Typhoon HIL, Inc.

Hardware-in-the-Loop Testing for Grid Stability and Resilience

How HIL can help a faster transition

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Agenda

- ☐ Digitalization, Decentralization and Decarbonization
- ☐ Model Based Engineering
- ☐ Modeling principles
- ☐ Protection and Control
- ☐ Microgrid Controller
- ☐ Examples on usage of HIL technology to improve grid resilience
- ☐ Conclusions

The three Ds

Digitalisation Decentralisation and Decarbonisation

Digitalisation

The new grid is all about software

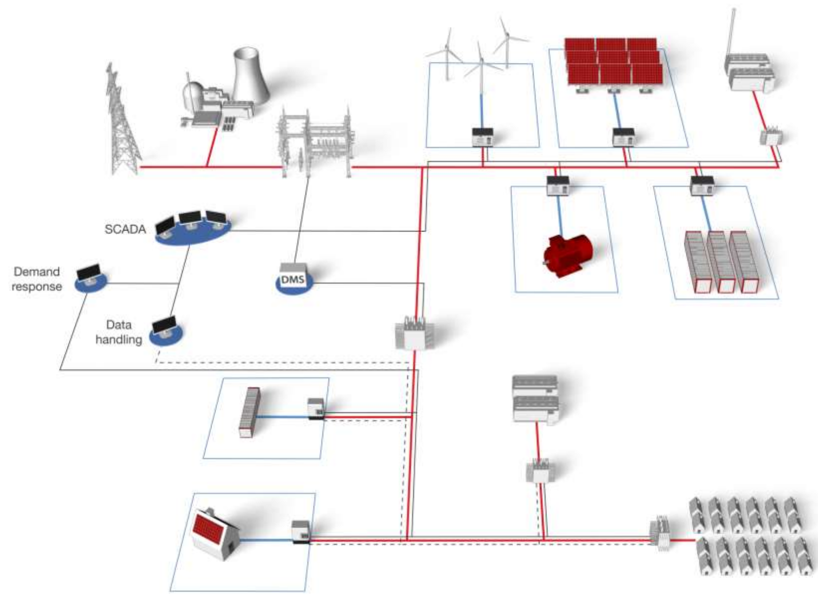
- The next-generation electricity grid is expected to integrate interoperable technologies – particularly in the energy, transport, information and communication fields with the aim to increase reliability, affordability and sustainability of grid and market operations, including:
  - electric mobility solutions,
  - demand response techniques,
  - distributed ledger technologies / blockchains,
  - storage devices,
  - distributed energy generators ,
- Digitalization is about making the power sector smarter and more flexible by collecting and analyzing more system and customer data, through sensors and 'smart meters,' and using the insights to tailor energy delivery and use via digital controllers and intelligent electronic devices.

Microgrid Knowledge: Build a better microgrid with Hardware in the Loop

Decentralisation

Power flowing both directions

- The power industry is no longer a one-way street with power flowing from a remote centrally located power station out to end users. Increasingly, power is flowing in two directions as consumers adopt technologies that allow them to generate and store energy.
- Most importantly, energy is moving from a supplier-customer model of centralized control to a peer-to-peer structure in which anyone can offer services of value to another—for example related to timing, location, delivery rate, or quality of service.



[Microgrid Knowledge: Build a better microgrid with Hardware in the Loop]

Decarbonisation

…thanks to electrification

- The third leg of this three-part trend is decarbonization. Both digitalization and decentralization inherently reduce primary energy use and consequently reduce emissions of carbon dioxide (CO2), one of the principal greenhouse gases.
- Electricity emerges as the critical energy vector and an unprecedented opportunity to foster a clean energy transition and the decarbonization of energy uses. The European Union is determined to increase its climate ambition by 2030, pushing to at least a 55% reduction in greenhouse gas (GHG) emissions compared to 1990, in order to achieve carbon neutrality by 2050.
- Electrification can speed up the decarbonization process and curb the impacts of climate change. It is a way to remove greenhouse gas emissions from energy consumption in many sectors, including in transportation

Electricity's strategic role in leading Europe's decarbonization | Enel Group

Model Based Engineering

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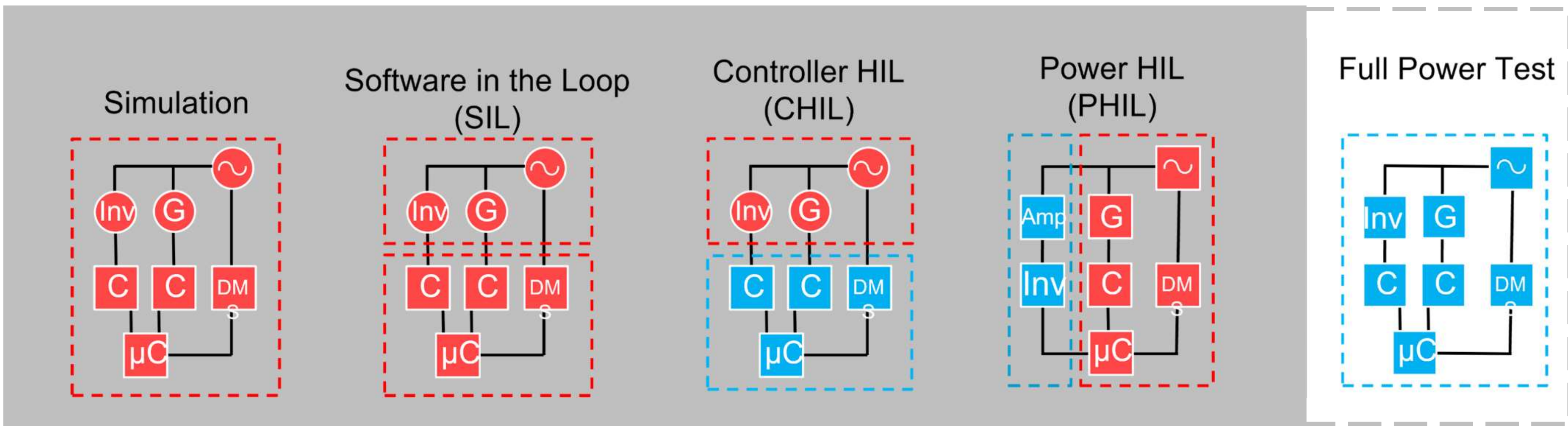
Model Based System Engineering

