SAND2019-6546PE

2019 Microgrid R&D Program Review Meeting

Advanced Protection Schemes for Microgrids

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Industry Need and Challenge

- Traditional distribution protection systems are designed for radial flows with 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*
- Adoption of microgrids also provides new challenges for protection
  - In order to provide reliability and resilience, microgrids must be protected and secure in grid-connected and islanded
  - The challenge of protecting microgrids limits their adoption
  - Microgrid protection is especially difficult for inverter-based systems because of the lack of models and inverters' low fault currents

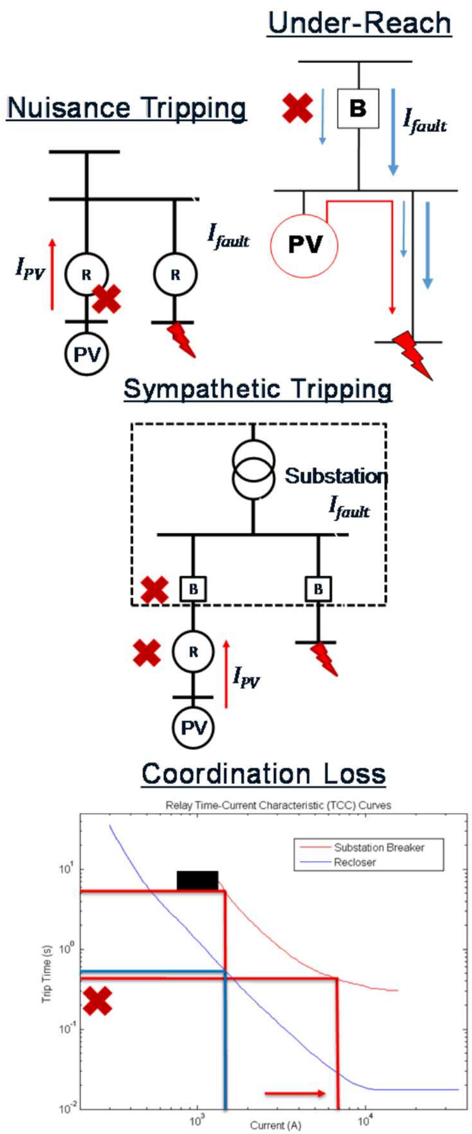
As microgrids proliferate with the sharp increase in renewable-fed distributed generation, islanded operation of microgrids that are fed entirely by inverter-based renewables is becoming an imminent reality

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
- ✓ Transfer trip strategies
- ✓ Anti-islanding detection
- ✓ Open-phase detection
- ✓ Interconnection transformer winding configuration and grounding
- ✓ Load rejection transient over-voltage



100% Inverter-Based System Protection Challenges

- 100% inverter-based systems present a new set of challenges for protection
- 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
  - With low fault currents, the fault currents are more sensitive to generation dispatch, complicating coordination
- Other Protection Challenges Include:
  - Inverters do not provide zero sequence or negative sequence fault currents (depending on the controls)
  - Inverters have no inherent inertia, and their transient responses vary depending on the controls. How does this impact Power Swing Blocking and Out-of-step Tripping functions?
  - Inverter fault current response depends on the pre-fault conditions (e.g. power output level, power factor, etc.), so they have to be included in the models and analysis

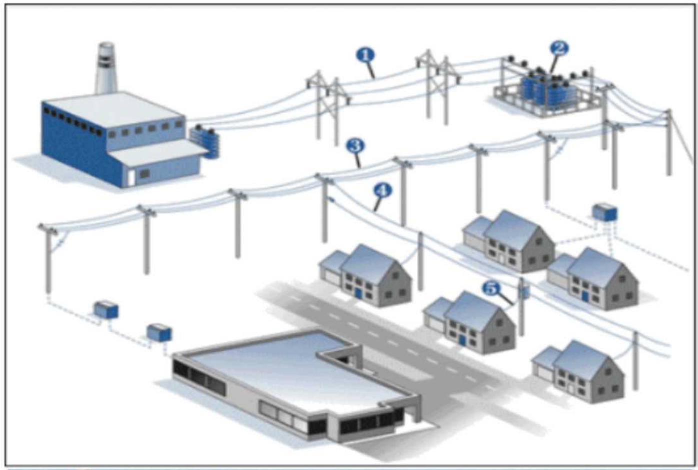
Microgrid Protection Challenges

- Variety of sizes, technologies, configurations of microgrids (dynamic topology)
  - Difficult to have a "*one size fits all*" solution.
- Islanded and grid-connected modes of operation
  - Significantly different fault levels makes coordination challenging.
  - Fault levels can be very sensitive to generation dispatch, complicating coordination
- Inverter-rich Microgrid has low fault current
  - Overcurrent might not detect the fault in the first place.
  - High-impedance faults are particularly problematic. Motor starts or inrush can look similar to high impedance faults
- Small geographical area with more resistive network
- Microgrids can be more sensitive to the disturbances and faults for critical customers, stability, etc.

Efficient microgrid protection schemes will also be beneficial for protecting distribution systems with very high penetration of renewable generators.

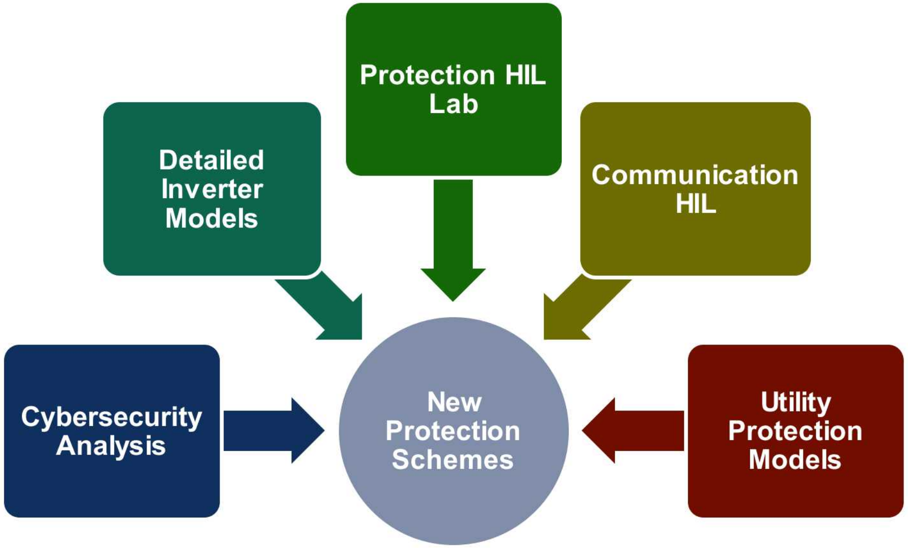
Project Objectives and Outcomes

- Holistic approach to address the challenges of distribution system and microgrid protection under high penetrations of inverter-based DER
- Develop, validate, and demonstrate highly reconfigurable communication-based protection schemes under dynamic distribution configurations with high DER penetrations including intentional islanding into microgrids
- Investigate protection system design for DC microgrids to address protection-related challenges of integrating DC microgrids to distribution systems
- Develop fault location algorithms for microgrids and distribution systems with high DER penetration and tested algorithms in simulations and HIL



