The Evolution of EV Charging and Its Impact on the Grid

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POWER CONVERSION

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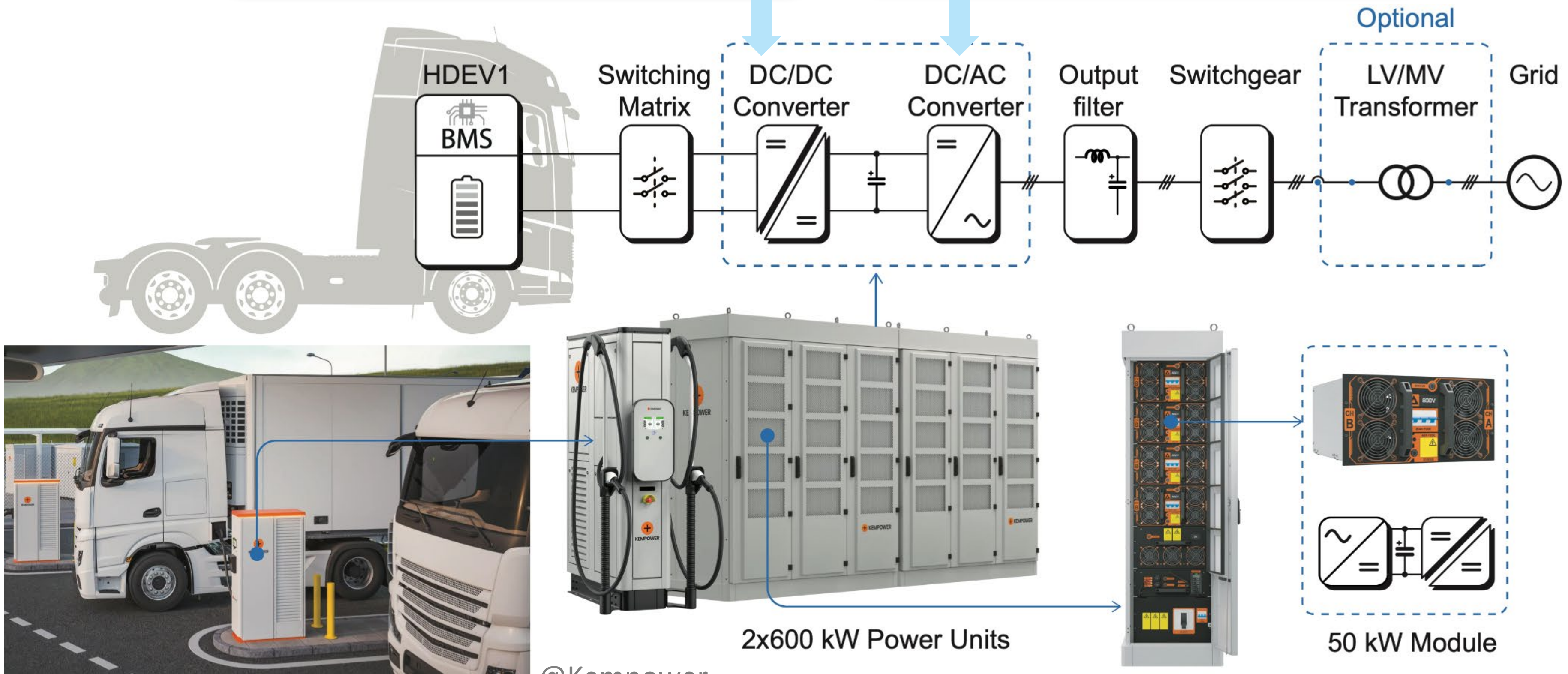
Duties of DC/DC

- ❑ To control charging current
- ❑ To ensure high efficiency even the battery voltage varies a lot

Duties of AC/DC

- ❑ To ensure low harmonics
- ❑ To ensure high power factor
- ❑ Grid support (advanced)



@Kempower

Source: Z Qin, et al, Innovative electric vehicle charging infrastructure for european transportation electrification: megawatt charging hubs with battery energy storage and solid-state transformers for medium-voltage grid integration, *IEM*, 2025

POWER ELECTRONICS TOPOLOGIES

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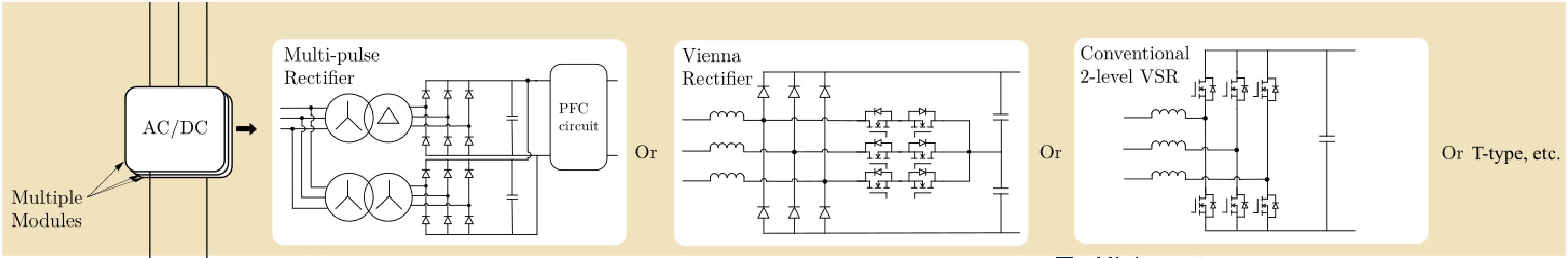
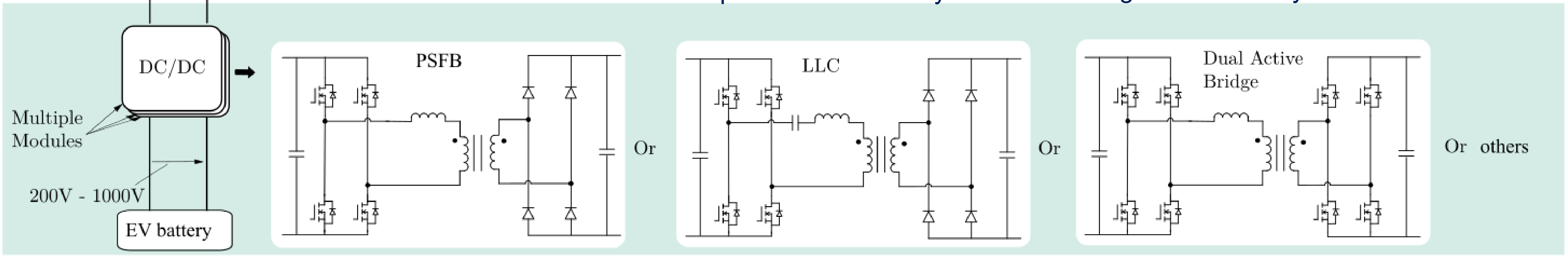


400V - 800V

- ❑ Low cost
- ❑ Unidirectional

- ❑ Medium cost
- ❑ Unidirectional with limited Q power controllability

- ❑ High cost
- ❑ Bidirectional (V2G enabled)
- ❑ High controllability



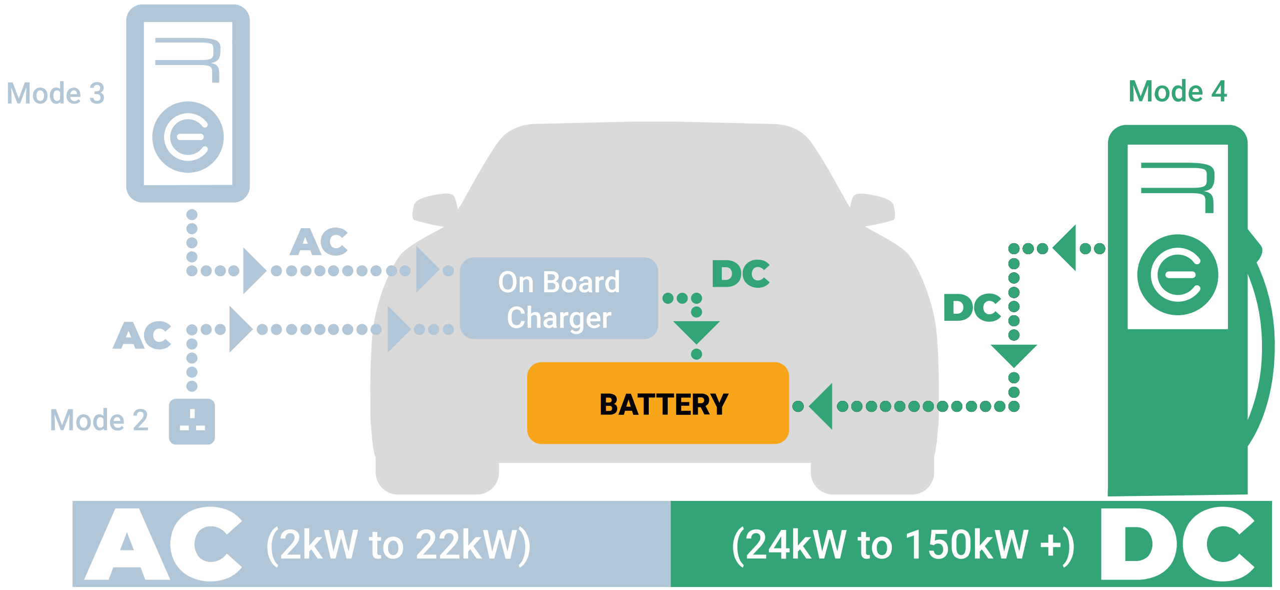
- ❑ ZVS, difficult in lagging leg
- ❑ high conduction loss
- ❑ Unidirectional

- ❑ ZVS
- ❑ low conduction loss
- ❑ Unidirectional
- ❑ Narrow voltage range

- ❑ ZVS
- ❑ high conduction loss
- ❑ Bidirectional (V2G enabled)
- ❑ Simple bidirectional power control

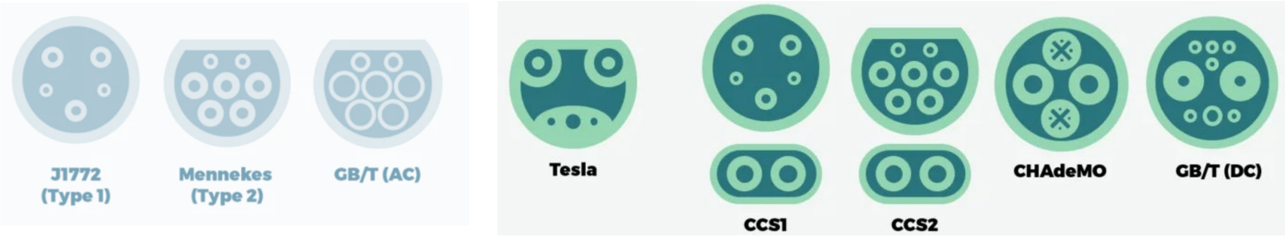
Source: L Wang, et al., "Grid Impact of Electric Vehicle Fast Charging Stations: Trends, Standards, Issues and Mitigation Measures-An Overview", *IEEE-OJPE*, 2021

AC VS DC CHARGERS



Residential AC charger

Commercial AC charger



NA JP | EU & rest MKT | CN

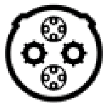
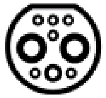
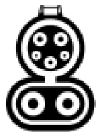
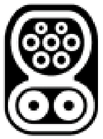
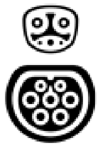
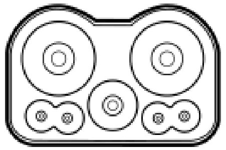
@Replenishh

NA | EU & rest MKT | JP | CN

DC fast charger @Autel

Source: Z Qin, et al., "Electric vehicle charging technology and its control", *Control of Power Electronic Converters and Systems V4*, Academic Press, 241-307, 2024

CHARGER PLUGS

Standard	CHAdeMO	GB/T	CCS Type 1	CCS Type 2	Tesla	ChaoJi
Compliant Standards	IEEE 2030.1.1 IEC 62916-3	IEC 62916-3	SAE J1772 IEC 62916-3	IEC 62916-3	No related items	CHAdeMO and GB/T (IEC and CCS not yet but is ongoing)
Connector Inlet						
Maximum Voltage (V)	1000	750	600	900	410	1500
Maximum Current (A)	400	250	400	400	330	600
Maximum Power (kW)	400	185	200	350	135	900
Maximum Market Power (kW)	150	125	150	350	120	N.A.
Communication Protocol	CAN		PLC		CAN	CAN
V2X Function	Yes	No			Unknown	Yes
Start year	2009	2013	2014	2013	2012	2020

Source: Netherlands Enterprise Agency, *The Electric vehicle charging – Definitions and explanations*, version January 2019

CHARGING POWER IS INCREASING

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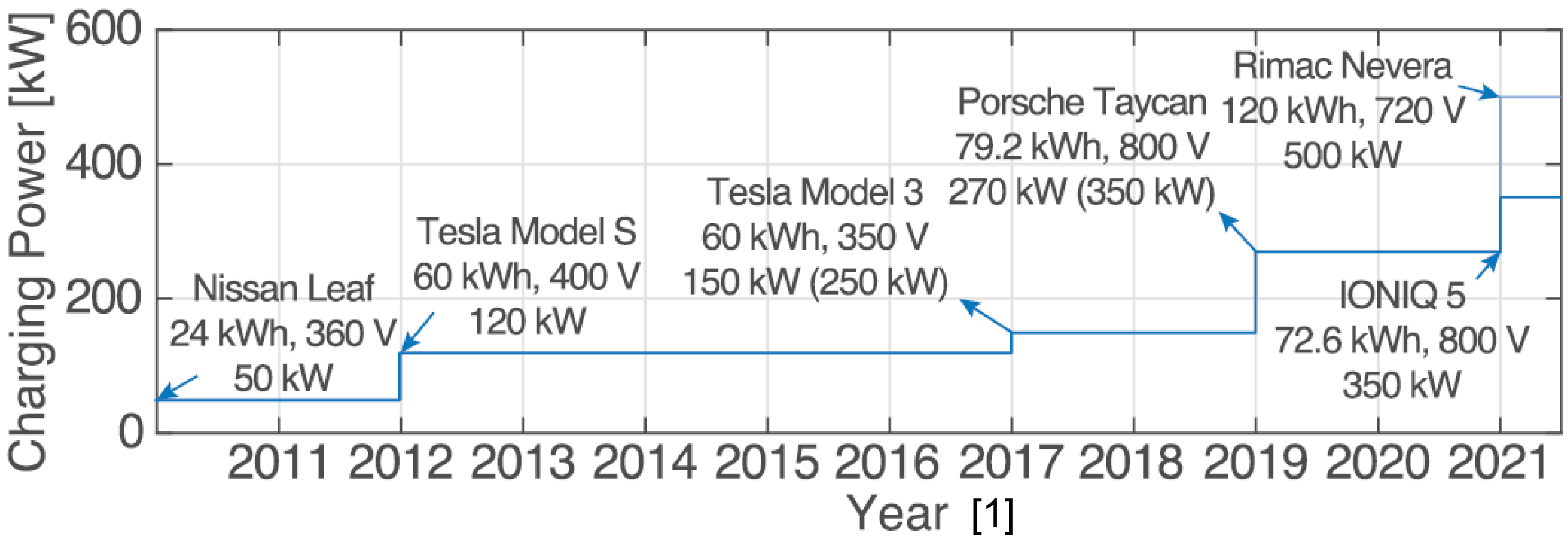


