International Workshop on
Dynamic Stability Challenges of the Future Power Grids

# Validation of Power Electronic Converters: From HIL Testing to Full Hardware Implementation


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Monday, 7 September 2026, Winterthur, Switzerland

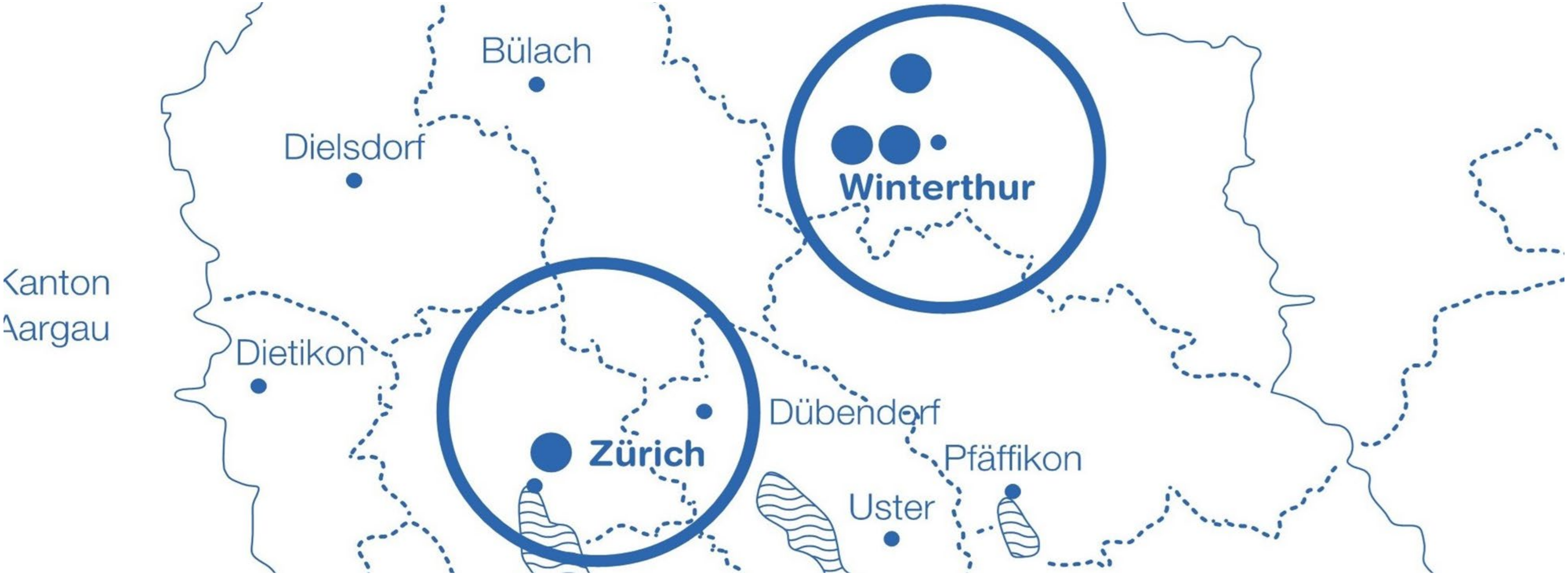
# Agenda

- Introduction
- Motivation
- Power Electronics Converters
- Example of Application
- Conclusions

# Who we are

# ZHAW


# ZHAW



Bülach
Dielsdorf
Winterthur
Kanton
Aargau
Dietikon
Zürich
Dübendorf
Pfäffikon
Uster

# Electric Power Systems and Smart Grids Group

**Guests**

**Dr. Mario R. Arrieta**

**Dr. Rafael Segundo**
Power Systems Dynamics and Control

**Dr. Miguel Ramirez**
Data Analytics and DSA

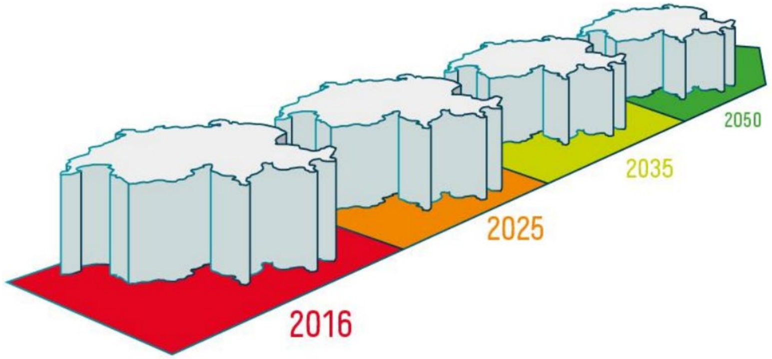
**Prof. Dr. Petr Korba**
Head of the EPS&SG

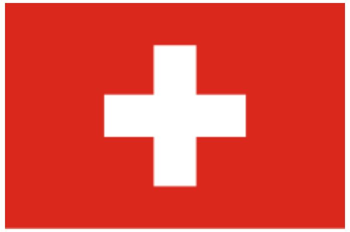
**Dr. Alfredo Velázquez**
Grid Integration of Power Electronics Converters

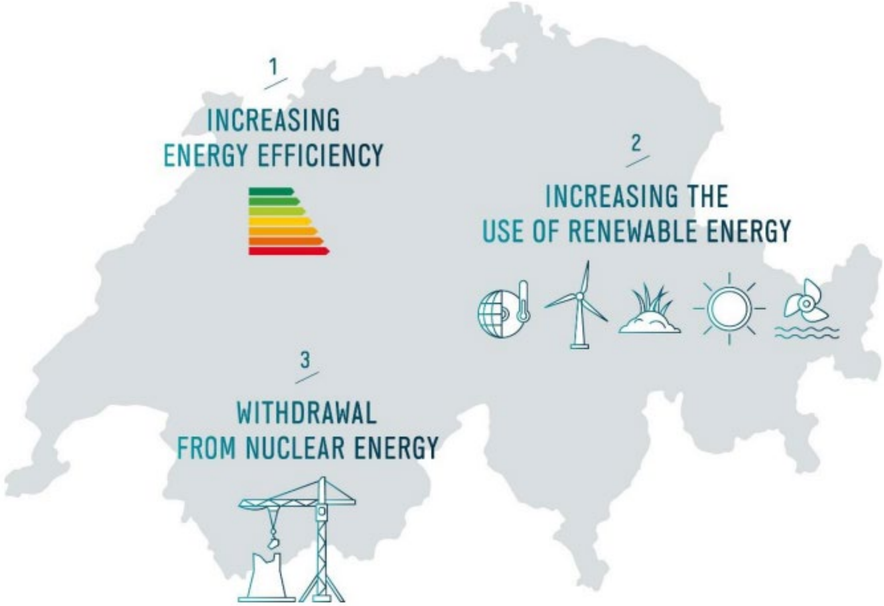
**Dr. Artjoms Obusevs**
Smart Distribution Automation

# Motivation

# Switzerland - Energy Strategy 2050






- **Increase energy efficiency.**
- **Increase the use of renewable energy.**
- **Withdraw or minimize nuclear energy.**

# Another Examples...

## In Europe:

**Germany -** Federal Climate Change Act.

- ❑ Strong integration of renewable energy by 2045.

**Denmark -** Danish Climate Act.

- ❑ Reduce emissions by 70% by 2030.

**France -** Energy and Climate Act.

- ❑ Carbon neutrality by 2050.

**UK -** Net Zero Strategy.

- ❑ Net-zero emissions by 2050.

## Around the world:

**Mexico -** Energy Transition Act.

- ❑ 35% renewable energy by 2030.

**Brazil -** National Energy Plan 2050.

- ❑ Reduce emissions by 70% by 2030.

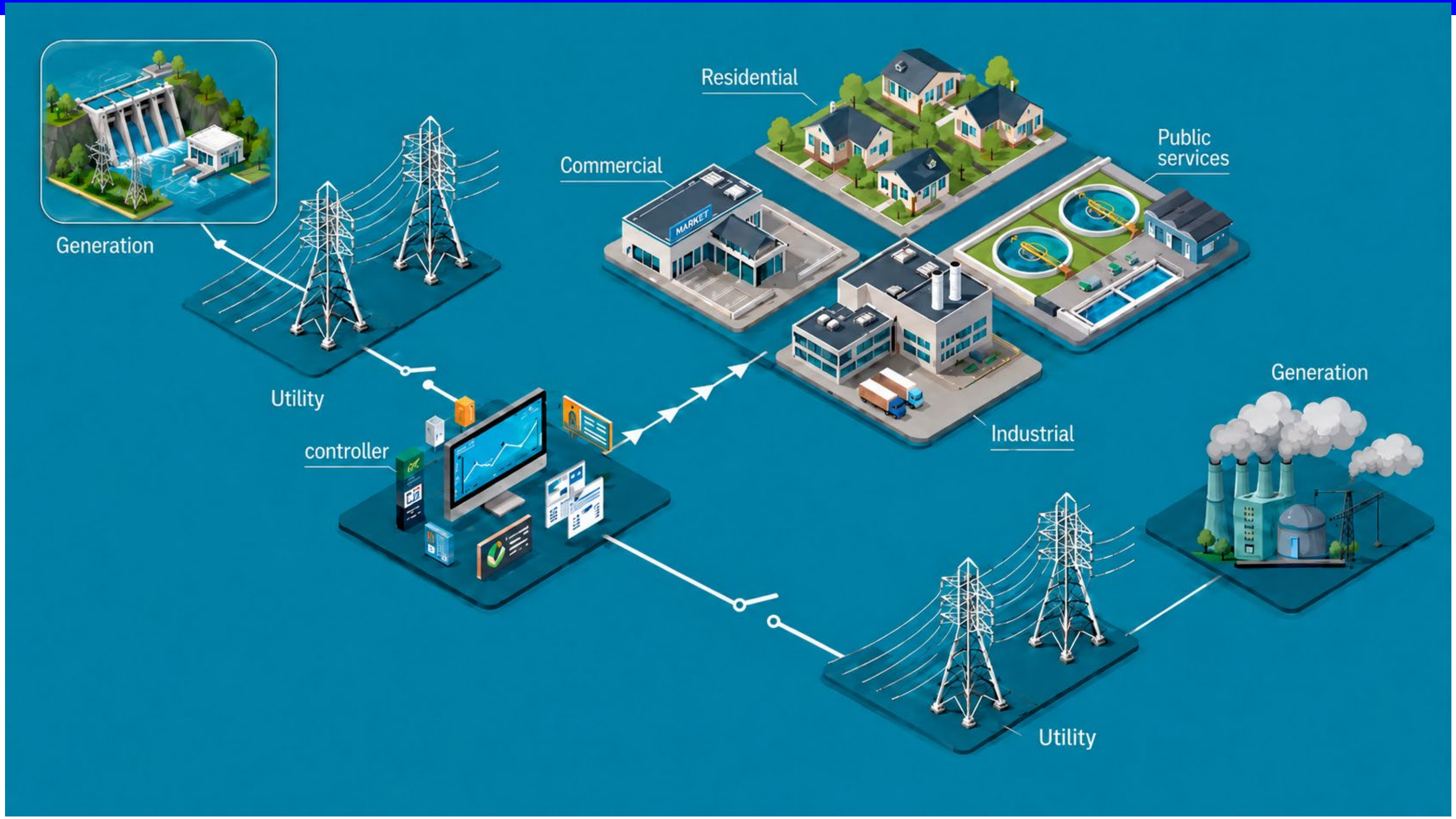
**Japan -** Green Transformation Act.