Technical Approach - Tasks

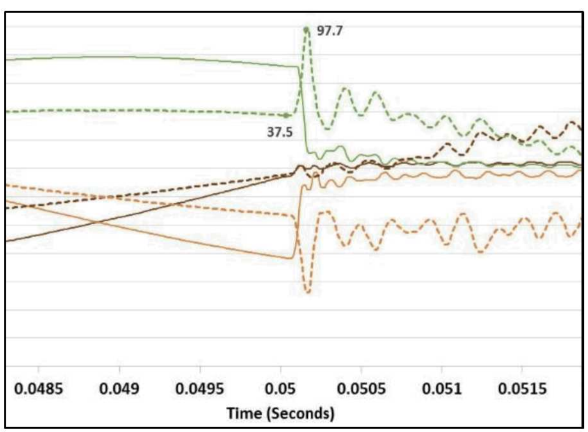
- PV Inverter models for fault studies
- Distribution system and microgrid protection under high DER penetration
- HIL protection analysis
- Fault location schemes for systems with high DER penetration
- Protection schemes for DC microgrids

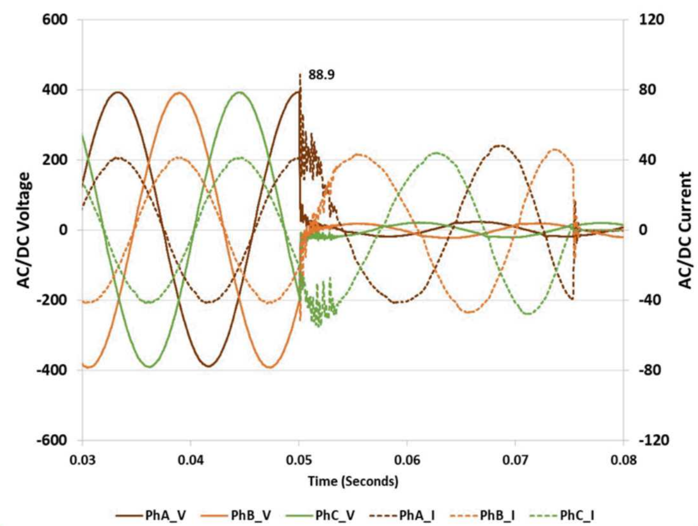


Distribution and Microgrid Protection
Adaptive Protection
Fault Location Analysis
DC and AC Protection Schemes

Inverter Short-Circuit Models

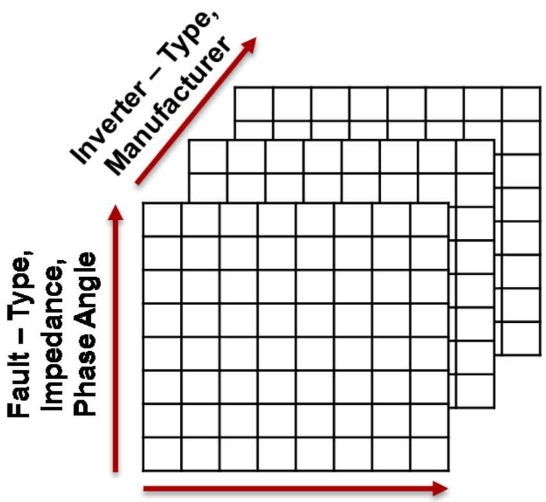
- It is important to have accurate models of inverters for dynamic studies and protection coordination
  - Initial spike (~0.1ms) depends on filter cap, system impedance, and pre-fault condition
  - Transients during control actions, lasting 2-8ms
  - Steady-state fault current based on the current limiter
- Models are challenging to develop because there are stark differences between manufacturers, single vs. three-phase inverters, PV vs. energy storage vs. grid forming inverters.



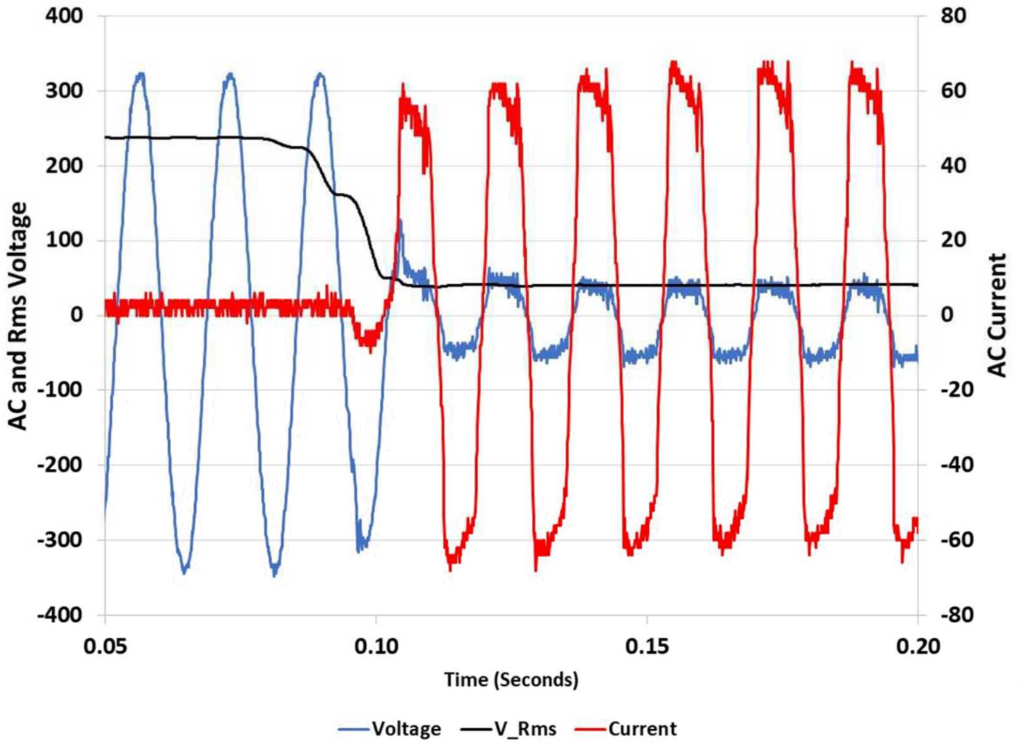


Inverter Fault Characterization

- Best way to fully characterize inverters for all transient and steady-state time scales is through testing (Sandia's DETL)
- Grid-following inverters generally have very low fault current contributions (1.1-1.2 of their rated current)
- Grid-forming energy storage inverters can deliver 2x the rated current for about 60 seconds

