Supra-EMC

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

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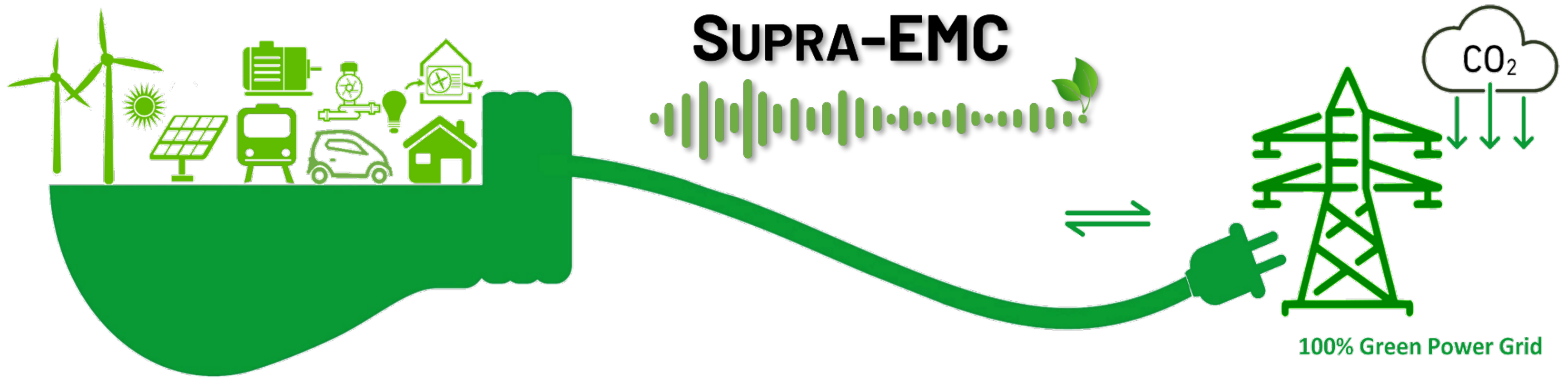


EMC

EMI/EMC IN POWER ELECTRONICS
RESEARCH GROUP

Aalborg University
AAU Energy

Outline

- ❑ Introduction to AAU Energy
- ❑ Background/Motivation
- ❑ Supra-EMC Project

Aalborg University, Denmark

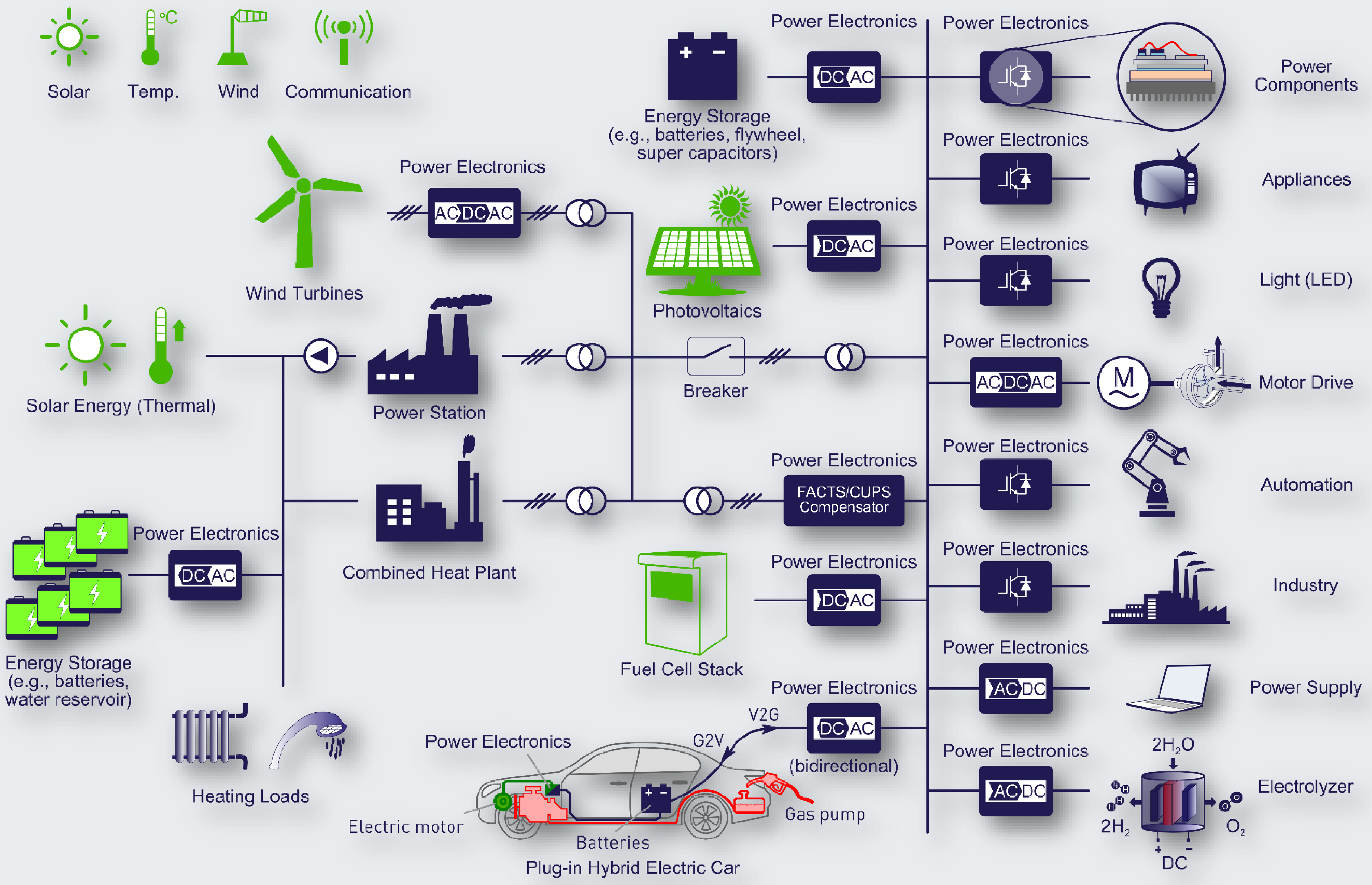
USNEWS 2021
Engineering
No. 6 globally
No. 1 in Europe
No. 3 in Electrical Engineering

Source:
https://www.usnews.com/education/best-global-universities/engineering

Established in 1974
22,000 students
2,300 faculty

PBL-Aalborg Model
(Problem-based learning)

Department of Energy at Aalborg University



Energy

Production
Distribution
Consumption
Control

60+ Faculty members,
120+ PhDs
30+ RAs & Postdocs
20+ Technical staff
80+ visiting scholars
60% of manpower on power electronics and its applications

Aalborg University, Denmark

Outline

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- ❑ **Background/Motivation**
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POWER ELECTRONICS

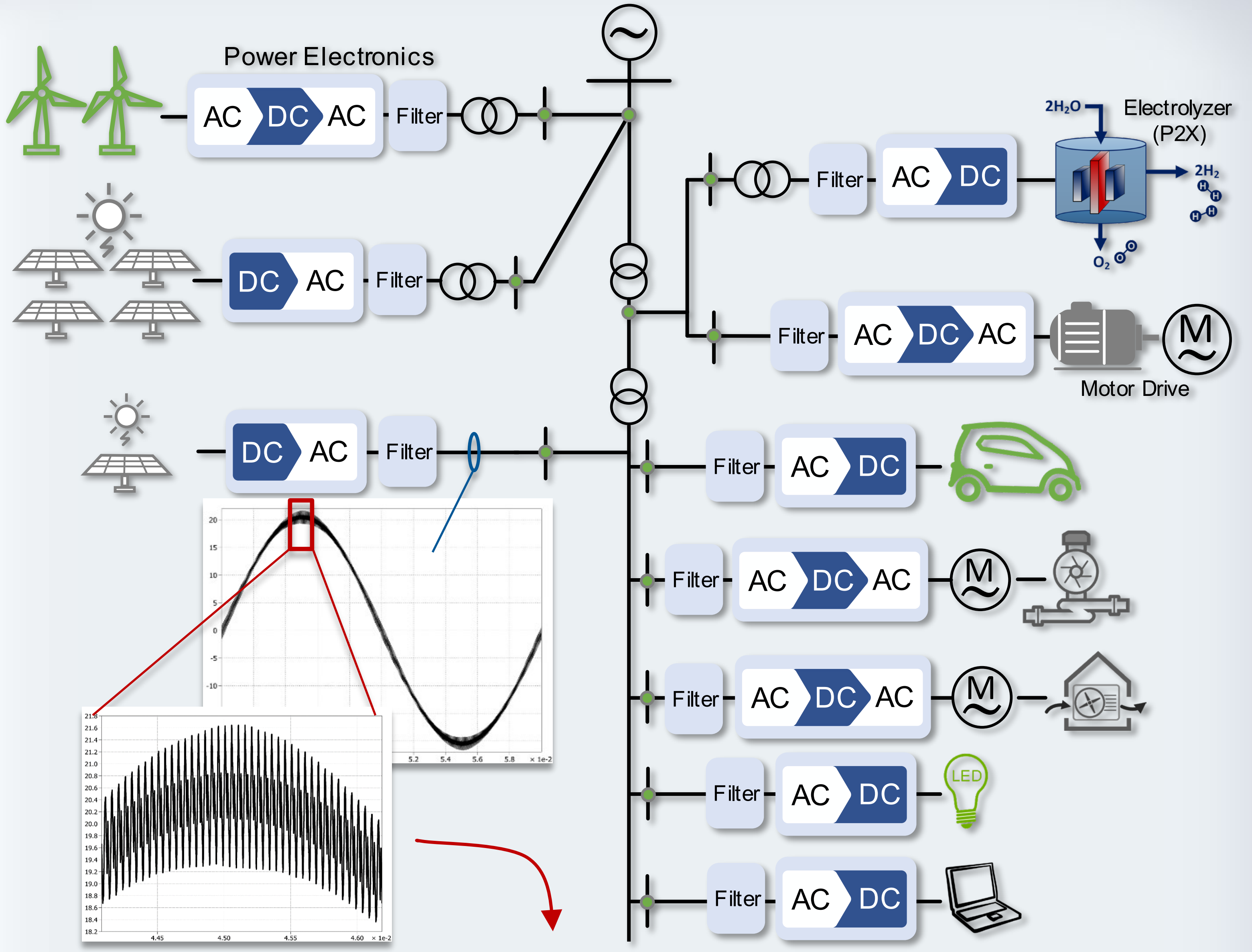
EMI/EMC Importance and Challenge

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

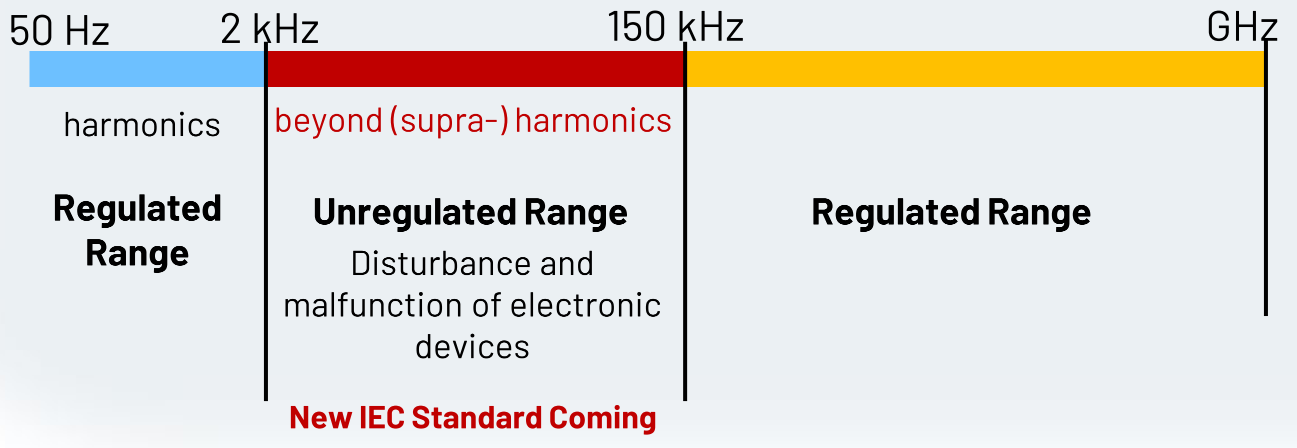
Power Electronics are an essential part of the **green transition**, currently processing **70%** of our electricity today

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



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



New Challenge

2kHz – 150 kHz Frequency Utilization

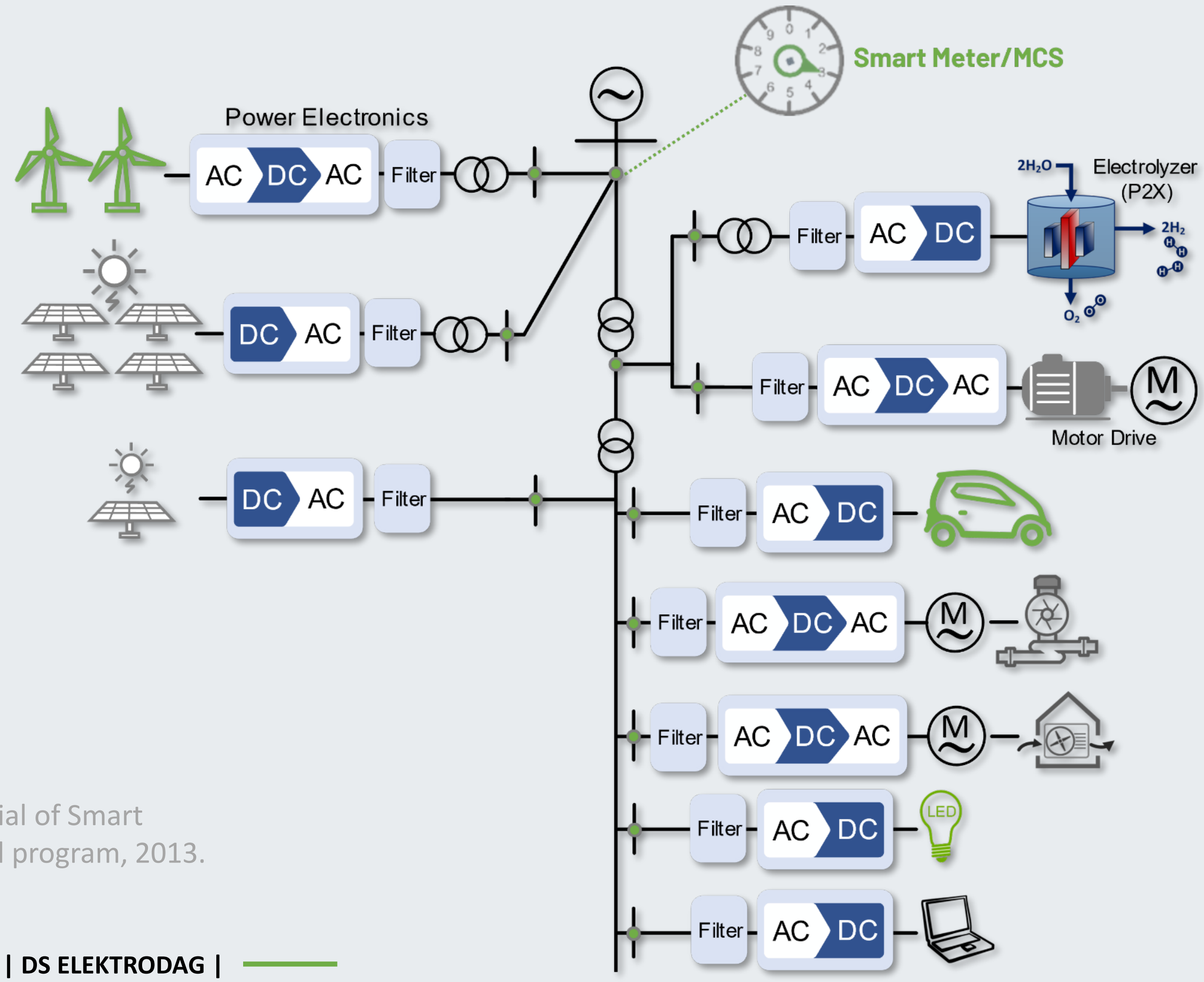
- ❑ Electric power grids are essential part of the green transition and to realize that smart meters are important part of it

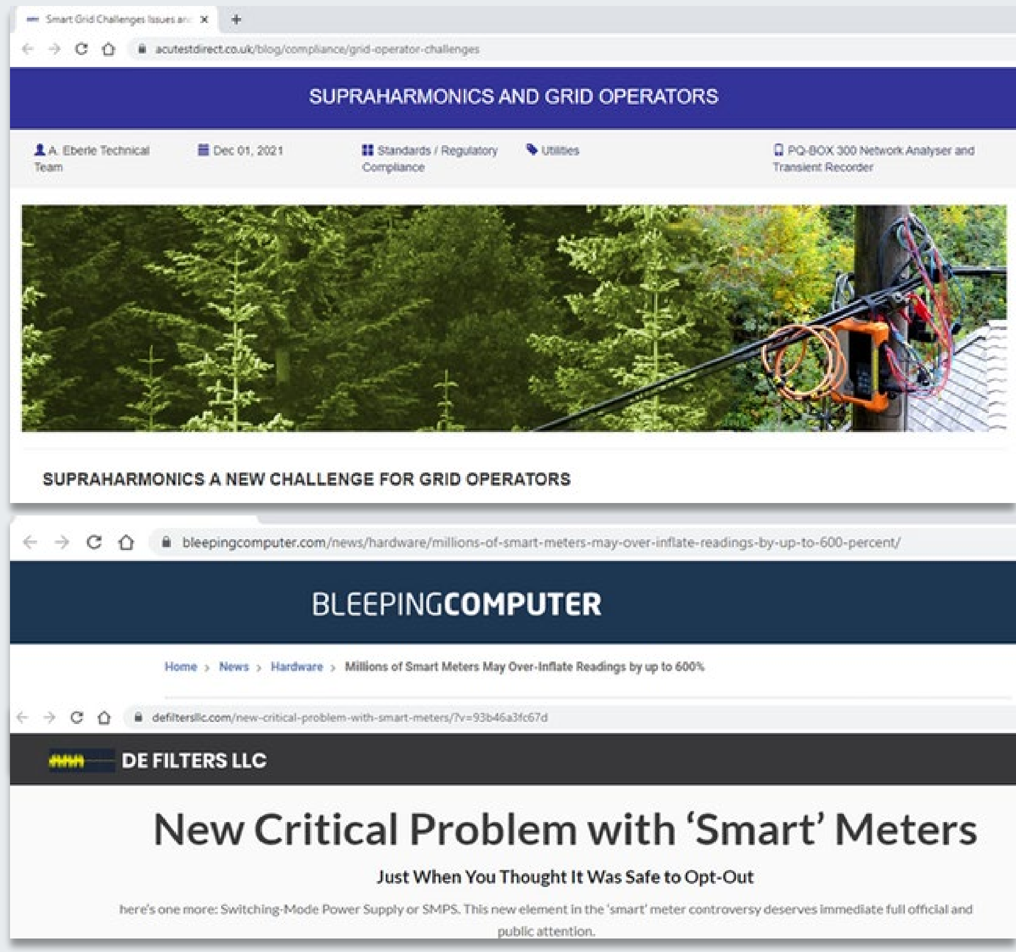
- ❑ There has already been a massive rollout and investment in smart meters/MCS in Europe (+160 mio installed), however, **error** readings is a huge issue due to **supraharmonics** from power electronics

It is estimated:

+240 million MCS in Europe

+40 billion € investment





Source: Accenture, "Realizing the Full Potential of Smart Metering", Accenture's Digitally Enabled Grid program, 2013.

New Challenge

2kHz – 150 kHz Frequency Utilization

Examples:

Source: CLC/TR 50627:2015

Equipment	Effect
Traffic lights & Traffic control system for public transportation buses	Malfunction
Solid state meter	Displaying wrong meter register values
MCS	Temporary or quasi-permanent loss of data transmission function
Contactless magnetic card reader	Malfunction of reading function
Ceramic hobs	Incorrect relay switching
Coffee cooker	Incorrect control lamp function
Notebooks	Disturbed cursor position
Street lighting	Unintentional switch-on and -off

⋮

New Challenge

Why? Impact!

- **Incompatible design of power electronic-based equipment**
  - ➢ EMI filters without damping (resonant frequency within 2-150 kHz)
  - ➢ Many PV inverters with only L-filter
  - ➢ Power converters impedance behavior (Shunting effect on PLC signals)
  - ➢ Interaction among power converters
  - ➢ Time-frequency behavior of emissions

- **Increased Emissions due to Ageing**
  - ➢ Dry-out of dc-link capacitors
  - ➢ Ageing of EMI filter capacitors

- **Consequence of incompatibility**

➢ Slowing down the trend towards carbon-free technologies
➢ Interrupting smart grid operation and measurement
➢ Malfunction and even catastrophic damage to other electronic devices
➢ Loss of operation/generation due to incompatibility and interaction

IEC Activities…

JWG6 & WG8 [2 kHz – 150 kHz]

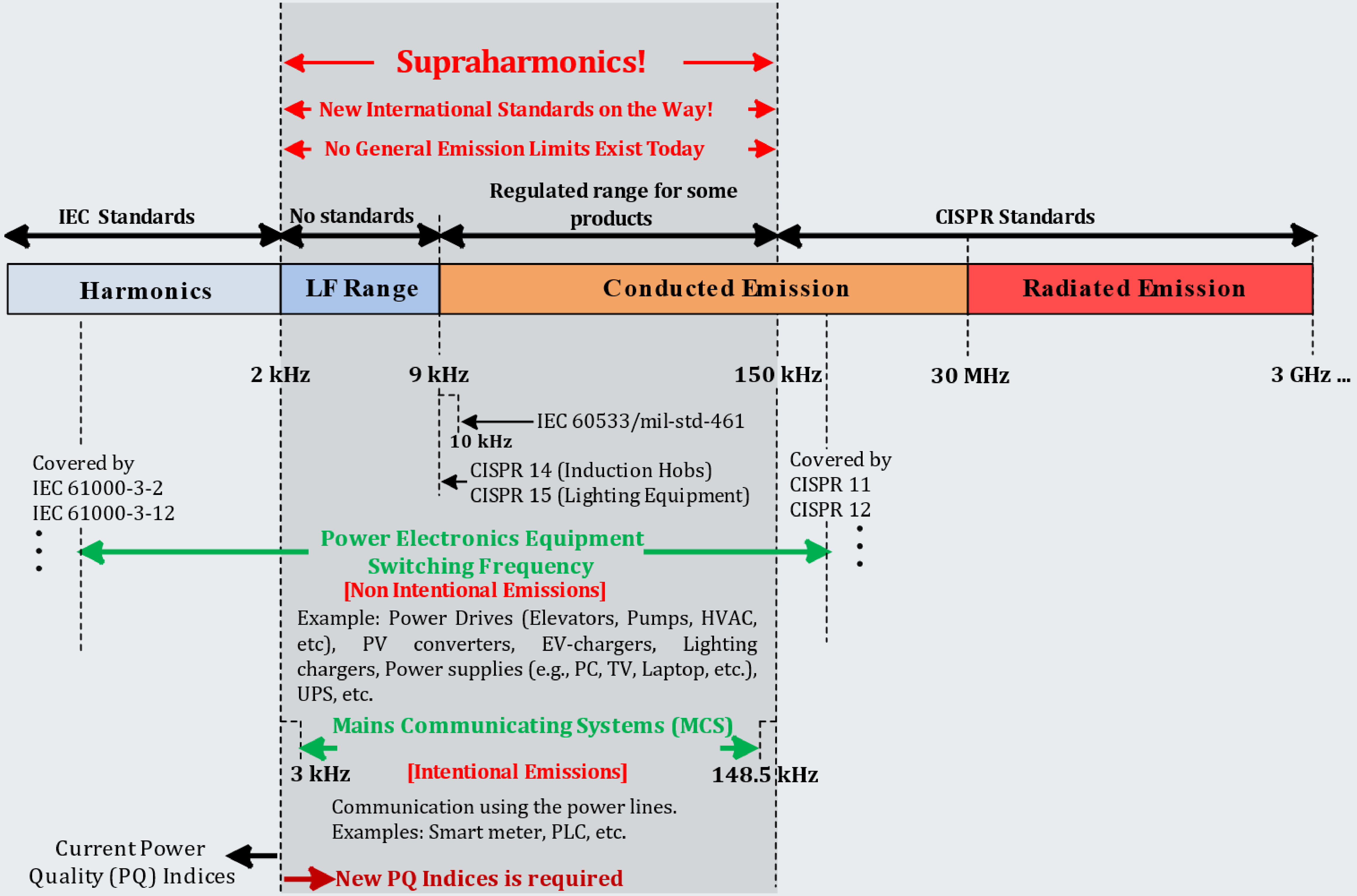
TR 50627: 2015	Study report on EMI between electrical equipment/systems in the frequency range below 150 kHz	Published
TS 62578, Ed2, 2015	Power electronic systems and equipment – Operation conditions and characteristics of active infeed converter (AIC) applications including design recommendations for their emission values below 150 kHz	Published
IEC 61000-2-2 +AMD1:2017+AMD2:2018	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	Electromagnetic compatibility (EMC) - Part 2-4: Environment - Compatibility levels in industrial plants for low-frequency conducted disturbances	**Limits agreed**
IEC 61000-6-3	Electromagnetic compatibility (EMC) - Part 6-3: Generic standards - Emission standard for residential, commercial and light-industrial environments	**Limits agreed**
IEC 61000-6-8	Electromagnetic compatibility (EMC) –Part 6-8: Generic standards – Emission standard for professional equipment in commercial and light-industrial locations	**Ongoing**

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**



OUTLINE

- ❑ Introduction to AAU Energy
- ❑ Background/Motivation
- ❑ **Supra-EMC Project**

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: 23.8 million kr. , IFD investment: 16.8 million kr. , co-financing: 7.04 million kr.)

