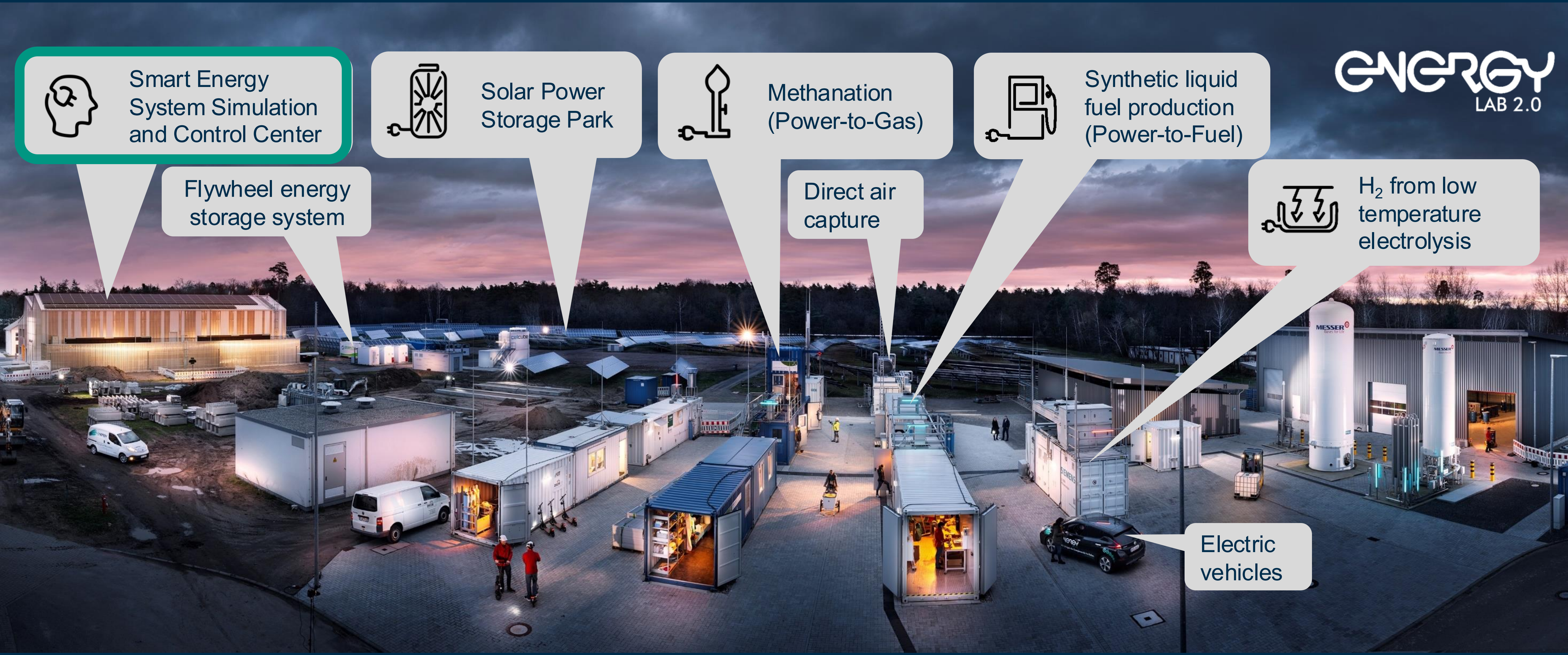
Advancements and solutions for low voltage DC residential grids at the Karlsruhe Institute of Technology

Giovanni De Carne, **Ömer Ekin**, Moein Ghadrdan, Veit Hagenmeyer

Karlsruhe Institute of Technology
26.11.25



Geothermal energy plant

Living Lab experimental buildings

HT thermal storage

Solid oxid fuel cell

Gas turbines

Smart Energy System Simulation and Control Center

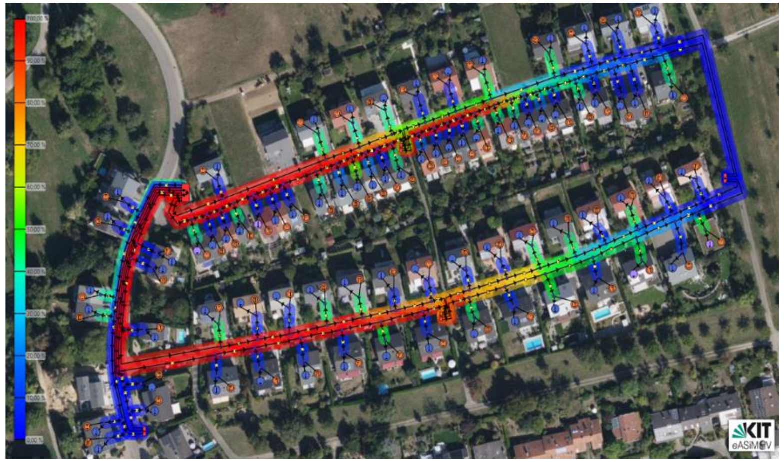
We are designing and operating future power grids on all voltage levels

- **Large-scale research infrastructure** for multi-energy system innovation
- We research and develop **methods** and **technologies** to design and operate resilient, decentralized, and sector-integrated energy systems

Smart Energy System Simulation and Control Center

System-of-Interest

(Distributed real-time) Simulation for operation and optimization of **large-scale power grids**



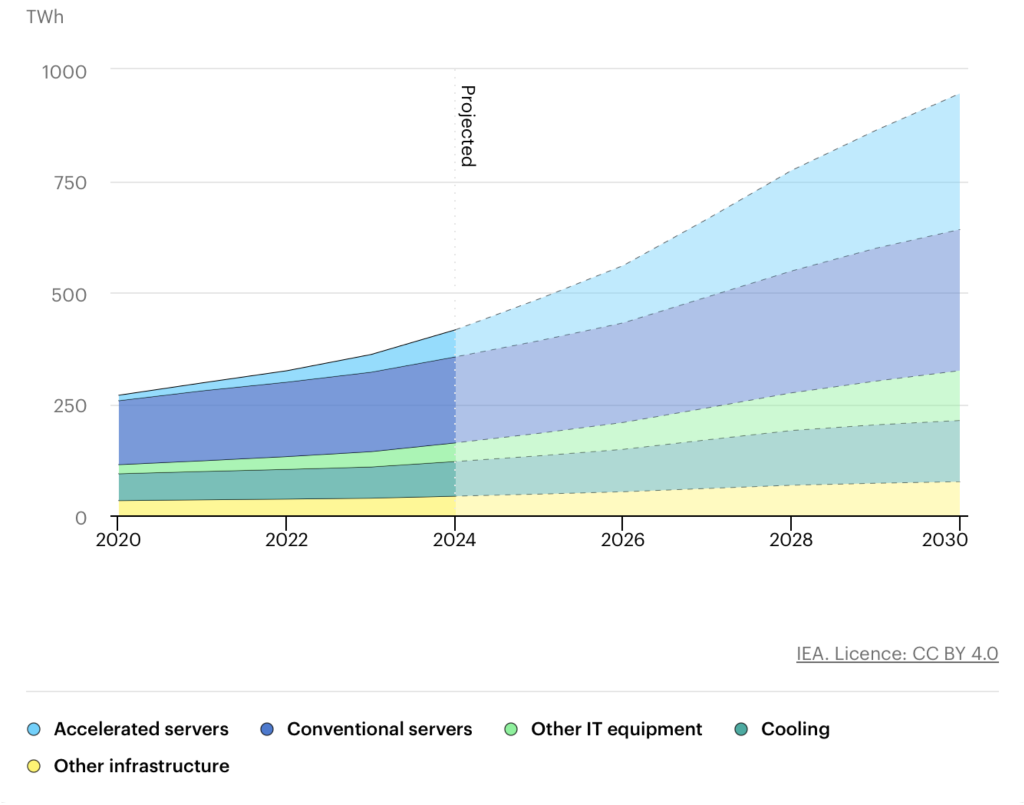
Flexible operation of microgrids and local LV grids **(System-under-Test)**

