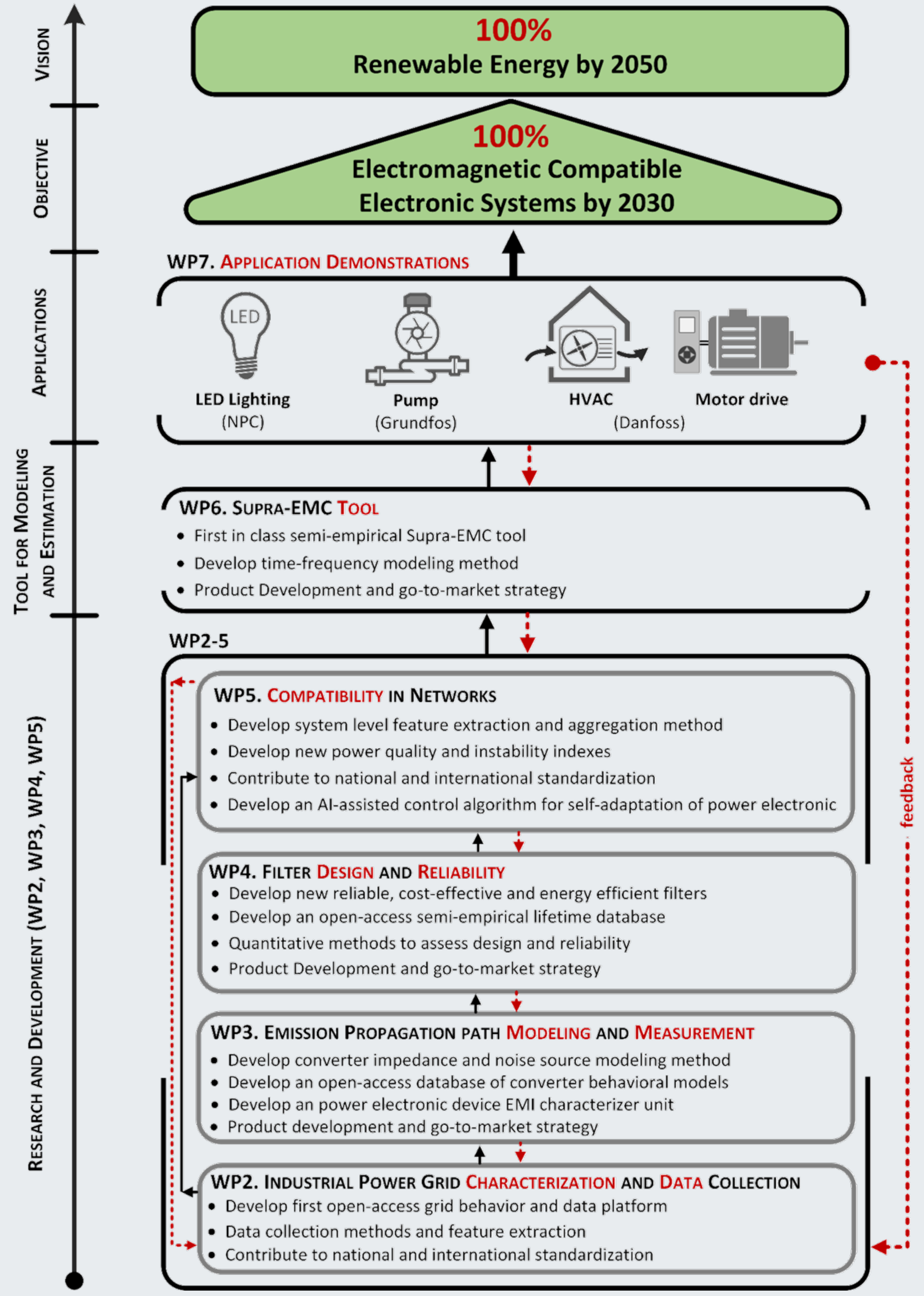
O1 Open access grid Supraharmonics data platform

O2 Digital Impedance Characterizer Device

O3 New EMI Filtering Techniques with reduced:
- Maintenance cost
- Energy loss

O4 Smart Control for Compatibility in Networks

O5 First in class Supra-EMC software enabling reducing:
- EMC design and optimization effort
- Development time and cost



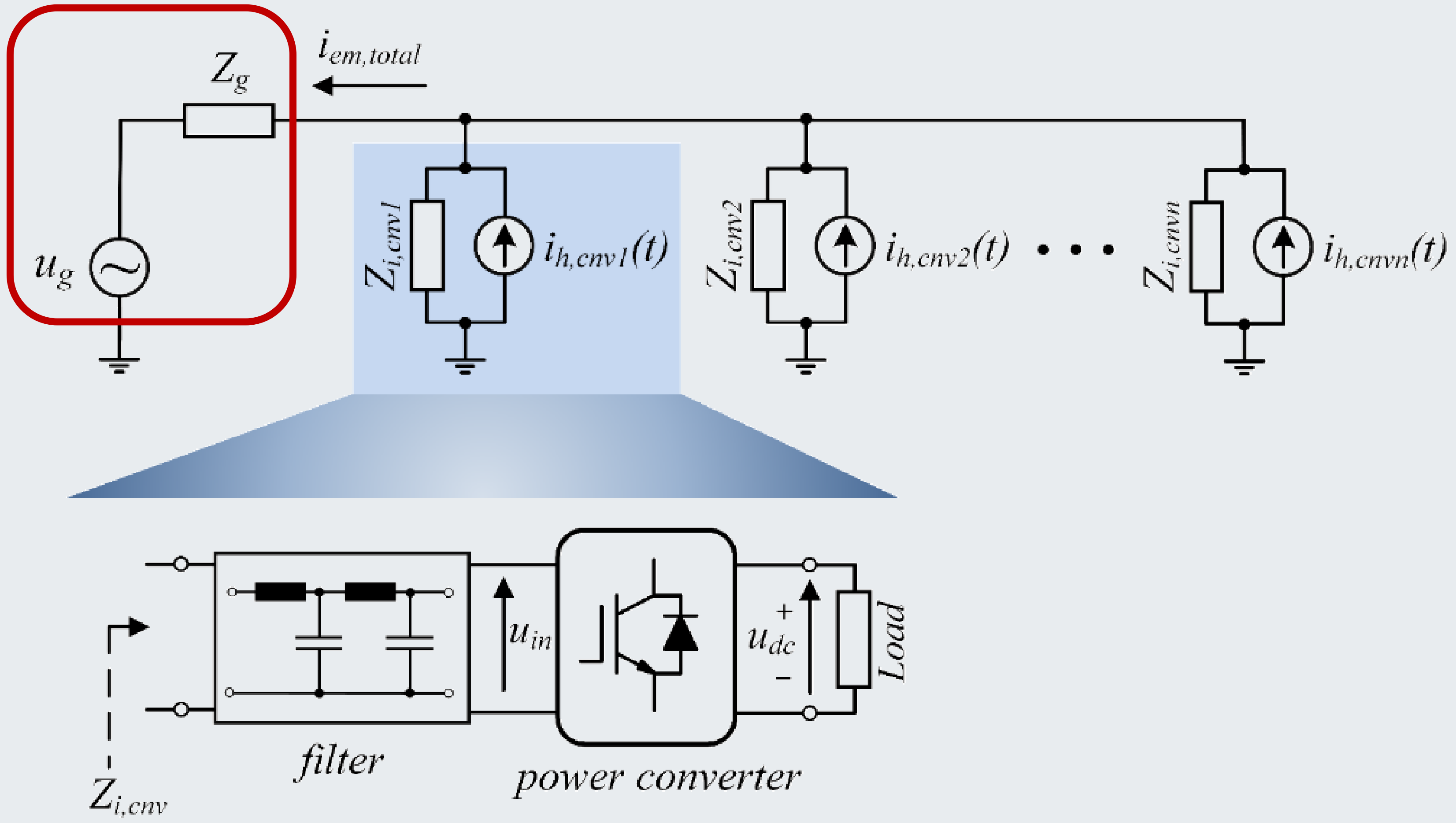
Outline

- ❑ Introduction to Supraharmonics in Power Electronics
- ❑ **Power Grid Characterization**
- ❑ Power Converter Noise Propagation Path Modeling
- ❑ EMC Filter Design
- ❑ Outlook for APECS (Newly Developed EMI Prediction Tool)

Power Grid Characterization (WP2)

Objectives:

- Power Grid **data collection** (2-150 kHz)
- Create a **database** of power grid impedance
- Create a **database** of power grid emissions
- Examine the suitability of defined **reference impedances** against actual power grid impedance
- Identify possible device and power grid impedance interactions (**stability**)
- Need to define **new AMN/LISN**?

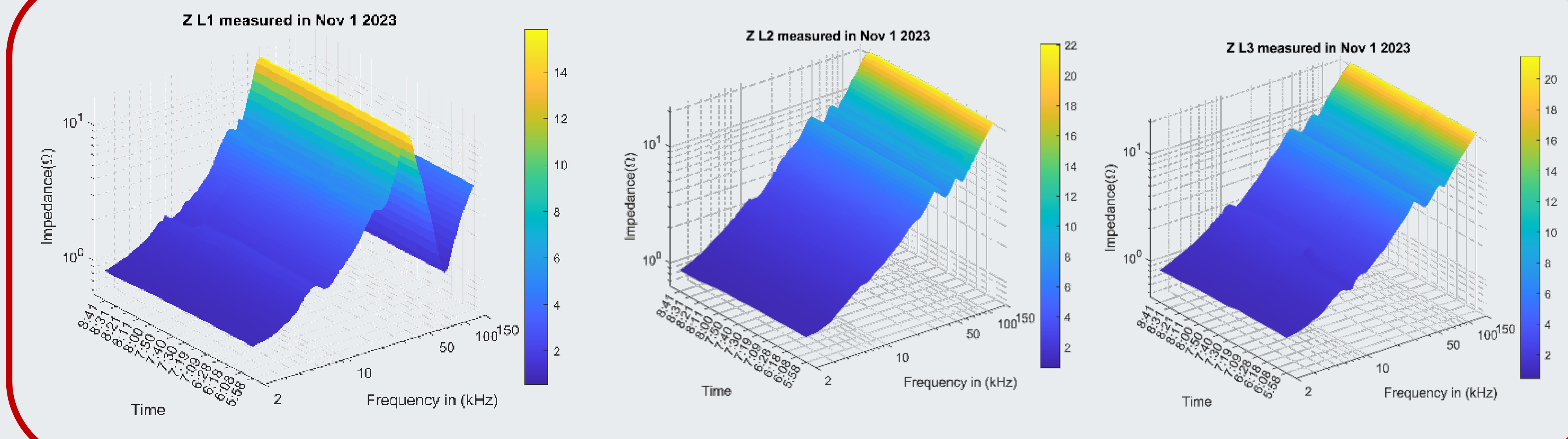


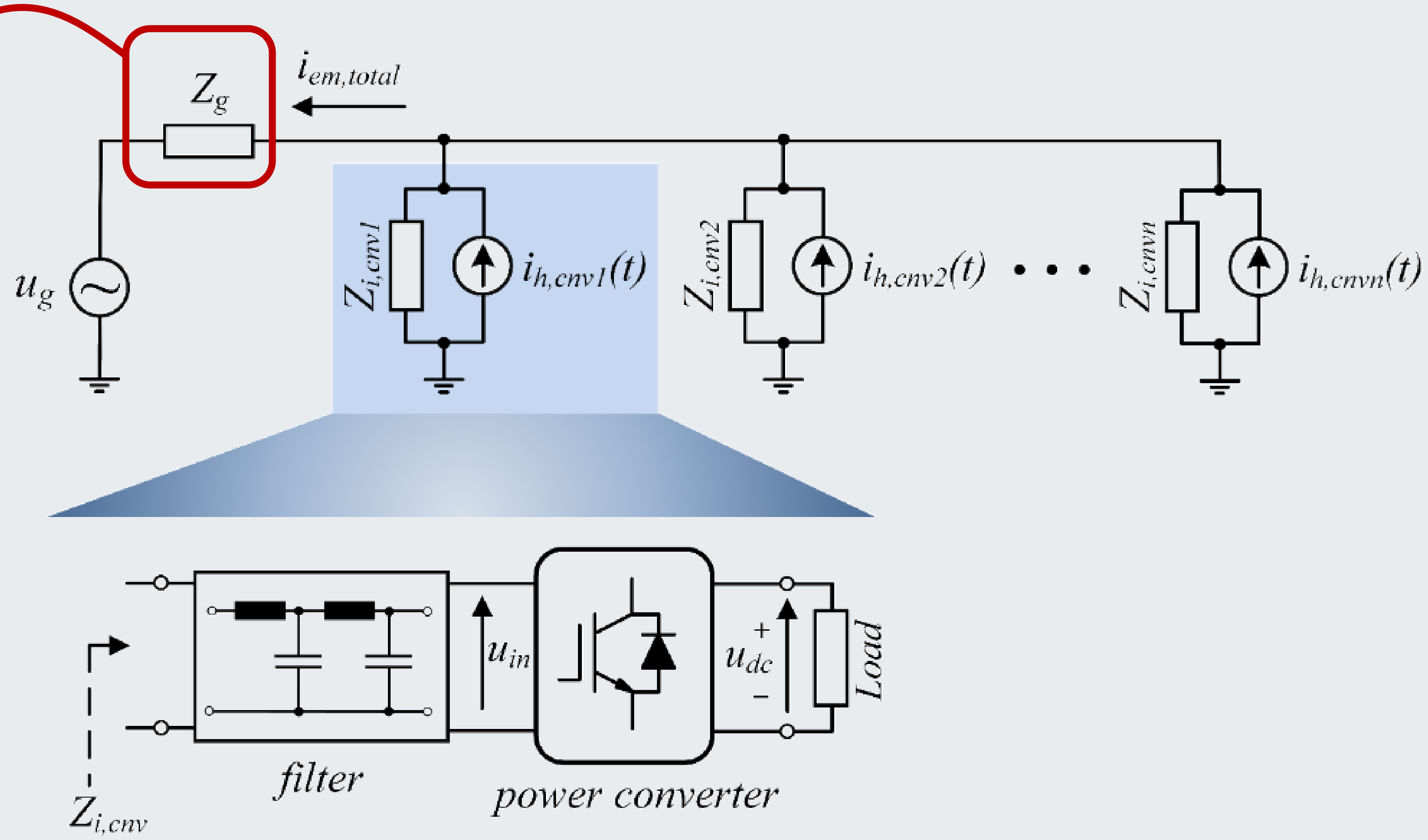
Important for:

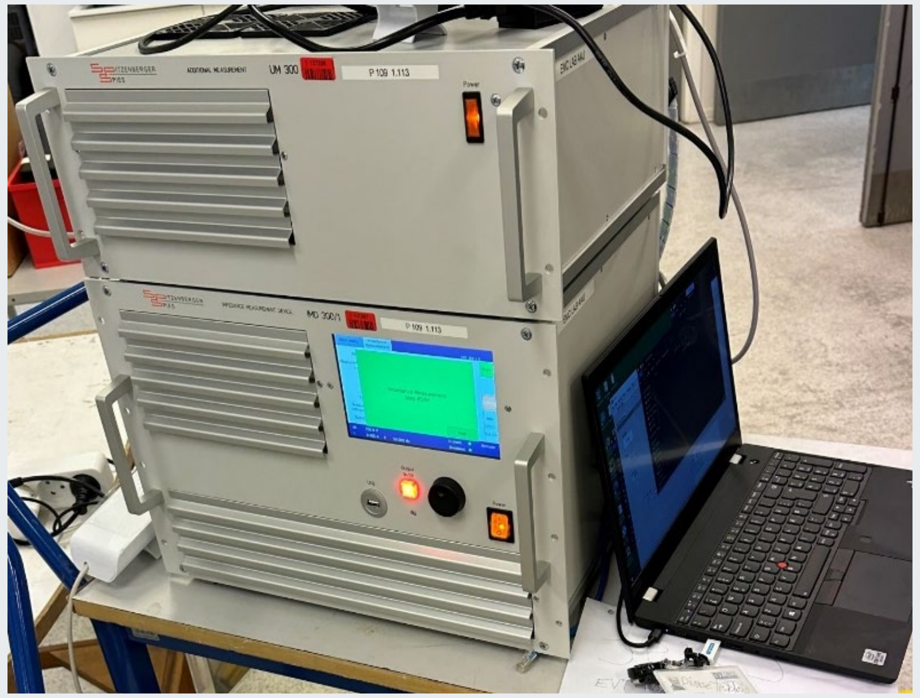
- Understand **emission propagation** at grid and device side
- **Simulate** emission propagation at device and system level
- **Solving** customer challenges

Power Grid Characterization (WP2)

Power Grid Impedance Measurement Results







IMD-300

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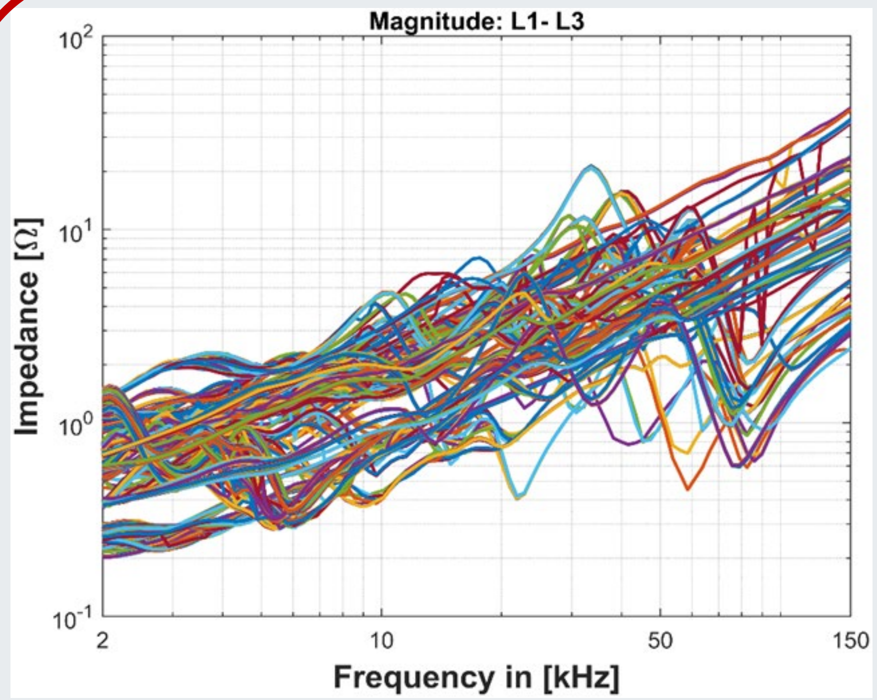
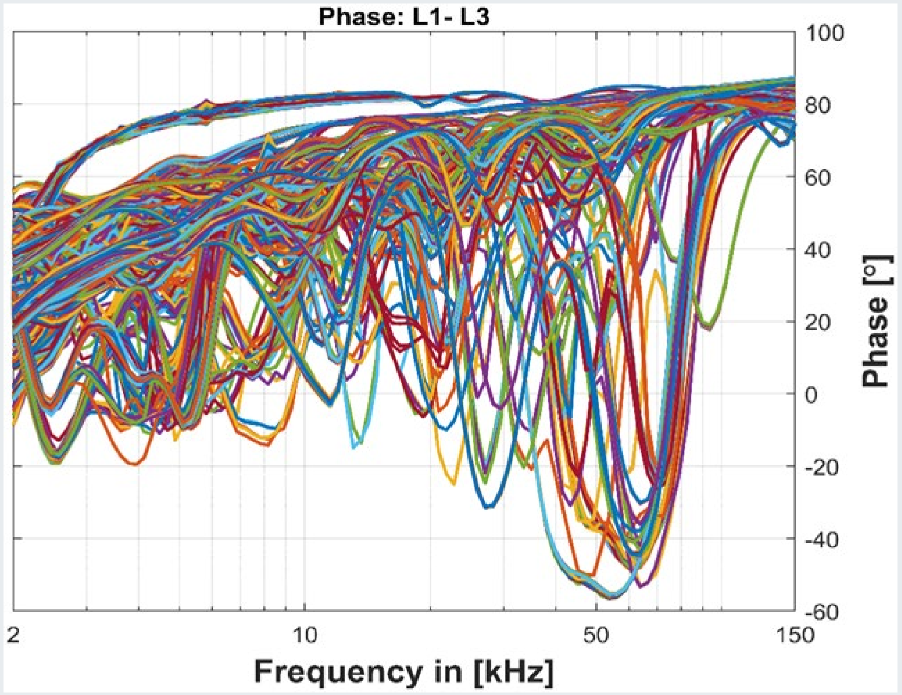
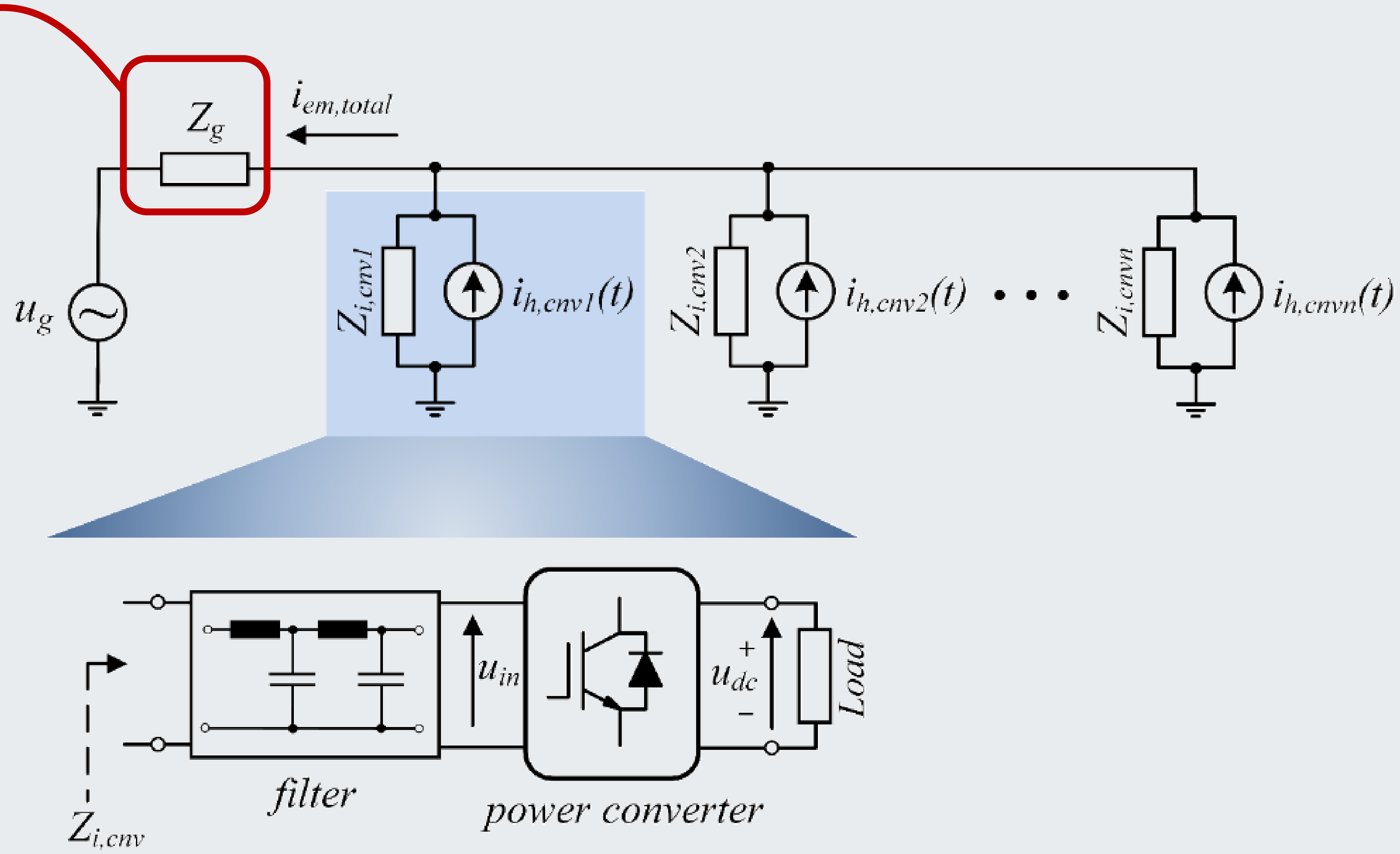
- So far **+1300 measured impedances** at four different locations (CP1, AR1, AR2, AL1, and SW) – 7 sites
- To understand **emission propagation** at grid and device side
- **Simulate** emission propagation at device and system level
- **Solving** customer challenges