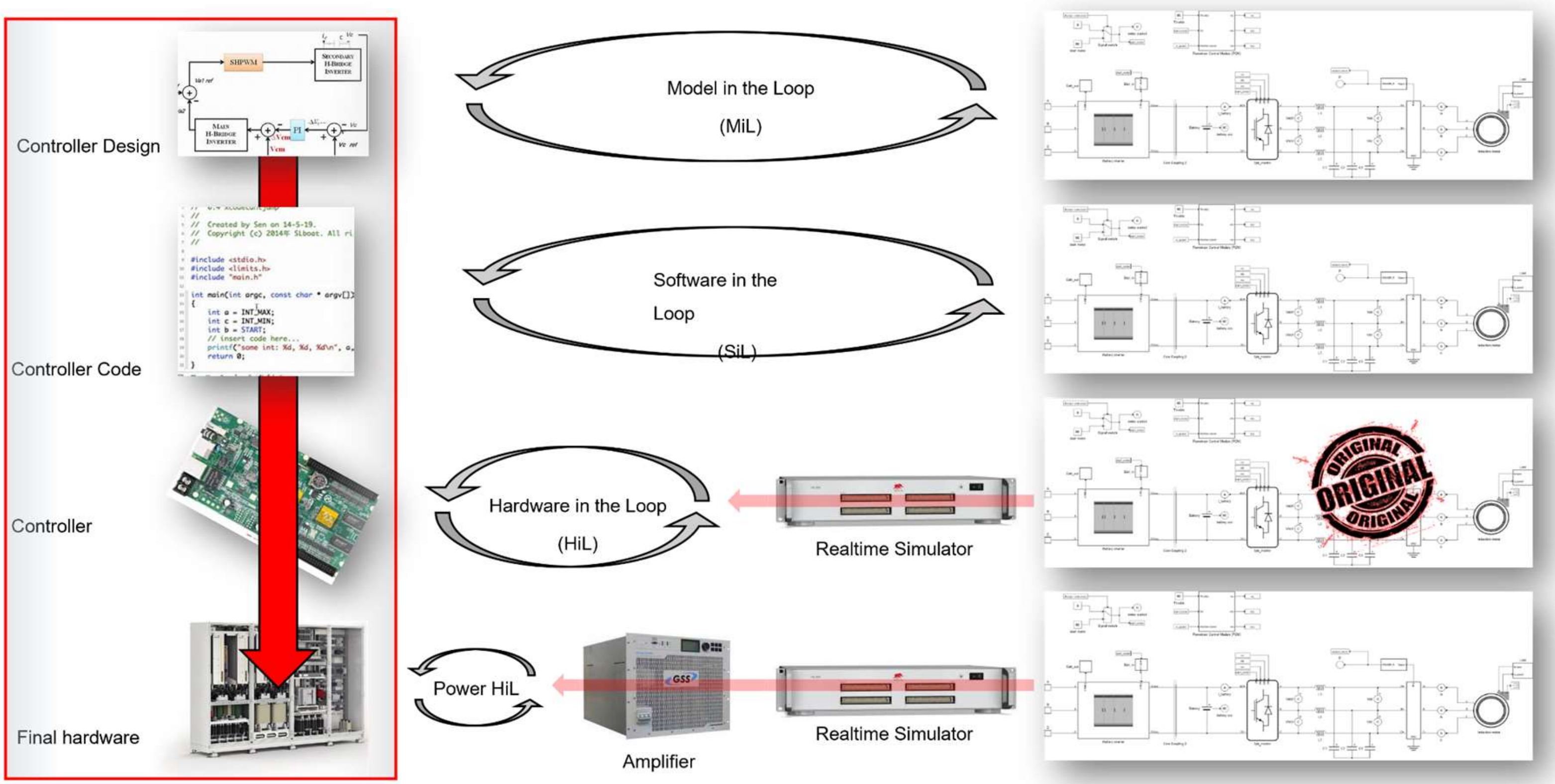
[Definition according to International Council on Systems Engineering (INCOSE)]

"Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.



Model Based System Engineering Methodologies

Model Based Controller Testing



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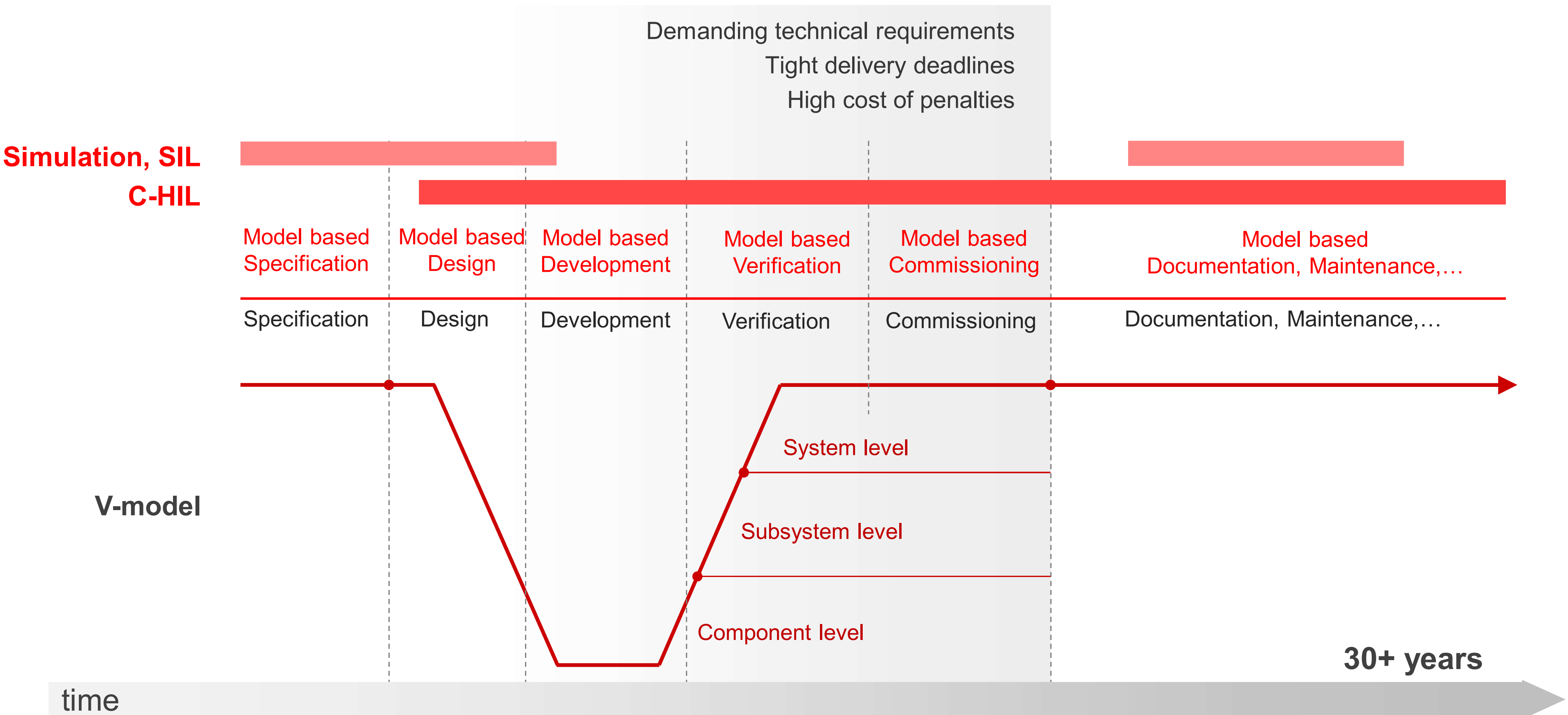
HIL at every project stage

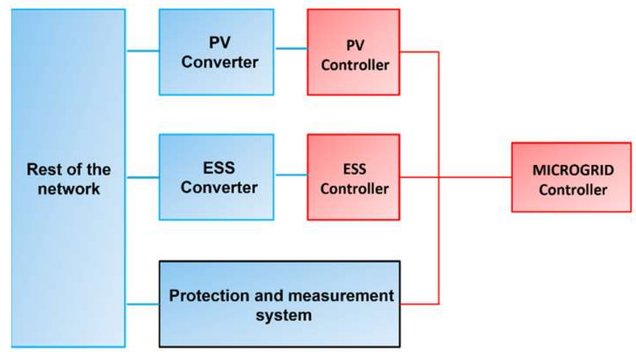
Model based. Test driven.