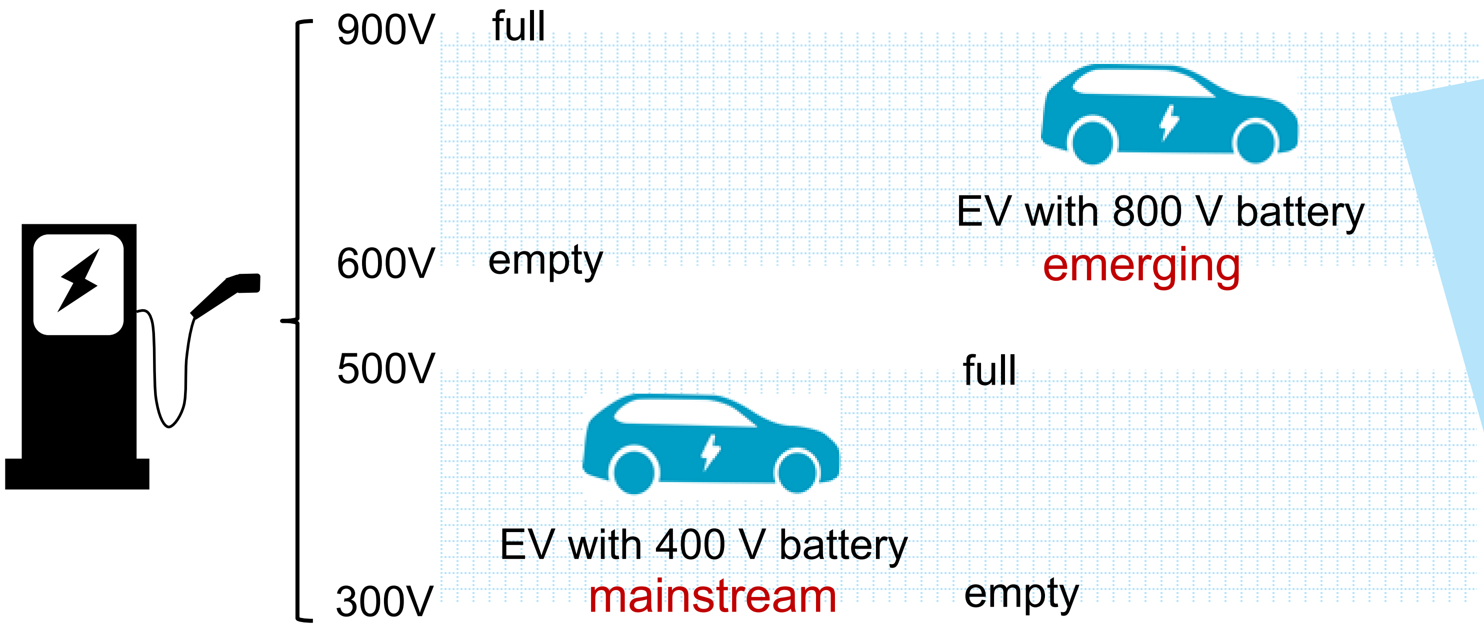
1 s Solid State EVs With 932-Mile Range, 10-Minute Charging by 2027

Normally, 20 kWh per 100 km
Around 1.8 MW charging power!!!

Source: [1] Rivera et al., Charging Infrastructure and Grid Integration for Electromobility, *Proceedings of IEEE*, 2023

Battery Voltage Is Increasing

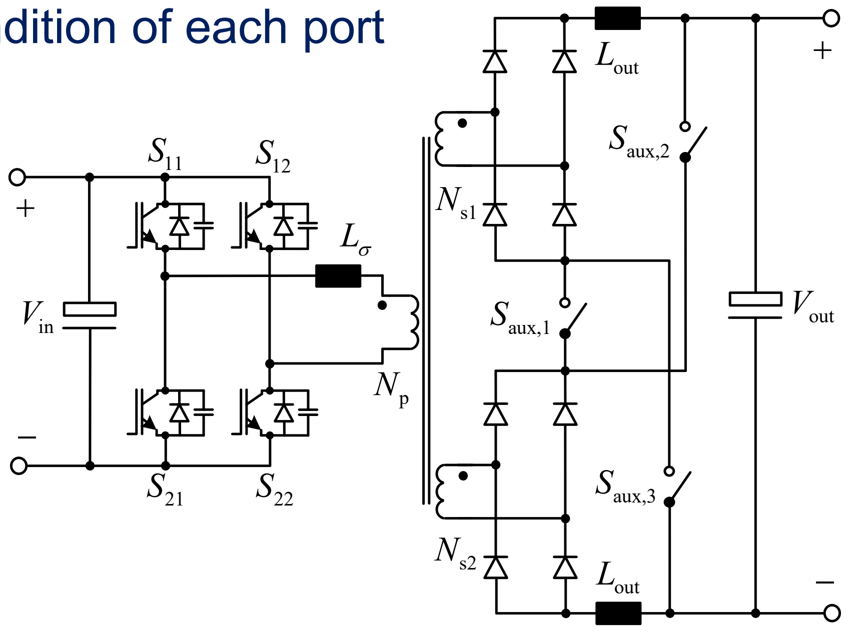
- EVs with 800V batteries are increasing in numbers. Chargers that can cover 300V~900V will have a good market

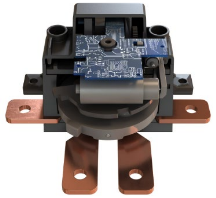


- Porsche: Taycan
- Tesla: Cyber truck
- Kia: EV6, EV9
- Hyundai: IONIQ 5/6
- BYD: ATTO 3, Dolphin, etc.
- XPeng: G9
- etc.

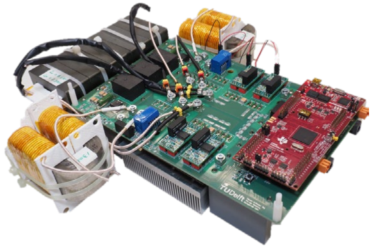
Reconfigurable Topology

- Switching between parallel and series to maintain a steady operation condition of each port



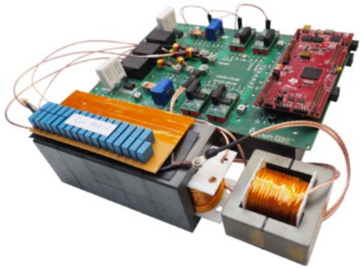


@Eaton BCS



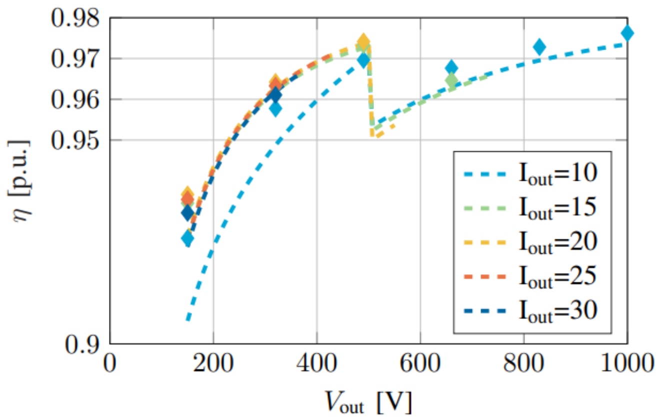
10 kW FSFB module

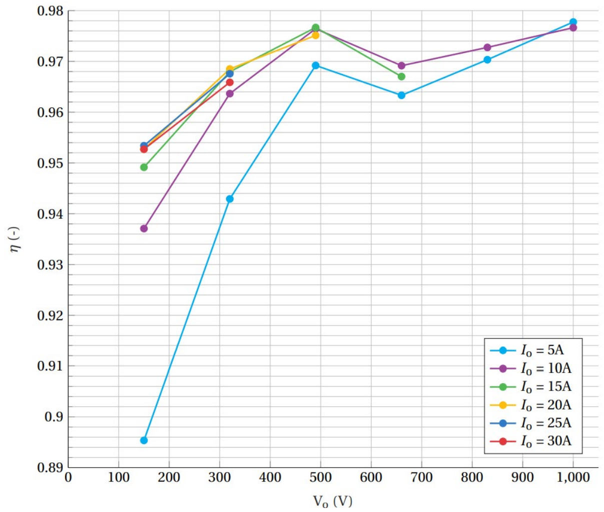
- 640-840V V_{in}
- 200-1000 V_{out}
- 30A $I_{out(max)}$



10 kW LLC module

- 640-840V V_{in}
- 200-1000 V_{out}
- 30A $I_{out(max)}$

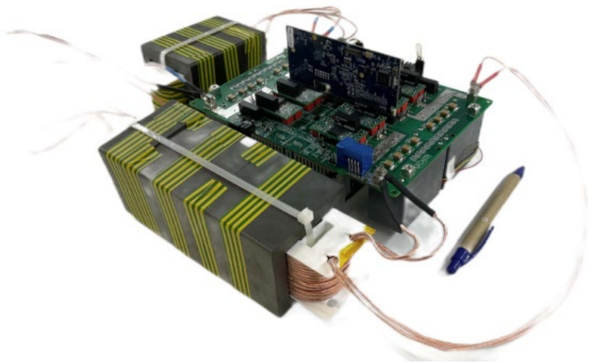




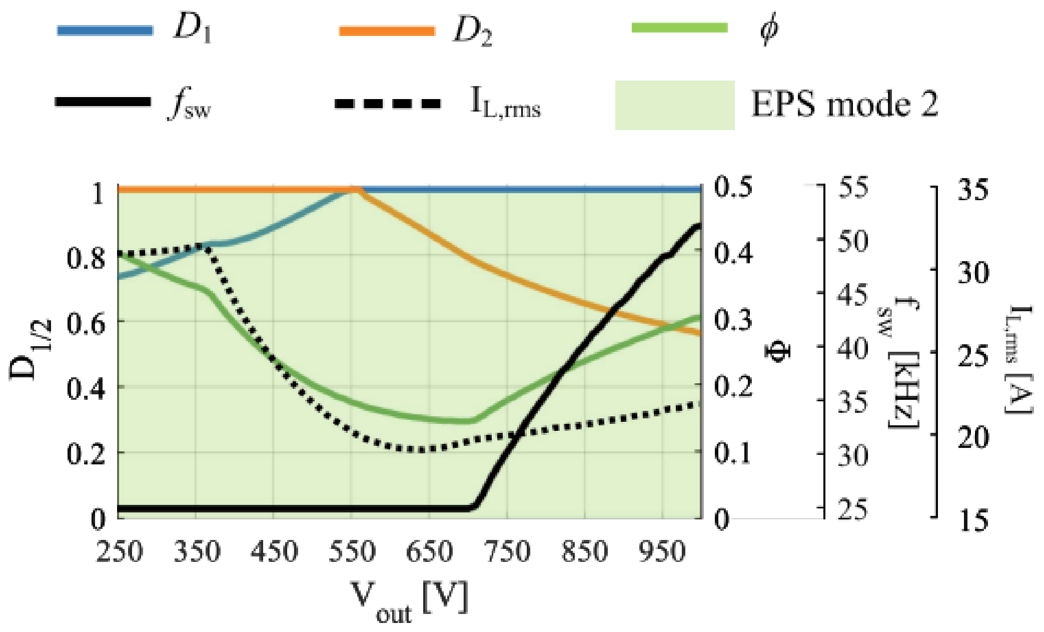
Source: D Lyv, et al., “Design and Implementation of a Re-configurable Phase-Shift Full-Bridge Converter for Wide Voltage Range EV Charging Application,” *TTE*, 2022

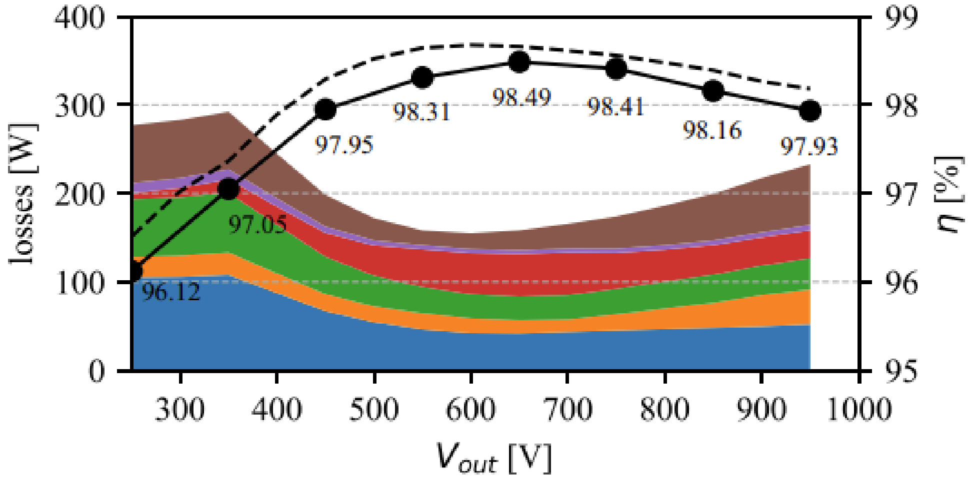
HYBRID OPERATION MODE

- Hybrid modulation strategies and variable switching frequency
- Maximize the ZVS region and minimize switching loss