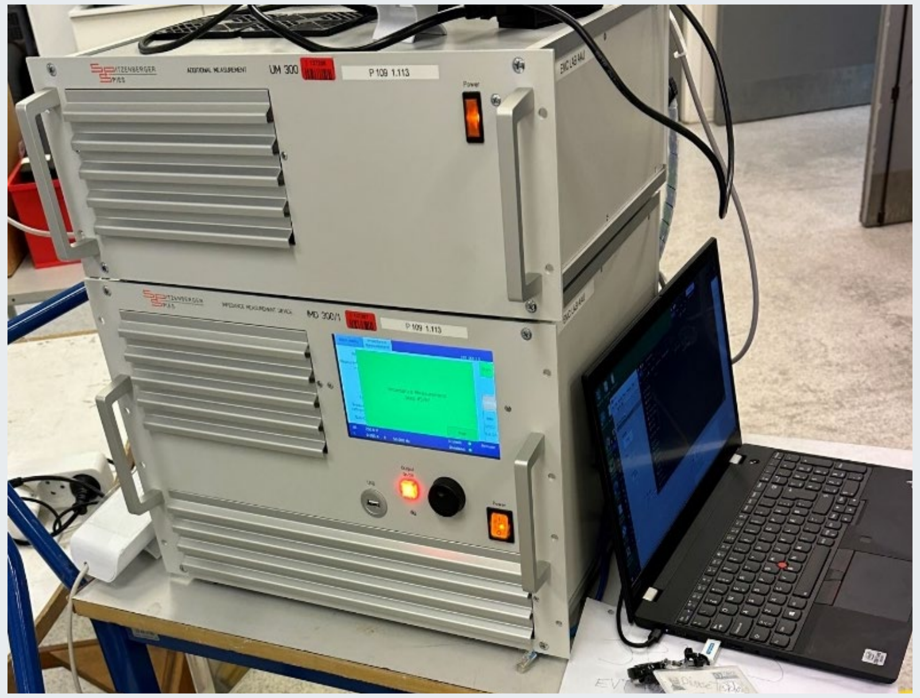
Power Grid Characterization (WP2)

Power Grid Impedance Measurement Results









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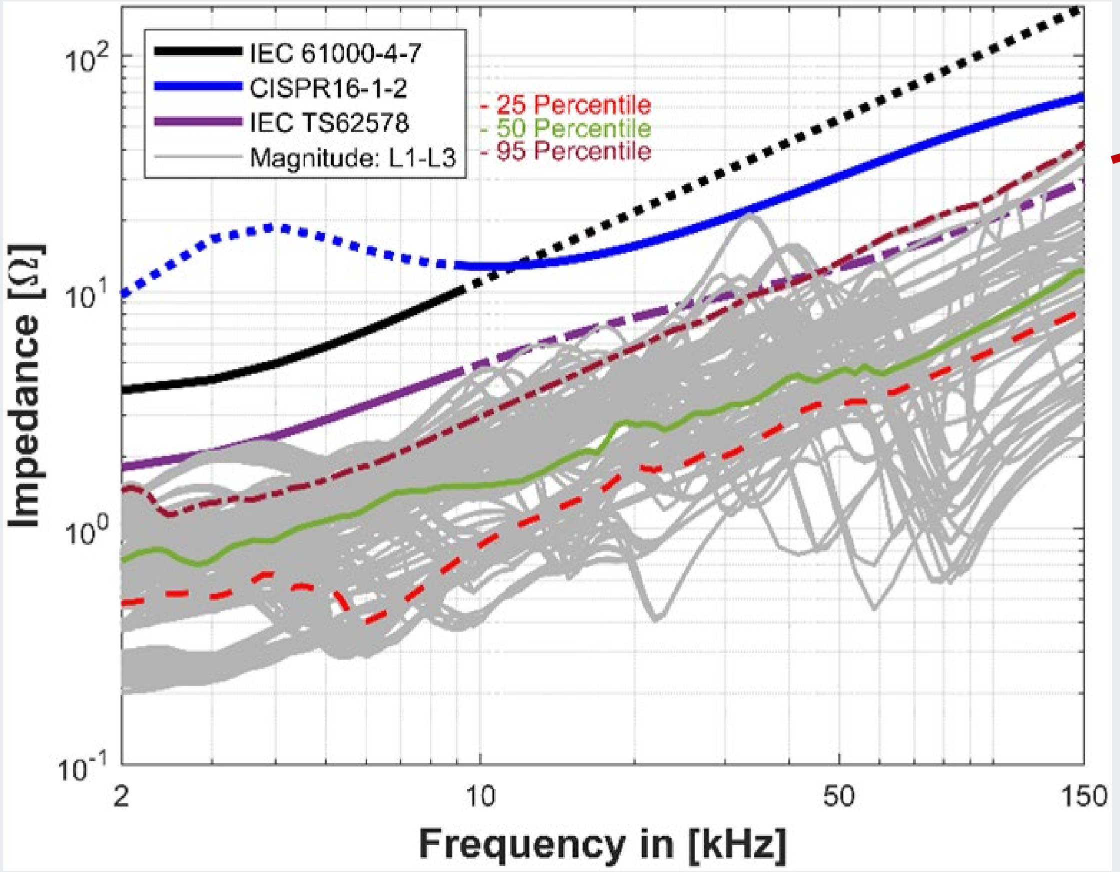
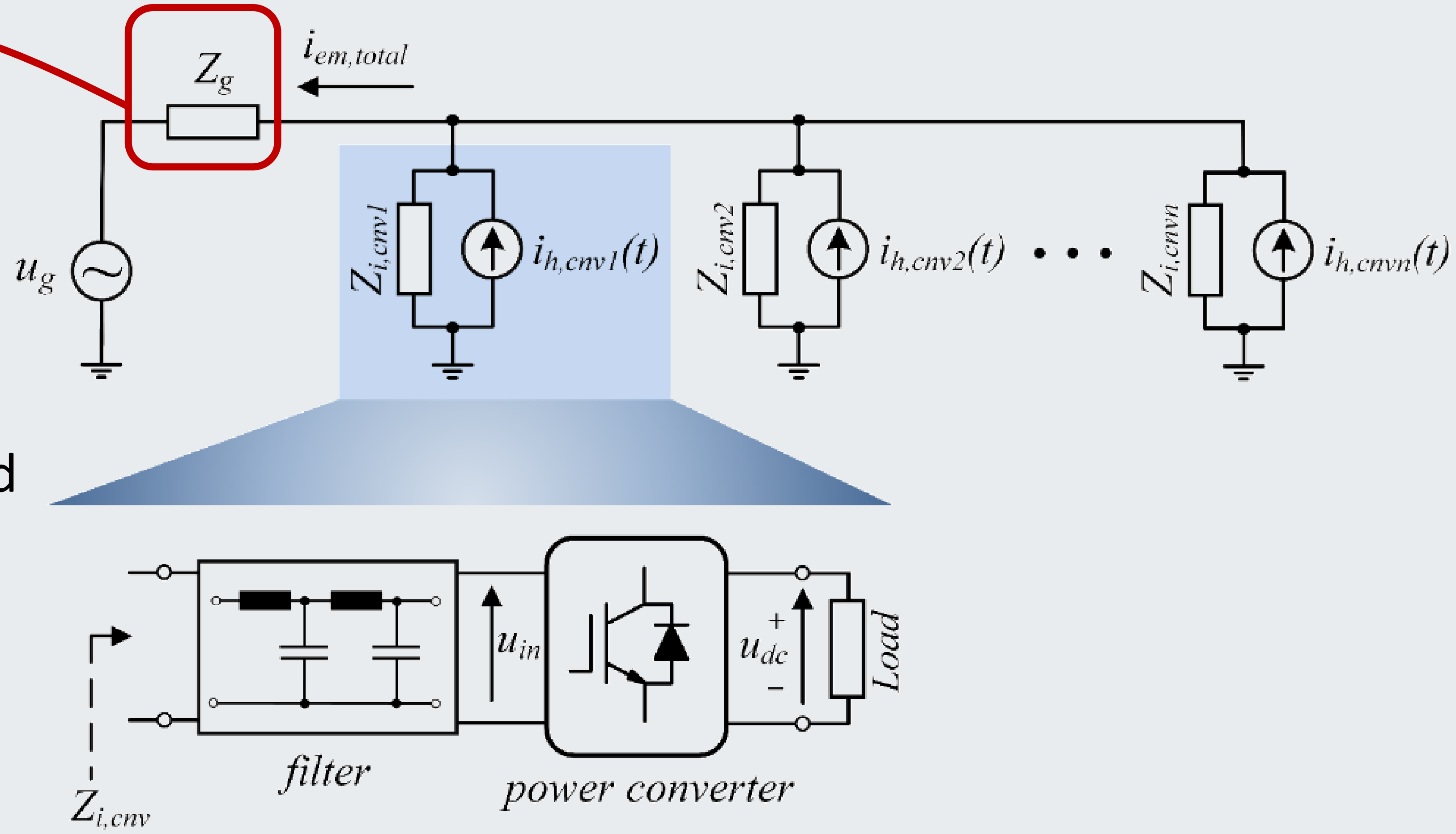
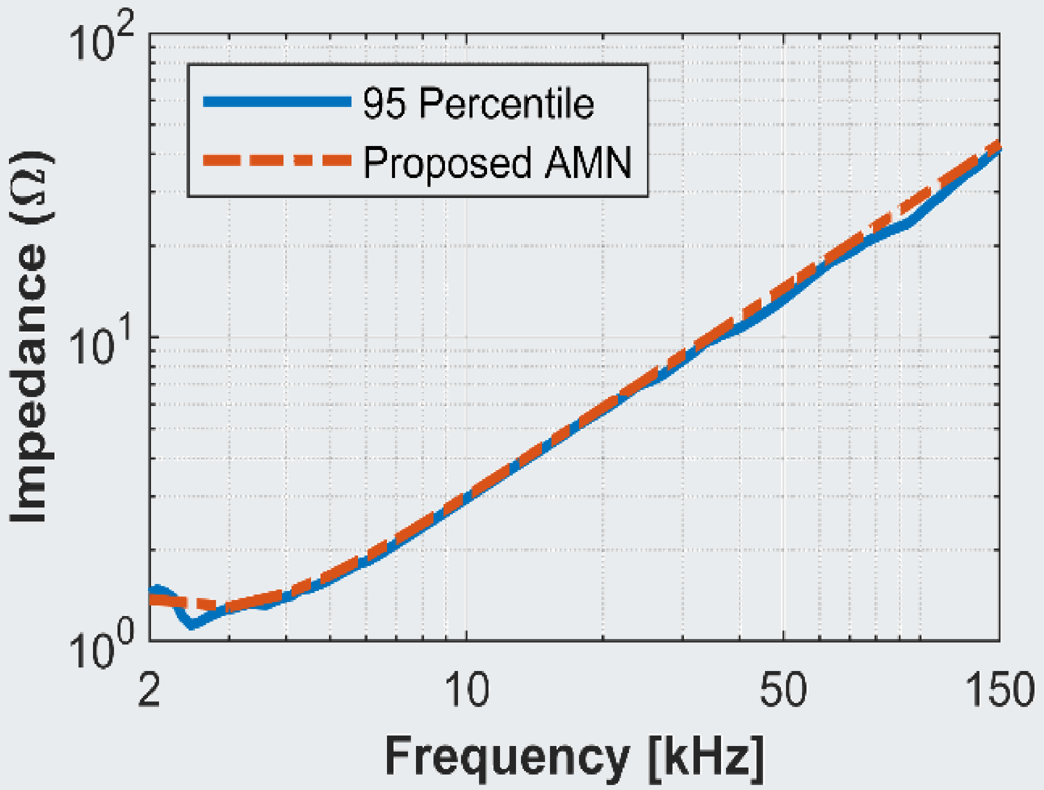
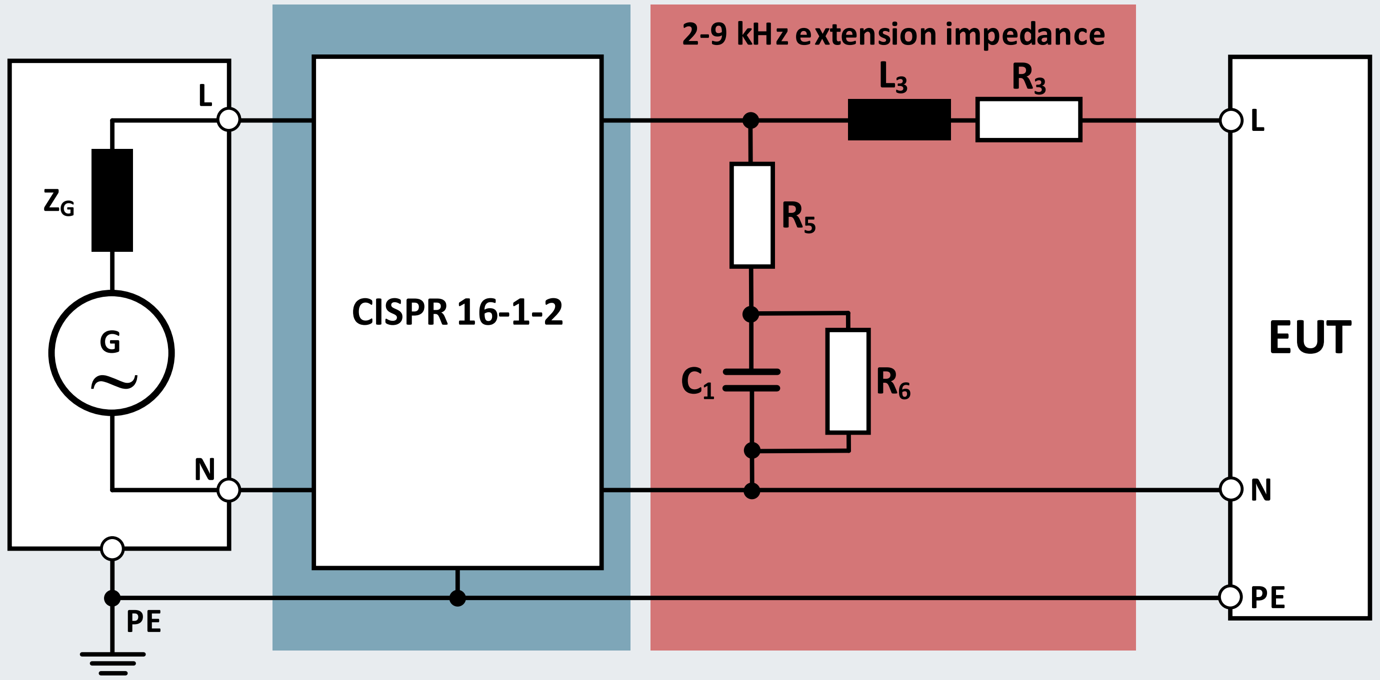
Power Grid Characterization (WP2)





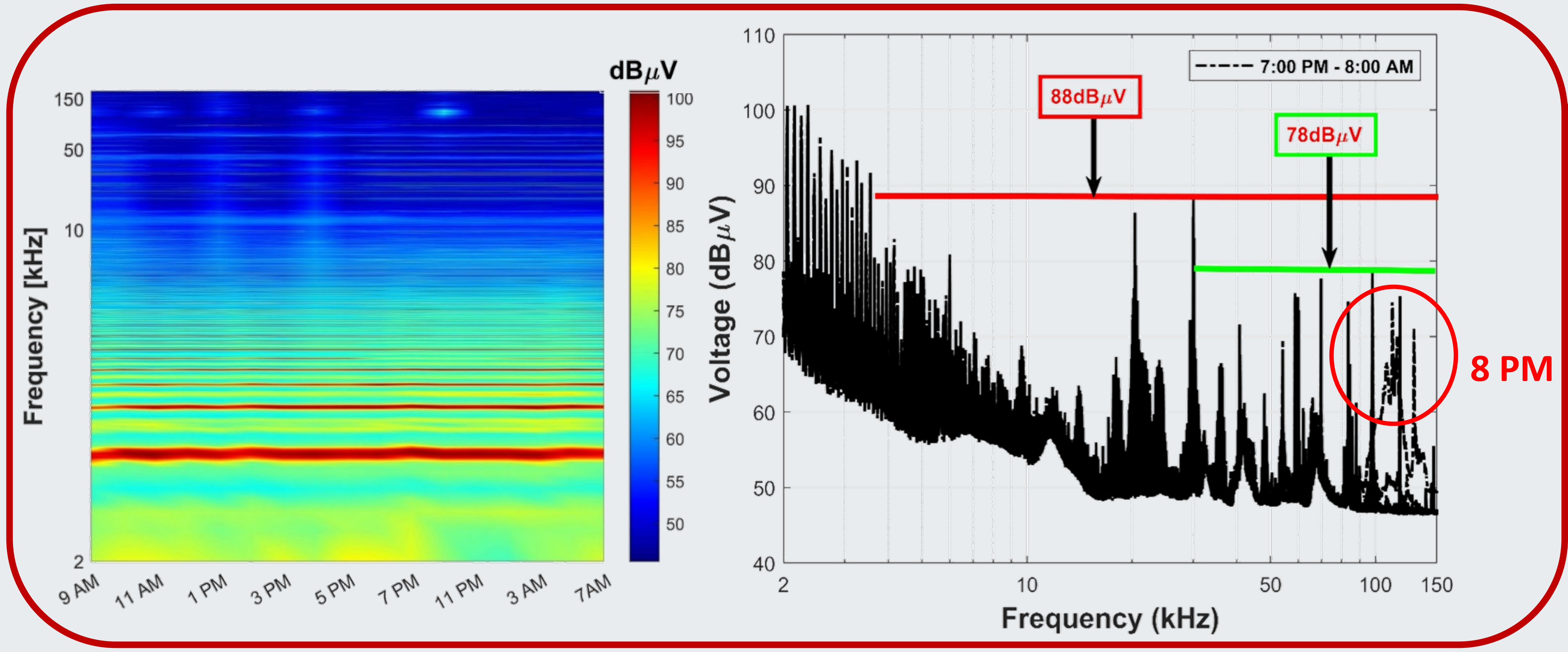
- Examine the suitability of defined **reference impedances** against actual power grid impedance
- Need to define **new AMN/LISN?**

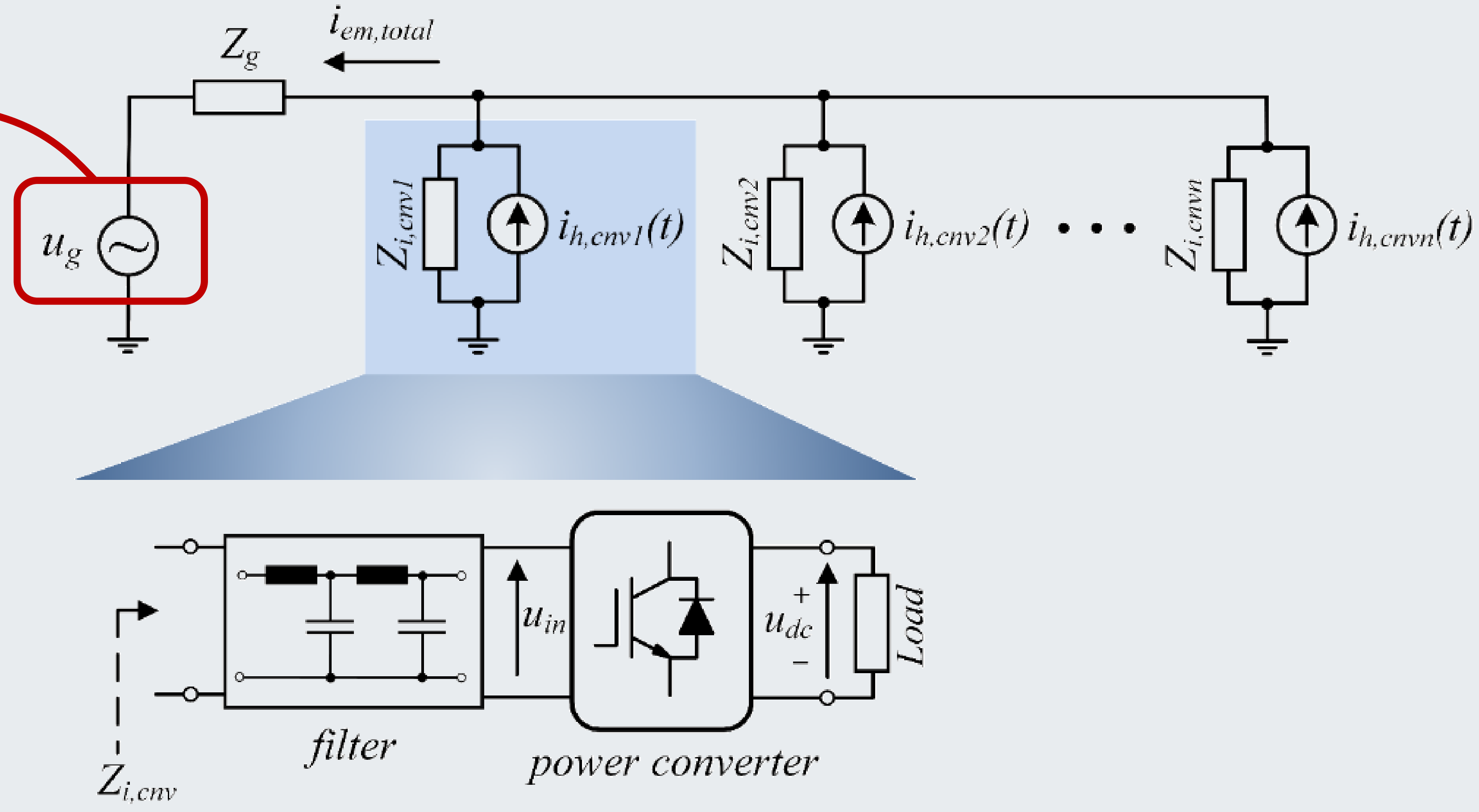


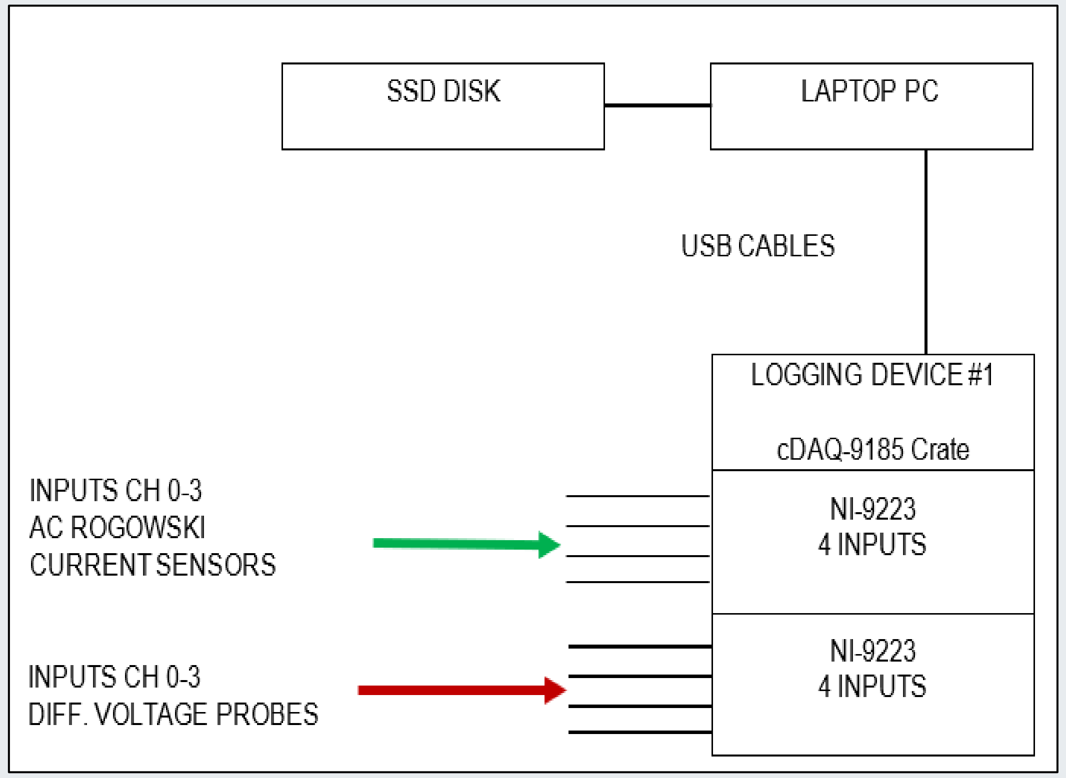


C1 = 200µF | R5 = 2.5Ω | R6 = 10kΩ
R3 = 0.6 Ω | L3 = 23 µH

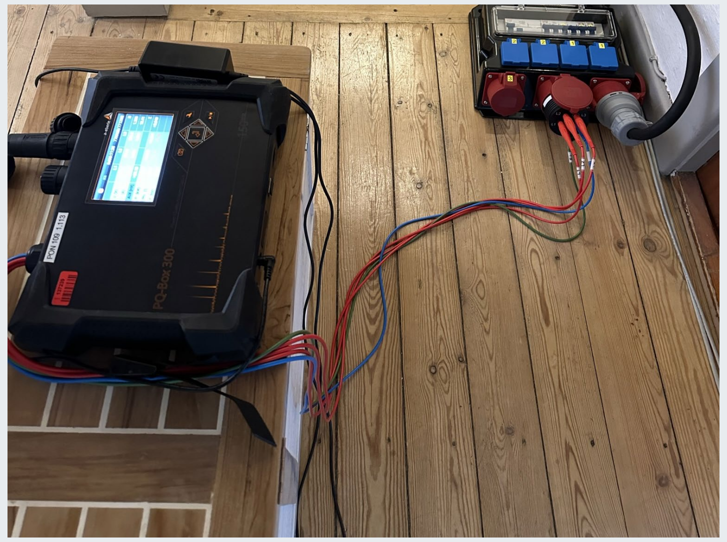
Power Grid Characterization (WP2)