- ❑ Carbon neutrality by 2050.

**Australia -** Australia’s Net Zero Plan.

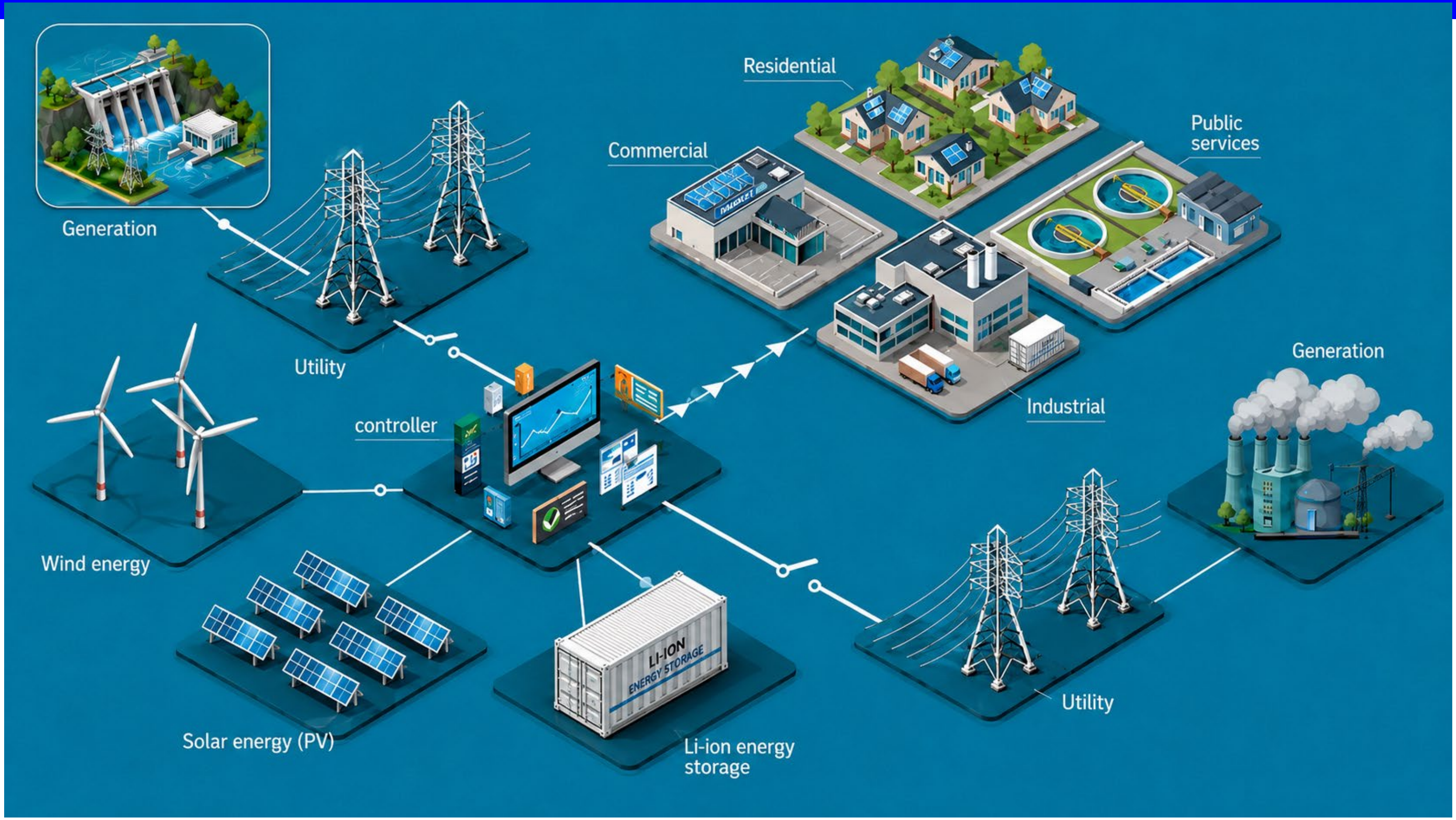
- ❑ Net-zero emissions by 2050.

# Where electricity comes from and where it goes.




Power Systems of the past. Enhanced by AI.

# Where electricity comes from and where it goes.




Modern Power Systems. Enhanced by AI.

# Power Systems

- Uses fossil fuel
- High emission of $CO_2$
- Enough body mass
- Resilient to disturbances

- Sufficient body mass
- Strong to disturbances and stability support
- Powered by a balanced clean energy mix
- Minimum emissions

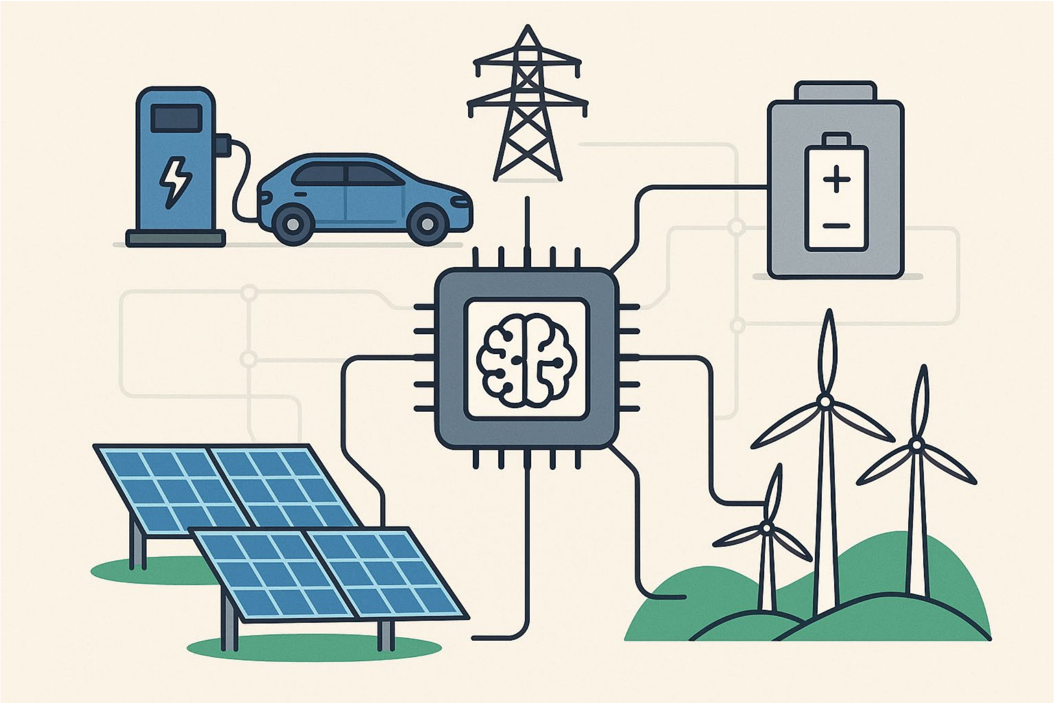
- Relies only on renewable energy
- Zero emission of $CO_2$
- Low body mass and weak to disturbances

*AI Generated Images.