Design and validation of digital twins of single devices **(Device-under-Test)**

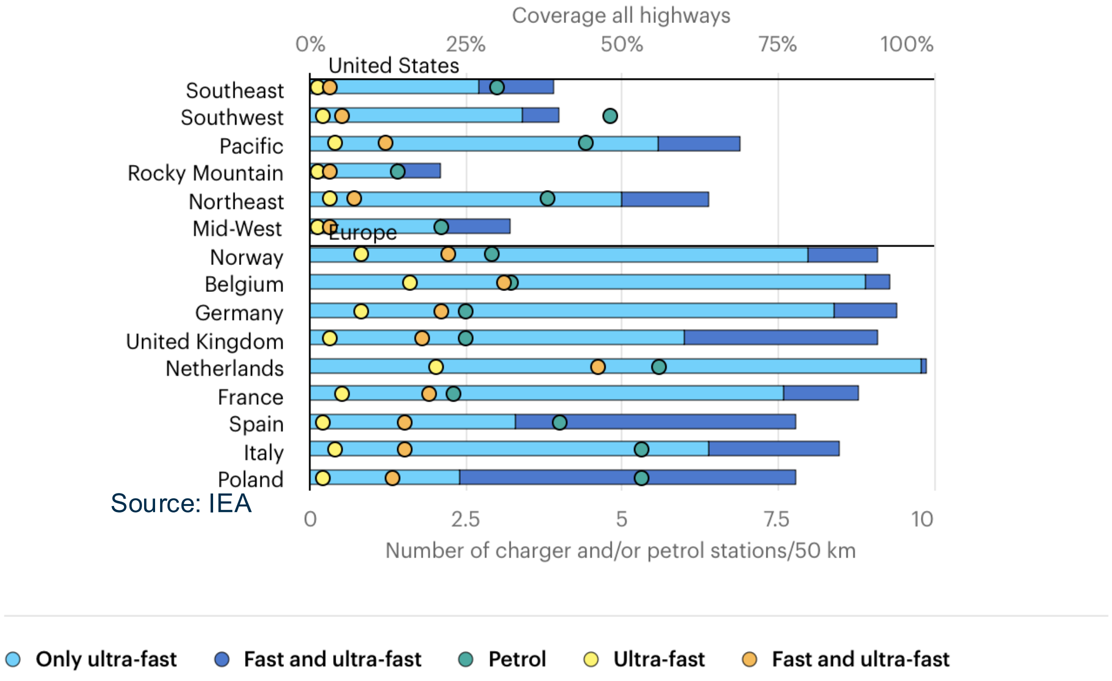
Contact: KIT-IAI, veit.hagenmeyer@kit.edu | KIT-ITEP, giovanni.carne@kit.edu

Shifting focus from DC-generation to DC-load technologies

Global data-center energy consumption

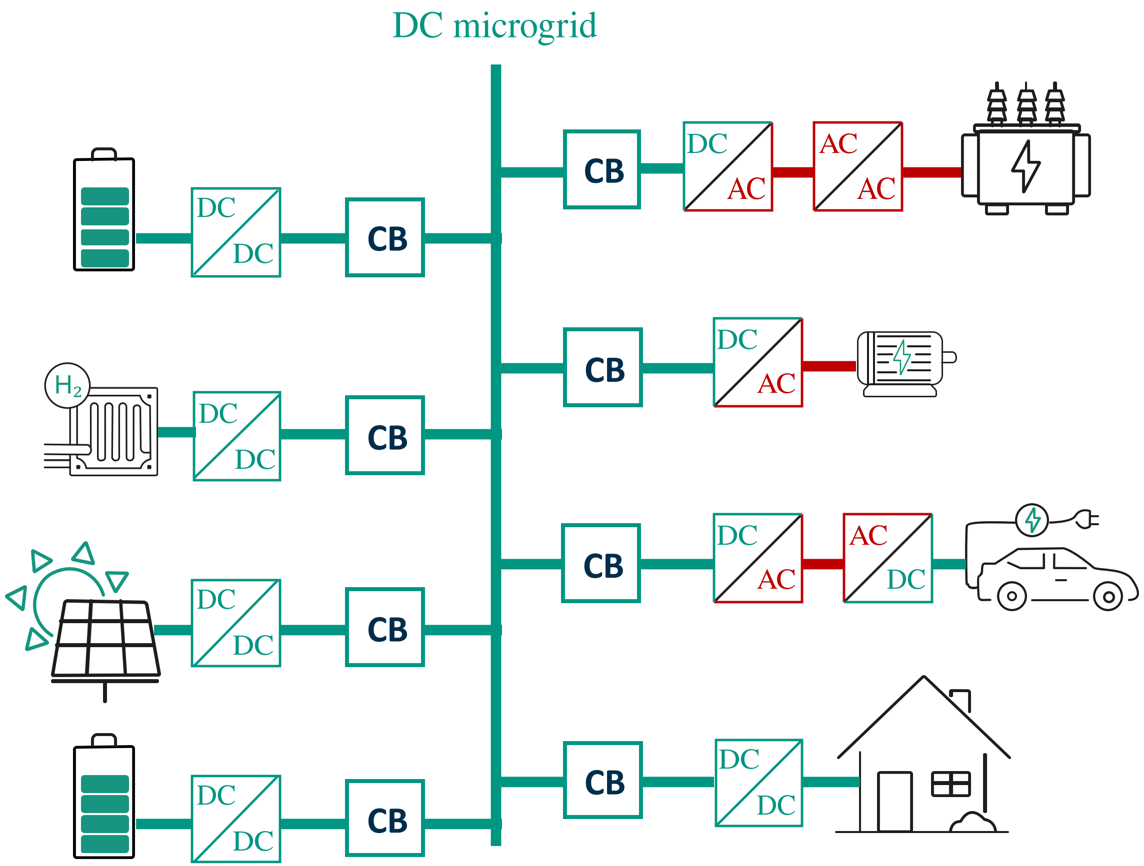


EV Charging station coverage in the world



Source: IEA

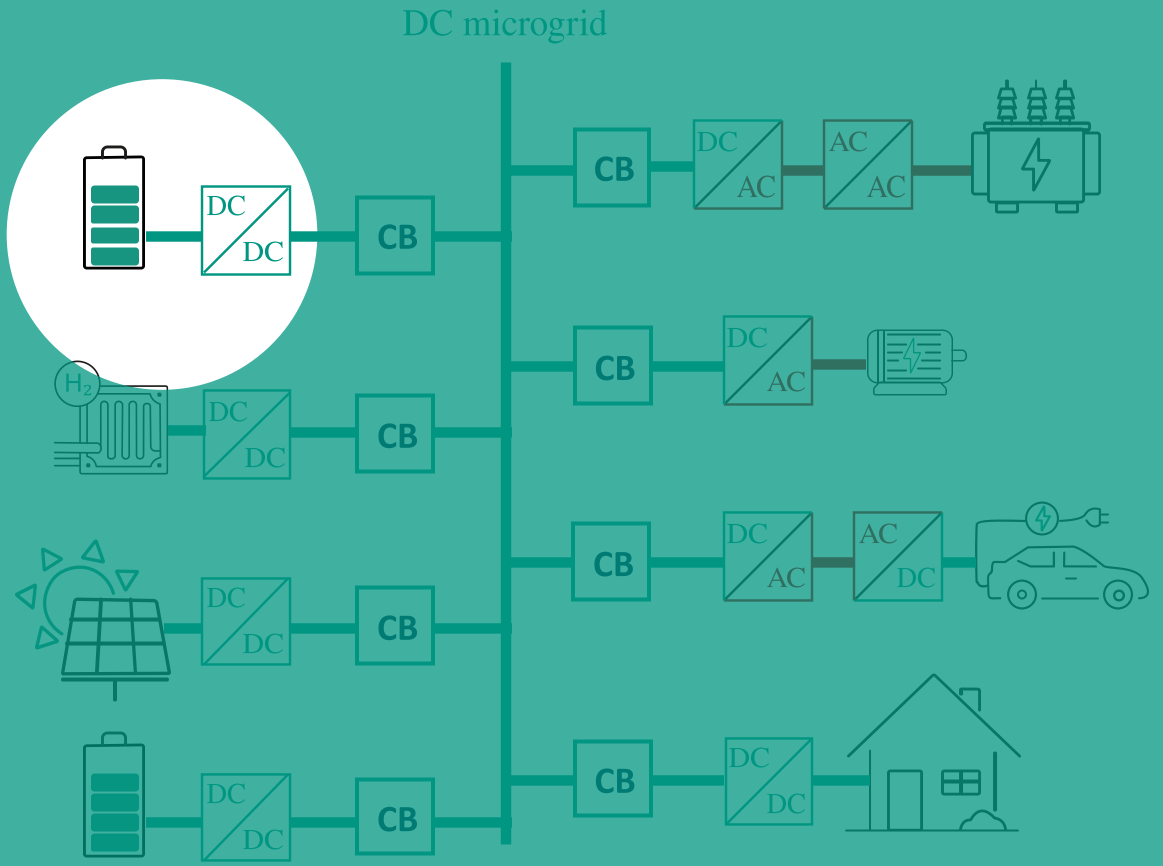
DC Grid Concept



DC Grid Concept

New elements in the game:

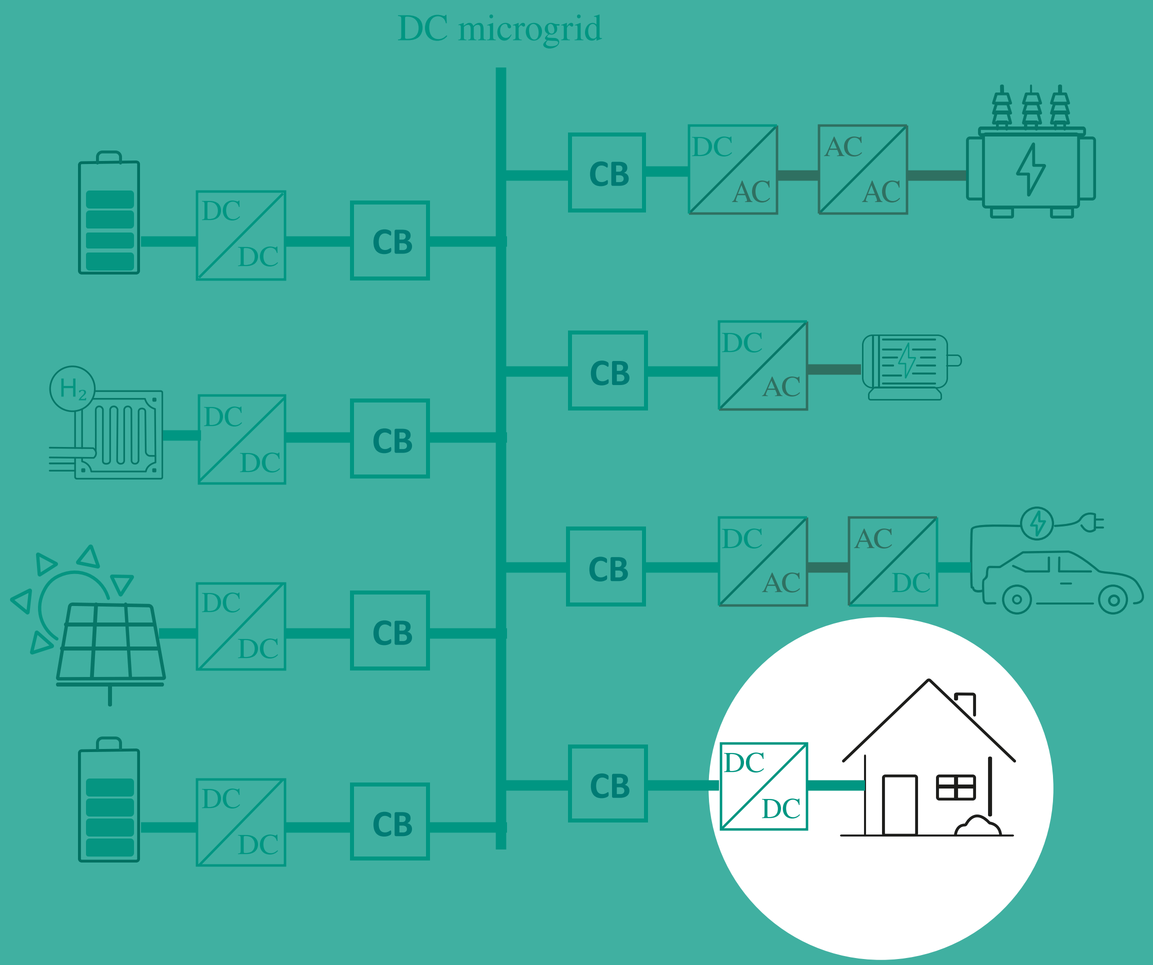
- **Energy Storage Systems**



DC Grid Concept

New elements in the game:

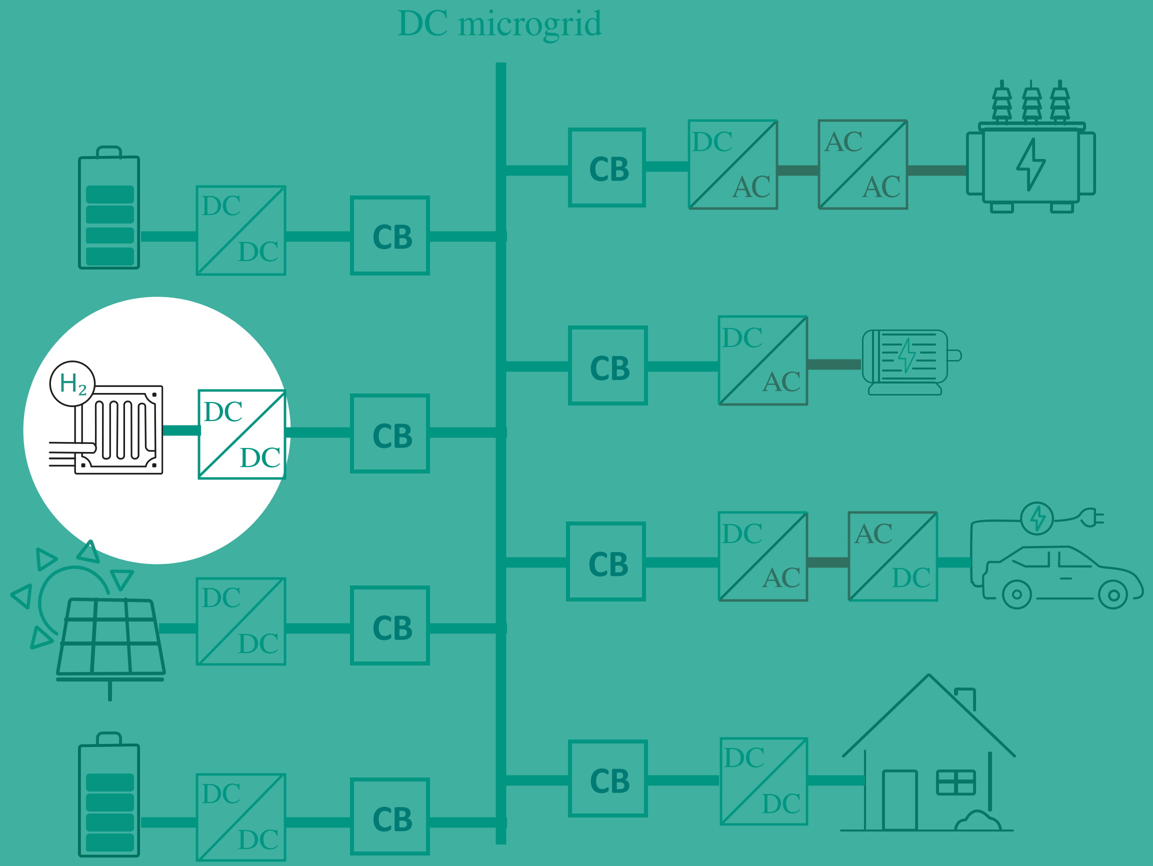
- **Energy Storage Systems**
- **Households**



DC Grid Concept

New elements in the game:

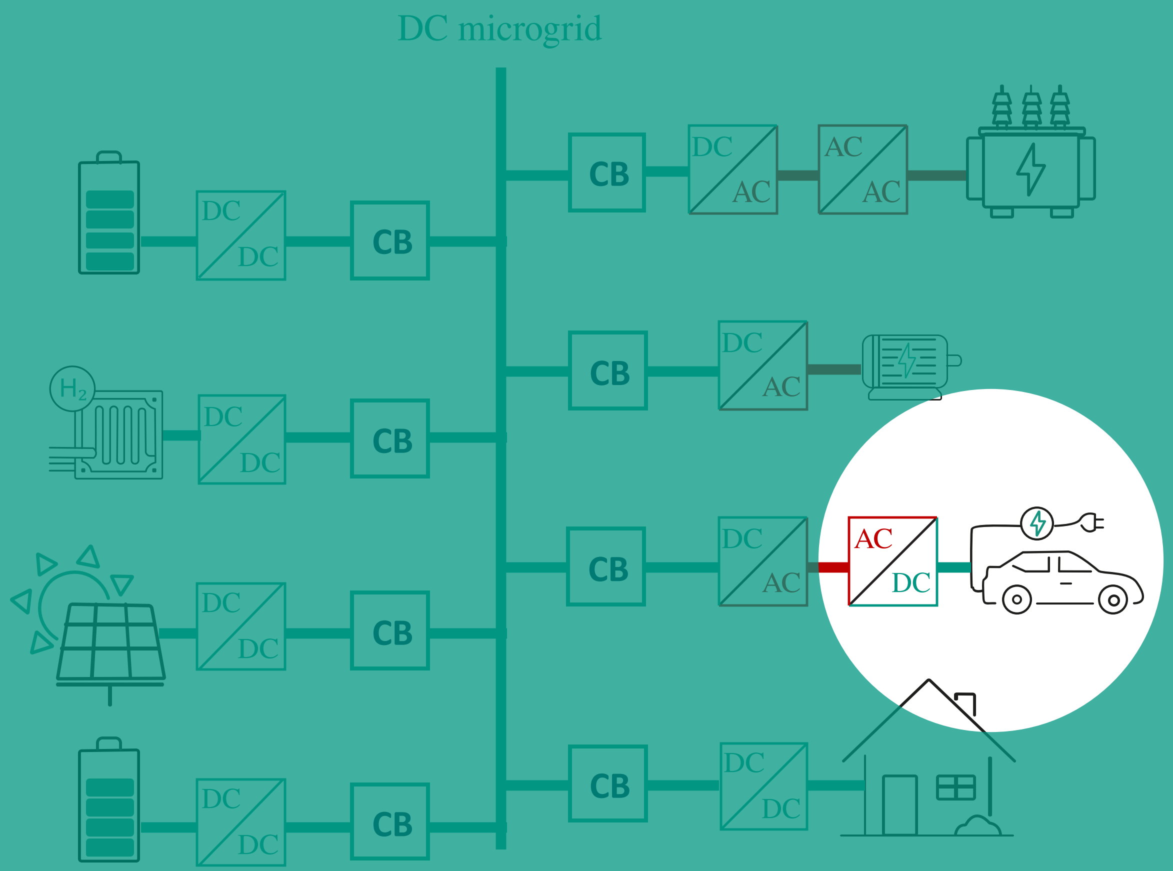
- **Energy Storage Systems**
- **Households**
- **Power-to-X Units**



