SAND2021-7782C

Controls and Fault Response of Inverter-Based Resources

Presenter: Matthew J. Reno
Sandia National Laboratories

IEEE PES General Meeting
Panel: “Control, Operation, and Modeling of Resilient Distribution Systems with High Penetration of Power Electronics”

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.

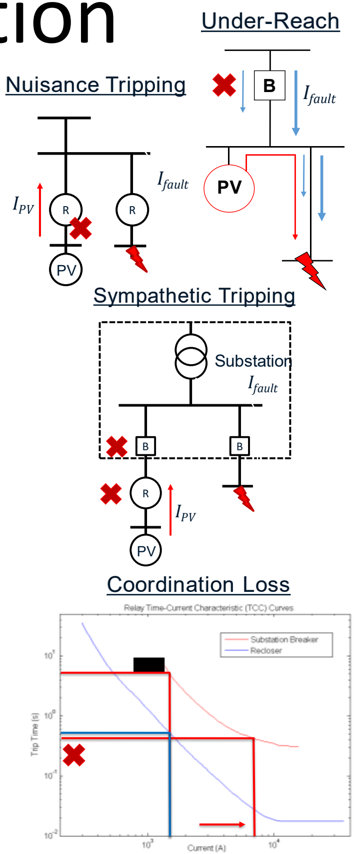
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Introduction

- Modern power grids include a variety of Distributed Energy Resources (DER) that use power electronic interfaces.
- Characterization and modeling of such DER under abnormal scenarios, such as faults, need to be studied and proposed.
  - Additional research and validation is needed for inverter models during transients or faults when they reach their current limiting controls.
  - However, inverter manufacturers are reluctant to provide such models or control schemes, in great part because of conflicts of intellectual property.
- Traditional protection systems are designed for large fault currents from synchronous and induction machines.
  - Short-circuit modeling and protection of traditional systems is well established.
  - Increasing penetration of inverter-interfaced resources underscore the need of inverter models for short circuit studies.
- Modern protective relays are starting to incorporate protection features suitable for transmission lines close to nonstandard generators or low-inertia systems.

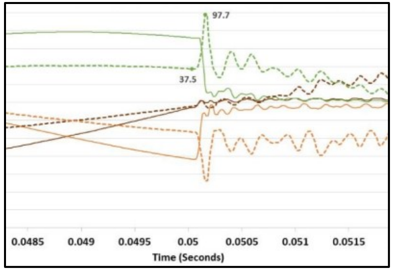
Inverter-Based DG Impacts on Protection

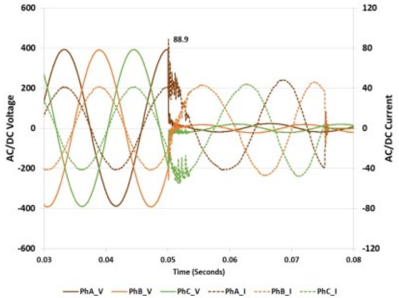
- The legacy protection was not designed for the presence of inverter-based DG
- Common Protection Issues and Impacts:
  - Reverse power flow and multiple injection points of fault current
  - Loss in coordination between protection devices
  - Relay desensitization
  - Load rejection transient over-voltage
- Inverters do not provide significant current during faults
  - Overcurrent protection schemes might not detect the fault
  - Fault currents can look similar to motor starts or inrush
  - Low fault currents can vary more proportionally to the generation dispatch, complicating coordination

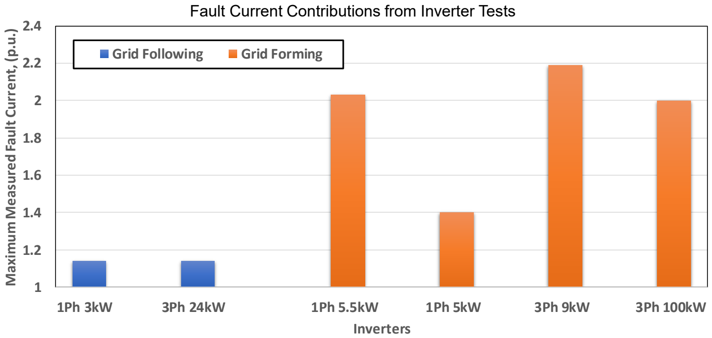


Inverter Short-Circuit Models

- It is important to have accurate models of inverters for dynamic studies and protection
  - Initial spike (~0.1ms) depends on filter cap, system impedance, and prefault conditions
  - Transients during control actions, lasting 2-8ms
  - Steady-state fault current based on the current limiter. Current based control schemes used in grid-following inverters (GFLI) tend to limit the current more aggressively (~1.2-1.5 p.u.) than voltage regulation schemes used in grid-forming inverters (GFMI) (2-3 p.u.)
- One way to understand and observe inverter dynamics under fault scenarios is through laboratory experimentation.