Setup of NI DAQ system for continuous logging of signals



PQ300

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- 24hr data is analysed (nearly 125 GB data)
- Looking at the supraharmonics frequency range (2-150 kHz), there are peaks around 20 kHz and 30 kHz
- In 2-150 kHz, peak value is around 85 dBµV
- There are some free frequency bands available

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- ❑ EMC Filter Design
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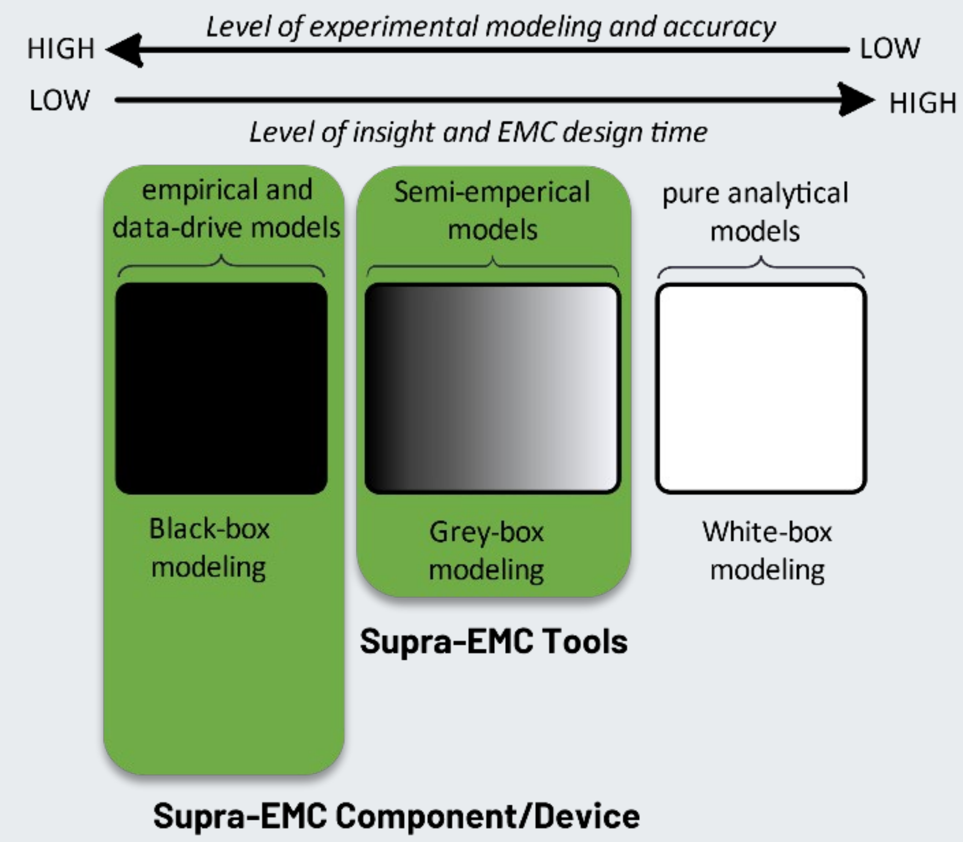
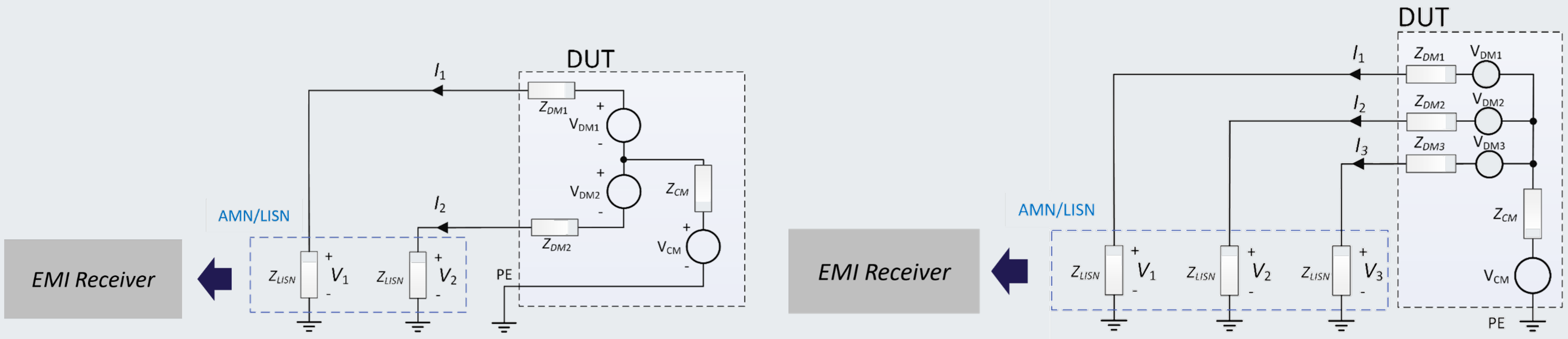
Power Converter Characterization (WP3)

Emission and Impedance Modeling



Modeling Principle:

- EMI **digital-model** based modeling (grey-box approach)
- Characterization of power converters (**black-box** approach)
- **Time-frequency** analysis
  - Capturing closed loop impedance
  - Components non-ideal behavior (e.g., magnetics saturation)
  - Developing equivalent circuits for conducted EMI noise estimation (DM and CM separately)



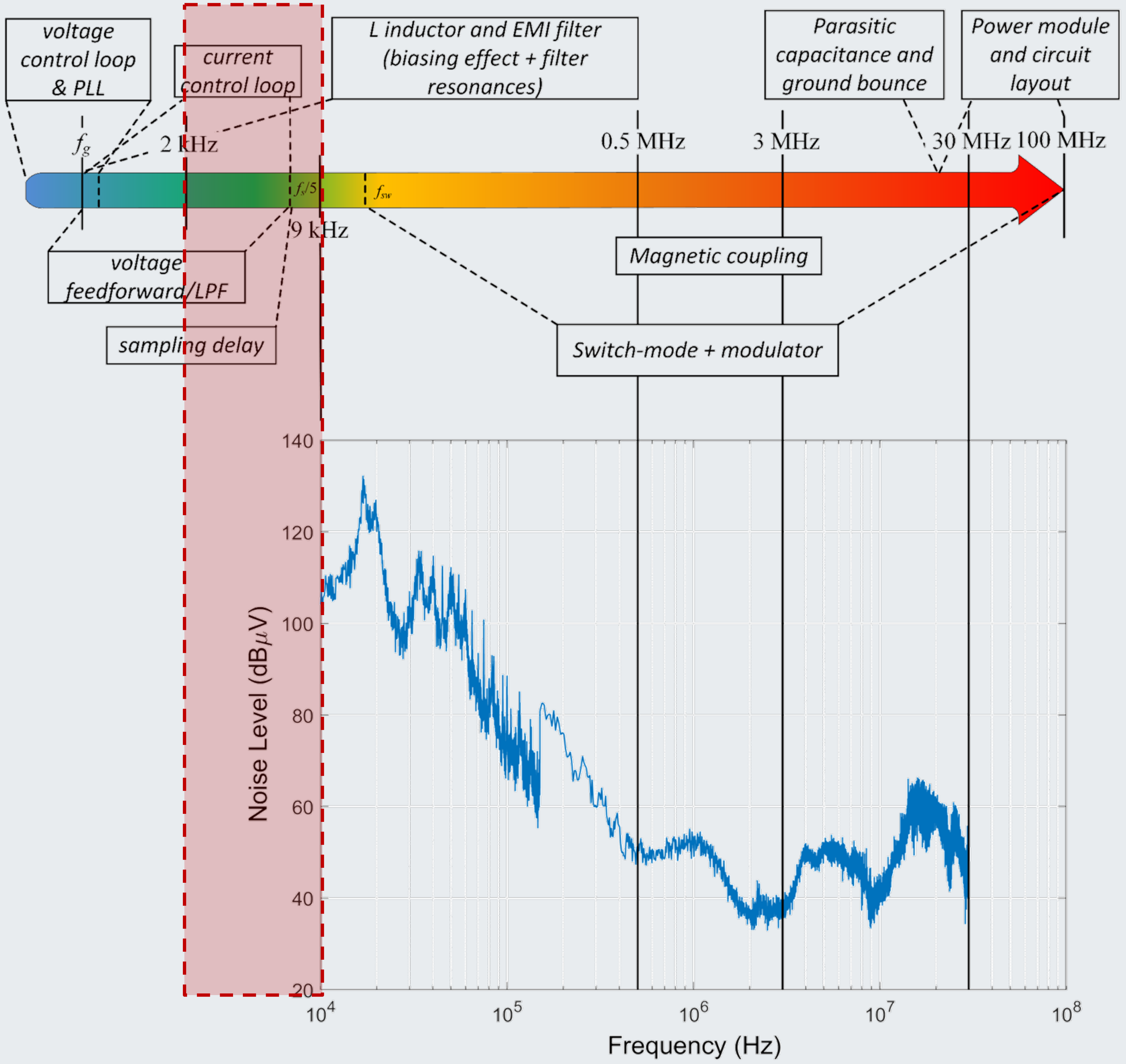
Equivalent circuit diagram of DM and CM noise sources in single-phase and three-phase power converters

- VDM, VCM: Semiconductor switching transients + Modulation
- ZDM: Passive components + Closed Loop Impedance
- ZCM: Parasitic capacitances to PE

Power Converter Characterization (WP3)

Emission and Impedance Modeling

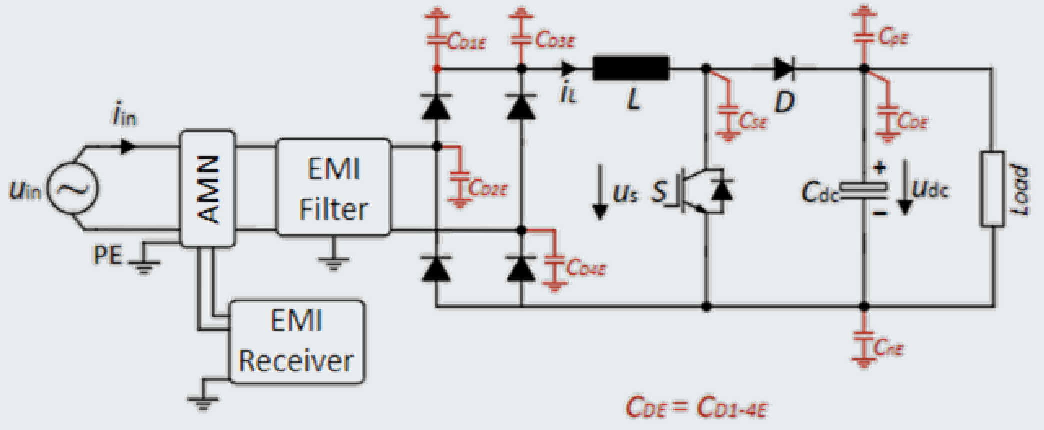
- ❑ **Different effects dominate depending on the frequency range of interest. Suitable methodologies must be adopted accordingly!**



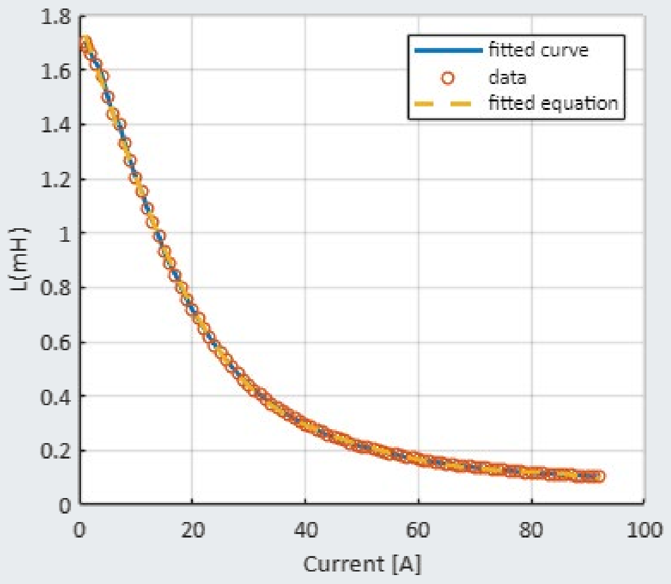
Power Converter Characterization (WP3)

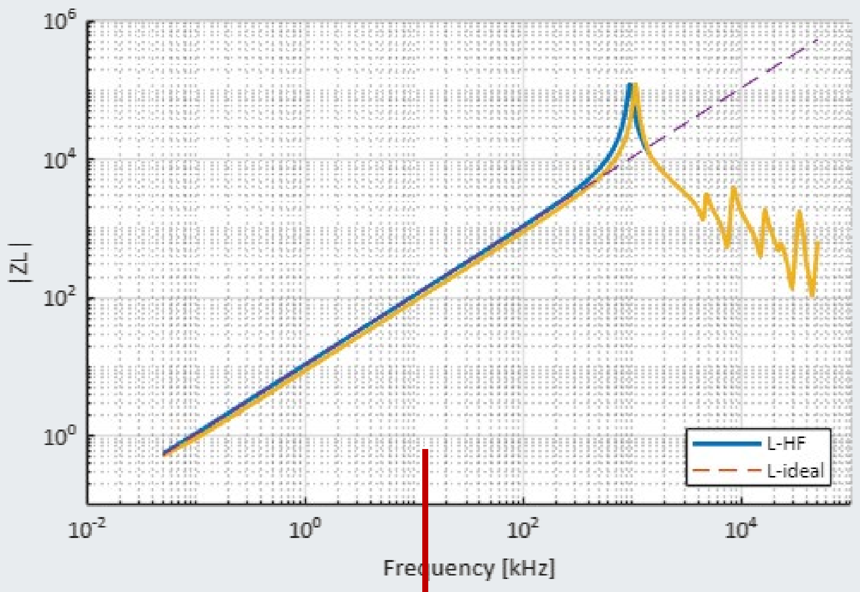
Single-phase PFC @ 20 kHz

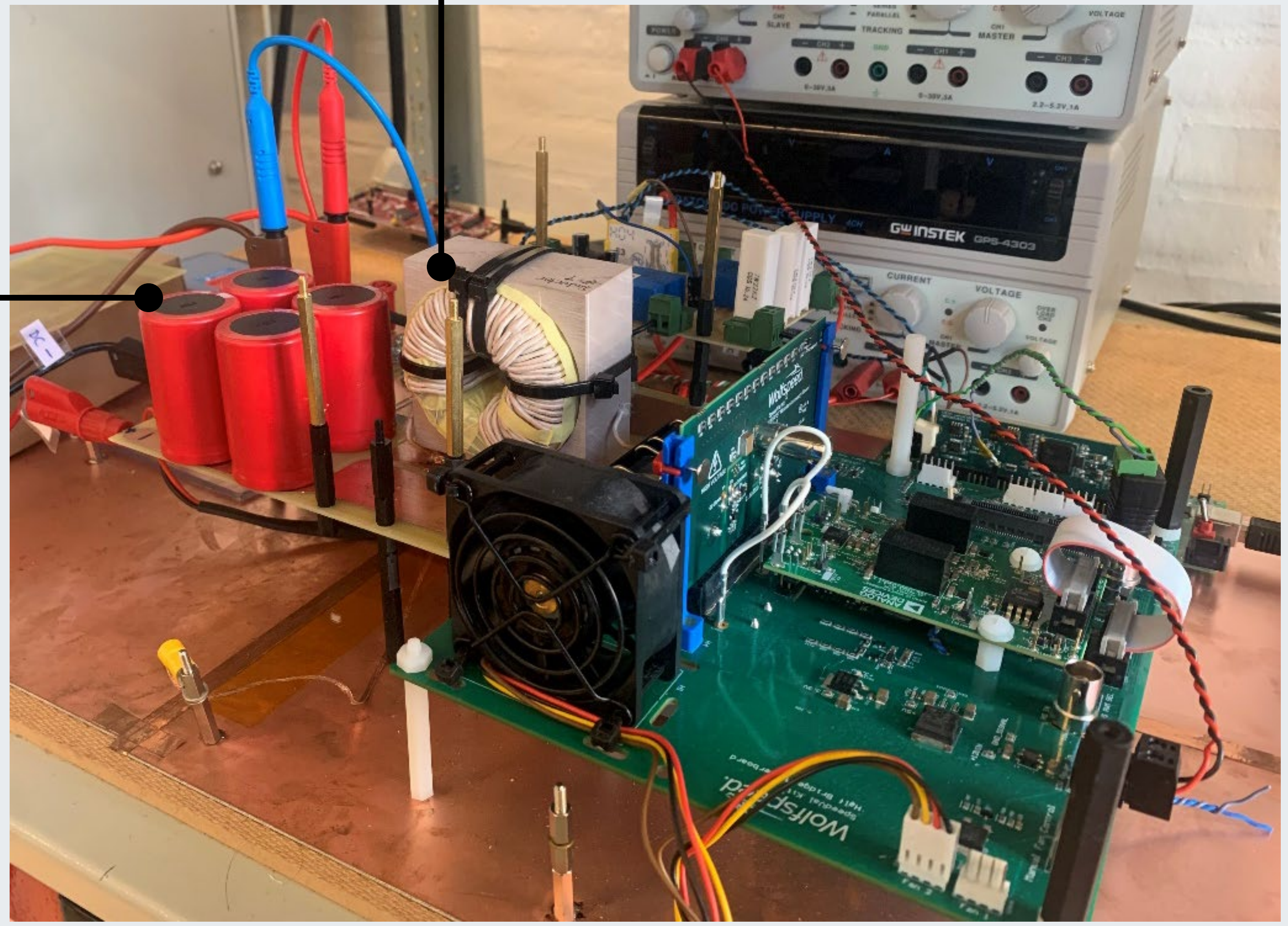
L [mH]	1.73	*Udc [v]*	400
Resr [Ω]	0.1101	*Po [kw]*	2

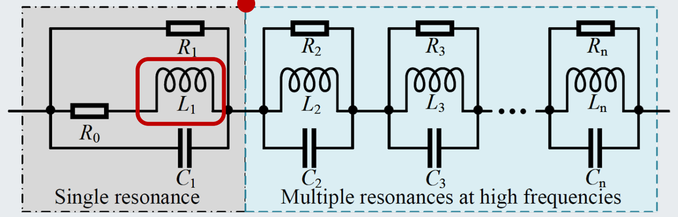


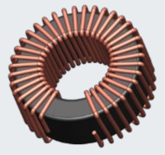
CpE [pF]	10
CnE [pF]	10
CmE [pF]	10
CDE [pF]	40
CSE [pF]	40
CS3E [pF]	10
CS4E [pF]	10

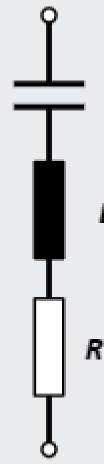




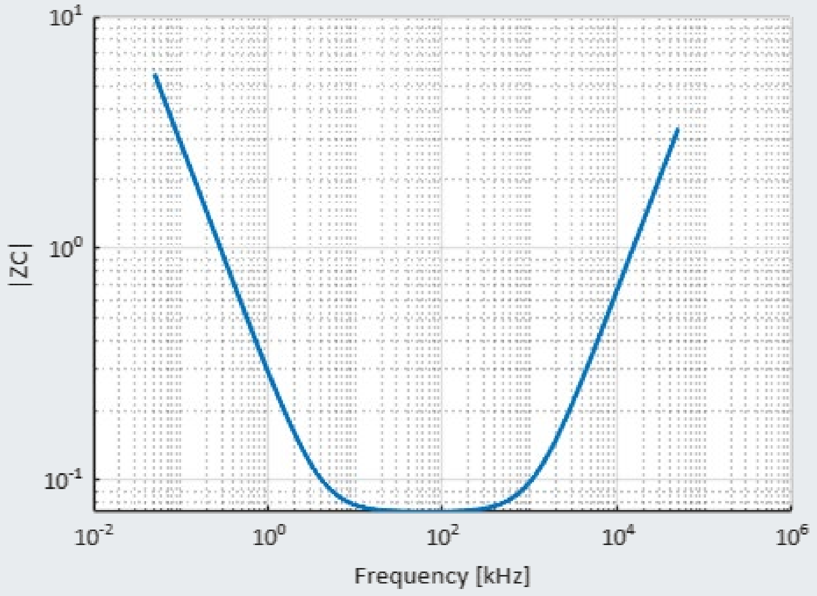








C [μF]	560
L (ESL) [nH]	10.52
R (ESR) [mΩ]	73
No. Cdc	1

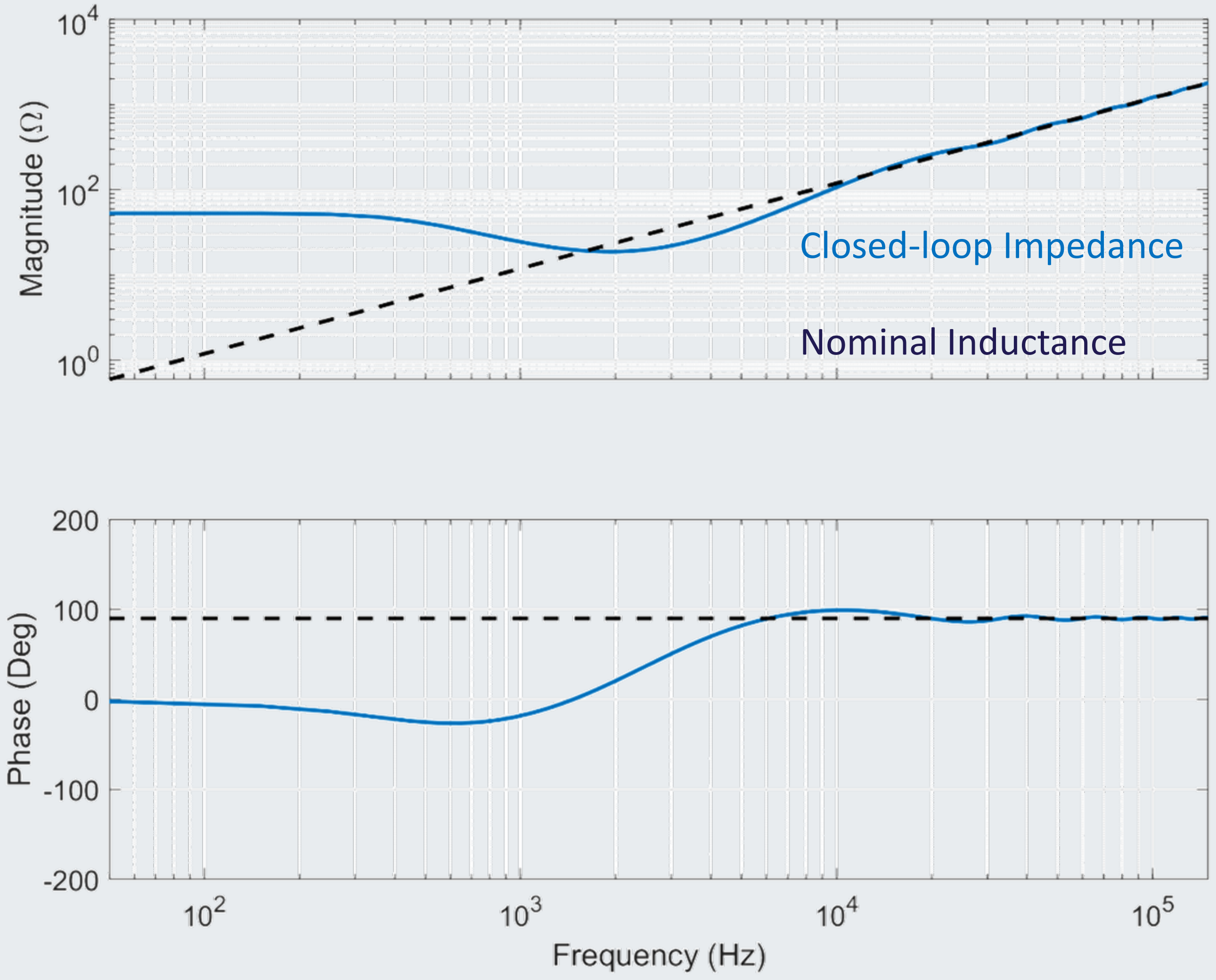


Power Converter Characterization (WP3)