C- HIL Testbed

Fast track to grid digitalization

- Testing supervisory control
  - Testing supervisory control requires a focus on communication. Testing communication can be done in a virtualized environment with simulated DERs and products specific communication registry maps.
- Testing interoperability
  - Before deployment, we extend our test environment with HIL Compatible editions of DER controllers, with original control firmware and software versions.
- Testing protection
  - Finally, we can add a protection layer to our testbed together with high accuracy signal conditioners, and run multiple operational scenarios, especially faulty scenarios



Modeling Principles

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Modeling Principles

Challenges of real-time and how to solve them

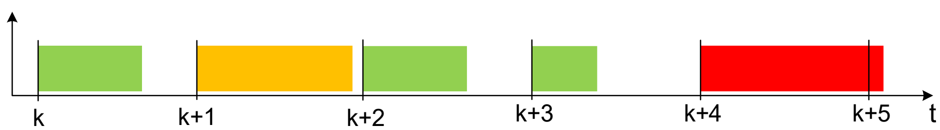
Piecewise linear approach

- ☐ Each switch states permutation is called a **mode** of the circuit
- ☐ For each circuit mode our model is LTI (switched LTI)
- ☐ Each circuit mode is discretized and represented by a state space matrix
- ☐ In order to reduce simulation runtime load, all state space matrices are pre-calculated and stored in the solver memory
- ☐ Number of modes (state space matrices) per circuit is $\mathbf{2^n}$ where **n** is the number of switch elements

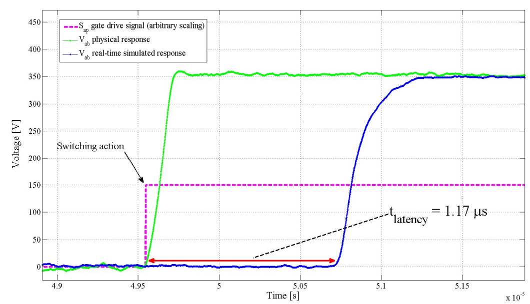
Modeling Principles

Problem definition: Real time constraints

- Discrete time with fixed simulation step
  - No time for iterations
- Strictly limited computation time for each simulation step
  - All the computations in every simulation step must be finished before the next simulation step starts to avoid overruns.



- Short response time required in PE HIL applications, comparable to the real power plant response time
  - Loopback latency

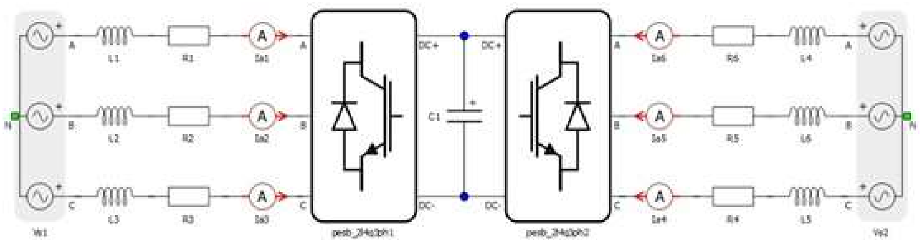


Modeling Principles

Real time simulation of power electronics and microgrid plants

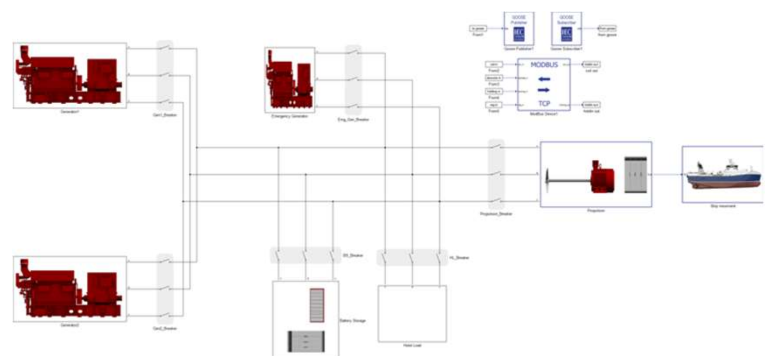
Power electronics

- ☐ Large number of high frequency switching devices
- ☐ Highly nonlinear
- ☐ Fast dynamics



Microgrid plants

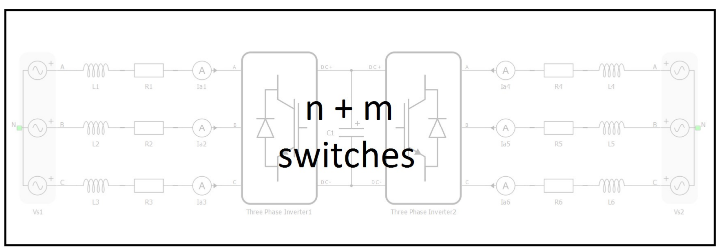
- ☐ Medium to fast dynamics due to converter-based generators
- ☐ Elements of primary and secondary control
- ☐ Interfaced with external controllers using communication protocols



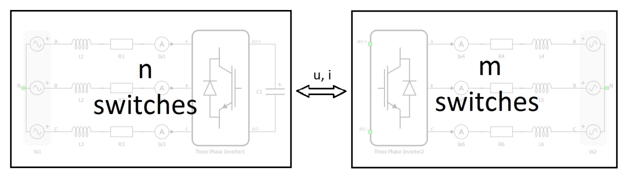
Modeling Principles

Circuit partitioning

- Two level back to back converter model
  - Has n (left converter) + m (right converter) switches in total
  - In this case n = m = 6
  - Number of modes: $2^{n+m} = 2^{12} = \mathbf{4096}$
  - Every additional switch doubles the number!



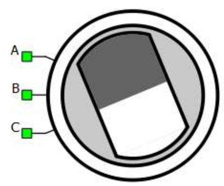
- Let's divide the circuit and make the parts talk together
  - Instead of 2^{n+m}, now there are $2^n + 2^m$ modes (**64+64=128** for this model)
  - Linear growth in memory usage on intra sub-circuit level
  - Another benefit: smaller sub-circuits can be calculated faster and in parallel



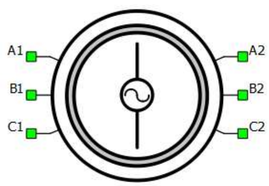
Modeling Principles

Electrical machines

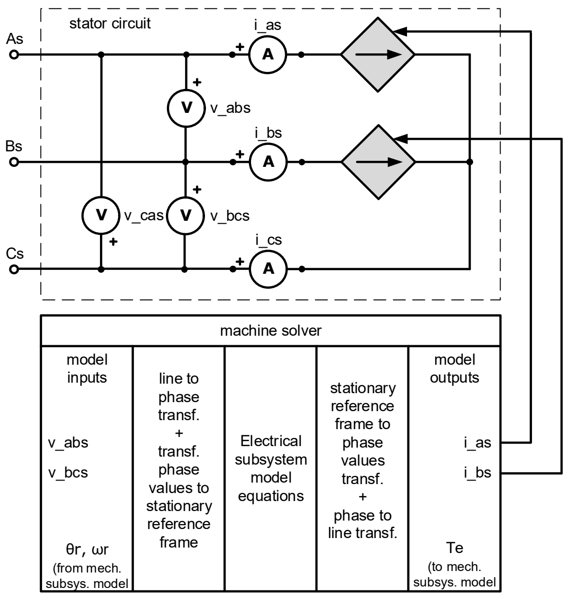
- Modeled with the help of a specialized machine solver
- Models consist of two parts
  - Electrical circuit part
  - Machine solver part
- Two types of machine circuit representation models available
  - Current source models
  - Voltage behind reactance models



