Holistic Modeling to Improve the Stability of Inverter-Dominated Power Grids

DOE SETO Workshop
Fast Time-Scale Modeling of Power Systems with Distributed Solar

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Advanced grid-forming (GFM) inverter controls, modeling and system impact study for inverter dominated grids

Project Objectives:

Develop a new impedance based large system stability analysis method.

Develop, implement and validate advanced controls for GFM PV inverter(s) to improve the stability of inverter dominated grid.

Develop high fidelity models to study GFM inverters' system impact.

Demonstrate the proposed technology in a 100% renewable test facility and a real PV plant.

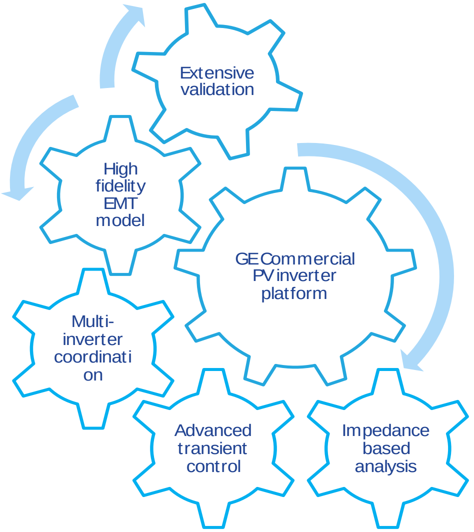
Technologies

- -Impedance based large system stability analysis
- -Advanced transient control
- -Consensus based multi-inverter coordination
- -High fidelity EMT modeling

Outcomes

- -Improved small signal and transient performance
- -Well-defined inverter interface characteristics
- -New toolsets to analyze the small signal stability and transient stability of inverter based large system
- -Autonomously coordinated DER resources

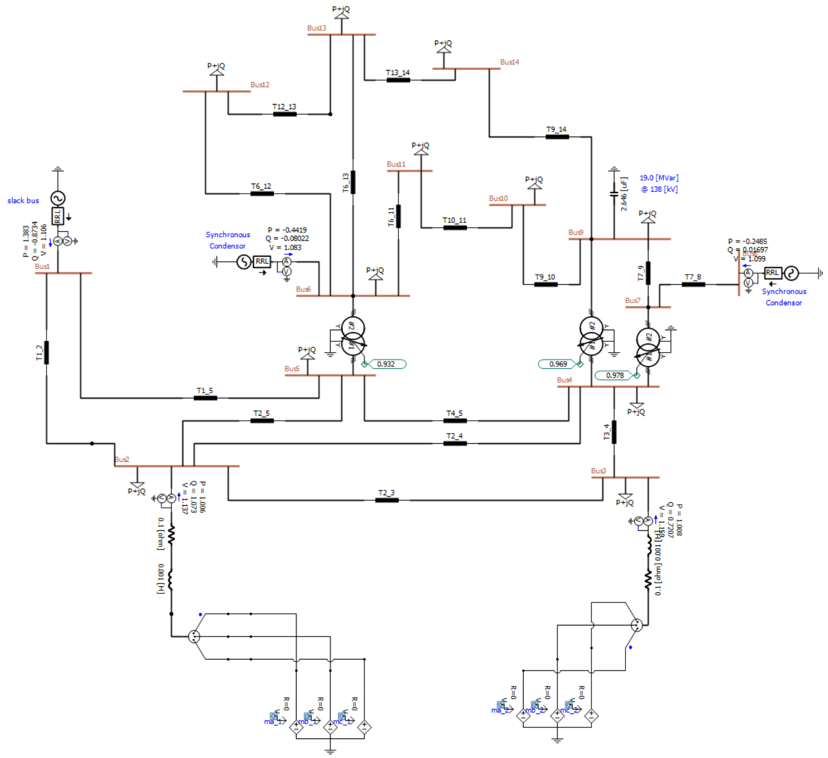
Project overview

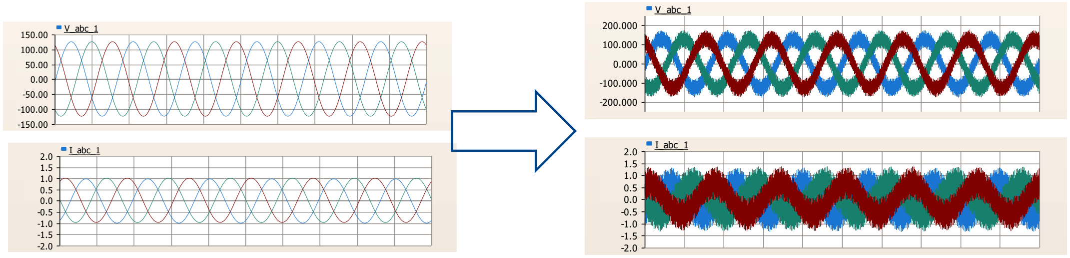


Technical approach

2x1MW GE LV5 Solar inverters

IBR system analysis and modelling gaps





- Small signal stability analysis with IBR systems
  - Large amount of inverters & mixed source system
  - Heterogeneous and proprietary controls from different vendors
- Large signal stability analysis with IBR systems
  - Generic transient analysis model does not reflect the actual behavior of the IBR resources
  - No well-accepted system analytical transient analysis method to guide the IBR control design

Table 2.1: Solar PV Tripping and Modeling Capabilities and Practices

Cause of Tripping	Can Be Accurately Modeled in Positive Sequence Simulations?	Can Be Accurately Modeled in EMT Simulations?
Erroneous frequency calculation	No	Yes
Instantaneous* ac overvoltage	No	Yes
PLL loss of synchronism	No	Yes
Phase jump tripping	Yes	Yes
DC reverse current	No	Yes
DC low voltage	No	Yes
AC overcurrent	No	Yes
Instantaneous* ac overvoltage—feeder protection	No	Yes
Measured underfrequency—feeder protection	No	No**