Noise Estimation

DM Results

❑ Example: Single-Phase PFC



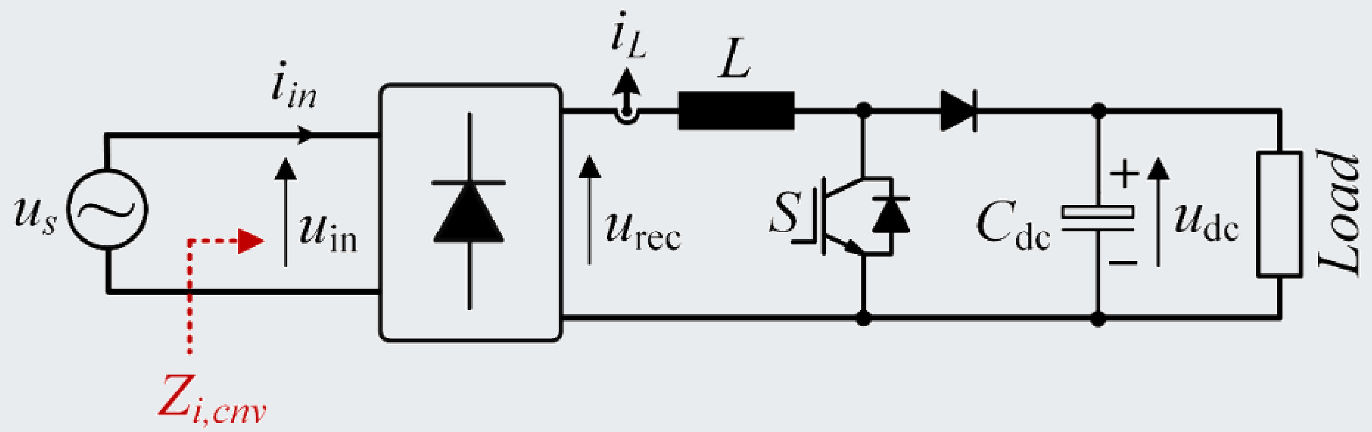


TABLE I PARAMETERS OF THE SYSTEM

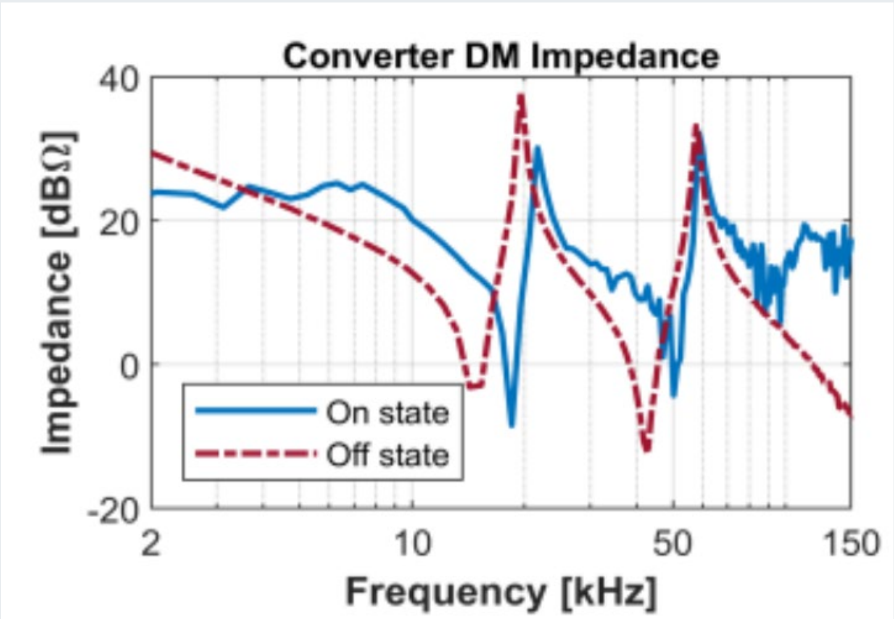
Symbol	Meaning	Value
U_s	Grid phase voltage	230 Vrms
f_g	Grid frequency	50 Hz
L	Boost inductor	1.9 mH
C_{dc}	DC link capacitor	500 µF
U_{dc}	Output voltage	400 V_{dc}
P_o	Rated power	2 kW
f_{sw}	*Switching frequency*	20 kHz

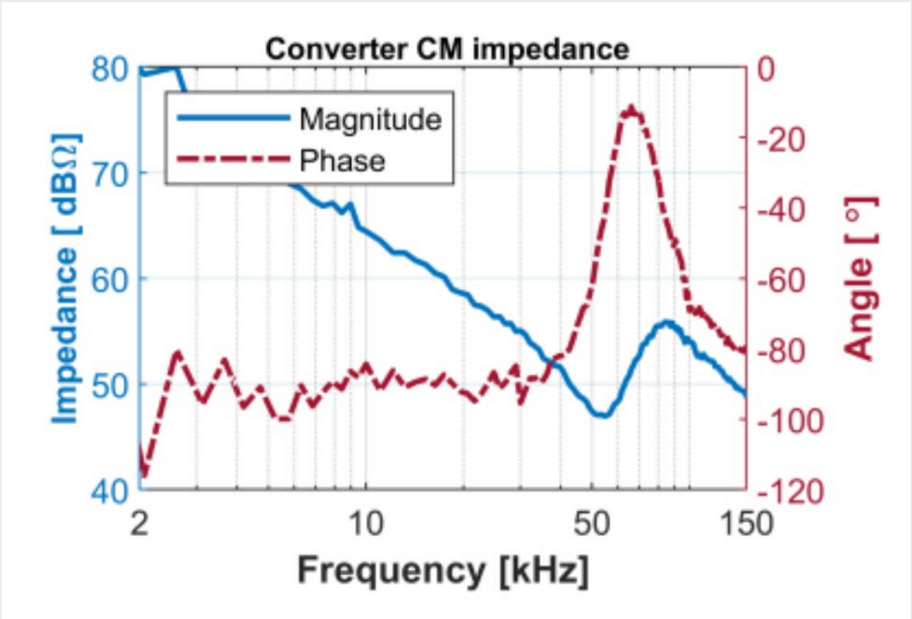
TABLE II EMI FILTER PARAMETERS

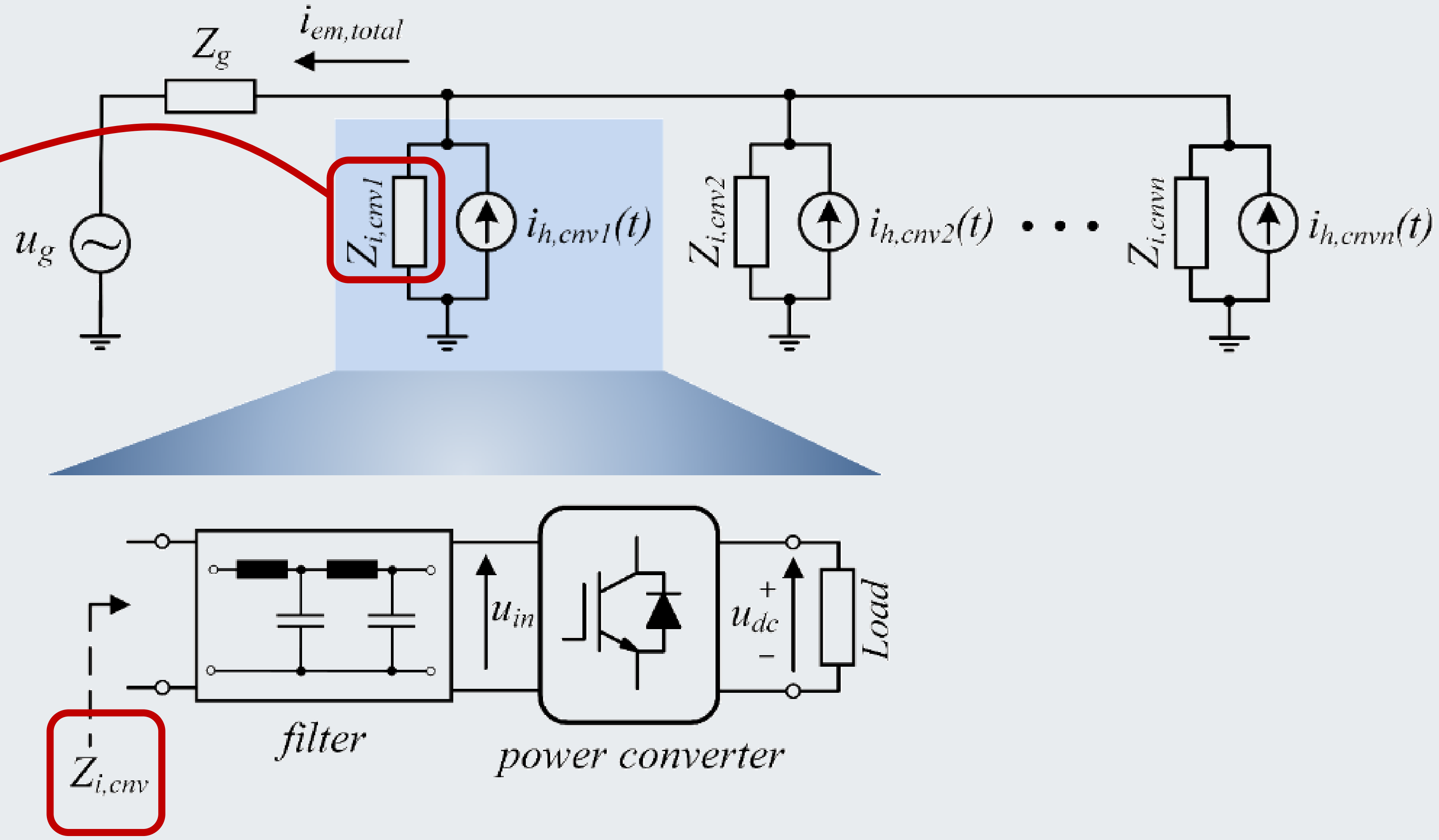
Symbol	Meaning	Value
C_{DM}	Differential mode capacitor	1.4 µF
L_{DM}	Differential mode inductor	180 µH
R_d	DAMPING RESISTANCE	11 Ω

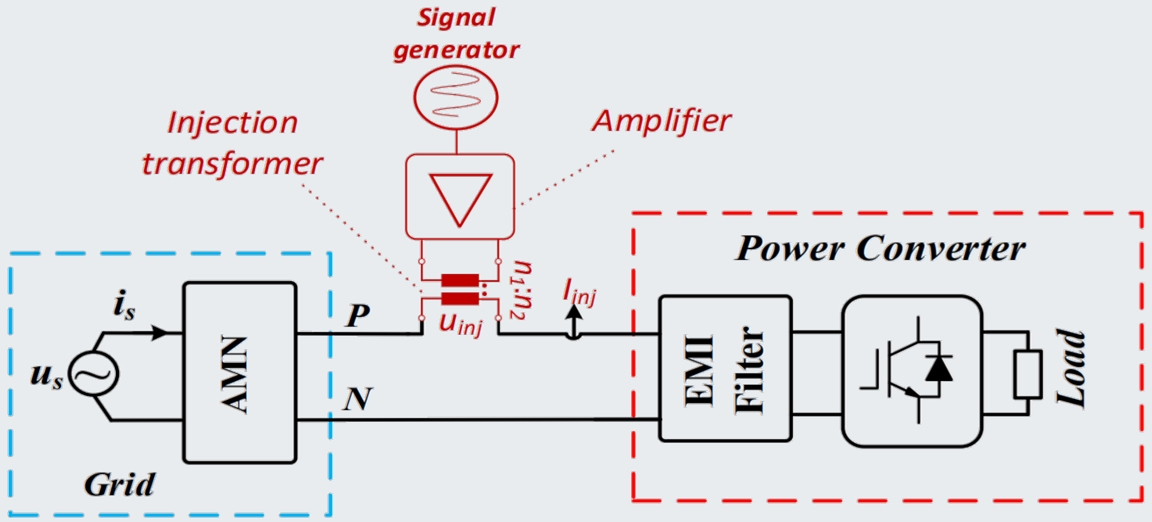
- ❑ Closed loop impedance effect is evident below the controller bandwidth
- ❑ At frequencies higher > BW input impedance becomes almost inductive (*L* in PFC)

Power Converter Characterization (WP3)

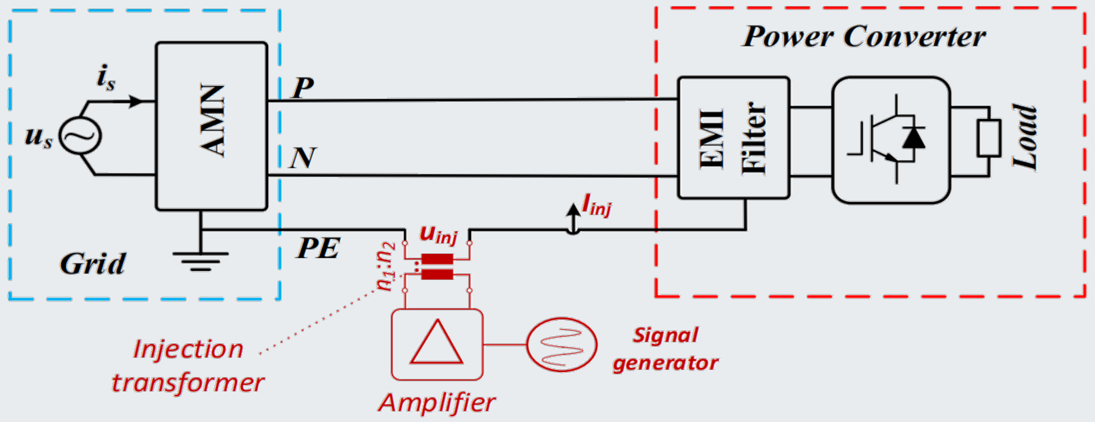








Circuit schematics to characterize the DM impedance of the single-phase converter.



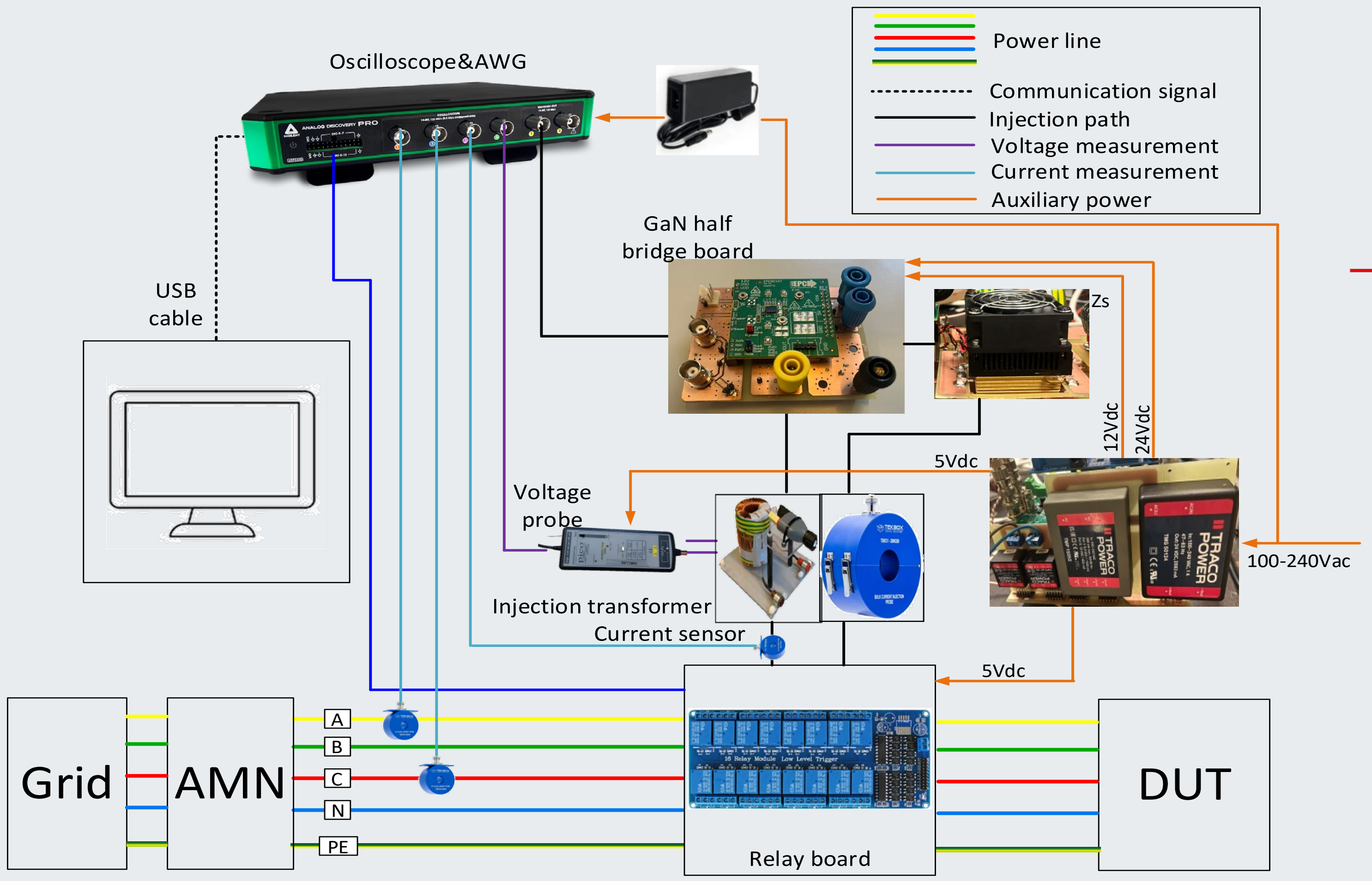
Circuit schematics to characterize the CM impedance of the single-phase converter.

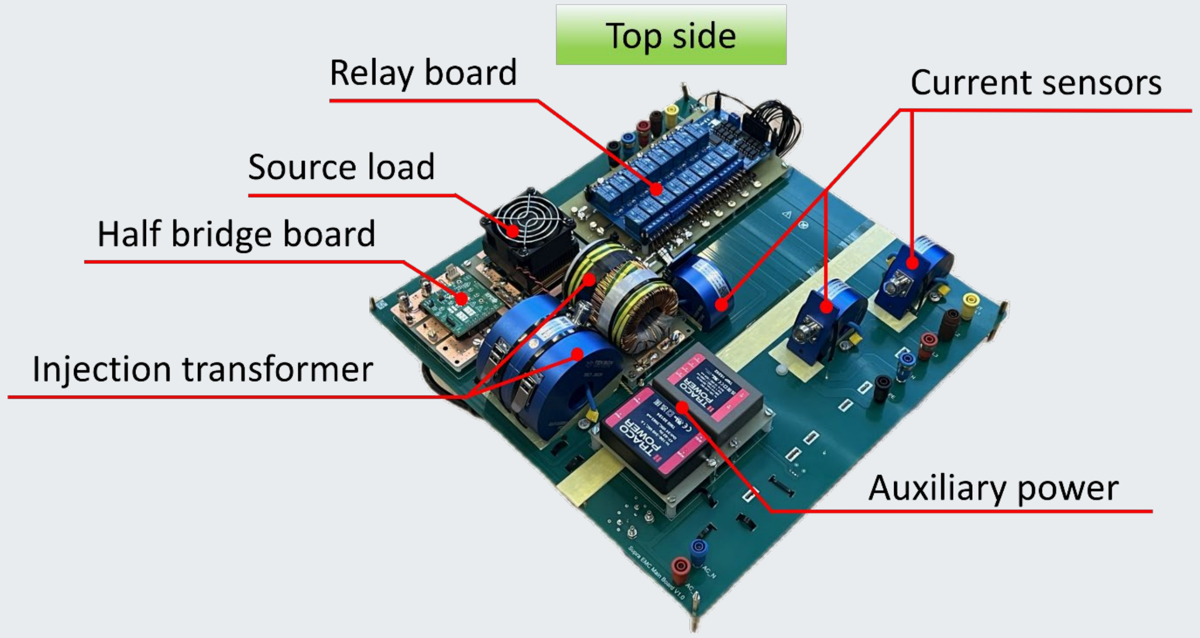
Black-Box Modeling Approach

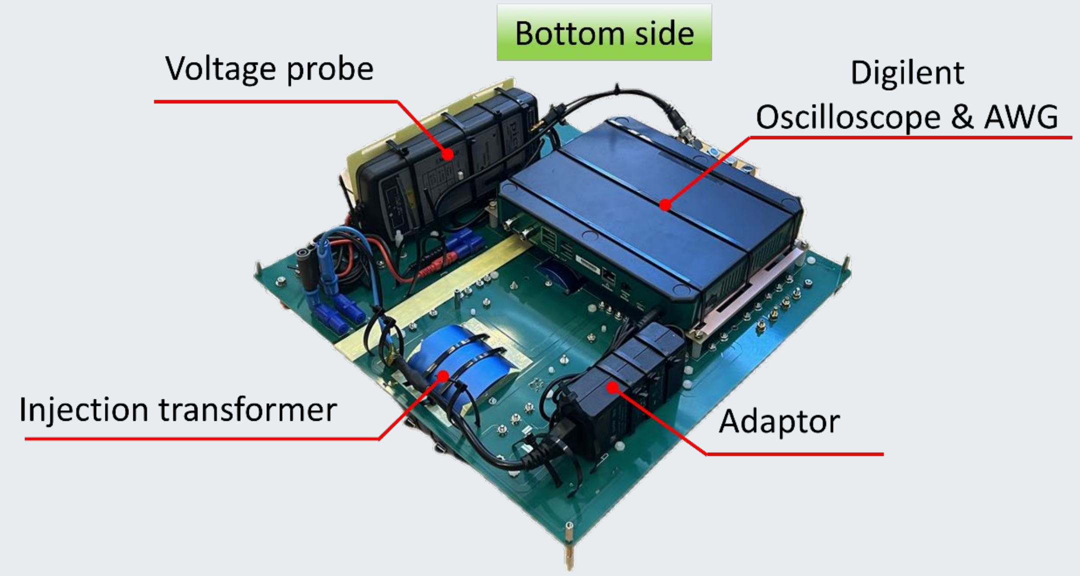
- Extract modal impedances, Z_{dm} and Z_{cm},
- Extract noise sources V_s