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

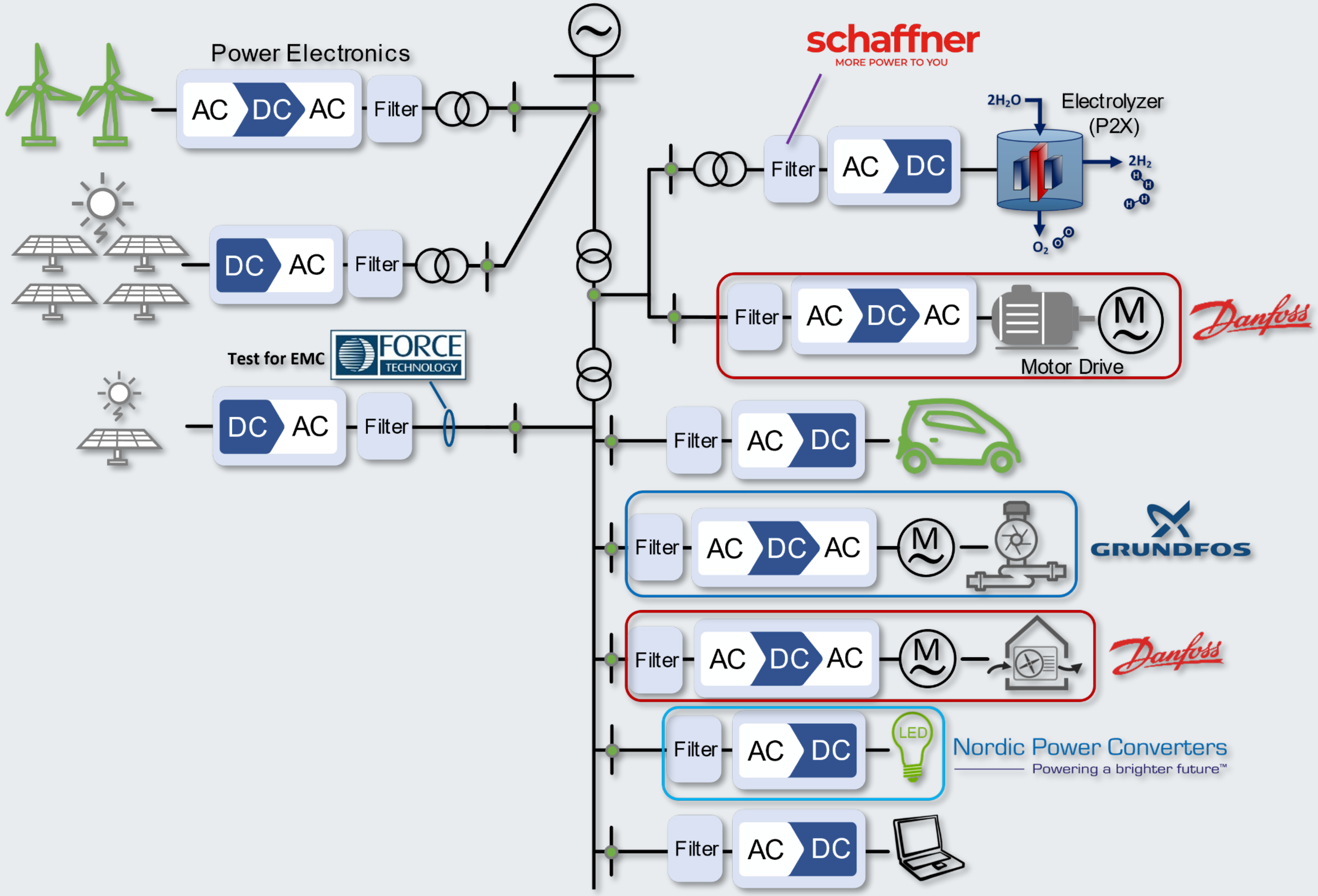
GRUNDFOS

schaffner
MORE POWER TO YOU

FORCE TECHNOLOGY

Nordic Power Converters
Powering a brighter future™

AAU ENERGY
AALBORG UNIVERSITY



Supra-EMC Overview

Project Objectives

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

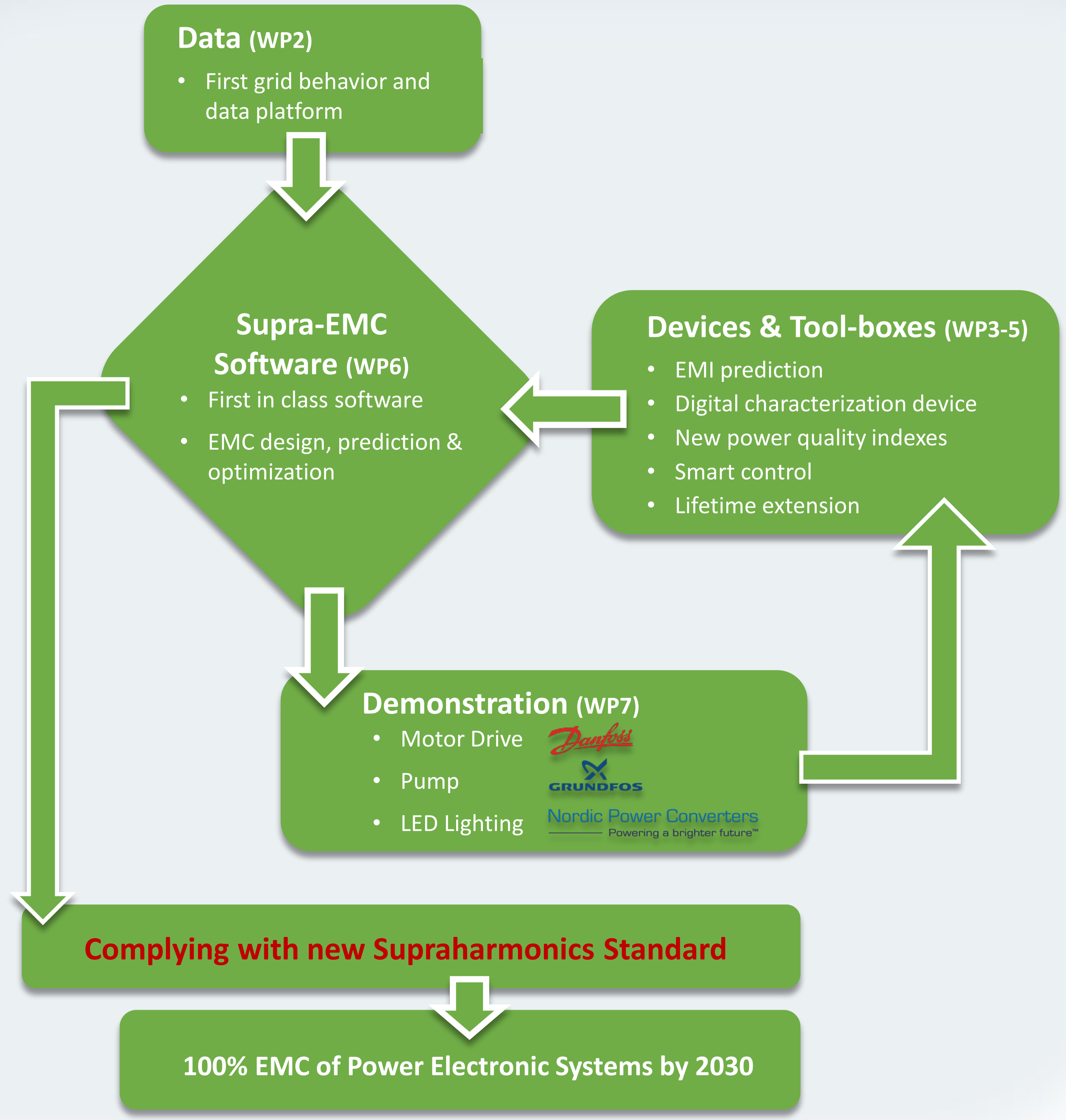
Q1 Open access grid Supraharmonics data platform

Q2 Digital Impedance Characterizer Device

Q3 New EMI Filtering Techniques with reduced:
- Maintenance cost
- Energy loss

Q4 Smart Control for Compatibility in Networks

Q5 First in class Supra-EMC software enabling reducing:
- EMC design and optimization effort
- Development time and cost



Power Grid Characterization (WP2)

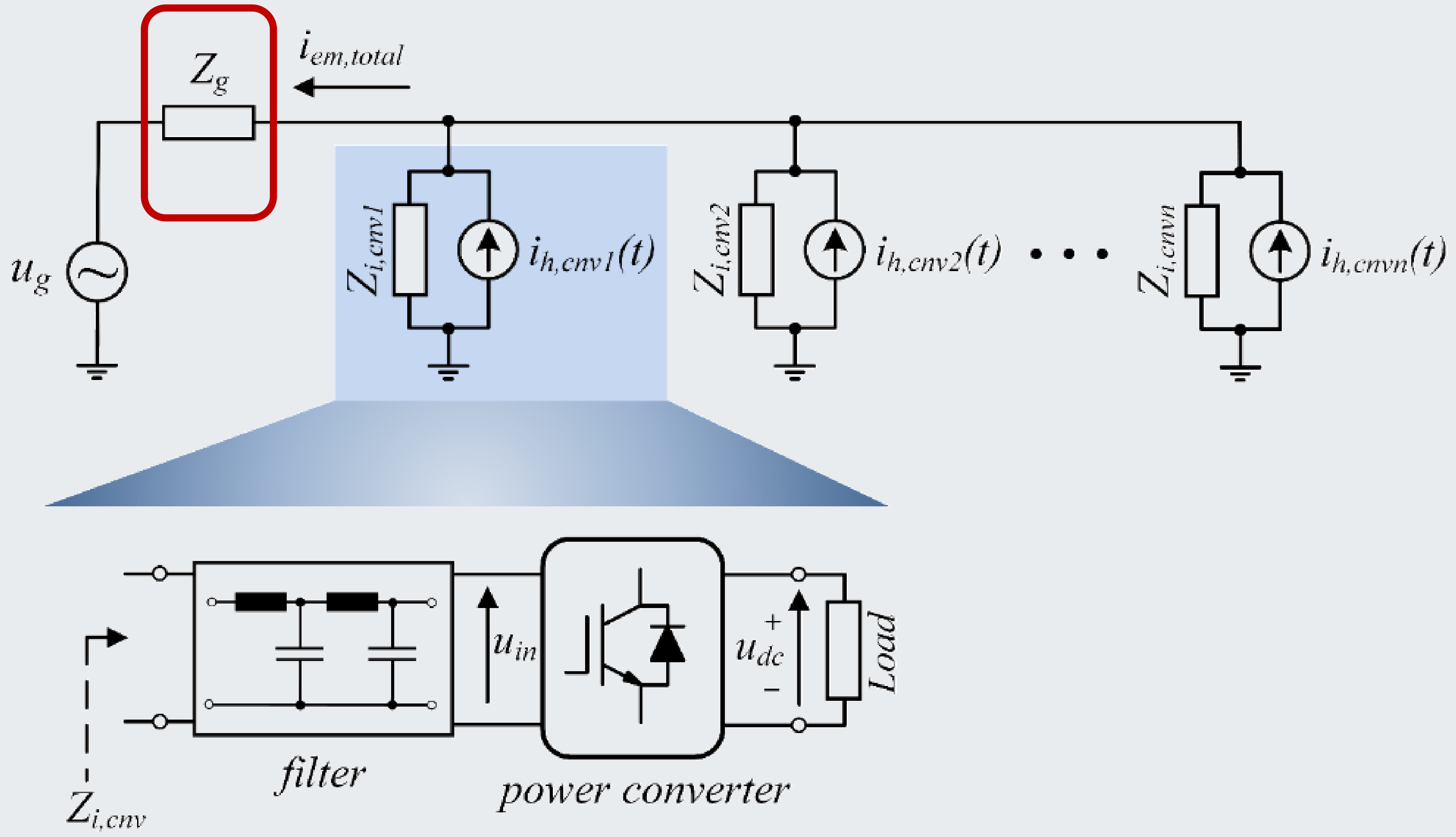
Power Grid Impedance Measurement and Characterization

Objectives:

- Power Grid Impedance **data collection** (2-150 kHz)
- Create a **database** of power grid impedance models
- 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:

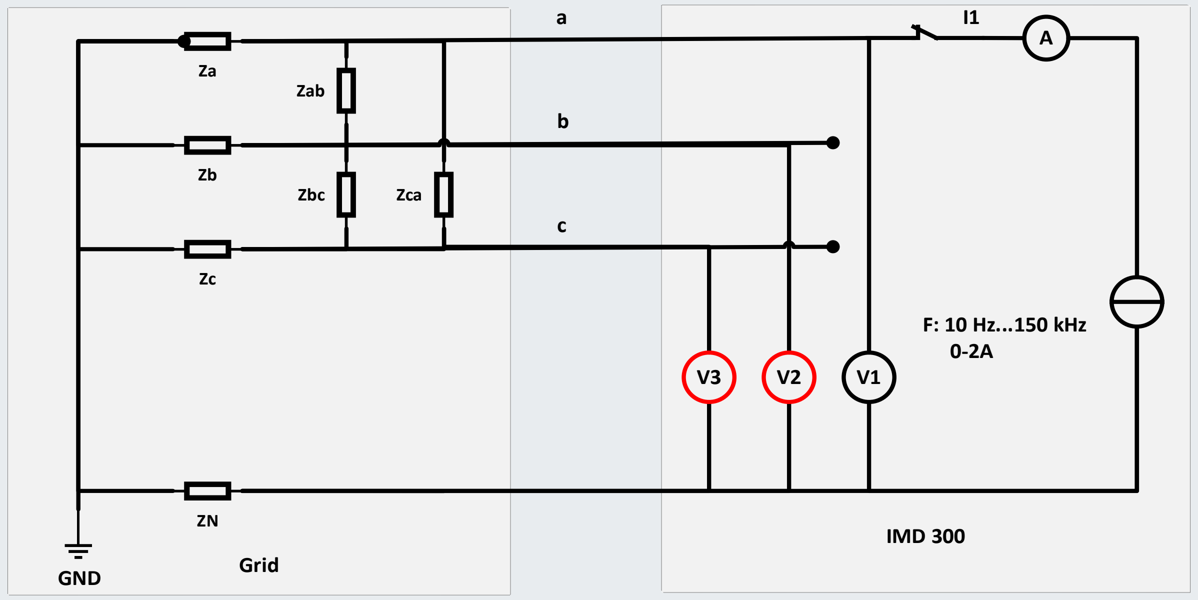
- Understand **emission propagation** at grid and device side
- **Simulate** emission propagation at device and system level
- **Solving** customer challenges



Power Grid Characterization (WP2)

Power Grid Impedance Measurement

- **Impedance Measurement Instrument:**
  - ✓ Spitzenberger IMD 300/1 with 3-phase extension unit UM 300
  - ✓ Injection of multi-tone frequency current
  - ✓ Self powering during measurement
  - ✓ Measure phase to neutral, the phase to ground and the coupling impedances



7. Technical data IMD 300/1

Measurement performance						
Channels	Single phase					
Impedance range	30mΩ … 100Ω					
Frequency range	10Hz … 150kHz					
Accuracy						
Impedance magnitude	Measuring range	f < 100Hz	100Hz ≤ f < 1kHz	1kHz ≤ f < 10kHz	10kHz ≤ f < 50kHz	50kHz ≤ f < 150kHz
	30mΩ ≤ Z < 50mΩ	20%	15%	15%	15%	20%
	50mΩ ≤ Z < 200mΩ	10%	10%	10%	10%	15%
	200mΩ ≤ Z < 500mΩ	5%	5%	5%	5%	10%
	500mΩ ≤ Z < 5Ω	2%	2%	2%	2%	4%
	5Ω ≤ Z < 50Ω	2%	2%	3%	3%	6%
	50Ω ≤ Z < 100Ω	2%	2%	3%	3%	6%
Impedance phase	Measuring range	f < 100Hz	100Hz ≤ f < 1kHz	1kHz ≤ f < 10kHz	10kHz ≤ f < 50kHz	50kHz ≤ f < 150kHz
	30mΩ ≤ Z < 50mΩ	5°	5°	5°	10°	20°
	50mΩ ≤ Z < 200mΩ	3°	3°	3°	8°	16°
	200mΩ ≤ Z < 500mΩ	1°	1°	1°	6°	12°
	500mΩ ≤ Z < 5Ω	1°	1°	1°	5°	10°
	5Ω ≤ Z < 50Ω	1°	1°	2°	5°	10°
	50Ω ≤ Z < 100Ω	1°	1°	3°	8°	16°
Max. voltage at measurement output	$300V_{rms}$ ($\pm 450V_{peak}$)					
Voltage measurement range	$300V_{rms}$ ($\pm 450V_{peak}$)					
Current measurement ranges	$\pm 3A_{peak}$ / $\pm 6A_{peak}$					
Max. output current	$2A_{rms}$ [2, 3]					
Syncronization voltage	10V … 287V / 45Hz … 65Hz					
Output current waveshape	Sine / sinusoidal					
Output current modes	Single frequency measurement Multiple frequency measurement (Overlapping of various frequencies)					
Measurement cycle duration	200ms measurement with input current followed by 200ms measurement without input current [4]					

Power Grid Characterization (WP2)

Power Grid Impedance Measurement Sites

Objective:

- Measuring and collecting as many as possible set of grid impedances in low voltage networks

Selected Sites (ongoing measurements):

- Aalborg (AL1)
- Aarhus (AR1 & AR2)
- Copenhagen (CP1 & CP2)
- Gråsten (GR1)

You are welcome to join the measurement campaign!

FORCE TECHNOLOGY

Per Thåstrup Jensen
Supra-EMC WP2 Leader
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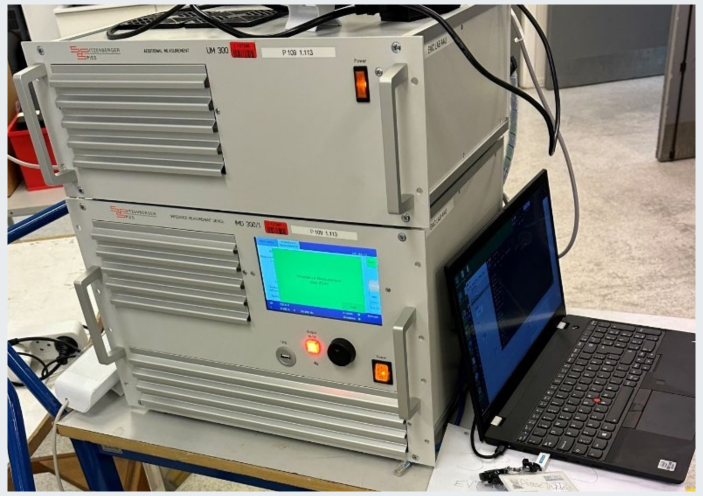
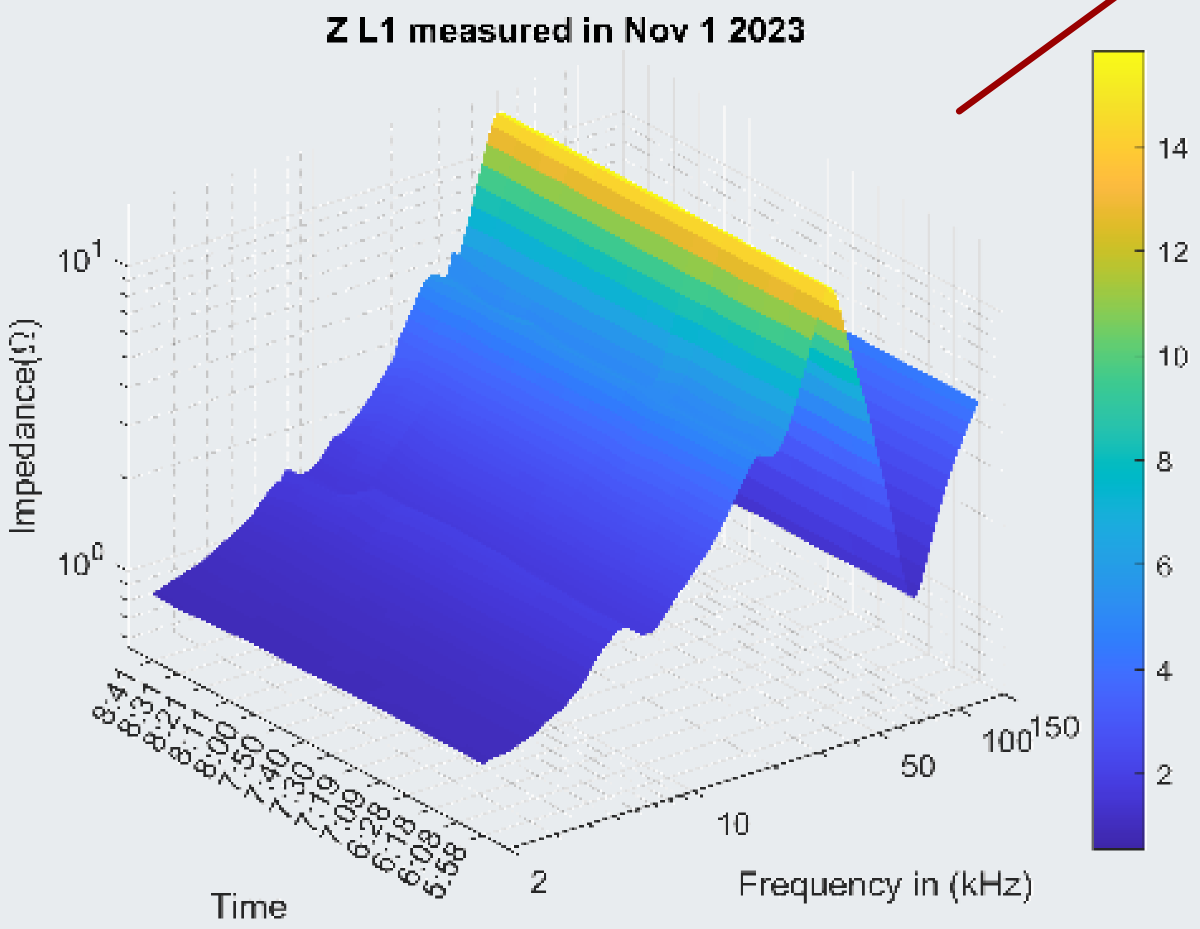
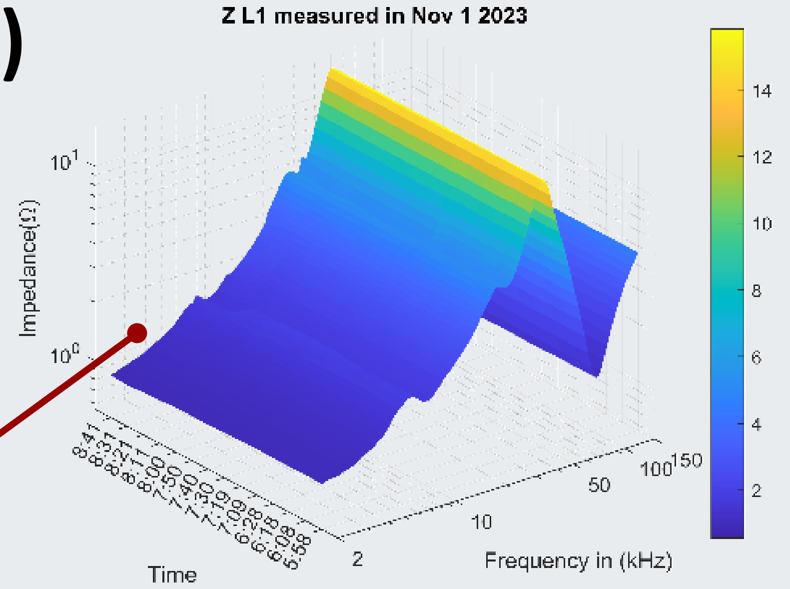


