Hardware-In-the-Loop technologies for next generation MVDC grids enabling flexible wind integration

Workshop on Grid Simulator Testing of Energy Systems and Wind Turbine Drivetrains
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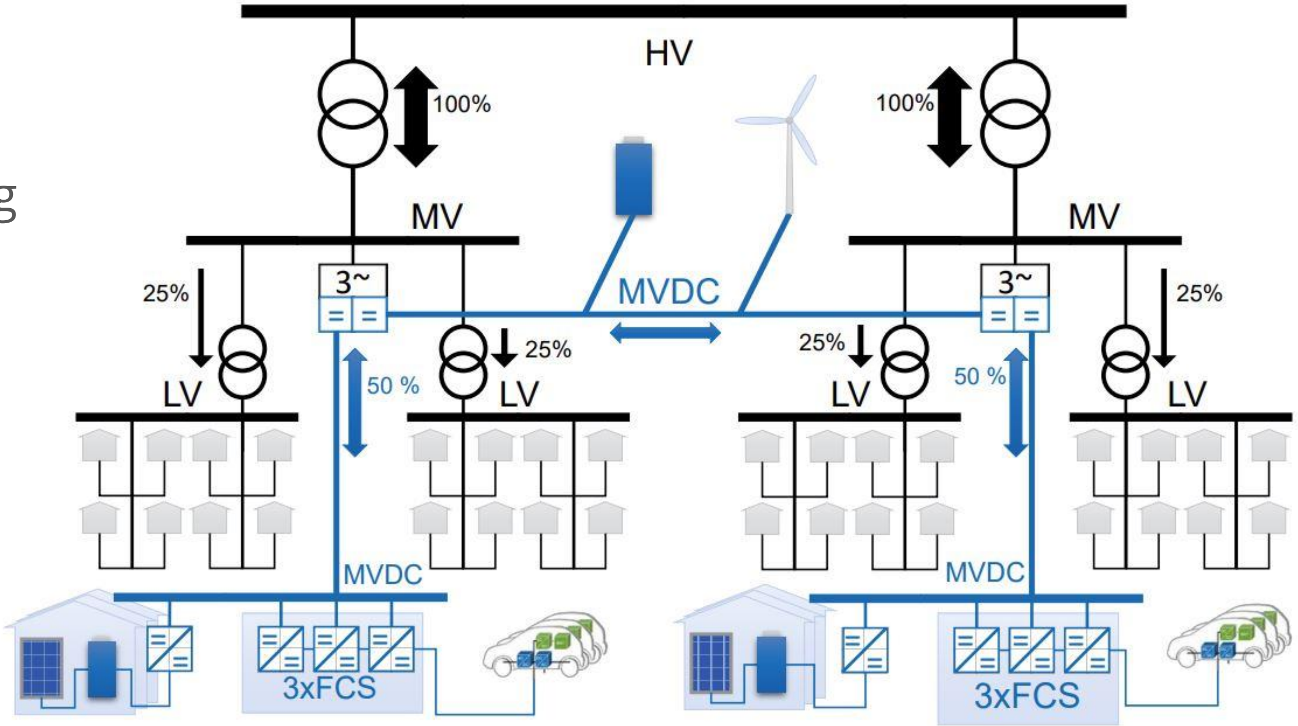
Outline

- MVDC grids based on three-phase Dual-Active Bridge (DAB3) converters
- Requirements for controller testing for DAB3 converters
- High-fidelity FPGA-based real-time simulation of MVDC grids

Next Generation Power Grids

- Significant changes of the grid infrastructure are required to ensure efficient, flexible and reliable integration of renewables and accommodate new demands
- Embedding DC-grid infrastructure into existing AC grids – DC links and DC grids improve the overall flexibility, reliability and efficiency
- The integration of DC grids into Medium-Voltage (MV) AC distribution grids – examples
  - ANGLE-DC: MVDC link in Europe designed as a controllable bidirectional link between two sections of an AC grid
  - Flexible Electrical Networks (FEN) Research Campus: Multi-terminal MVDC demonstration project at the Campus of the RWTH Aachen University



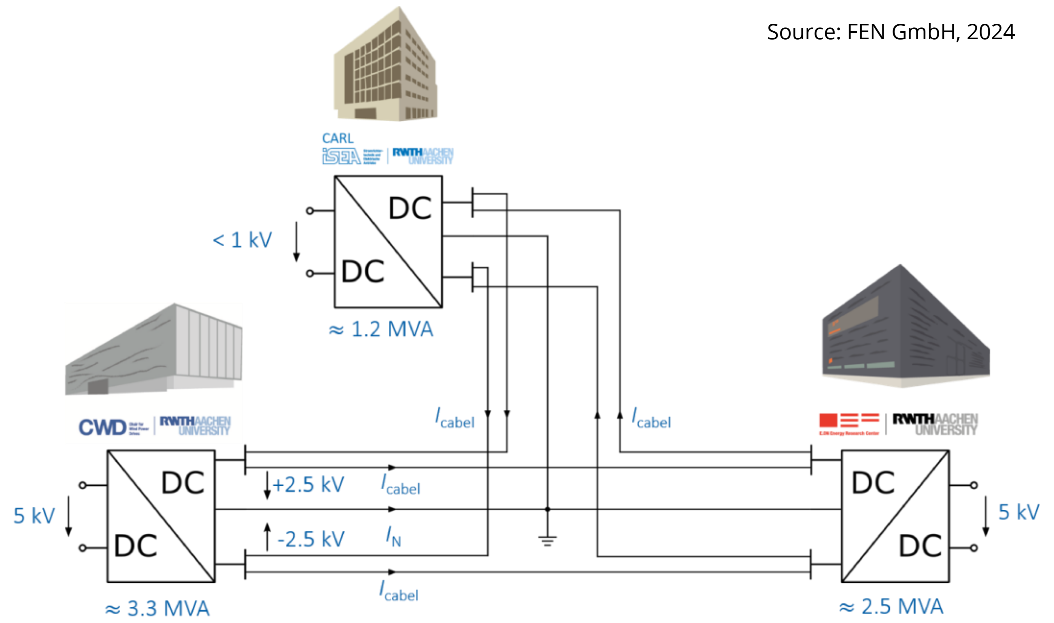
Source: R. W. De Doncker, „Distribution Grids with DC Technology“, Aachen DC Grid Summit, 2018