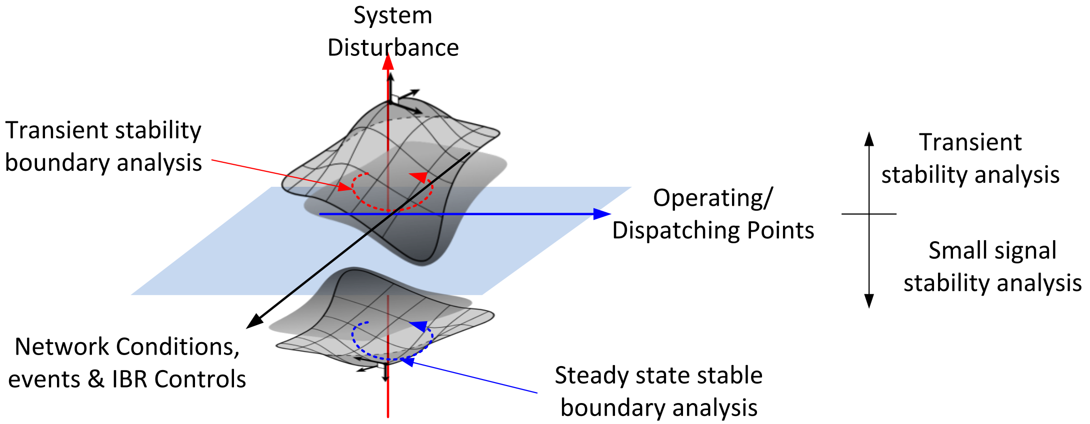
* Sub-cycle ** Due to very limited protective relay models in EMT today

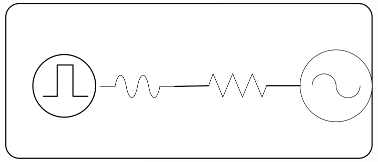
(source: NERC Odessa Disturbance Report)

No single model can address all the problems

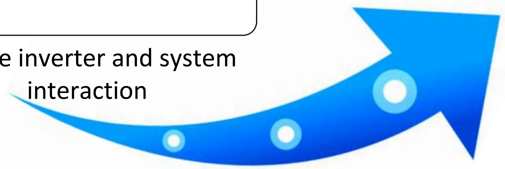
Holistic approach to stability analysis-overview

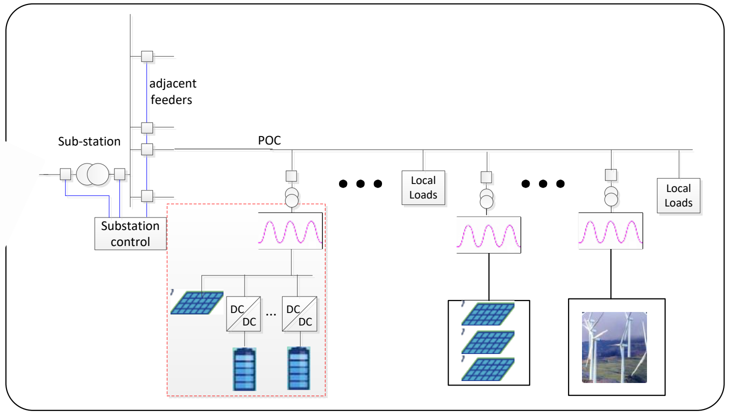
System stability study





Simple inverter and system interaction





Large IBR system

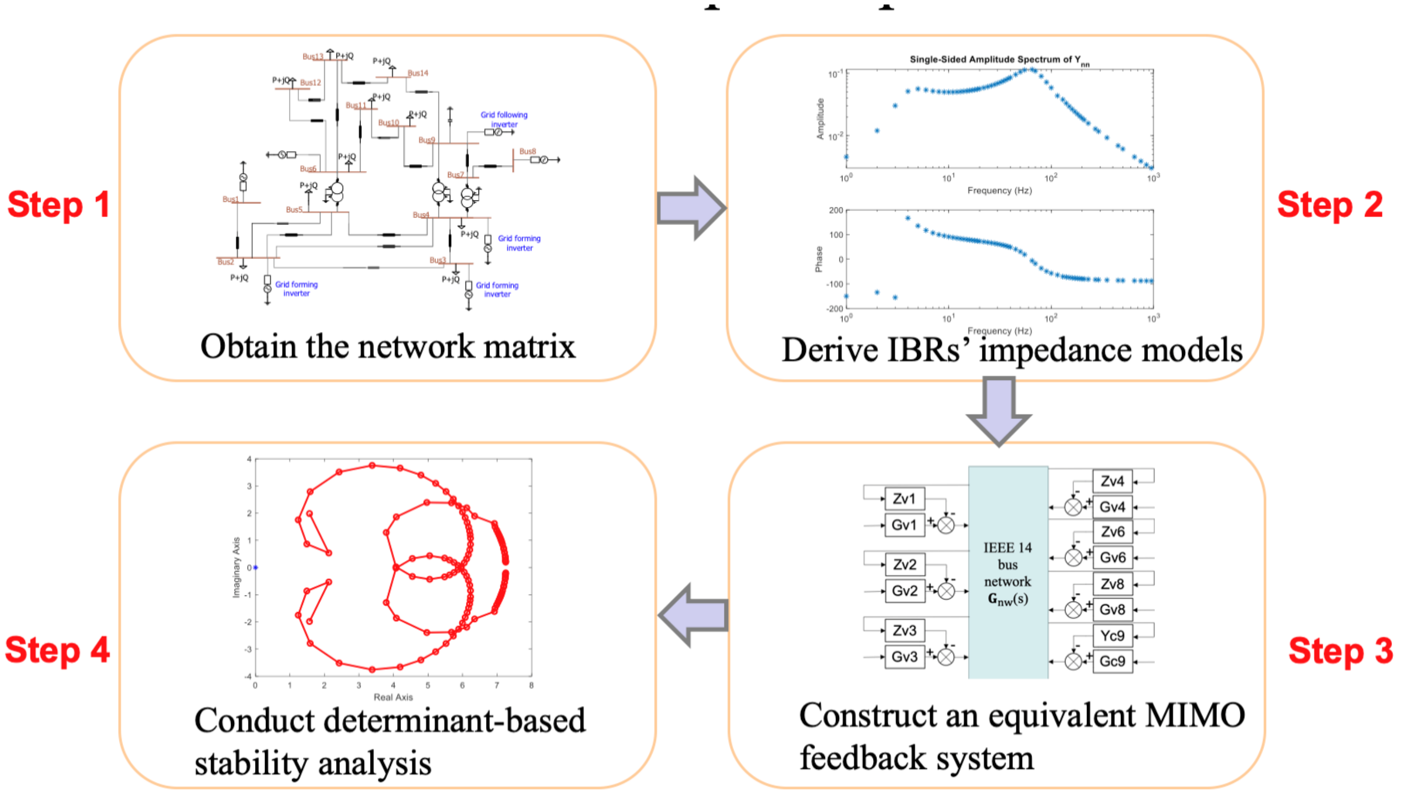
System scale up

Holistic approach:

- Small signal stability(impedance-based analysis)
- Transient stability(Energy function-based analysis)
- Stable operation boundary
- Large system modeling
- High fidelity EMT modeling
- Validation in C-HIL and PHIL system