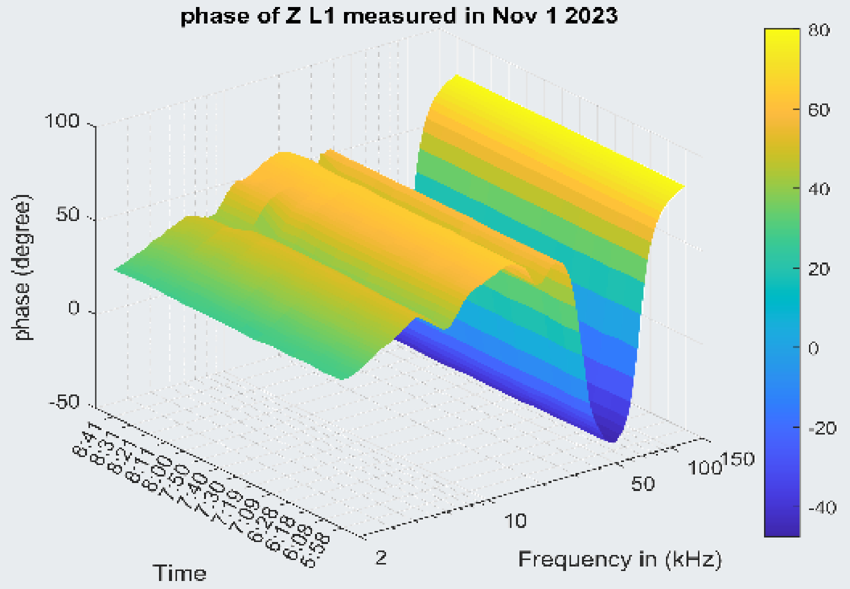
Power Grid Characterization (WP2)

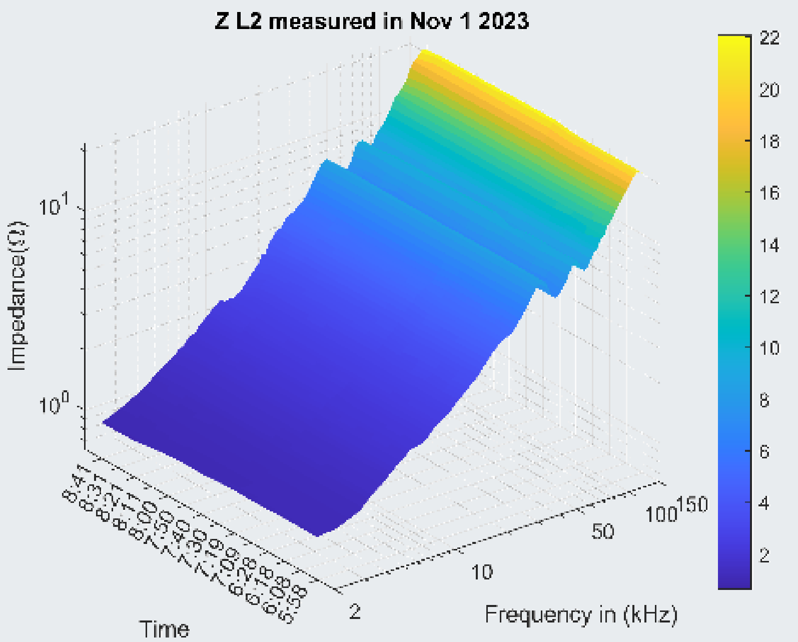
Power Grid Impedance Measurement Results

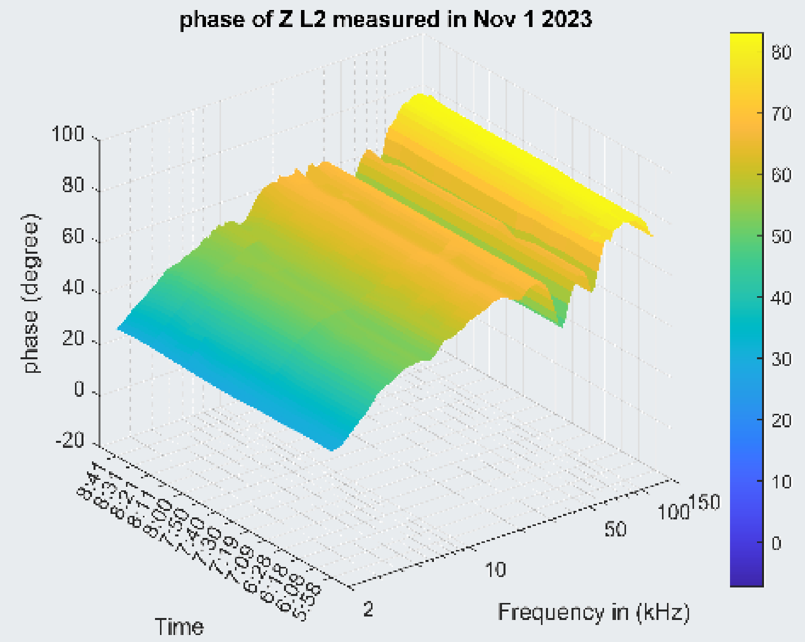
- Exemplary measurement at **CP1** location
- 156 Impedance measurements
- Distinct resonance around 40 kHz and 85 kHz in L1
- Almost inductive-resistive behavior in L2 and L3

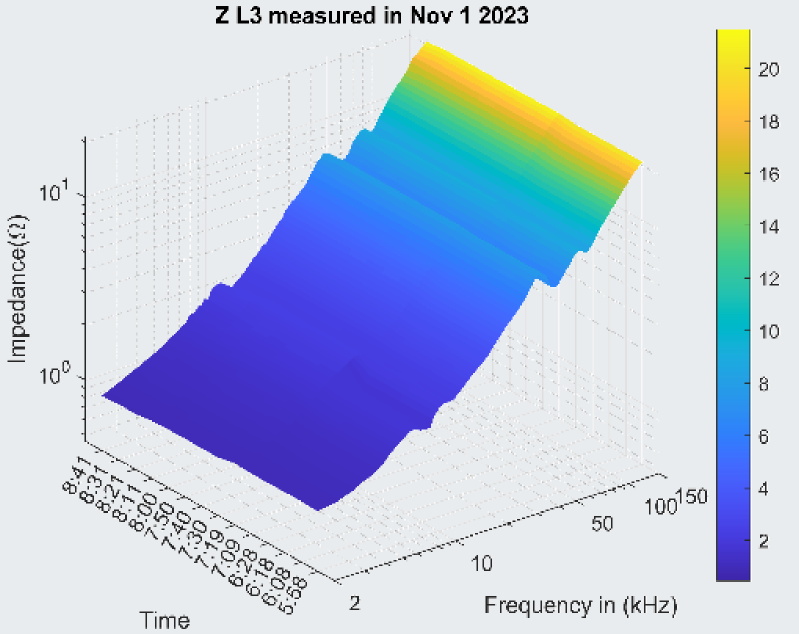


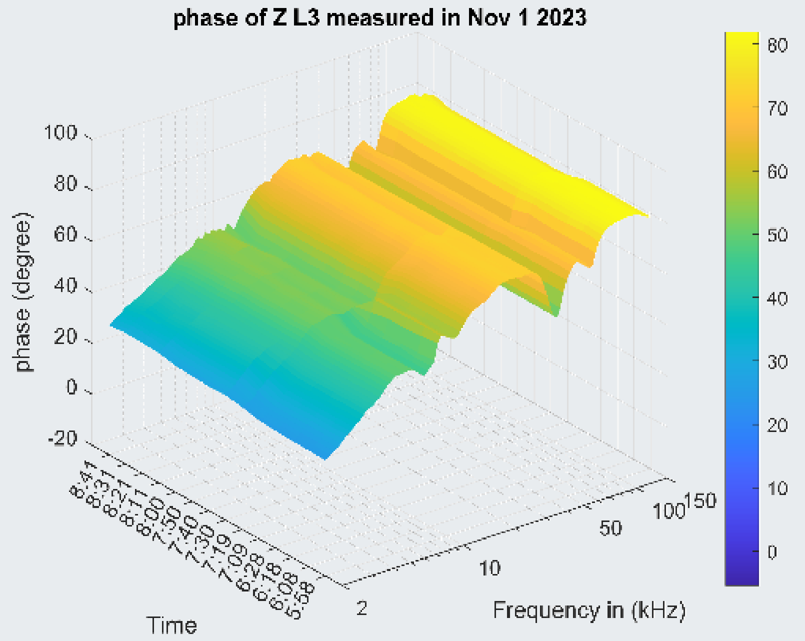










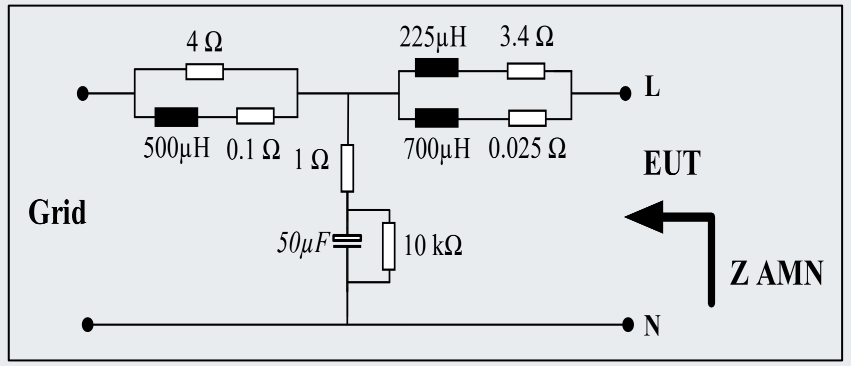


Power Grid Characterization (WP2)

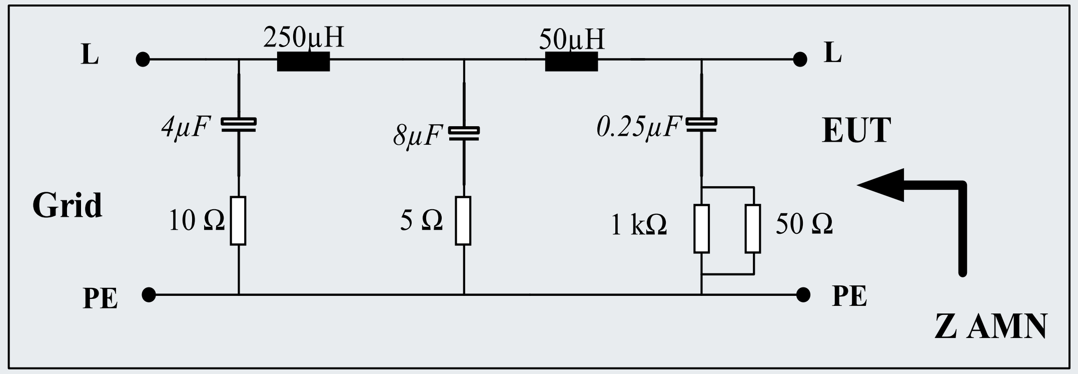
Reference Impedances

- Suitability of AMN/LISN for representing realistic impedances as in low voltage grids? (2-150 kHz)

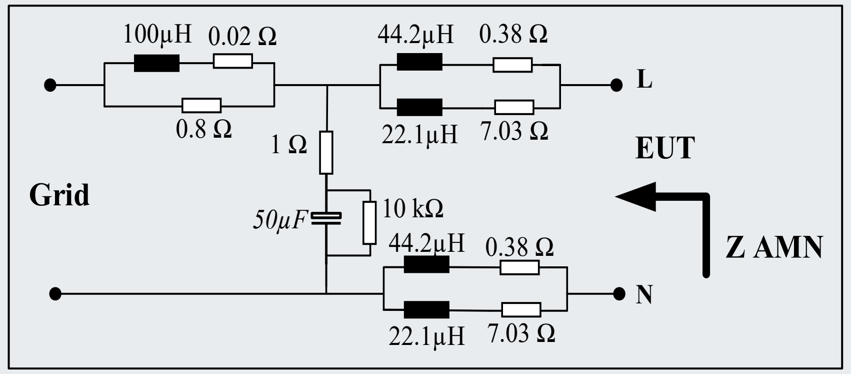
IEC 61000-4-7

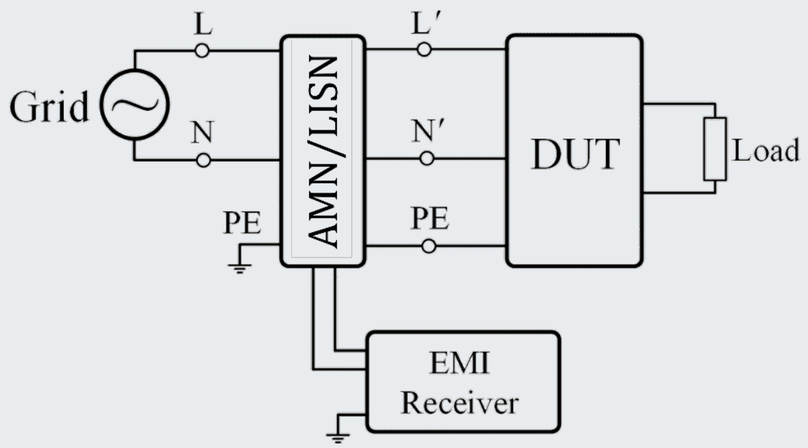


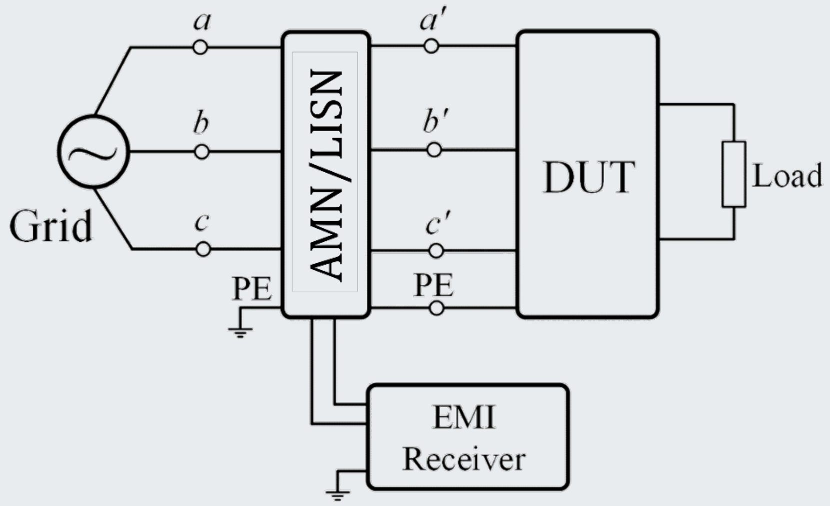
CISPR 16-1-2

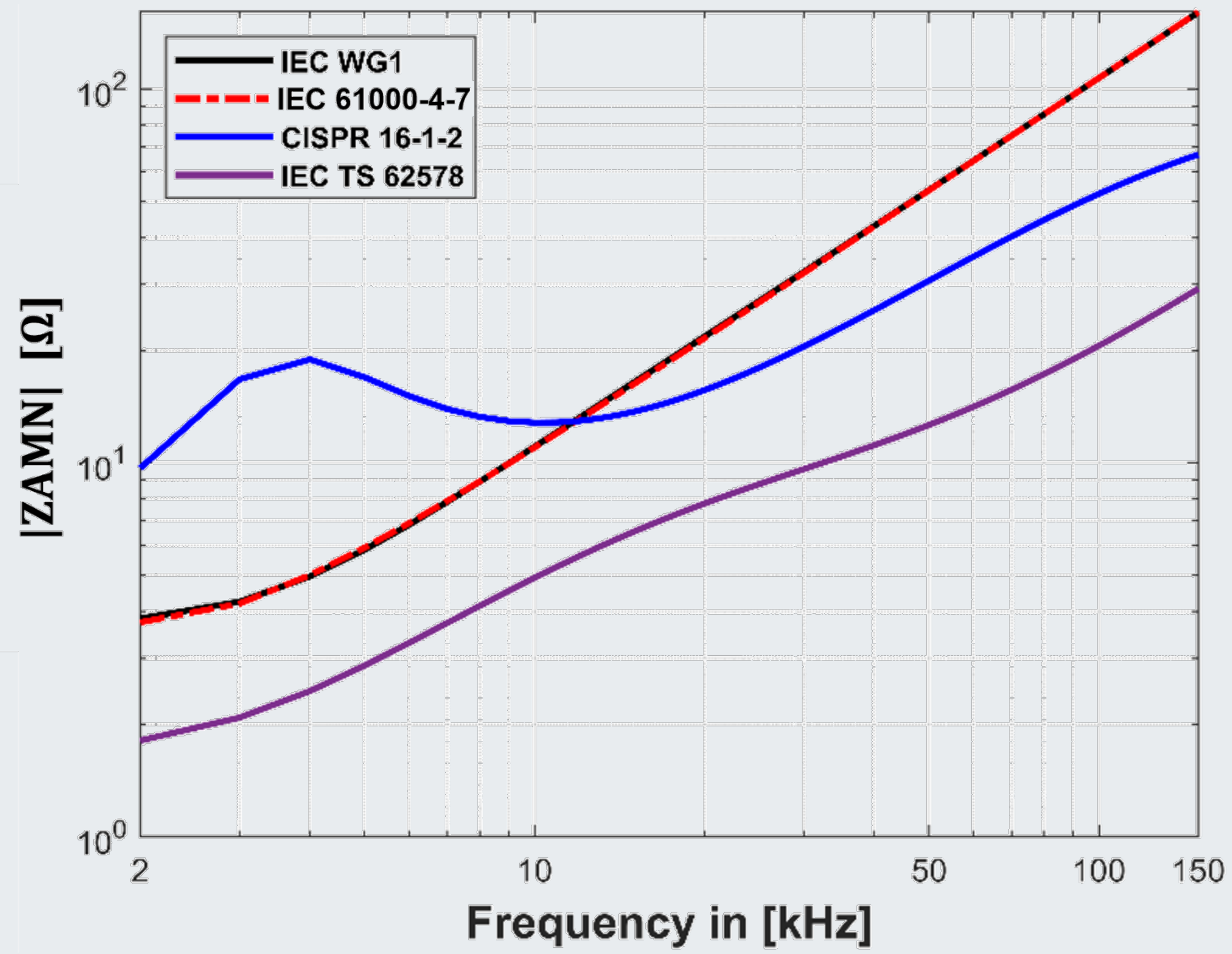


TS 62578







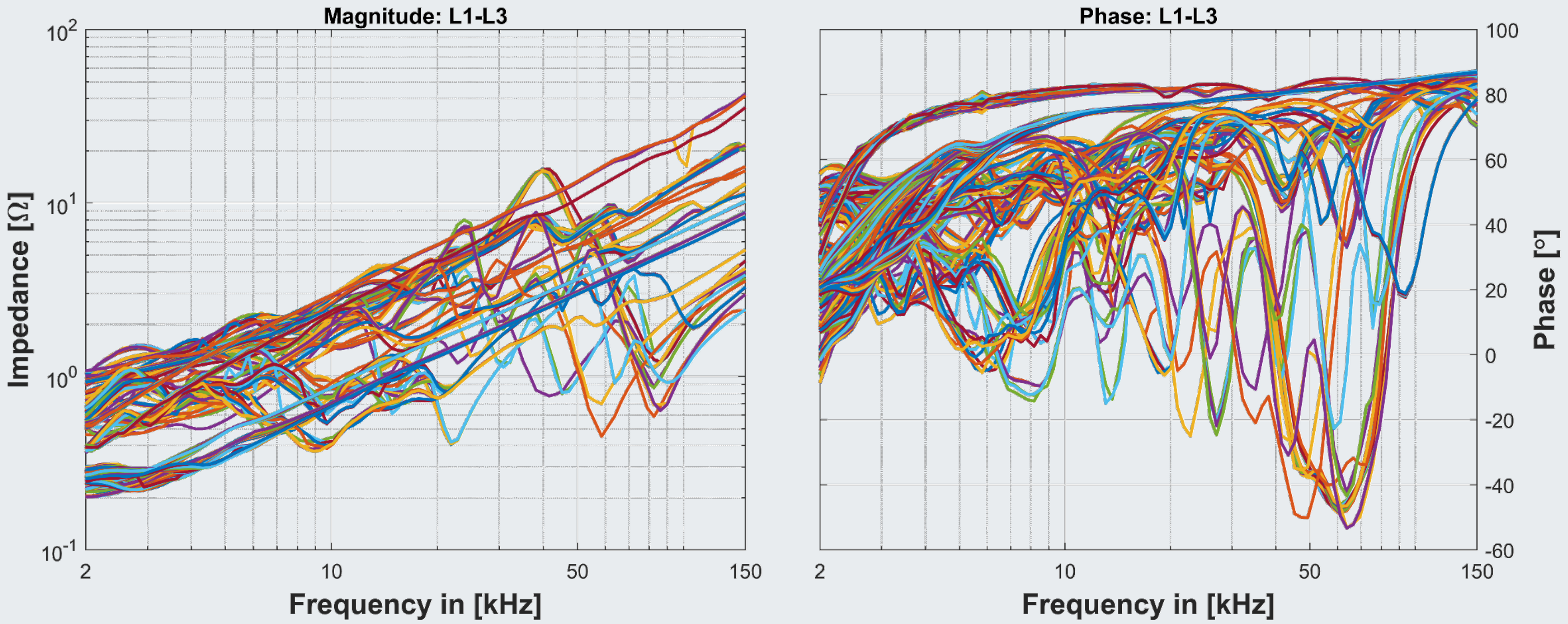


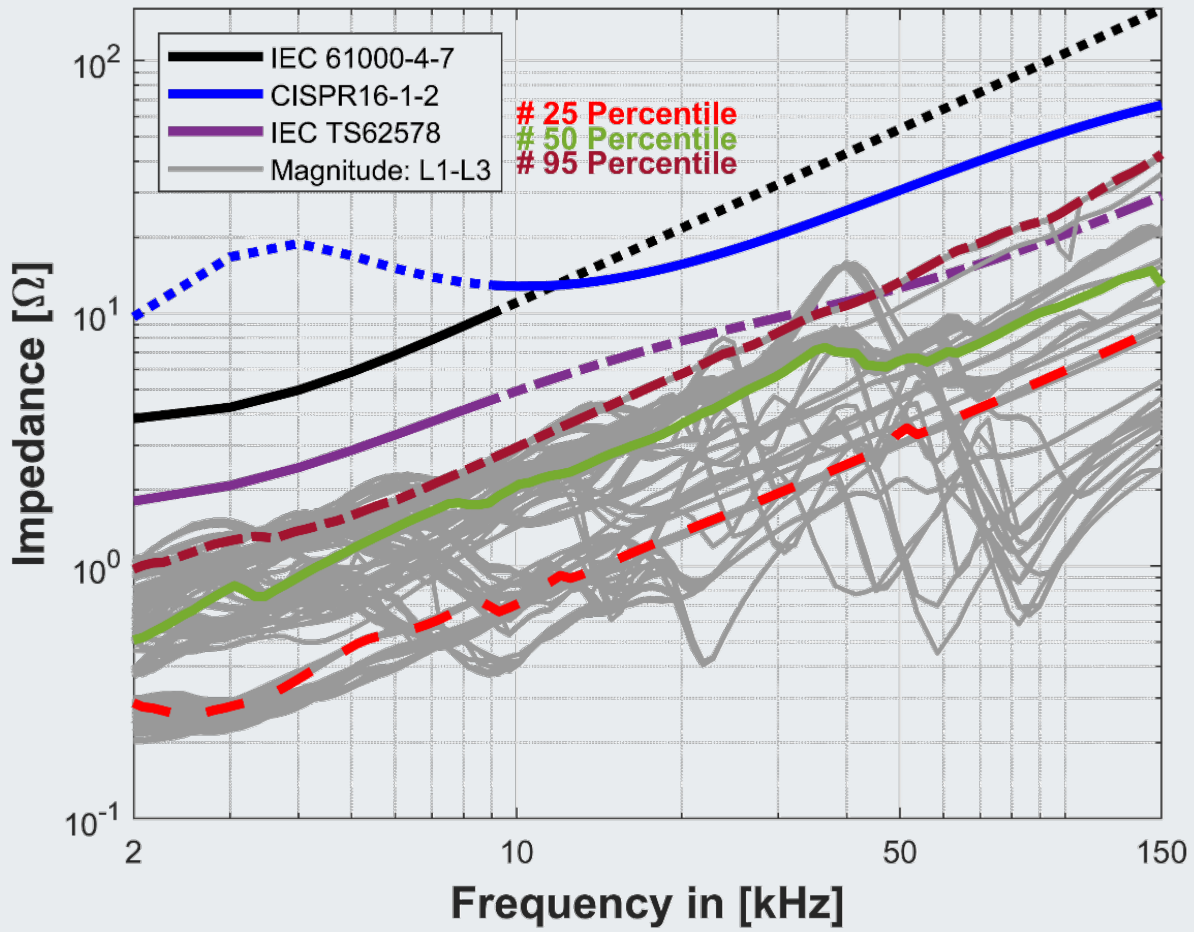
Magnitude of reference impedances with in 2-150 kHz [L-N]