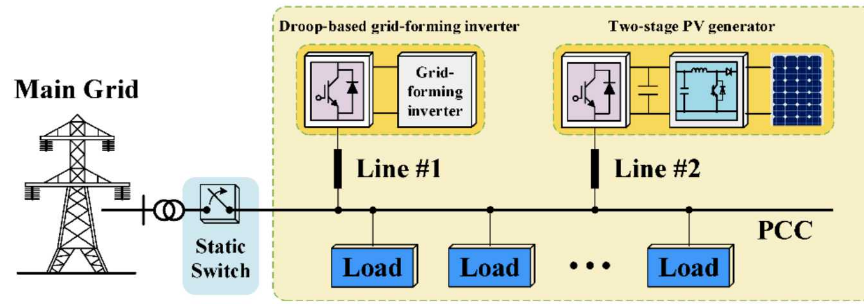


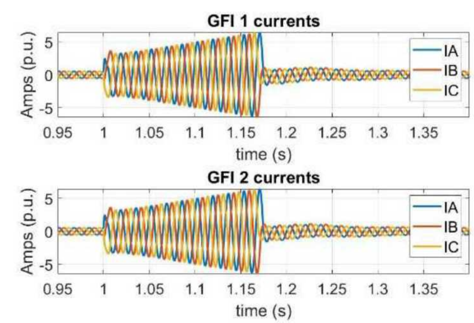
Hardware results from large test matrix of different inverters, faults, and settings



Grid-Forming Inverter Lab

- Power Hardware in the Loop (PHIL) low inertia real-time simulation
  - I. Testing of commercial GFIs
  - II. Validate dynamic behavior of GFIs under faults
  - III. Provide insightful information to the design and coordination of protection schemes for microgrids with high penetration of DERs
  - IV. Developing test procedures to initiate the standardization
- Unbalanced modeling of GFIs
- Interactions with commercial and R&D protection devices (SEL)

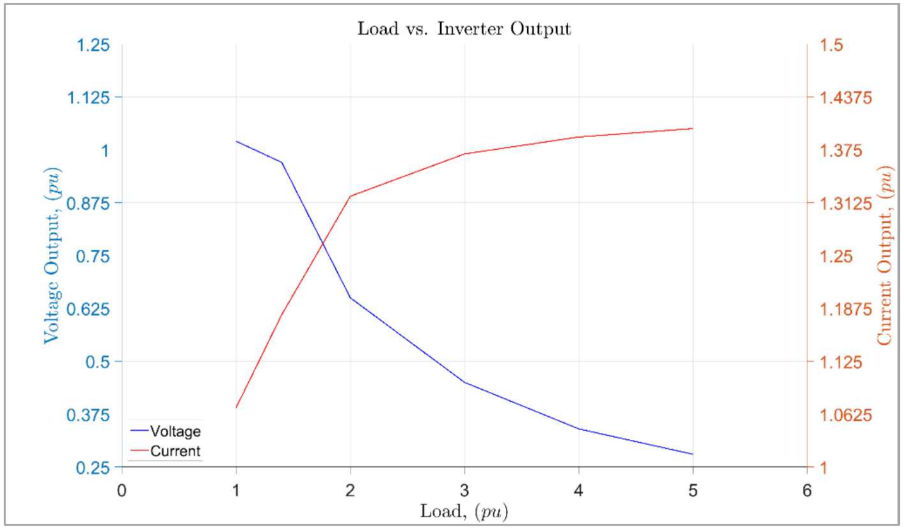




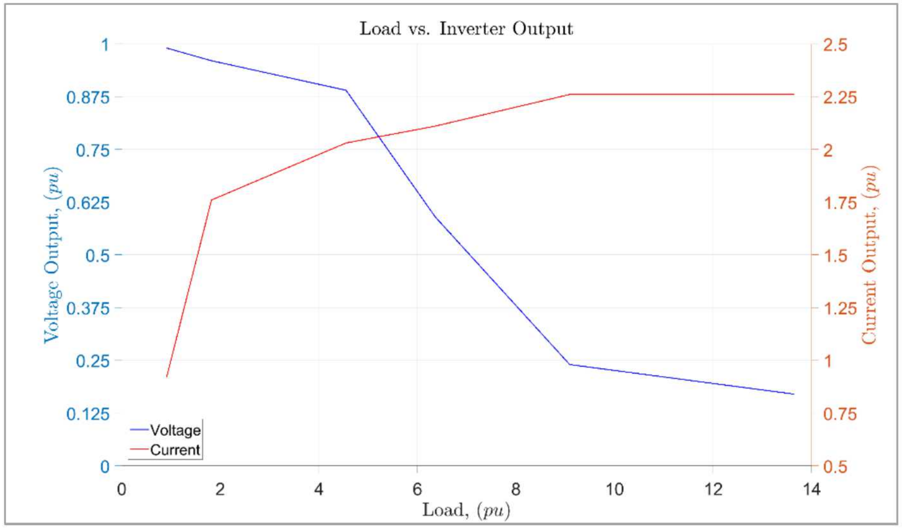
- Grid Forming Inverters
  - Hardware Testing of Commercial Inverters
  - Developing and Validating Models
  - Interactions with Protection Systems
  - Transmission Stability Analysis
  - New Power Electronic Controls
  - Generic Models and Standards

Grid-Forming Inverter Fault Testing

- Split phase GFMI subjected to a load greater than the rated output of the inverter, but with a resistance much greater that that of a bolted fault (R>1ohm)
- Depending on the control scheme of the inverter larger loads can be supported for a short period of time to support heavy load starts such as induction motors