Multi-dimensional stability analysis

Small signal stability analysis

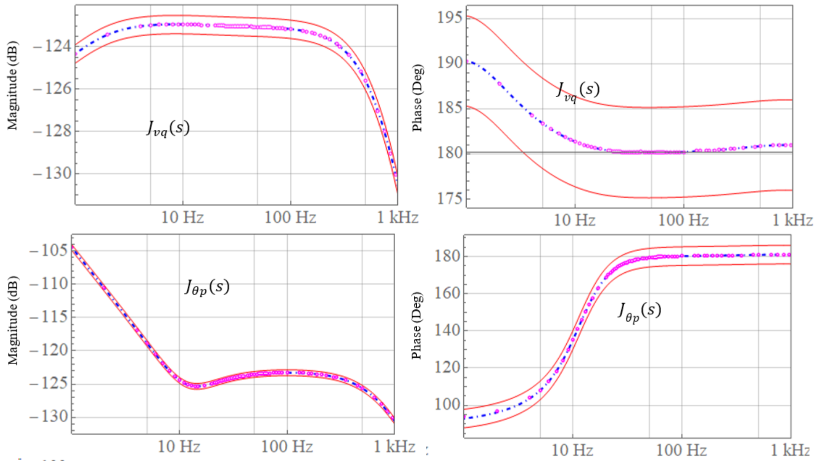


System small signal stability:

- Impedance model- based method
- Standard transient analysis software model file format input
- Analytical or black-box inverter impedance model
- General Nyquist Criteria for stability analysis
- Automation process for large system

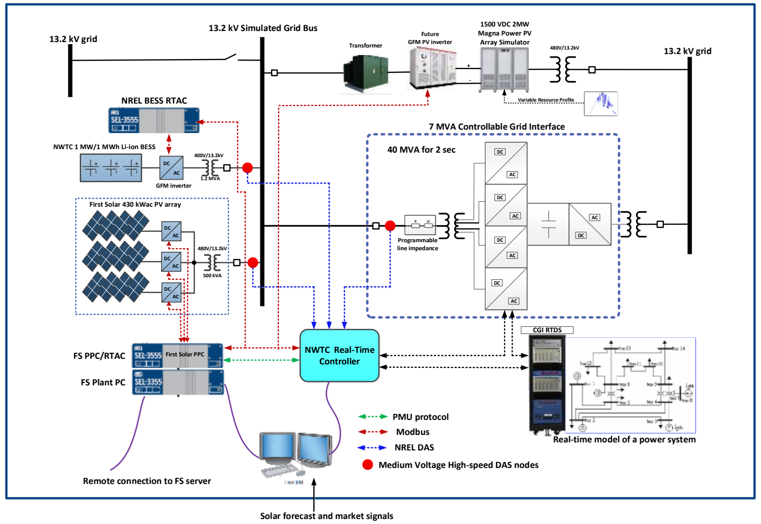
Automatic process to analyze IBR system stability

Impedance model validation

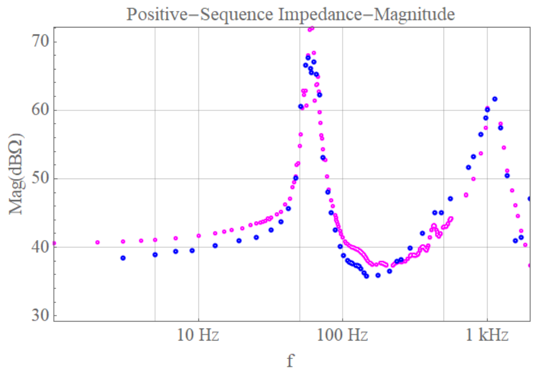


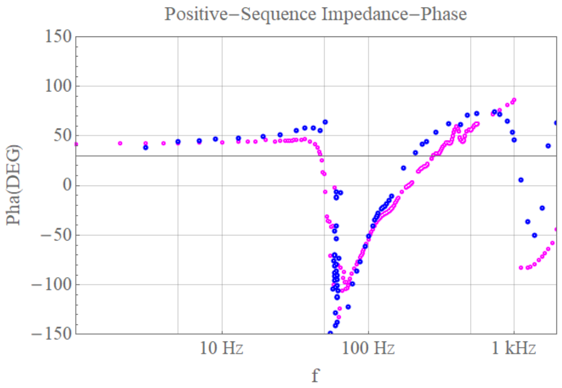
PSCAD EMT model validation

RTDS system validation



Real system validation

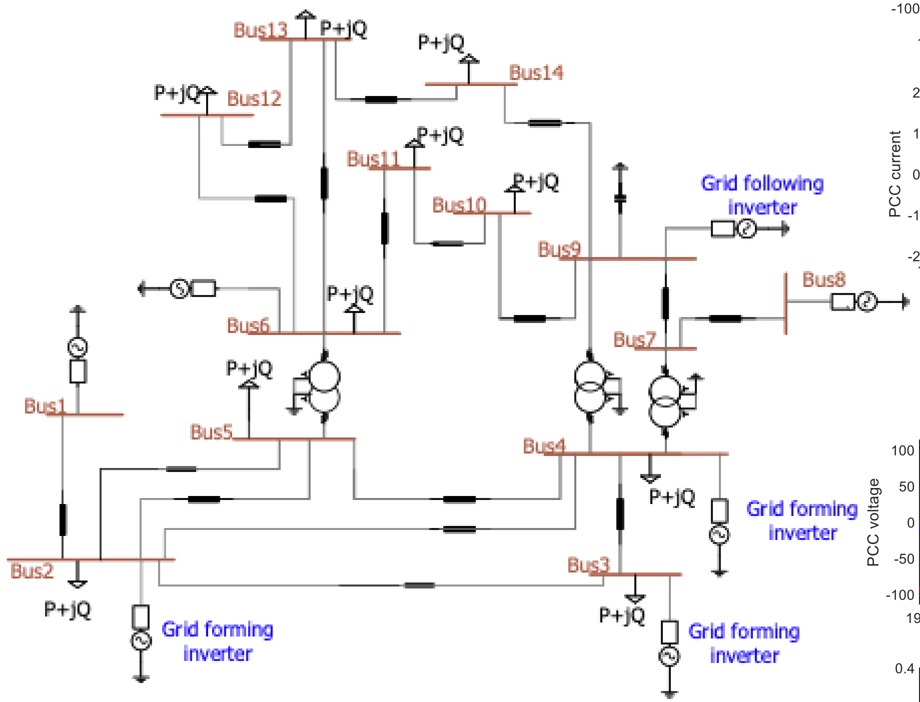




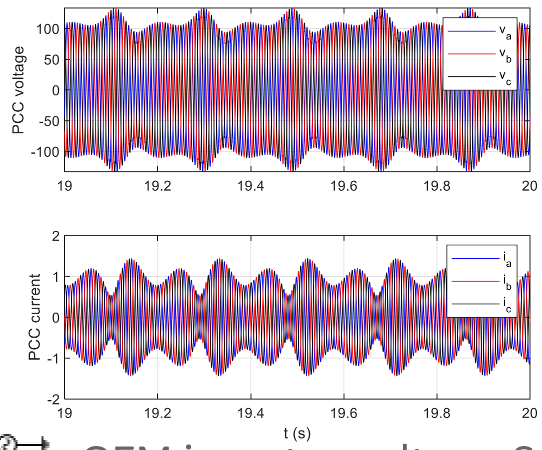
RTDS vs Real hardware(Blue-Real measurement, Pink-RTDS measurement)