Permanent Magnet Synchronous Machine with Salient Rotor1



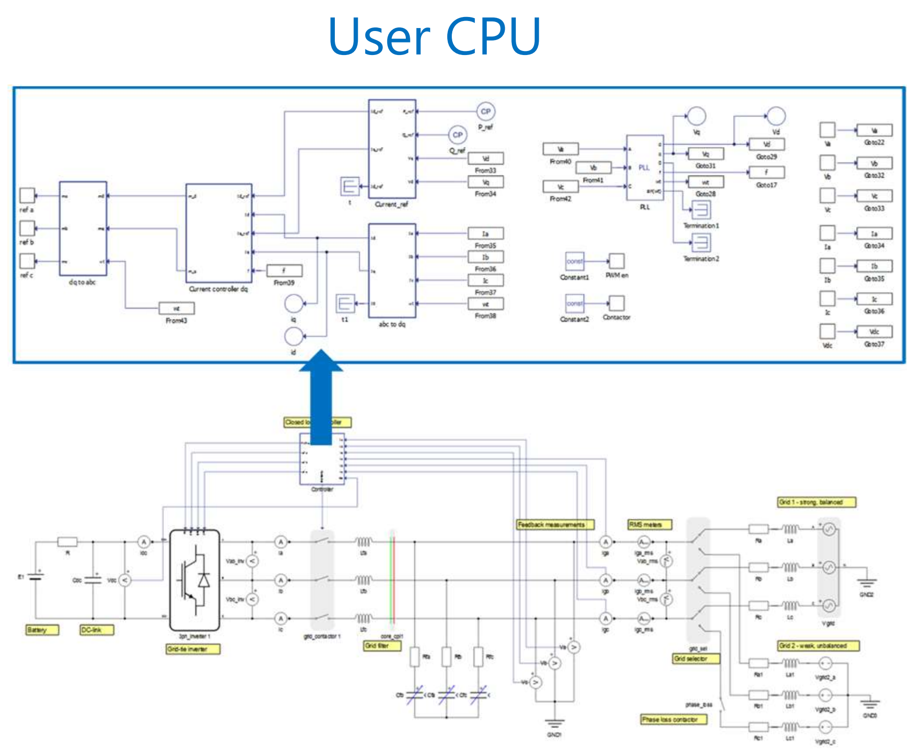
Open Winding Induction Machine1



Modeling Principles

Signal processing components

- Typically used to simulate control or slow dynamics physical models
- Running on User CPU
- Multiple simulation rates supported
- Typically slower than the electrical (FPGA solver) rate
- Implemented in C code
- User defined C functions
- Can interact with electrical domain components

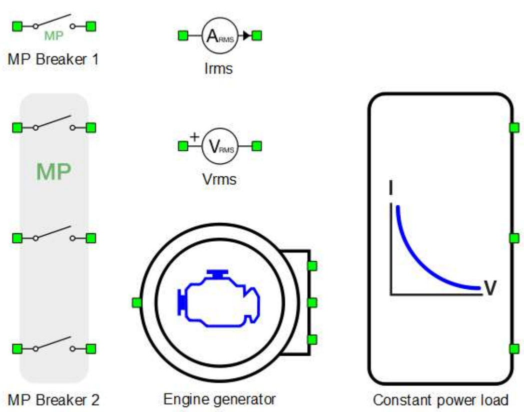


Modeling Principles

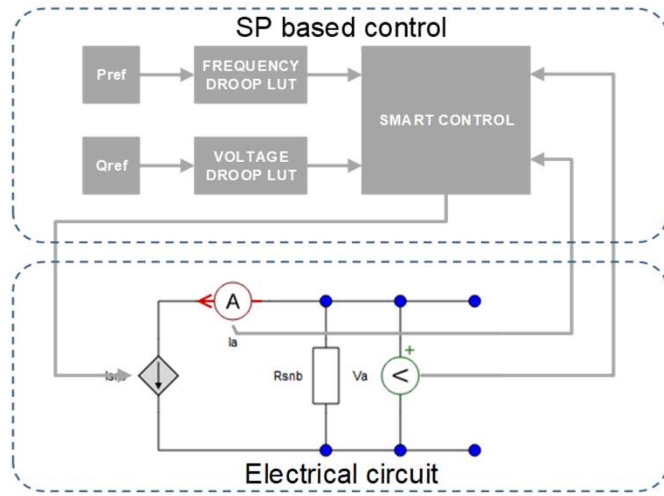
Hybrid components

- Composed of both
  - electrical circuitry and
  - signal processing components

- Hybrid components



- Example: constant power load



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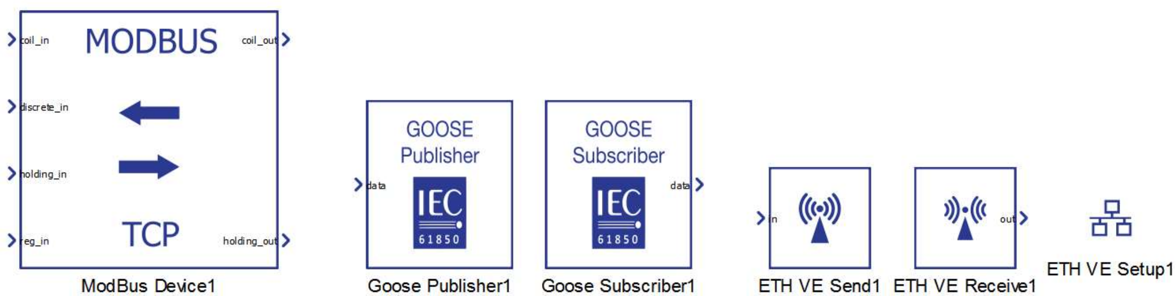
Modeling Principles

Communication protocols

- Communication components



- Connecting internal signal processing components with external devices

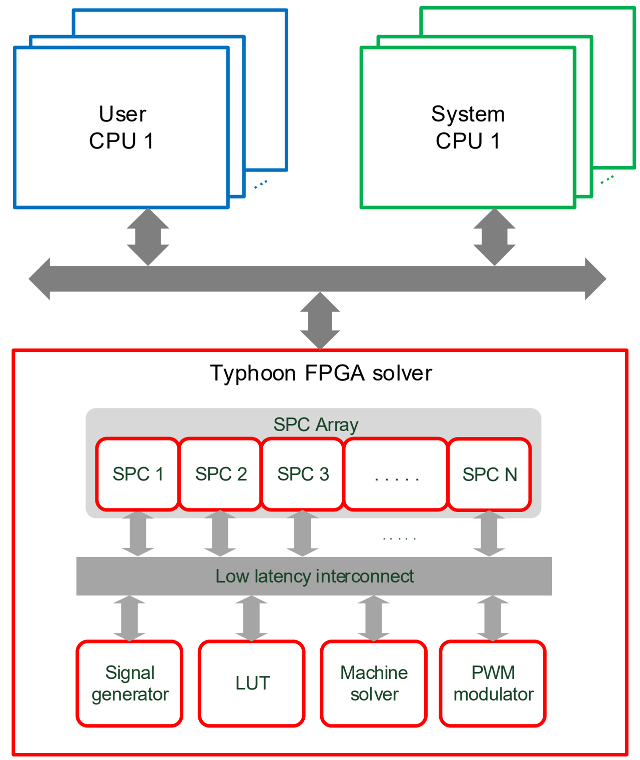
Model mapping

System architecture

- **Typhoon FPGA solver** – a specialized, proprietary FPGA-based multi-core processor optimized for time-exact simulation of electrical domain models.