Flexible Electrical Networks (FEN) Research Campus

- FEN research grid – demonstration of MVDC grid
  - Connecting laboratories that host test benches in the MW power range
  - 3-terminal bipolar MVDC grid (± 2.5 kV)
- Research activities – novel control, protection, monitoring and automation concepts
  - Voltage control based on Active Disturbance Rejection Control (ADRC) concept
  - Protection concept – breakless DC grids

FEN MVDC Research Grid

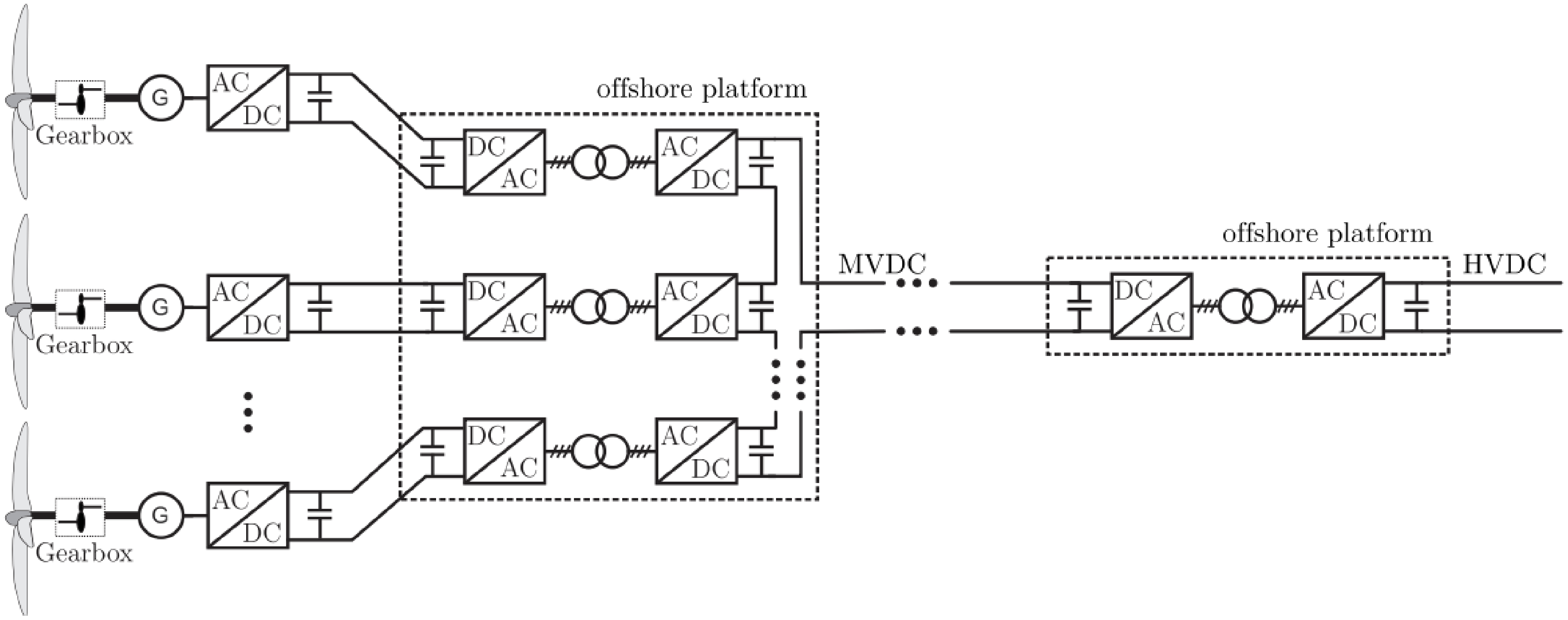
Source: FEN GmbH, 2024



- Extensive utilization of simulations, Hardware-in-the-Loop (HiL) testing and experiments with design prototypes and power devices
  - Real-time simulation and HiL significantly reduce cost and time requirements in transitioning from offline simulation studies towards experiments
  - **Safe** and **flexible** environment for testing of control and protection solutions for **high-power** devices

MVDC Collector Grids for Wind Integration

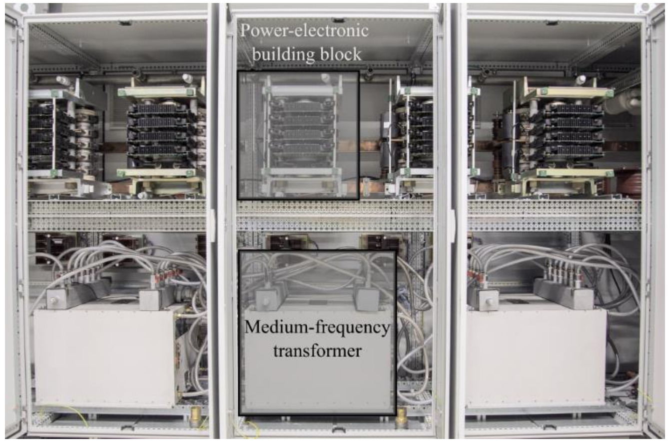
- Leverage MVDC grid for collection of wind energy
  - Increased efficiency and reduced costs compared to AC solution
  - Modular converter system based on Dual-Active Bridge (DAB) converters
  - Galvanic isolation of wind turbine converters



Stieneker, Marco, Jan Riedel, Nils Soltau, Hanno Stagge, and Rik W. De Doncker. "Design of series-connected dual-active bridges for integration of wind park cluster into MVDC grids." EPE Journal 26, no. 2 (2016): 39-46.