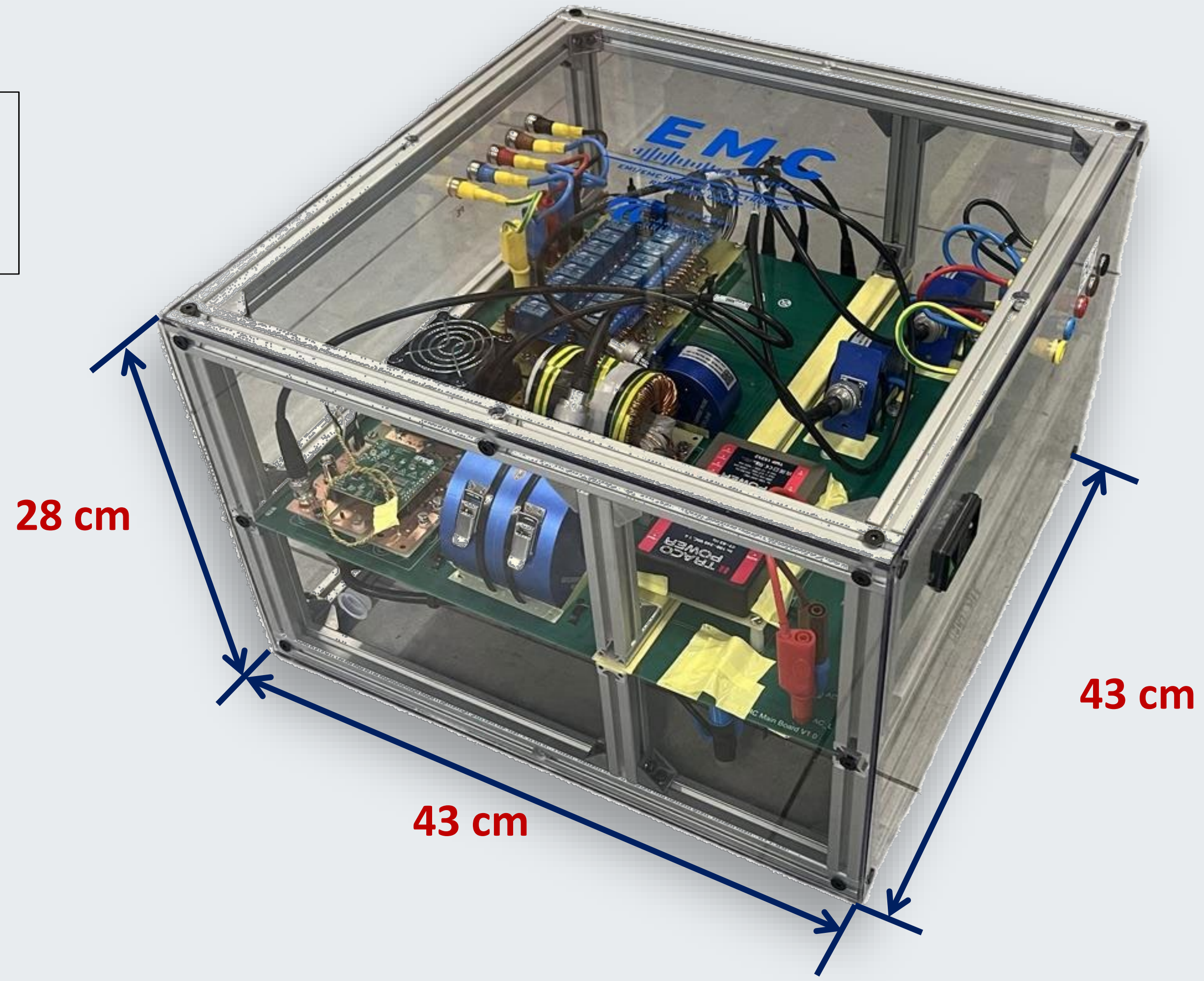
Power Converter Characterization (WP3)

Black-Box Characterization Device









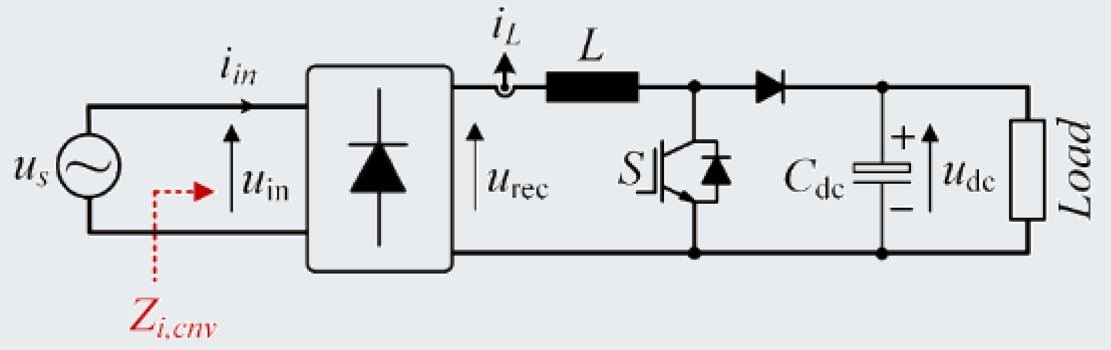
Black-Box Device

- Extract modal impedances, Z_{dm} and Z_{cm},
- Extract noise sources V_s
- Full black-box model (up to 500 kHz)
- User-friendly GUI
- Multi-tone injection approach
- 4-wire measurement

Power Converter Characterization (WP3)

Impedance Modeling (Closed Loop) Validation

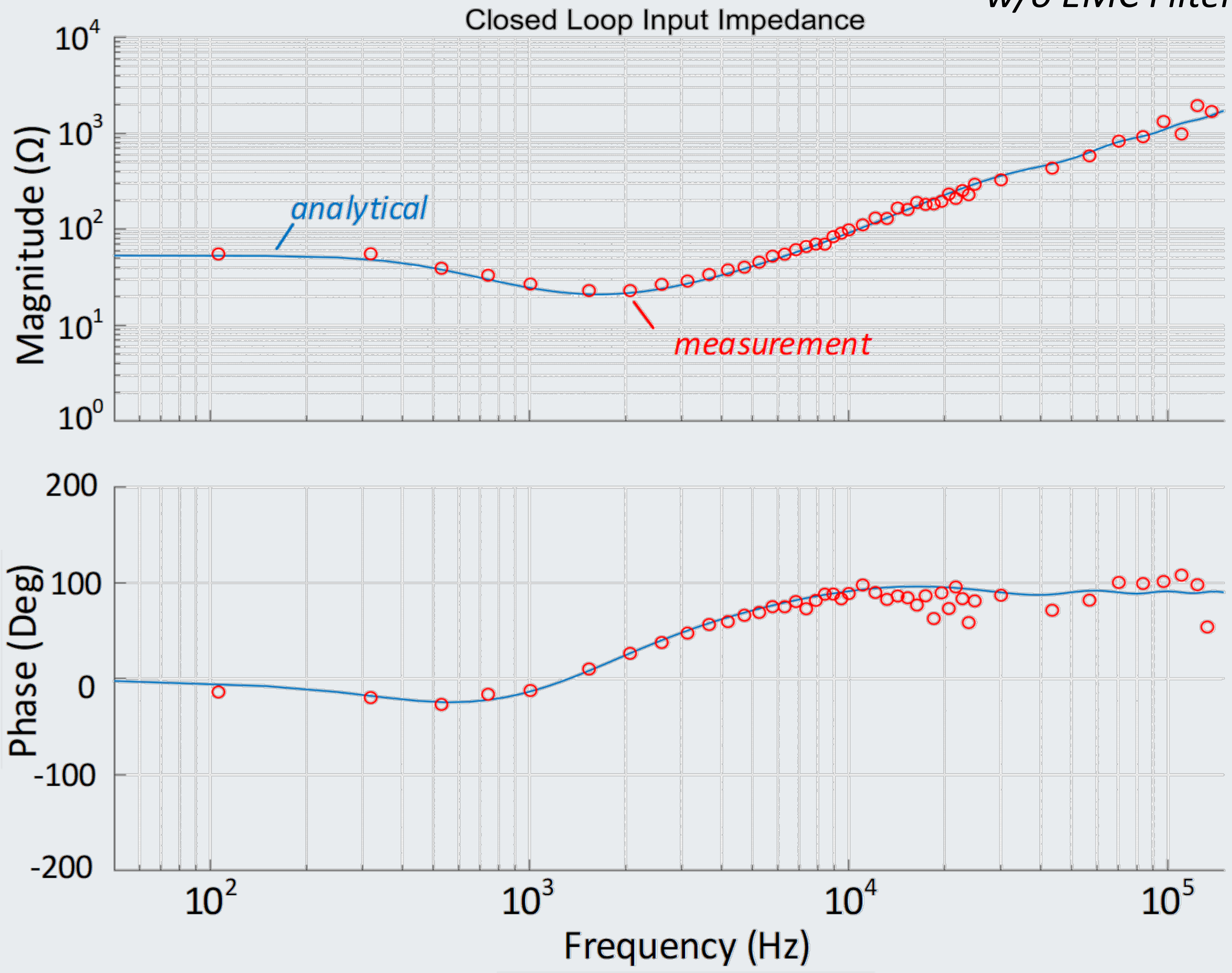
Case Study: Single-Phase PFC



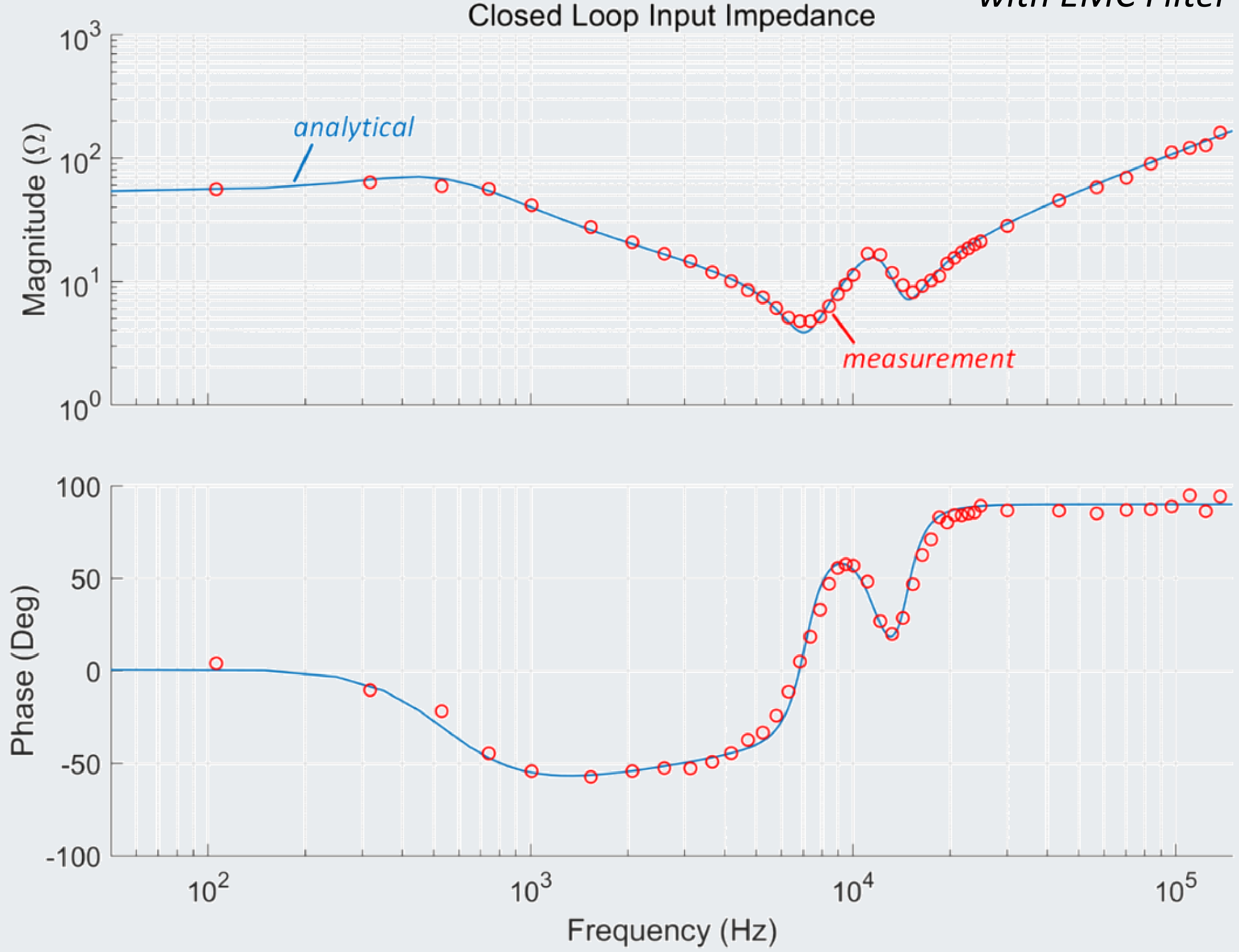
Po = 1 kW
LPF = 0.5 kHz
fs = 20 kHz
Kp = 0.06
Ki = 300

- ❑ Analytical model matches very good!

w/o EMC Filter



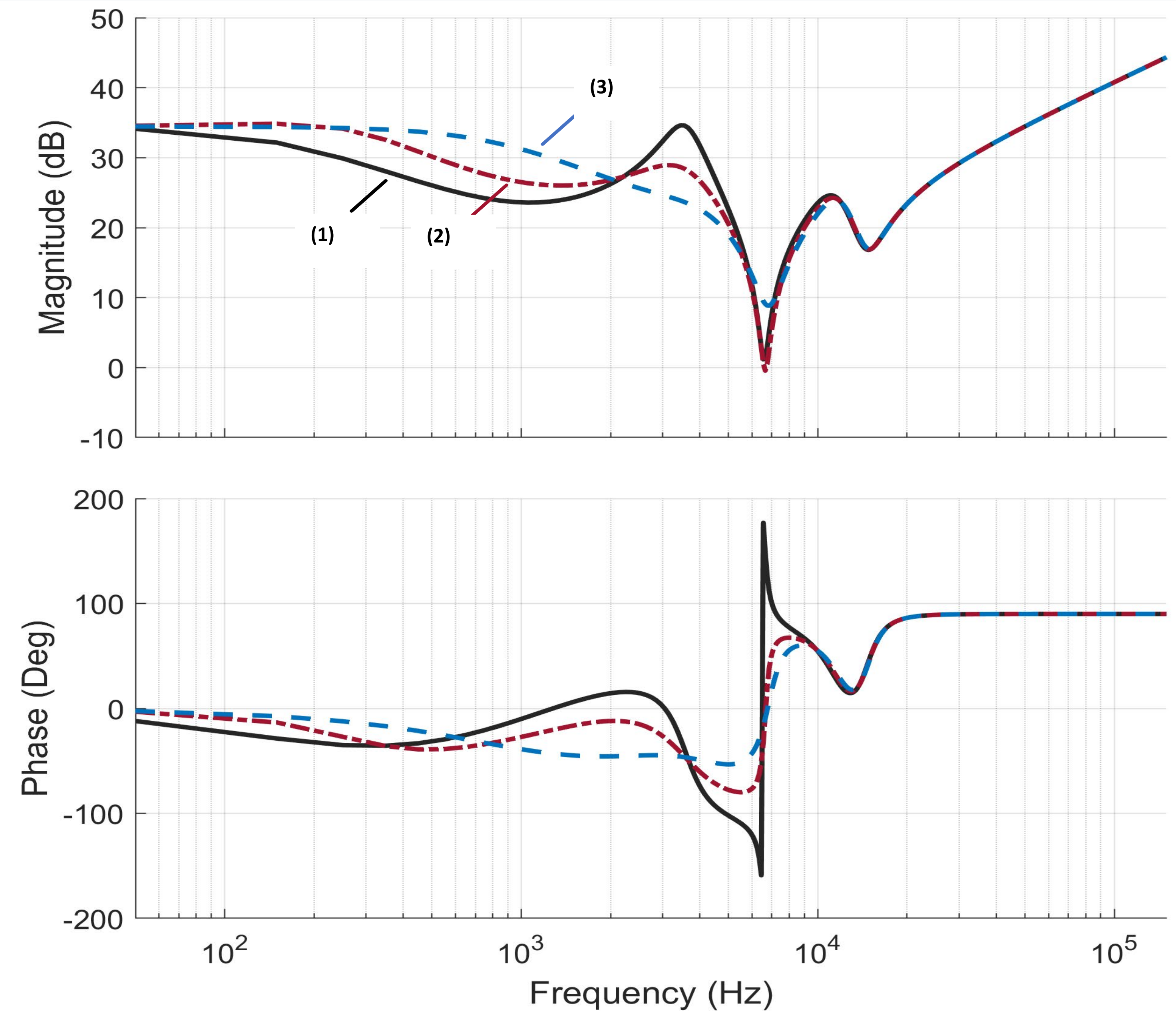
with EMC Filter



Power Converter Characterization (WP3)

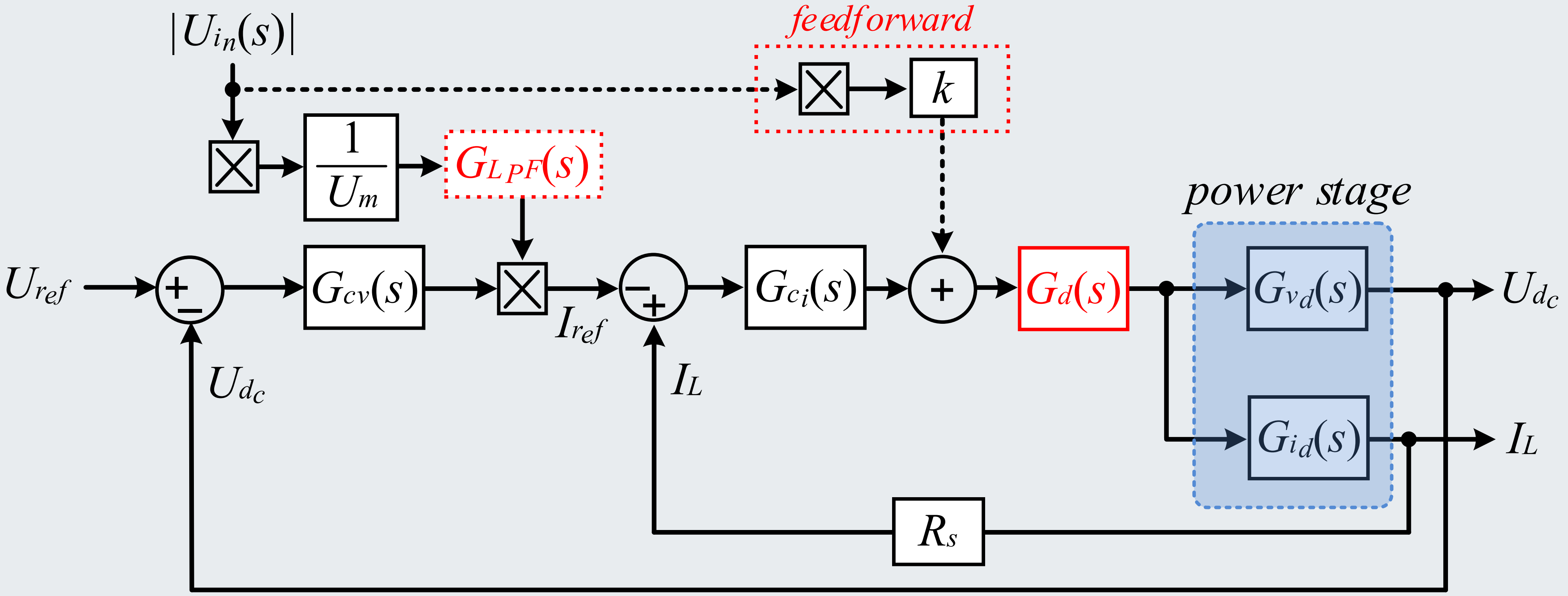
Impedance Modeling (Closed Loop)

Case Study: Single-phase PFC



Effect of phase lead compensation on closed input impedance of PFC converter at 1 kW with f_s = 40 kHz, with single update sampling and f_c = 2320 Hz.

- Modifying the control loop can **reshape** the closed loop impedance

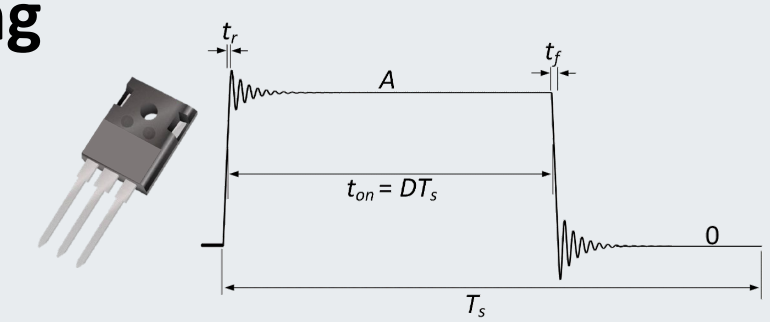


(1): Without compensation
(2): With Lowpass filter
(3) : With input voltage feedforward

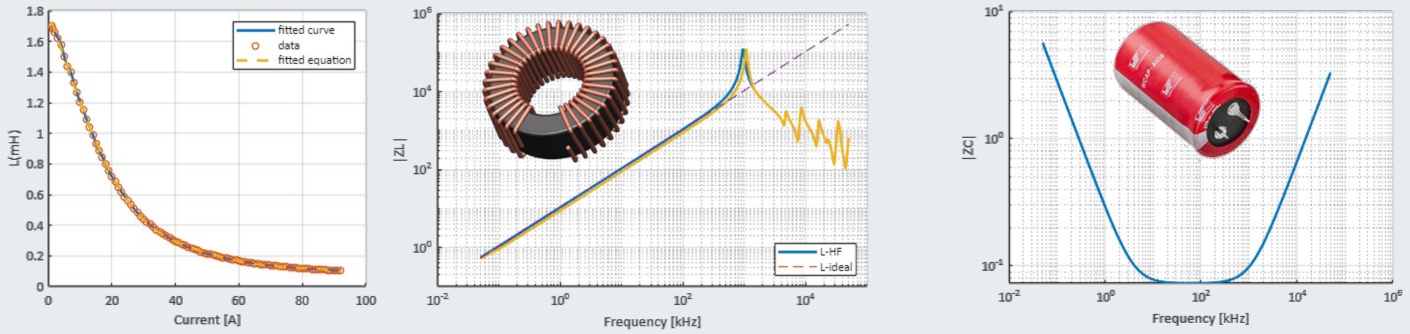
Power Converter Characterization (WP3)