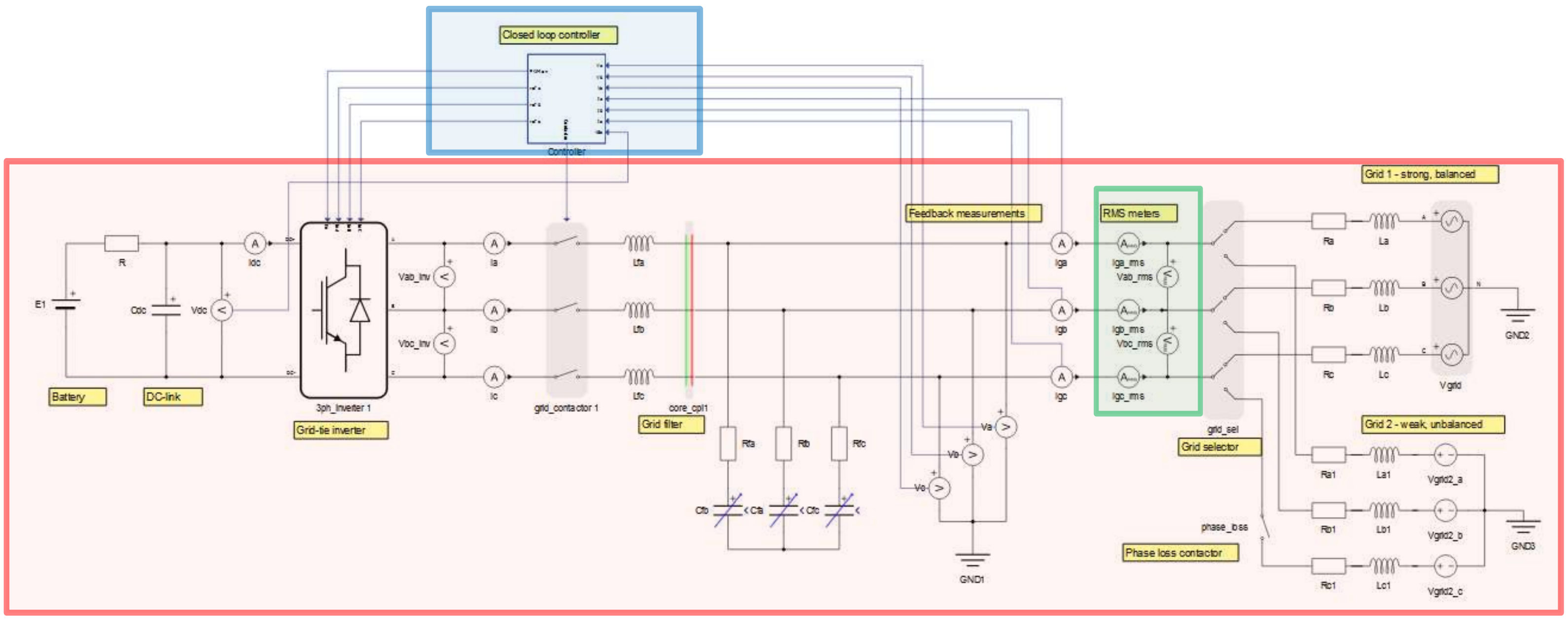
- **System CPU** – one or more general purpose processors that are indirectly controlled by the user. Typically used to assist FPGA solver with certain low dynamics electrical domain components.

- **User CPU** – one or more general purpose processors that are under direct user control. They execute sub-models composed of signal processing components. Typically used to simulate controls or low dynamics physical models.



Model mapping

Example model



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Protection and Control

Testing Novel Protection Schemes

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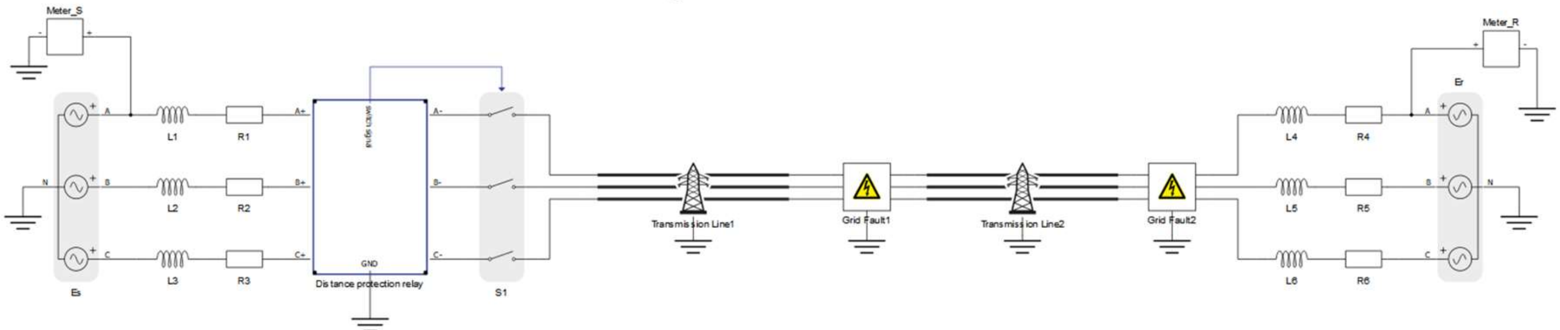
Benefit of HIL for Protection and Control Testing

- Digital simulation of the network allows protection equipment to be subjected to virtually all possible faults and operating conditions in a controlled flexible environment
- Since the simulation runs on real time on the HIL device, the protection device can be interfaced to the grid model and be tested in closed loop.
- An HIL setup will support in:
  - Testing innovative protection algorithms before field installation
  - Development and pre-commissioning of protection schemes for utilities, even with multi-vendor IEDs.
  - Testing interoperability and communication
  - FAT and documentation

Distance protection relay with false tripping prevention

Electrical Model

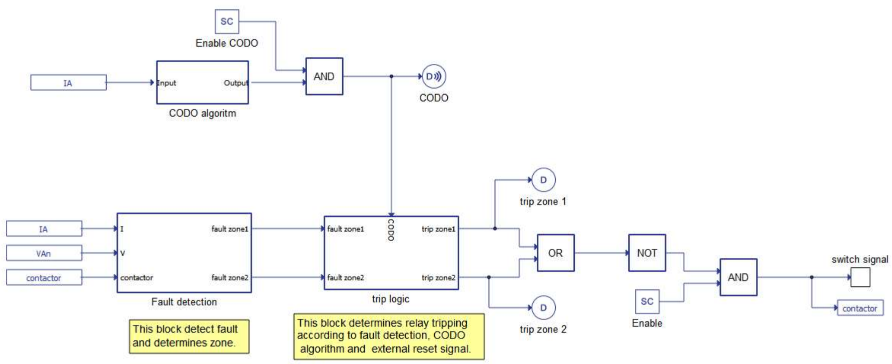
- A distance relay is a type of protection relay most often used for transmission line protection. Distance relays measure the impedance from the installation side to the fault location and operates in response to changes in the ratio of measured current and voltage.



- The parameters of the grids are V= 230 V and f = 60 Hz. The grids are connected by a transmission line, of length 100 km. At the transmission line, two faults are located: a 3-phase fault in the middle and a 1-phase fault at the end of transmission line. Between the grid on the left side and transmission line there is a Distance protection relay which is controlling the contactor located next to it.