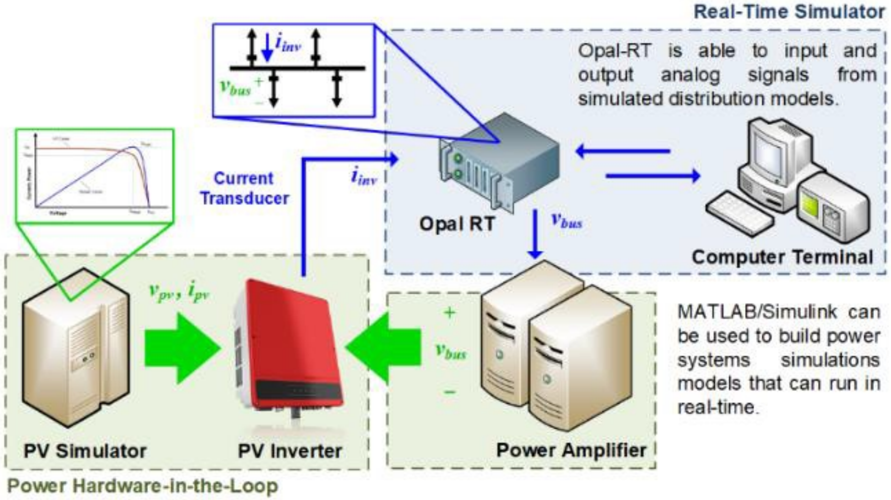


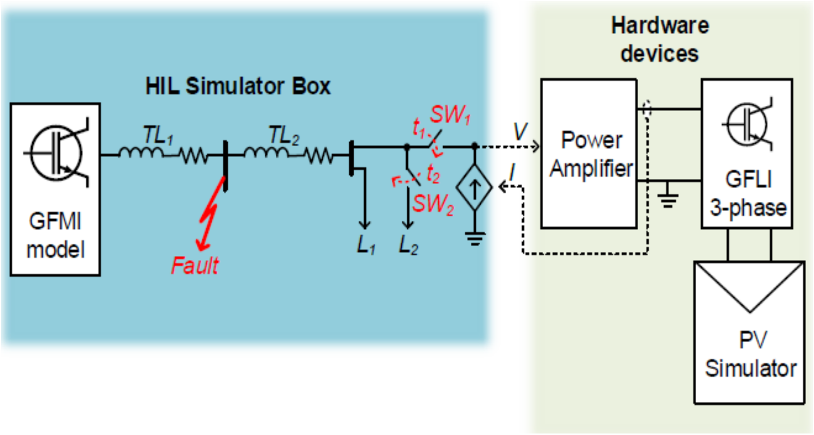




Experimental testing setup for grid-following inverters (GFLI)

- Power Hardware in the Loop (PHIL) setups provide advanced fault testing capabilities.
- This experimental PHIL setup can test and validate GFLI dynamics under faults in different conditions – grid connected, islanded low inertia microgrid