Power Grid Characterization (WP2)

Power Grid Impedance Measurement Results

- So far **624 measured impedances** at four different locations (CP1, AR1, AR2 and AL1)
- Within 2kHz – 150kHz mostly inductive-resistive behavior (only 10% capacitive behavior observed)
- Variation of resonances (time dependent)



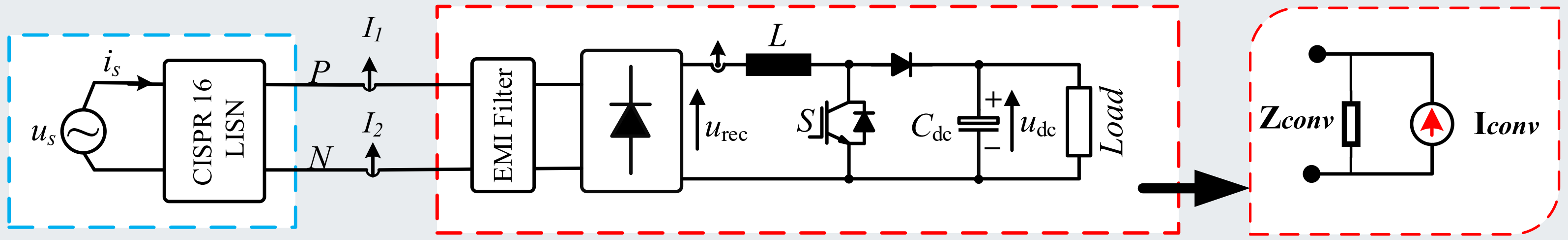


- In 2-9 kHz, IEC61000-4-7 shows nearly 4 times higher impedance
- Big difference observed between CISPR 16-1-2 and measured impedance in 9-150 kHz.
- Relatively IEC TS 62578 better represents the measured impedance
- Conservative representation by IEC 61000-4-7 and CISPR 16-1-2

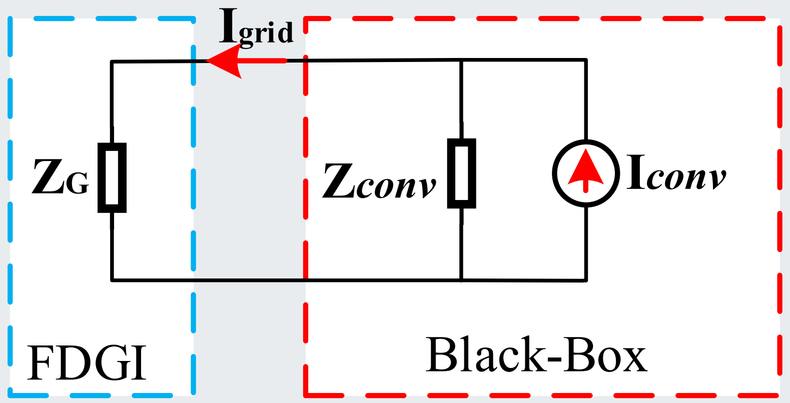
Power Grid Characterization (WP2)

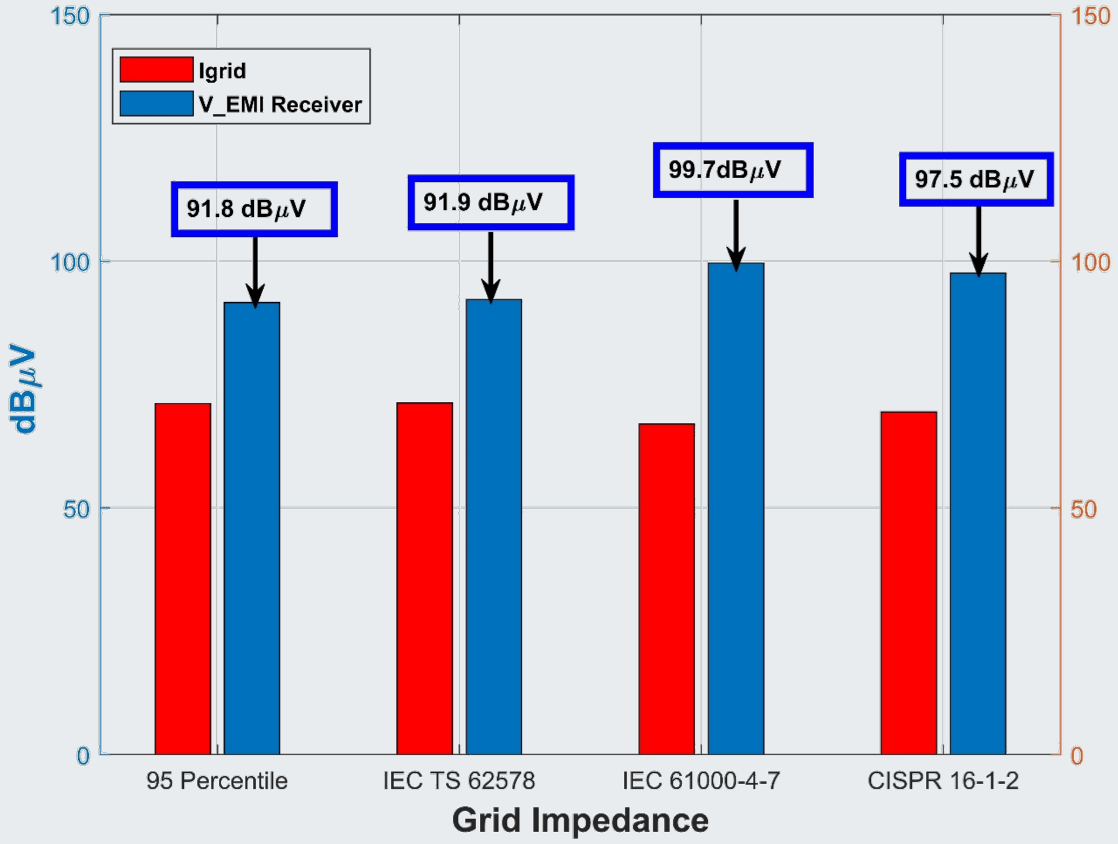
Power Grid Impedance Effect on Emission Propagation

- Exemplary case study with single-phase PFC
- There is about 8 dB difference of voltage estimation at the EMI receiver between 95 percentile and IEC61000-4-7 reference impedance
- **Higher reference impedance** leads to **overestimation** of the device EMI



$$I_{grid} = \frac{Z_{conv}}{Z_{conv} + Z_G} I_{conv}$$





Emission @ 40 kHz

Power Grid Characterization (WP2)

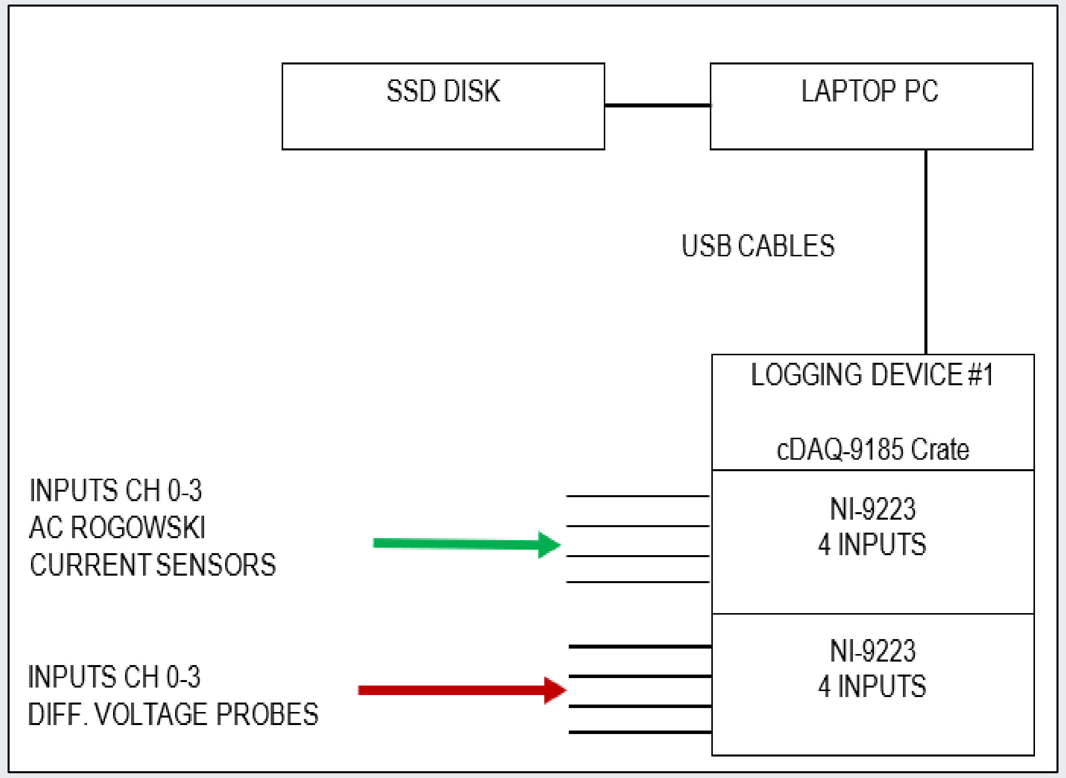
Power Grid Emission Measurement

Objectives:

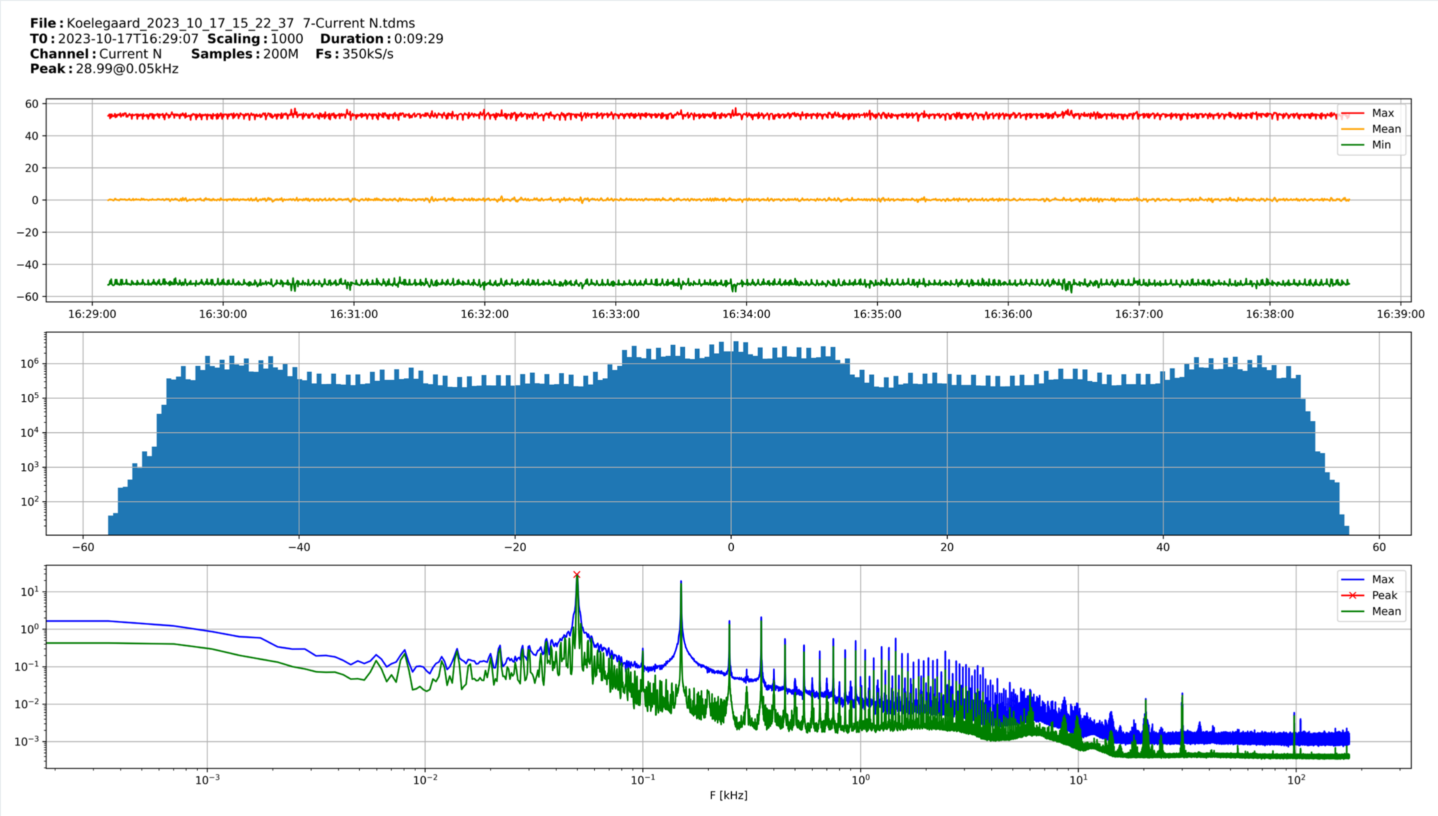
- Power Grid emission **data collection** (2-150 kHz)
- 24hr measurements
- Identify **free frequency bands**

Measurement Devices:

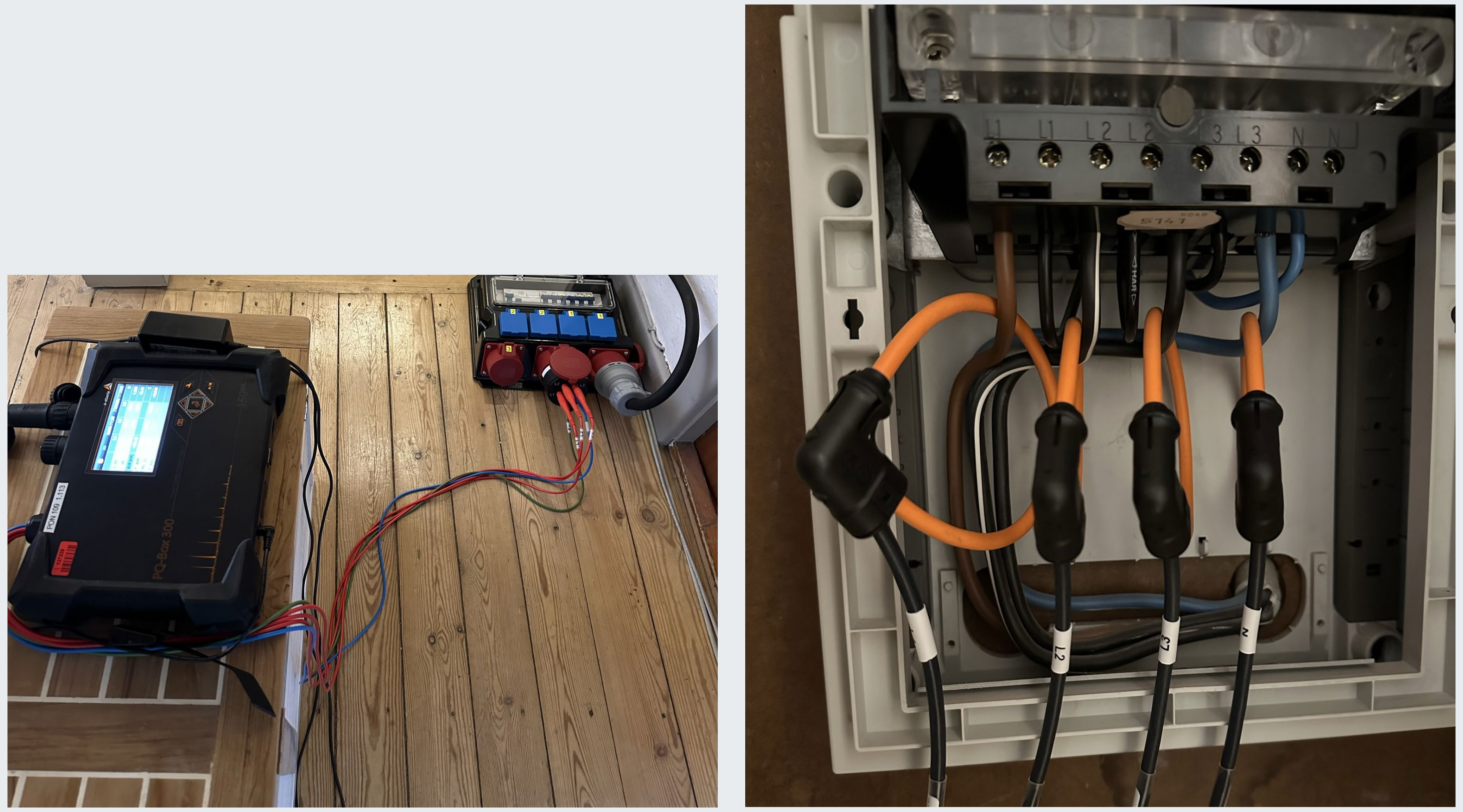
- ✓ PQ300: for short period data logging
- ✓ NIDAQ: long period data logging