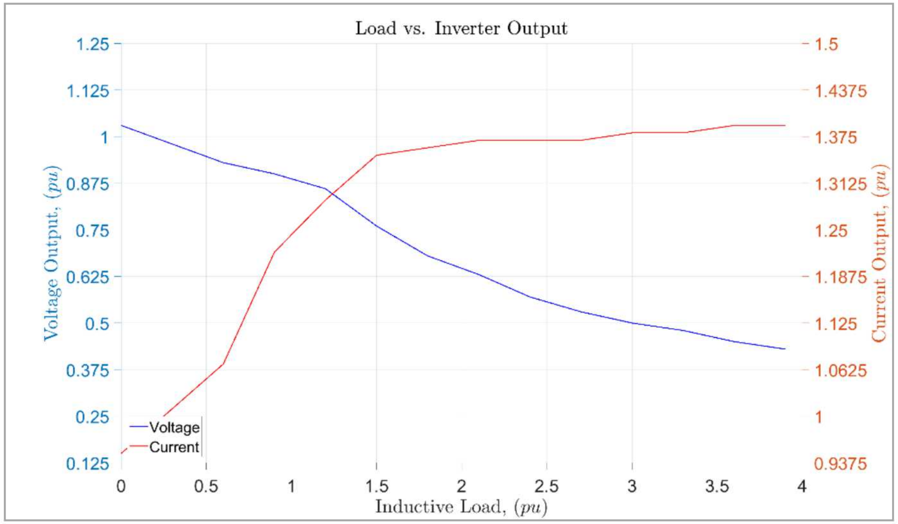
GFI without Overload Support



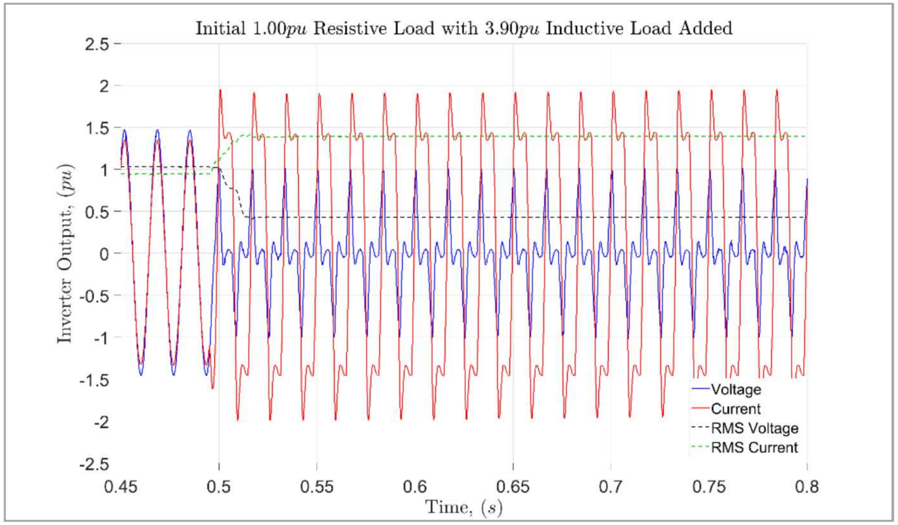
GFI Overload Support

Grid-Forming Inverter Fault Testing

- Inductive Fault
  - With the GFMI operating at its rated power on a resistive load, an 3.9pu inductive load is added, similar to a large motor start
  - Similar to the high impedance loads the voltage collapses with increasing inductive load, however the output current is shifted to account for the reactive component of the load and the output voltage is severely distorted



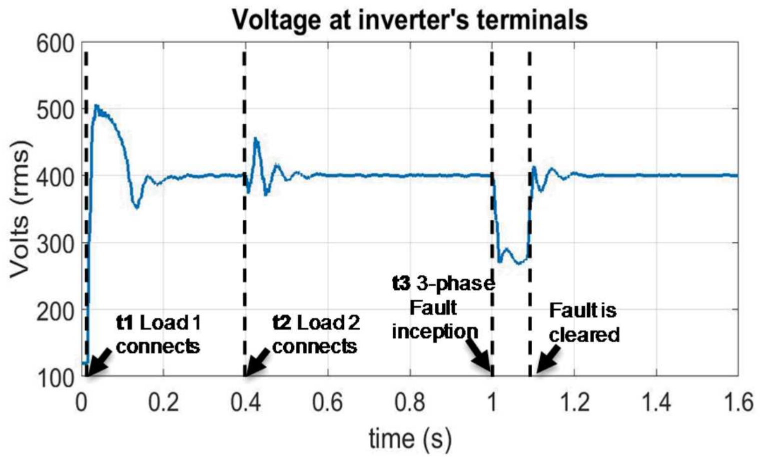
GFI without Overload Support

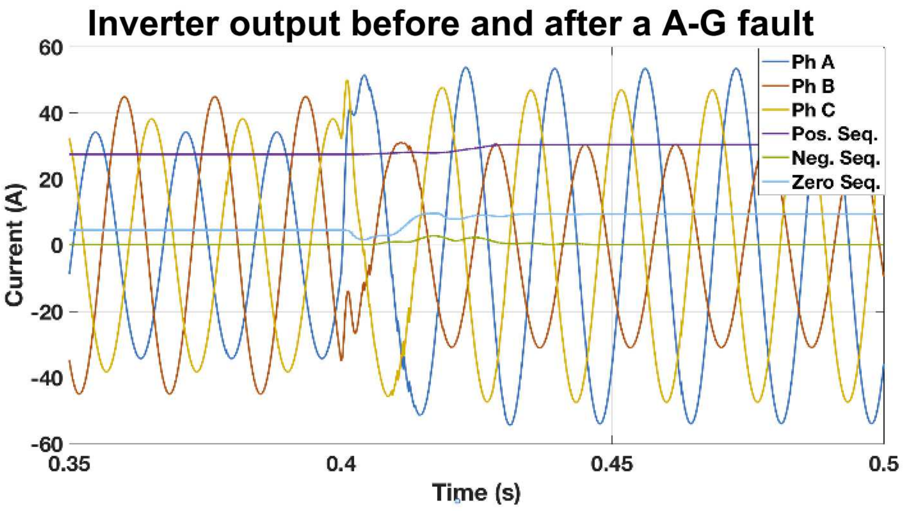


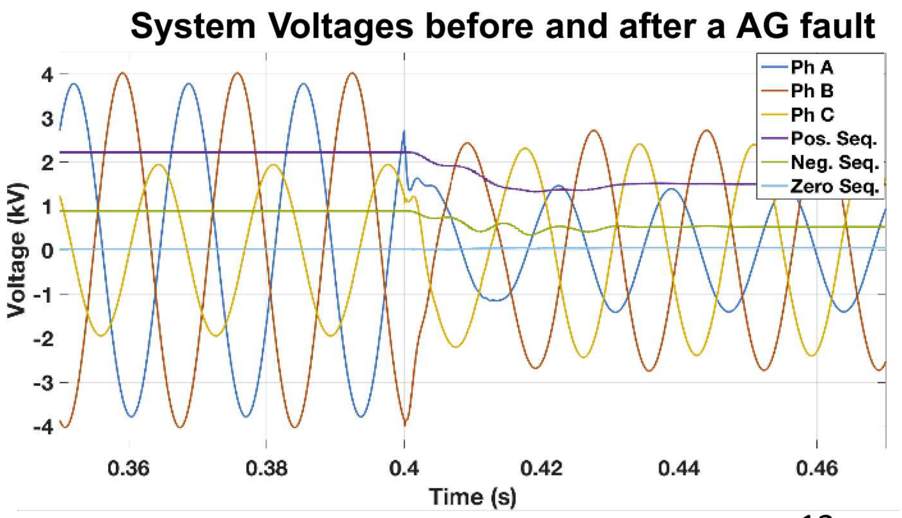
GFI without Overload Support at 3.9x Inductive Load