DC Grid Concept

New elements in the game:

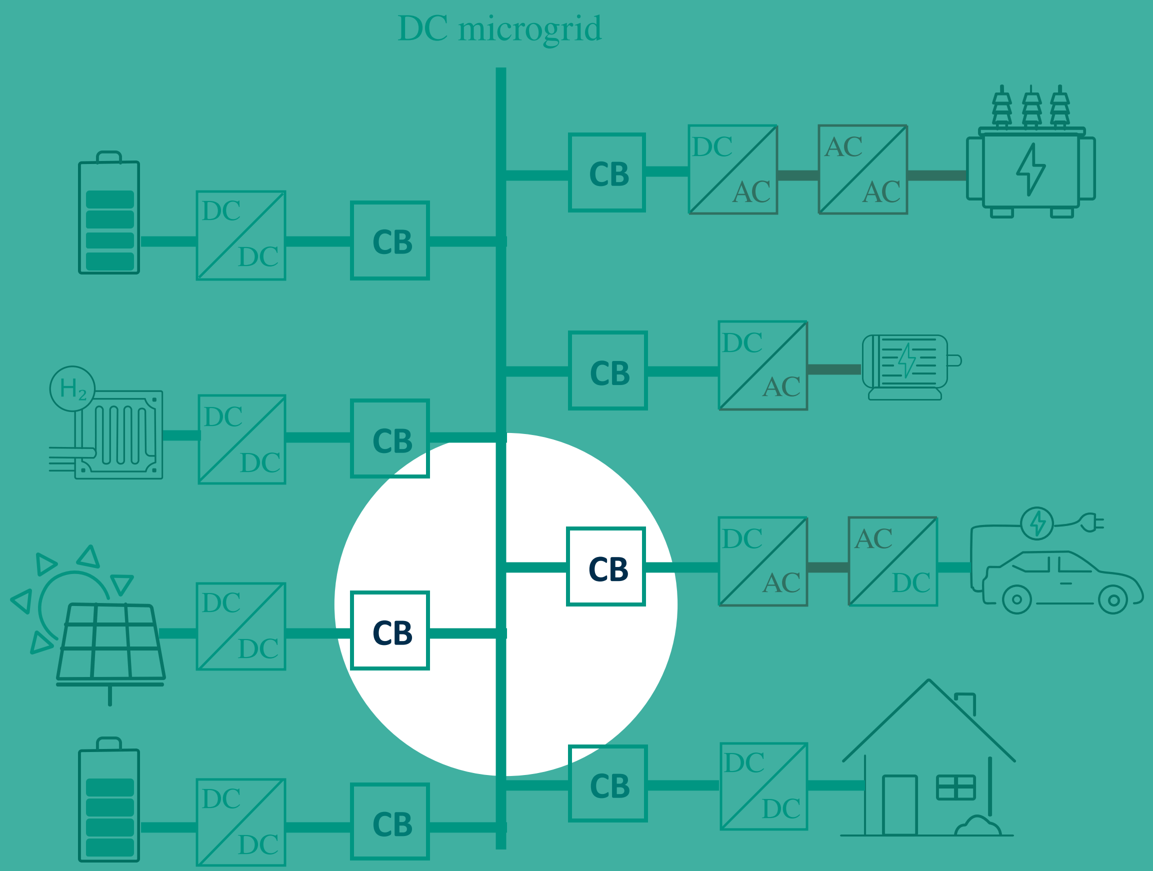
- **Energy Storage Systems**
- **Households**
- **Power-to-X Units**
- **EV Charging Stations**



DC Grid Concept

New elements in the game:

- **Energy Storage Systems**
- **Households**
- **Power-to-X Units**
- **EV Charging Stations**
- **Protection Systems**

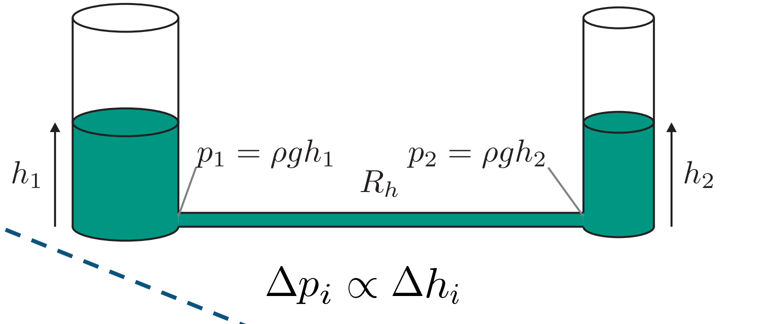


Innovative control approaches

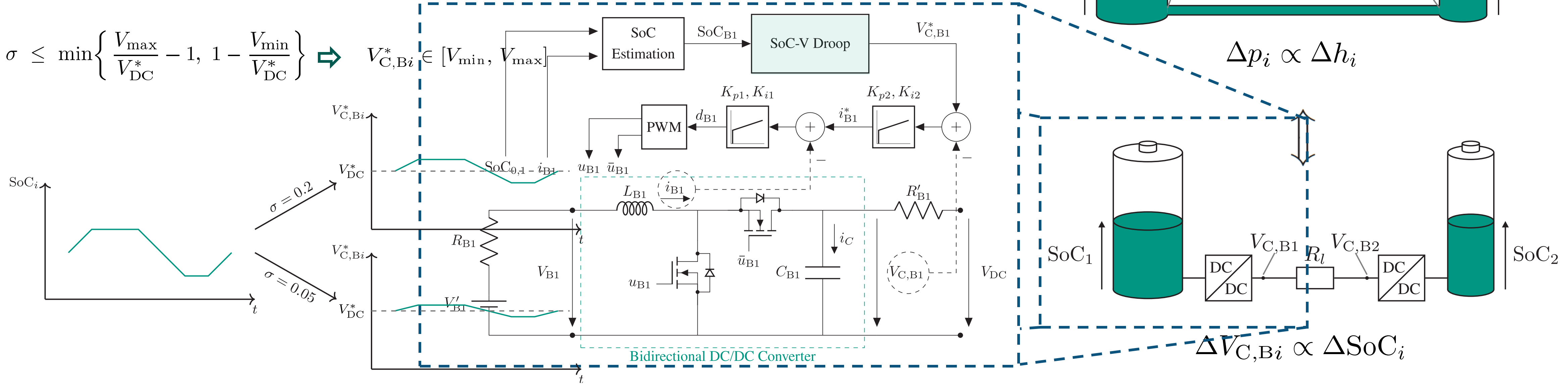
State-of-Grid (SoG) Control Concept

- Inspired by: **Communicating Vessels Principle**
- Local energy state of charges (SoC) are projected into: Voltage deviation (DC side) and Frequency deviation (AC side)These observable signals act as proxies for global grid state.
- Each unit reacts locally → global coordination emerges

$$V^*_{\mathrm{C,B}i} = V^*_{\mathrm{DC}} \left(1 + \sigma \frac{\mathrm{SoC}_i - \mathrm{SoC}^*_i}{\mathrm{SoC}_{\Delta,i}}\right), \qquad \text{for } i \in \{1, \ldots, n\}.$$