EMI Modeling

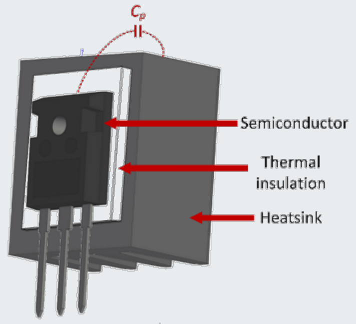
- Switching characteristics



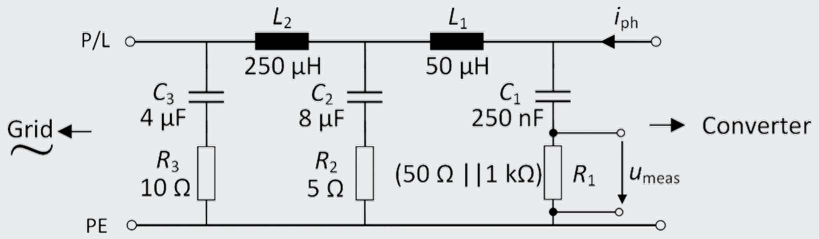
- Passive components HF model



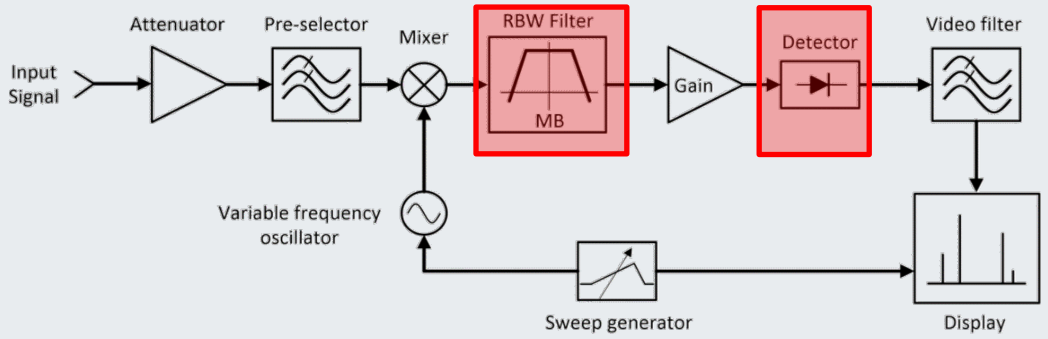
- Parasitic capacitance

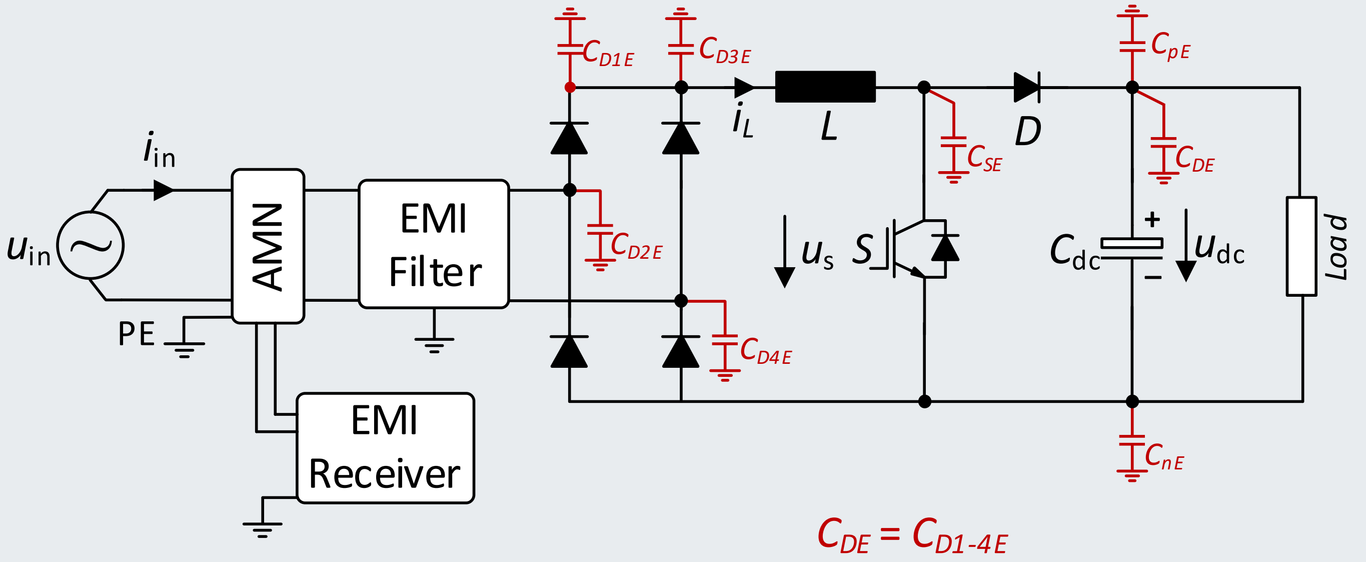


- AMN/LISN



- EMI Receiver

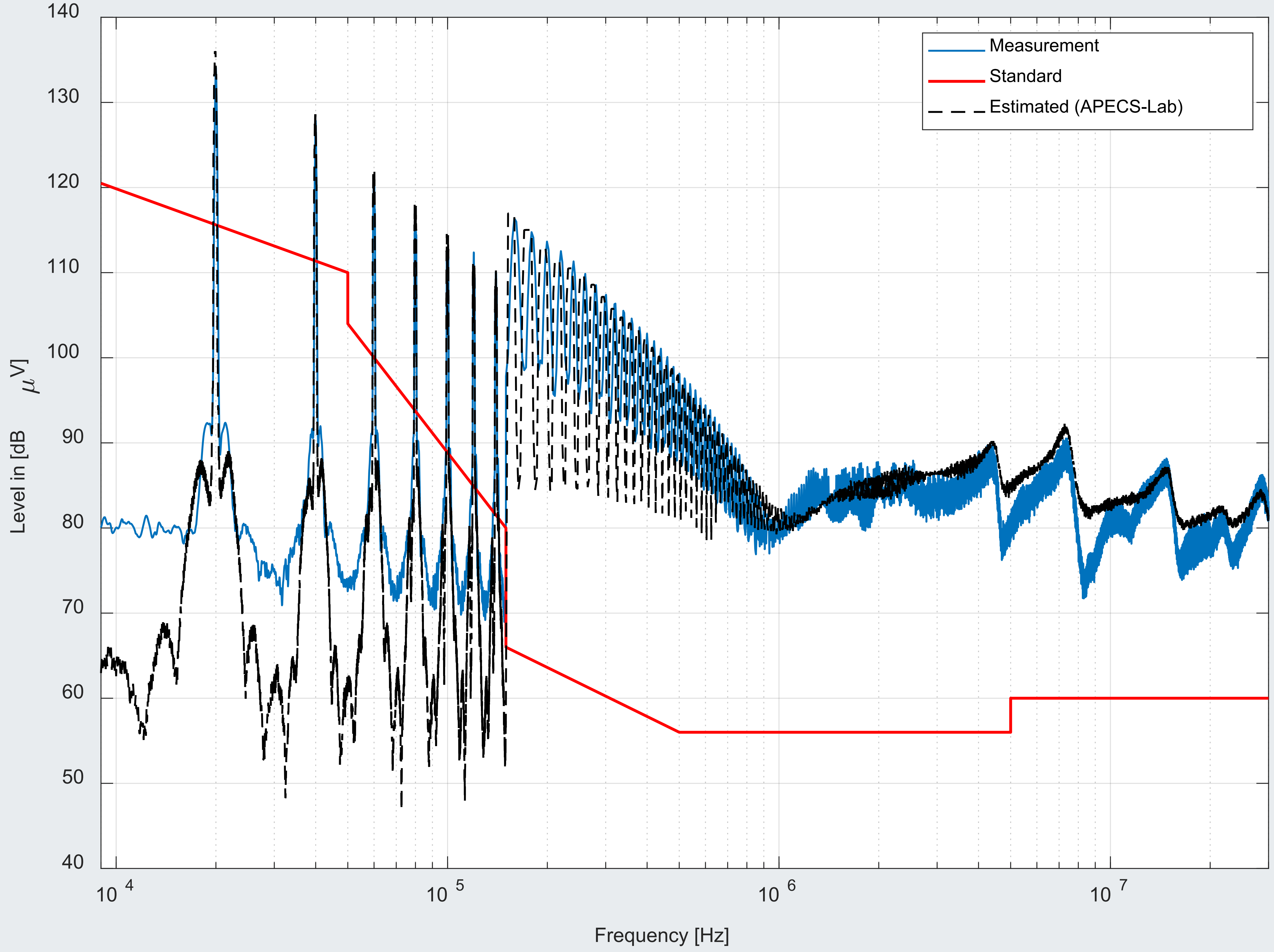




Power Converter Characterization (WP3)

Noise Estimation

Single-phase PFC @ 20 kHz – no EMI filter



OUTLINE

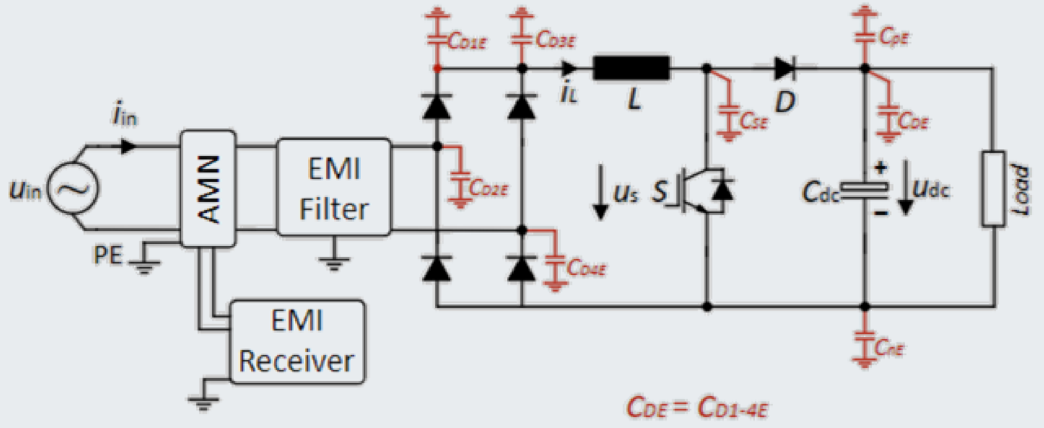
- ❑ Introduction to Supraharmonics in Power Electronics
- ❑ Power Grid Characterization
- ❑ Power Converter Noise Propagation Path Modeling
- ❑ **EMC Filter Design**
- ❑ Outlook for APECS (Newly Developed EMI Prediction Tool)

Filtering (WP4)

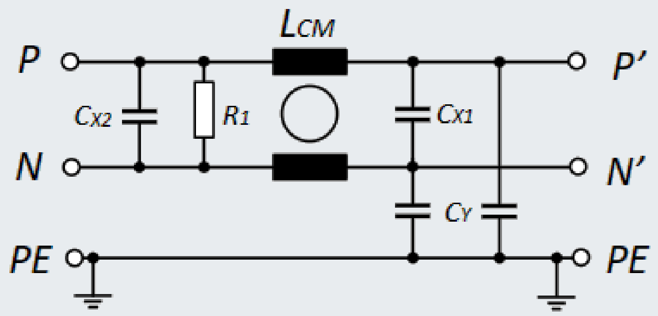
WP4.1: Passive filtering size and volume optimization

Single-phase PFC @ 20 kHz

L [mH]	1.73	*Udc [v]*	400
Resr [Ω]	0.1101	*Po [kw]*	2



CpE [pF]	10
CnE [pF]	10
CmE [pF]	10
CDE [pF]	40
CSE [pF]	40
CS3E [pF]	10
CS4E [pF]	10



Grid side

Converter side

CLC Filter

Significant improvement on volume and cost!

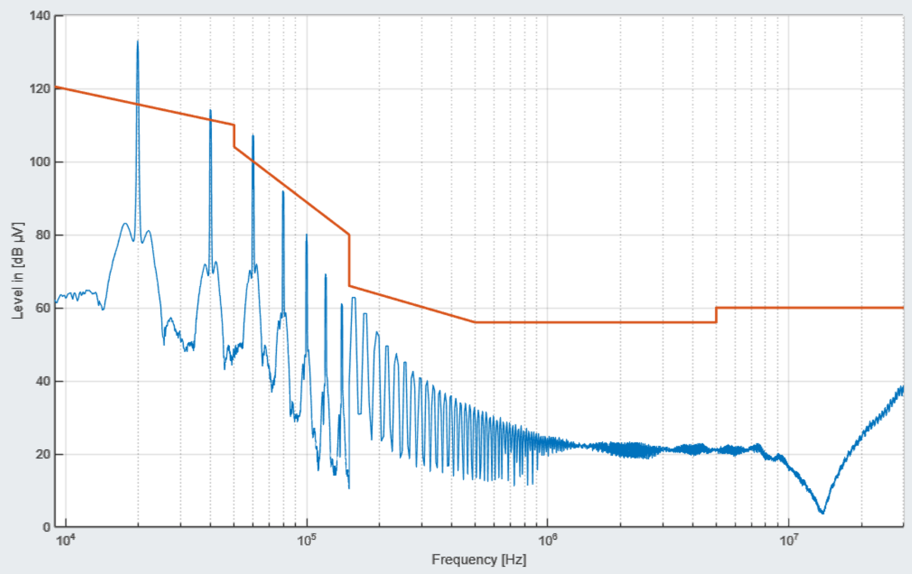
Estimated total EMI of the single-phase PFC converter

Fixed switching frequency, To meet >150 kHz limit

- Power Loss -	
DM Loss (W)	2.935
CM Loss (W)	0.0031
Total Loss (W)	2.938

Total Price (based on 1 QTY) = 132.92 DKK

Volume = 47.3 cm^3

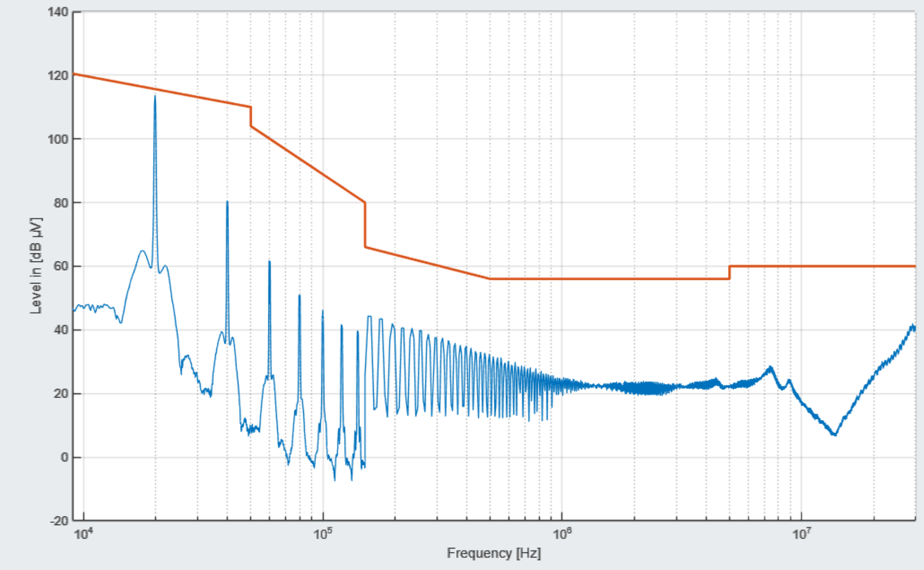


Fixed switching frequency, To meet <150 kHz limit

- Power Loss -	
DM Loss (W)	2.947
CM Loss (W)	0.0031
Total Loss (W)	2.951

Total Price (based on 1 QTY) = 207.74 DKK

Volume = 153.6 cm^3

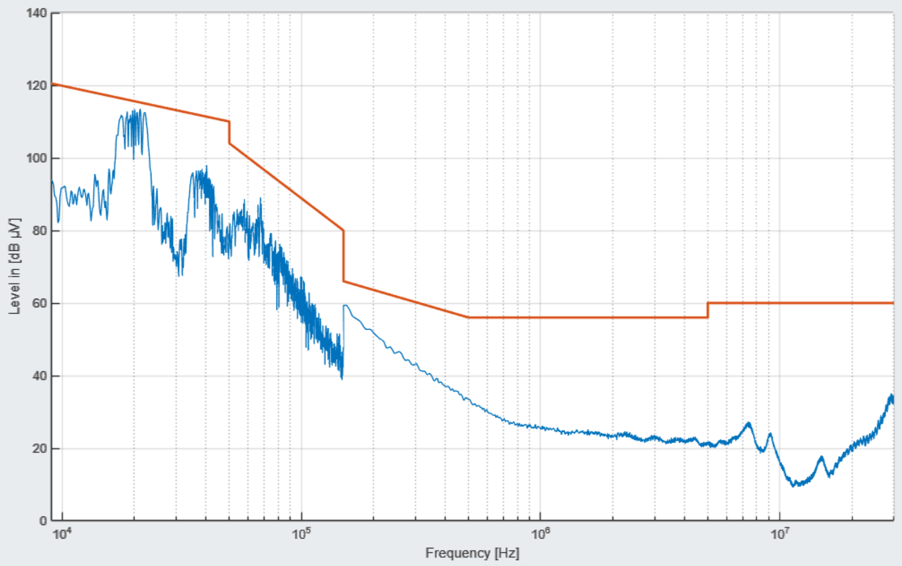


Frequency dithering Δf = 6 kHz, To meet <150 kHz limit

- Power Loss -	
DM Loss (W)	3.029
CM Loss (W)	0.0036
Total Loss (W)	3.032

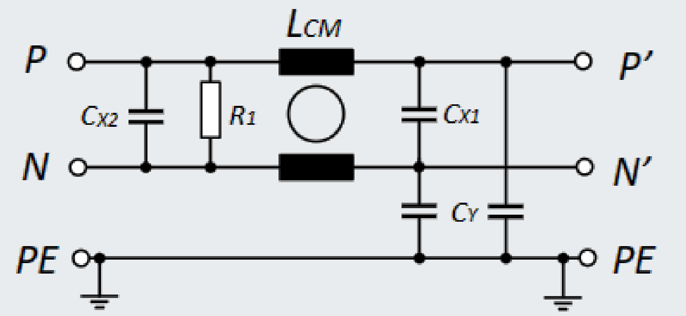
Total Price (based on 1 QTY) = 85.44 DKK

Volume = 58 cm^3



Filtering (WP4)

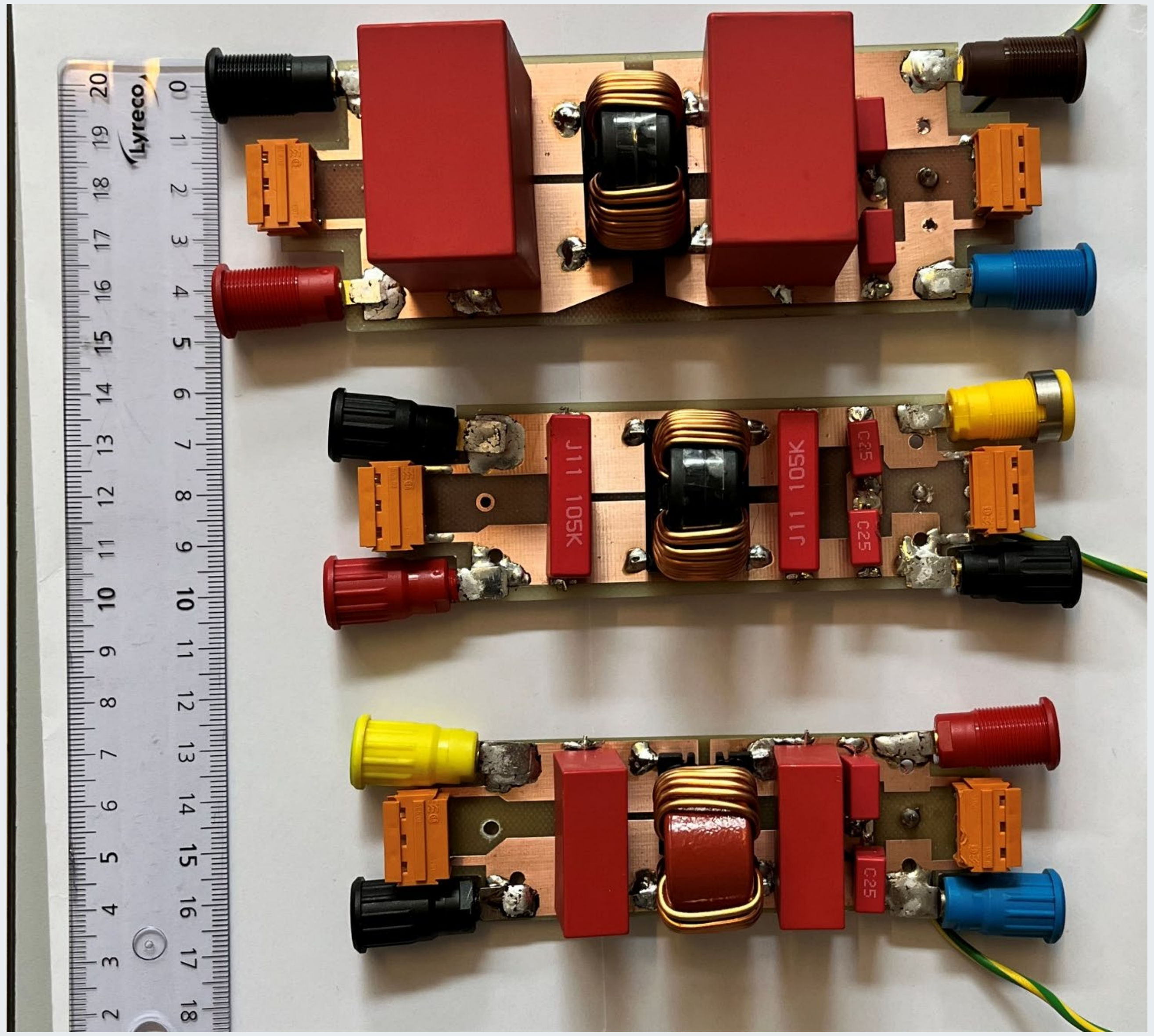
WP4.1: Passive filtering size and volume optimization



Grid side

Converter side

CLC Filter



CASE II

Volume = 420 cm^3

CASE I

Volume = 182 cm^3

CASE III

Volume = 195 cm^3

Selected components **CASE I**

CX1 [nF]	1000	CX2 [nF]	1000
CX1 Model No.	890334027009_1uF	CX2 Model No.	890334027009_1uF
Company	Würth Elektronik	Company	Würth Elektronik
CX [nF]	0	CY [nF]	15
CX Model No.		CY Model No.	890324022007_15nF
Company		Company	Würth Elektronik
LCM (mH)	12	LDM (µH)	0
LCM Model No.	7448051012	LDM Model No.	
Company	Würth Elektronik	Company	

Selected components **CASE II**

CX1 [nF]	1e+04	CX2 [nF]	1e+04
CX1 Model No.	890414028002CS_1(	CX2 Model No.	890414028002CS_1(
Company	Würth Elektronik	Company	Würth Elektronik
CX [nF]	0	CY [nF]	15
CX Model No.		CY Model No.	890324022007_15nF
Company		Company	Würth Elektronik
LCM (mH)	12	LDM (µH)	0
LCM Model No.	7448051012	LDM Model No.	
Company	Würth Elektronik	Company	

Selected components **CASE III**

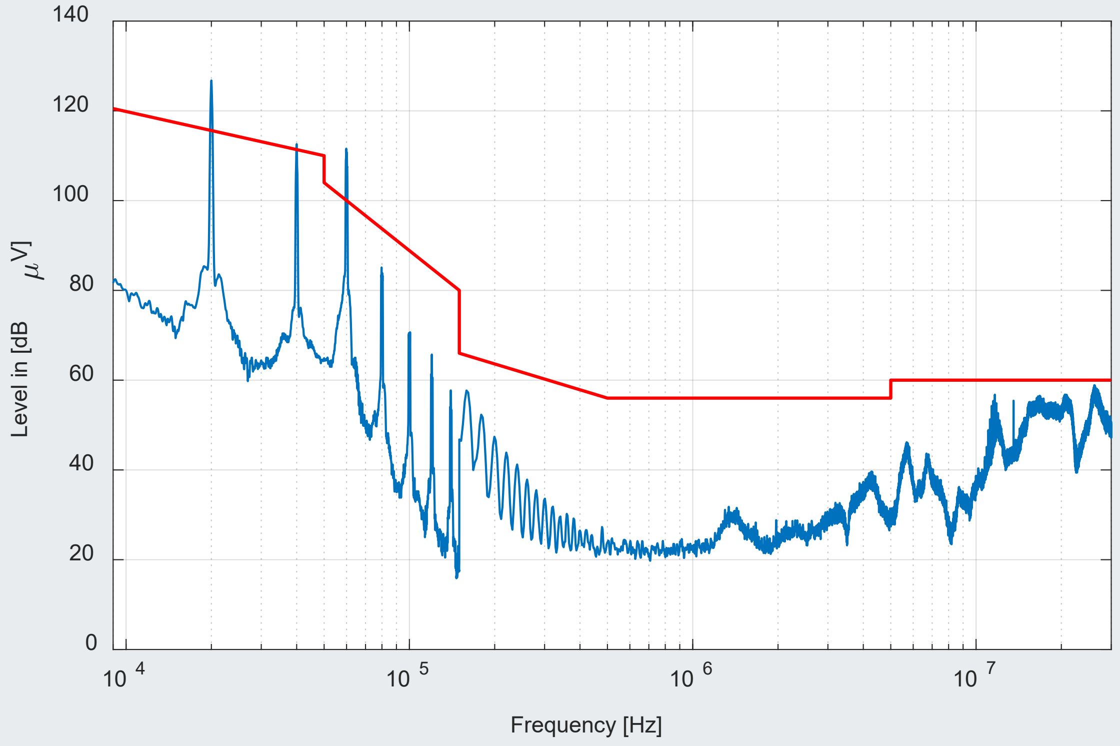
CX1 [nF]	2200	CX2 [nF]	2200
CX1 Model No.	890334027021CS_2,	CX2 Model No.	890334027021CS_2,
Company	Würth Elektronik	Company	Würth Elektronik
CX [nF]	0	CY [nF]	15
CX Model No.		CY Model No.	890324022007_15nF
Company		Company	Würth Elektronik
LCM (mH)	1	LDM (µH)	0
LCM Model No.	7448251201	LDM Model No.	
Company	Würth Elektronik	Company	