11 kW DAB module

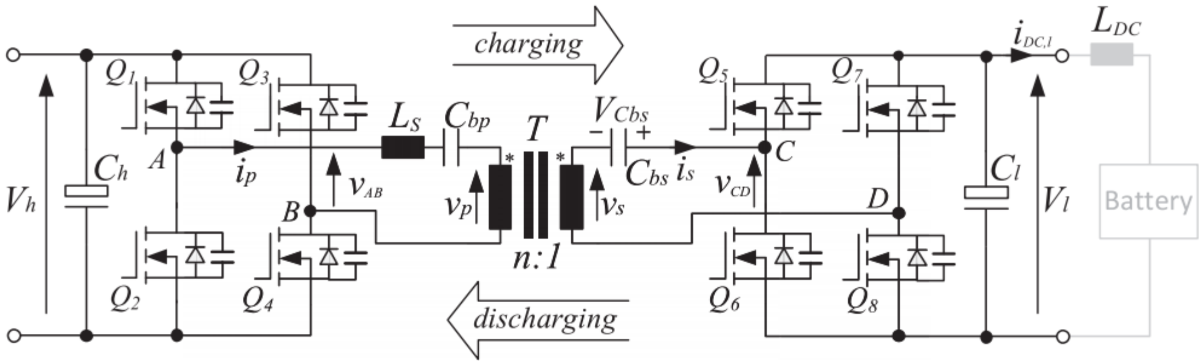


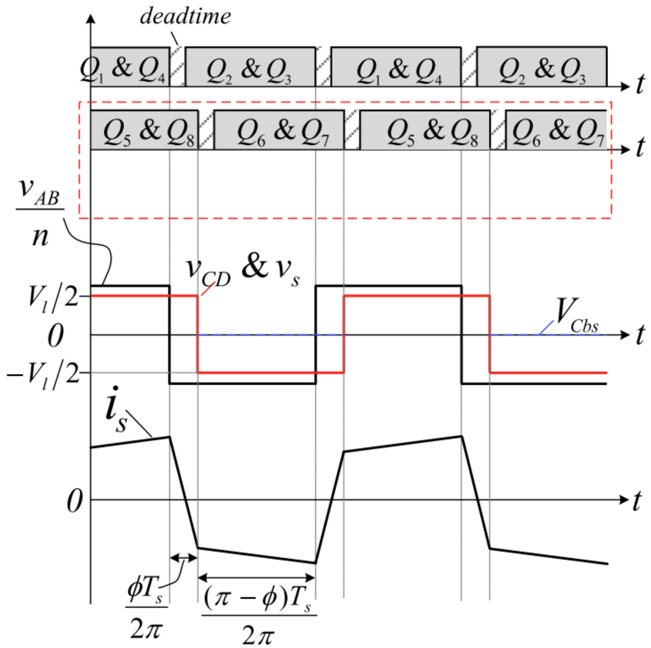


Source: D Lyv, et al., "ZVS-Optimized Constant and Variable Switching Frequency Modulation Schemes for Dual Active Bridge Converters," *IEEE OJPEL*, 2023

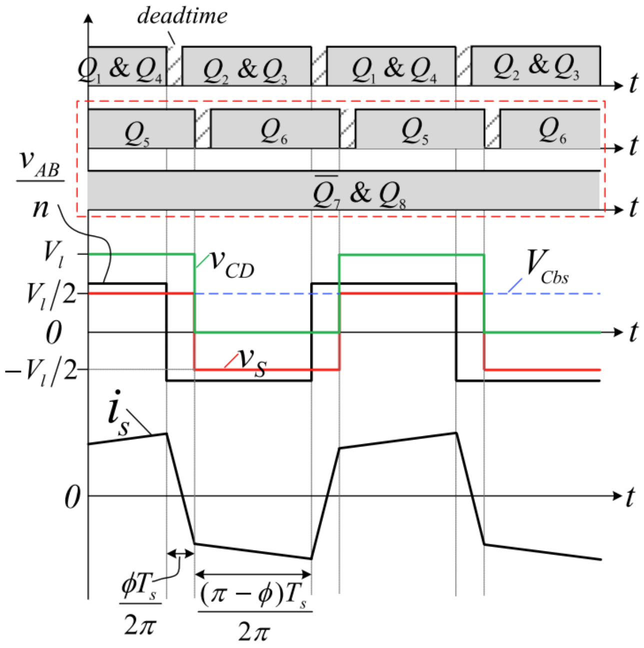
HYBRID OPERATION MODE

- DC blocking capacitor voltage control
- Operation switching between the full and half-bridge mode
- Change hard-switching to soft-switching
- Reduce core loss





@ low V_{batt}, *full bridge mode*, $V_{cbs} = 0$



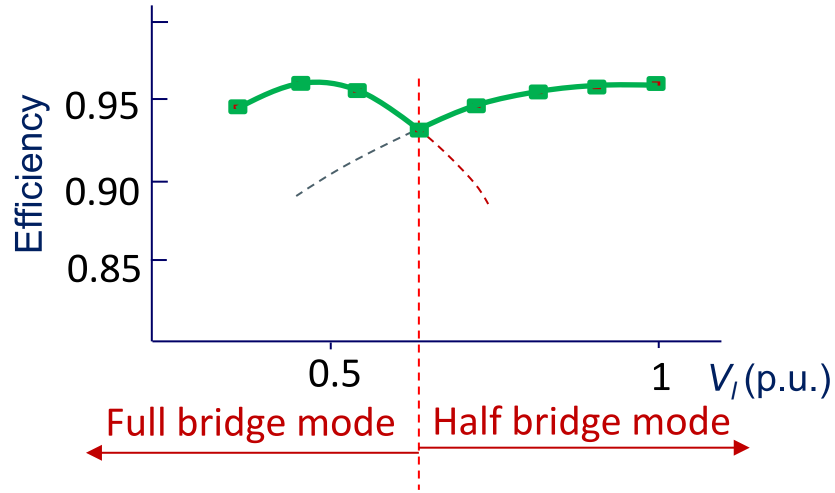
@ high V_{batt}, *half bridge mode*, $V_{cbs} = V_{batt}/2$

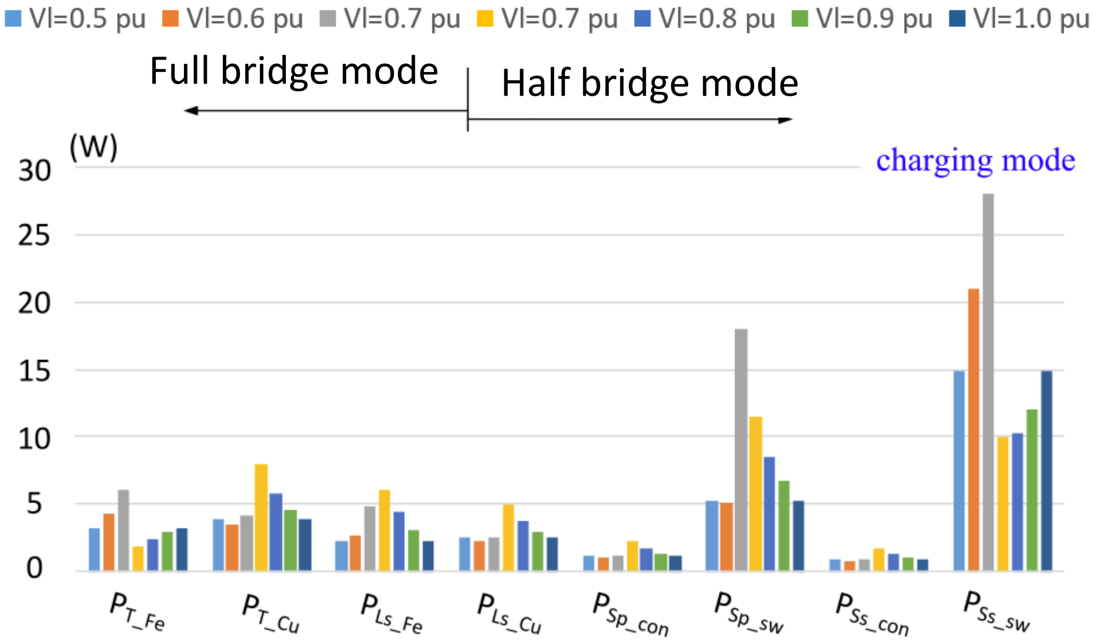
Source: Z Qin, et al., "A Dual Active Bridge Converter With an Extended High-Efficiency Range by DC Blocking Capacitor Voltage Control," *IEEE TPEL*, 2018

HYBRID OPERATION MODE

- DC blocking capacitor voltage control
- Operation switching between the full and half-bridge mode
- Change hard-switching to soft-switching
- Reduce core loss

5 kW DAB module



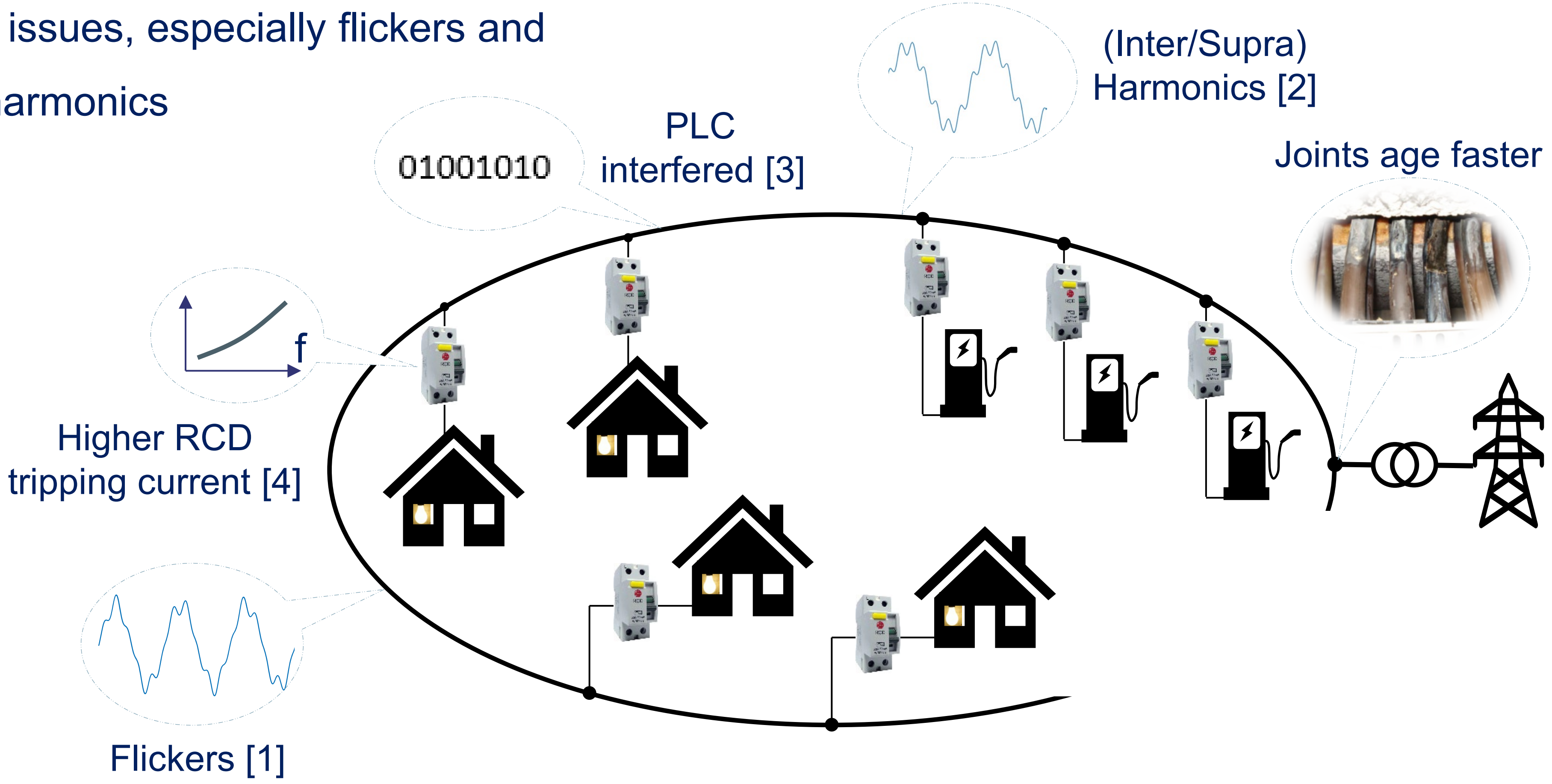


Loss breakdown

Source: Z Qin, et al., "A Dual Active Bridge Converter With an Extended High-Efficiency Range by DC Blocking Capacitor Voltage Control," *IEEE TPEL*, 2018

Power Quality Issues

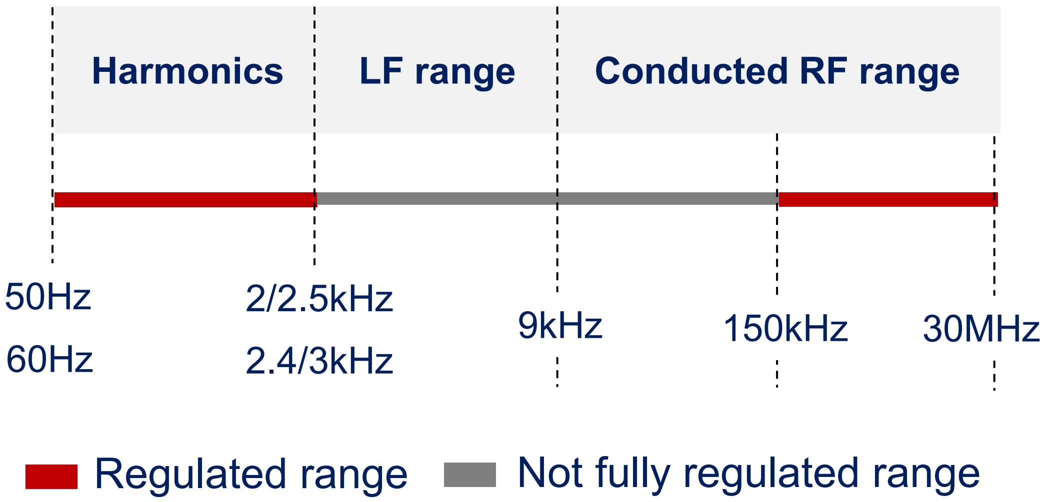
- EV charging is associated with power quality issues, especially flickers and supraharmonics