# What is the role of power electronics in all of this?


Charging Stations

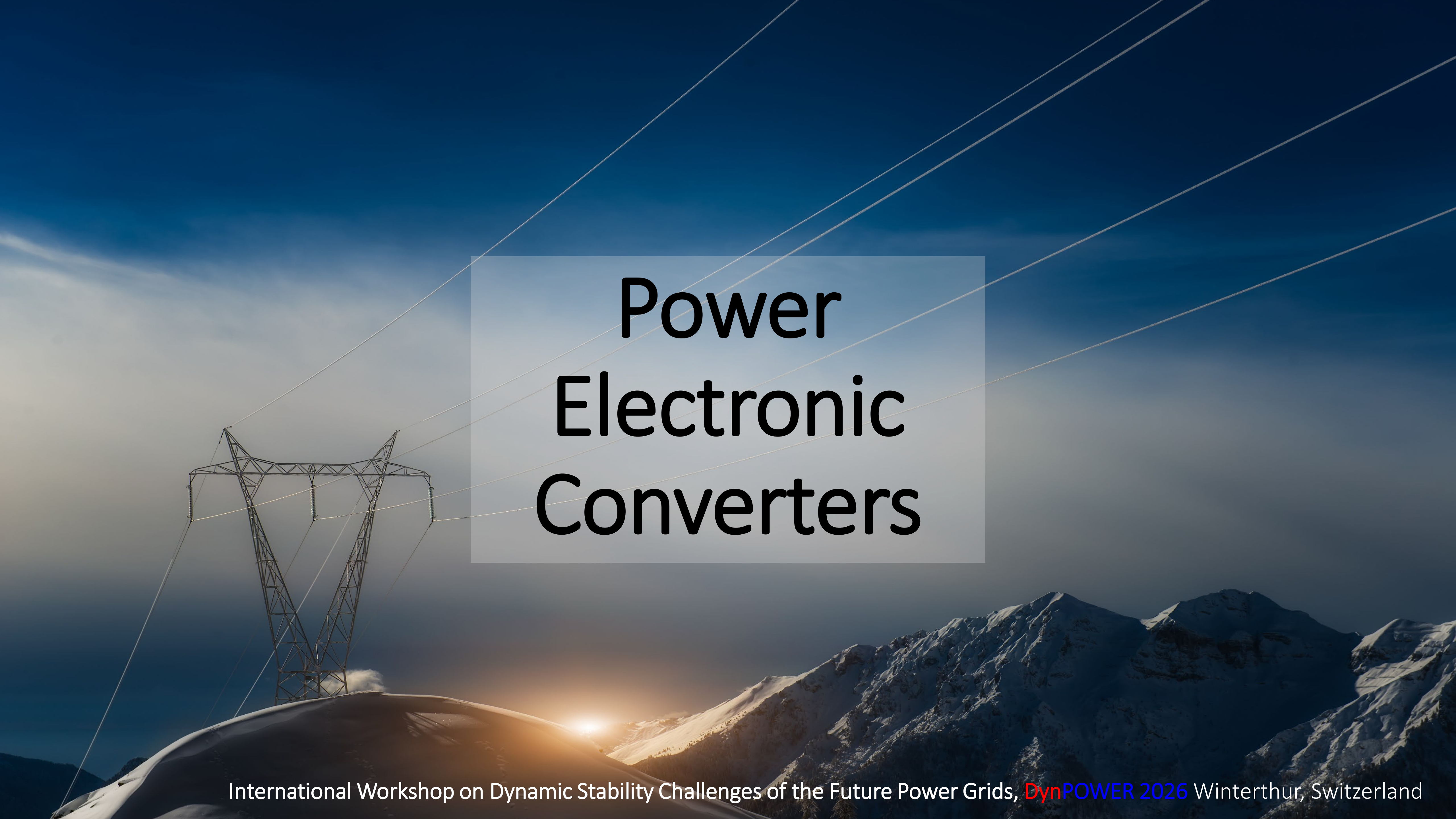
Solar Energy



Role of Power Electronics. AI Generated.

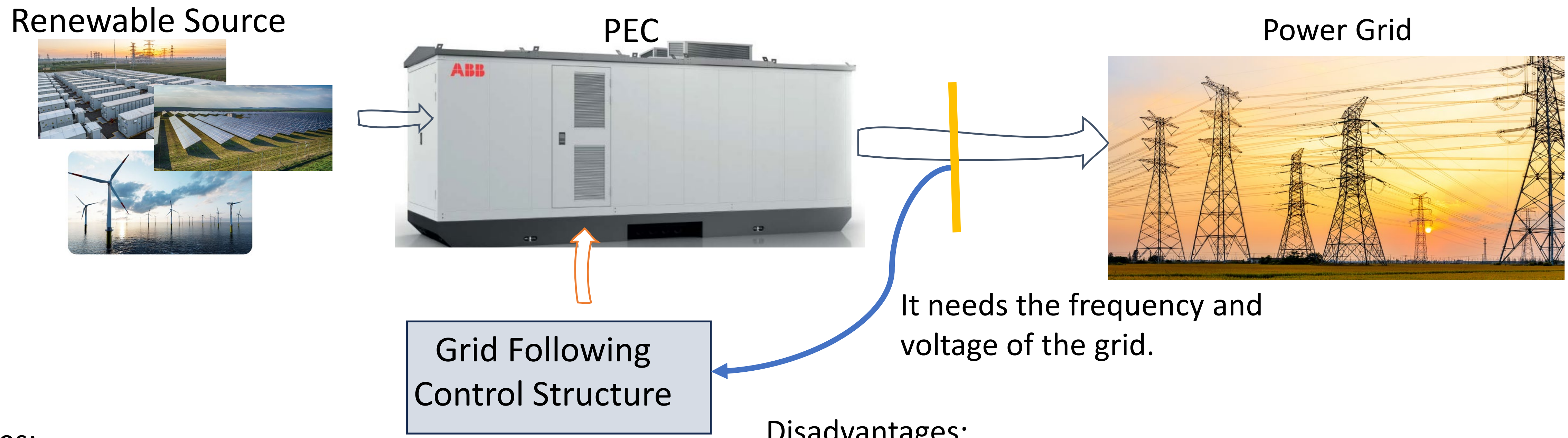
Energy Storage

Wind Energy



# Power Electronic Converters

# What is a Grid Following Power Electronic Converter?




Advantages:

- Easier synchronization with strong grids.
- Simple control structure and widely used in existing grid-connected systems
- Mature technology: Widely adopted and standardized.

Disadvantages:

- Cannot operate without an existing voltage reference (depends on the grid).
- Provides limited frequency and voltage support. No inertia support.
- Poor performance under weak-grid or fault conditions.

# What is a Grid Forming Power Electronic Converter?

Renewable Source

PEC


Power Grid

Grid Forming Control Structure

It can form its own voltage and frequency to establish or sustain the grid.

Advantages:

- Can establish and regulate voltage and frequency autonomously.
- Provides strong frequency and voltage support to the grid.
- Provides virtual inertia
- Enables operation in islanded or weak-grid conditions.

Disadvantages:

- More complex control and protection schemes.
- Less mature technology with less commercial implementations.
- Depends on a stable DC bus.

# History Recap

Renewable energy becomes available

1

How do we integrate it?

2

Use Power Electronics Converters

The grid is already strong and "stable" (polluting a lot)

3

what should PECs do?

4

Just follow the grid

We have many converter-based resources

5

Why are problems appearing?

6

The grid becomes weaker and less supported.

7

What do we need now?

8

Converters that also support the grid

# Main Research Question.

Energy Storage

Solar Energy

Wind Energy

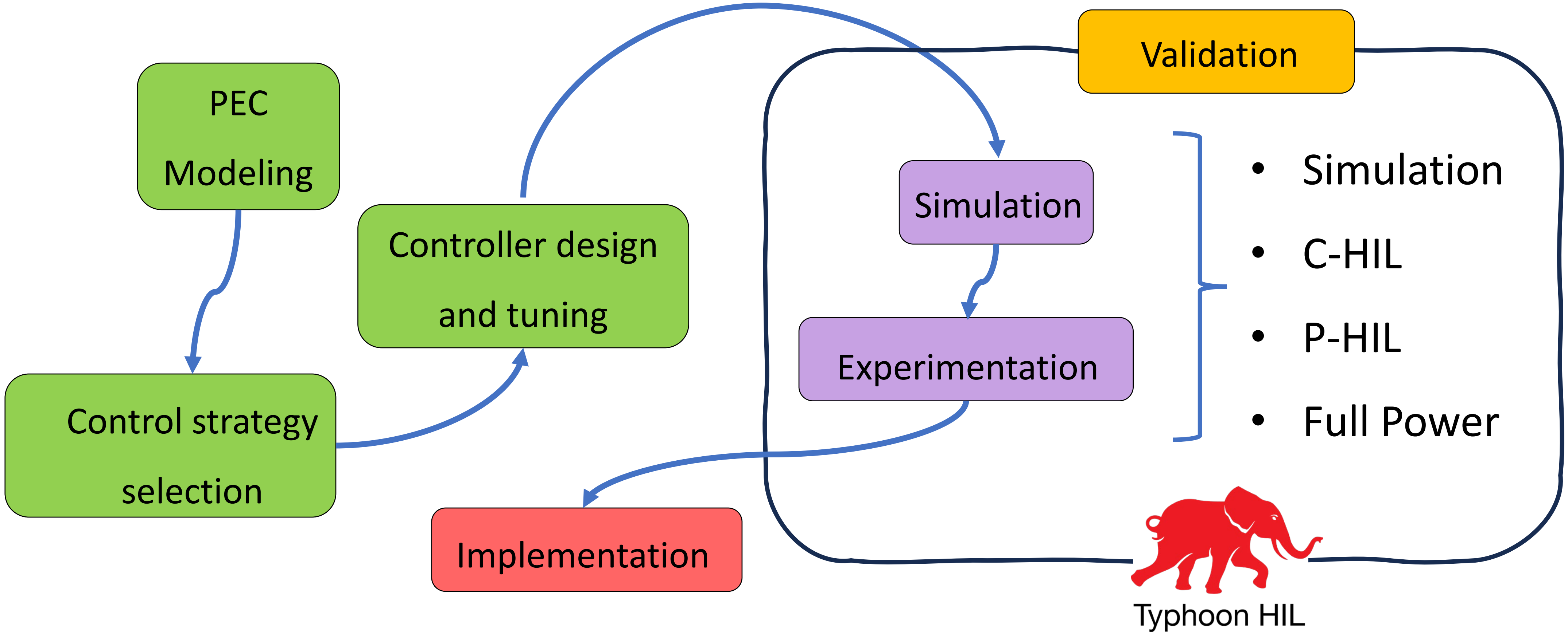

Power Electronics Converter (PEC)

- ***How can these technologies be controlled and connected to the electrical grid, and how does this affect the overall power system?***

# Development and Testing

# Development and Testing

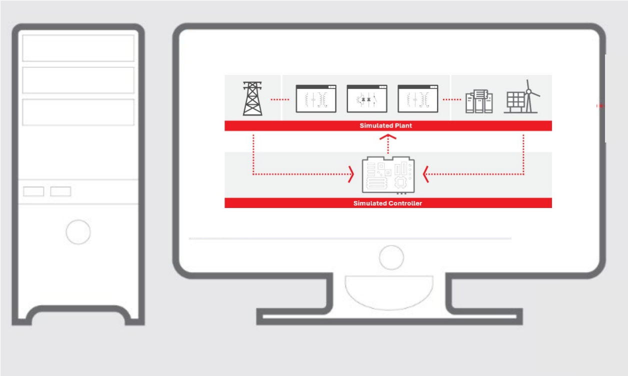
The above is the process that I follow for the development of control structures for PECs.