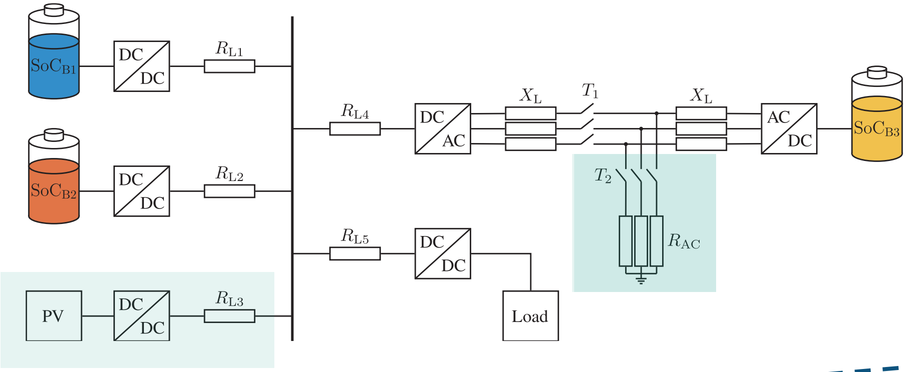
$$\sigma \leq \min\left\{ \frac{V_{\max}}{V^*_{\mathrm{DC}}} - 1,\ 1 - \frac{V_{\min}}{V^*_{\mathrm{DC}}} \right\} \Rightarrow V^*_{\mathrm{C,B}i} \in [V_{\min}, V_{\max}]$$

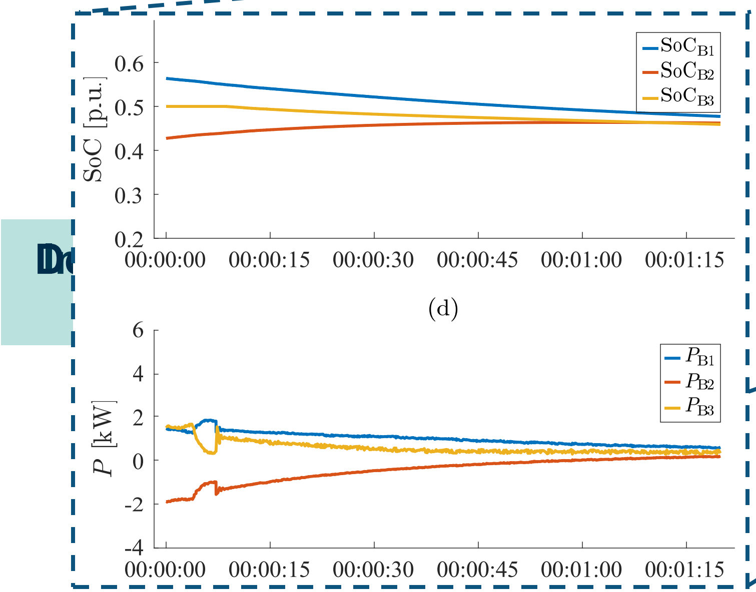


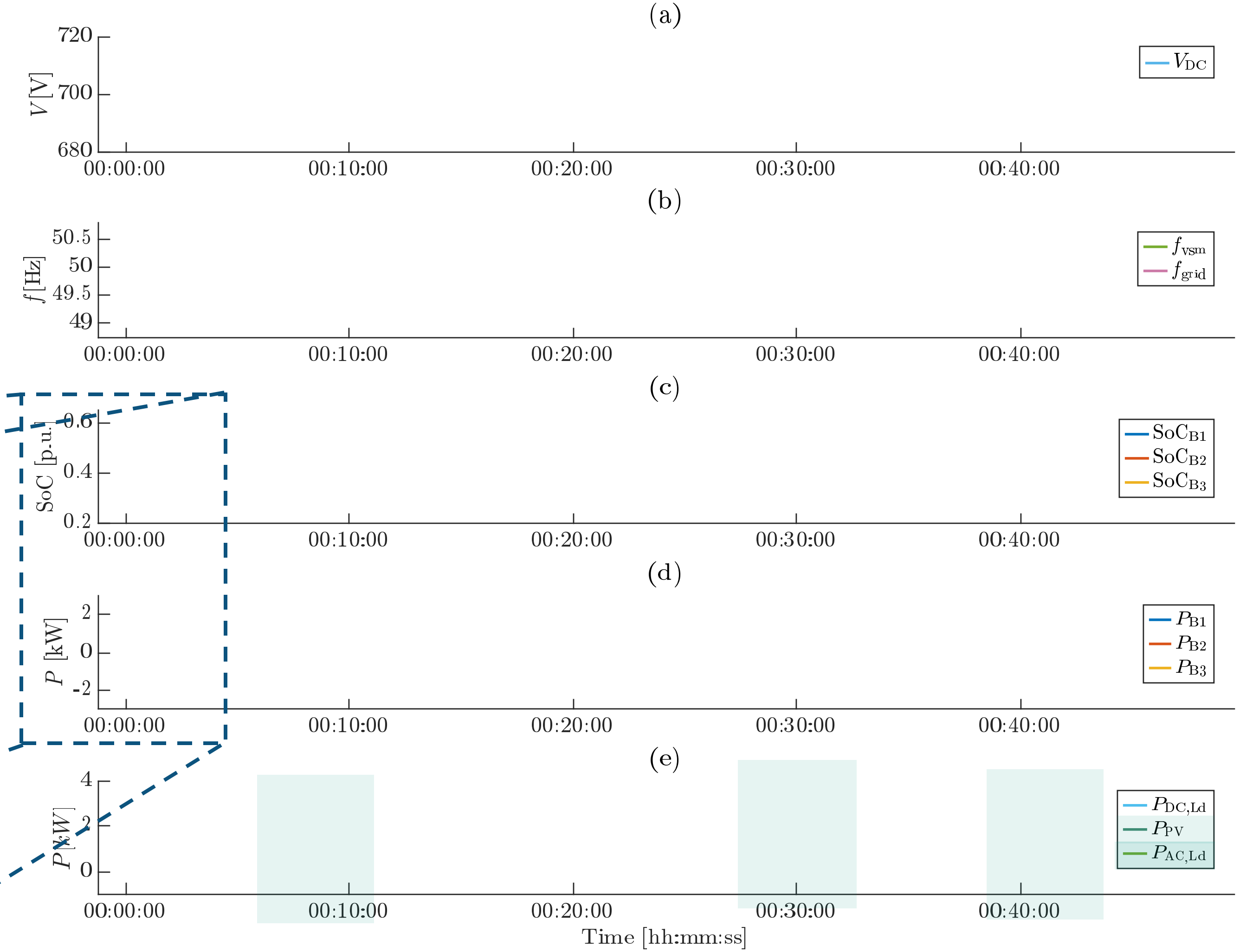
Ö. Ekin, G. D. Carne and V. Hagenmeyer, "Decentralized Control of DC Microgrids: Introducing the State-of-Grid Concept: How the Principles of Communicating Vessels Could Be Used in DC Microgrid Control," in IEEE Industrial Electronics Magazine, doi: 10.1109/MIE.2025.3607070.

State-of-Grid (SoG) Control Concept

DC-AC SoC Balancing







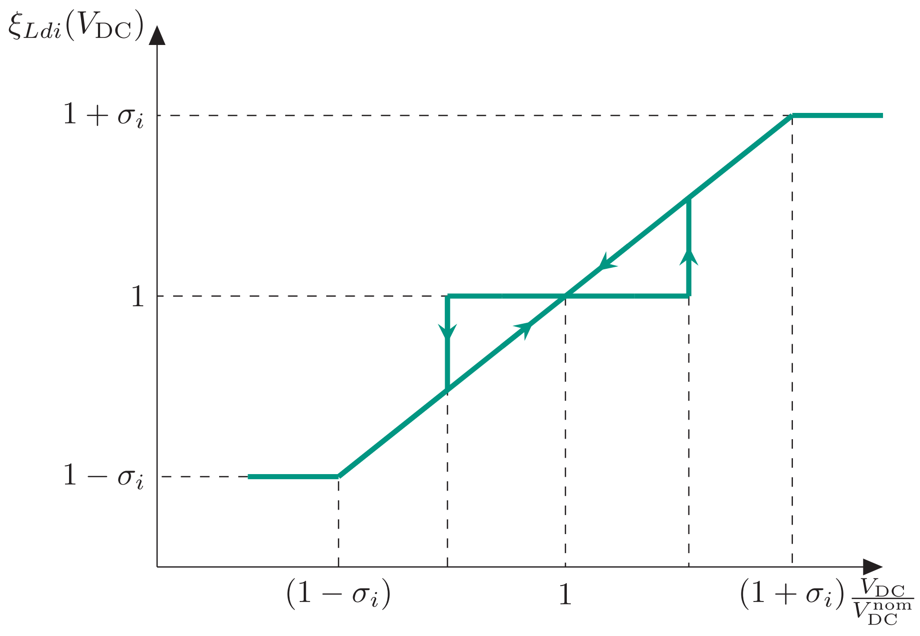
Ö. Ekin, M. Leuthaeusser, G. D. Carne and V. Hagenmeyer, "State-of-Grid Based SoC Balancing and AC Coupling Control for DC Microgrids," in IEEE Transactions on Industrial Electronics, in press.