Multiple level of validation to make sure modeling is correct

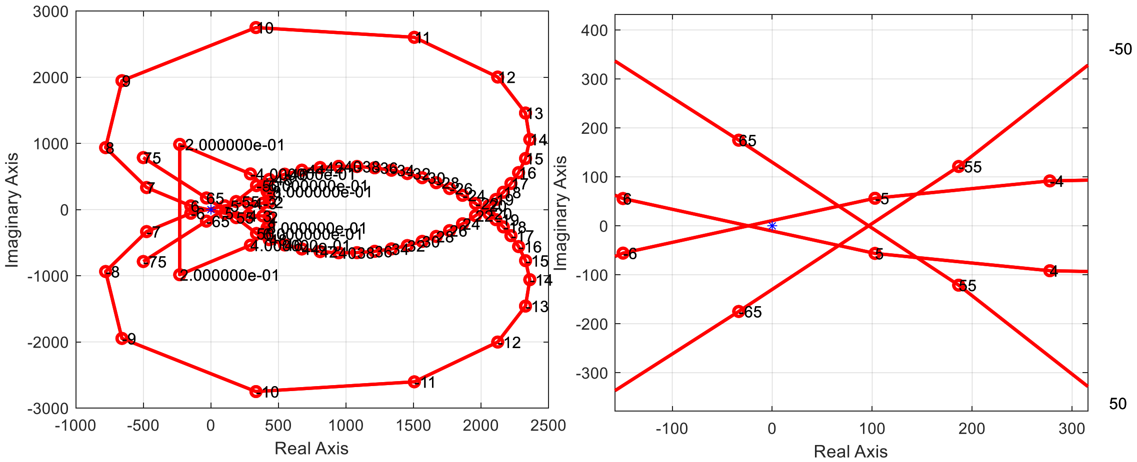
Application of the developed tool



Modified IEEE-14 bus model with IBRs added

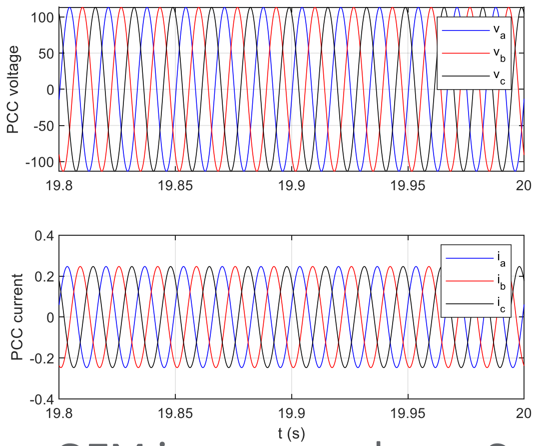


GFM inverter voltage & current

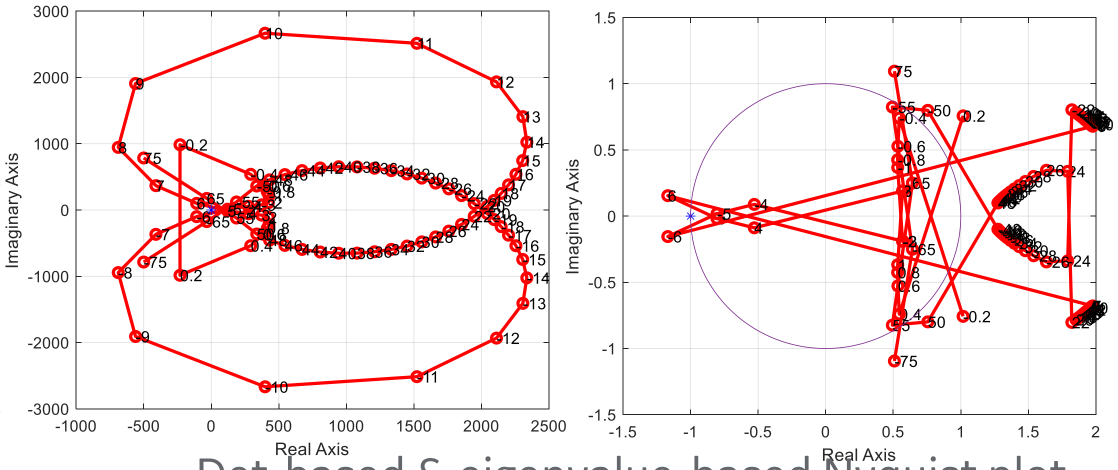


Det-based Nyquist plot

Unstable case



GFM inverter voltage & current



Det-based & eigenvalue-based Nyquist plot

Stable case

Process for transient stability analysis/improvement

1. Develop reduced-order analytical model
   - Define reduced-order differential-algebraic equation set and network damping, inertia, & susceptance (D_a, M, bl_v); validate with full-order model
   - Derive system-wide energy function and inverter power flow expressions for pre-transient, transient, and post-transient conditions
2. Evaluate potential energy surface for post-event condition
3. Identify the critical energy (potential energy of controlling unstable equilibrium point) for maintaining system transient stability
4. Predict system transient stability
5. Apply control strategy to improve the transient stability

Case study using energy function based transient stability analysis

Fig. A: Mesh network containing a grid-tie + three GFM inverters:

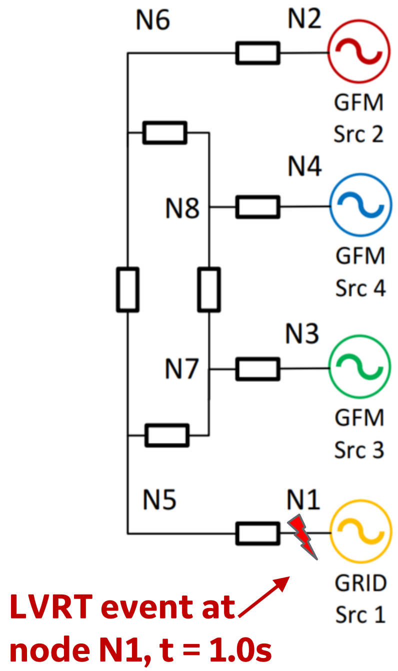
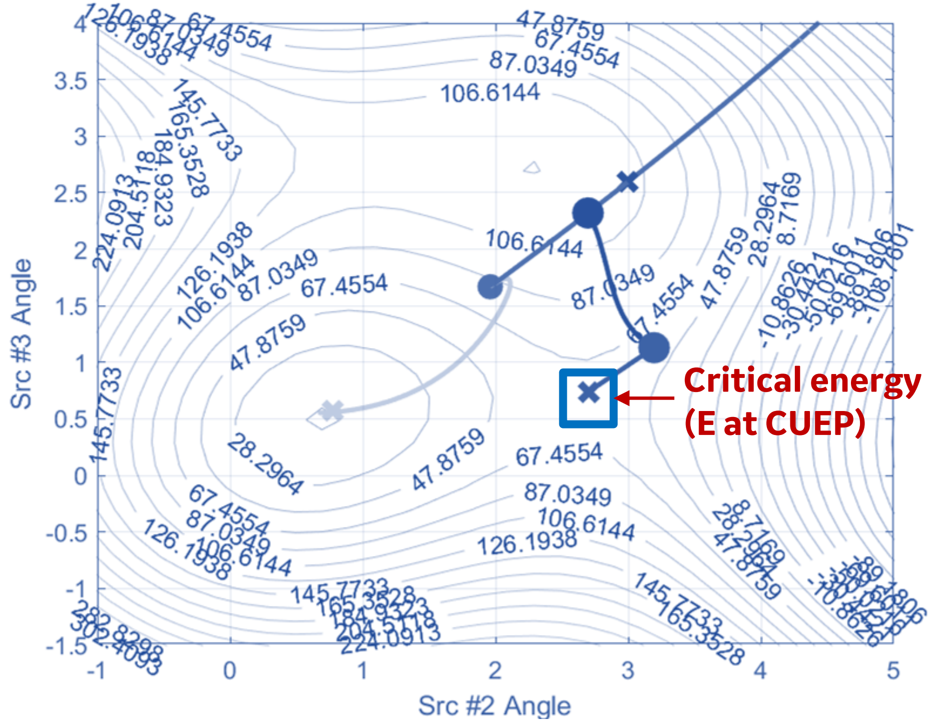


Fig. B: 2D 'Slice' of 3D Potential Energy Surface for Post-Event Condition:

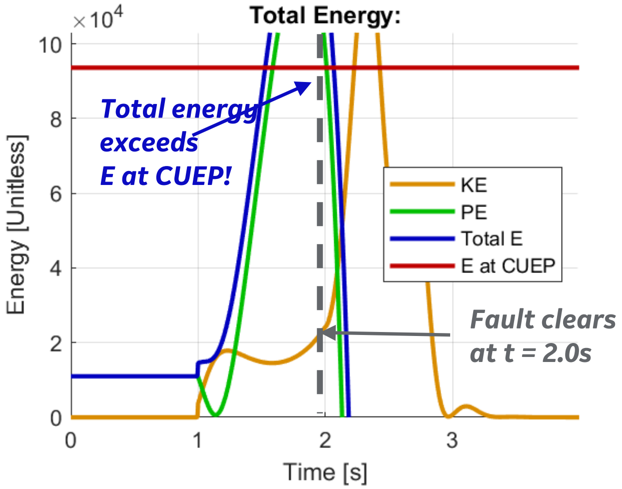


LVRT event applied to a 3-GFM inverter system

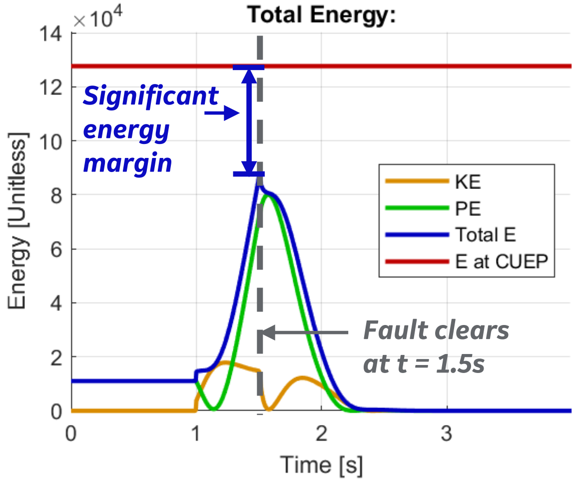
Use case study-stability analysis for an LVRT event

Energy function based transient stability prediction

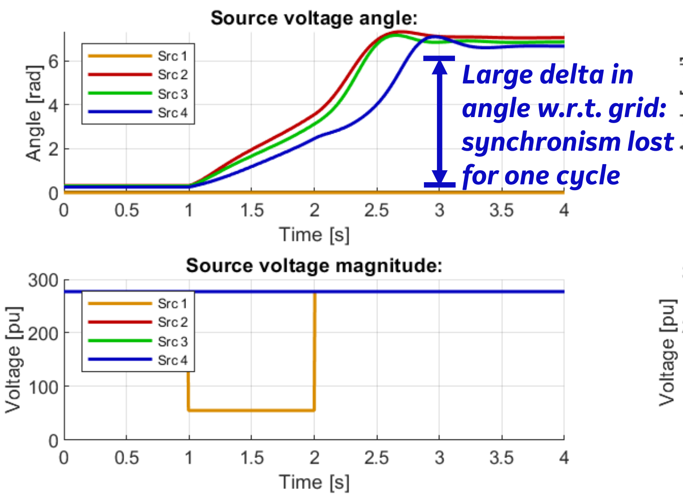
Event 1—Fault clears at t=2.0s:

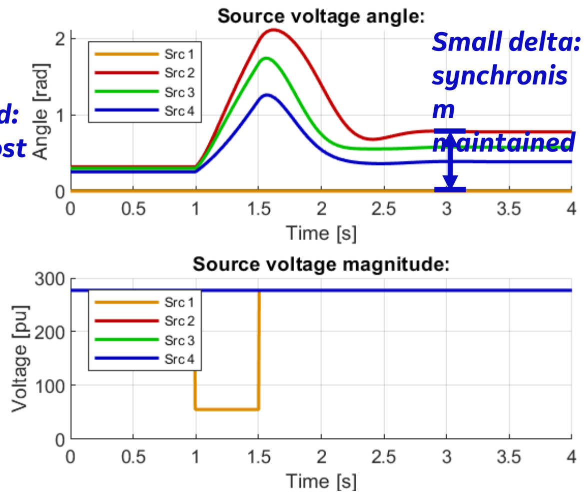


Event 2—Fault clears at t=1.5s:



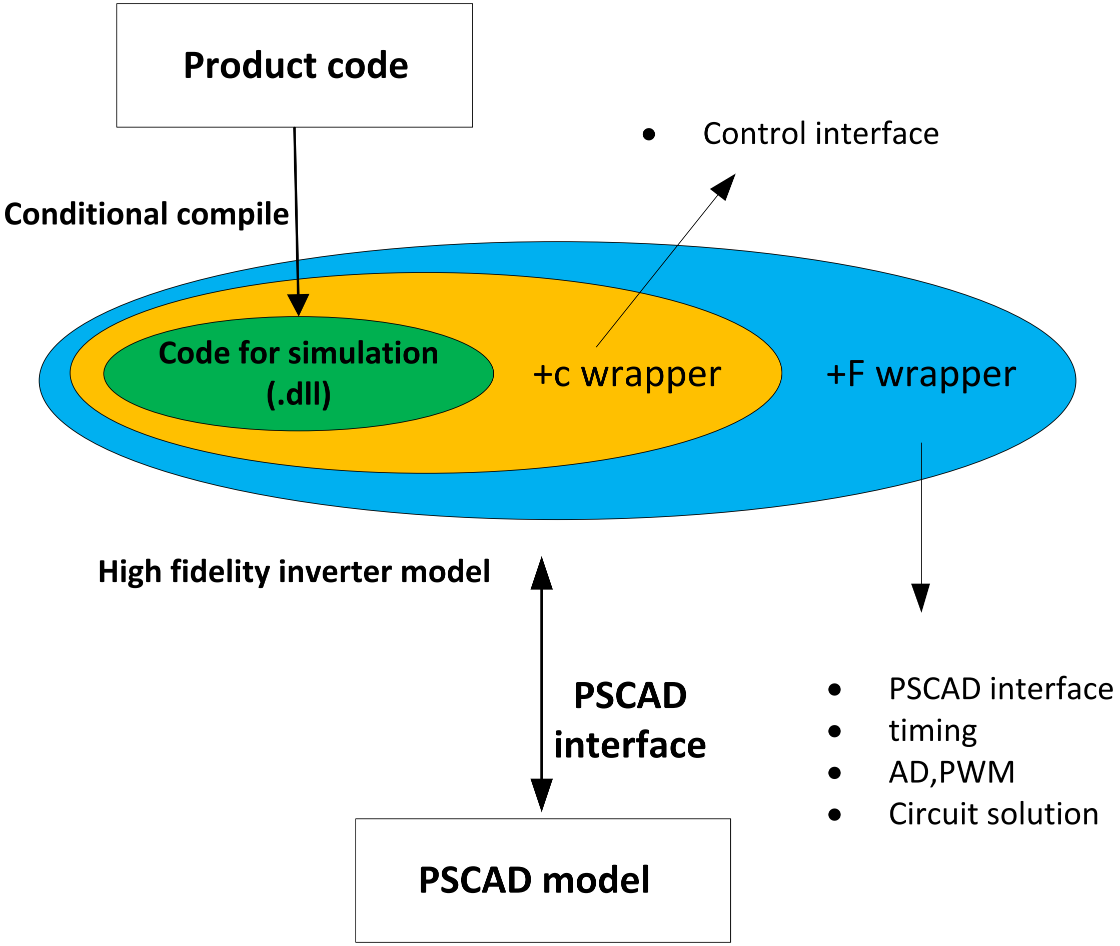
Time domain simulation validation





EMT simulation results match the prediction

High-fidelity EMT modeling of IBR resource

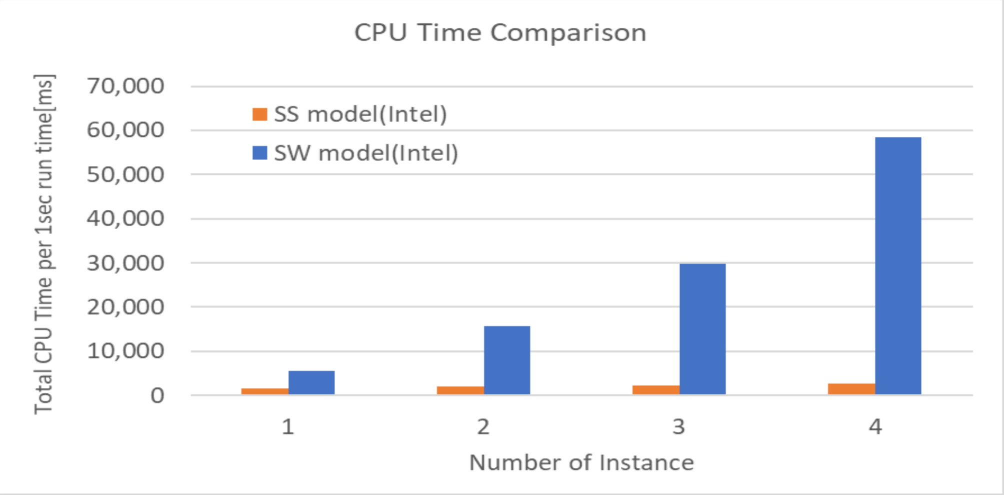


- Fixed simulation time step in PSCAD
- Fine time step inside PSCAD time step based on switching behavior and control timing
- Accurate PWM representation