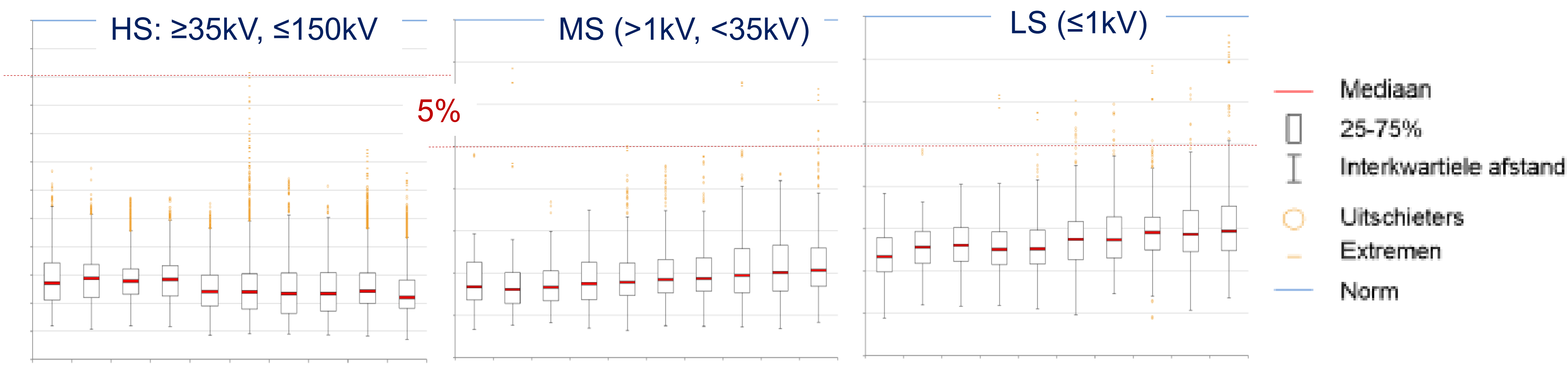


Source:
[1] https://teslamotorsclub.com/tmc/threads/lights-in-house-flicker-while-charging-new-model-3.149841/
[2] T Slangen, V Ćuk, S Cobben, "Summation of supraharmonic currents (2–150 kHz) from EV fast charging stations," Electric Power Systems Research 220, 2023
[3] L Hasselgren, G Mademlis, Å Lindbeck, et. al. "Inverter Interference on Charging Communication System during 400 V DC Charging of Vehicle," EMC Europe, 2022
[4] T Slangen, B Lustenhouwer, JFG S Cobben, et. al. "The Effects of High-Frequency Residual Currents on the Operation of Residual Current Devices," in the Proc. Of ICREPQ 2021

POWER QUALITY ISSUES

- Harmonics are reducing in high voltage grids, and increasing in low and medium voltage grids



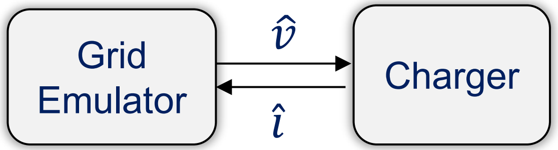


Jaartal THD 95% (2011~2020) [1]

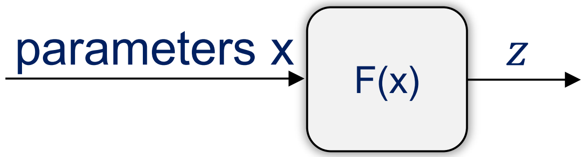
Source: [1] Spanningskwaliteit in Nederland - Resultaten 2020

GRAY BOX IMPEDANCE MODELLING

- White box modelling needs the hardware and control parameters as input, but usually unavailable
- Black box modelling doesn't need the parameters, but cannot cover the whole operation range
- Gray box modelling has advantages of both of them

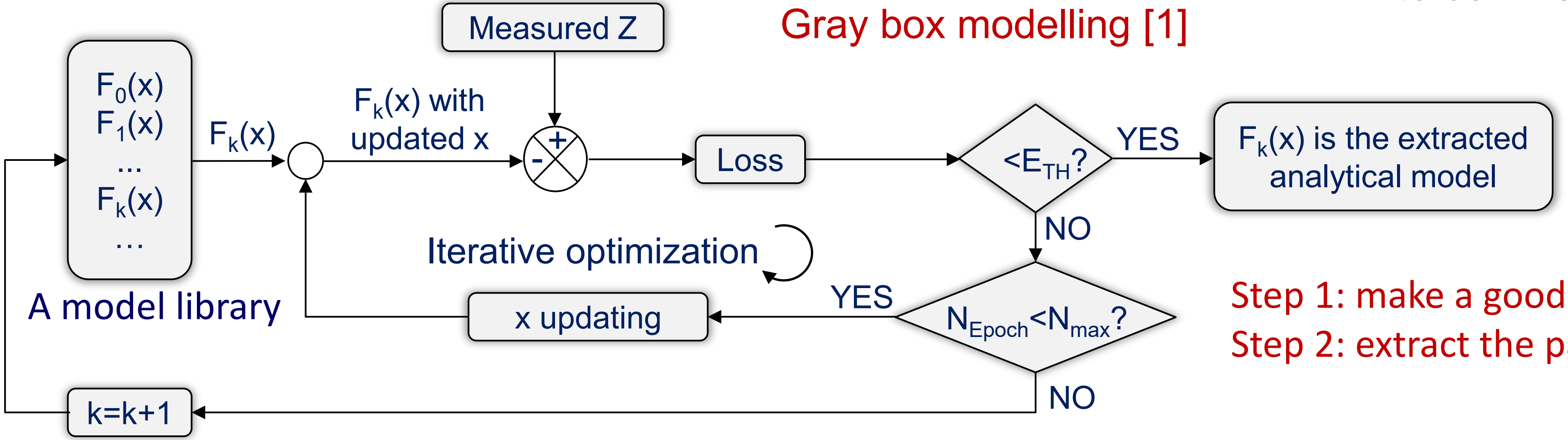


Black box modelling $z = \frac{\hat{v}}{\hat{\imath}}$



White box modelling

Gray box modelling [1]

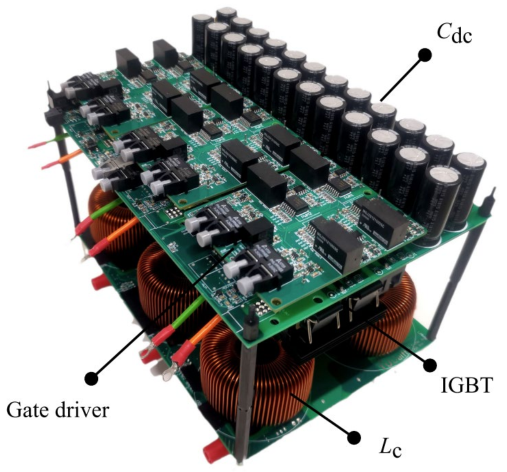


Step 1: make a good guess of the model
Step 2: extract the parameter values

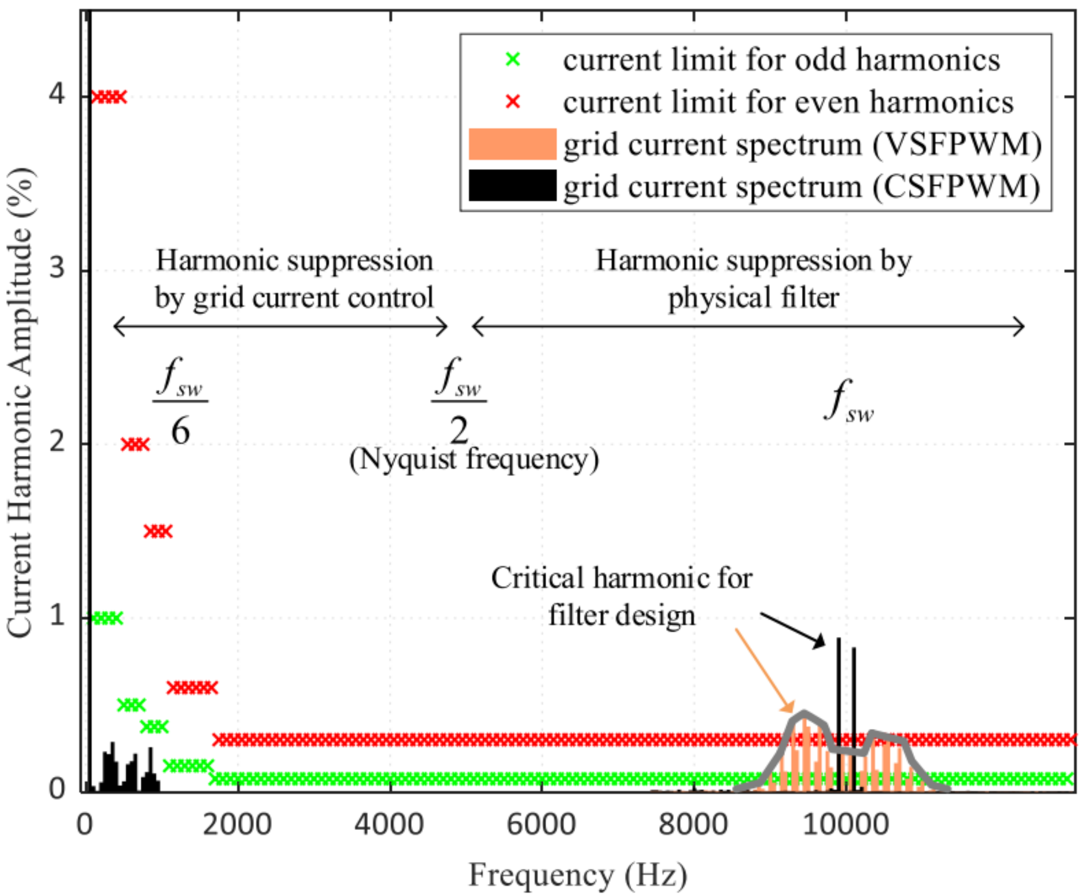
Source: [1] L Wang, et. al. "A gradient-descent optimization assisted gray-box impedance modeling of ev chargers," *TPEL*, 2023

SUPRAHARMONICS MITIGATION

- ❑ Fixed switching frequency creates harmonics with high peak
- ❑ Variable switching frequency will spread out the harmonics.
- ❑ THD is still the same



- ➢ 10 kW rectifier module
- ➢ Peak efficiency 98.6%



IEEE-519 harmonic current standard and typical grid current harmonic spectrum with CSFPWM and VSFPWM.

Source: Y Wu, et. al. "Frequency Design of Three-phase Active Front-End Converter with Reduced Filter in EV Chargers," *TTE*, 2024

SUPRAHARMONICS MITIGATION

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- ❑ Variable switching frequency will spread out the harmonics.
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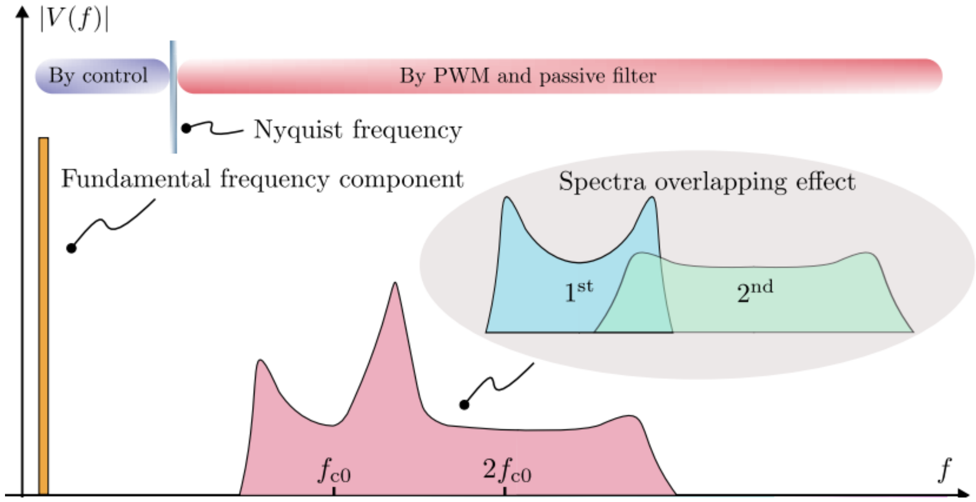
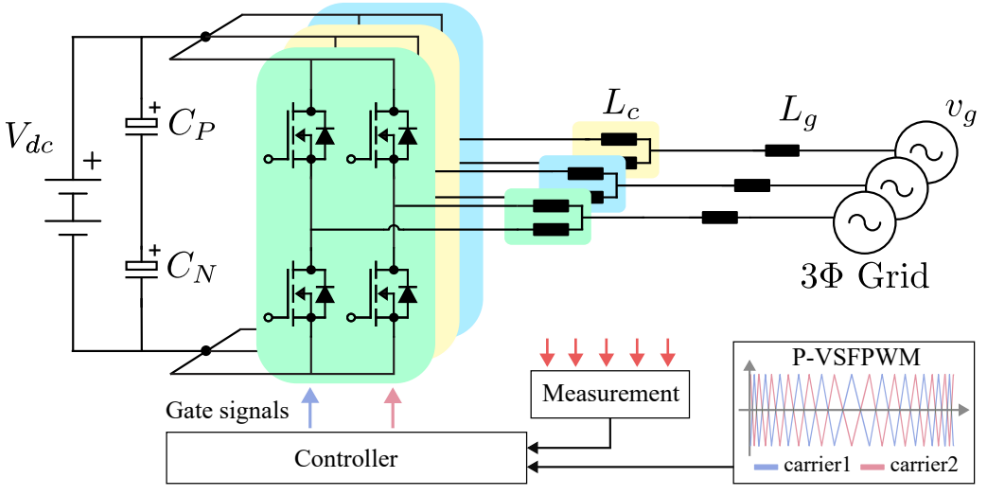
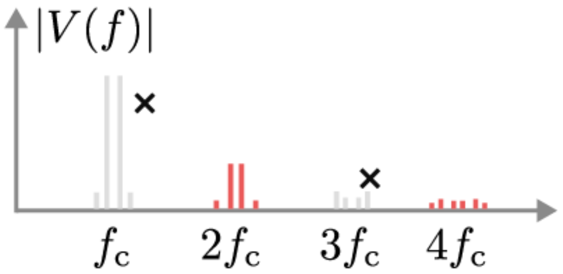


- The spead out of the harmonics may have overlap with each other and create peak again





- Interleaving will solve the problem

Source: Y Wu, et. al. "Frequency Design of Three-phase Active Front-End Converter with Reduced Filter in EV Chargers," *TTE*, 2024