Grid-Forming Inverter Simulation

- Controller is stable and maintains reference voltage during load changes and faults
- Zero and negative sequence currents for unbalanced loads and faults with grid-forming inverters

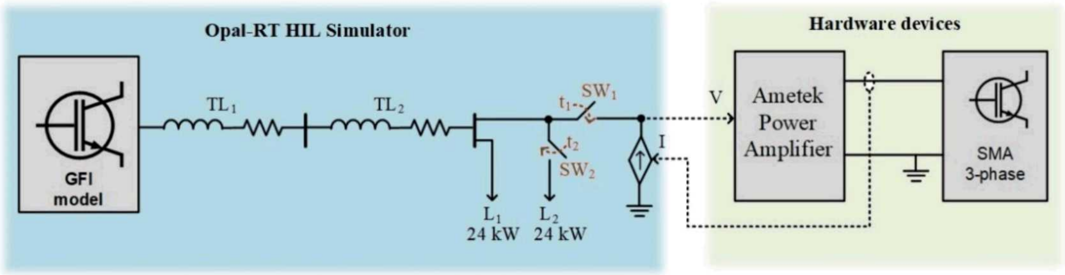


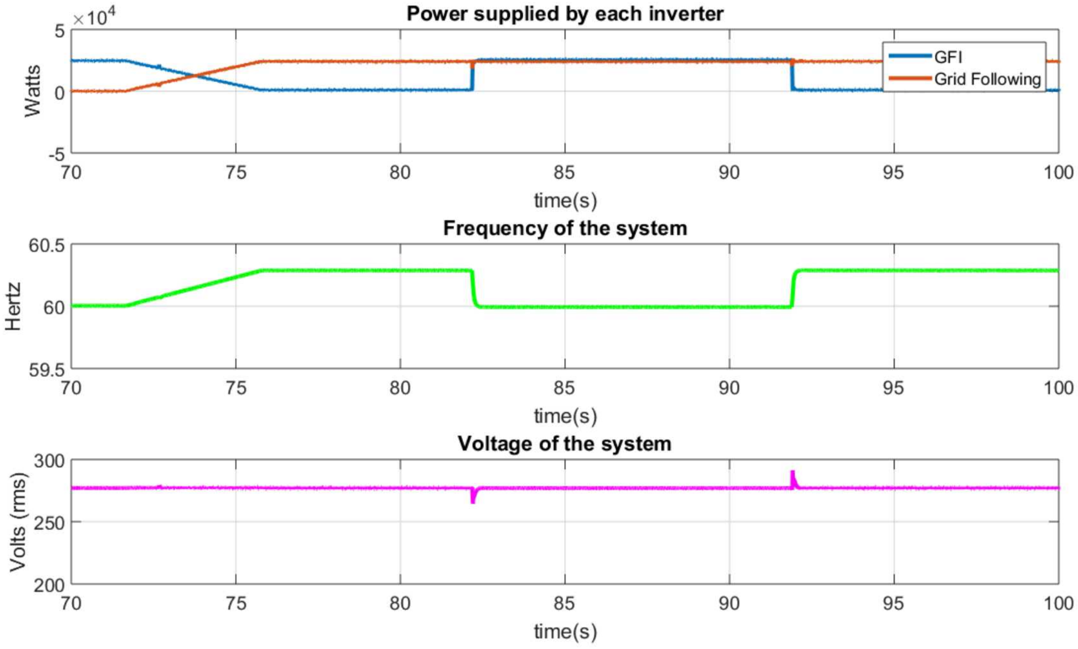




Grid-Forming Inverter in HIL

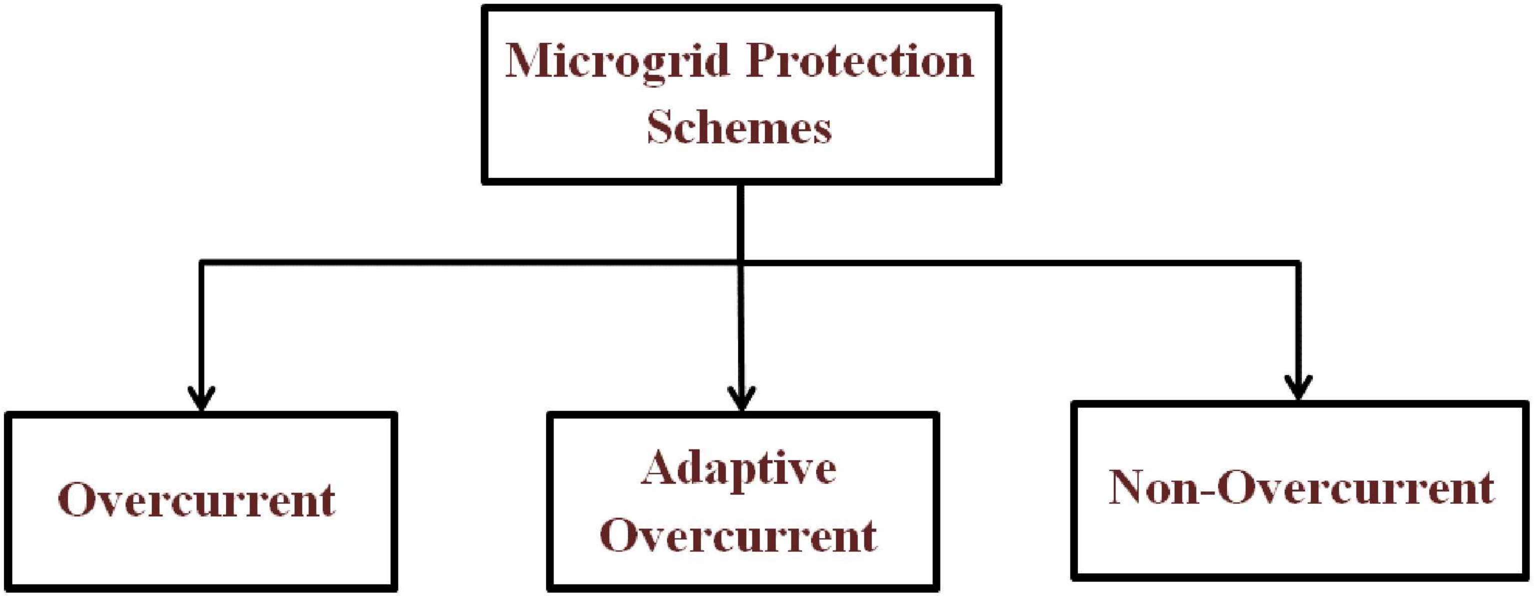
- A grid-forming inverter (GFI) is modeled in the simulator box (Opal-RT) for real-time simulation with grid-following inverter in the hardware side of the system
- Both inverters share two loads (24 kW each), but the GFI must dictate and regulate the voltage and frequency of the system
- At t1, the grid-following inverter connects to the system and supplies most of L1
- At t2, L2 connects and the GFI provides the power needed to supply L2. Due to the load sharing droop-characteristics, the frequency drops to a new value