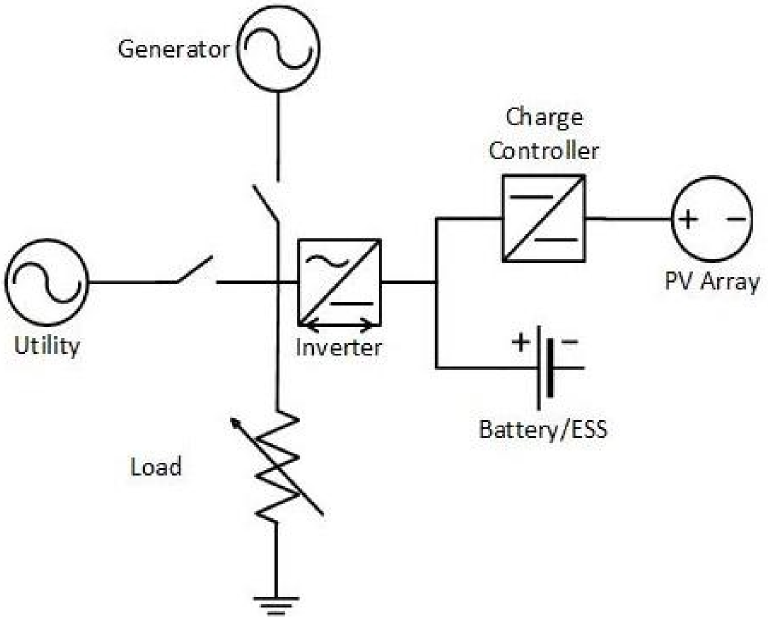




J. Hernandez-Alvidrez, N. S. Gurule, M. J. Reno, and A. Summers, "Simulation of Grid-Forming Inverters Dynamic Models using a Power Hardware-in-the-Loop Testbed. ," IEEE Photovoltaic Specialists Conference (PVSC), 2019.

Experimental testing setup for grid-forming inverters (GFMI)

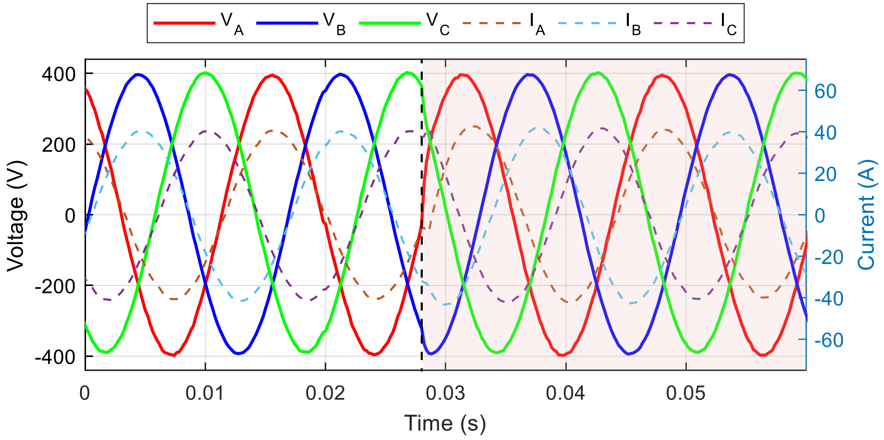
- With the inverter either removed from the EPS or in an islanded state, a variable load is utilized to source current from the inverter.
- DC power can be from PV, Battery/ESS, or ideal DC power supply. Inverter response is evaluated using battery emulator.
- By increasing the absorbed power of the load to a value greater than the rated power of the inverter, the voltage will drop below nominal, similar to that of a line-to-line or line-to-neutral faults.

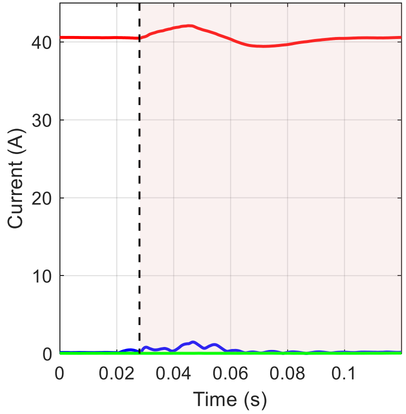


N. S. Gurule, J. Hernández-Alvídrez, M. J. Reno, A. Summers, and J. D. Flicker "Grid-forming Inverter Experimental Testing of Fault Current Contributions ," IEEE Photovoltaic Specialists Conference (PVSC), 2019.

GFLI Response to Phase Angle Jumps

- During a fault, the voltage angle suddenly changes due to the new X/R ratio with the fault resistance
- For grid-following inverters (GFLI), the PLL tracks the voltage angle to keep a specific power factor
- Experimental tests shown for a 24 kVA inverter with a 20° shift in all three phases (3-phase-to-ground fault) – PLL controls the current back to the setpoint (unity power factor) in ~2 cycles