SUPRAHARMONICS MITIGATION

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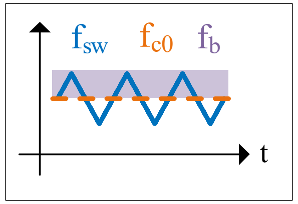
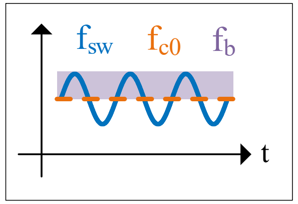
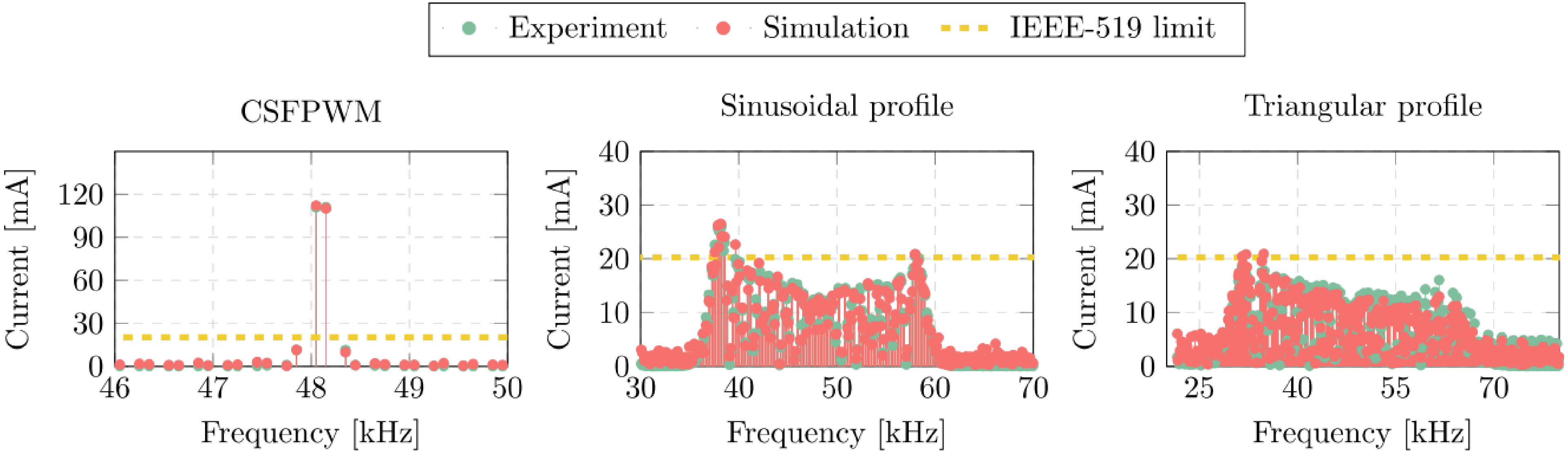
- Fixed switching frequency creates harmonics with high peak
- Variable switching frequency will spread out the harmonics.
- THD is still the same



Triangle profile



Sinusoidal profile

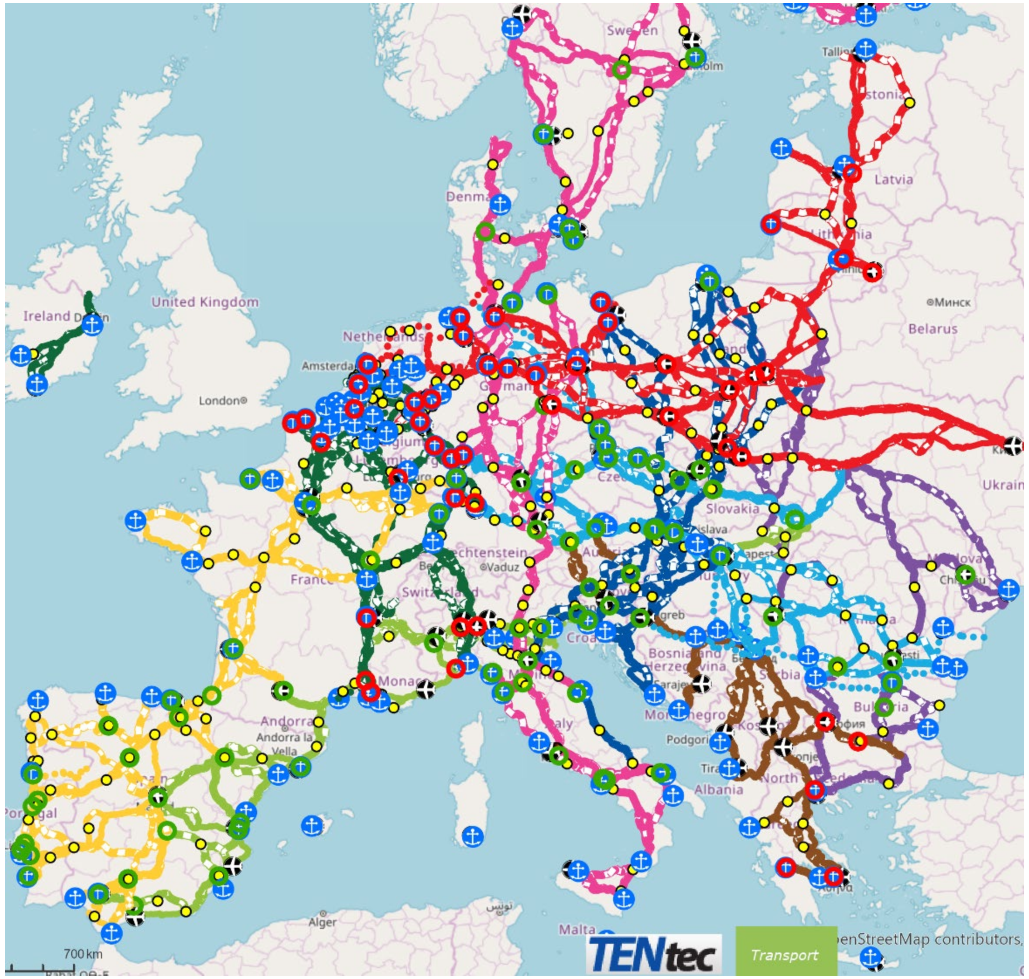


Source: Y Wu, et. al. "Frequency Design of Three-phase Active Front-End Converter with Reduced Filter in EV Chargers," *TTE*, 2024

More challenges to grids

TEN-T

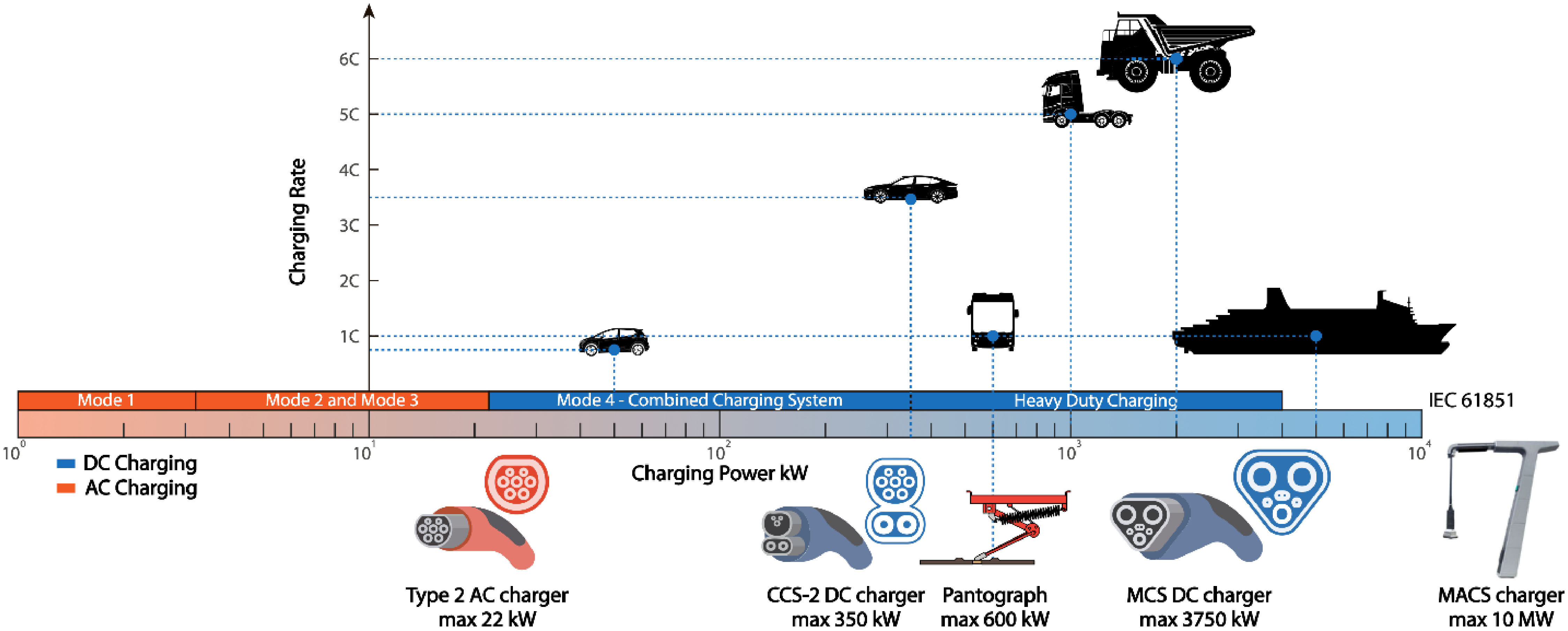
- By 2025, < 60 km interval, > 150 kW charger
- By 2030, < 100 km interval, > 350 kW charger
- By 2030, most maritime ports should offer shore power



Trans-European Transport Network (TEN-T)

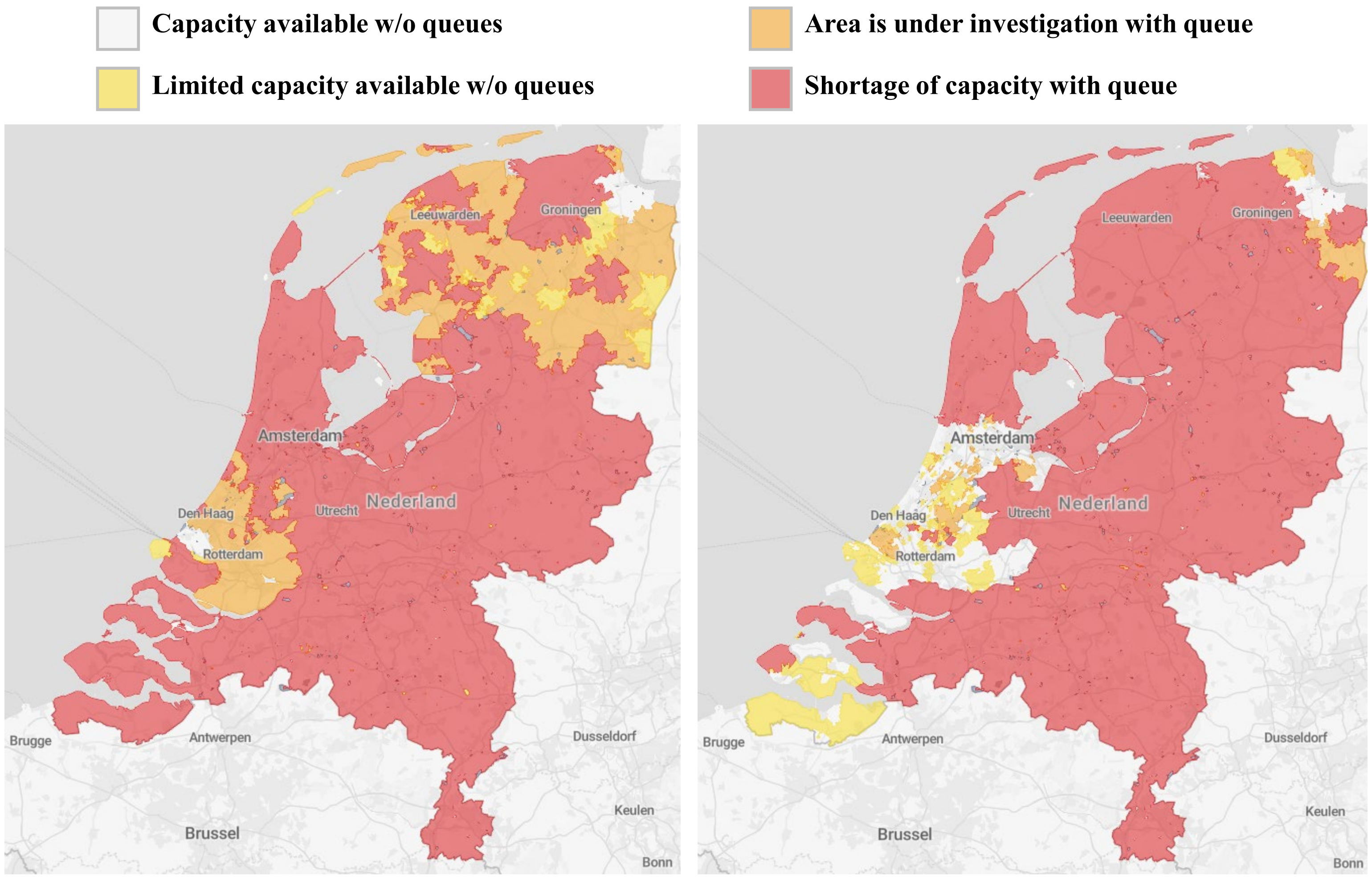
Source: European Commission, DG MOVE, TENtec Information System, based on Reg. 2024/1679

MEGA WATT CHARGING



Source: Z Qin, et al, Innovative electric vehicle charging infrastructure for european transportation electrification: megawatt charging hubs with battery energy storage and solid-state transformers for medium-voltage grid integration, *MELE*, 2025

GRID CONGESTION



(a) Consumption congestion (b) Generation congestion

Source: *Netbeheer Nederland*

- In Netherlands, any user larger than 60 kW needs to wait around 7 years to get a new grid connection

GRID FEE

Connection capacity	One-off connection fee (€)	Annual fee to maintain the connection (€)
> 175 kVA to 630 kVA via LS measurement	34002	1455
> 630 kVA to 1000 kVA via LS measurement	36000	
> 1000 kVA to 1750 kVA via MS measurement	58000	
> 1750 kVA to 5000 kVA	330000	3642

Contracted transport capacity	Transportation service			
	Fixed charge	Variable tariff		
	Transport per month (€)	kW contract per month per kW (€)	Double tariff per kWh (€)	Reactive power consumption per kVARh (€)
151 to 1500 kW	36.75	2.0250	0.0198	0.017
> 1500 kW	230	1.8958	0.0198	0.017