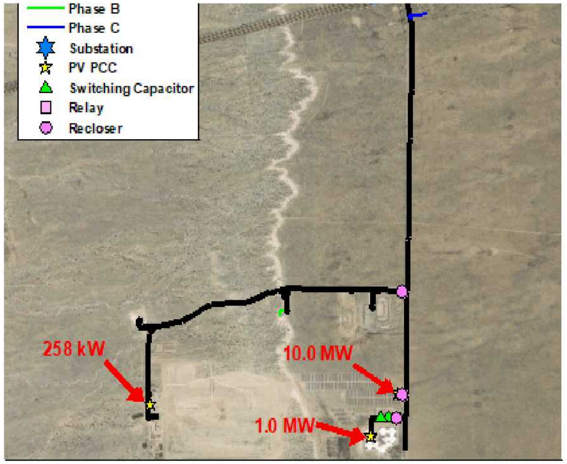
Microgrid Protection

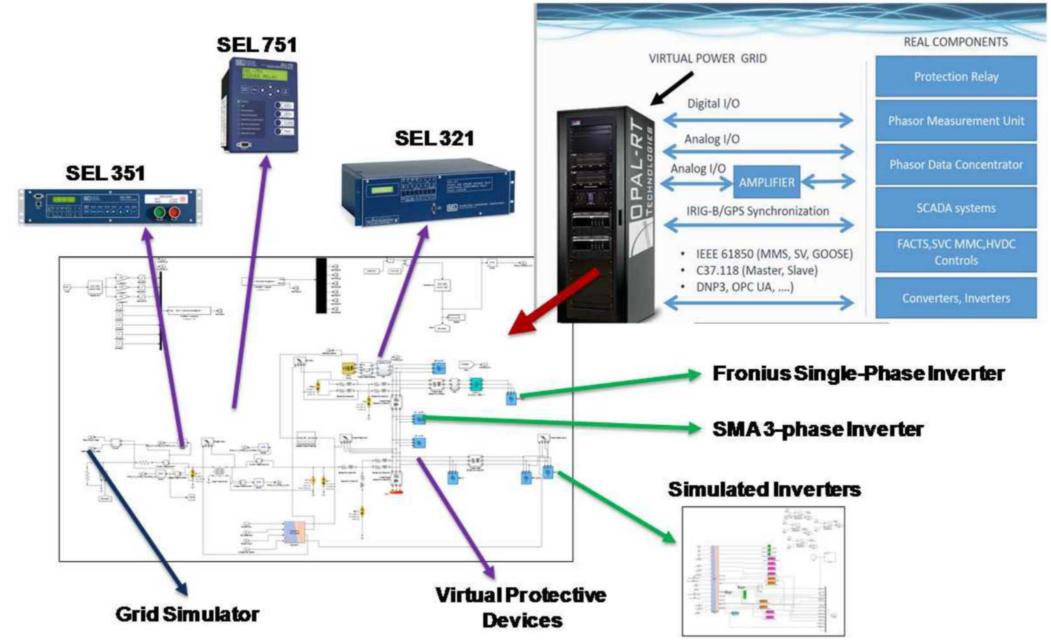
- Holistic approach to address the challenges of distribution system and microgrid protection under high penetrations of inverter-based DER
- Develop, validate, and demonstrate highly reconfigurable communication-based, adaptive overcurrent, and non-overcurrent schemes



Protection PHIL Lab

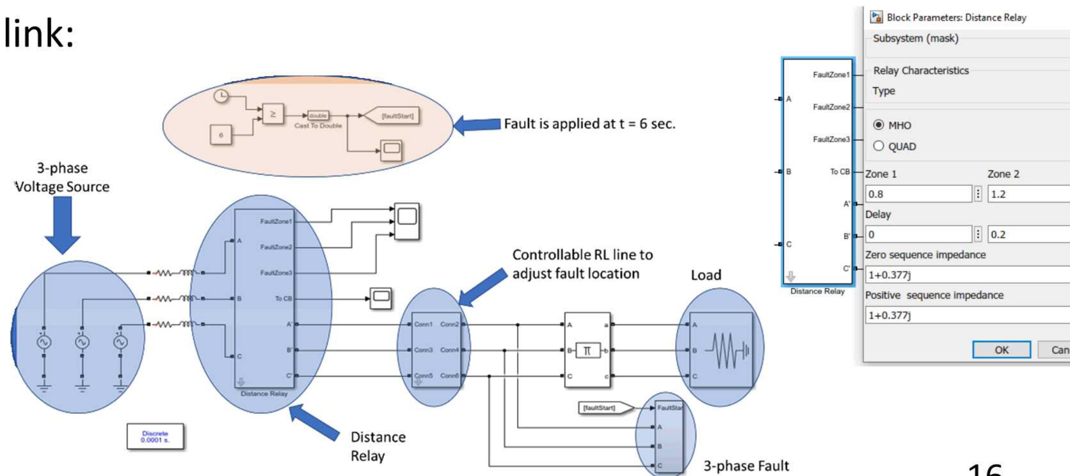
PNM Feeder Models and Protection Settings





Creating a distance relay model in Matlab/Simulink:

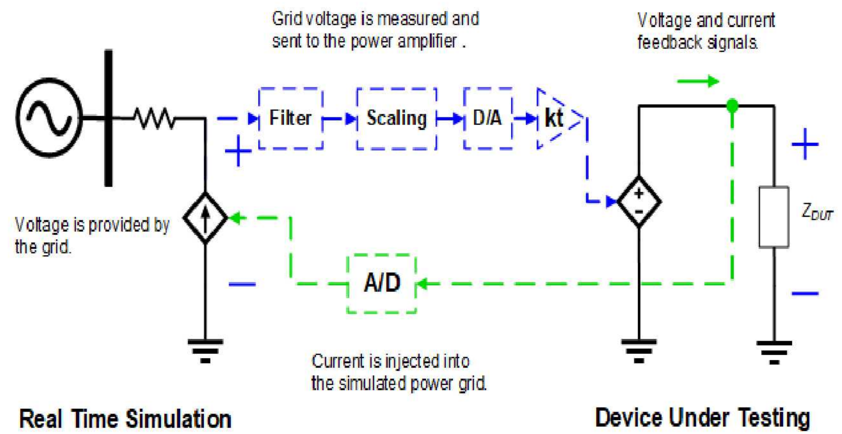
- Multiple zones of operation
- Customizable reach and delay settings
- Accommodating Mho and quad curves
- Accommodating phase and ground faults