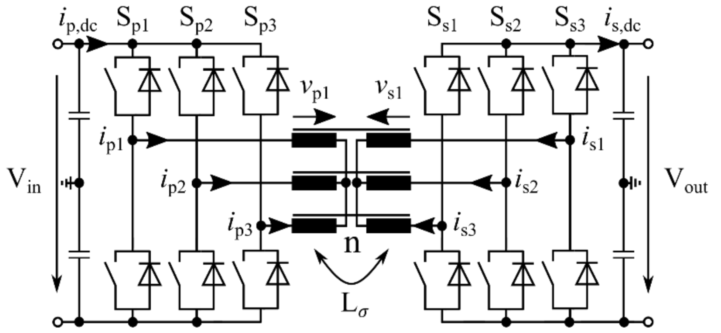
High-Power DC-DC Converter for MVDC Grid

- Three-phase Dual-Active Bridge (DAB3) converter
  - Galvanically isolated bidirectional topology with a high-efficiency operation at a relatively low level of the hardware complexity
  - Recognized as a promising solution for MVDC grids
  - Simple control of power transfer based on phase shifting primary and secondary AC voltages
- High-power Medium-Voltage DAB3 converter prototype
  - Six power-electronic building blocks and three medium-frequency transformers

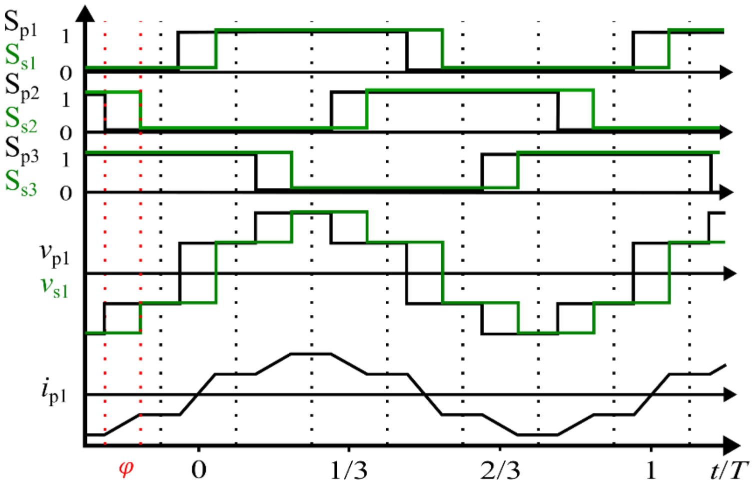


Source: FEN GmbH, 2024

DAB3 converter topology

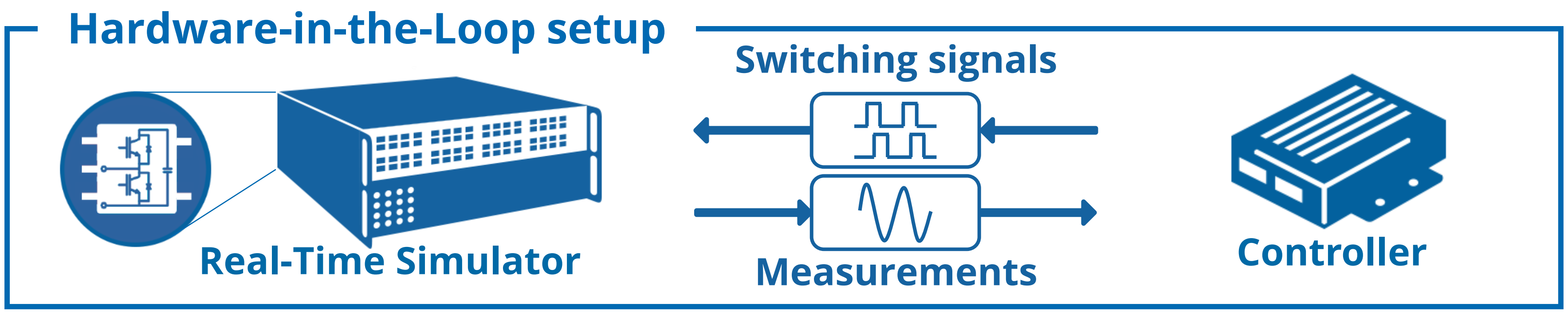


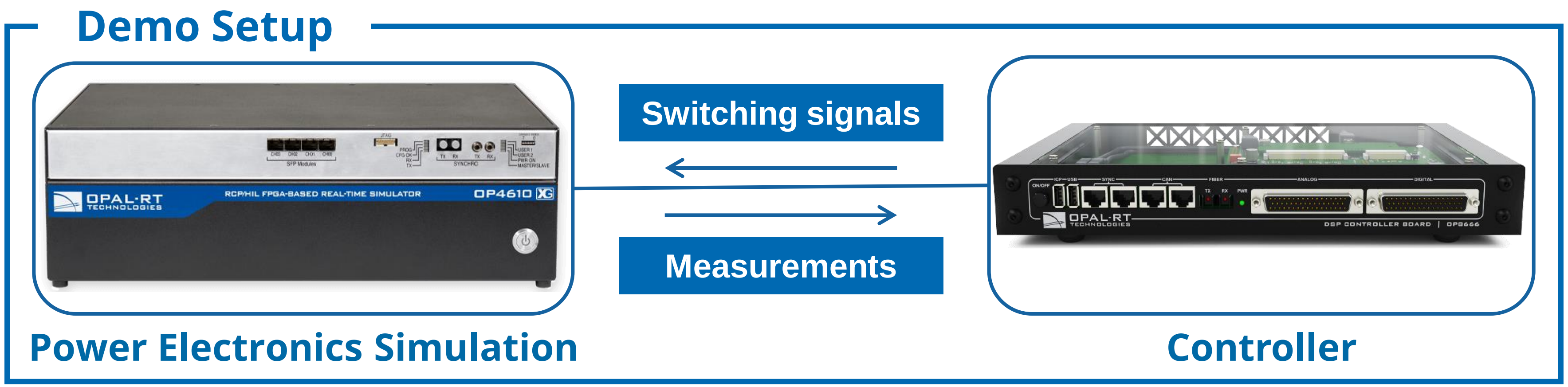
Steady-state operation



HIL Testing of Converter Controls for Hybrid AC/DC Grids

- HIL testing enables validation of control, protection and monitoring solutions at an early stage of the system design and provides a safe environment for comprehensive and flexible testing
- The main challenge of RTS in the context of hybrid AC/DC grids is the simulation of a multi-converter system including detailed power electronics converter models