Setup of NI DAQ system for continuous logging of signals



5.5 GB per 9½ minute of sampling for 8 channels, 500 kS/s

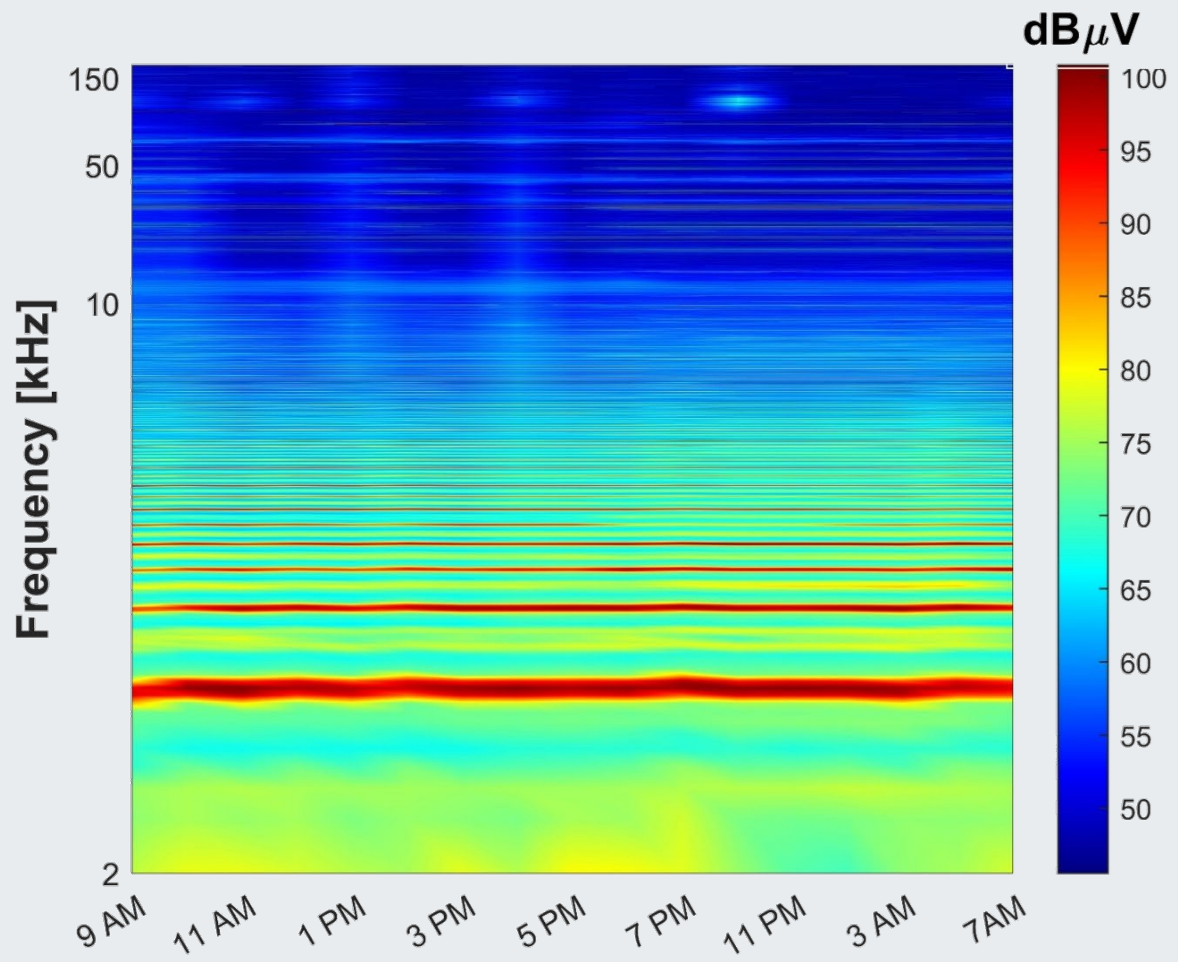


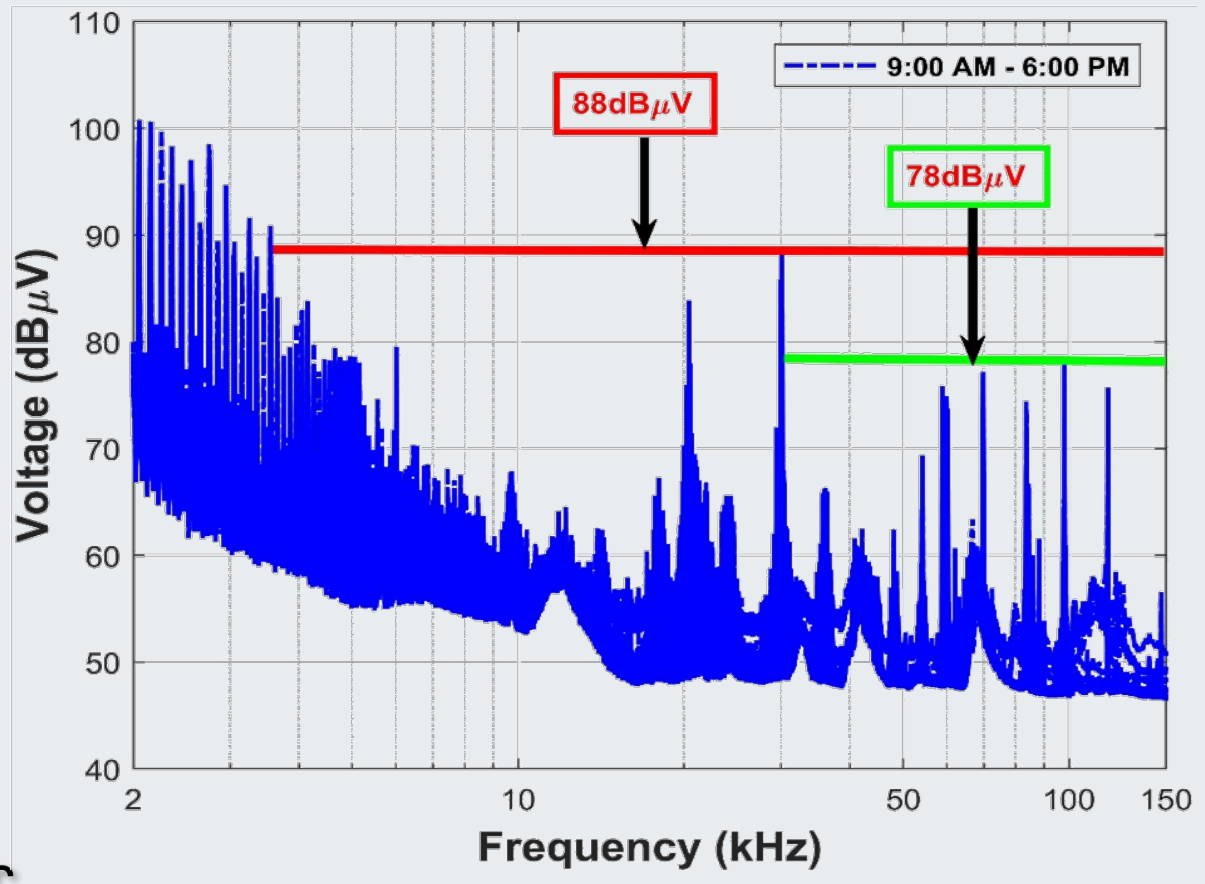
PQ300 with Rogowski current probes

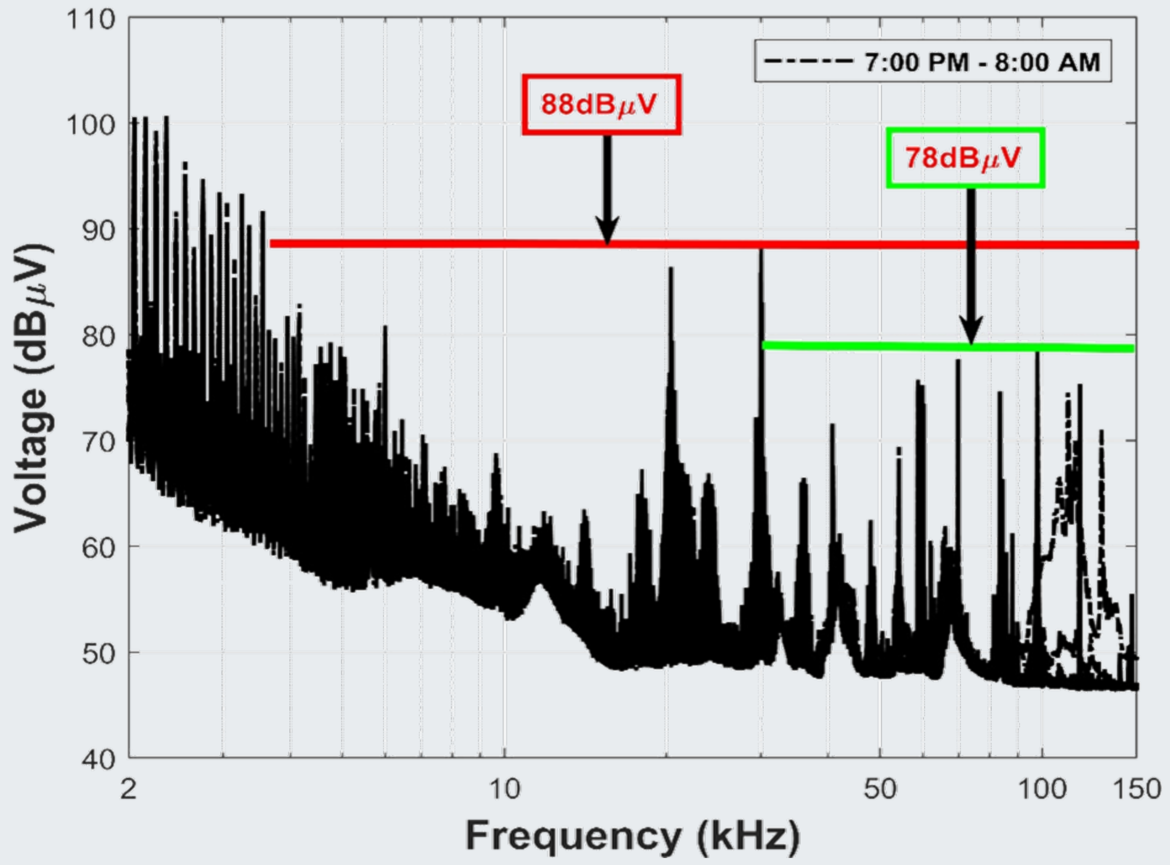
Power Grid Characterization (WP2)

Power Grid Emission Measurement

- 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
- More measurements at different locations and enviroment are required

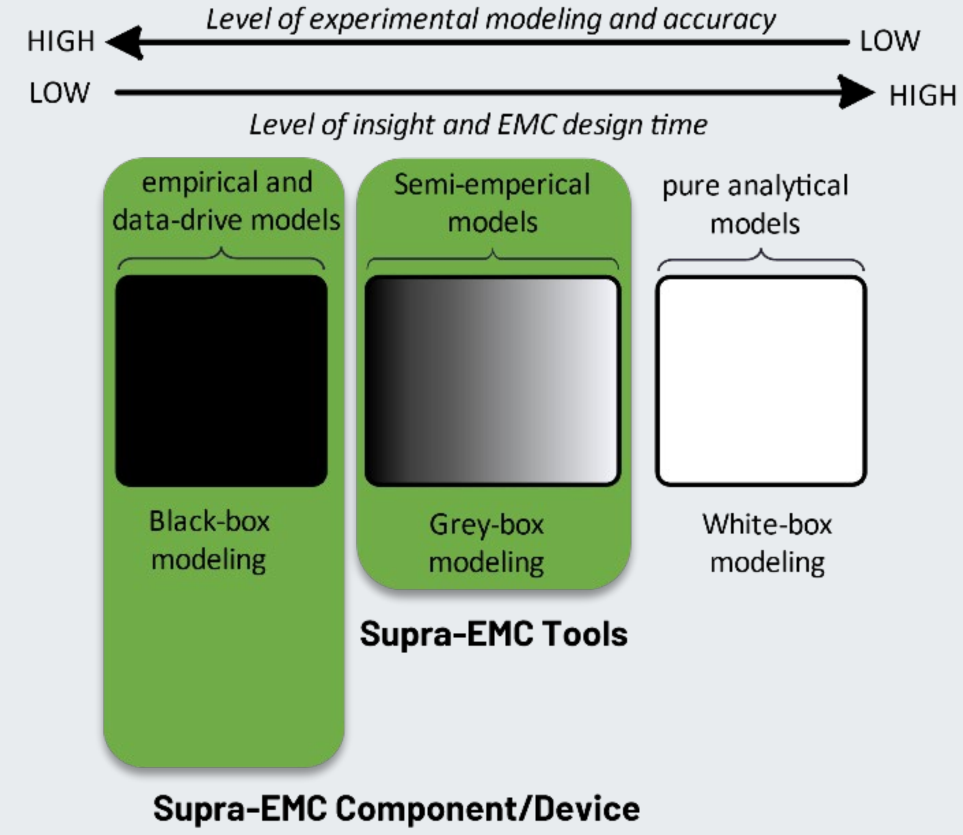






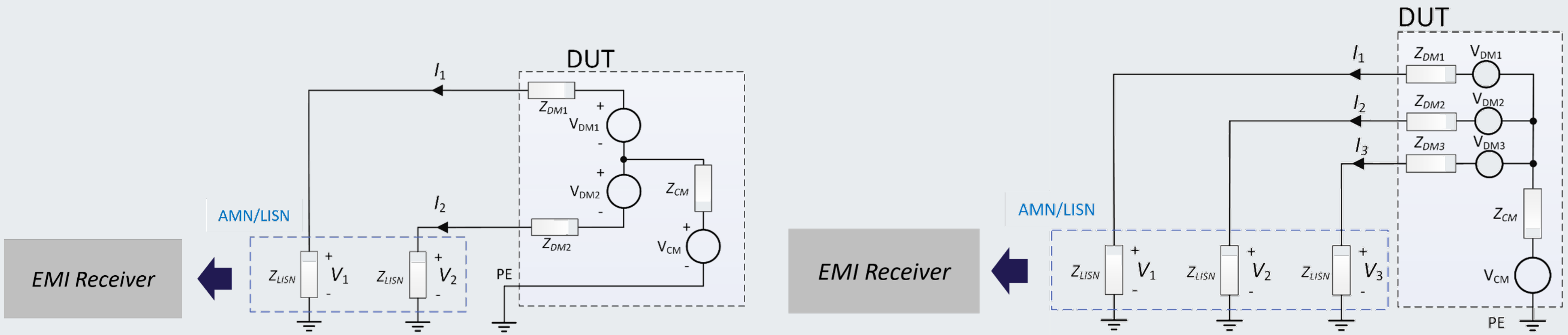
Power Converter Characterization (WP3)

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

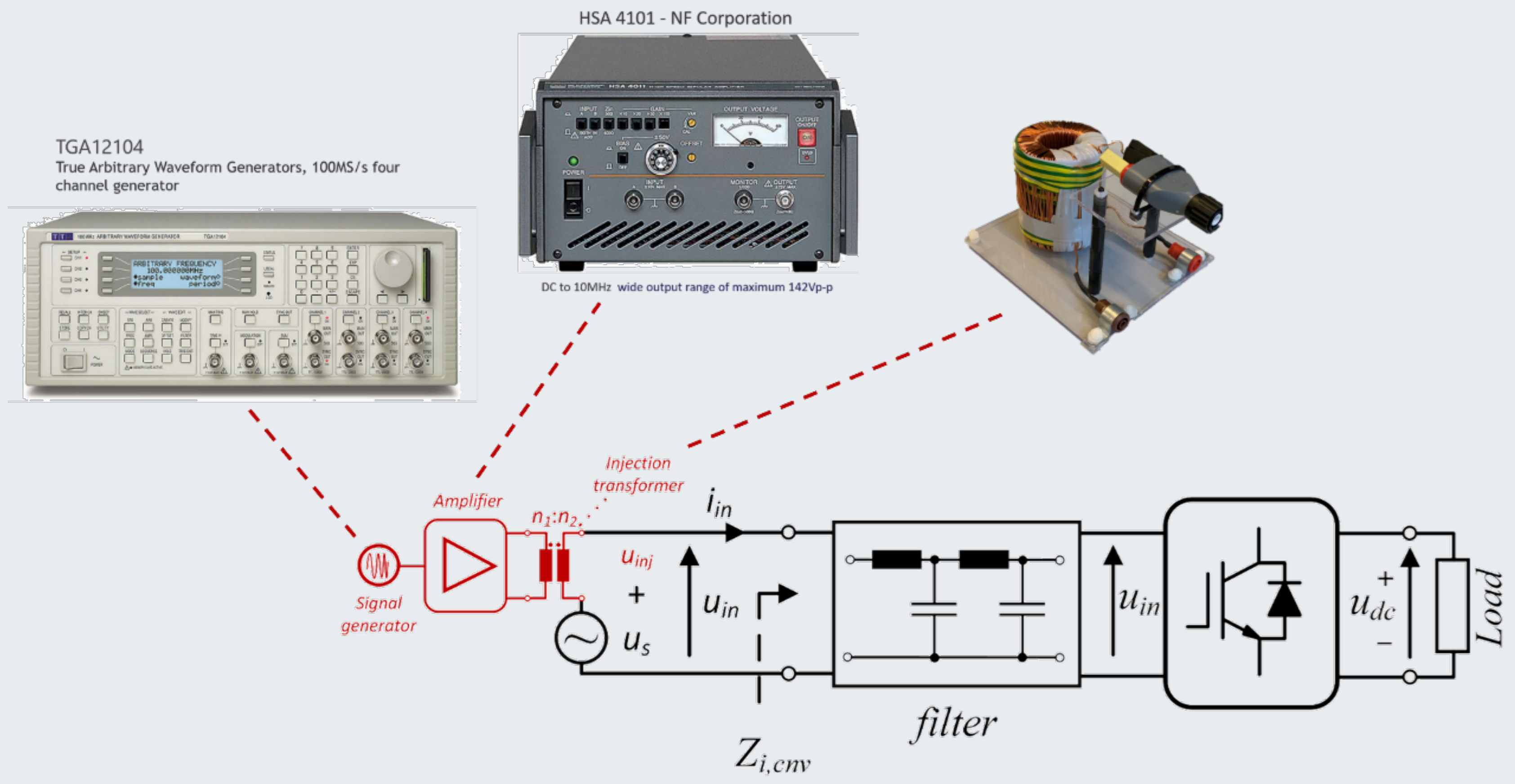
- VDM, VCM: Semiconductor switching transients + Modulation
- ZDM: Passive components + Closed Loop Impedance
- ZCM: Parasitic capacitances to PE

Power Converter Characterization (WP3)

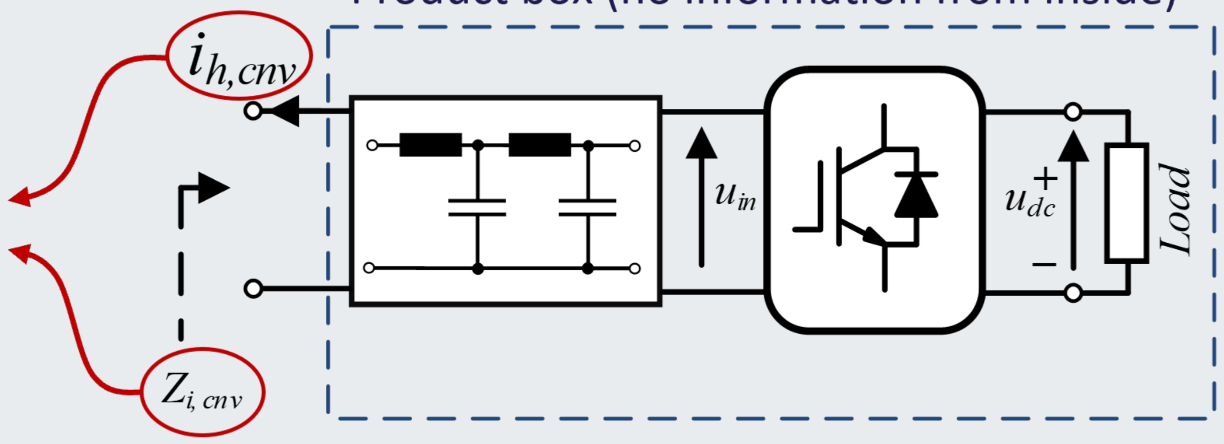
Impedance Characterizer Device and Black-Box Modeling

Impedance characterizer device:

- Measuring **input/output impedance** of power converters under **real operation** (2 kHz – 150 kHz)
- Suitable for **validation** of developed analytical/numerical models
- Using **multi-tone** injection approach (quite fast)



Measure noise and impedance. Feed them as input to the tool. The tool will automatically estimate the EMI



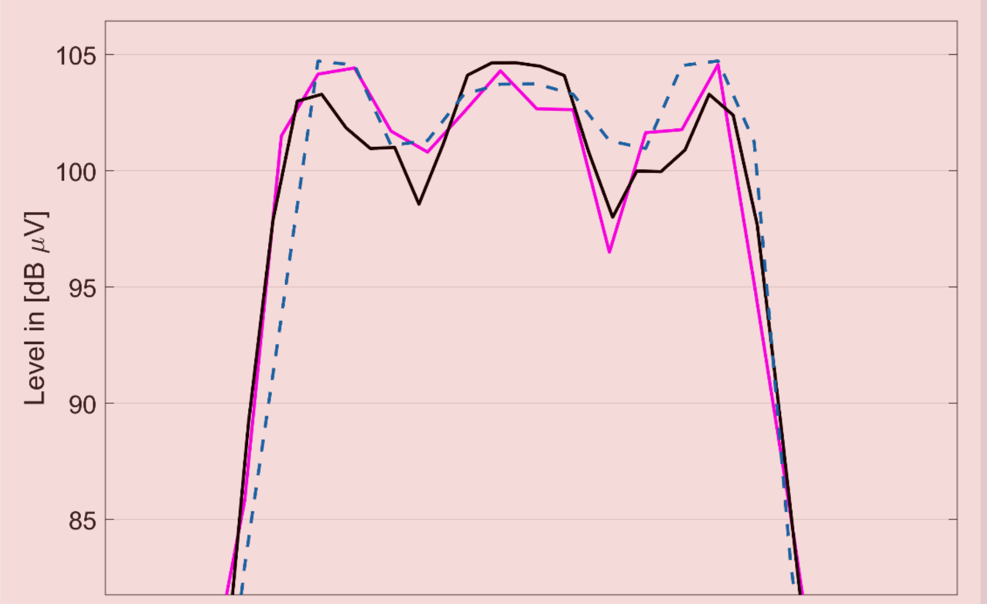
Black-box:

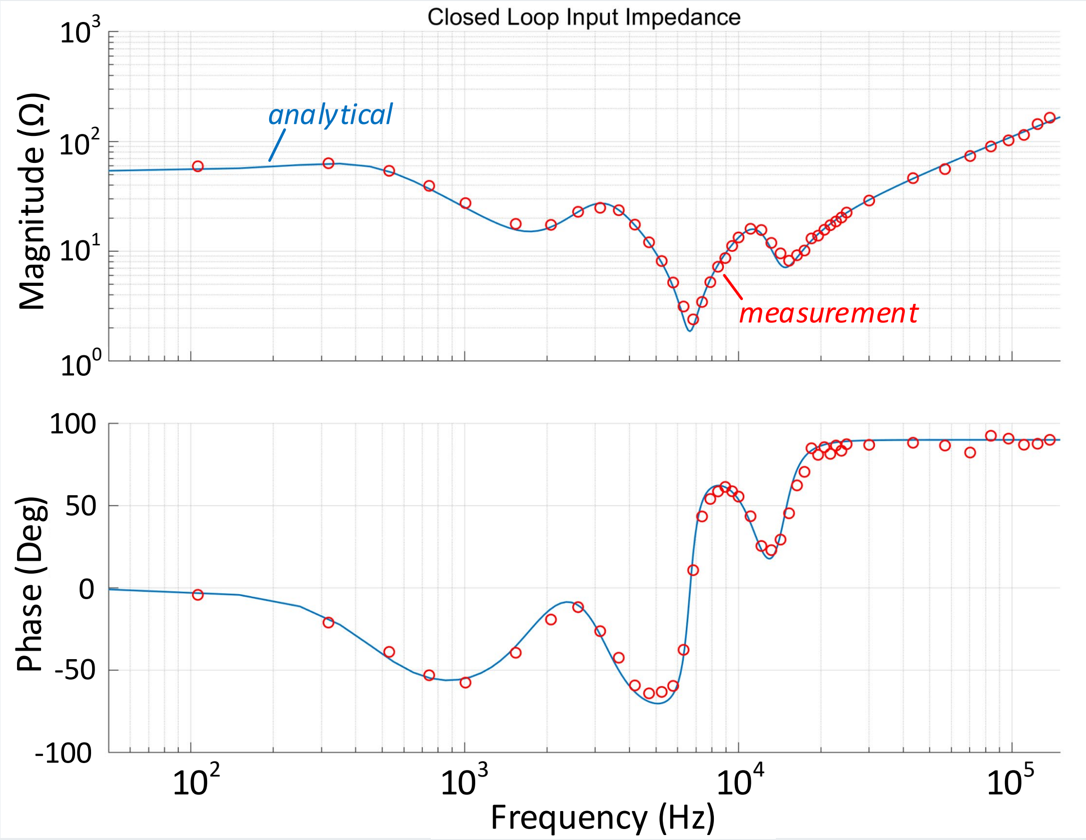
- EMI **estimation** using extracted black-box model
- Suitable for **validation** of developed models
- Suitable for developing models of different power converter **without** having detailed **knowledge**
- To build a **compact digital characterization device** to extract black-box model

Power Converter Characterization (WP3)

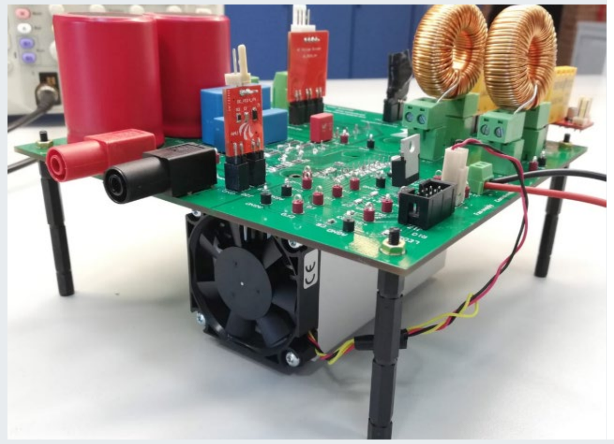
Validation

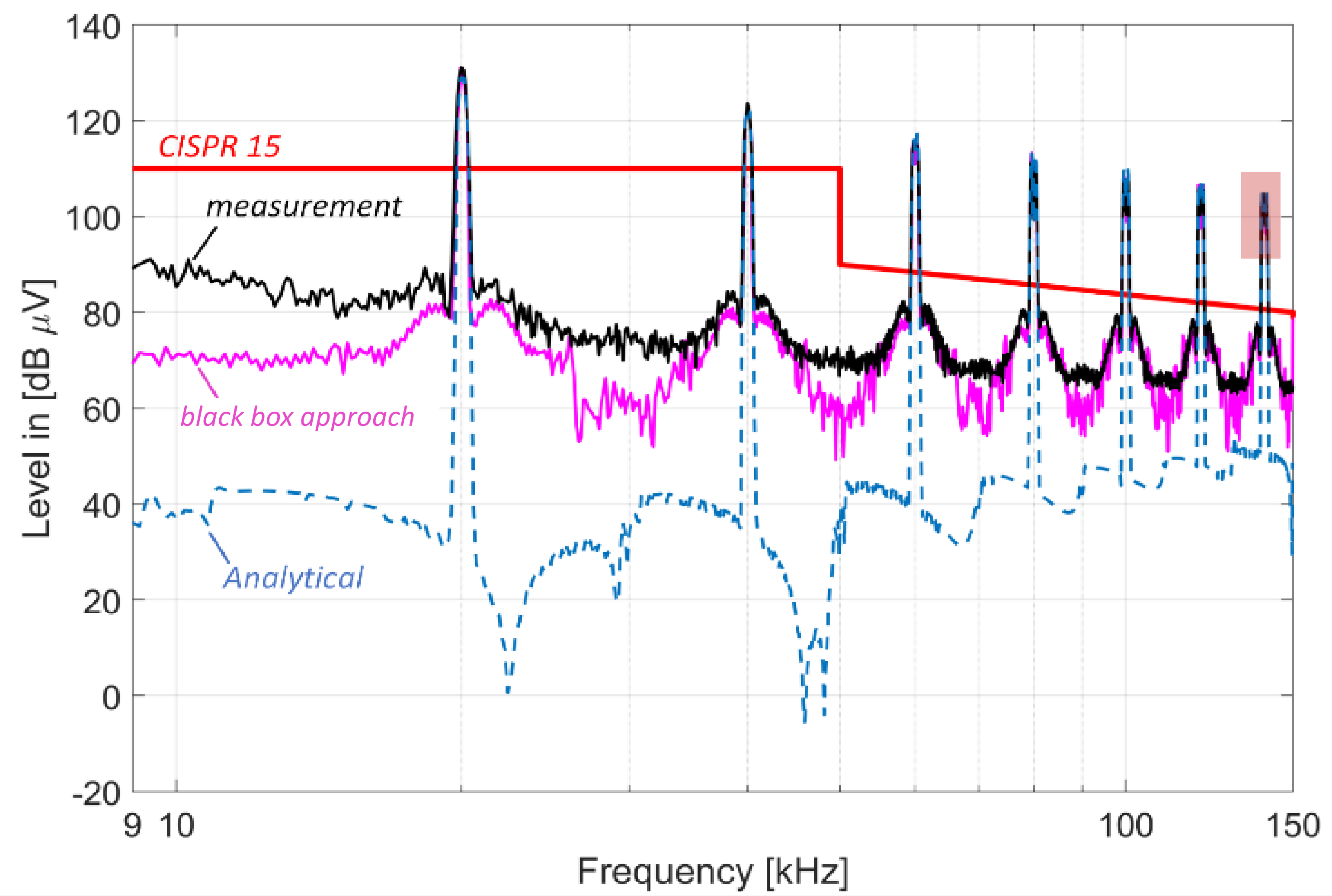
- Exemplary validation with single-phase PFC
- Excellent agreement among the obtained results
- Analytical approach is quite fast in simulating EMI with acceptable accuracy
- Further investigation on sensitivity analysis of the black-box and analytical model is needed





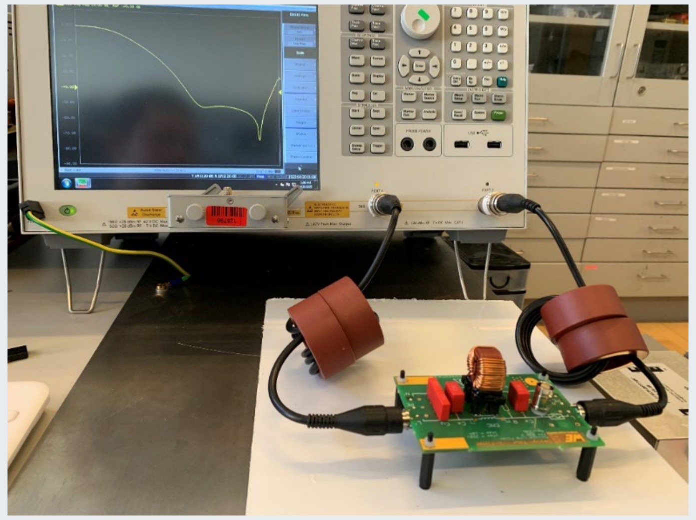
Validation of developed analytical closed loop impedance model of power converter (2 kHz – 150 kHz) with multi-tone injection approach.