LS: ≤1kV;
MS: > 1kV, ≤20kV;
TS: 50kV;
HS: > 50 kV

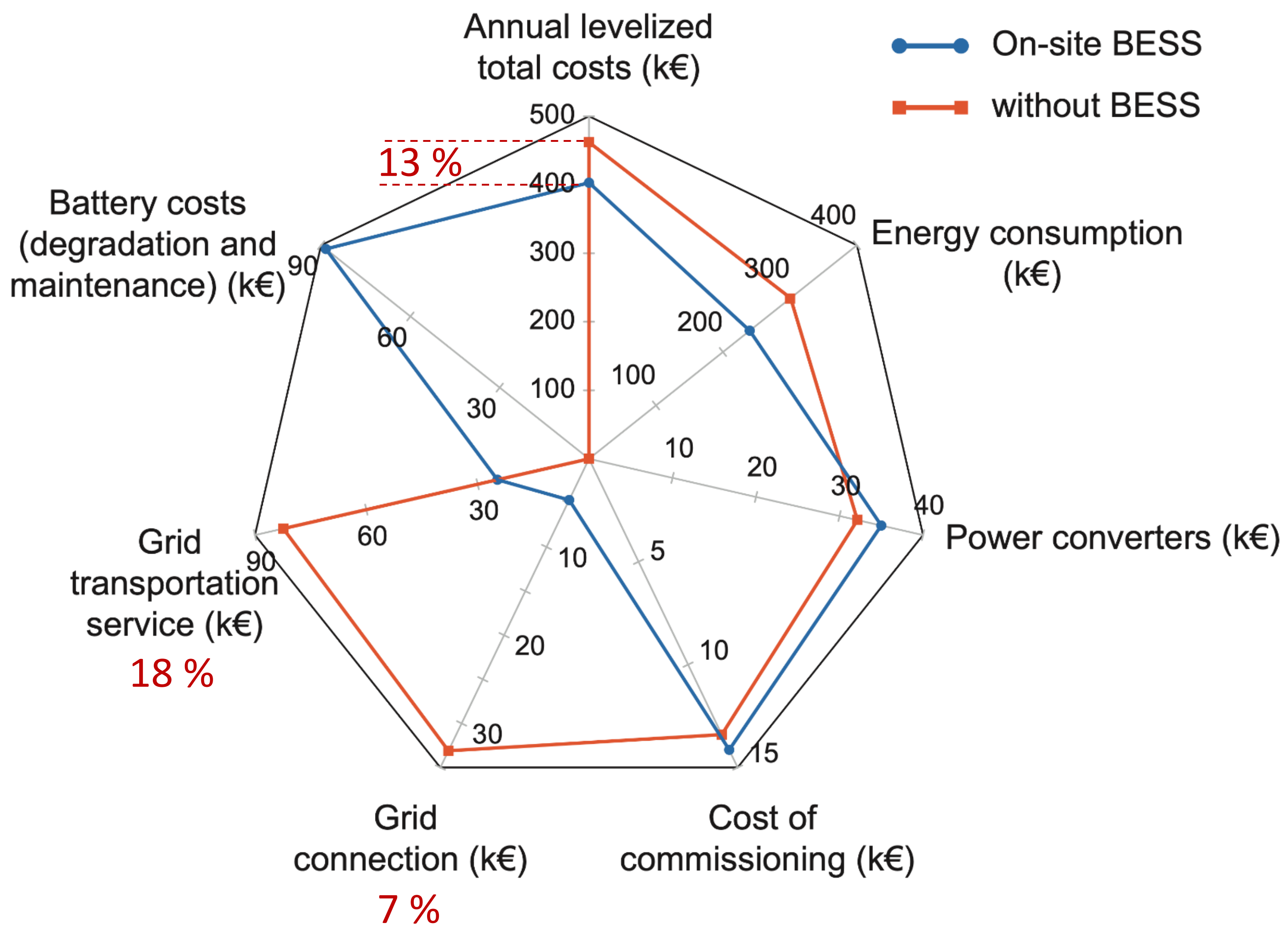
- When connected to grid, **you pay** not only per kWh, but also **per kW**
- You pay more with higher peak grid power, even with fixed average grid power

Source: published data from Stedin – A DSO in Netherlands. The data is for year 2025

MEGA WATT CHARGING

- Total charging load: 3.5 MW
- W/O BESS: grid connection 3.5 MW
- With BESS: grid connection 1 MW, battery 2.5 MW / 2.5 MWh
- Battery service life 11.2 years

- Grid fee keeps increasing
- Battery cost keeps decreasing



Source: A Ahmad, et. al. "Techno-economic analysis of energy storage systems integrated with ultra-fast charging stations: A dutch case study," *eTransportation*, 2025
Z Qin, et al, Innovative electric vehicle charging infrastructure for european transportation electrification: megawatt charging hubs with battery energy storage and solid-state transformers for medium-voltage grid integration, *MELE*, 2025

PILOT PROJECTS/PRODUCTS

- 6 Chargers x 320 kW
- Grid maximum power 200 kW
- 2.45 MWh used battery
- 24 charges per day around 800 kWh

1360kW
行业最大功率液冷充电系统

$1.5 m^2$
占地面积小

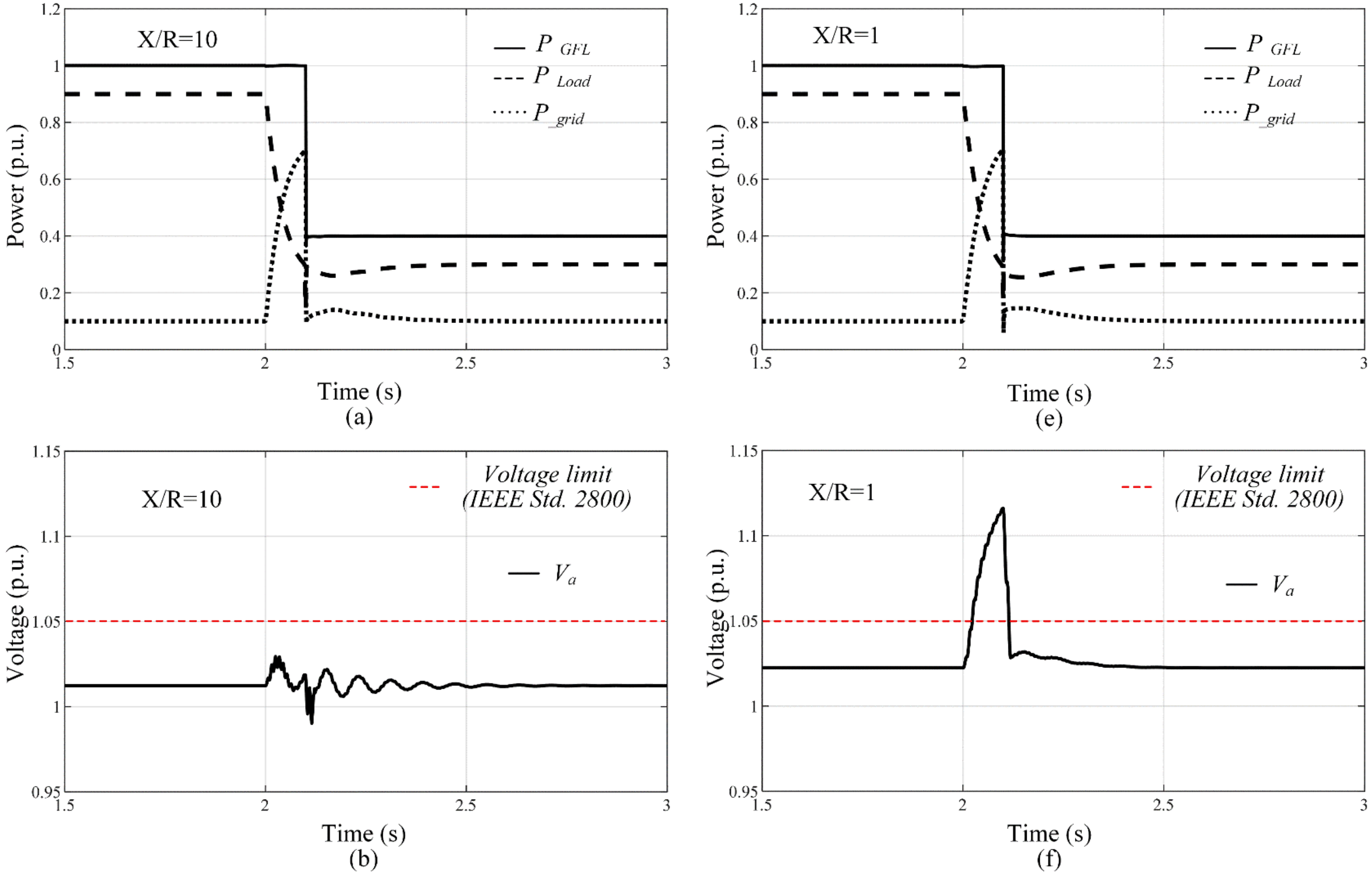
一桩双枪
功率智能分配

Source: BYD, Super e-Platform

Source: Audi charging hub

How to control the BESS

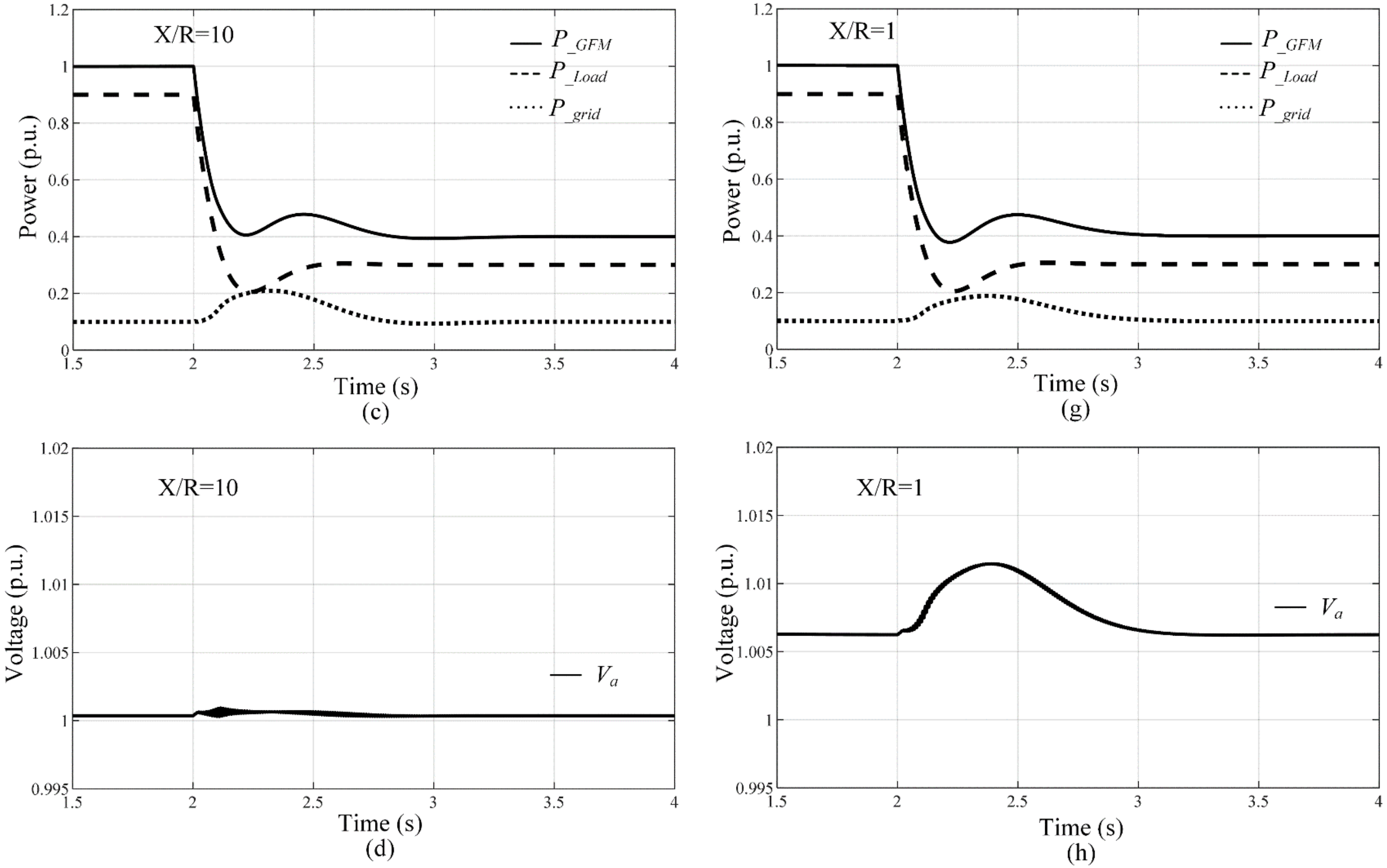
BESS in grid following control



When grid connection has a capacity much lower than the charging hub capacity, charging load change can induce significant grid voltage variation. Grid voltage forming control will be necessary

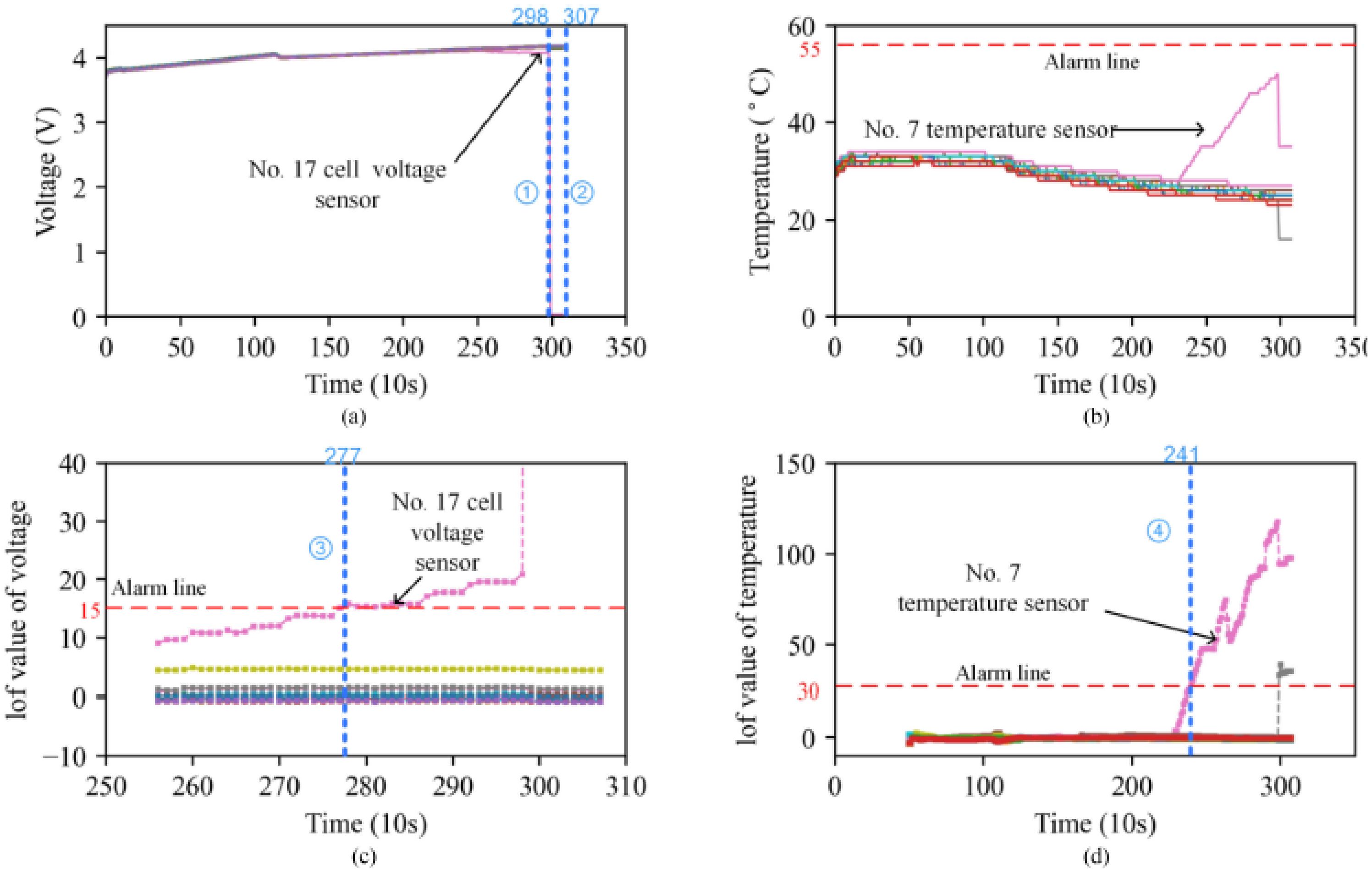
How to control the BESS

BESS in grid forming control



When X/R is low, the voltage will be significantly influenced by both active and reactive power. The grid forming control needs to be adapted