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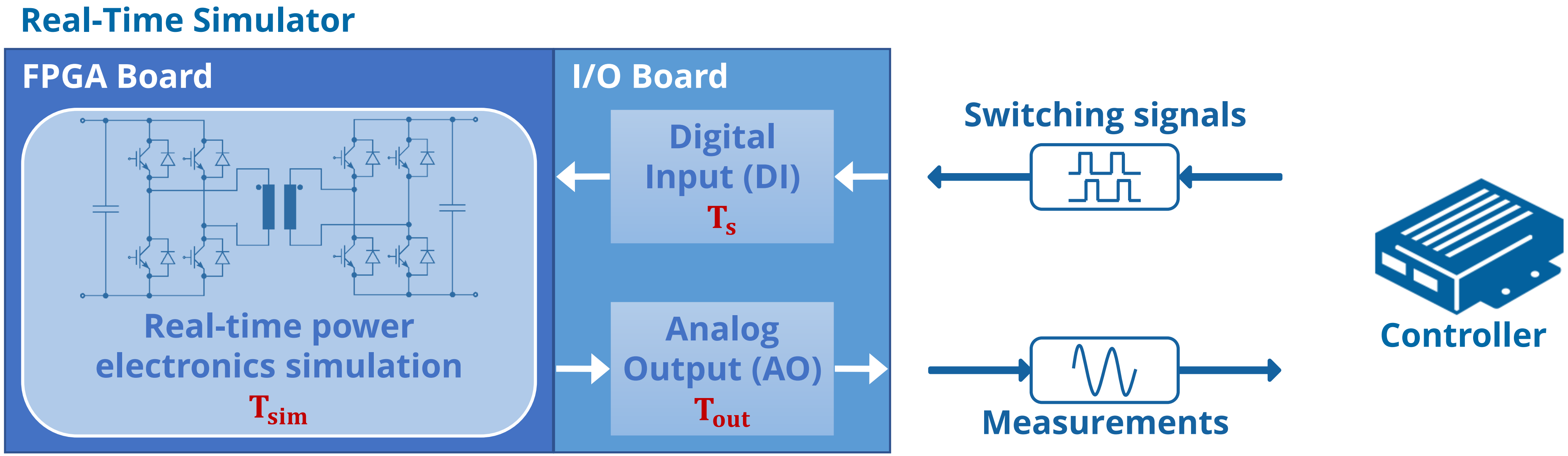
High-fidelity Controller Testing: The Key Characteristics



- RTS for high-fidelity controller testing:
  - Detailed switch model (* deepness level A, A+)
  - Numerical integration methods and simulation time step T_{sim}
  - DI sample time for acquisition of switching signals T_s
  - AO sample time for providing measurements T_{out}
  - Total latency – from DI to AO
- RTS for large-scale power electronics simulations:
  - Number of switching devices in a simulation model
  - Number of input and output channels
  - Modular design for multi-FPGA simulation
  - Multi-rate simulation capability for optimal resource utilization and FPGA-CPU co-simulation

*G. De Carne *et al*., "Which Deepness Class Is Suited for Modeling Power Electronics?: A Guide for Choosing the Right Model for Grid-Integration Studies," in *IEEE Industrial Electronics Magazine*, vol. 13, no. 2, pp. 41-55, June 2019, doi: 10.1109/MIE.2019.2909799.

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Sampling of Switching Signals in HIL Applications

- Effective duty cycle d_e in the simulation environment following the sampling of switching signals at T_s for a switching period T_{sw}:

Accuracy

$$d - \frac{T_s}{T_{sw}} < d_e < d + \frac{T_s}{T_{sw}}$$

Resolution

$$q_d = \frac{T_s}{T_{sw}}$$

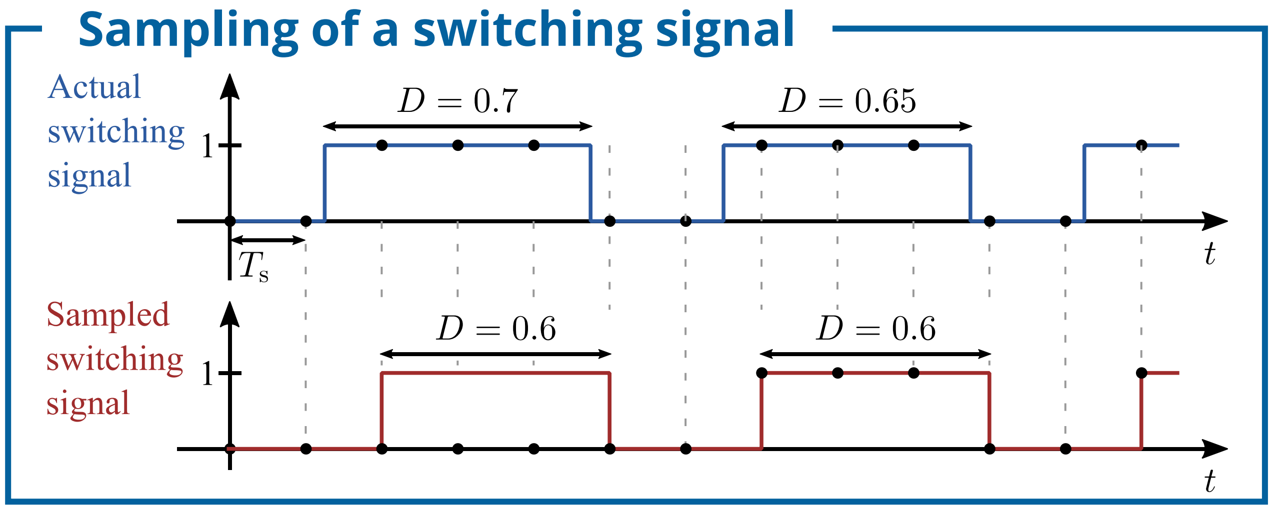
- Problem: if you don't do oversampling, the equations above become:

Accuracy

$$d - \frac{T_{sim}}{T_{sw}} < d_e < d + \frac{T_{sim}}{T_{sw}}$$

Resolution

$$q_d = \frac{T_{sim}}{T_{sw}}$$



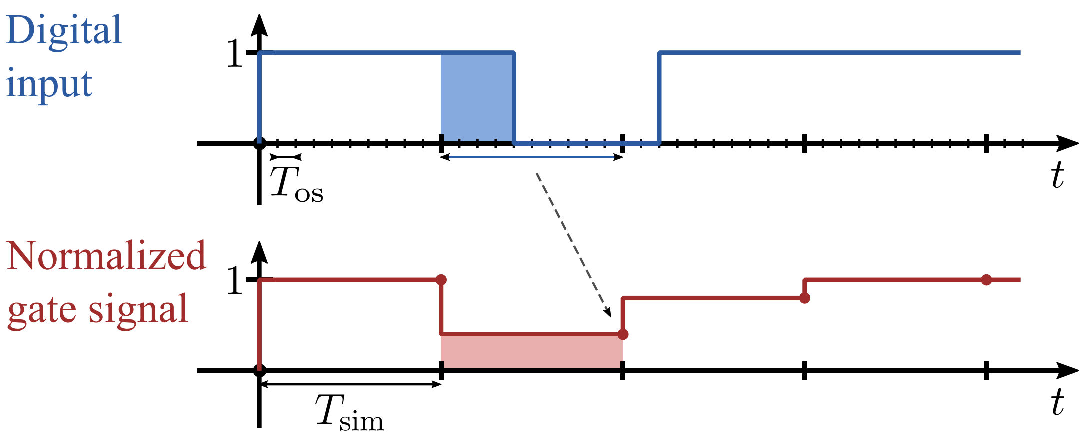
Oversampling thanks to eHS Gen5 Solver

- Switching signals sampled at a higher frequency than the simulation rate ($\mathbf{T_s < T_{sim}}$) – oversampling of switching signals
- Switching signals normalized to account for intra-time-step events

$$S_{norm}^{N+1} = \frac{T_{ON}}{T_{sim}}, \qquad 0.0 \leq S_{norm} \leq 1$$

- Normalized switching signals used in interpolation functions for calculating voltage/current

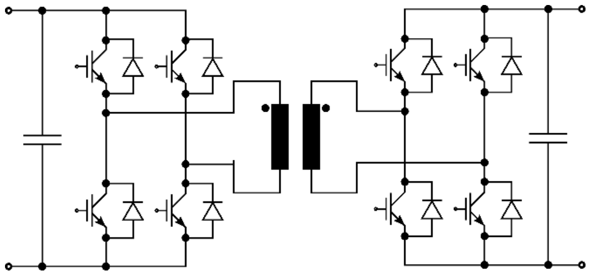
Oversampling of switching signals

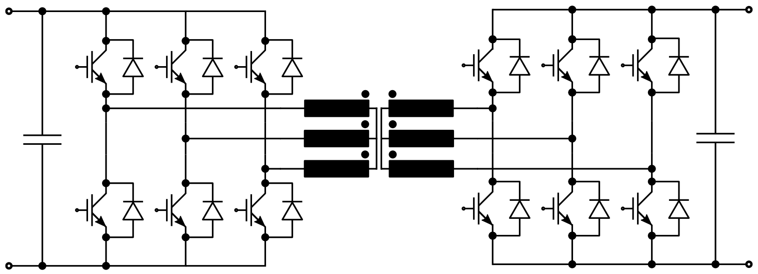


Real-Time Simulation of Dual-Active Bridge Converters

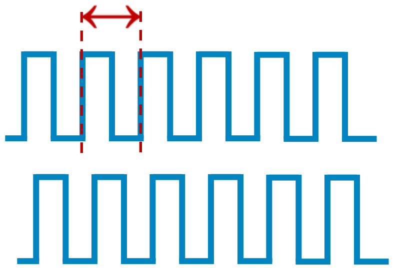
Challenge

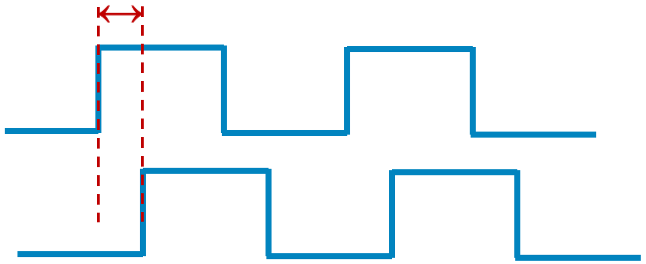
- **High-Fidelity** Real-Time Simulation of ***Dual-Active Bridge Converters***





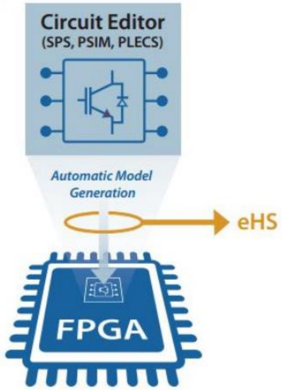
- High power density → high switching frequencies: $> 50\ \mathrm{kHz}$
- High-power converters → high-resolution phase-shift modulation: $< 10\ \mathrm{ns}$