Validation of analytical and black-box modeling approaches for estimated emission below 150 kHz

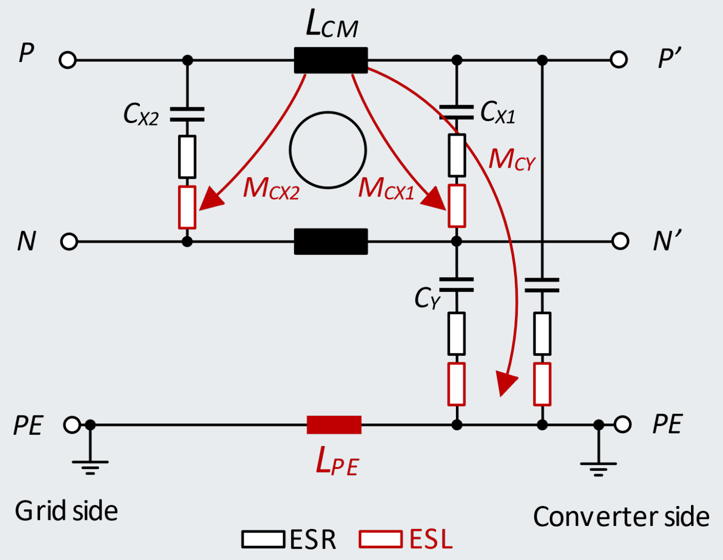
Filtering (WP4)

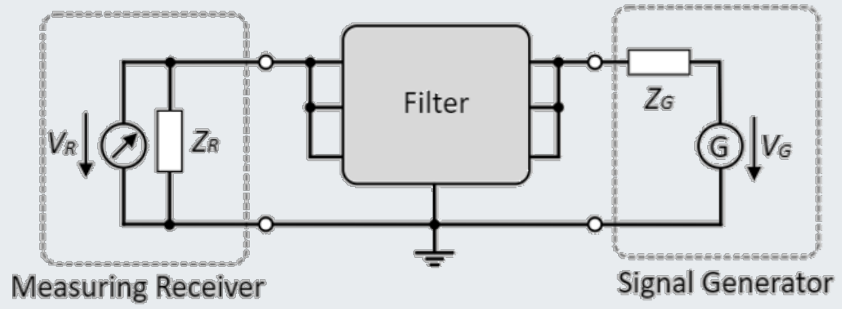


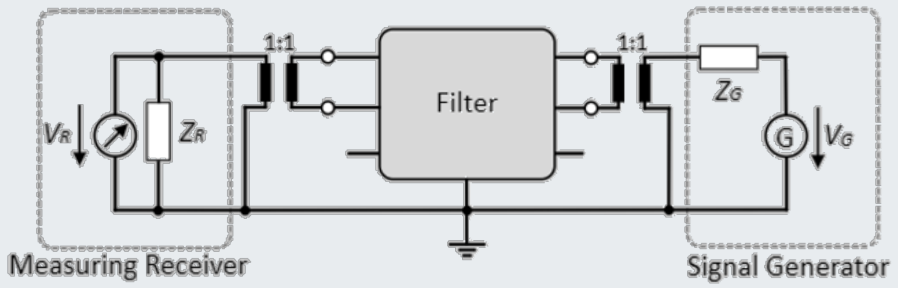
Filter Design and Reliability

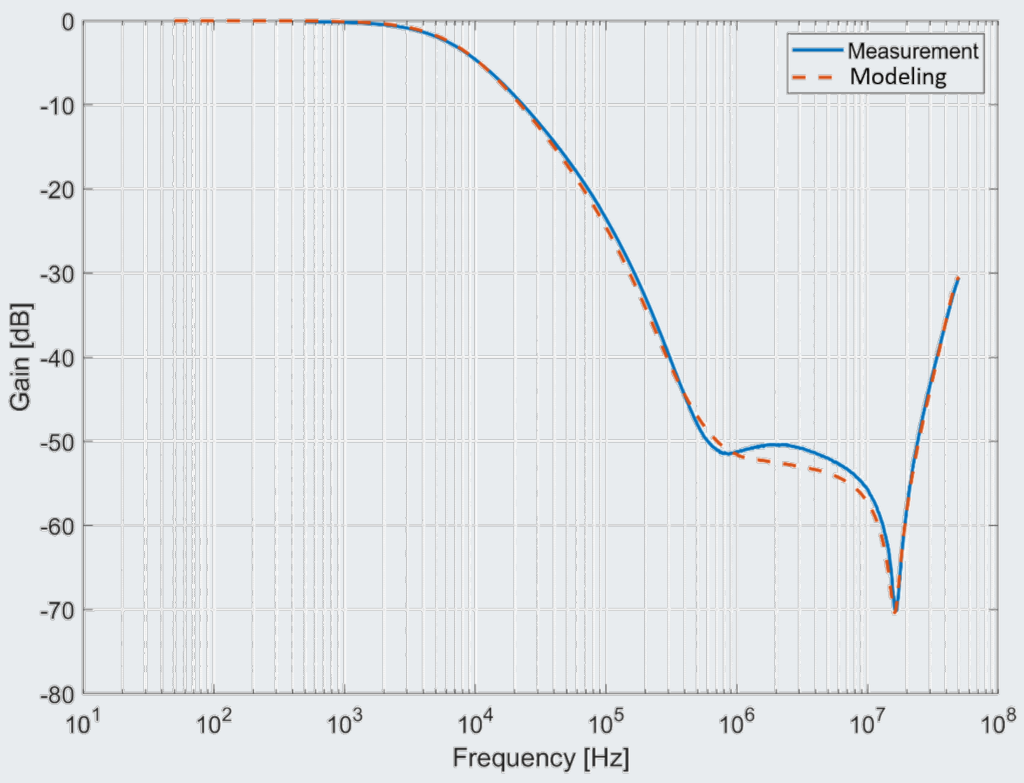
Objectives:

- Passive filtering modeling
- Passive filter volume calculation and optimization
- Filter lifetime effect and prediction

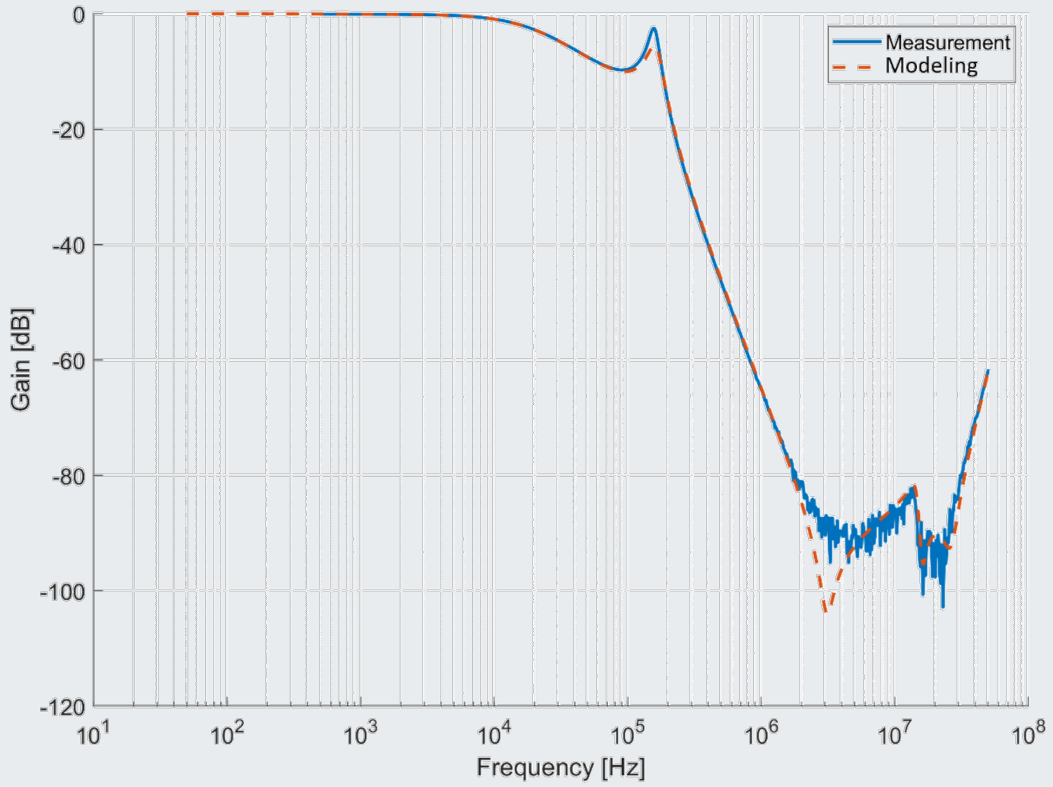








Asymmetrical filter gain measurement and modeling



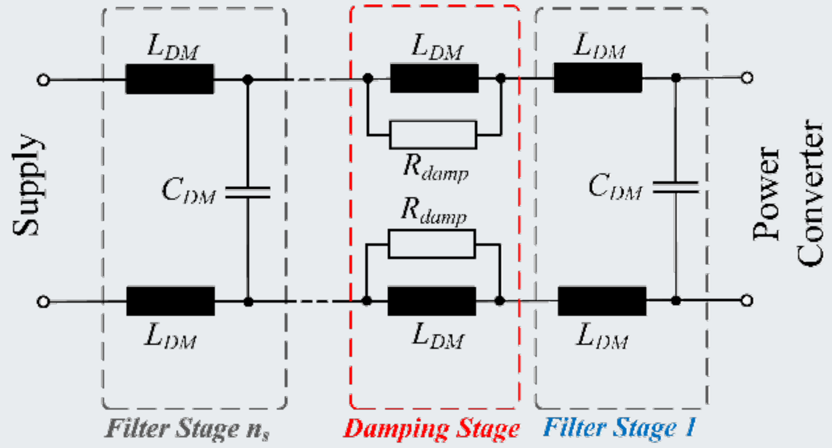
Symmetrical filter gain measurement and modeling

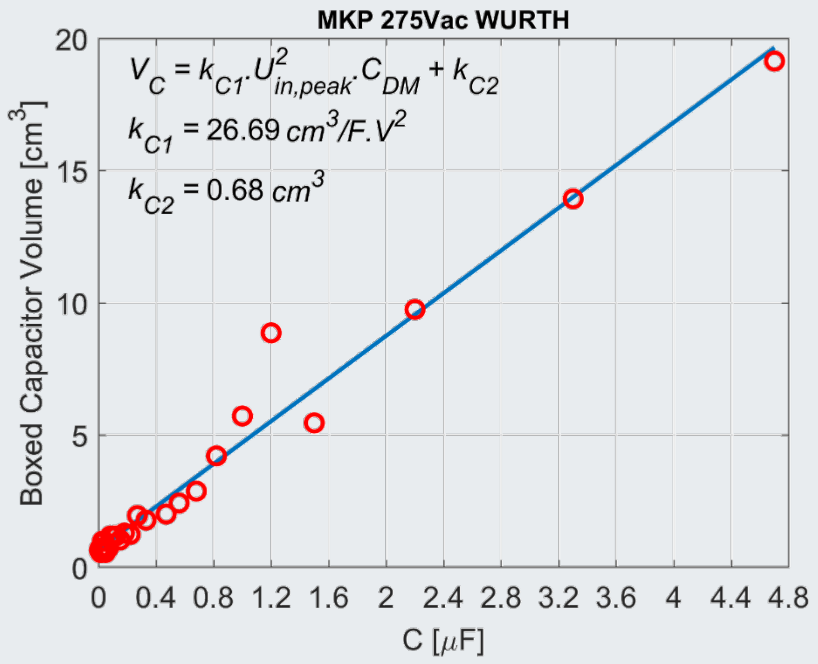
Filtering (WP4)

Filter Design and Reliability

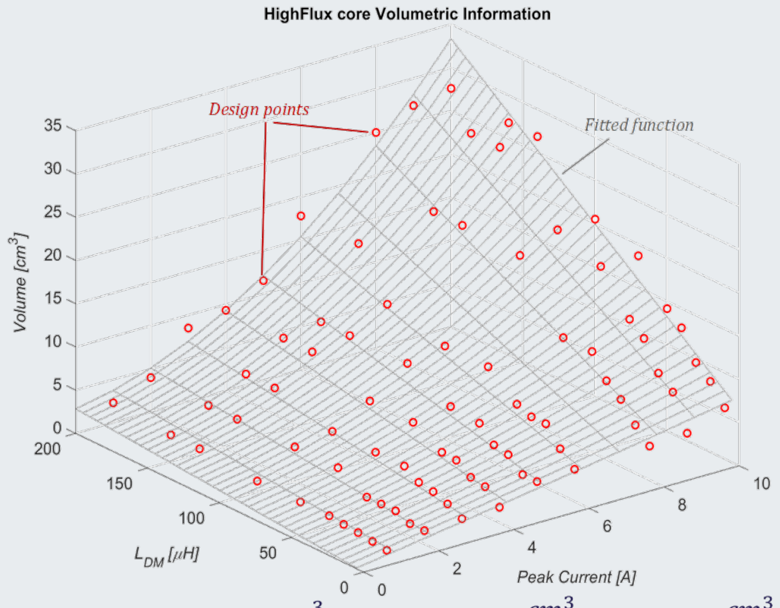
Objectives:

- Passive filtering modeling
- Passive filter volume calculation and optimization
- Filter lifetime effect and prediction





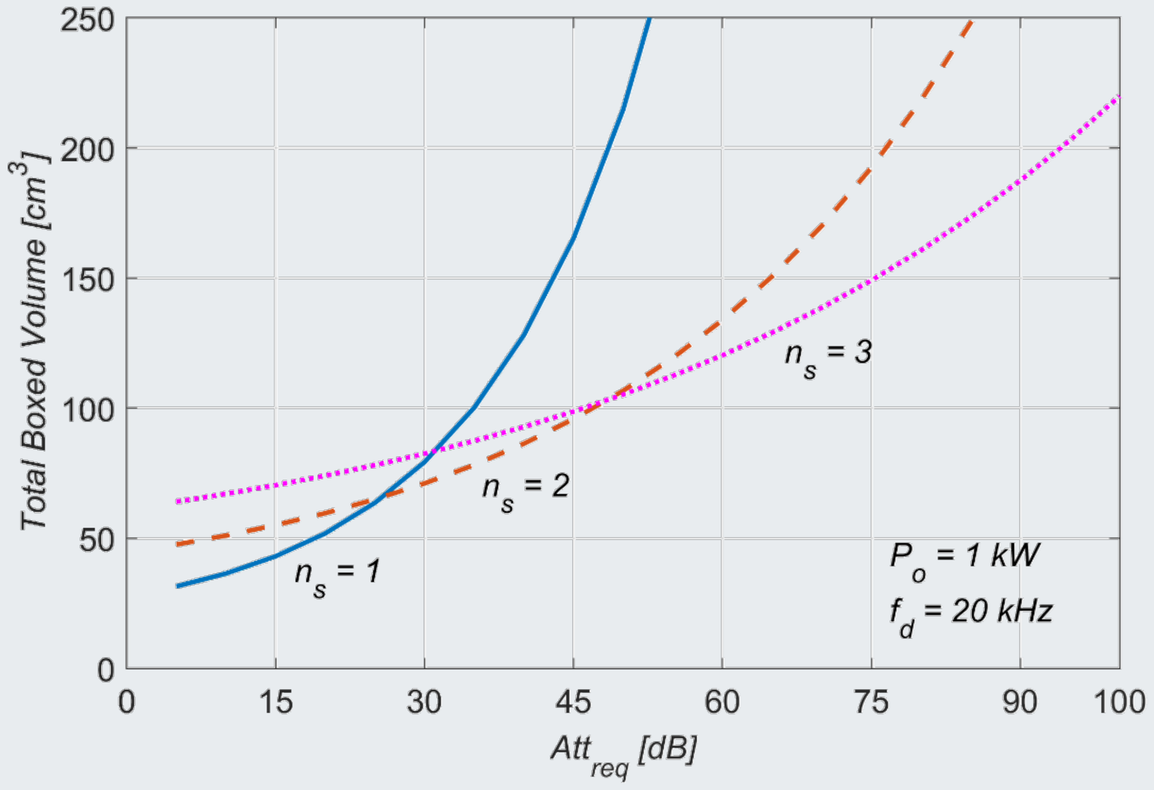
$$V_L = k_{L1}.\hat{I}^2_{in}.L_{DM} + k_{L2}.L_{DM} + k_{L3}.\hat{I}_{in}$$



$k_{L1} = 0.0012 \frac{cm^3}{\mu H.A^2}$ $k_{L2} = 0.0142 \frac{cm^3}{\mu H}$ $k_{L3} = 0.65 \frac{cm^3}{A}$

Extracted volumetric information of film capacitor and magnetic components

C_{DM} = WURTH MKP 275ac
L_{DM} = Hflux, multilayer, μ_r = 60



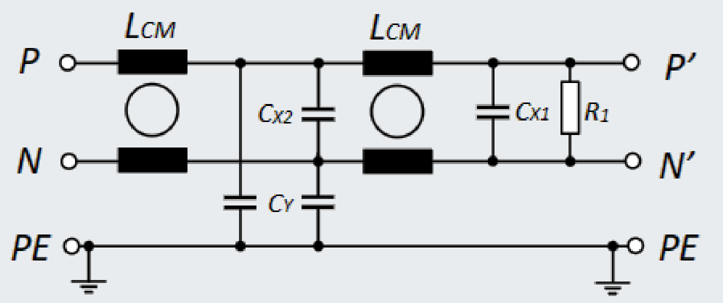
EMI filter total boxed volume vs required attenuation considering 1, 2, 3 filter stages

Filtering (WP4)

Filter Design and Reliability

Objectives:

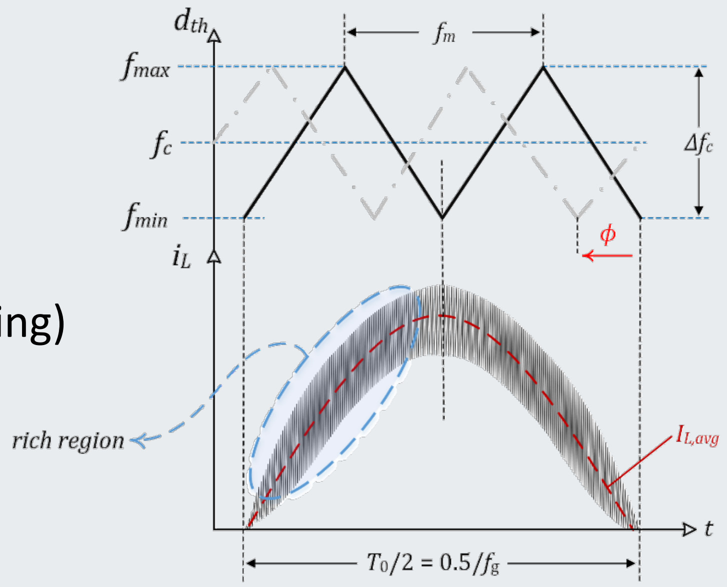
- Passive filtering modeling
- Passive filter volume calculation and optimization
- Filter lifetime effect and prediction

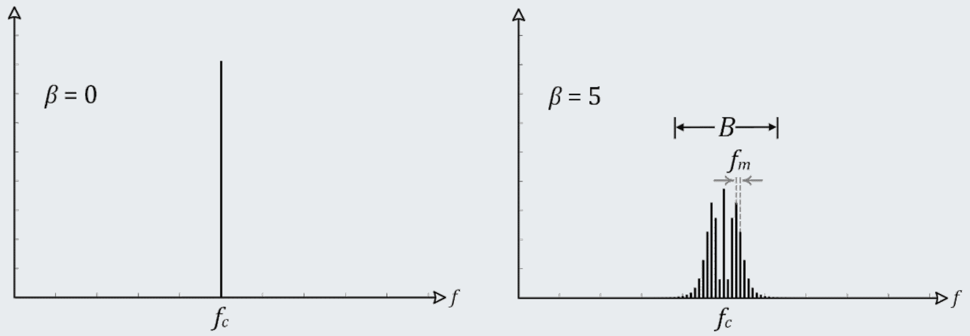


Grid side

Converter side

Spectral shaping (frequency dithering)