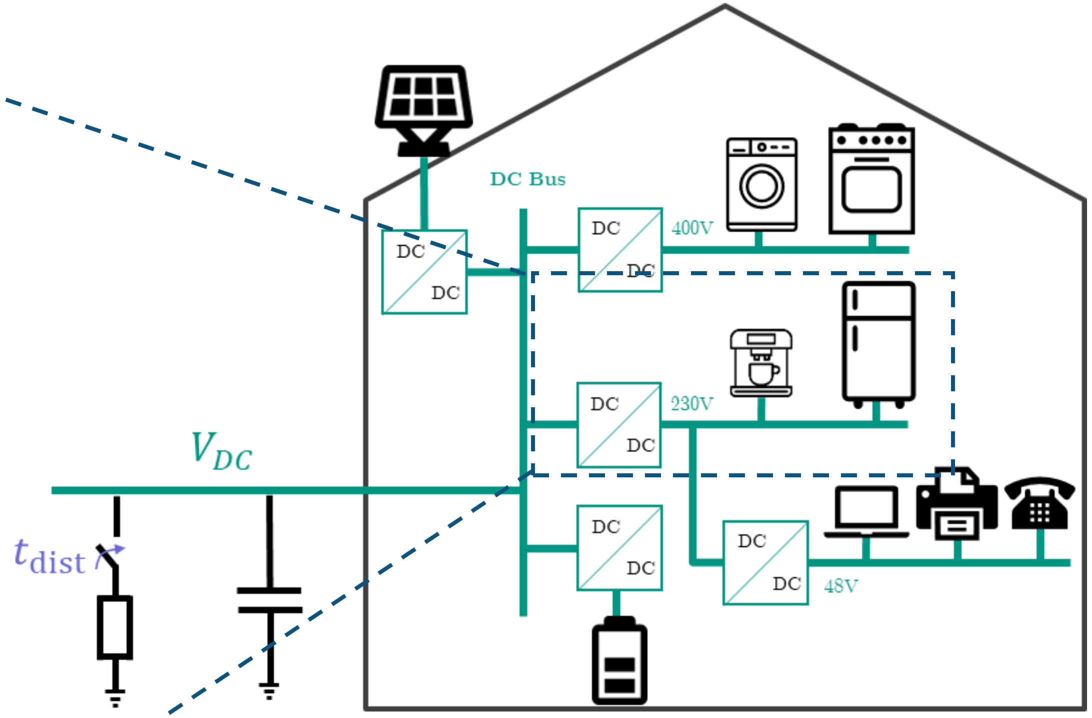
Grid-supportive Load (GSL) Control Concept

GSL

$$V^{*}_{\mathrm{Ldi}} = V^{\mathrm{nom}}_{\mathrm{Ldi}} \xi_{\mathrm{Ldi}}(V_{\mathrm{DC}})$$

e.g. $\sigma_i = 0.05$ → 5% variation

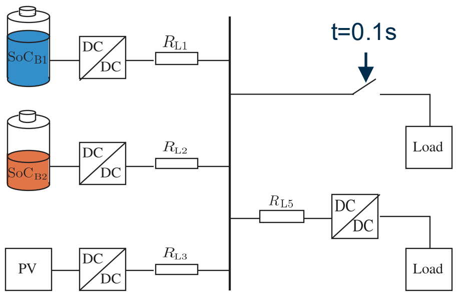




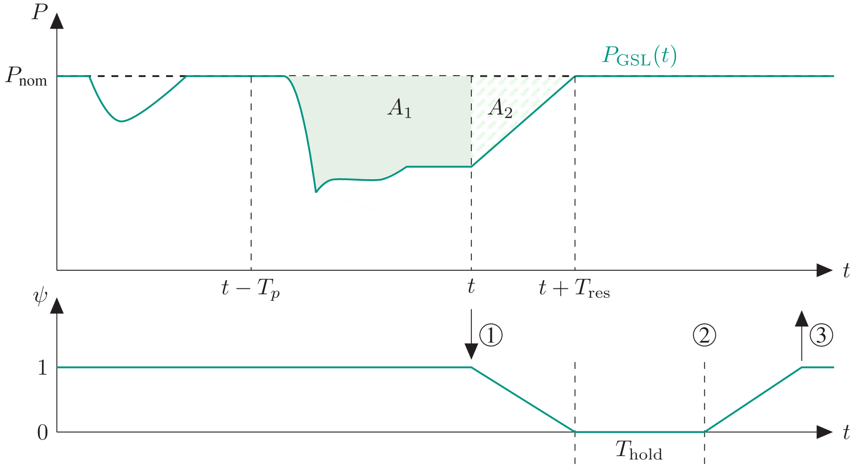
Ö. Ekin, G. D. Carne, V. Hagenmeyer. Grid-Supportive Load Control for Residential ZIP Loads in DC Microgrid. TechRxiv. November 19, 2024. DOI: 10.36227/techrxiv.173198914.48430763/v1

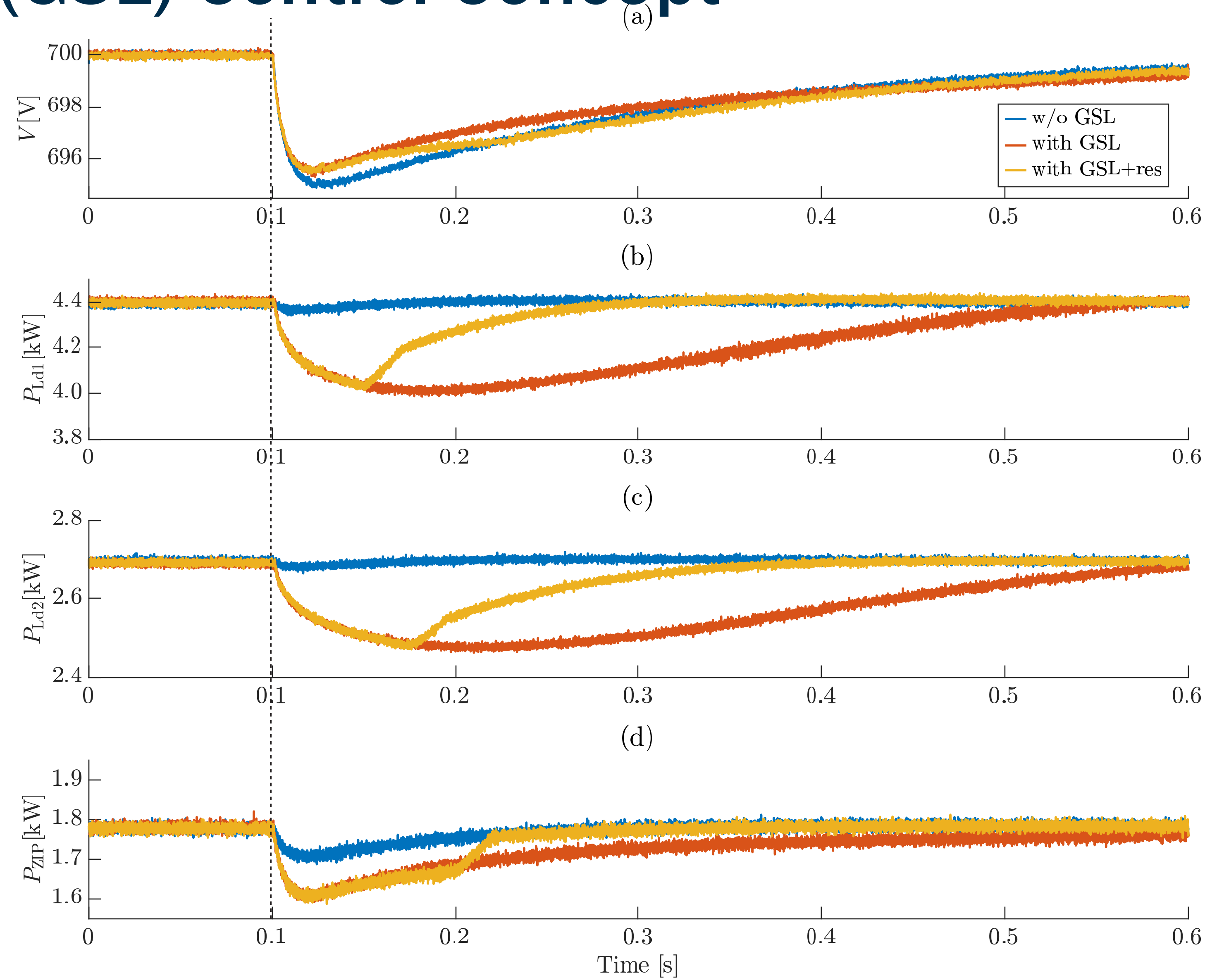
Grid-supportive Load (GSL) Control Concept

GSL



Restoration Strategy





Ö. Ekin, G. D. Carne, V. Hagenmeyer. Grid-Supportive Load Control for Residential ZIP Loads in DC Microgrid. TechRxiv. November 19, 2024. DOI: 10.36227/techrxiv.173198914.48430763/v1