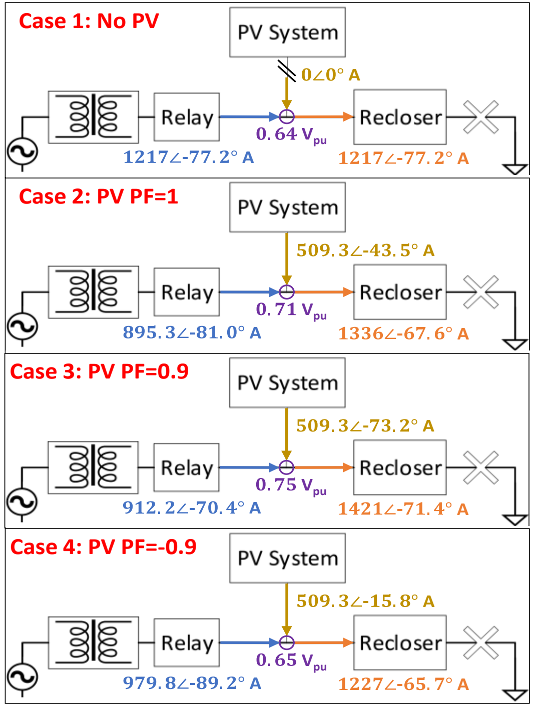
R. Darbali-Zamora, J. Johnson, M. J. Reno, and N. S. Gurule, "Evaluation of Photovoltaic Inverters Under Balanced and Unbalanced Voltage Phase Angle Jump Conditions," IEEE Photovoltaic Specialists Conference (PVSC), 2020.

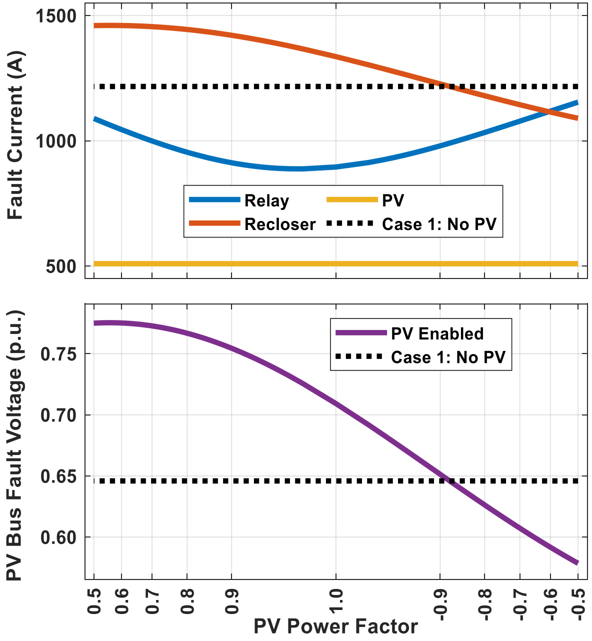
IEEE PES Power & Energy Society®

IEEE

Advanced Inverter Impacts on Distribution Protection

- Because the GFLI PLL quickly resynchronizes during faults, the angle of the inverter fault current injection is dependent on the power factor of the inverter before the fault
- The inverter current angle changes the current magnitude through the protection devices (changing coordination)

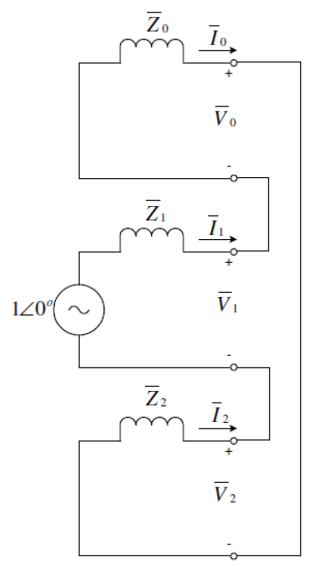




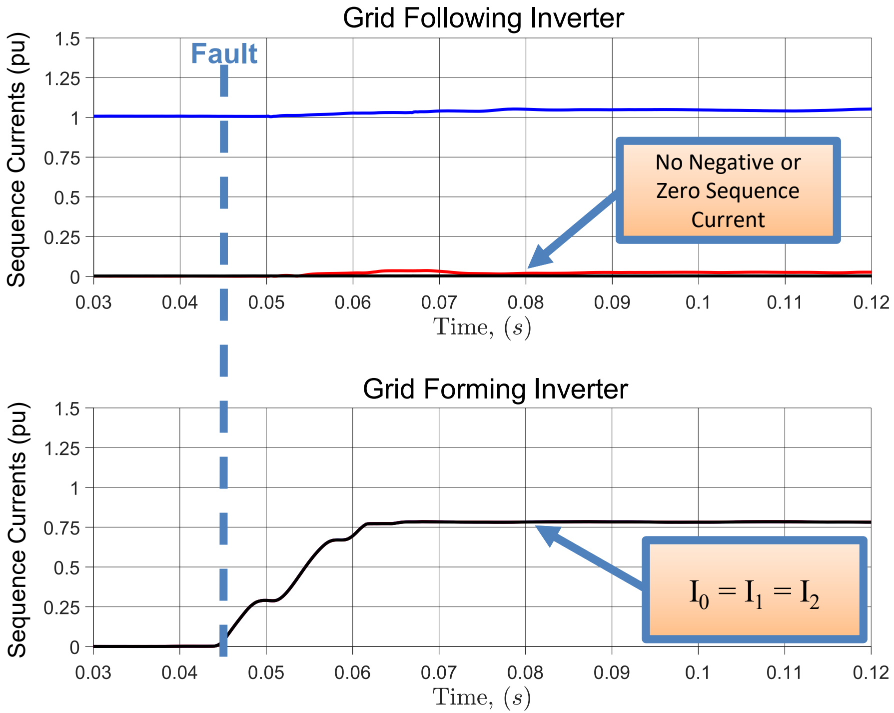
N. S. Gurule, J. A. Azzolini, R. Darbali-Zamora, and M. J. Reno “Impact of Grid Support Functionality on PV Inverter Response to Faults”, IEEE Photovoltaic Specialists Conference (PVSC), 2021.