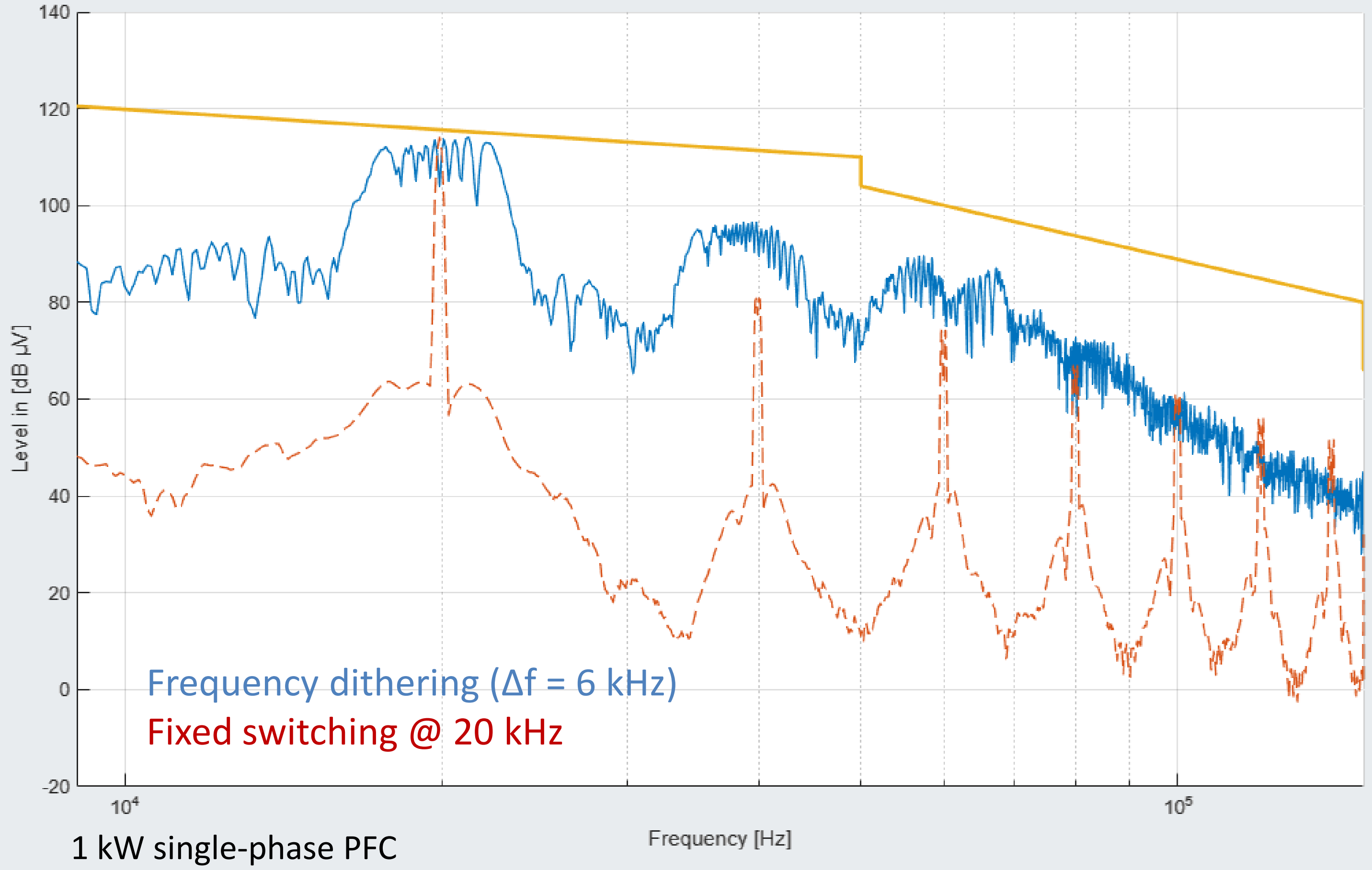


Fixed switching @ 20 kHz

C_{X1} = 4700 nF
C_{X2} = 3300 nF
C_Y = 15 nF
L_{CM} = 12 mH
Total Boxed Volume = 60.9 cm^3

Frequency dithering (Δf = 6 kHz)

C_{X1} = 1500 nF
C_{X2} = 820 nF
C_Y = 15 nF
L_{CM} = 12 mH
Total Boxed Volume = 37.5 cm^3



1 kW single-phase PFC

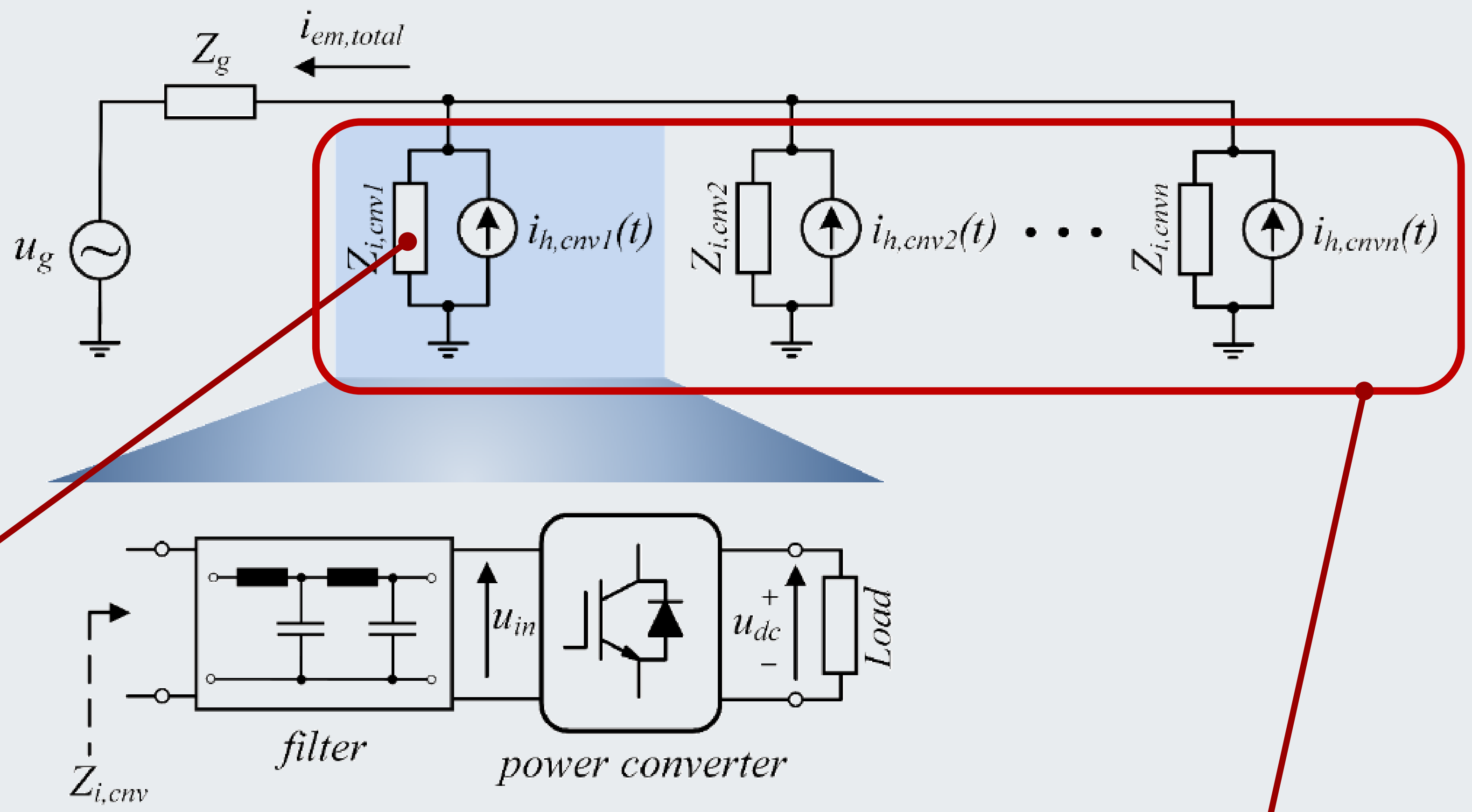
Applying spectral shaping to reduce the required EMI filter size and volume
1.6 times difference!

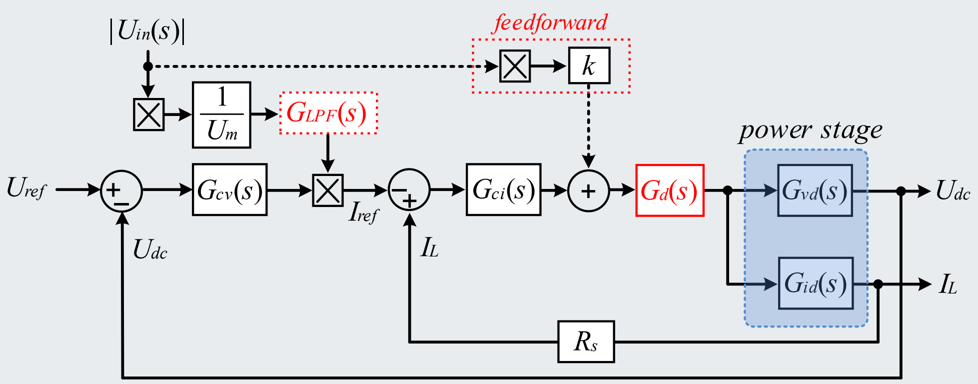
Compatibility in Networks (WP5)

System Level Study

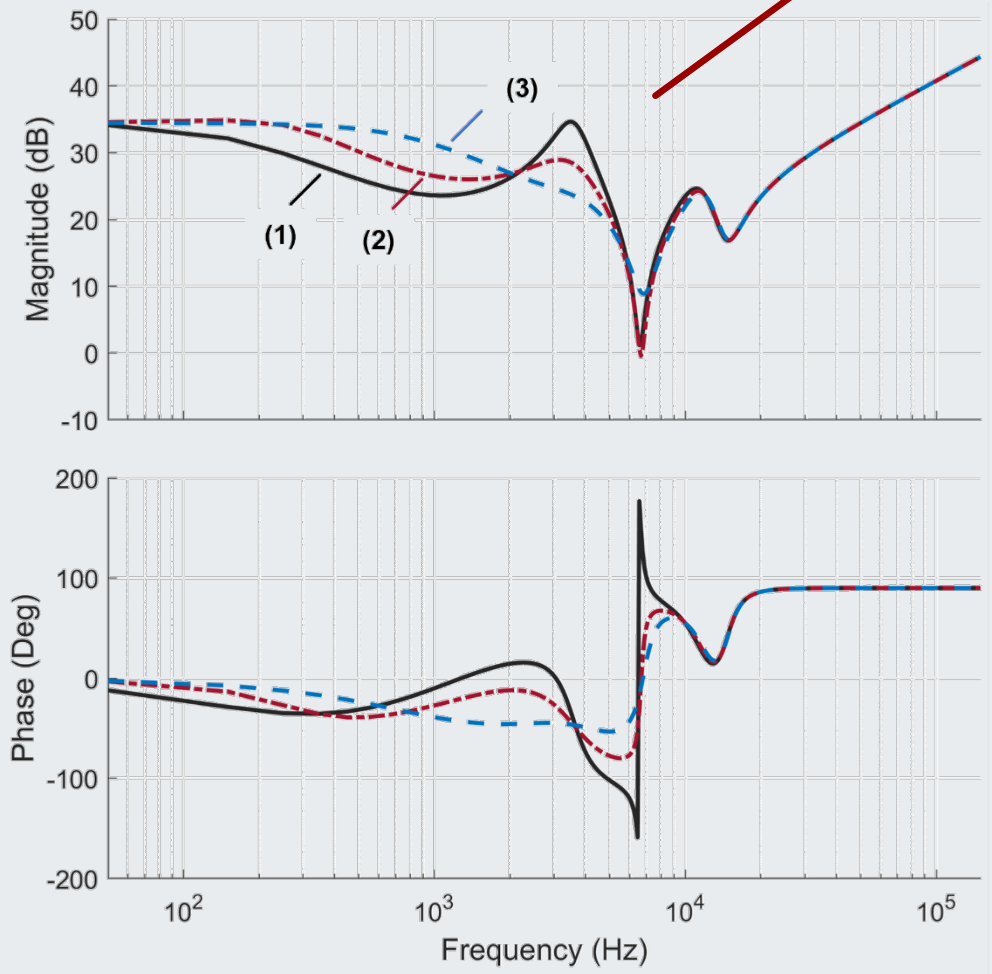
Objectives:

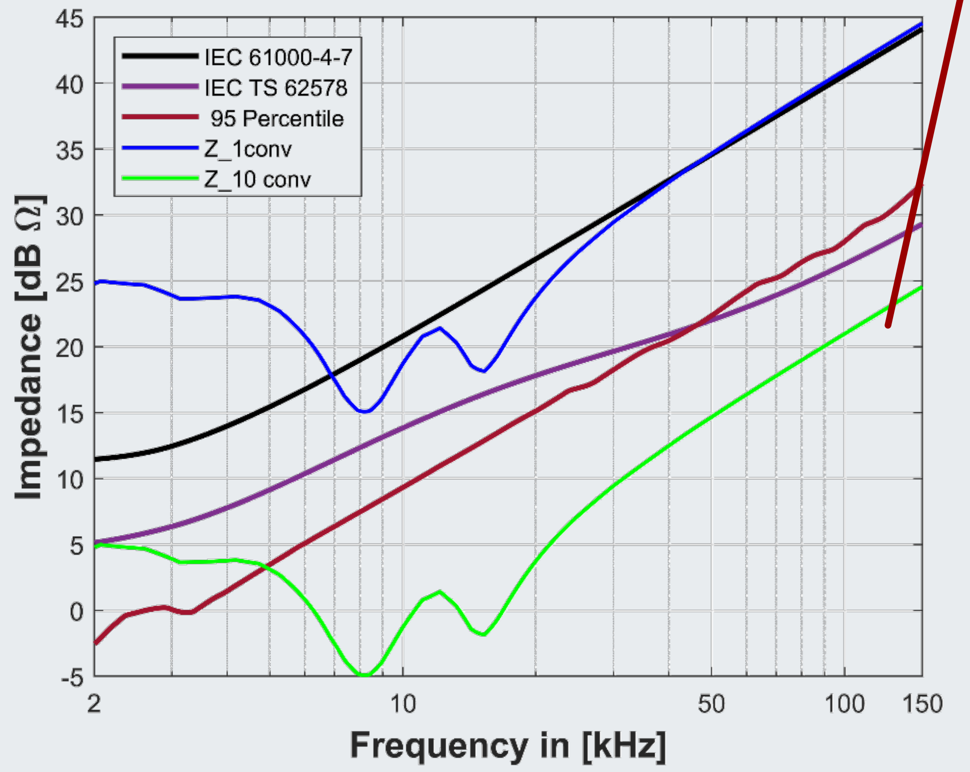
- Develop aggregated models and validation
- Self-adaptive control (re-shape impedance behavior)
- Investigating system level stability (power converter interactions)
- Investigating system level compatibility





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



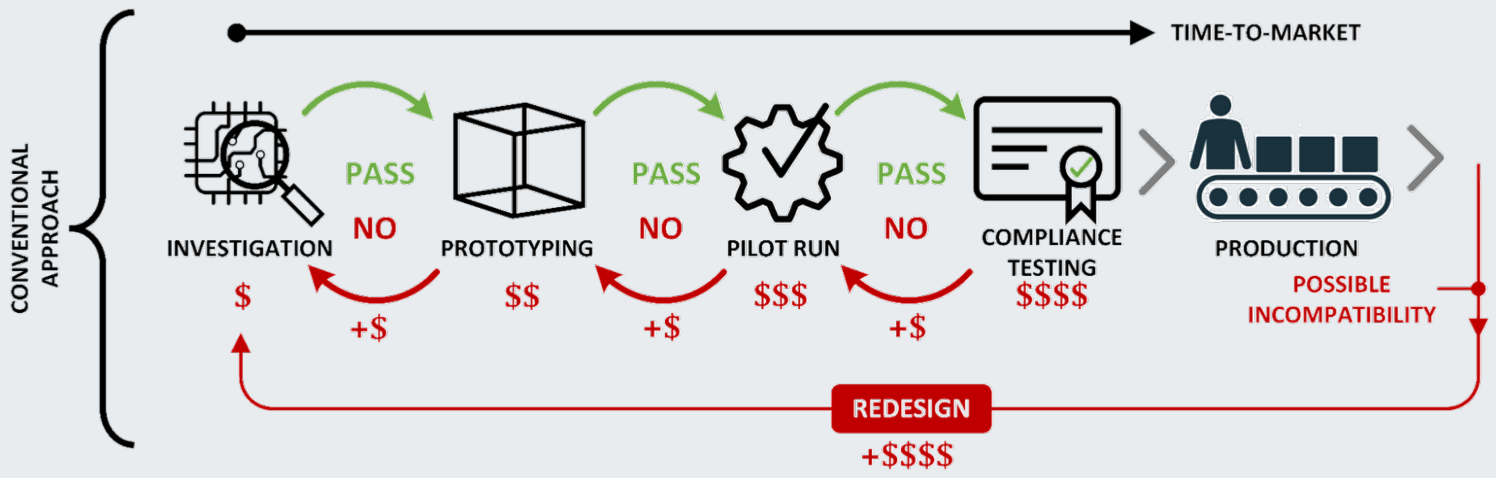


Multi-converter impedance vs reference impedances

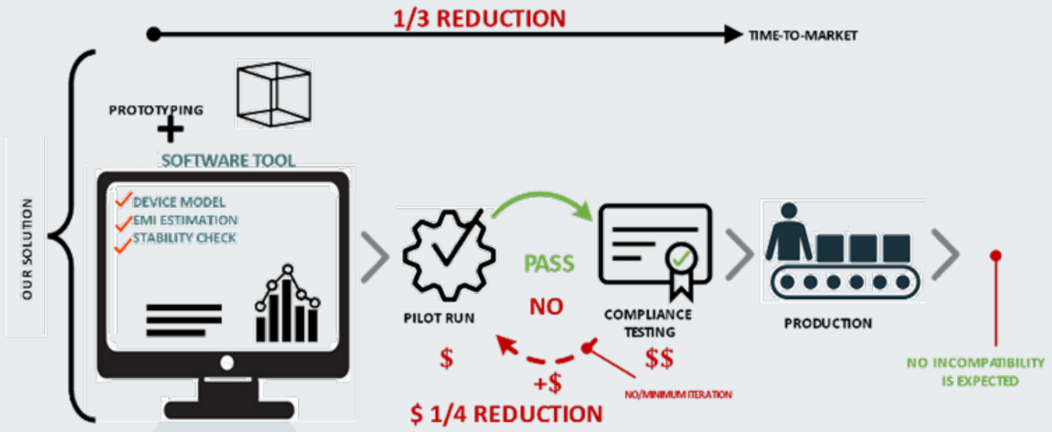
Supra-EMC Tool (WP6)

Conventional EMC Design

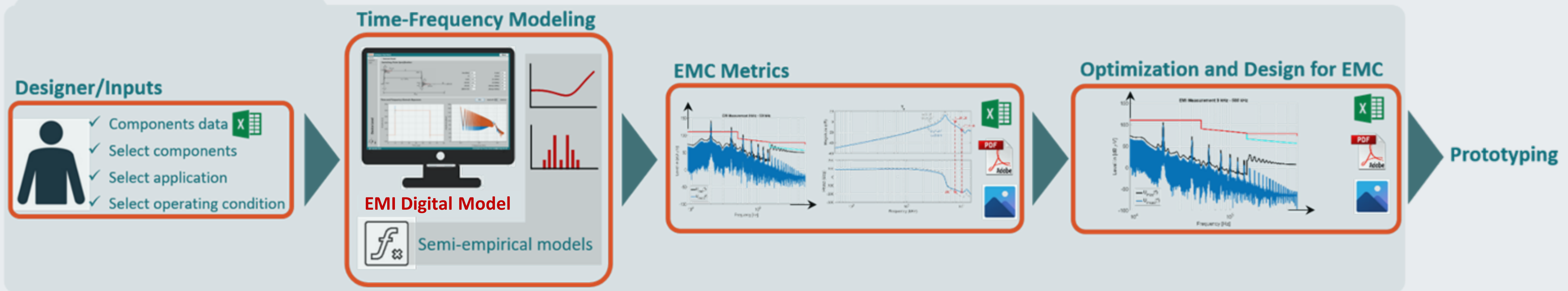
- **50%** of products fail EMC testing the first time! [1], [2]
- EMC testing accounts for **30%-50%** of product development **time** and **cost**
- EMC filters accounts for more than **30%** of **cost** and **volume** [3]
- Lack of EMC filter volume and size **optimization algorithm**
- Challenge of 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.
[3] D. O. Boillat, F. Krismer and J. W. Kolar, "EMI Filter Volume Minimization of a Three-Phase, Three-Level T-Type PWM Converter System," in IEEE Transactions on Power Electronics, vol. 32, no. 4, pp. 2473-2480, April 2017.
[4] https://www.tek.com/blog/financial-case-emi-emc-pre-compliance-test-solution



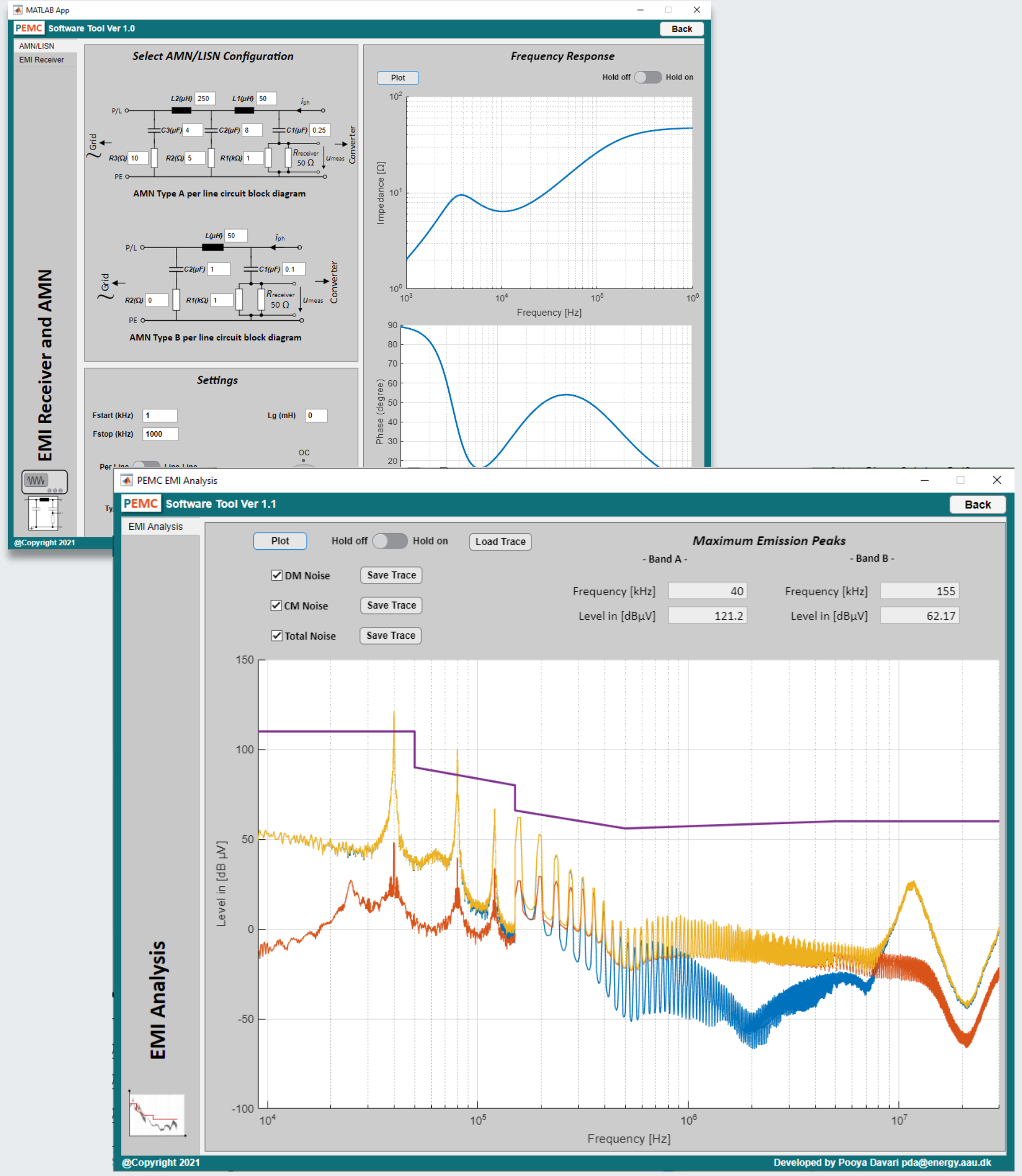
- Reduced EMC assessment **cost** and **time** (solving EMI early in design cycle)
- **Computationally-efficient** EMC analysis (digital model)
- User friendly interface
- EMI filter volume **optimization**
- Easy to cope with continuous **new EMC standard updates**