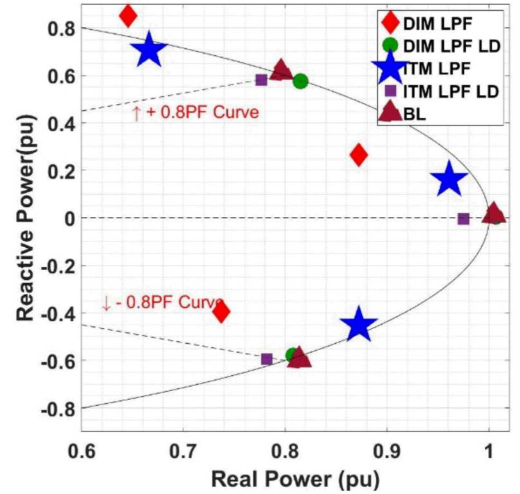


Interface Methods For Power HIL

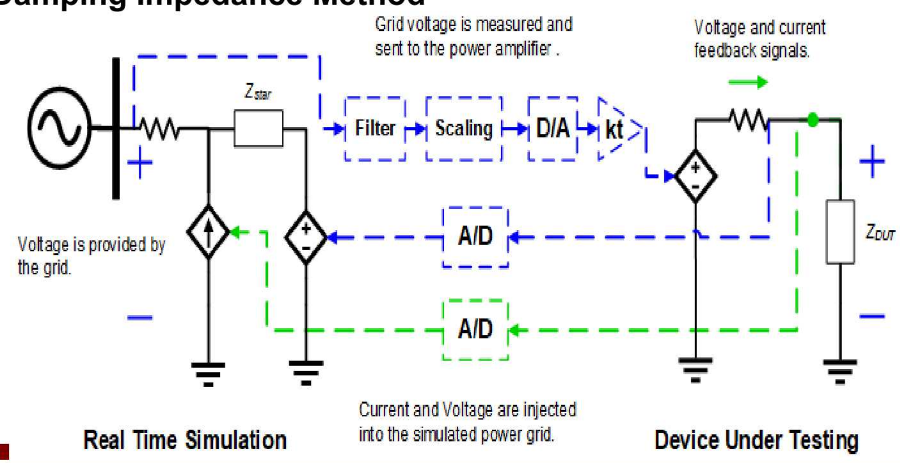
- High accuracy is important for protection HIL analysis, especially reactive power support low-voltage ride-through