# Model-Based Engineering

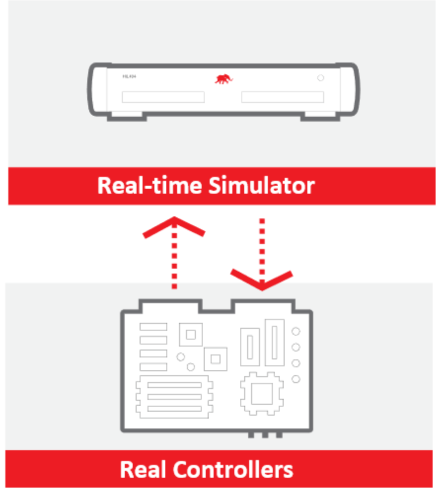
Motivation

- Increased complexity
- Software-driven systems
- Agile design iterations and rigorous validation

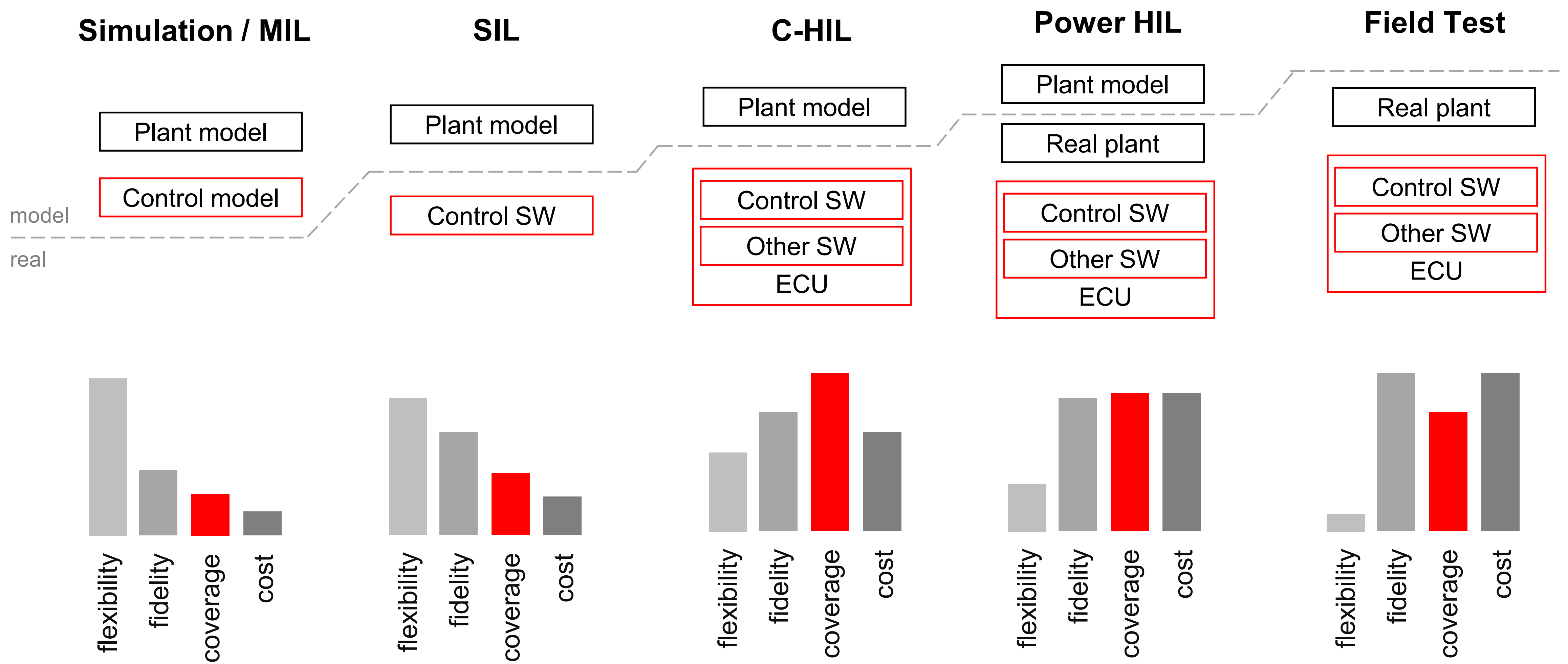



Model-Based **Engineering**

Employ digital models to support the **entire lifecycle**, from early design to commissioning and maintenance, **from component-level to system integration**.

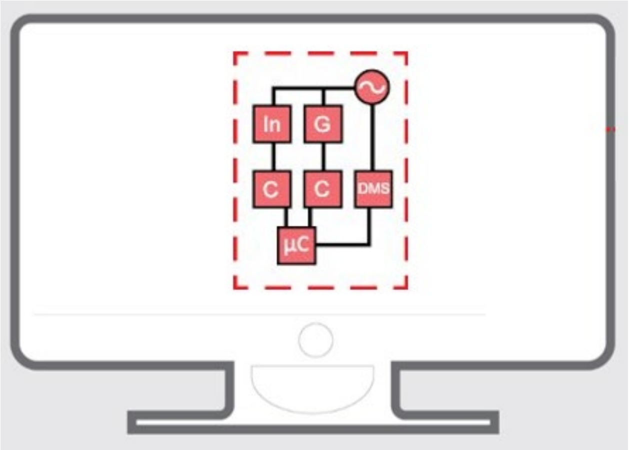


# Control Testing Methods



# Offline Simulation

Model-in-the-Loop
(MIL)



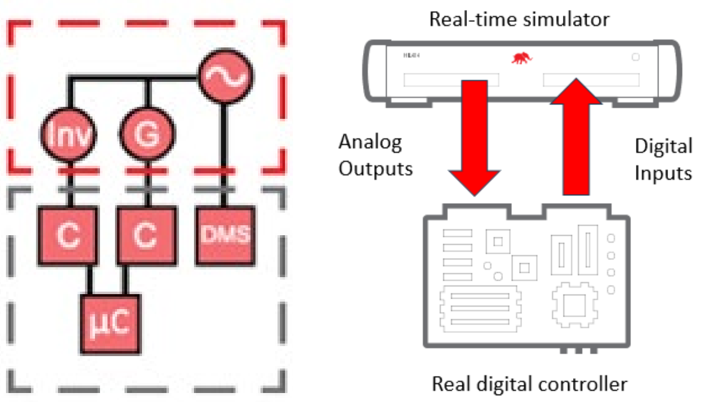

❖ The **power system**, the **PEC**, the **DC power supply (PV, Battery or other converter)** and the associated **global control structure** are simulated offline, using TyphoonSim platform.

✓ Offline simulation gives full flexibility without real-time constraints

✓ Especially useful for early stage component specification and controller design.

# C-HIL

Controller Hardware in the Loop (C-HIL)

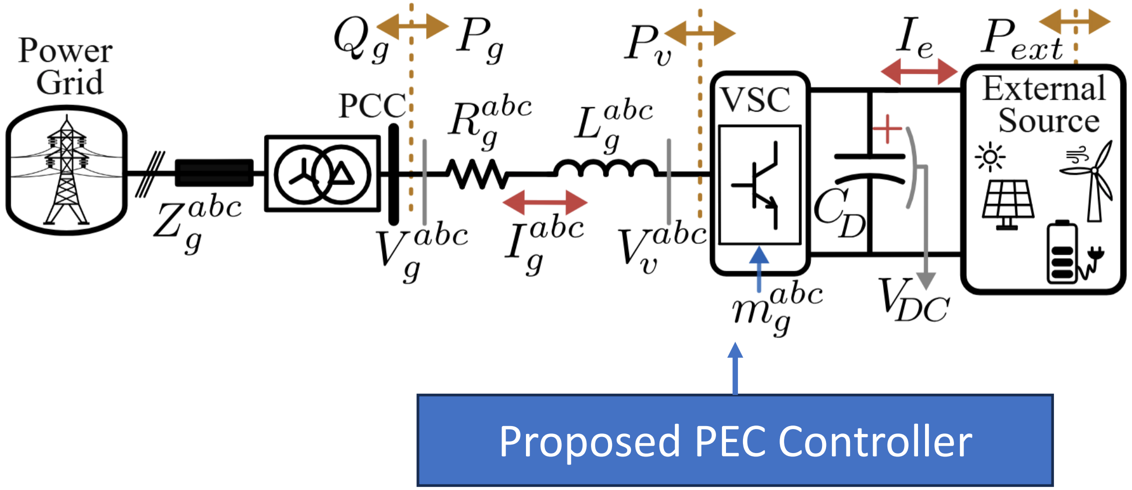



- ❖ The **power system**, the **PEC**, and **the DC power supply** are simulated and executed in real time within the **Typhoon HIL device**.
- ❖ The **global control structure** is implemented on **an external controller**.
- ❖ Physical connection interface is needed to perform the test.

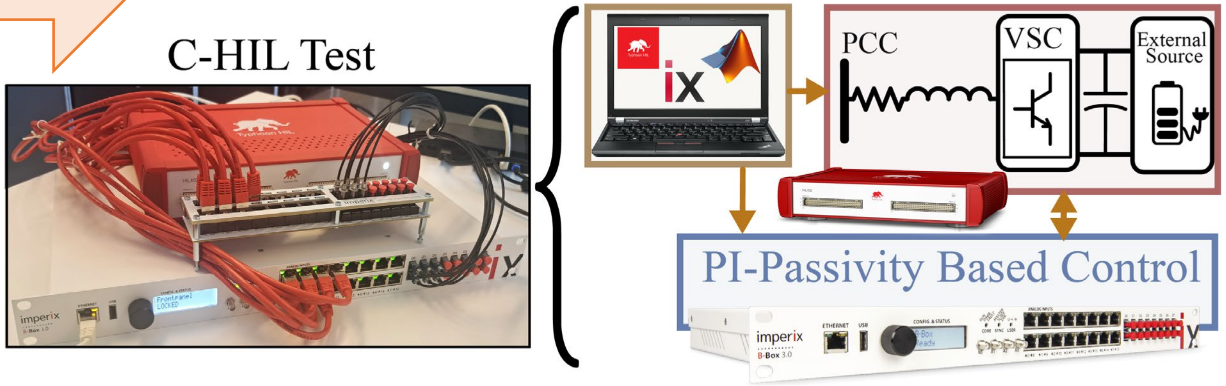
✓ Useful for system integration and controller testing

# C-HIL Example - Research

Developed idea.