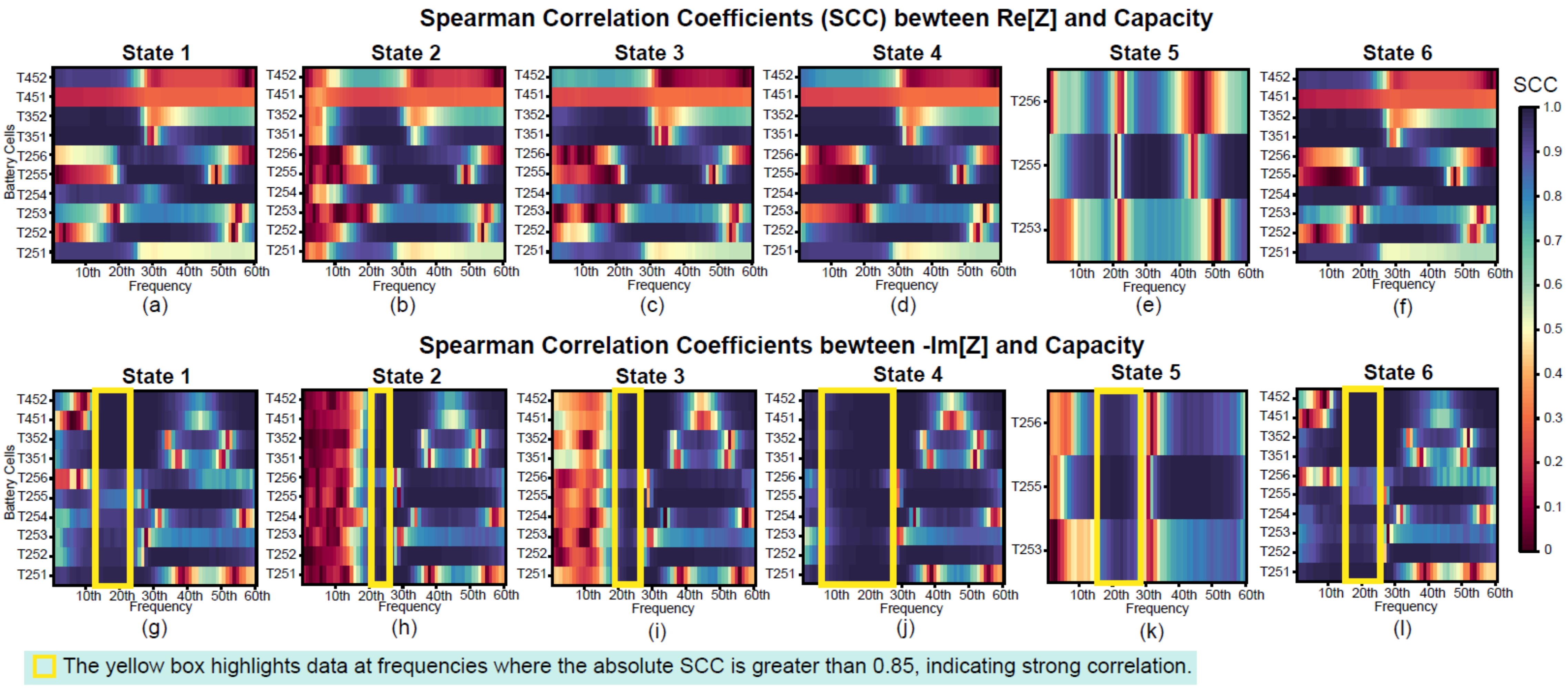
BATTERY FAULT DETECTION



- ❑ LOF value helps identify the problematic cell

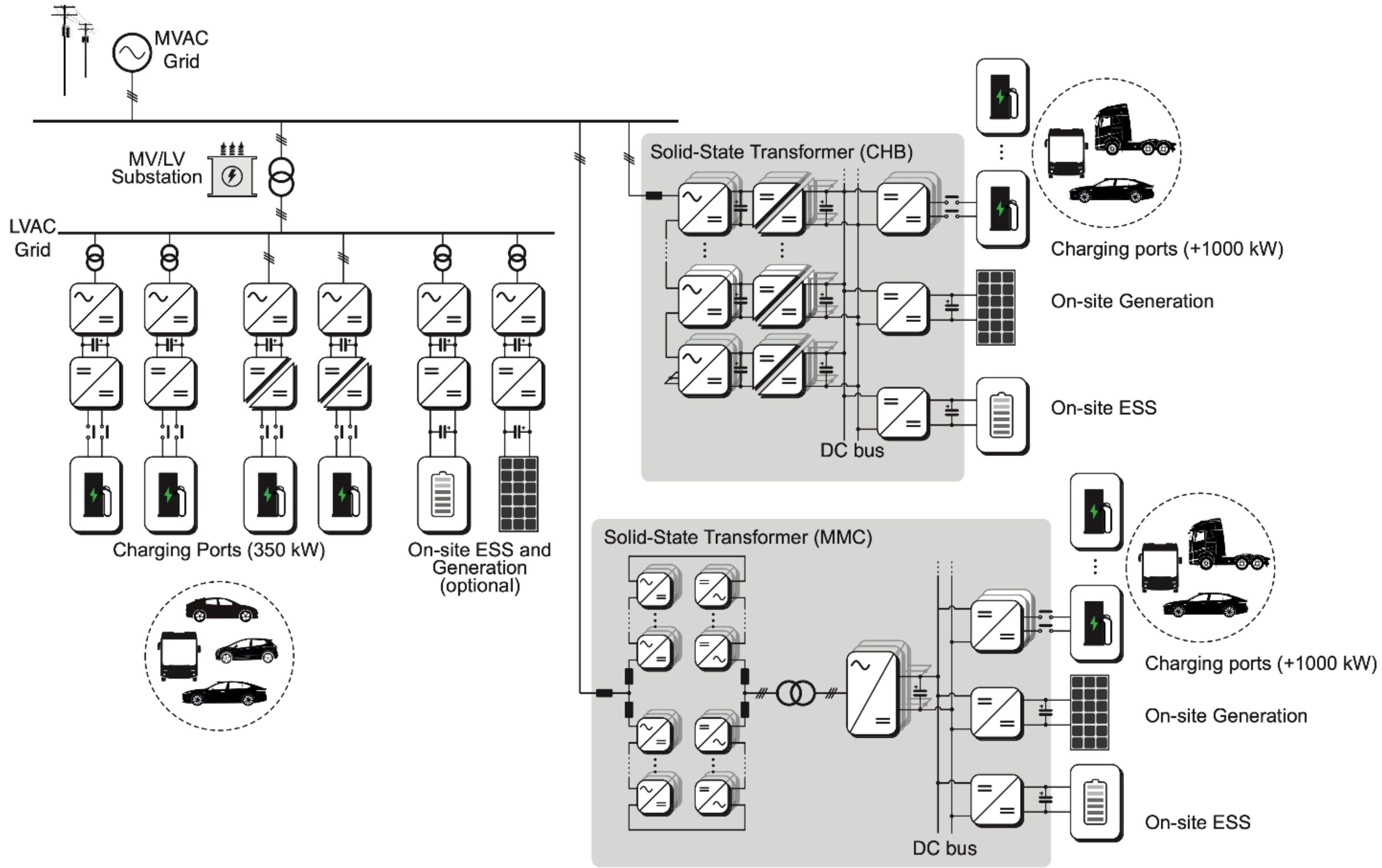
Source: Z Sun, et. al, An Online Data-Driven Fault Diagnosis and Thermal Runaway Early Warning for Electric Vehicle Batteries, *TPEL*, 2022

EIS BASED APPROACH FOR SOH ESTIMATION



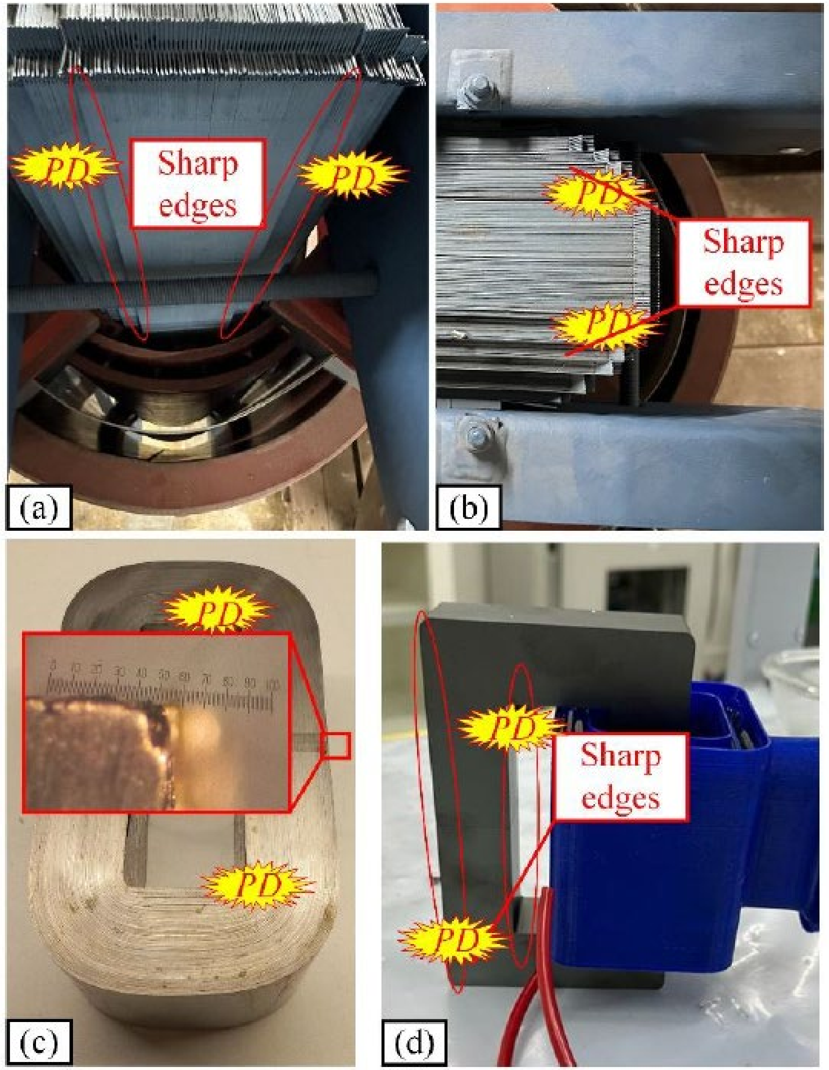
Source: R. Liu, et. al, "A Transformer-Enhanced Framework for Lithium-ion Battery Capacity Estimation Using Limited Imaginary Impedance Feature", *Journal of Energy Storage*, 2025

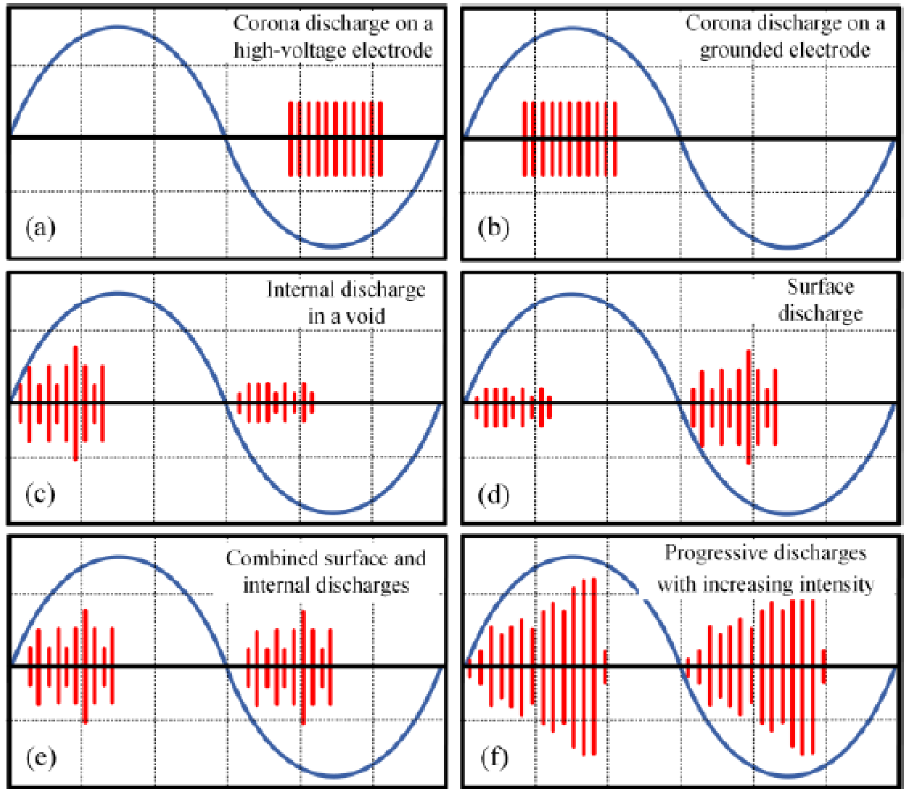
MEDIUM VOLTAGE GRID INTEGRATION



Source: Z Qin, et al, Innovative electric vehicle charging infrastructure for european transportation electrification: megawatt charging hubs with battery energy storage and solid-state transformers for medium-voltage grid integration, *MELE*, 2025