Our solution

FPGA-based
electrical
Hardware
Solver

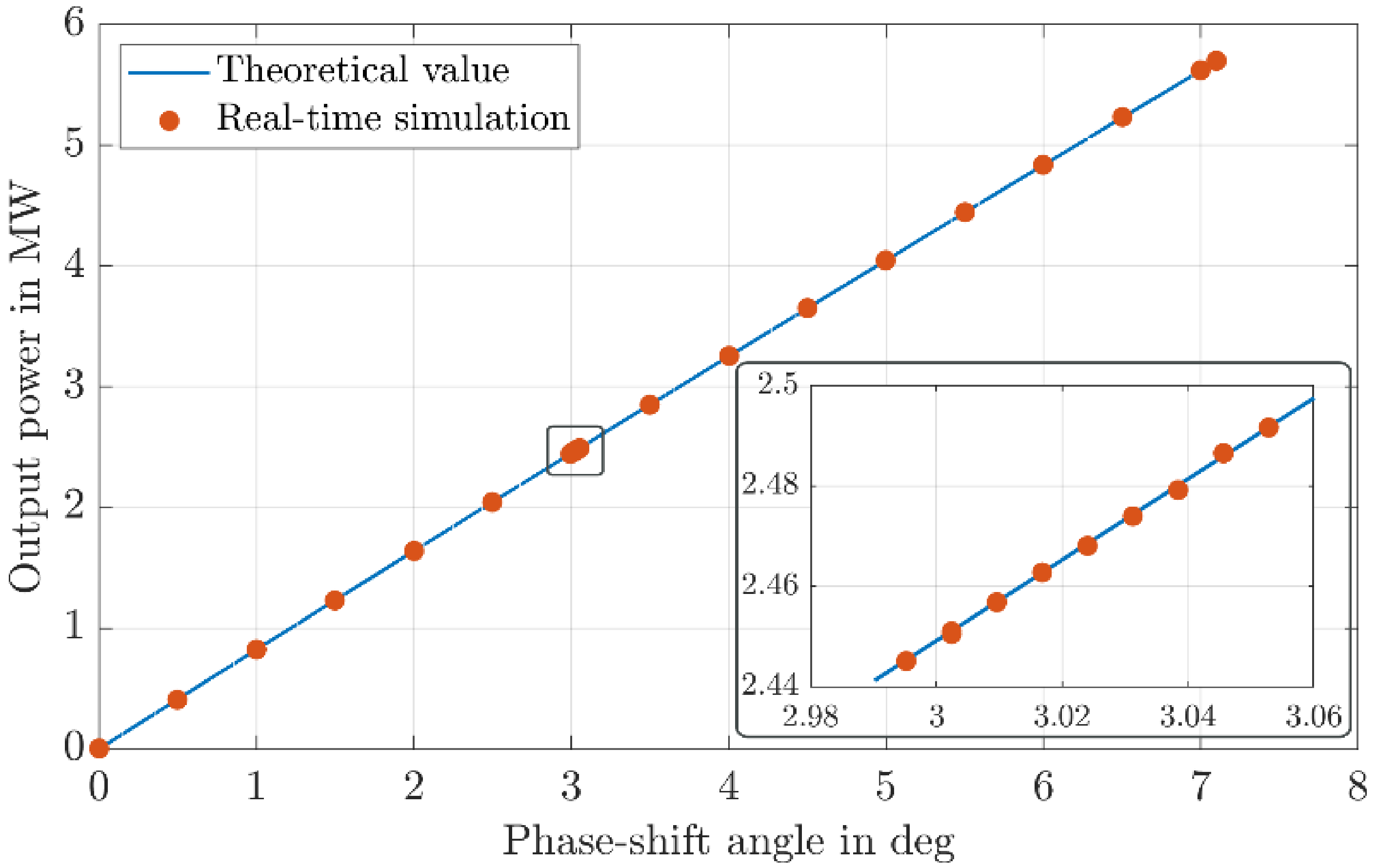


eHS Generation 5:

- Low simulation time steps $\sim\mathbf{100\ ns}$
- Oversampling of gate signals faster than the simulation rate $< \mathbf{1\ ns}$
- Time-Stamped Bridge converter models with high-order numerical interpolation methods

High-Fidelity Real-Time Simulation of High-Power DAB3 Converter

Output power



- Real-time simulation (RTS) with oversampling
  - Simulation time step **130 ns** for 3-phase DAB
  - Oversampling gate signals at **625 ps**
  - A high-degree of RTS fidelity with respect to theoretical values of the output power
- Simulation results of DAB3 converter for reference phase-shift around 3°
  - With **increments of 20ns** – which is lower than the simulation time step

Reference:
R. Mencher, M. Stevic, J. Mathé, D. Hoff, R. Venugopal and R. W. Doncker, "Real-Time Simulation of Medium-Voltage Dual-Active Bridge Converters for High-Fidelity Controller Testing," *2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe)*, Aalborg, Denmark, 2023.