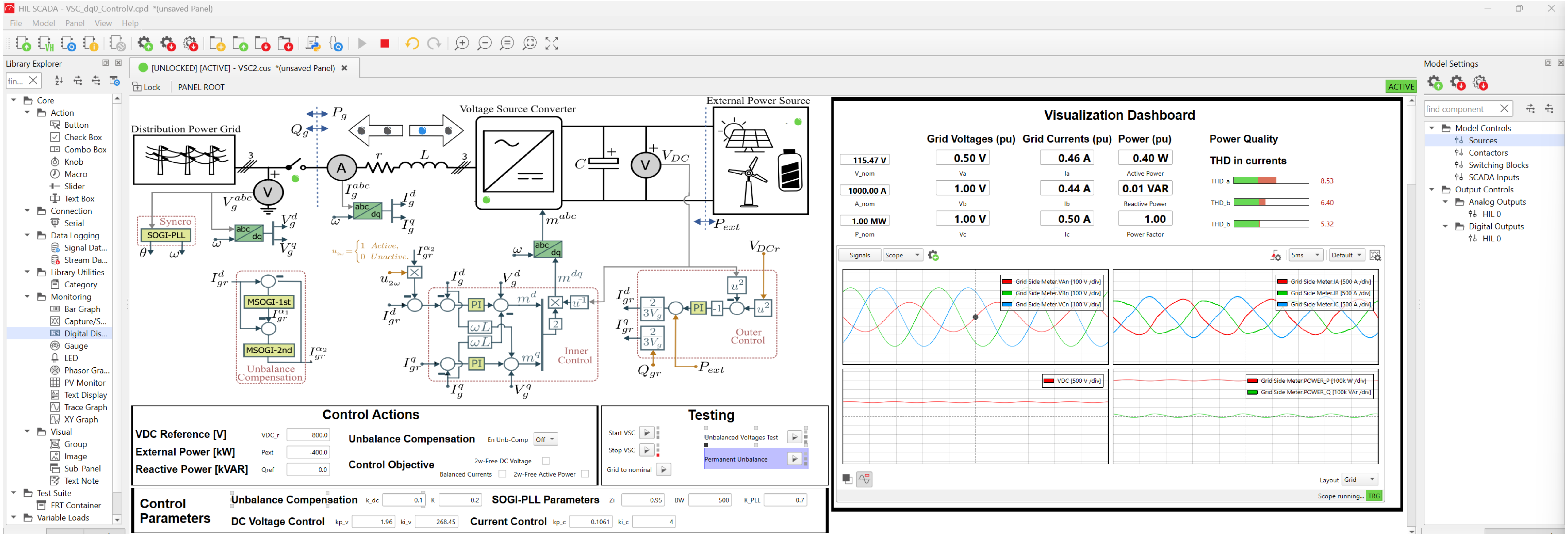

C-HIL Validation




It was employed:

1. One Typhoon HIL 404 device.
2. One Imperix B-BOX 3 RCP controller.
3. One HIL interface device from Imperix.

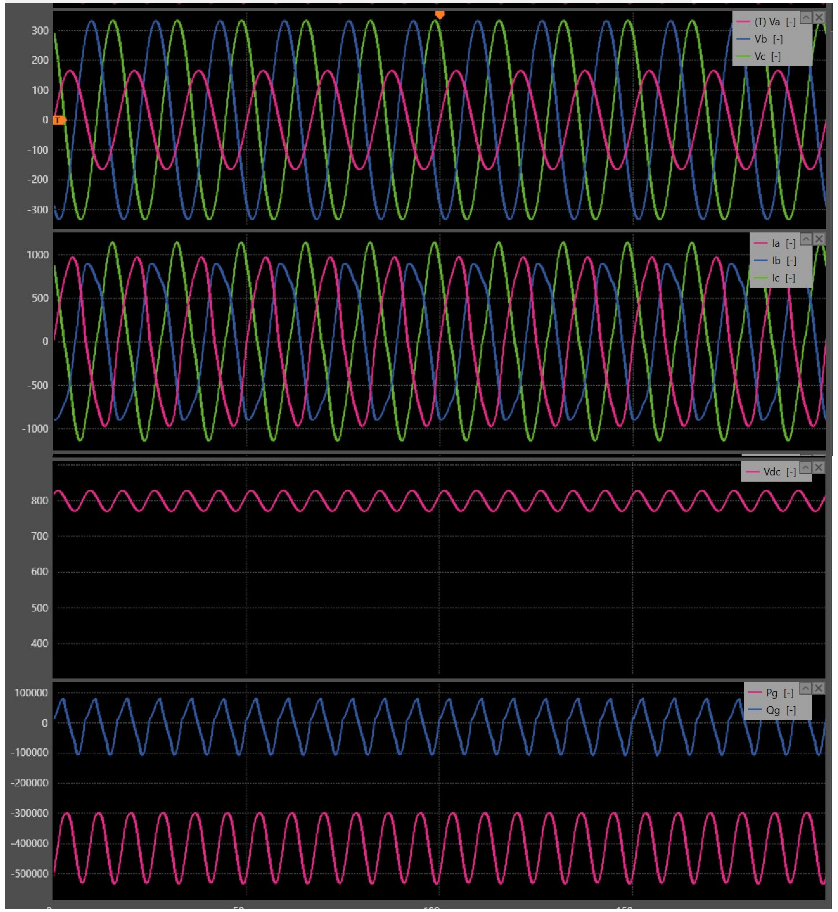
# C-HIL Example – SCADA



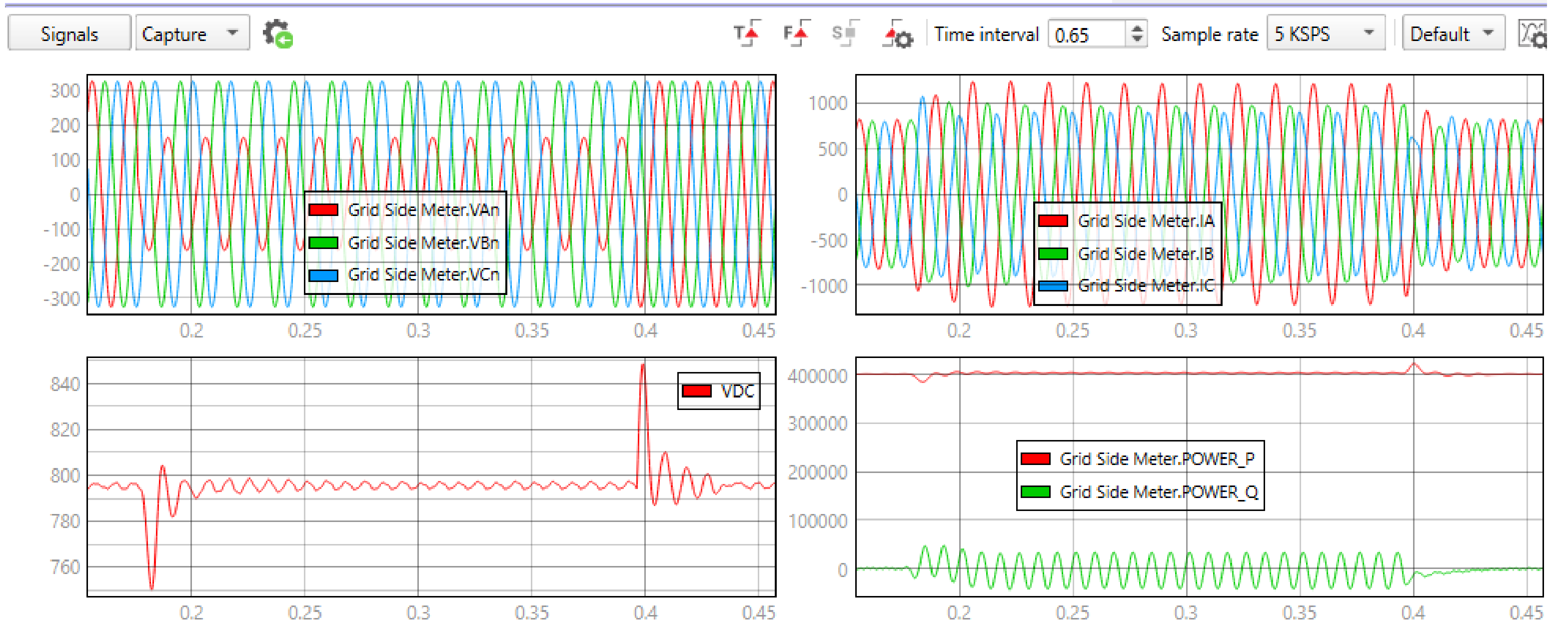

✓ The implemented SCADA system can modify control setpoints in real time, activating or deactivating functionalities, and executing tests for different phenomena, while simultaneously recording data.