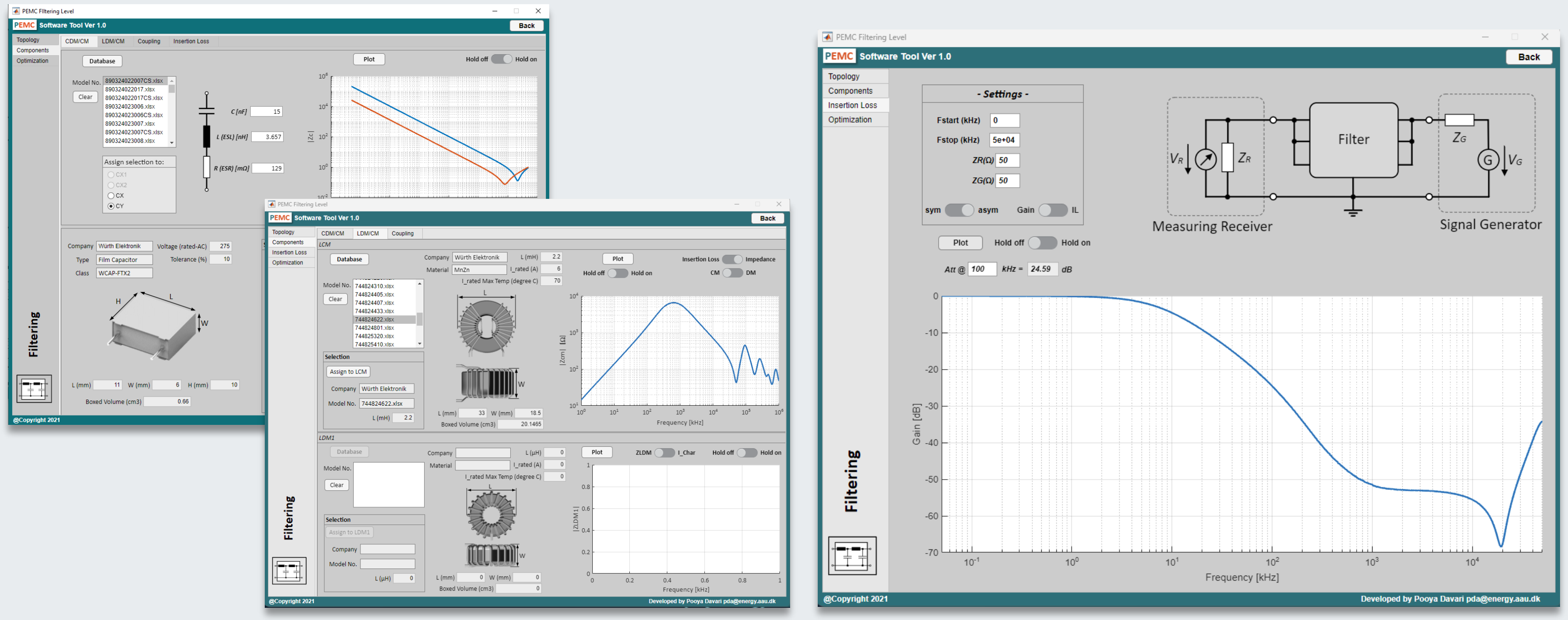


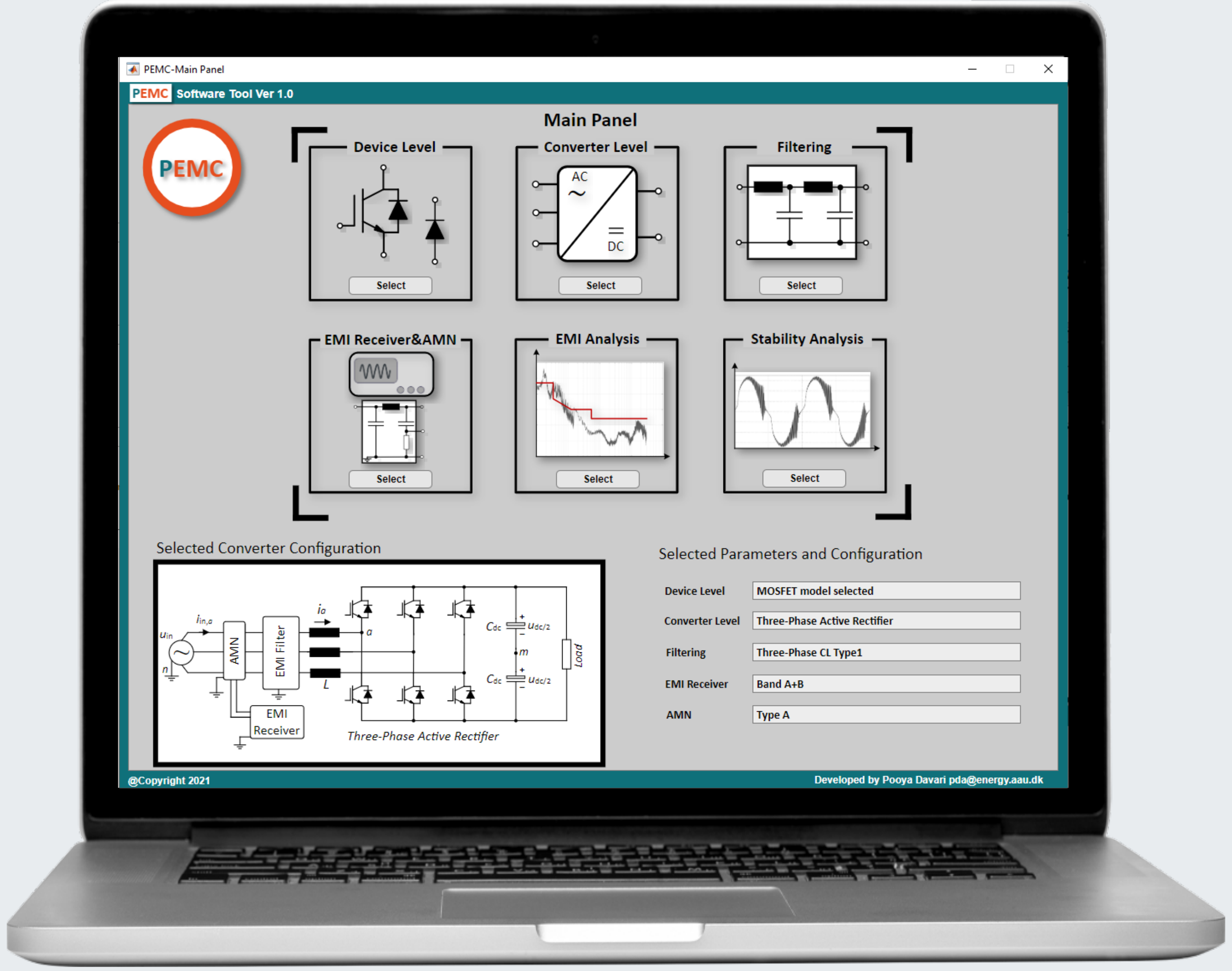
Supra-EMC Tool (WP6)

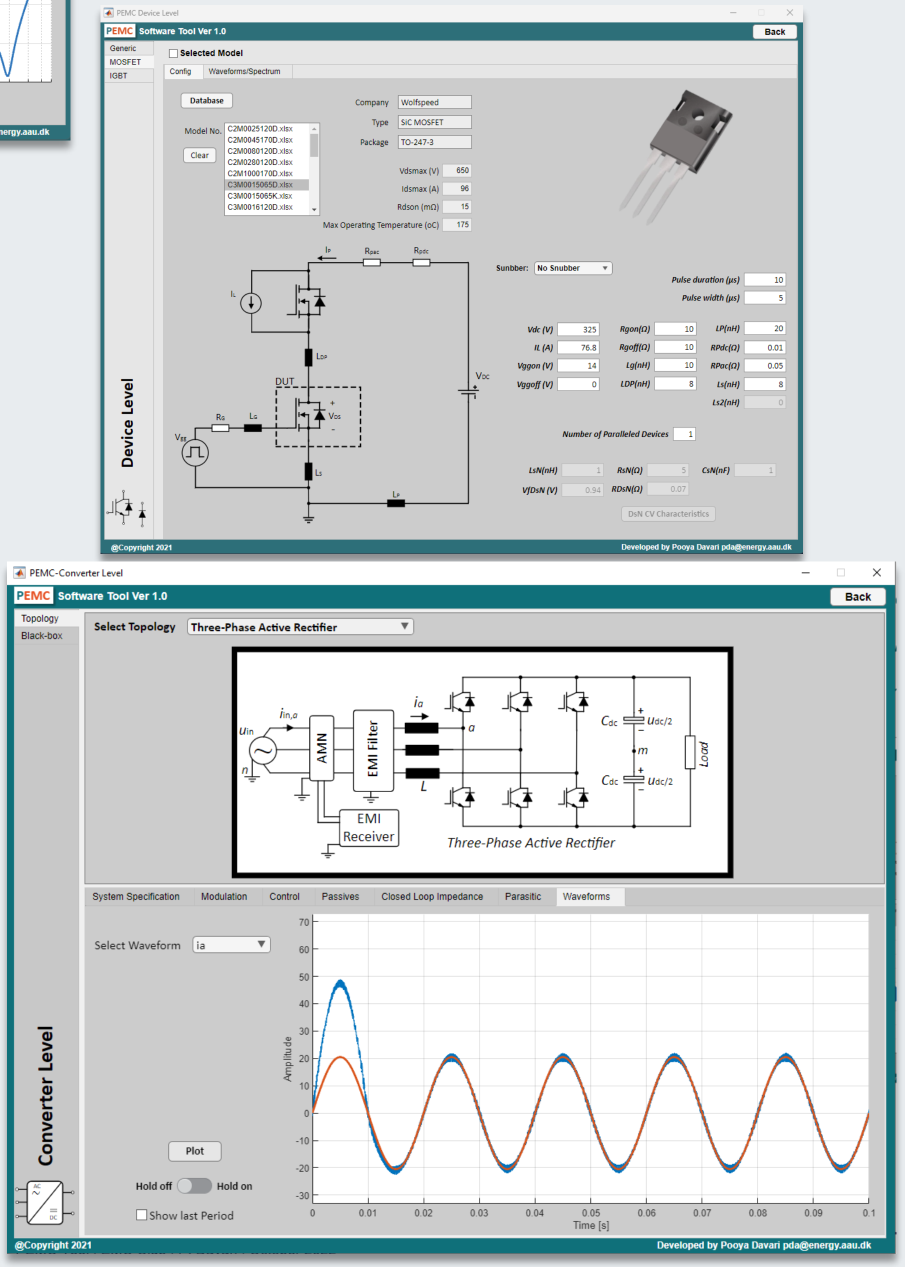
PEMC Software

- Supported by IFD-InnoExplorer
- Converter level EMI estimation
- Final version for licensing will be launched soon!



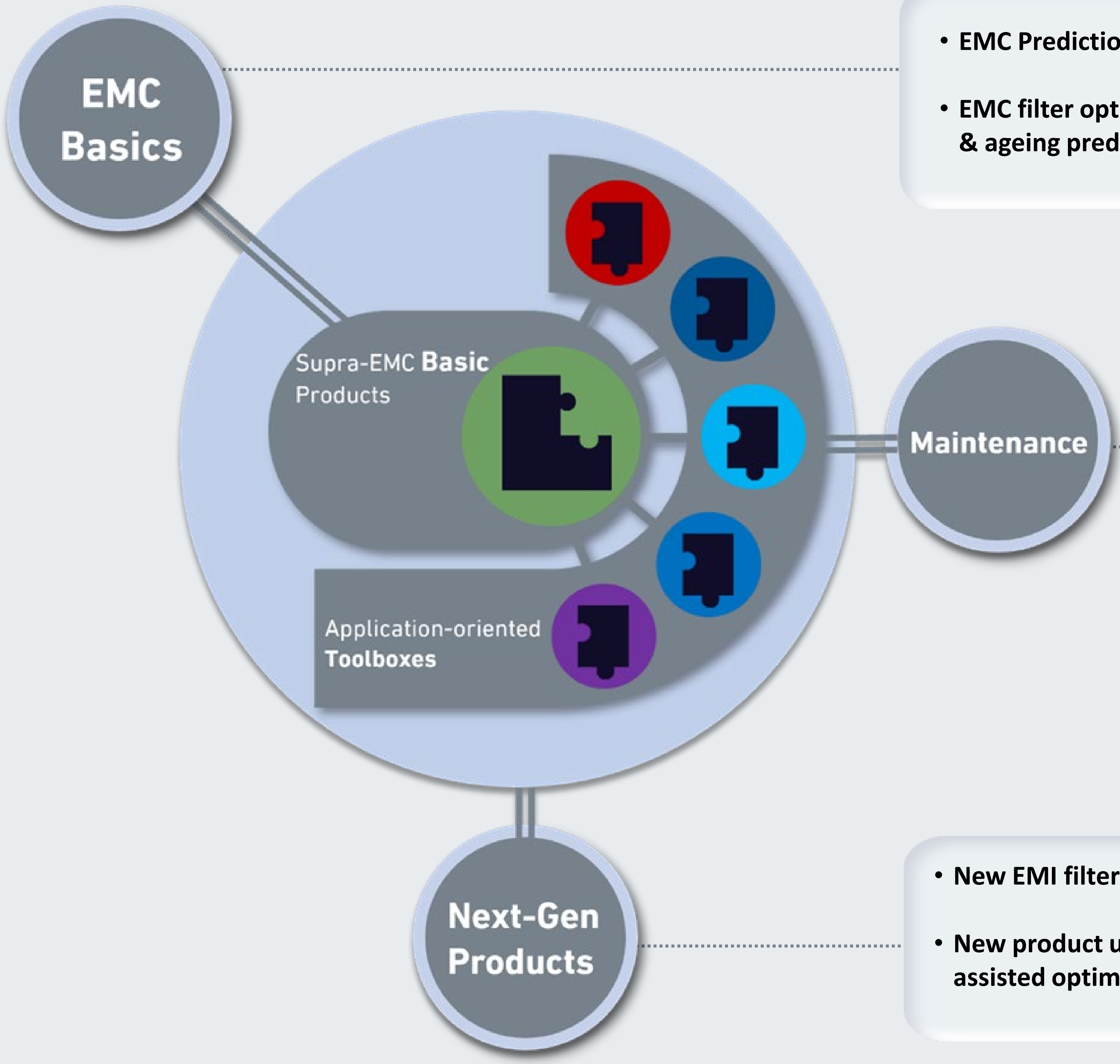






Supra-EMC Tool (WP6)

Application Oriented and System Level Simulation



- EMC Prediction
- EMC filter optimization & ageing prediction

- Customers product upgrade
- Continuous development

- New EMI filter products
- New product utilizing AI-assisted optimized EMC design

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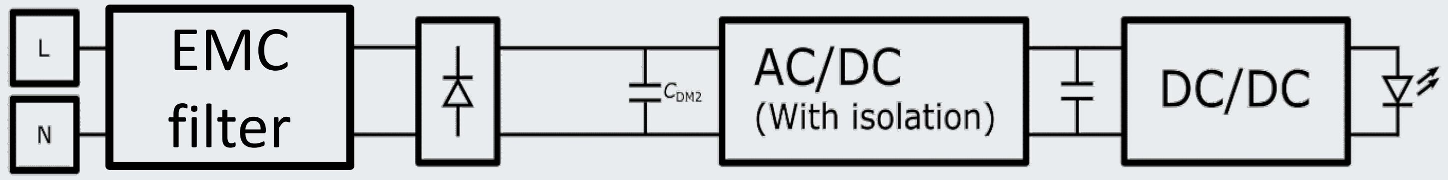
MORE POWER TO YOU

Applications (WP7)

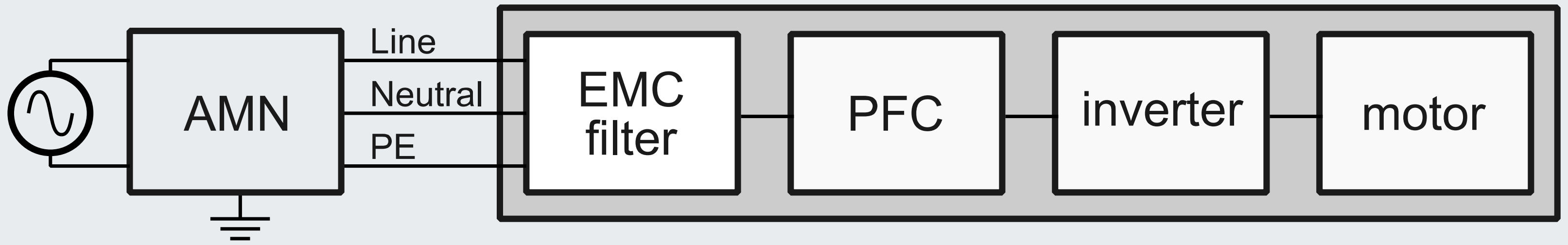
Selected use cases for validation

Objectives:

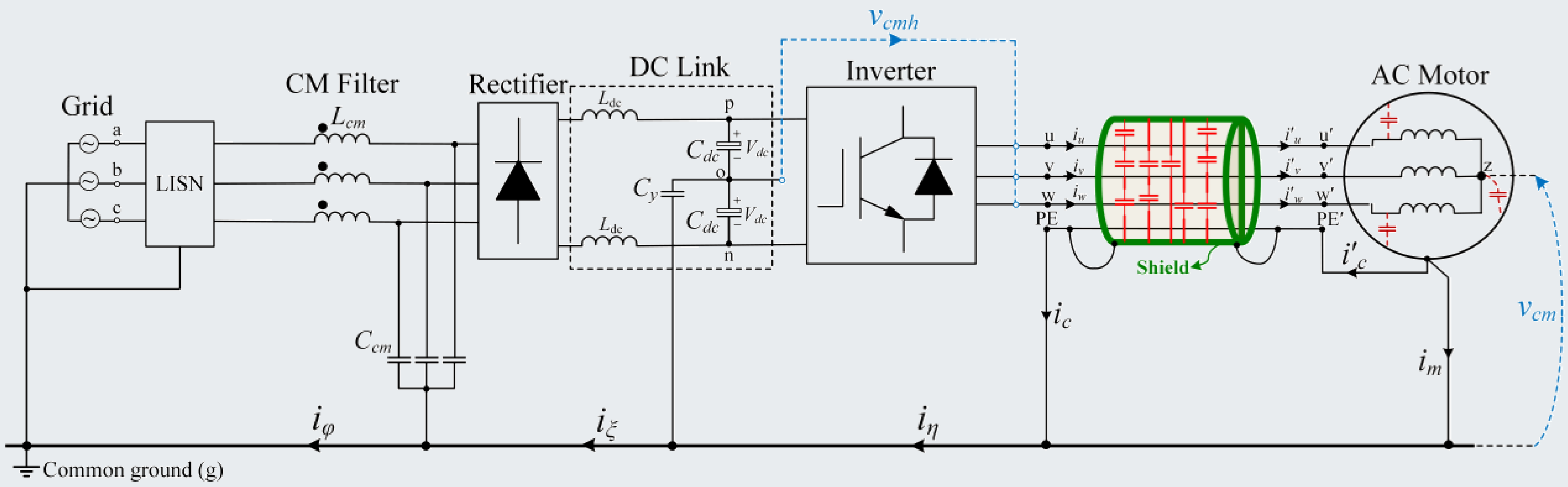
- **Demonstration** & **validation** of the proposed methods
- **Fine-tuning** of the developed models



LED (Lighting)



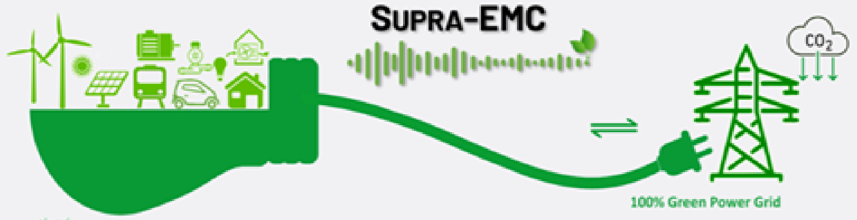
Motor drive (Pumping)



Motor drive (HVAC)

Dissemination (WP8)

- ✓ **Supra-EMC webpage:** www.Supra-EMC.energy.aau.dk



Innovation Fund Denmark

Danfoss GRUNDFOS schaffner FORCE TECHNOLOGY Nordic Power Converters AAU ENERGY AALBORG UNIVERSITY

IFD-GS SUPRA-EMC

Supraharmonics ElectroMagnetic Compatibility strategies in power electronic based power grid

Link to IFD-GS Supra-EMC at VBN (Aalborg University's research database)

- ✓ **Annual Symposium (2025, 2026 and 2027)**
- ✓ **Technical Specification Report to Danish Standardization**

EMI/EMC in Power Electronics Research Group

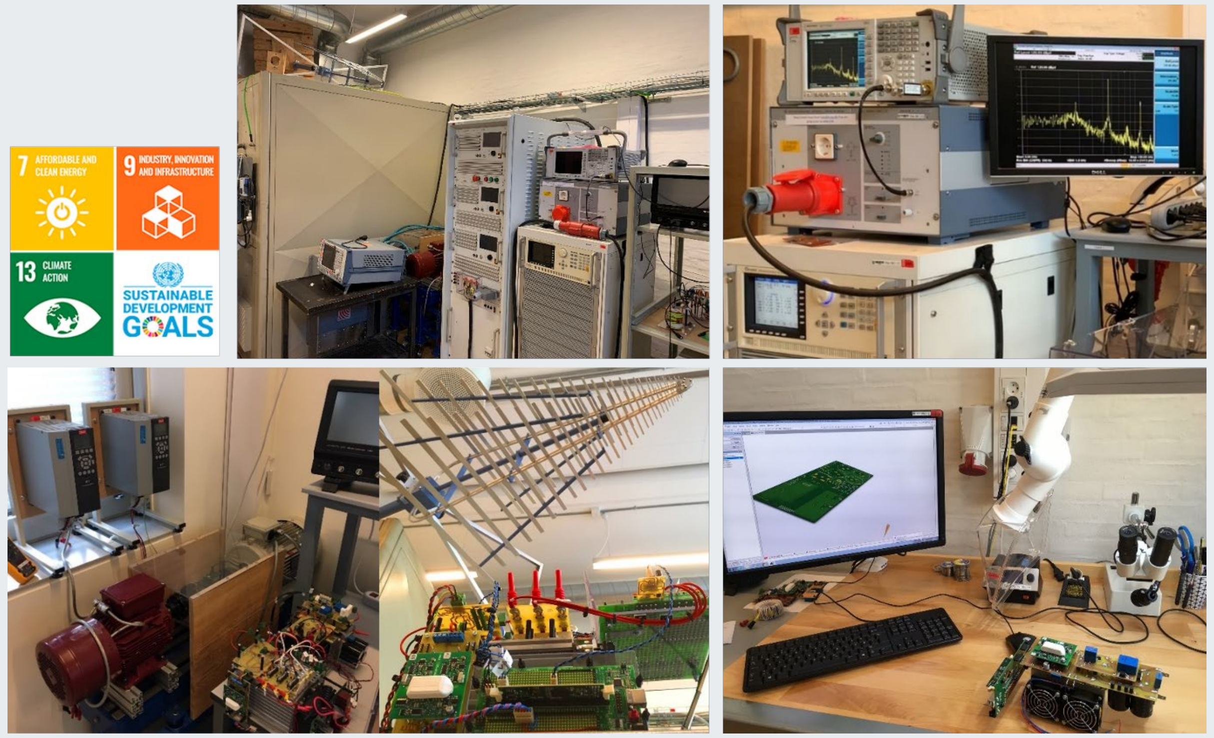
EMC
EMI/EMC IN POWER ELECTRONICS RESEARCH GROUP

EMI/EMC IN POWER ELECTRONICS

- 01 HIGH SWITCHING AND FAST TRANSIENTS MODELING
- 02 FILTER DESIGN & INTEGRATION
- 03 PRODUCT DESIGN & APPLICATIONS
- 04 TESTING AND VALIDATION
- 05 VIRTUAL DOMAIN MULTI-PHYSICS ANALYSIS TOOLS
- 06 EMERGING WBG-BASED POWER CONVERTERS

Vision

To develop innovative power electronic converters and systems for current and future power grid and all relevant applications, which posses low-interference and high-power quality to cope with Electromagnetic (EMC) requirements at device and system levels. This will ensure electromagnetic compatibility of next generation power electronic systems which enables smooth transition to "green power" and to reach green transition goals.



Link (EMI/EMC in Power Electronics Research Group)

Link (List of Project)

Link (EMI/EMC in Power Electronics Industrial/PhD Course)

References

1) P. Xue and P. Davari, "A Temperature-Dependent dVCE/dt and dIC/dt Model for Field-Stop IGBT at Turn-on Transient," in IEEE Trans. Power Electron., 2023.
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EMI/EMC IN POWER ELECTRONICS
RESEARCH GROUP

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Thank you!