WP4: Filter Design and Reliability

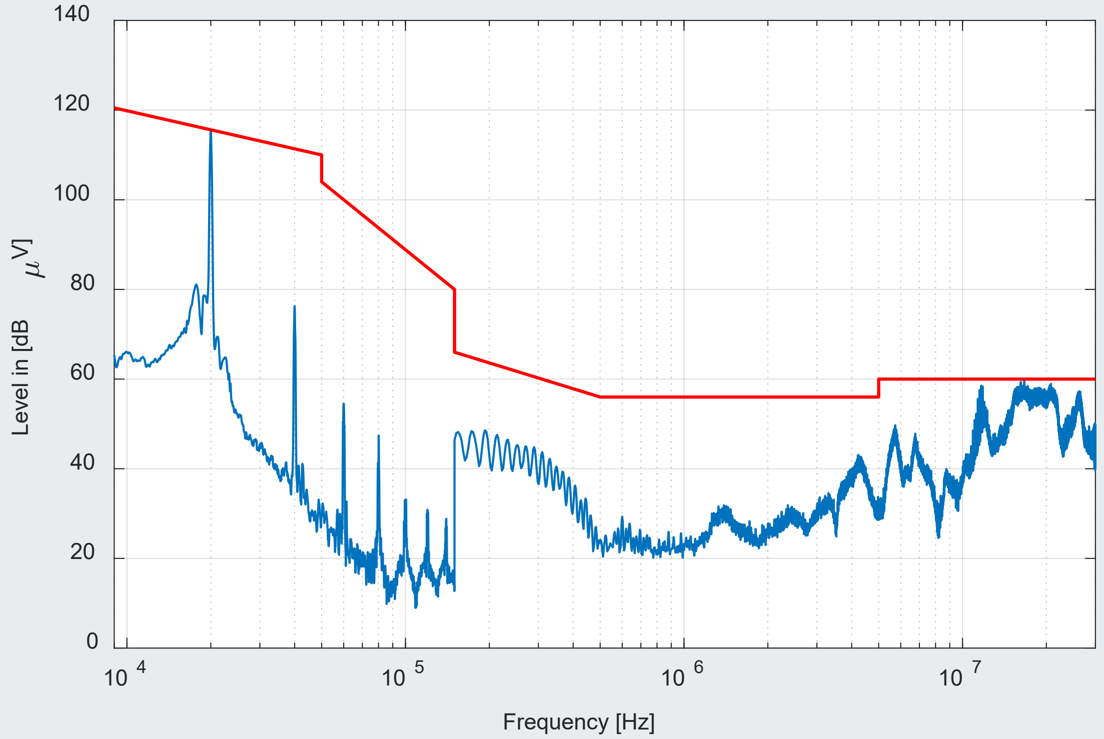
WP4.1: Passive filtering size and volume optimization

Experimental results

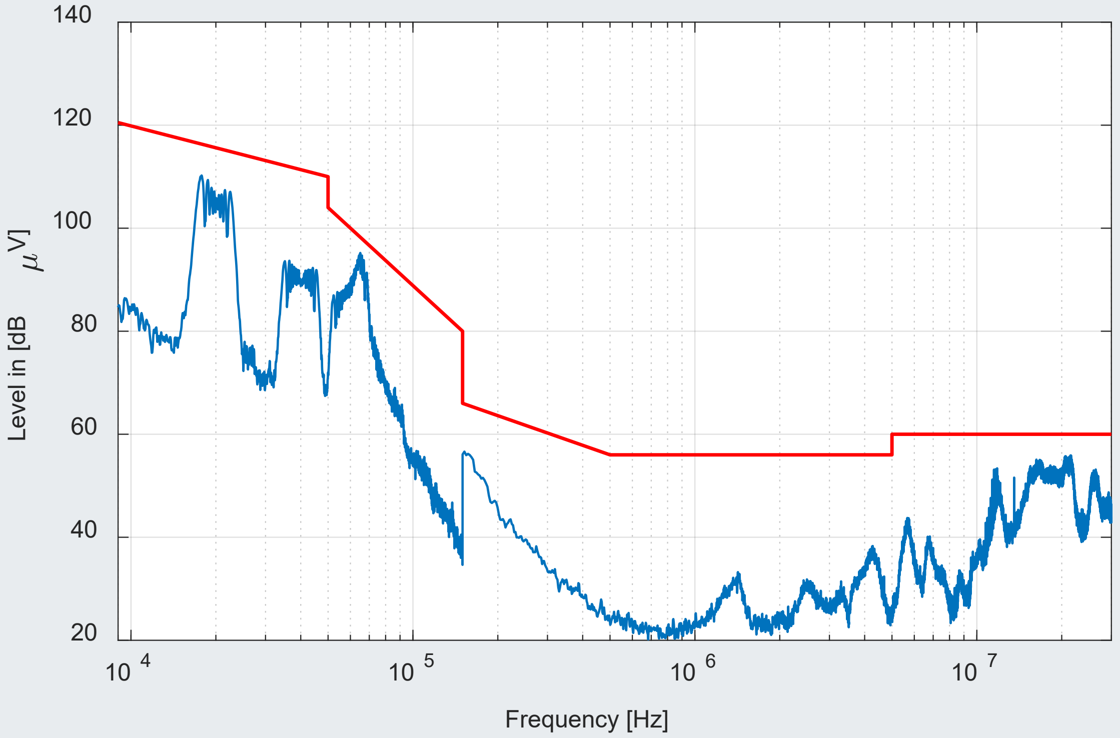
CASE I



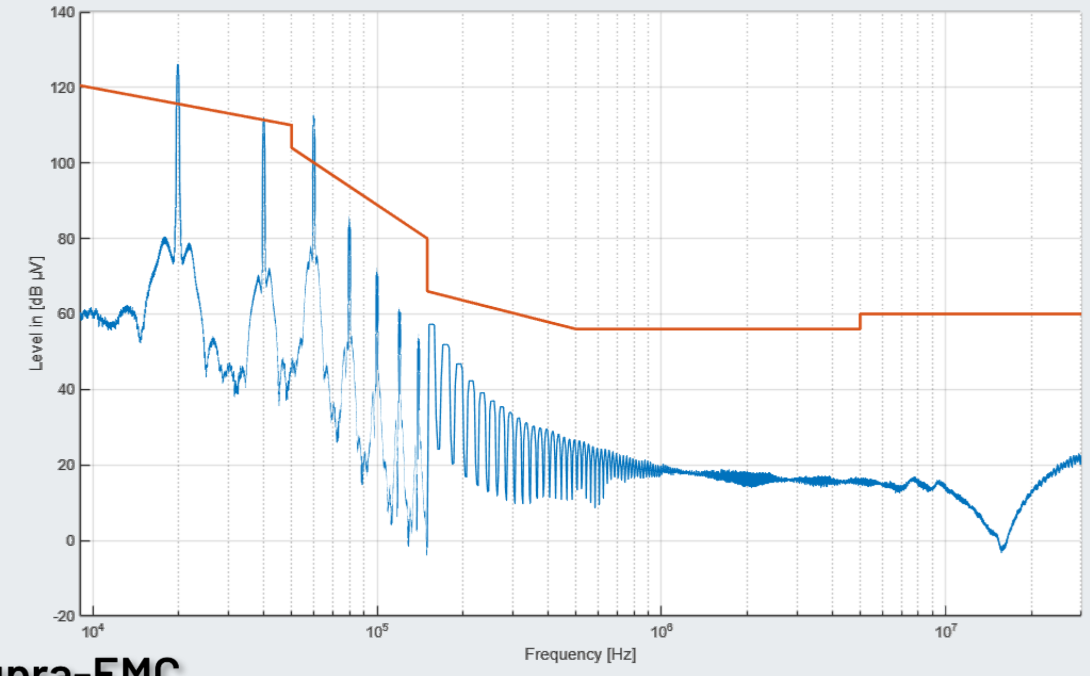
CASE II

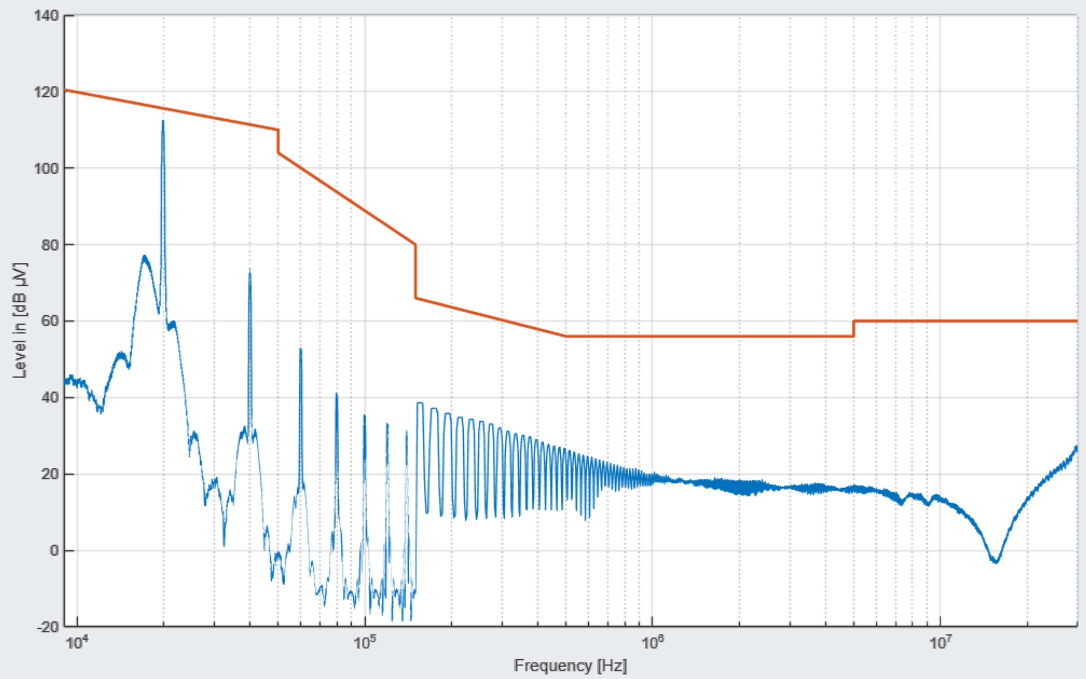


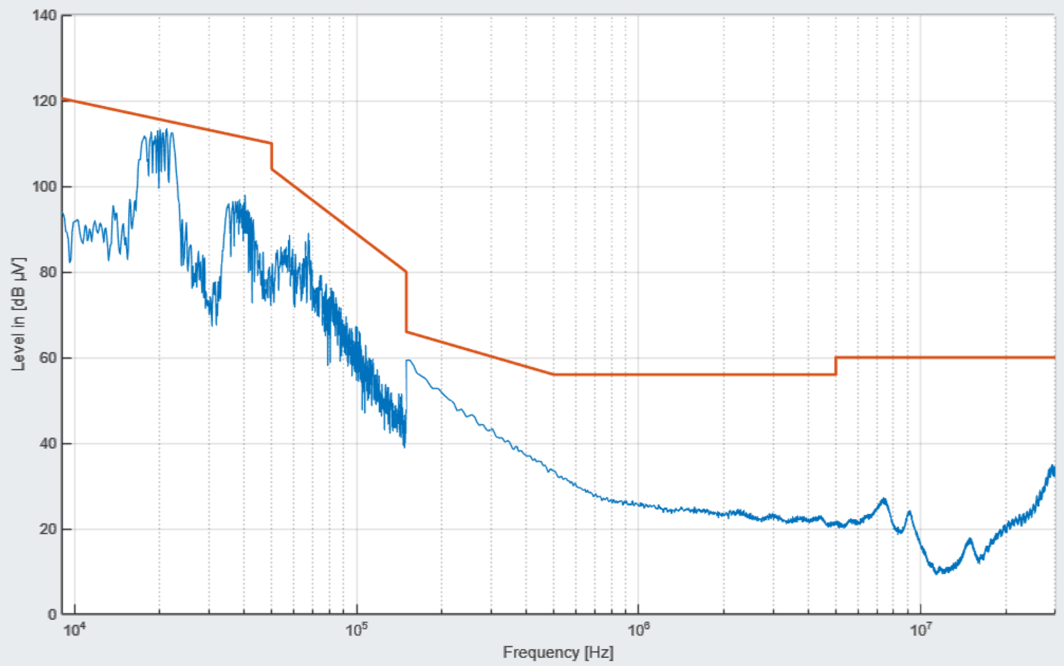
CASE III



Predicted results







Filter Reliability (WP4)

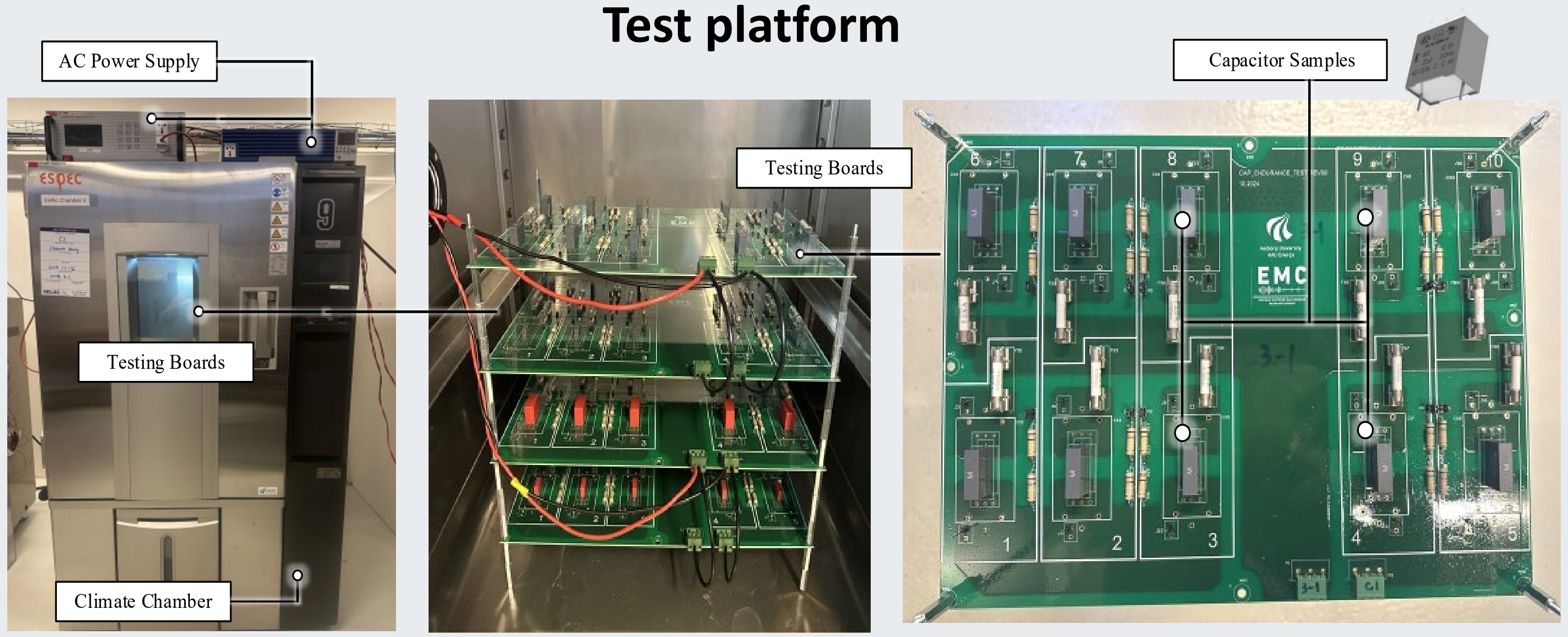
Capacitor accelerated degradation test

- *Six types of EMI suppression capacitors from three manufacturers are tested under four different test conditions (240 capacitor samples in total).*

Test Conditions

Test condition	1	2	3	4
AC Voltage (RMS)	V_rated	V_rated	V_rated	V_rated
AC frequency	50 Hz	50 Hz	50 Hz	50 Hz
Chamber Temperature	85 ºC	85 ºC	125 ºC	110 ºC
Chamber humidity	85 %	70 %	-	-

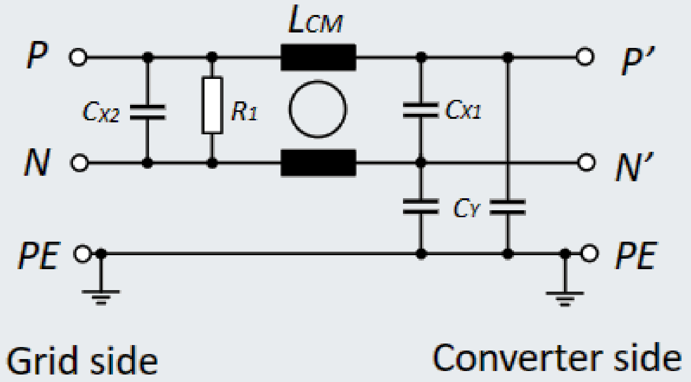
Test platform



Capacitors under test

Number	Brand	Value (uF)	Class	Voltage (V)	Tolerance	Pitch size (mm)	Samples	Dielectric	Max temp	THB grade
1	Pikor	1	X2	305	20	27.5	40	MKP	105	-
2	Pikor	0.1	X2	305	20	15	40	MKP	105	-
3	Kemet	1	X2	310	20	22.5	40	MKP	110	IIB
4	Kemet	0.1	X2	310	10	15	40	MKP	110	IIB
5	Wurth Electronic	1	X2	275	10	22.5	40	MKP	105	-
6	Wurth Electronic	0.1	X2	275	10	15	40	MKP	105	-

Filter Reliability (WP4)

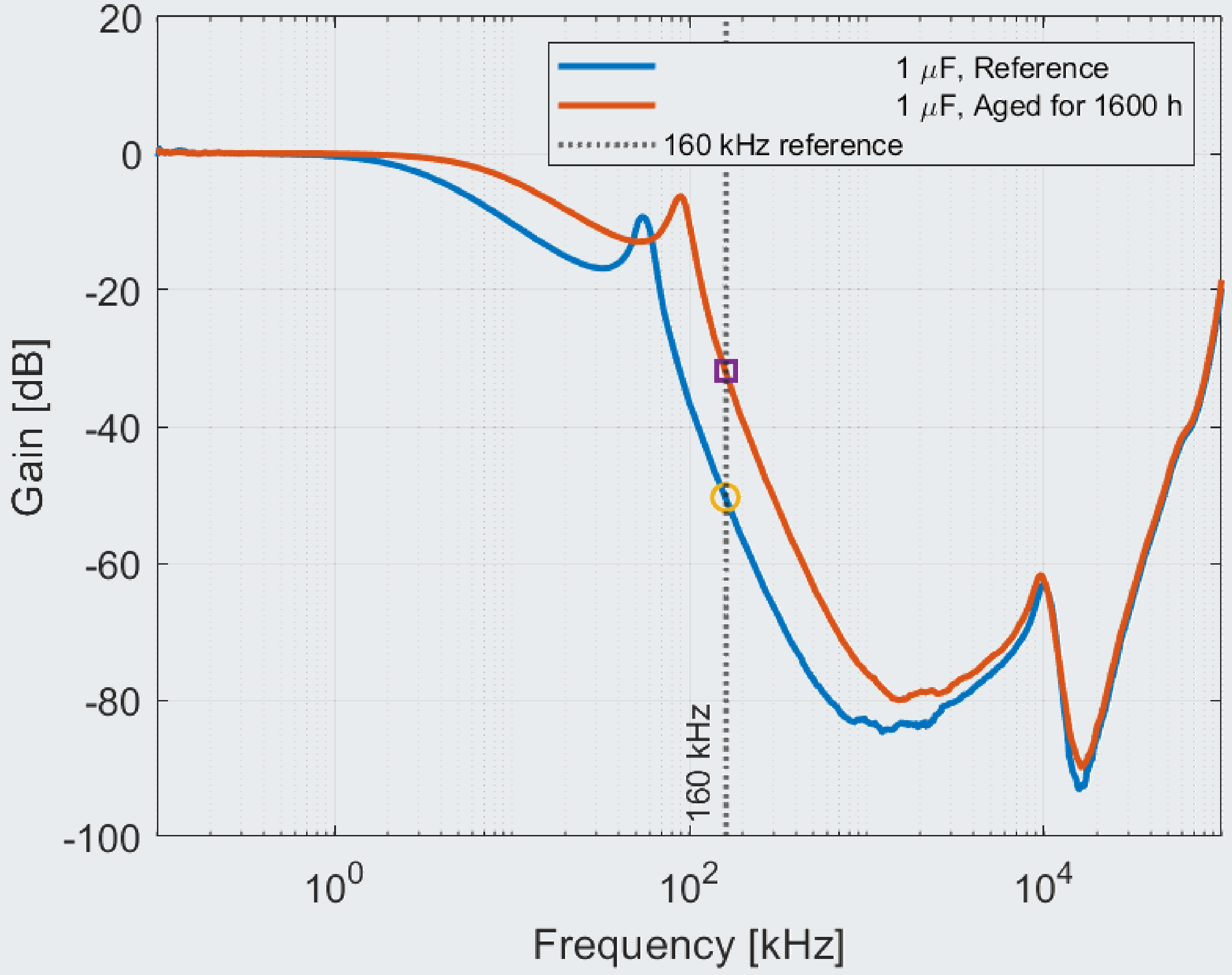


CLC Filter

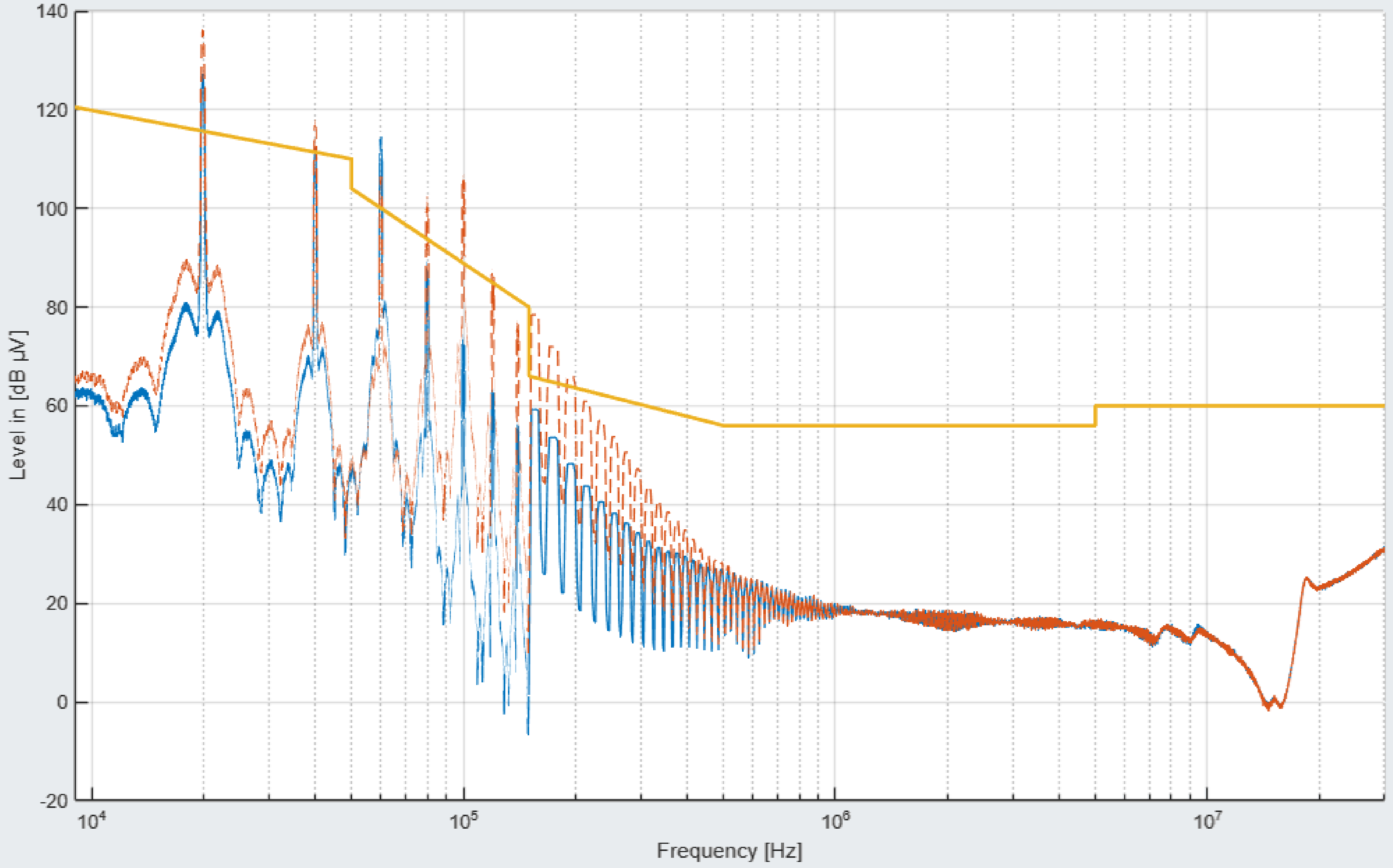
➢ EMI analysis

- **Test results**

- **Capacitor: Case 5 (1uF)**
- **Test condition:** 85 % RH/85 ºC, rated voltage



Comparison of DM Gain Using Reference and Aged Capacitors (1600 hours)