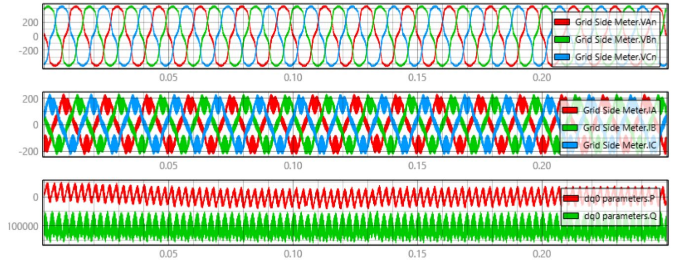
# C-HIL Example – Type of Results

## Imperix Interface




## Typhoon SCADA



# C-HIL Example – Industrial Case

**Tesla – Deploying Megapack at Scale**

- “Products designed for fast and simple installation ensuring projects are deployed and connected to the grid on time and as fast as possible.”
- “C-HIL helps us deliver a real-time simulation of the Megapack, to mimic how the Megapacks would respond once the site is fully operational.
- “C-HIL testing is a force multiplier for our deployment speed. It helps us compress what would be otherwise traditionally months of field testing and commissioning into days of lab validation”

Available online on YouTube (Tesla, 2014) - https://www.youtube.com/watch?v=32C0_8_296k

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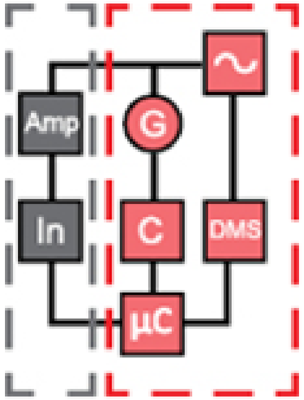
# P-HIL

Power Hardware in the Loop (C-HIL)




- ❑ The **power system** is simulated and executed in real time within the **Typhoon device**.
- ❑ The **PEC** and **DC external supply** are physical devices connected to an **AC amplifier**.
- ❑ The **global control structure** is implemented on an **external controller**.
- ❑ The **AC amplifier** is controlled by the **Typhoon device**.

✓ Validate the controller with real power exchange, including power amplifiers, sensors, delays, and interface dynamics.

Typhoon HIL

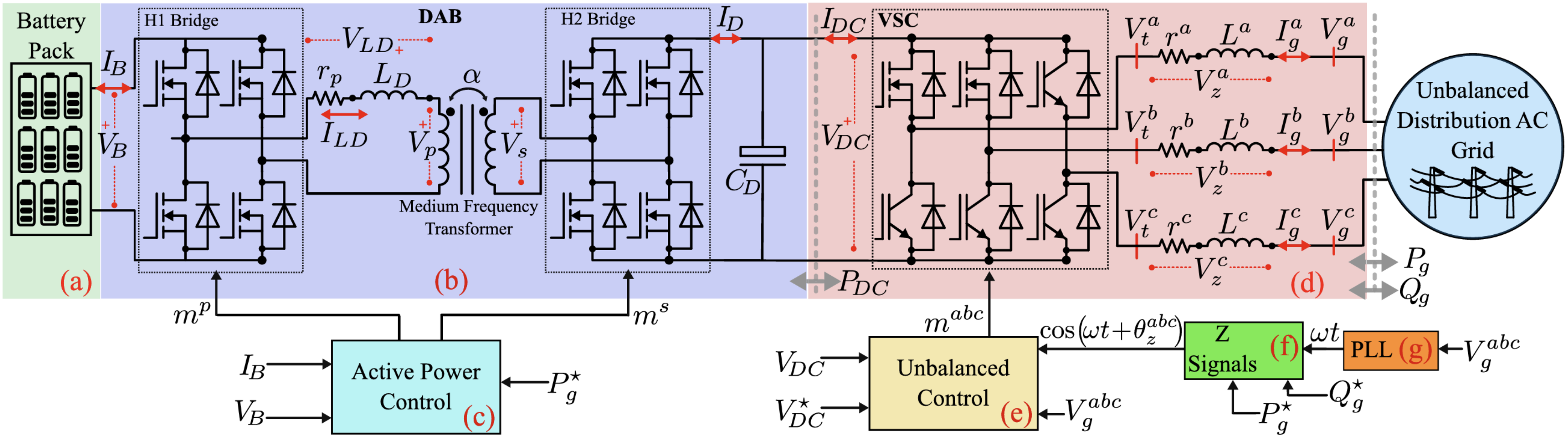
imperix

REGATRON programmable power

# P-HIL Example

P-HIL Validation

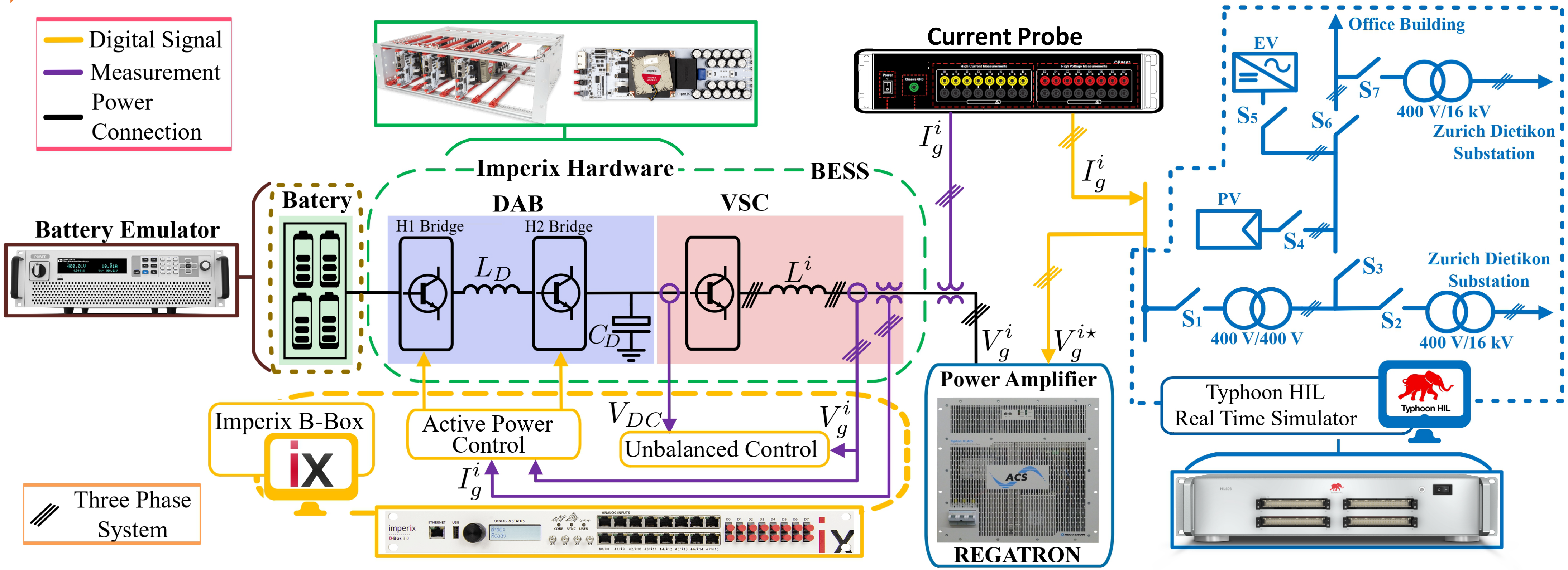
Developed idea.



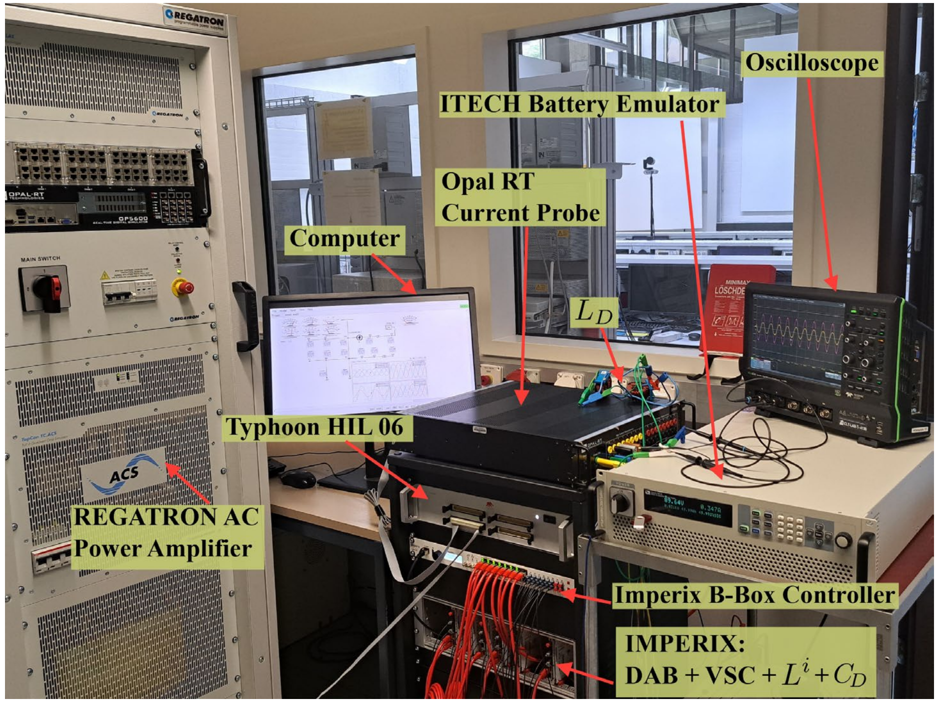
# P-HIL Example

P-HIL Validation

It was employed: * One Typhoon HIL 606 * One Battery Emulator * One Power Amplifier * One Imperix B-BOX 3 RCP controller * One 3 ph Curren Probe * Two PECs made by Imperix Hardware.



# P-HIL Example: Key Insights




It was employed:

- One Typhoon HIL 606
- One Battery Emulator ITECH
- One Power Amplifier REGATRON
- One Imperix B-BOX 3 RCP controller
- One 3 ph Curren Probe
- Two PECs built with Imperix Hardware.

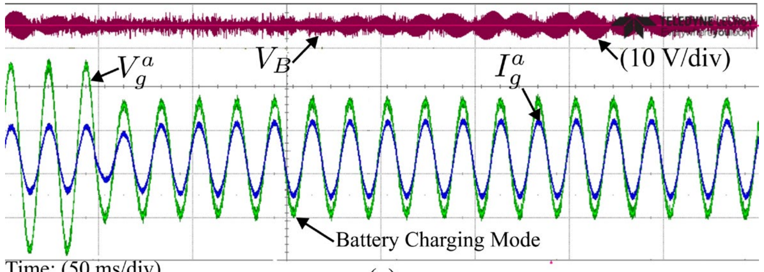
✓ The results obtained with this platform can be considered highly reliable.