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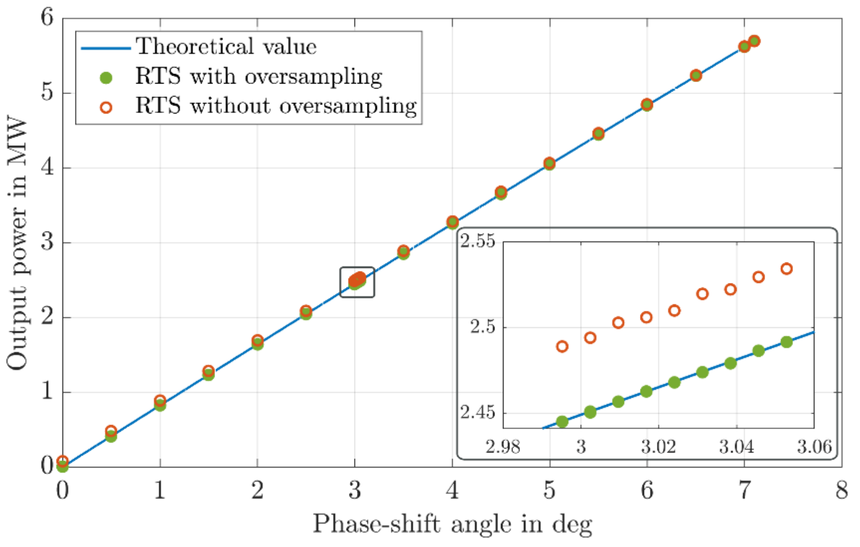
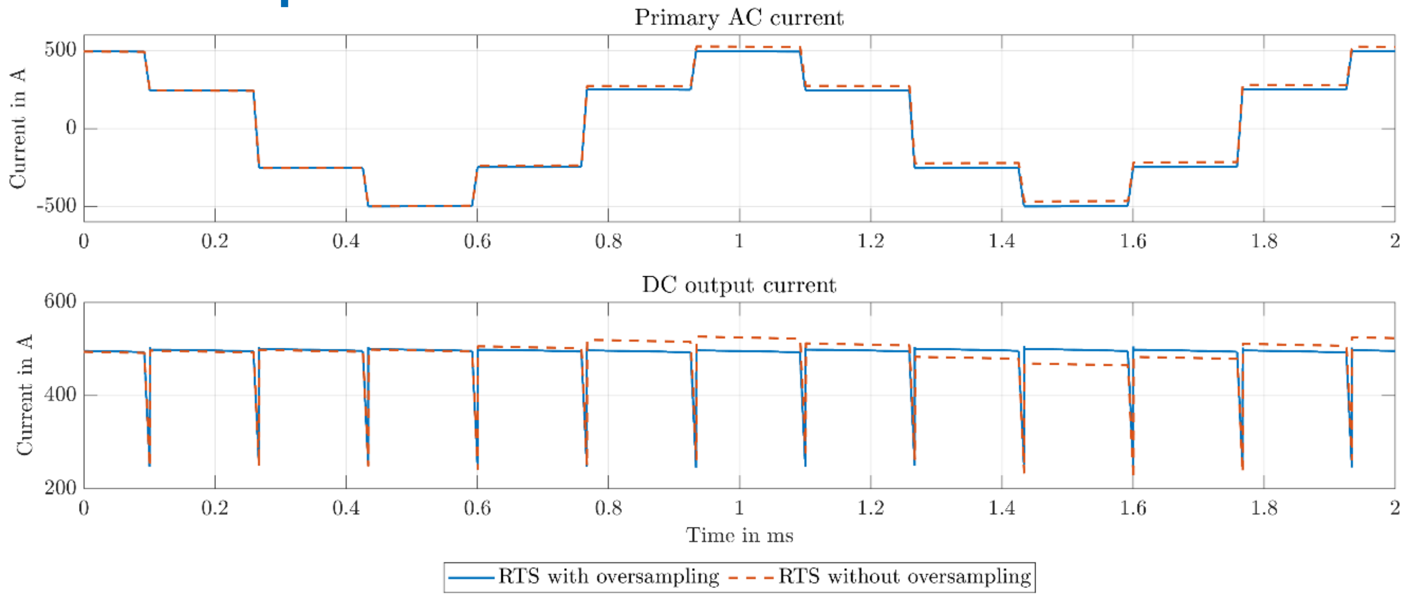
Comparison of RTS with/without oversampling

- RTS without oversampling exhibits oscillations in peak AC current and DC output current of the DAB3 converter

Simulation results: output power



Simulation results of DAB3 converter for reference phase-shift of 3°

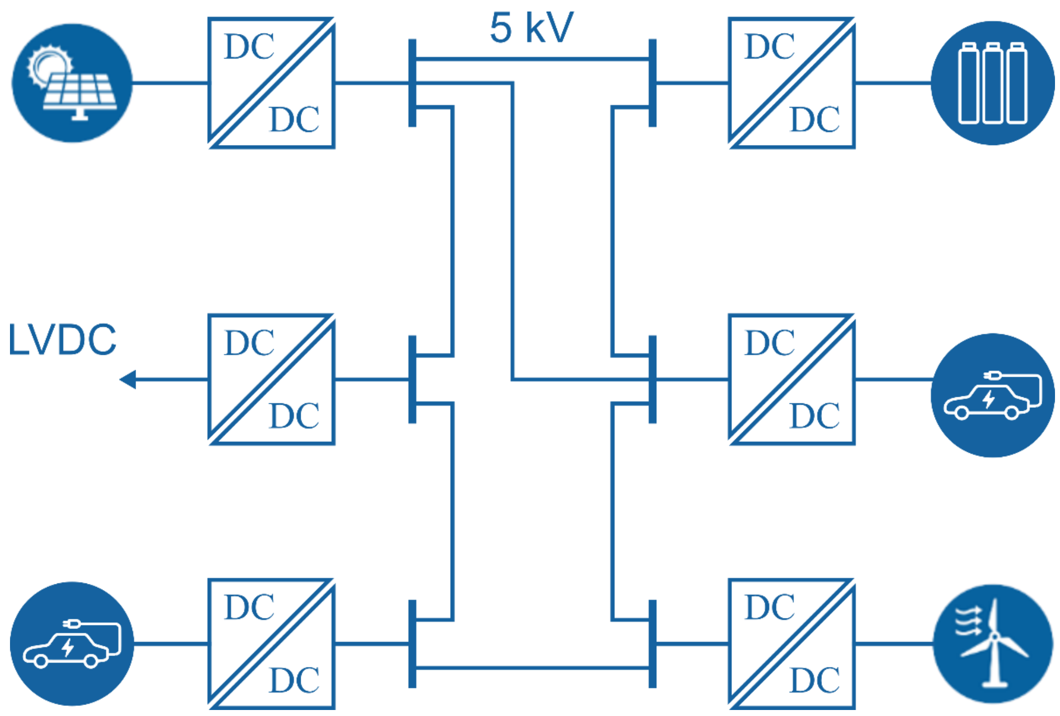


Reference:
R. Mencher, M. Stevic, J. Mathé, D. Hoff, R. Venugopal and R. W. Doncker, "Real-Time Simulation of Medium-Voltage Dual-Active Bridge Converters for High-Fidelity Controller Testing," *2023 25th European Conference on Power Electronics and Applications (EPE'23 ECCE Europe)*, Aalborg, Denmark, 2023.