Distance protection relay with false tripping prevention

Distance protection Algorithm with Closing Opening Difference Operator (CODO)

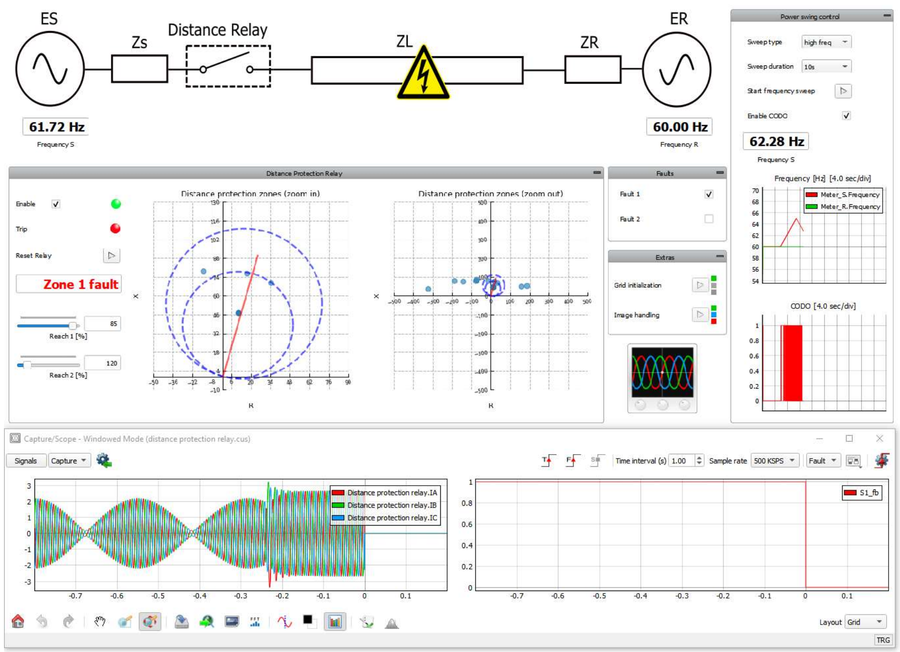


The CODO algorithm is a contribution from one of the winning models of the 10for10 Typhoon HIL Awards program of 2019. The featured model's author is Prof. Adriano Peres de Morais from the UFSM university

- The fault detection block is responsible for detecting the fault in the transmission line and determining if fault is inside zone 1, zone 2 or in both of them,
- The Closing Opening Difference Operator (CODO) algorithm block calculates the fault filtering signal according to the model, based on mathematical morphology (MM),
- Finally, the trip logic block is responsible for calculating the trip signals according to the fault detection signal, the CODO algorithm signal, and an external reset signal.

Distance protection relay with false tripping prevention

SCADA interface and Test Results



- ☐ The SCADA panel offers the most essential user interface elements (widgets) to monitor and interact with the simulation at runtime,
- ☐ The relay responds to a change in the impedance value. The impedance value depends on the frequency in the grid and on the presence of a fault in the transmission line.
- ☐ By changing this impedance, the CODO signal changes, and we can observe it in the trace graph.

Microgrid Model

De-risking Distributed Energy Resources integration

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Microgrid model

…to test a microgrid controller

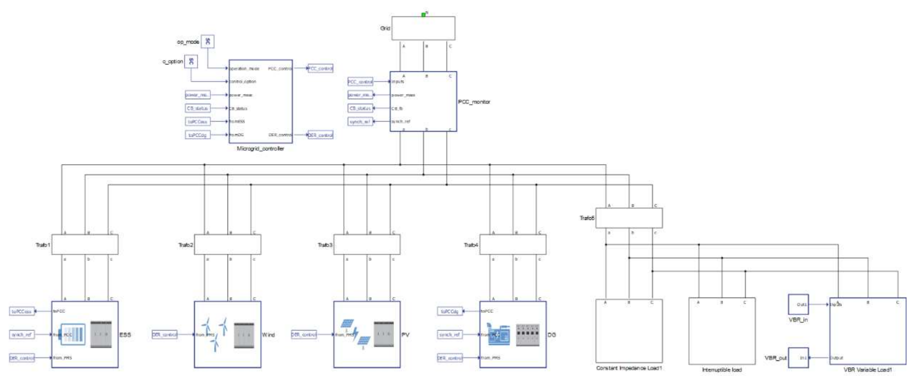
- The Microgrid Controller (MC) is the brain of the microgrid. It can monitor and issue commands to the DER units and command the synchronization relay to connect or disconnect the microgrid from the main grid, depending on the operation mode requested by the microgrid operator and any grid faults.
- The MC also handles power flow regulation through the PCC. By sending power references to the grid-forming DER, the active and reactive power flowing through the PCC can be zeroed, allowing for smooth intentional islanding.
- The example in the next slides demonstrates a MC's ability to handle a microgrid islanding situation by observing the net power flow at the point of common coupling (PCC) and engaging grid-forming mode in different distributed energy resources (DERs).

Plug-and-play microgrid library and testing of microgrid controller (typhoon-hil.com)

Microgrid model

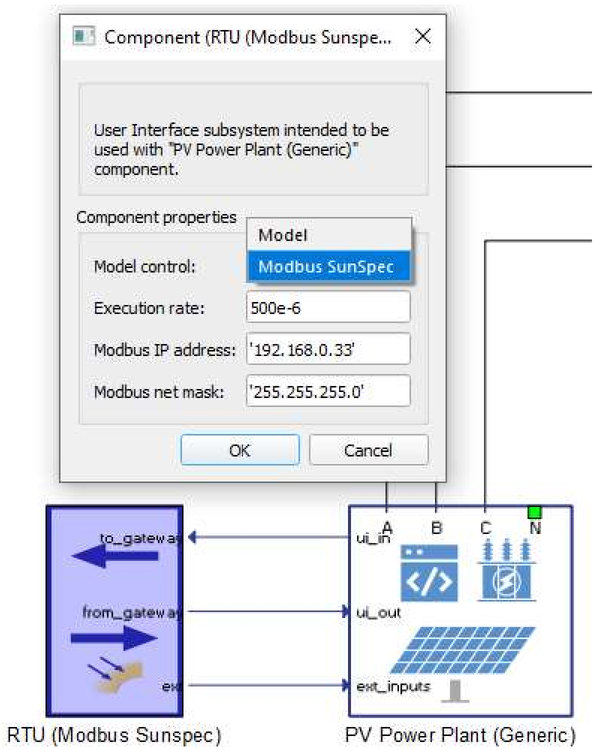
….to test converters controllers

- ☐ The microgrid model consists of four DERs (an Energy Storage System (ESS), a Wind Plant, a PV Plant, and a Diesel Genset (DG)) and three types of loads (a constant load, an interruptible load, and a variable load), all connected to the same point of common coupling (PCC).
- ☐ Each DER has its own 12.5kV/480V transformer
- ☐ The ESS, the Wind Plant, the PV Plant are all converter-based.



Microgrid model

With signal processing or industry standard communication protocols

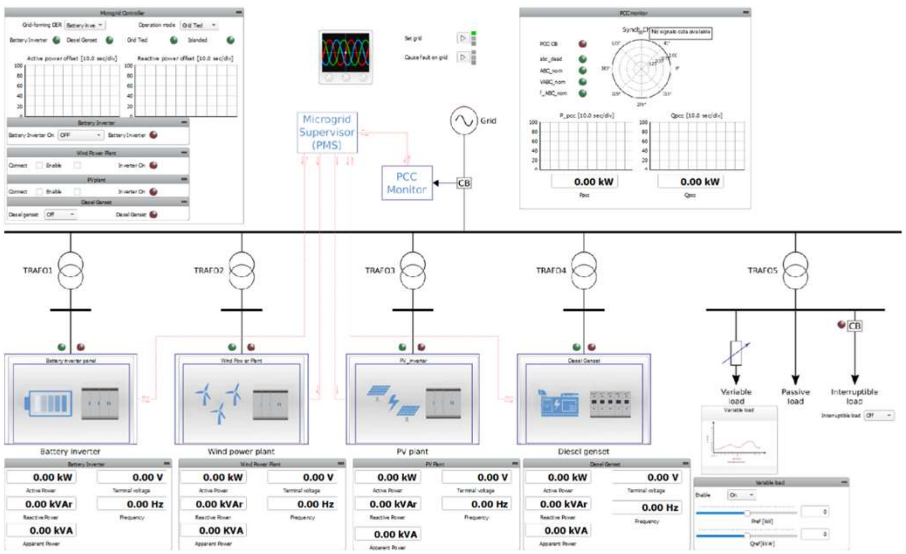


The microgrid controller can initially be modeled using Signal Processing components, for instance in the development and engineering phase (S-HIL). The real, external controller can later one replace the simulated one.