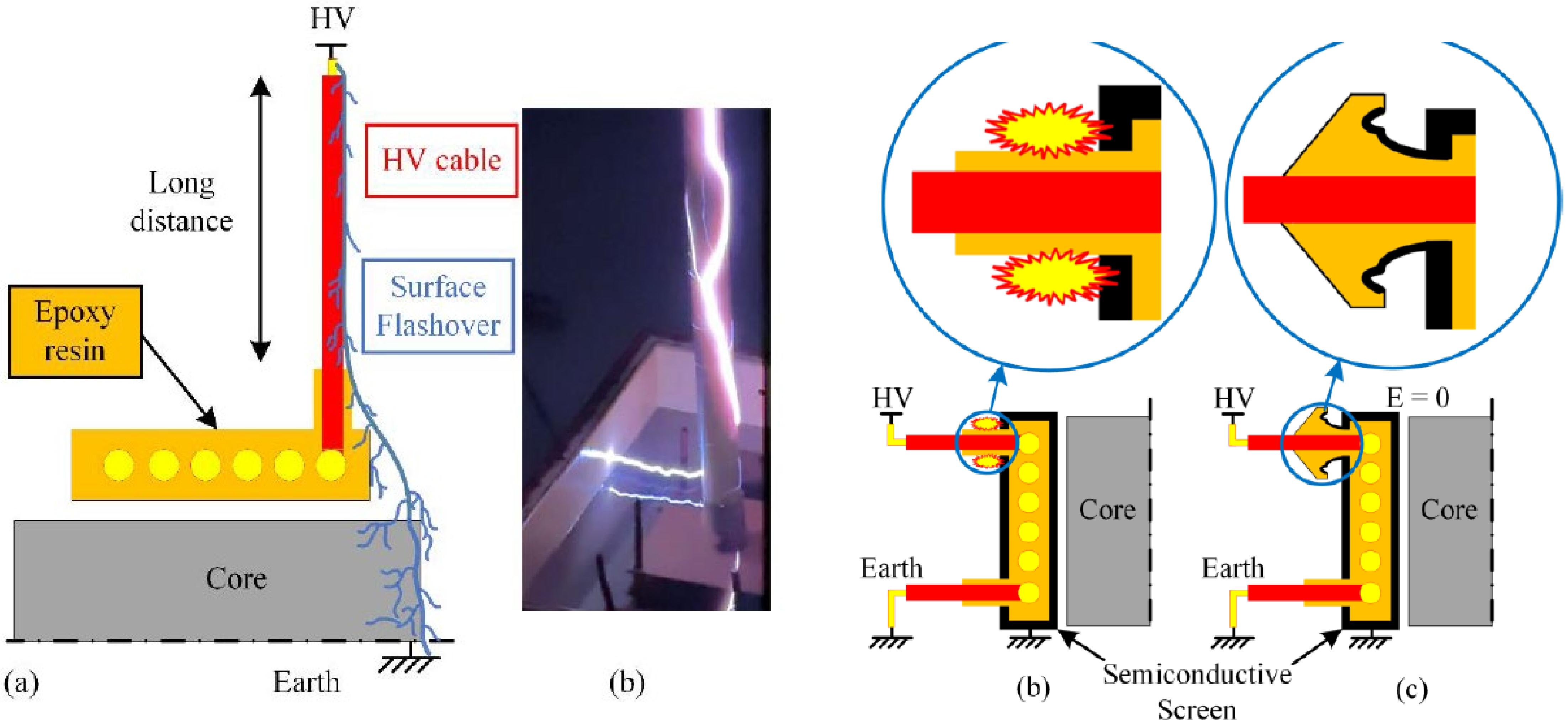
PARTIALLY DISCHARGE





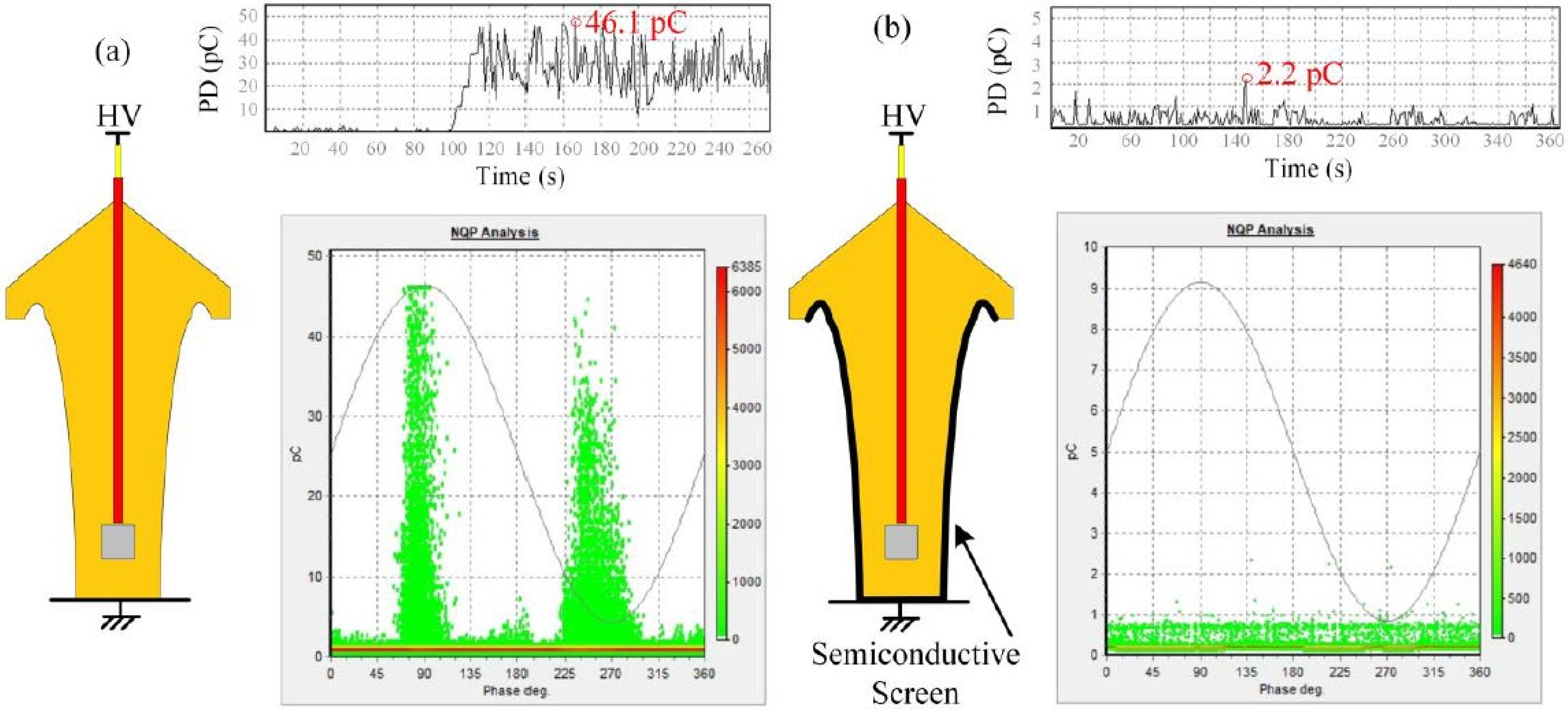
Source: Reza Mirzadarani, et. Al., Partial Discharge Mitigation of Medium-Voltage, Medium-Frequency Dry-Type Transformers Using Semiconductive Screening, *OJPEL*, 2026

SURFACE FLASH OVER LONG DISTANCE



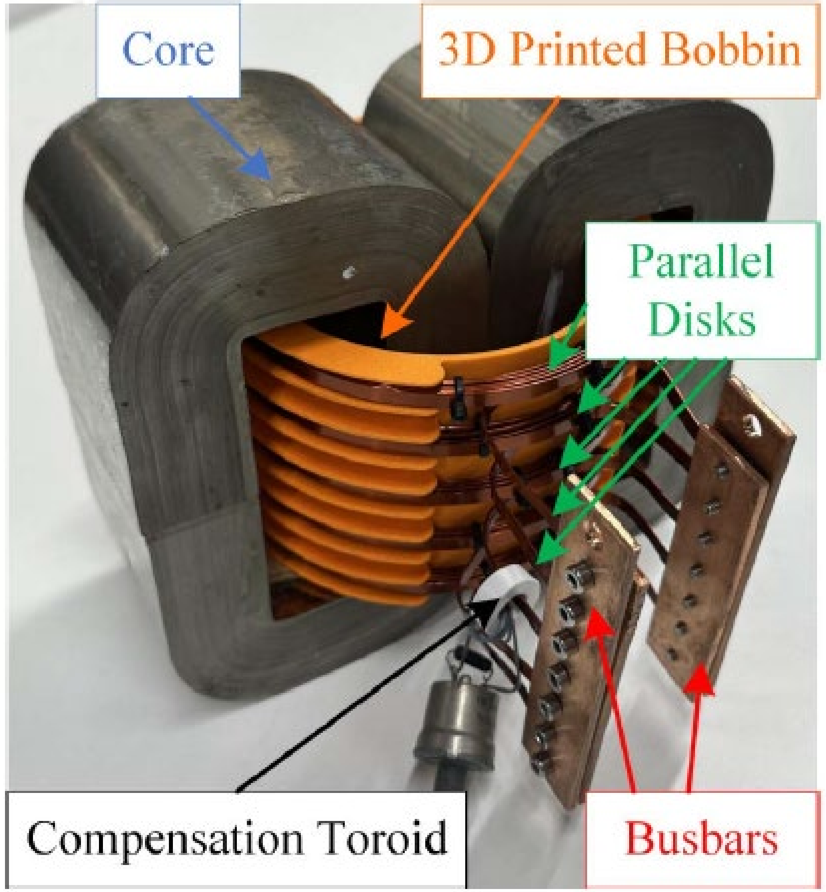
Source: Reza Mirzadarani, et. Al., Partial Discharge Mitigation of Medium-Voltage, Medium-Frequency Dry-Type Transformers Using Semiconductive Screening, *OJPEL*, 2026

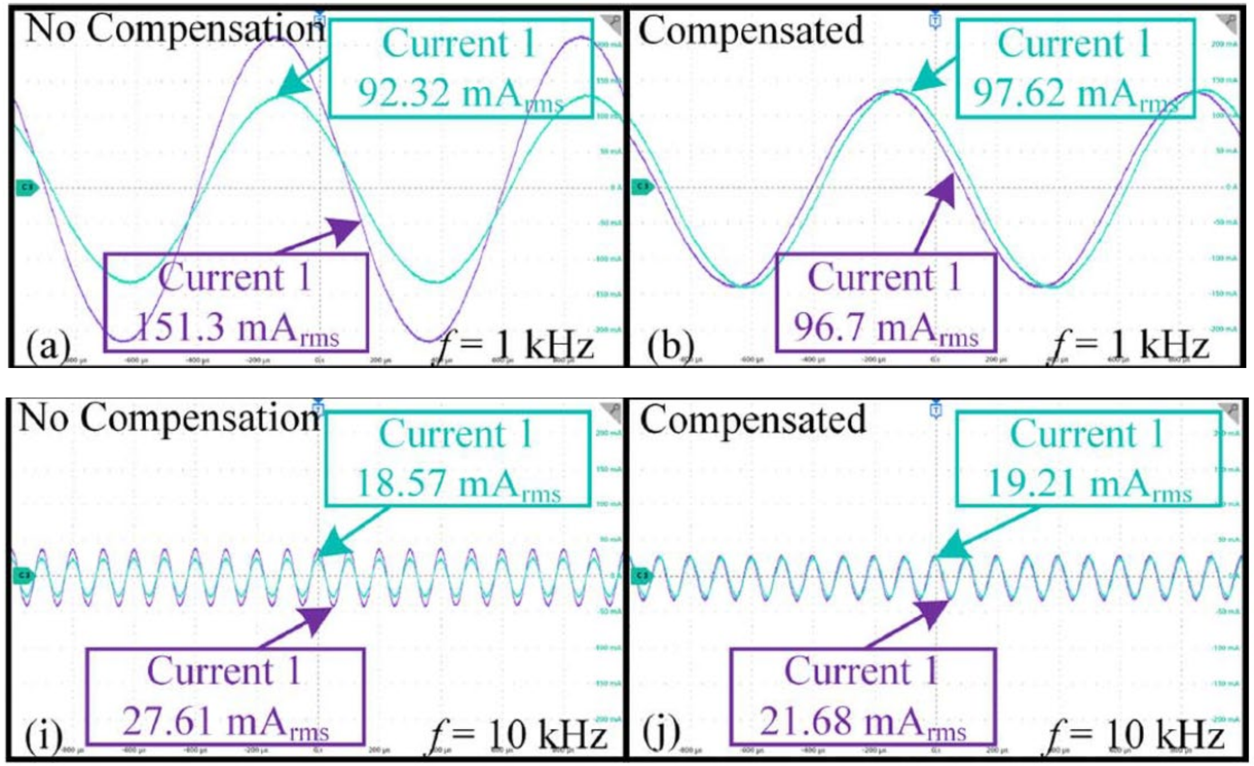
Proposed stress cone and semicon screening



Source: Reza Mirzadarani, et. Al., Partial Discharge Mitigation of Medium-Voltage, Medium-Frequency Dry-Type Transformers Using Semiconductive Screening, *OJPEL*, 2026

PARALLEL DISK WINDING AND PROPOSED SOLUTION





Source: R Mirzadarani, et. Al., Current Balancing Technique for the High-Current Windings of Medium-Frequency Transformers, *TIE*, early access

KEY TAKEAWAYS

- Transportation electrification is rapidly developing, and charging power has reached the megawatt level.
- Grid is getting congested, and the charging load is making the situation worse. To further improve the level of transportation electrification, this issue must first be resolved.
- Charging loads are characterized by high peak power and low average power. Integrating battery energy storage into charging hubs can effectively ease grid congestion and reduce grid connection costs.
- However, lithium batteries still face issues such as large errors in state monitoring and difficulty in extinguishing fires once they start. High-precision battery management systems that can accurately estimate battery state and predict battery failures are urgently in need of technological breakthroughs.
- With DC bus-based charging hubs, solid-state transformers can demonstrate greater advantages. Meanwhile, as the energy sector undergoes electrification, the rising cost of raw materials for traditional transformers and increasingly longer lead time are creating favorable conditions for the adoption of solid-state transformers. Insulator design and partially discharge are the remaining challenges in medium voltage power electronics.

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