× The time required to start testing with this platform can be considerably high.

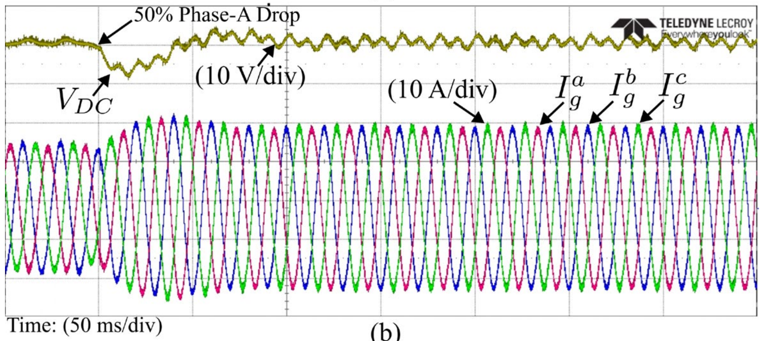
# P-HIL Example – Type of Results

The same types of results as in **C-HIL** can be obtained: **Post-processed data, data using Typhoon HIL as SCADA and data using Imperix as SCADA.**

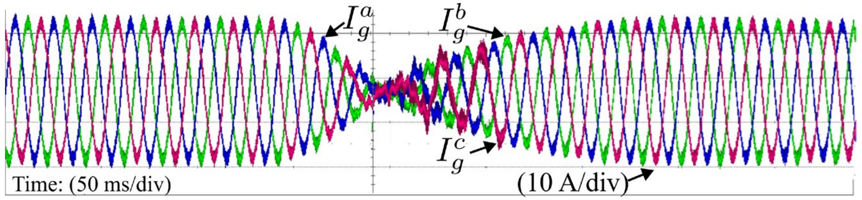
Additionally, electrical waveforms can be captured **directly from the power hardware** using differential probes and an oscilloscope. These **direct measurements provide higher-fidelity experimental evidence**, as they are acquired directly from the physical signals without relying on software-based data acquisition or post-processing.



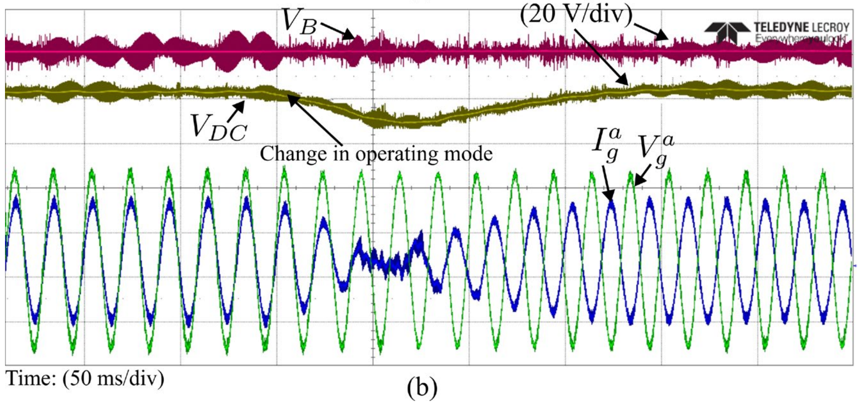

(a)




(b)




(a)



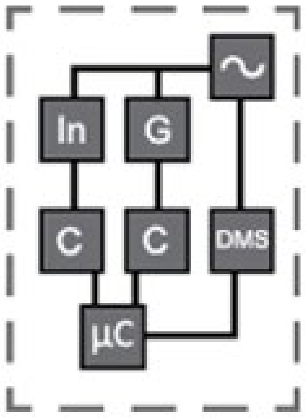

(b)

It was employed:

1. One Typhoon HIL 404 device.

# Full Power

Full Power

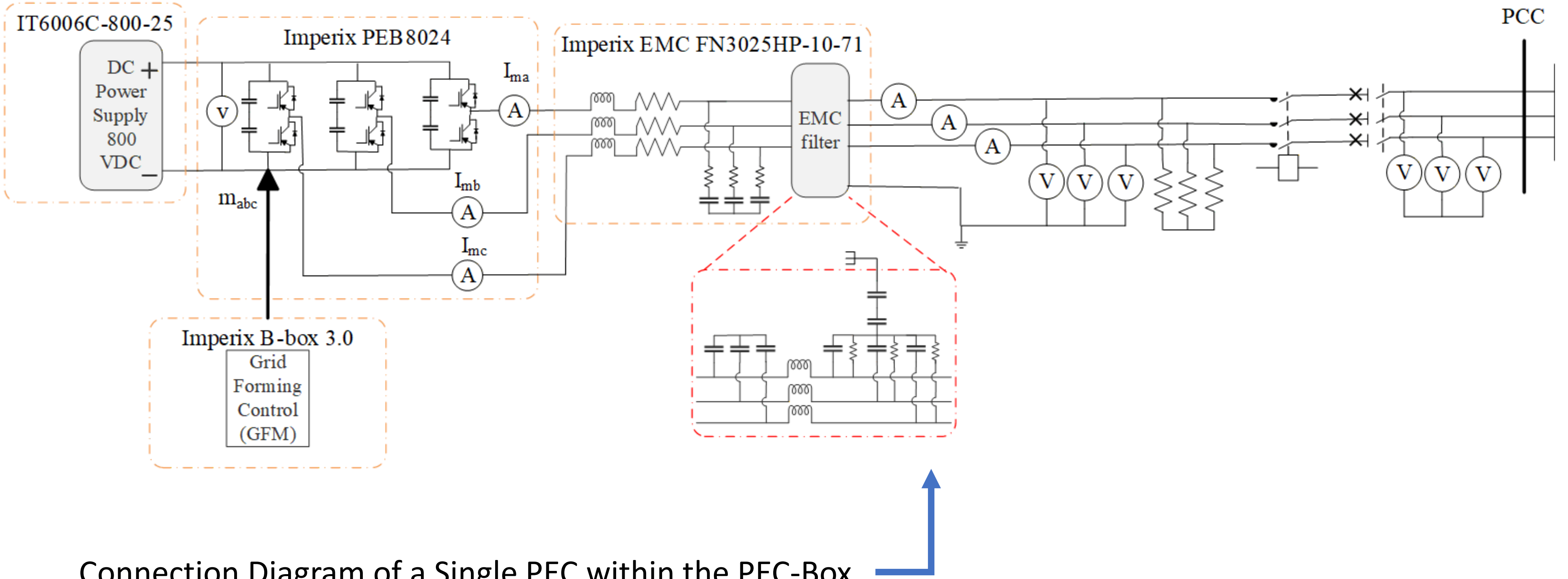



- The **PEC** and **DC external supply** are physical devices connected to the **utility grid** or **physical microgrid**.
- The **global control structure** is implemented on an **external controller**.
- **Power is physically exchanged** between the PEC and the actual electrical system; no simulated power interface is involved.
- **Electrical variables are measured directly from the physical system** and used for control, protection, and validation.
- The **Typhoon device** serves as **SCADA** and **Data Acquisition** system.

Typhoon HIL imperix LUCAS-NUELLE SIEMENS ABB

# Full Power

The **Power Electronics Converters Box (PEC-Box)** is a platform developed in our lab that enables the testing of up to **four GFL/GFM converters**, with a rated capacity of **16 kVA per converter**.

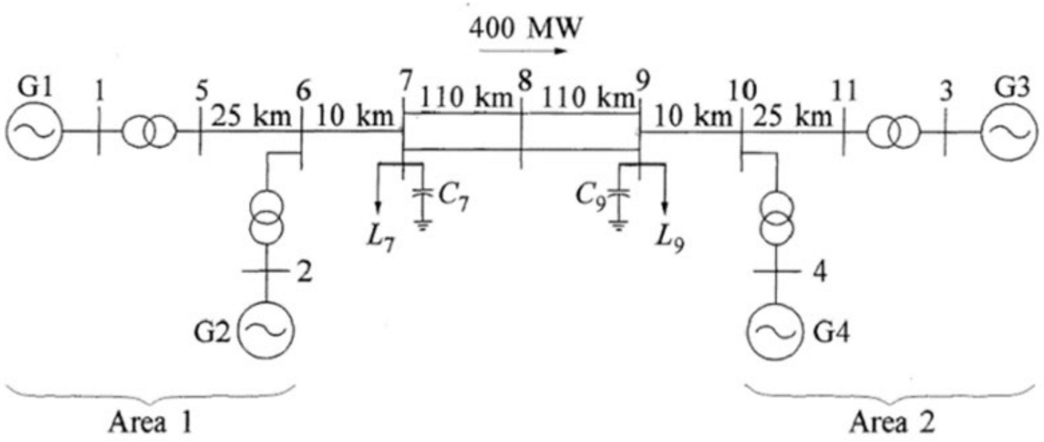




Connection Diagram of a Single PEC within the PEC-Box

# Full Power – System under Test

The **four-machine power system** is a benchmark model widely used to study power-system dynamics and stability.