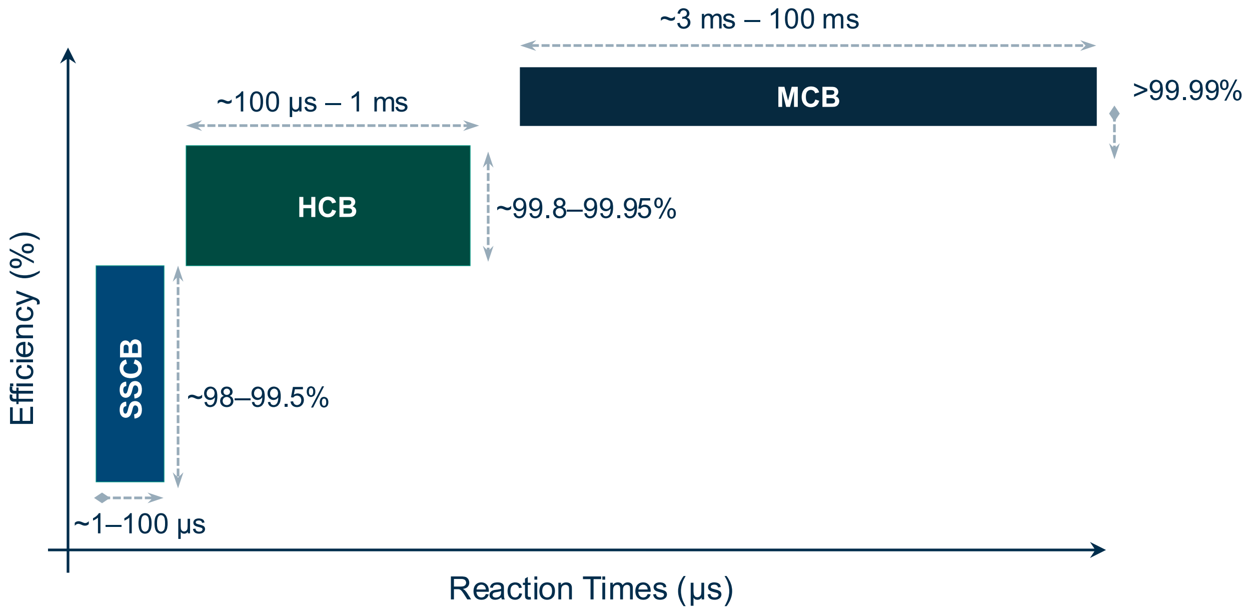
DC protection

Key Insights on DCCB Technologies

- **No single technology can deliver both highest efficiency and fastest reaction time,**

→ At first glance, trade-offs may seem inevitable between speed and efficiency

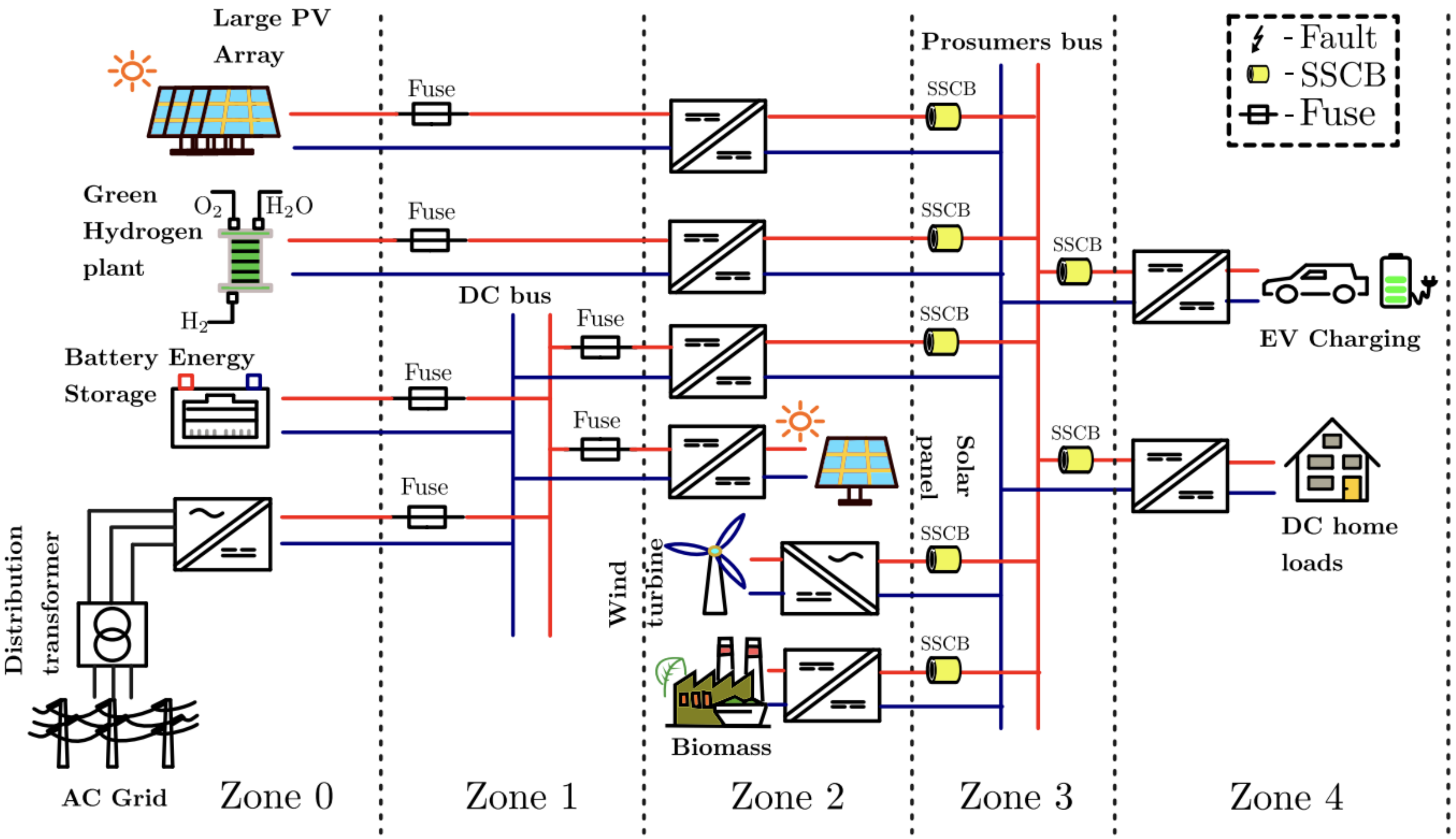
- **Mechanical breakers remain practical in certain applications (PV outputs)**
- **Hybrid Circuit Breakers occupy the middle ground, yet remain slow for critical fault scenarios**
- **SS DCCBs may be efficient enough, but cause power loss, and need heavy cooling systems, and larger size**



Remain ~10 times more expensive and larger than AC counterparts

M. Ghadrdan, S. N. Banavath and G. De Carne, "A Coordinated DC Protection Strategy Based on Prioritized DC-link Capacitor Fault Interruption," 2025 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE)

DC Protection Zoning System



Zone 0: Low Voltage Power sources with high overcurrent
$V_d \leq 1500$ V
$I_d > 500$ A

Zone 1: Protected with Fuse
$V_d \leq 1500$ V
$I_d \leq 500$ A

Zone 2: Current controlled converters
$V_d \leq 1500$ V
$I_d \leq 500$ A

Zone 3: Solid-state protection
$V_d \leq 400$ V to GND (± 800 V)
$I_d \leq 50$ A

Zone 4: Consumers with current limited loads
$V_d \leq 400$ V to GND (± 800 V)
$I_d \leq 50$ A

Indian Institute of Technology Dharwad

P. Pithanisetty, D. Dsa, S. N. Banavath, E. L. Carvalho, G. De Carne and D. Vinnikov, "A Coupled Inductor-Based SSCB With Reduced Components for DC Microgrid Protection," in *IEEE Transactions on Power Electronics*, vol. 40, no. 8, pp. 11428-11441, Aug. 2025, doi: 10.1109/TPEL.2025.3551740.