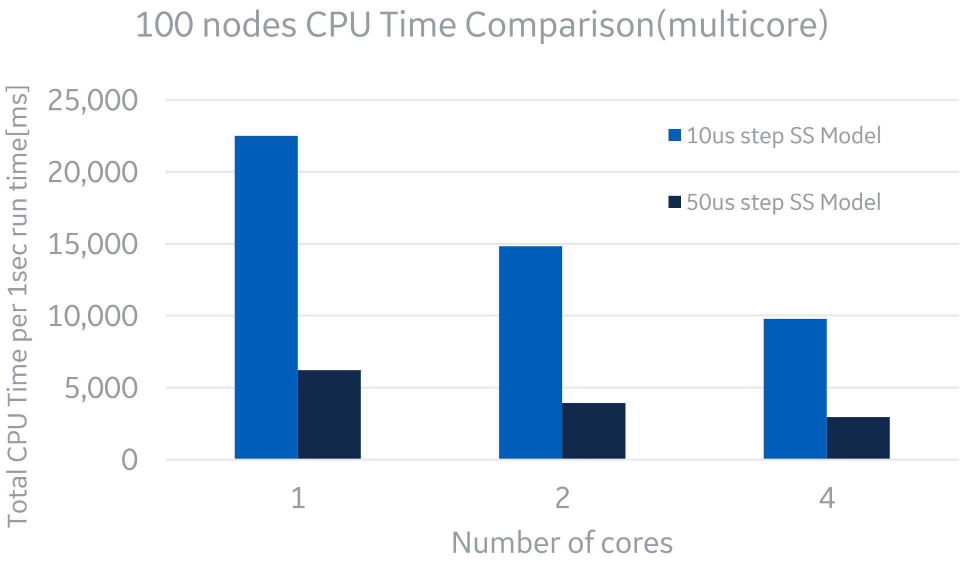
- Multiple instantiations
- Compiler option
- Simulation time step selection
- Parallel simulation
- Multi-core capability

Generic or black box?