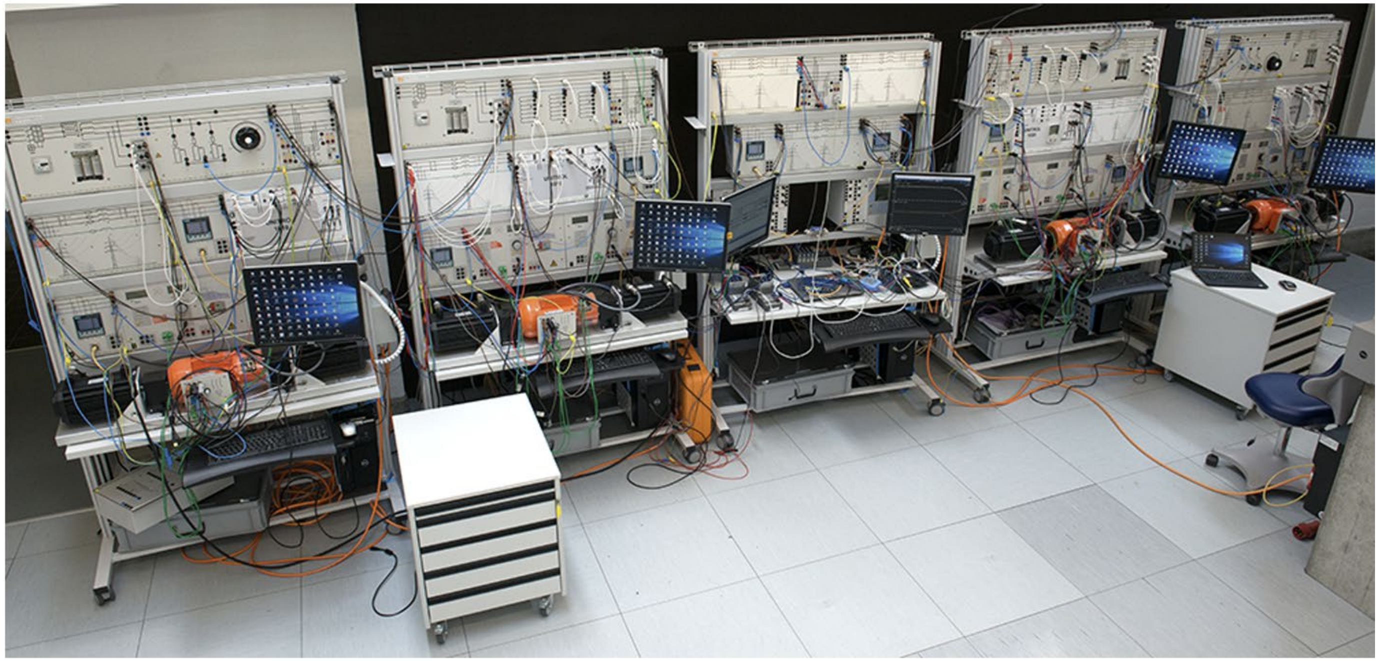
It represents the interaction of multiple **synchronous generators, transmission lines, and loads** under realistic grid conditions.

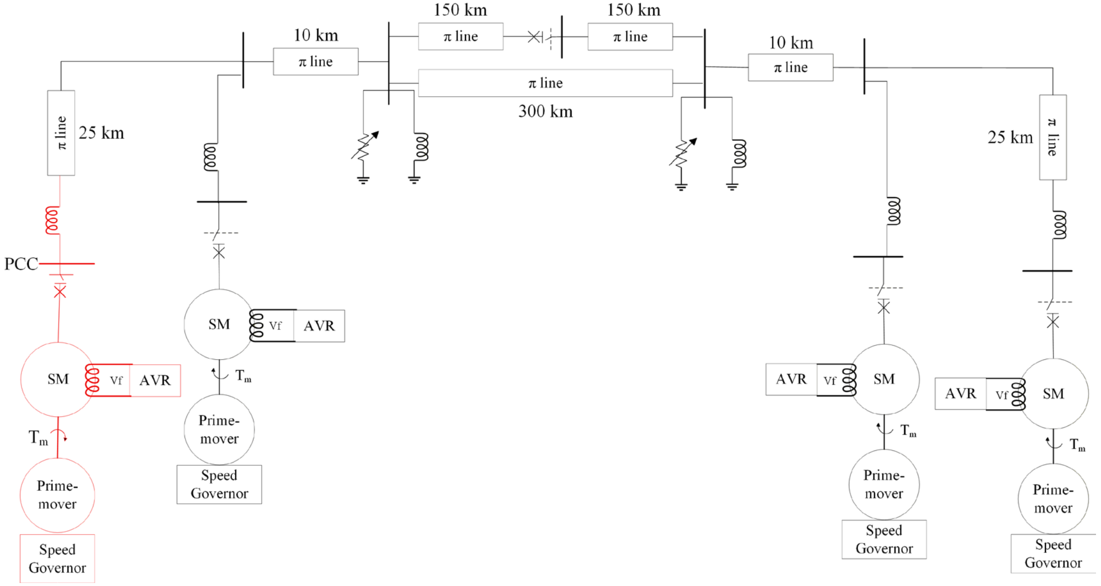



**Turns out…**

# Full Power – System under Test

We have our own **scaled four-machine power system** implemented in our lab.



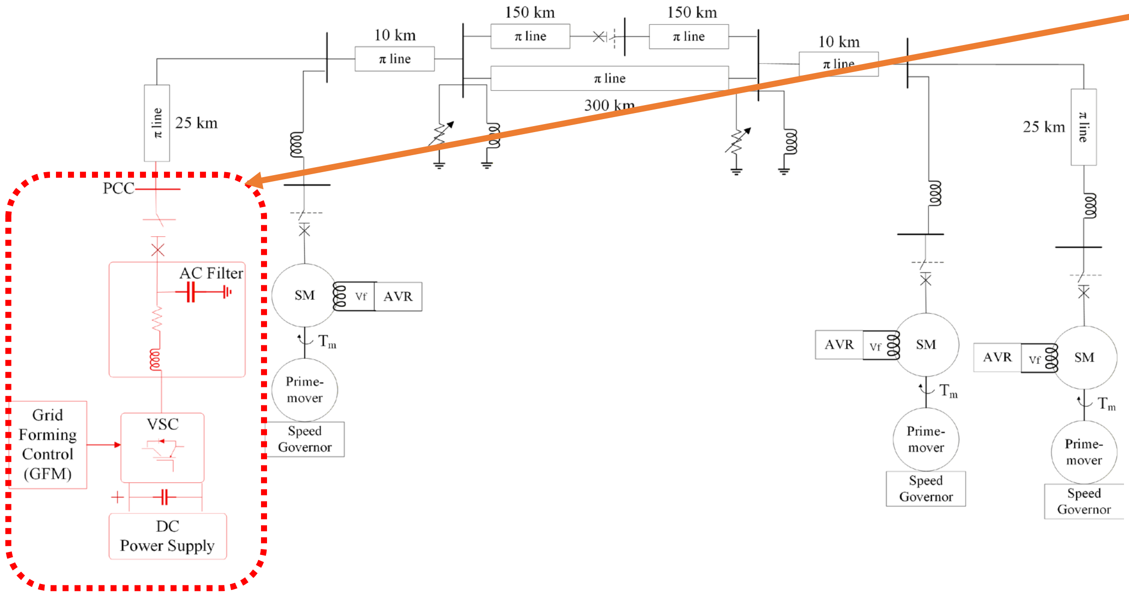



It includes:

- 4 synchronous machines with exciters and governors
- 11 buses as grid connection points
- Transmission lines and transformers
- Electrical loads representing consumption
- Tie-lines for power exchange between areas

# Full Power – System under Test

One synchronous machine was replaced by a grid-forming converter from our PEC-Box.




We perform:

- Smooth synchronization of the GFM converter with the system.
- Active and Reactive power changes in the system.
- System frequency regulation by the GFM converter.

# Want to see a live demo?

# Beyond DynPOWER 2026 Day

**Live Laboratory Demonstration**

*Renewable Energy Integration in Modern Power Grids.*

- The complete system will be demonstrated **live during tomorrow's additional event at our university**.

**Beyond DynPOWER 2026 Day**

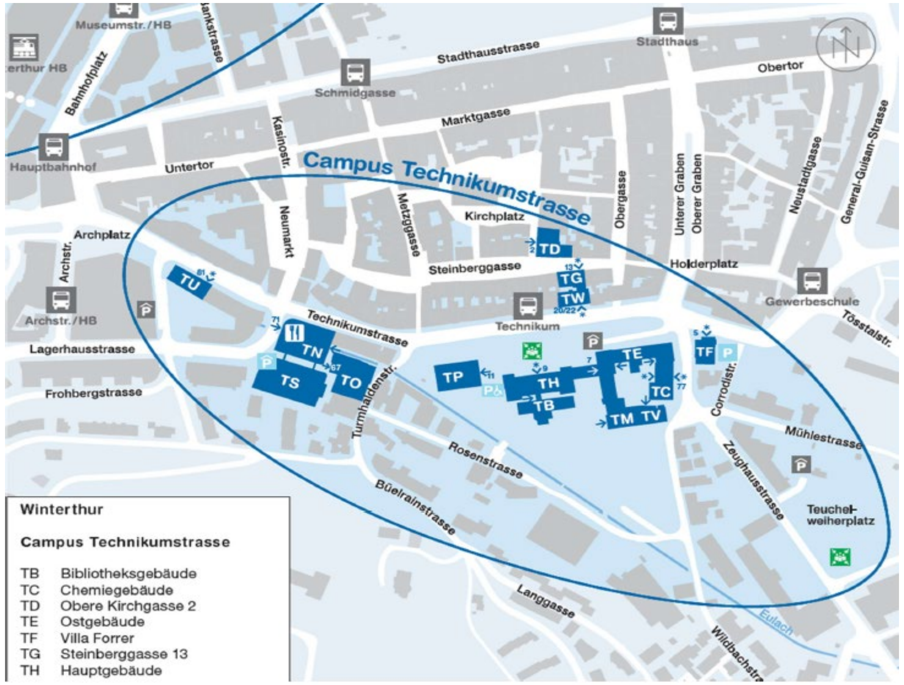
📅 9 September 2026 | 11:00–11:30

📍 ZHAW School of Engineering, Winterthur

**Free Registration · Exclusively In person**

**Venue**

Electric Power Systems Laboratory in Room TB 149 at the ZHAW School of Engineering, located at Technikumstrasse 9, 8401 Winterthur.




Conclusion

# Conclusion

- This presentation focused on the **different testing and validation approaches** used within our research group.

- However, **testing is only one part of our research activities**. We actively participate in **national and international research projects**, covering the complete research process from **concept development to experimental validation**.

- This means transforming an **original concept for PECs** into a validated solution through **simulation, HIL testing, and full hardware implementation**.

- The resulting research is reported through **research projects and internationally recognized scientific publications**.

**What may appear as only one or two figures in a scientific paper can represent months of development, implementation, testing, and validation.**

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