DM Gain Variation at 160 kHz for Reference and Aged Capacitors

Case no.	Ref. Gain @ 160 kHz (dB)	Aged Gain @ 160 kHz (dB)	ΔGain (dB)	
5	-50.37	-31.9	18.47	

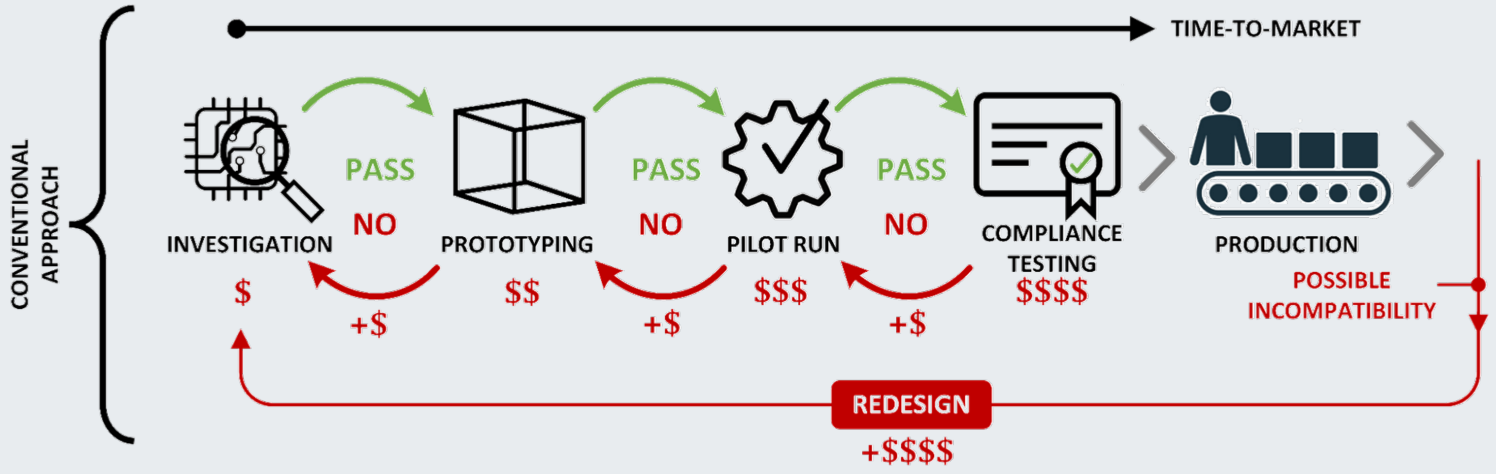
Outline

- ❑ Introduction to Supraharmonics in Power Electronics
- ❑ Power Grid Characterization
- ❑ Power Converter Noise Propagation Path Modeling
- ❑ EMC Filter Design
- ❑ **Outlook for APECS (Newly Developed EMI Prediction Tool)**

Power Electronics EMC Design Tool

Conventional EMC Design

- **50%** of products fail EMC testing the first time! [1], [2]
- EMC testing accounts for **30%-50%** of product development **time** and **cost**
- EMC filters accounts for more than **30%** of **cost** and **volume** [3]
- Lack of EMC filter volume and size **optimization algorithm**
- Challenge of coping with **new upcoming standards**



Sources
[1] Why 50% of Products Fail EMC Testing the First Time
[2] Precompliance EMI Debug, Application Note, Rohde & Schwarz, 2020.
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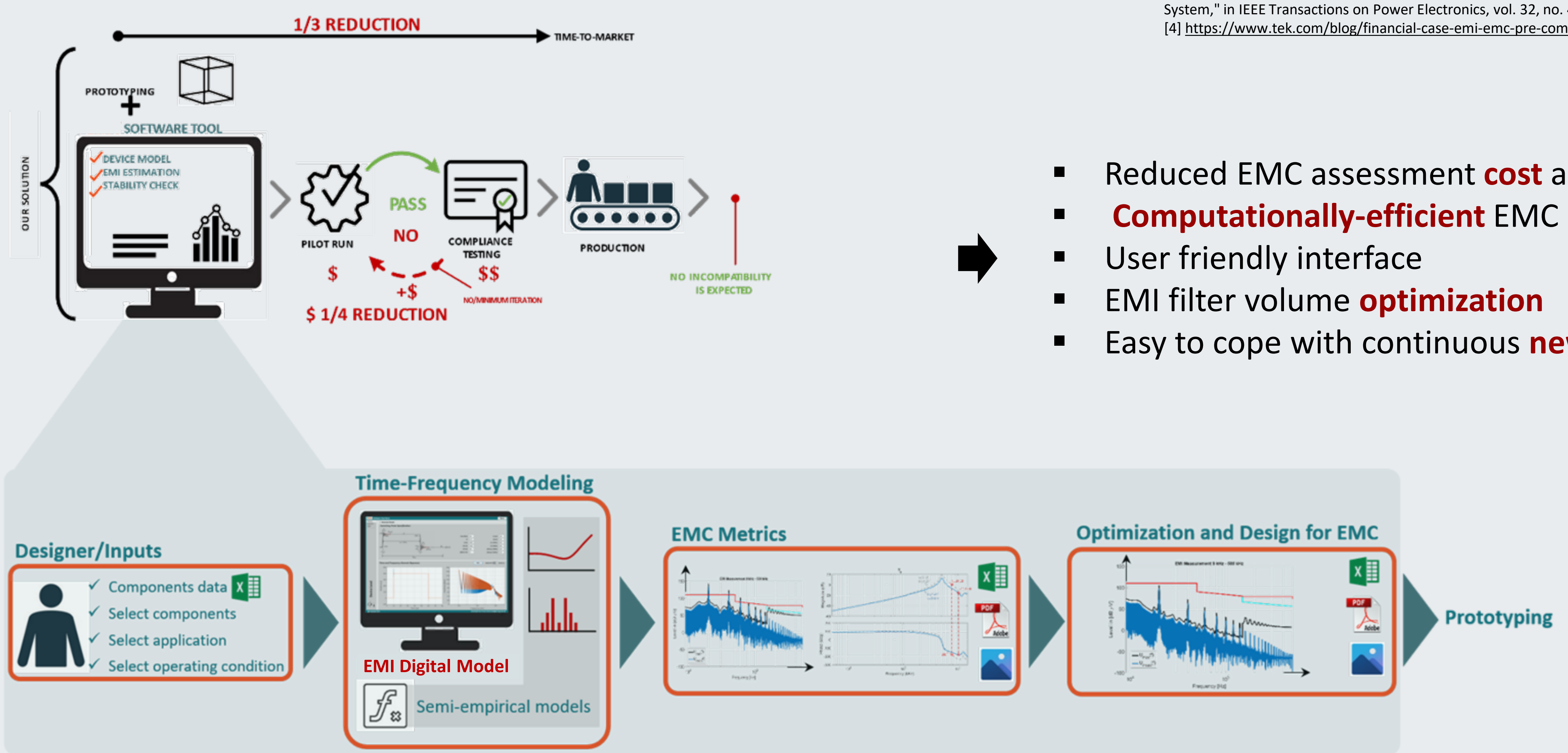
[4] https://www.tek.com/blog/financial-case-emi-emc-pre-compliance-test-solution

Our Solution

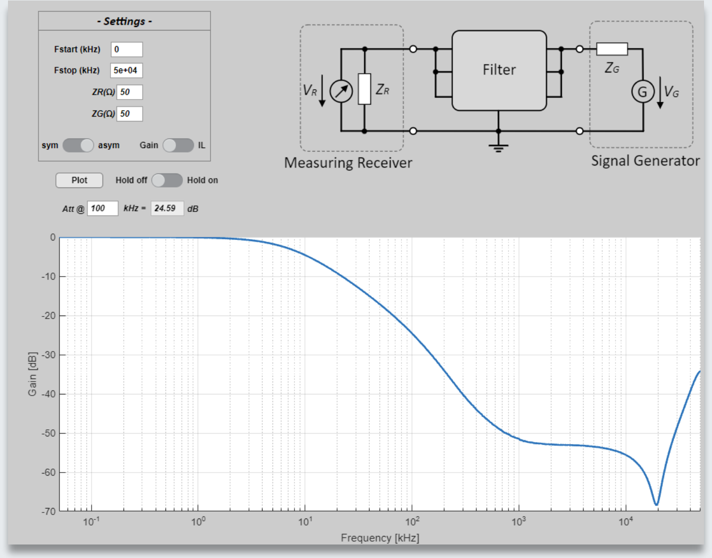


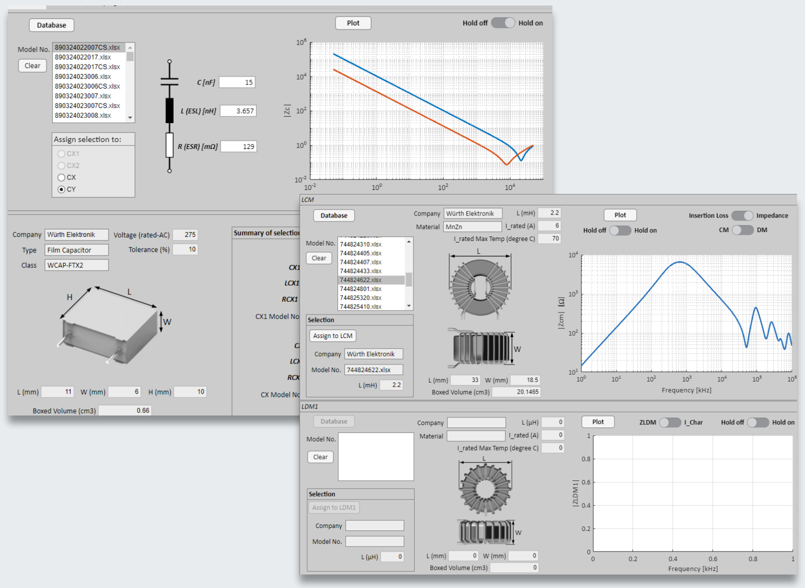
- Reduced EMC assessment **cost** and **time** (solving EMI early in design cycle)
- **Computationally-efficient** EMC analysis (digital model)
- User friendly interface
- EMI filter volume **optimization**
- Easy to cope with continuous **new EMC standard updates**

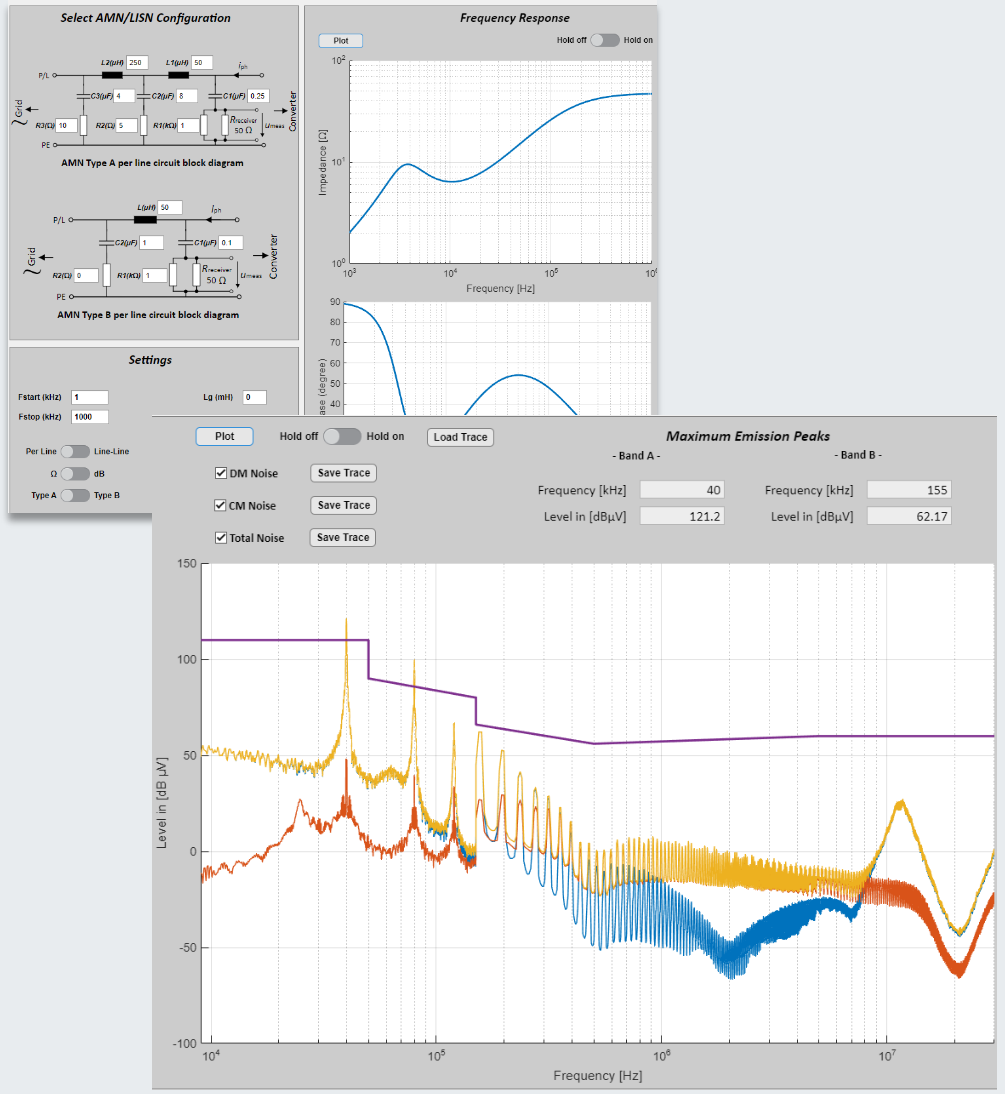
APECS-Lab

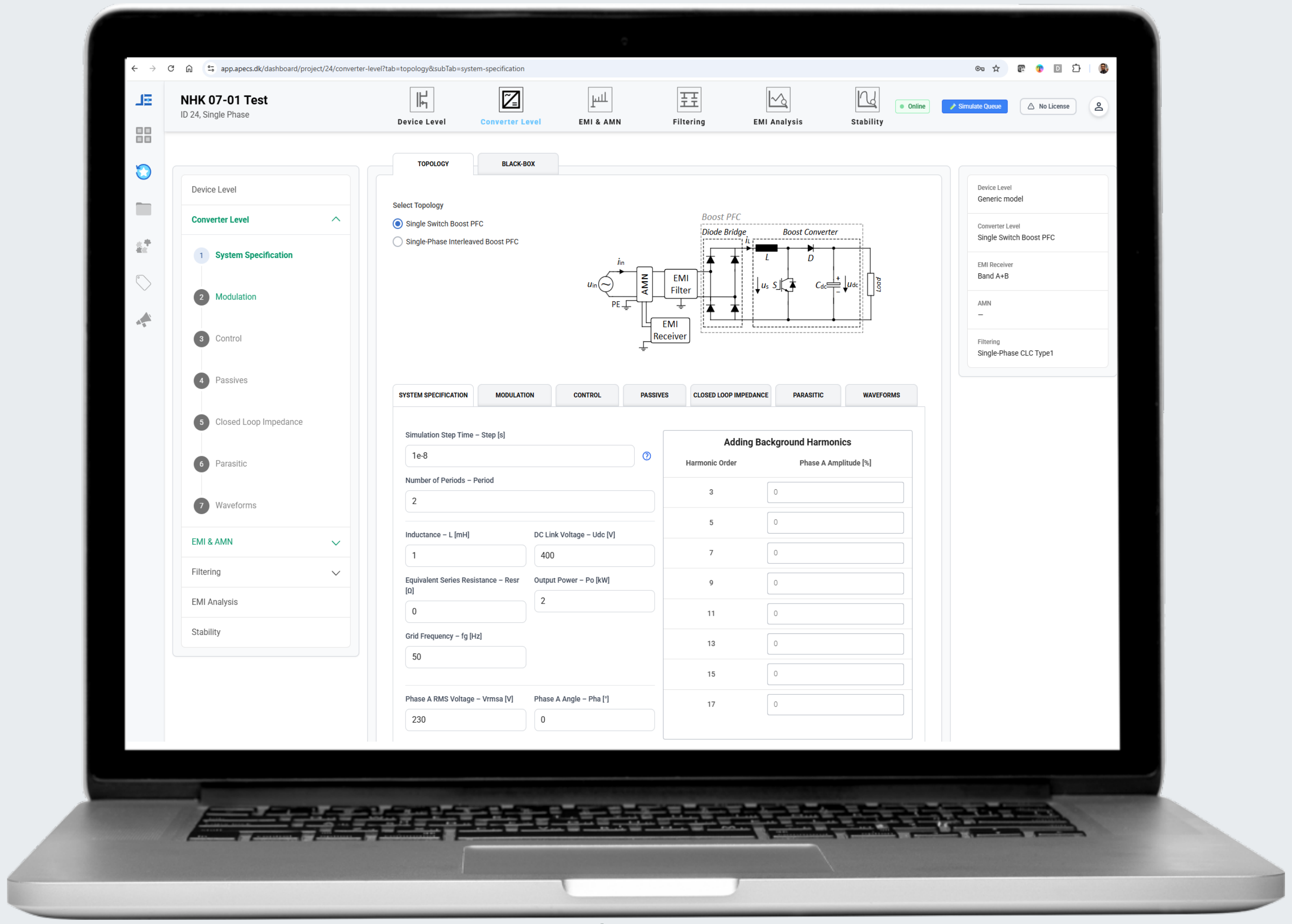
APECS
ADVANCED POWER ELECTRONIC SOLUTIONS

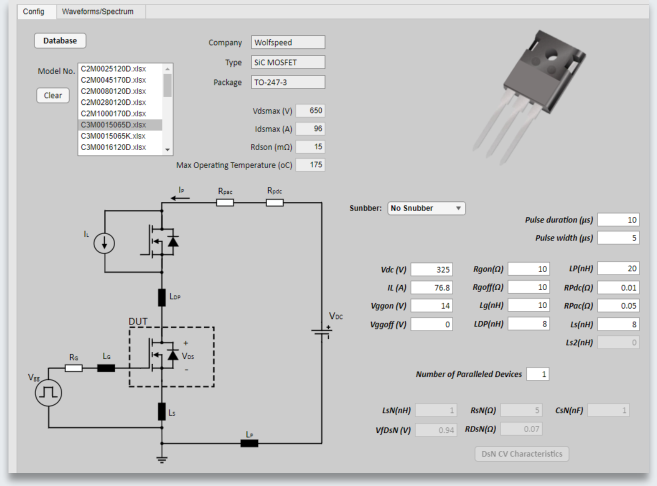
- ✓ **25%-40%** product development cost reduction
- ✓ **30%** faster time-to-market
- ✓ **+100 times** faster simulation time (**Accelerate**)
- ✓ **Focused** solely on power electronic converters

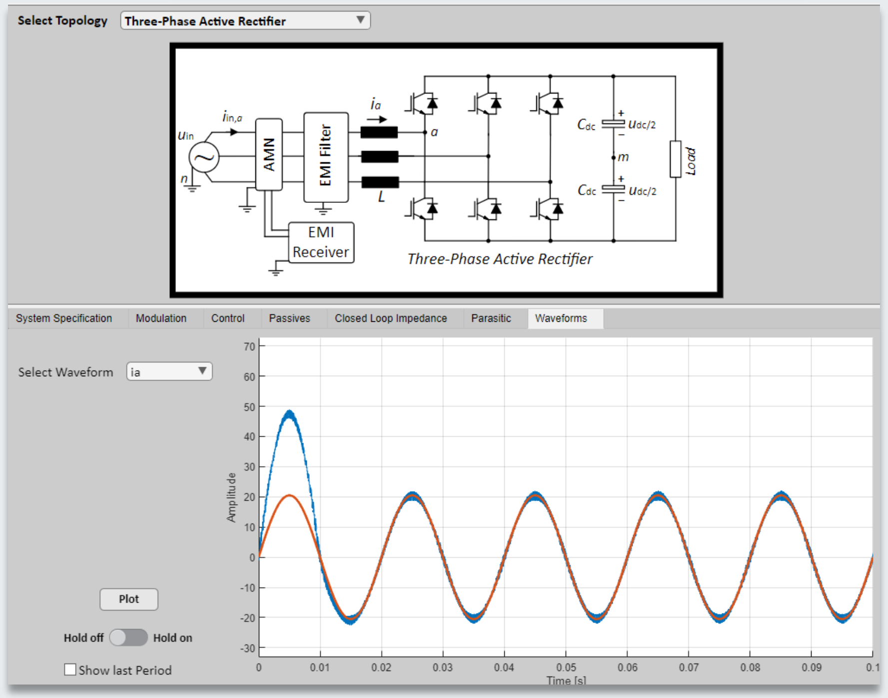












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APECS Key Features

A **best-in-class** software solution, streamlining power electronics compatibility to **accelerate** the global green transition

Power Electronic EMI Digital Model

Advanced numerical modeling platform for precise EMI analysis and simulation in power electronic systems.

- ✓ Device-specific modeling
- ✓ Fast computation engine
- ✓ Accurate EMI prediction

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- ✓ Multiple converter topologies
- ✓ Extensive component database
- ✓ EMC filter design support
- ✓ Automated EMC design

APECS
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Power Electronics EMC Design Tool

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Thank you

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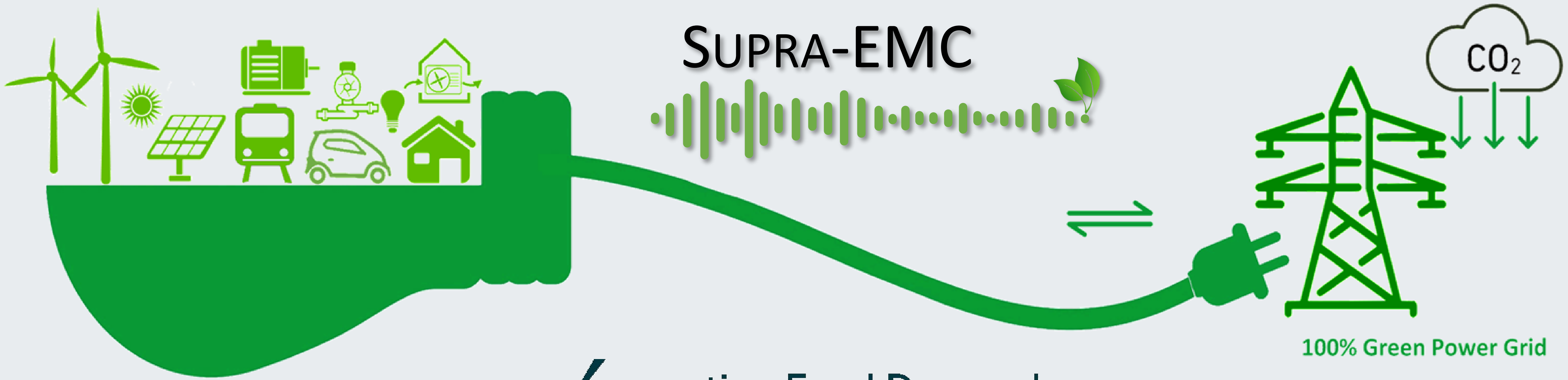

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