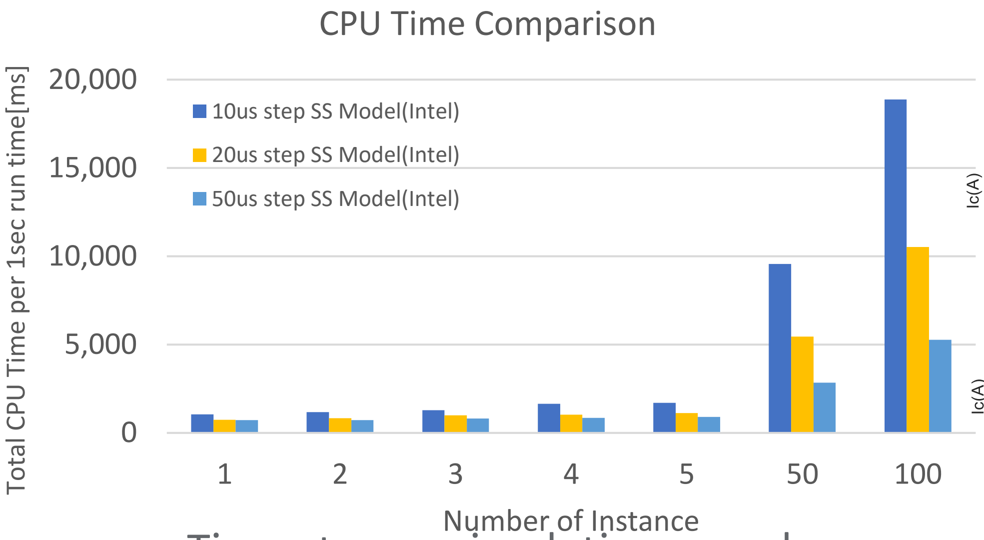
EMT model performance



Compared with switching model

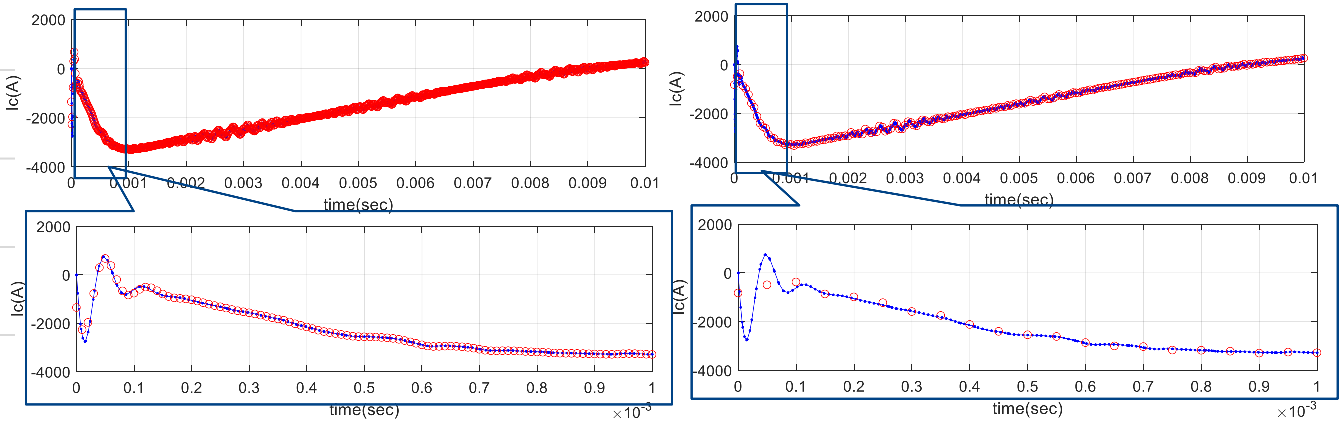


Multi-core vs simulation speed



Time step vs simulation speed

"O" PSCAD simulation result
".-" Reference result



10μs simulation step

50μs simulation step

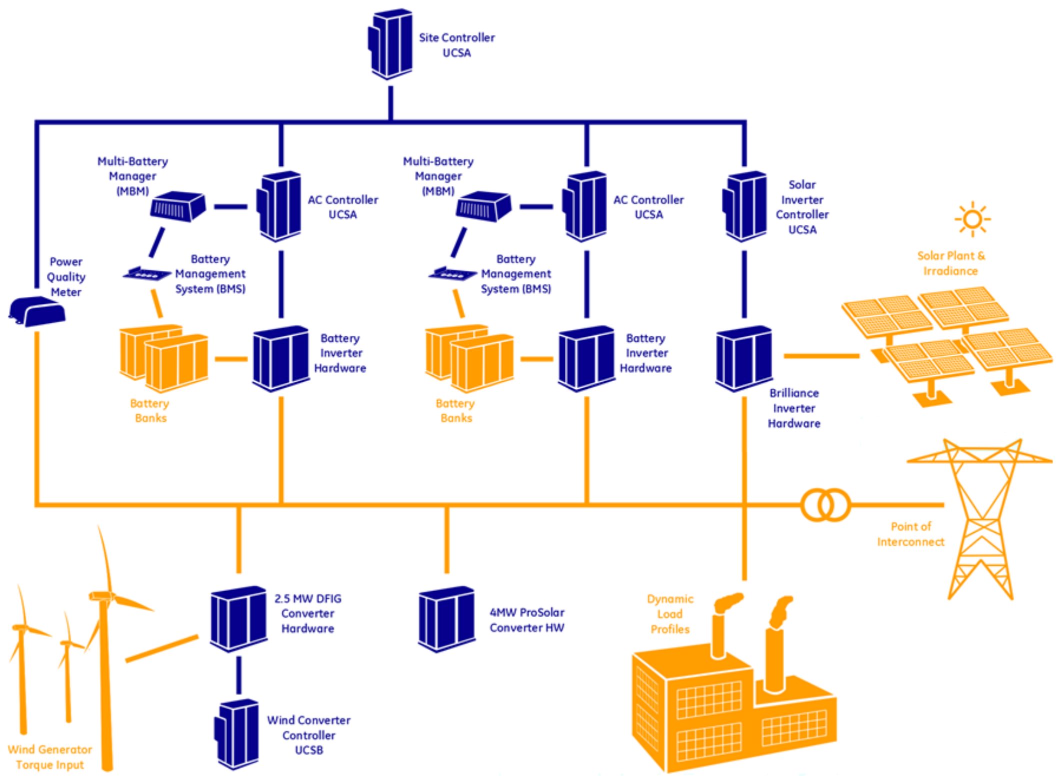
Real time digital simulation system

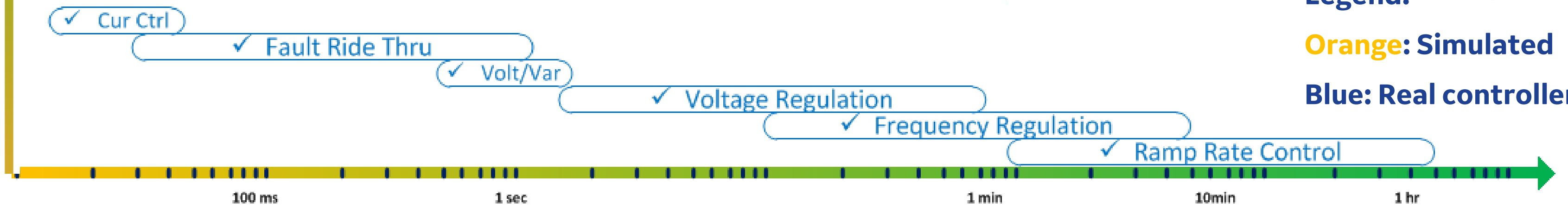
Benefits:

- ❑ Real controllers in the loop
- ❑ All layers of communication
- ❑ All levels of control complexity
- ❑ Overall system performance benchmarking

Current capability:

- ❑ 5MW Solar
- ❑ 4MW BESS system
- ❑ >10MW Wind



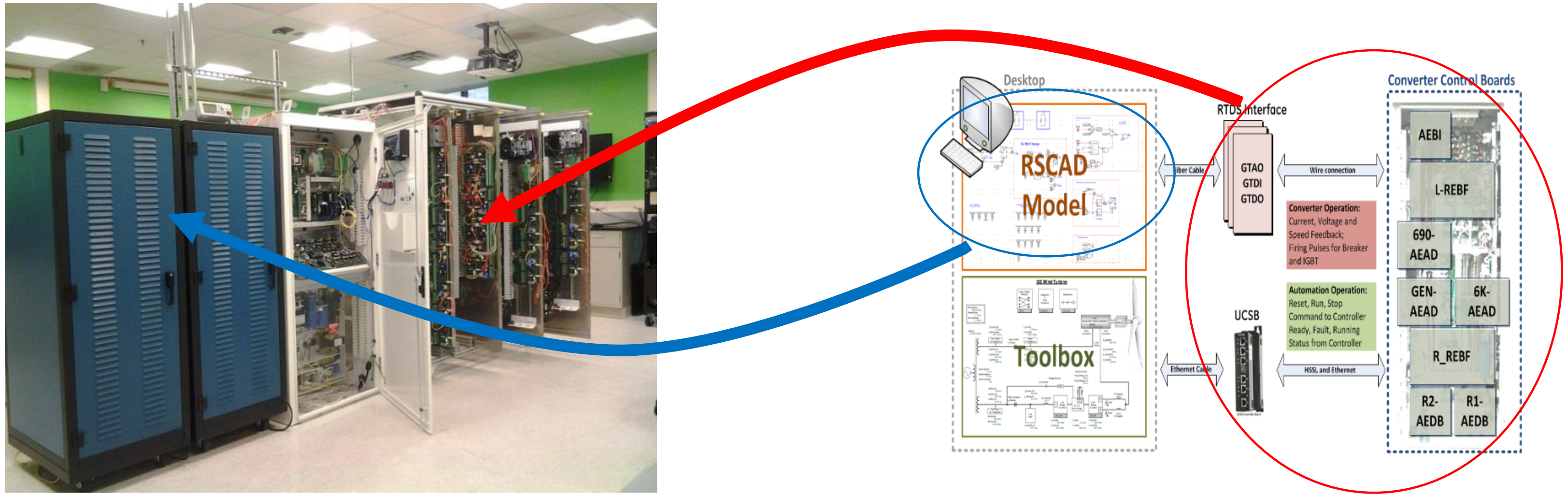


Legend:

Orange: Simulated

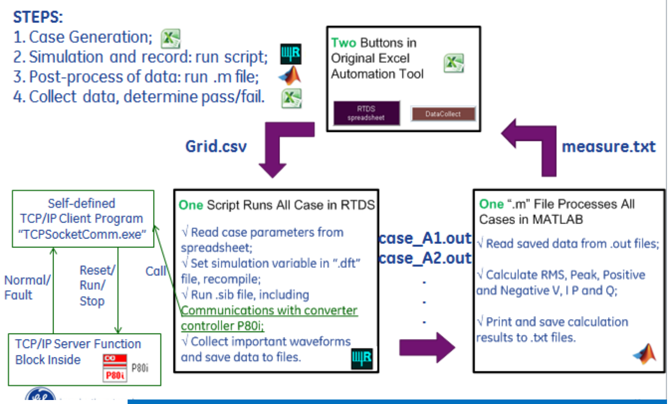
Blue: Real controller

Automated modeling & validation process

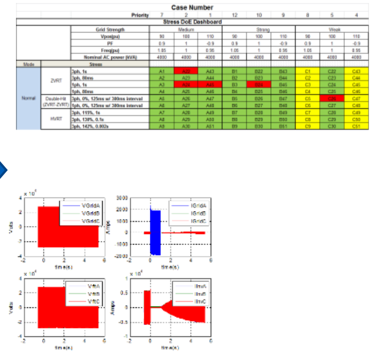


RTDS HIL system

Wind converter RTDS system structure



Automation process



1-Fully automated process

2-Fast DOE speed

3-Data processing and results presentation tool to aid analysis

Characterization and Analysis

Acknowledgements

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