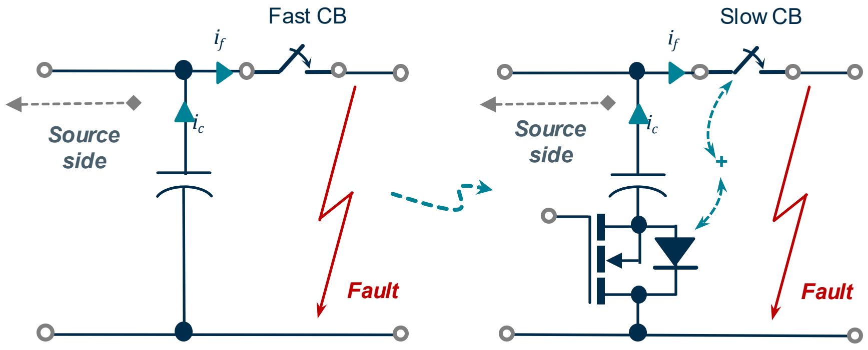
Multi-breaker Configuration Based on Prioritized Capacitor Zone Protection

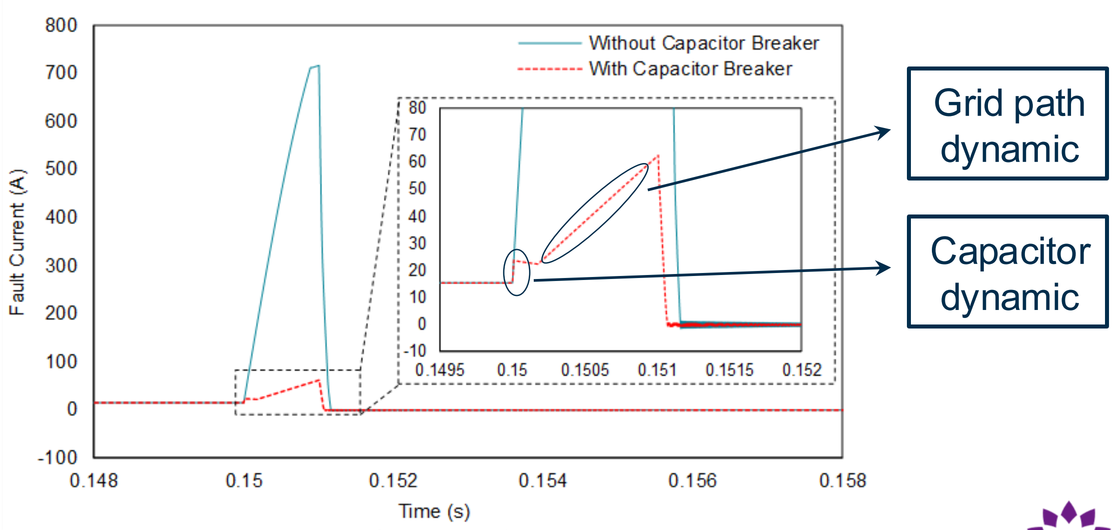
- Compared to missing natural zero-crossings and arc risk, the **main issue** is **bulky capacitors** causing a **rapid fault current rise,**
- **Unlike AC systems, two energy sources can feed the fault:**

→ Capacitor path: Lower inductance → much faster, but lower power

→ Source path: Higher inductance → slower, carries the main power

- **Single-breaker in main path demands both low power loss and high speed,**
- **Unlike AC protection systems, multi-breaker configuration may be optimal.**





Fault current at the output of a 3-phase diode-bridge rectifier

M. Ghadrdan, S. N. Banavath and G. De Carne, "A Coordinated DC Protection Strategy Based on Prioritized DC-link Capacitor Fault Interruption," 2025 IEEE International Conference on Power Electronics, Smart Grid, and Renewable Energy (PESGRE)

Coupled Inductor-Based SSCB with Reduced Components

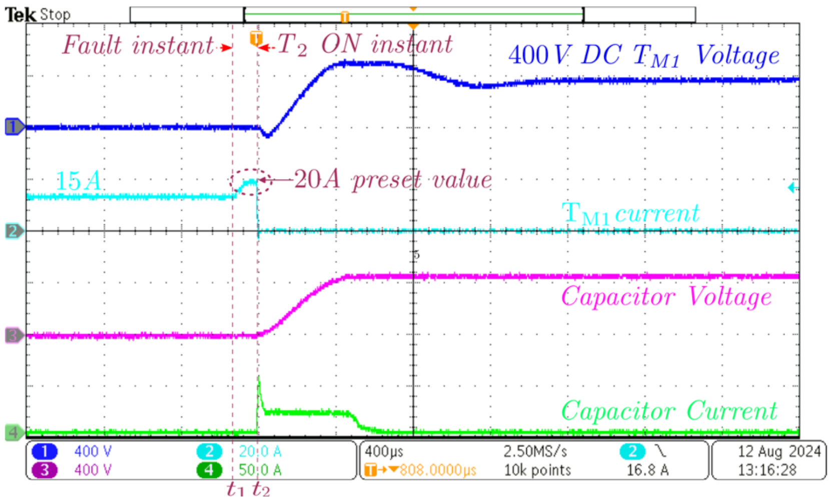
- Bidirectional thyristor-based SSCB using:

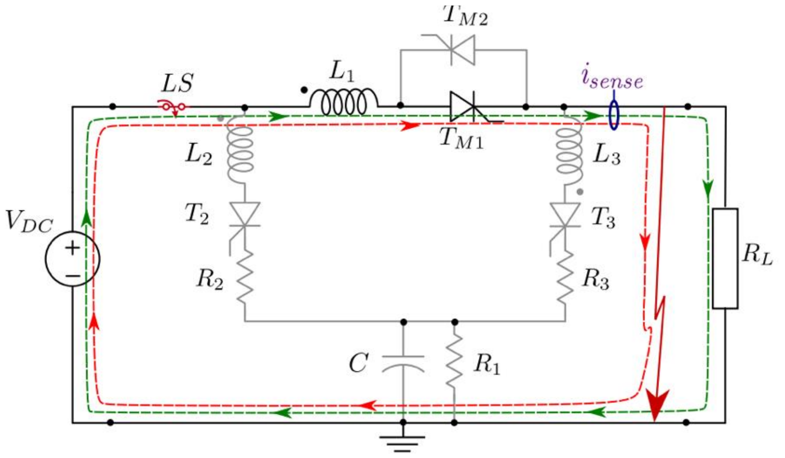
→ Three-winding coupled inductor (L1 main, L2/L3 auxiliary) ,

→ Two anti-parallel main SCRs (TM1/TM2),

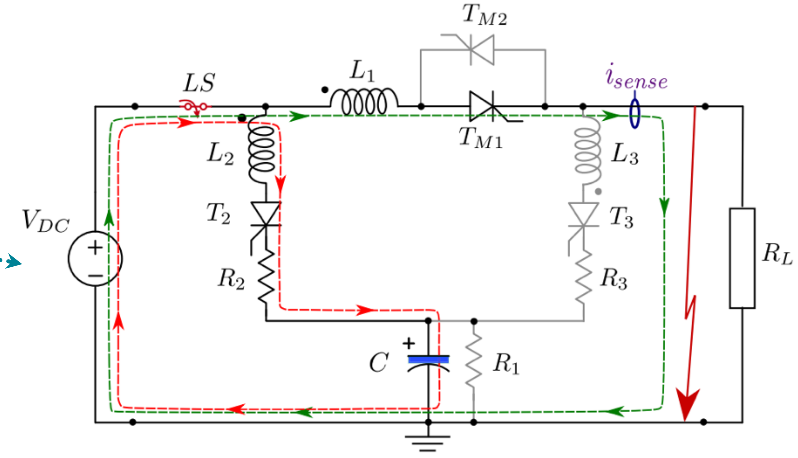
→ Two auxiliary SCR (T2/T3), one capacitor, current-limiting and discharge resistors.

- **Fewer active/passive components,**
- **adjustable trip level and manual trip,**
- **eliminating diodes in the main path,**





Normal Operation



Fault Condition

P. Pithanisetty, D. Dsa, S. N. Banavath, E. L. Carvalho, G. De Carne and D. Vinnikov, "A Coupled Inductor-Based SSCB With Reduced Components for DC Microgrid Protection," in *IEEE Transactions on Power Electronics*, vol. 40, no. 8, pp. 11428-11441, Aug. 2025, doi: 10.1109/TPEL.2025.3551740.

Conclusive Remarks

- DC Microgrids offer enhanced control possibilities due to the flexibility of power electronics converters
- They offer energy management optimization and at the same time provide frequency regulation services to the AC grid.
- Bottleneck → protection systems!
- Working to realize cost-effective and flexible solutions for DC protection
- A lot needs still to be done:
  - Standards on control, implementation, safety
  - Business cases for industry and household customers
  - Teaching focus in universities → Next Gen Engineer needs to know about DC grids!

Prof. Dr.-Ing. Giovanni De Carne
Director of the Institute for Technical Physics
Head of “Real Time System Integration” group
Helmholtz young investigator group leader

Karlsruhe Institute of Technology
Institute for Technical Physics (ITEP)

Email: giovanni.carne@kit.edu
Website: https://www.itep.kit.edu/rtset/

RTSET

M.Sc. Ömer Ekin
PhD Candidate

Karlsruhe Institute of Technology
Institute for Automation and Applied Informatics (IAI)
Email: oemer.ekin@kit.edu
Website: https://www.iai.kit.edu/RPE-Team_3826.php

SESCL