Each DER has an interface to the microgrid controller, either based on signal processing components (in the S-HIL setting) or based on one of the industry-standard communication protocol components (CAN, Modbus, IEC61850) for C-HIL.

Microgrid model

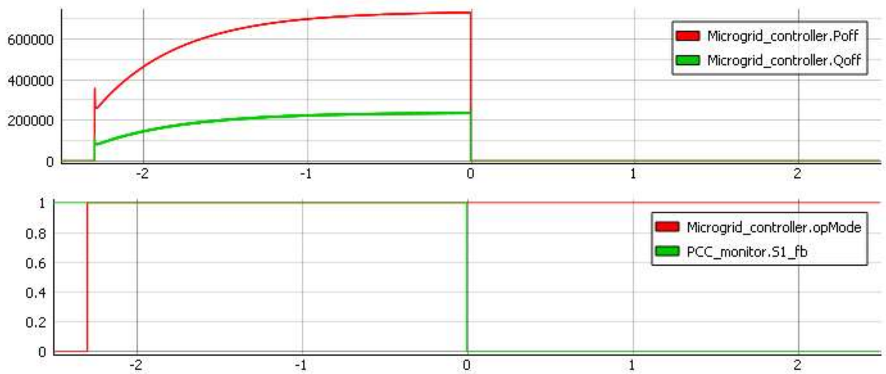
Grid forming DERs



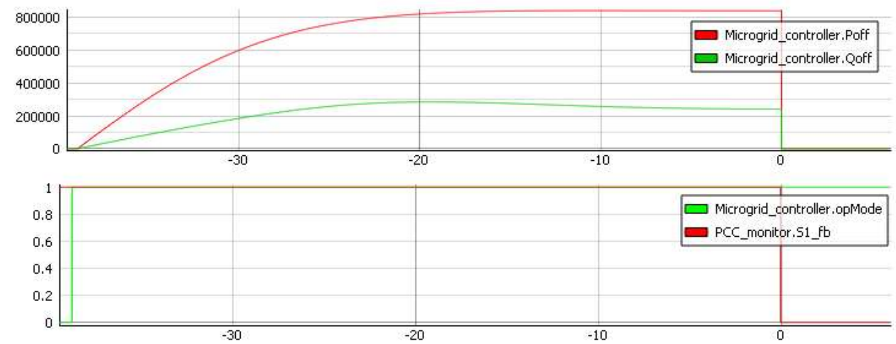
- The first scenario is when all DER units are enabled and connected to the main grid. In this configuration, the DER units operate in grid-following mode.
- The microgrid operator can change the microgrid status by issuing a command to change the operation mode from “Grid Tied” to “Islanded”, which configures an intentional islanding.
- The microgrid operator can decide which grid forming capable DER is the main unit, be it the the Battery Inverter or the Diesel Generator.

Microgrid model

Transition from grid-tied to islanded mode using the battery



Transition from grid-tied to islanded mode using the Diesel Generator



Due to the inertia and different dynamics of the DG, the response is slower compared to the battery.

Conclusion

Conclusions

How (C-)HIL helps engineering a stabler grid

- ☐ Time domain short circuit analysis, failure mode analysis, coordination study analysis
- ☐ DER interoperability and microgrid functional testing
- ☐ Early testing of a grid against short circuits, phase losses, component failures and over voltage, low and over voltage ride through
- ☐ Conduct of a sensitivity analysis of the entire network in real-time
- ☐ Testing of a controller’s hardware, firmware, software and communications under all operating conditions that include faults in both islanded and grid connected modes
- ☐ HIL testing can be used to improve grid interconnection requirements that regulators place on projects by virtue of more extensive scenario-based testing.
- ☐ With C-HIL spend less time on PHIL tests, and approach them with more confidence, address critical issues before you risk damaging real equipment

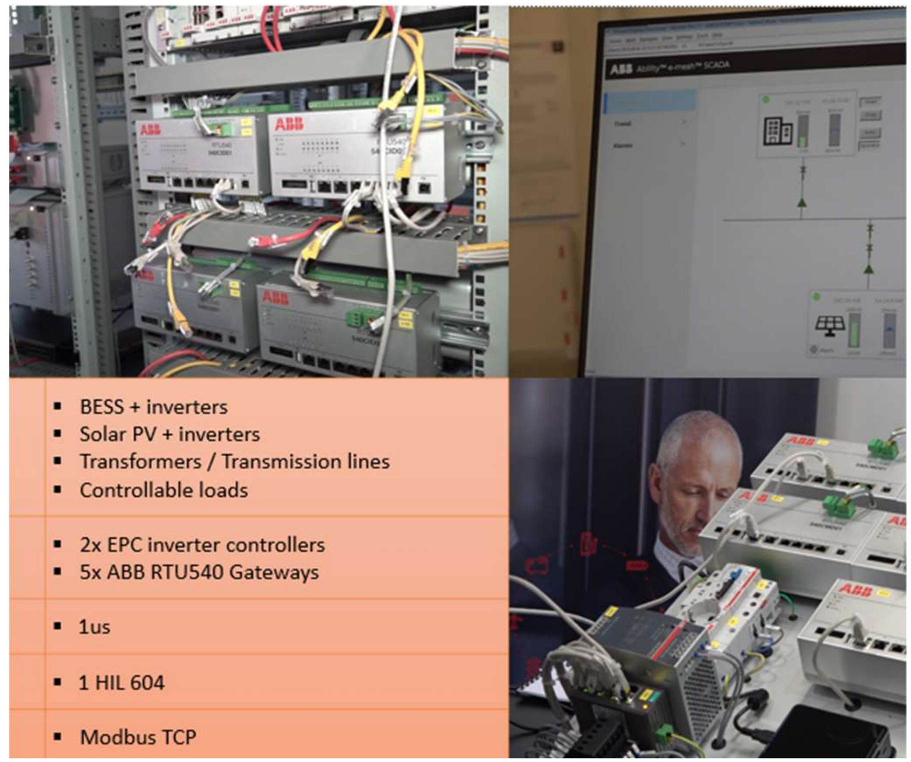
Customer Use Cases

Typhoon HIL

Experience Hitachi Energy with Typhoon HIL

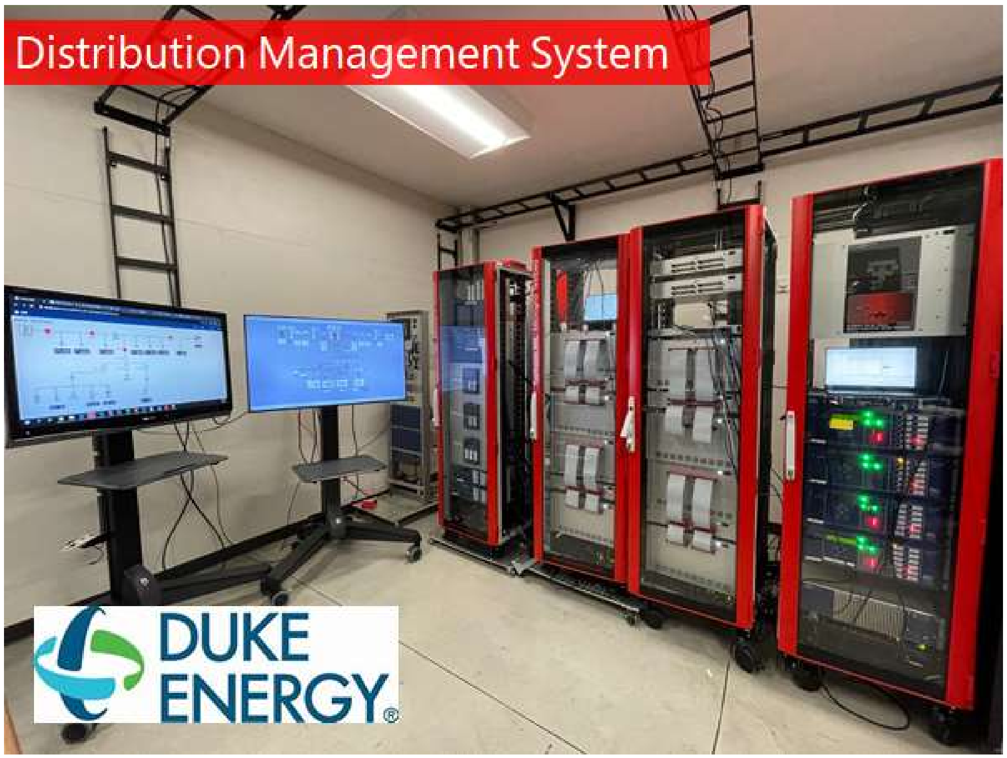
[Spotlight | Hitachi Energy Microgrid e-mesh™ Digital Ecosystem]