Inverter Tests – Single-Line-to-Ground Fault

Single-Line-to-Ground Fault Diagram



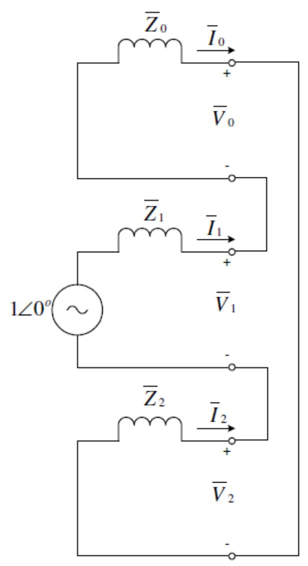
$$I_0 = I_1 = I_2$$



M. J. Reno, S. Brahma, A. Bidram, and M. E. Ropp, “Influence of Inverter-Based Resources on Microgrid Protection: Part 1: Microgrids in Radial Distribution Systems,” IEEE Power and Energy Magazine, 2021.

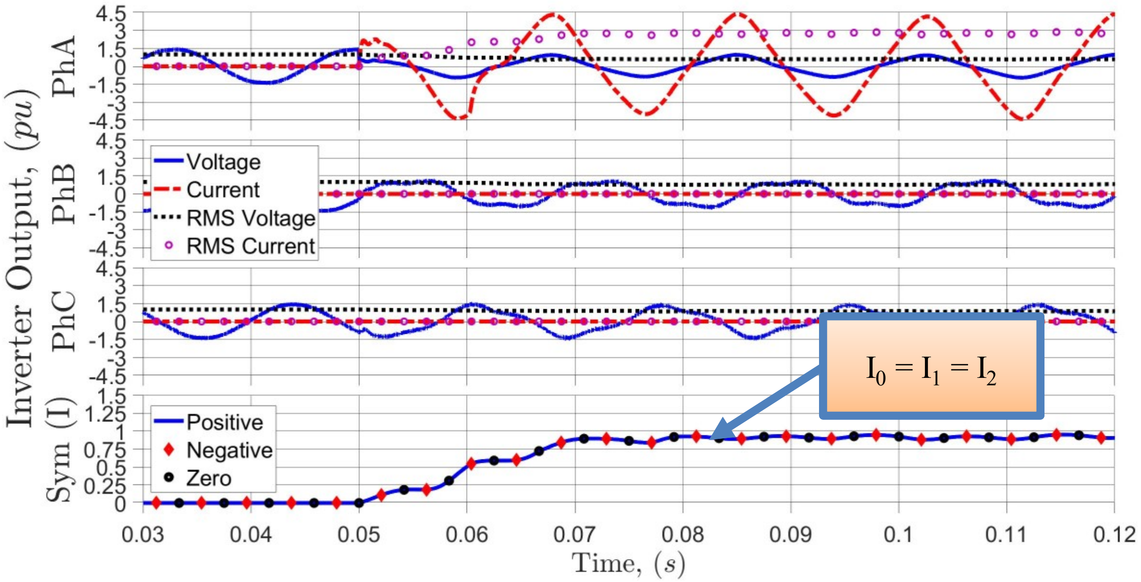
Inverter Tests – Single-Line-to-Ground Fault