Real-Time Simulation of DAB3 converters in MTDC grids

Challenge

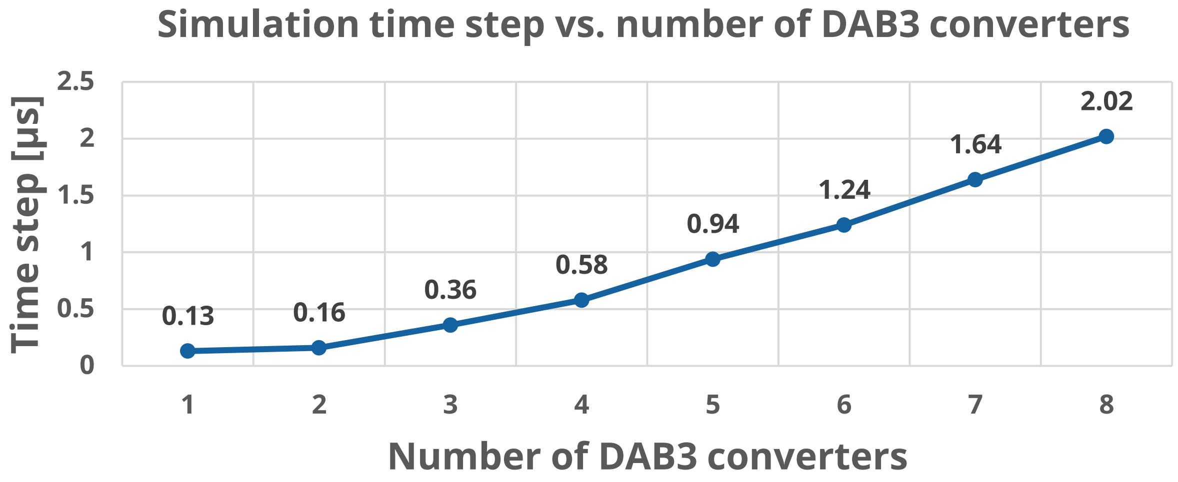
- High-Fidelity Real-Time Simulation of Multi-Terminal Direct-Current (MTDC) grids consisting of three-phase Dual-Active Bridge Converters (DAB3)



Our solution

Scalable FPGA-based electrical Hardware Solver (eHS):

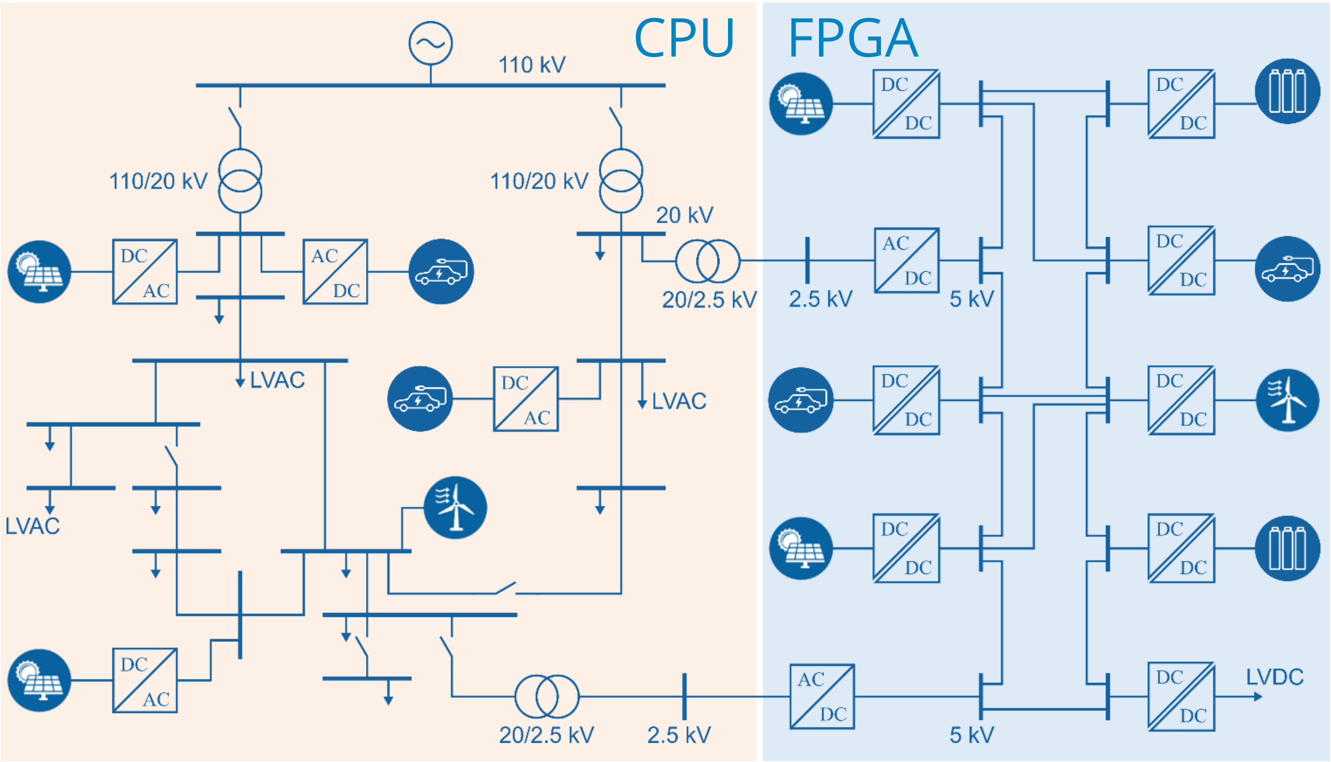
- Optimal utilization of FPGA resources: simulation of models with **large** number of switches at **low** simulation time steps – up to 128 switches on a **single** FPGA



Real-Time Simulation of Hybrid AC/DC grids

Challenge

- High-Fidelity Real-Time Simulation of a hybrid AC/DC grid with distributed generation units
- Large-scale multi-converter system



Our solution

Multi-rate simulation environment:

- Simulation of the entire hybrid AC/DC grid model in a single simulator
- CPU-FPGA co-simulation interface as a library block
- Reconfigurable FPGA-based **electrical Hardware Solver (eHS)** to support various converter topologies
- Enhanced solver for CPU-based simulation of AC systems with distributed generation units and inverter-interfaced loads

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Thank you for your attention

Questions?

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Reference: https://magazine.rpi.edu/spring2018/features/resilient-power-grid.html