- ☐ **Application:** The e-mesh Control is designed for the seamless integration of renewables with traditional energy assets.
- ☐ **Challenge:** Ensuring that multiple e-mesh controls communicate in a coordinated way.
- ☐ **Solution:** Typhoon controller Hardware-in-the-Loop used to design and test e-mesh controls
- ☐ **Result:** Typhoon HIL accelerated e-mesh control development time and increased test coverage.
- ☐ **HIL Tested** means flexibility, reliability, optimized, and great performance.



Microgrid Integration, Protection, and Energy Management

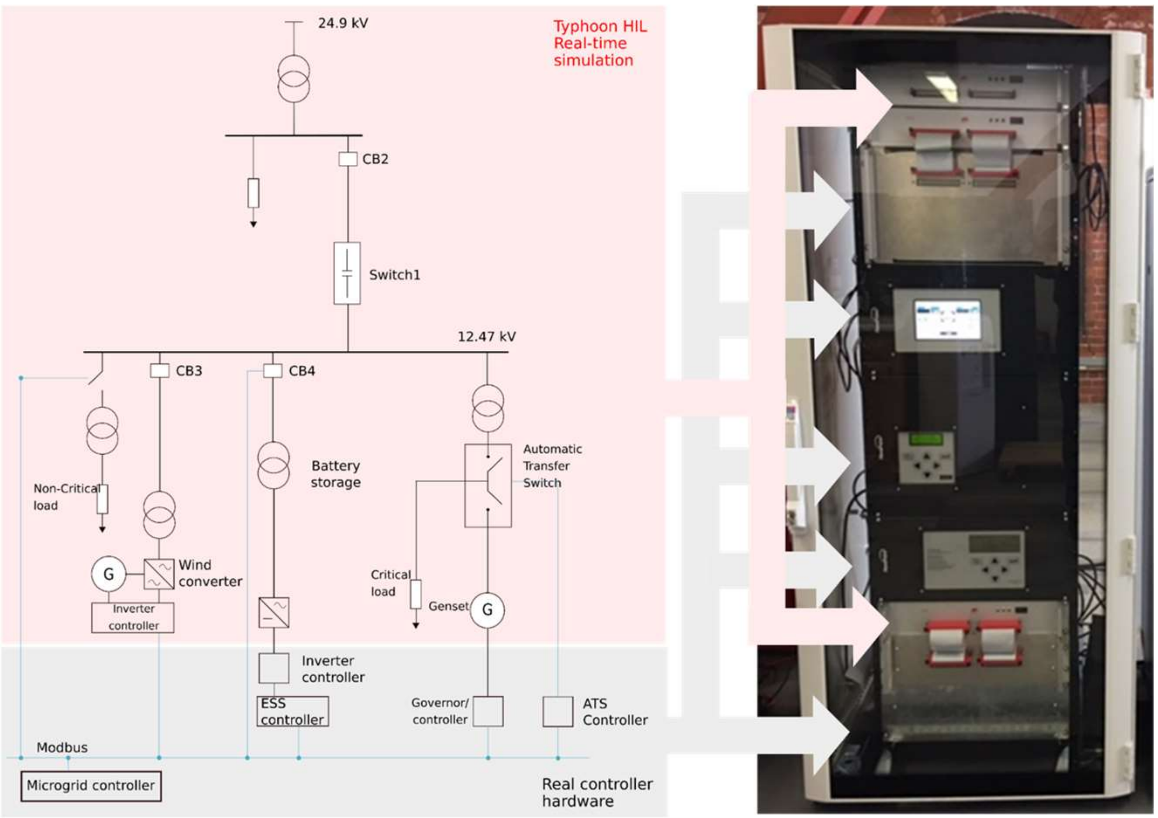
Duke Energy



- Controllers in the loop
  - ABB PCS100
  - SEL RTACs x 4
  - SEL 751
  - SEL 787
  - SEL700G
  - SEL651RX3
  - SEL351
  - SEL451
  - Beckwith Capbank
  - Beckwith Tapchanger
  - EATON CL7
  - EATON CB800
  - Hitachi Powerstore
- Real Time Emulators
  - 6 x Typhoon HIL604
- Signal Conditioning
  - 7 x HILConnects

Tactical and Military Microgrids

[Raytheon uses Typhoon HIL to Design and Test Otis Microgrid Controls]



- Modeled
  - Automatic transfer switch
  - Genset
  - Wind Turbine Inverter
  - BESS Inverter
  - Controllable loads
- Controllers In the loop
  - ASCO Soft Load Controller
  - ASCO Group 5 transfer switch controller
  - ASCO power manager XP
  - Dynapower inverter controller
- Simulation step: 2μs
- HIL setup: 3 x HIL 603

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Typhoon HIL online resources

Use Cases, webinars and tutorials

SB

- Blog | Typhoon HIL
- Spotlight | Hitachi Energy Microgrid e-mesh™ Digital Ecosystem - Part 1 – YouTube
- Typhoon HIL Spotlight | Schneider Electric Active Filter Solution – HILTested
- Typhoon HIL Spotlight | Schneider Electric Hybrid Inverter–HILTested Episode 1
- Schneider Electric | AccuSine PCSn Brings Efficiency to Your Power Network
- Microgrid Spotlight | Otis National Guard Base Microgrid – YouTube
- Communication Protocols
- Microgrid Library Tutorials
- Demos

Typhoon HIL online resources

Published Papers

SB

- ☐ Evaluation of the Communication Delay in a Hybrid Real-Time Simulator for Weak Grids
- ☐ Cost and Cybersecurity Challenges in the Commissioning of Microgrids in Critical Infrastructure: COGE Case Study
- ☐ Hybrid Smart Transformer for Enhanced Power System Protection Against DC with Advanced Grid Support
- ☐ Cyber-Resilient Sliding-Mode Consensus Secondary Control Scheme for Islanded AC Microgrids
- ☐ Agent-Based Distributed Energy Resources for Supporting Intelligence at the Grid Edge
- ☐ Short-Circuit Analysis of DER-Based Microgrids in Connected and Islanded Modes of Operation (mdpi.com)
- ☐ Hardware-in-the-Loop Experimental Validation for a Lab-Scale Microgrid Targeted by Cyberattacks
- ☐ FAULT CURRENT STUDY OF MICROGRIDS IN GRID-CONNECTED AND ISLANDED MODES OF OPERATION
- ☐ Real-time Smart Microgrid Simulation: The integration of communication layer in electrical simulation
- ☐ Controller hardware in the loop testing of microgrid secondary frequency control schemes - ScienceDirect

Thank you for your attention!

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