Single-Line-to-Ground Fault Diagram



$I_0 = I_1 = I_2$

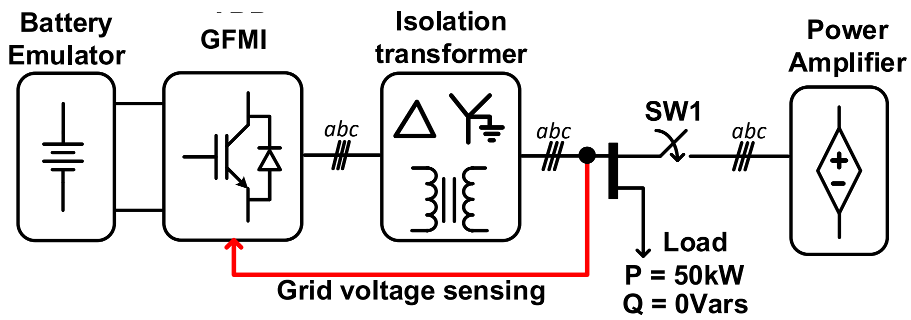
100 kVA GFMI provides negative sequence currents (I_2), and zero sequence currents (I_0) provided by the delta-wye step-up transformer

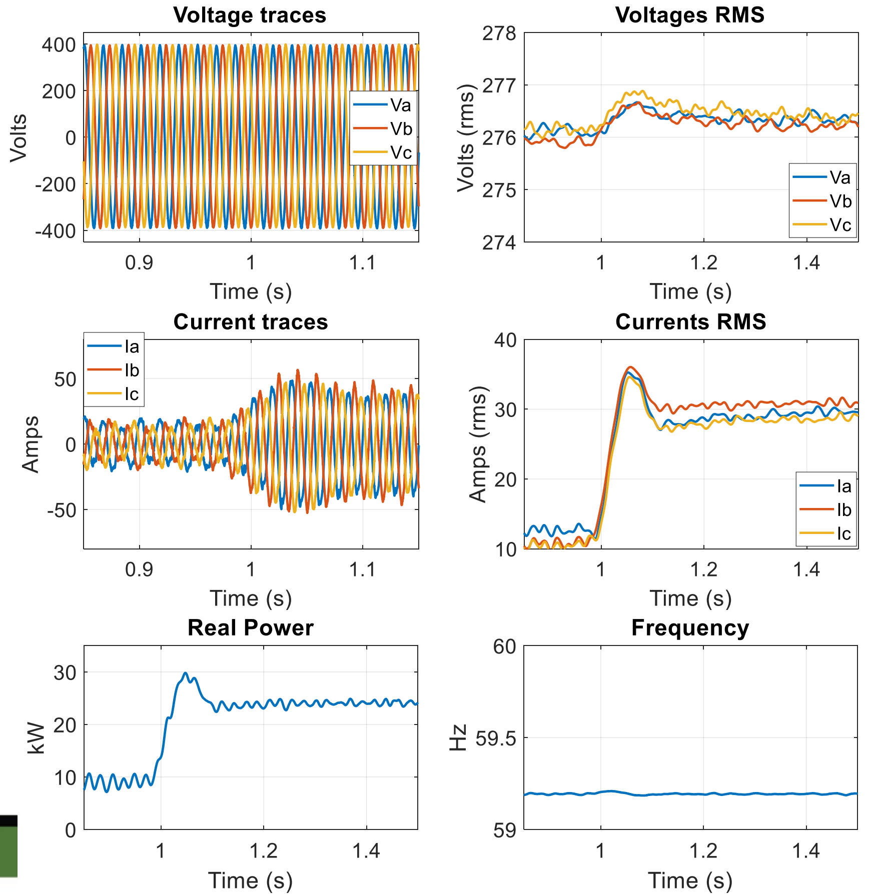


N. S. Gurule, J. Hernandez-Alvidrez, R. Darbali-Zamora, M. J. Reno, and J. D. Flicker, "Experimental Evaluation of Grid-Forming Inverters Under Unbalanced and Fault Conditions," IEEE Industrial Electronics Conference (IECON), 2020.

Grid-Forming Inverter Mode Transition Experiment

- With GFMI and load on one side of a contactor (SW1), starting with GFMI in grid-following mode and grid connected. Open contactor to test the transition of the inverter from grid-following to grid-forming





Conclusions

- Accurate characterization and modeling of inverter-based DER under fault scenarios will play an important role in the protection of microgrids or low-inertia systems.
- Hardware experiments provide validation data that is valuable for developing inverter-based models for modeling distribution systems with high penetration of power electronics
  - Real-time PHIL interfaces simulation with hardware such that the inverter models can be directly compared to the hardware response to the same signal
  - Advanced PHIL simulation setups can also help with fault dynamics since they provide the interfacing of DERs with more realistic operational scenarios.

QUESTIONS?

mjreno@sandia.gov