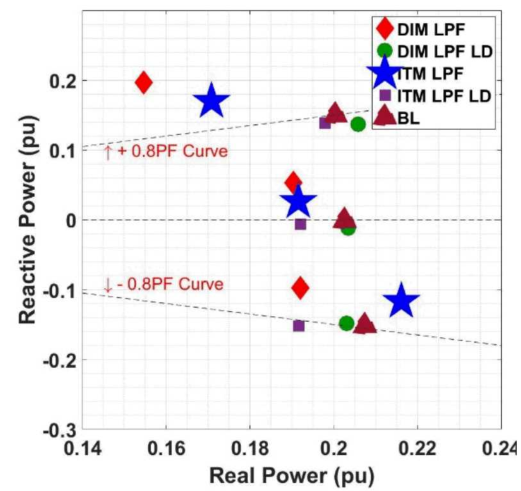
Ideal Transformer Method





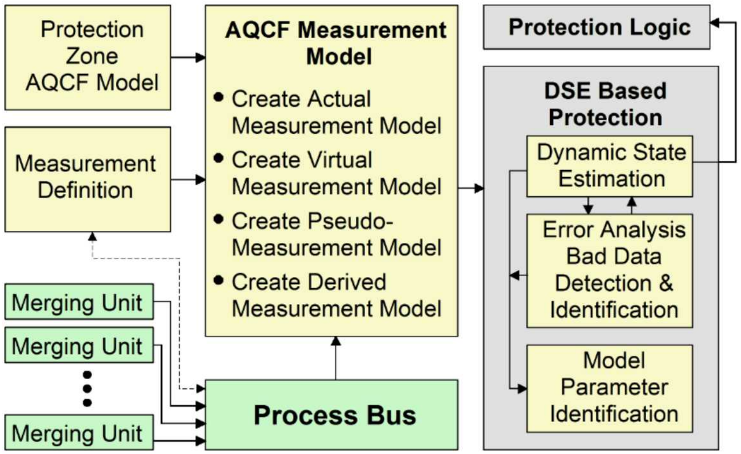
Damping Impedance Method

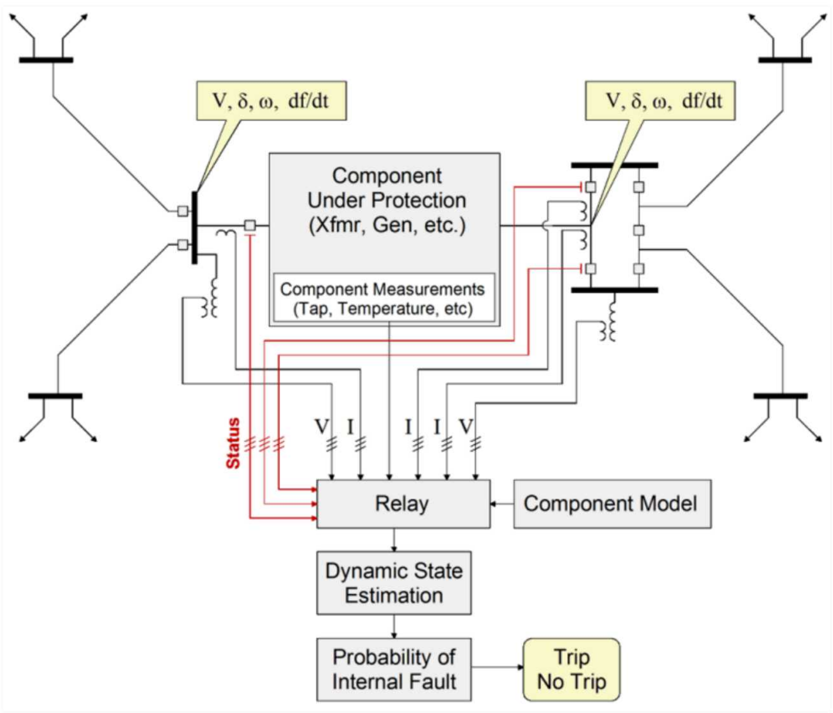


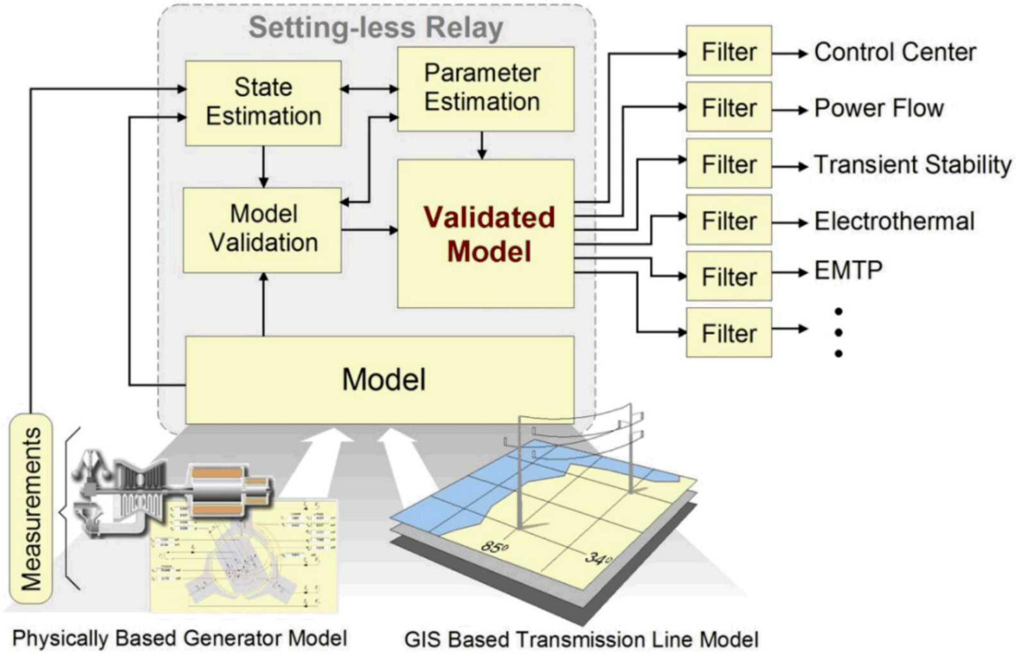


Settingless Protection

- Dynamic state estimator fits the streaming data to the dynamic model, and protection logic is based on DSE results

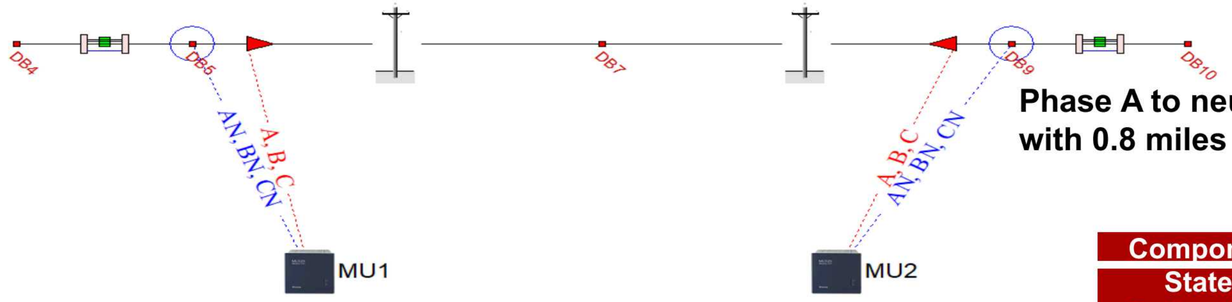






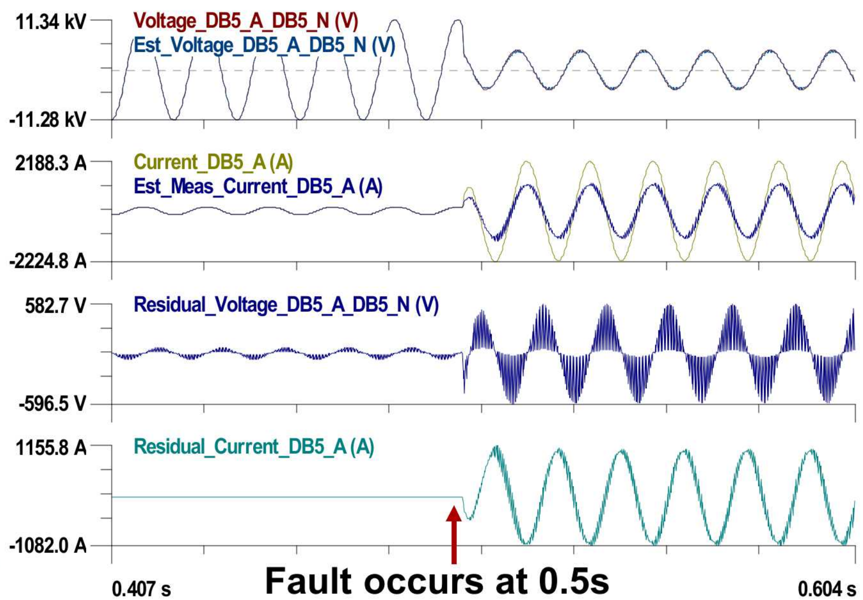
Settingless Protection Simulation

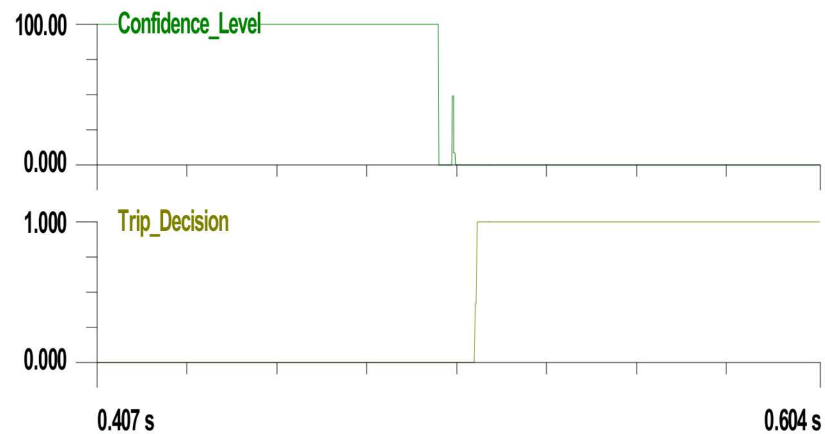
- Feeder model for NE U.S. utility run in real-time with varying load and PV
- Virtual PMU measurements are transmitted to PMU merging unit using C37.118 UDP communication. Merging unit communicated real-time to dynamic state estimator for settingless protection



Phase A to neutral fault at DL4 with 0.8 miles away from bus DB9

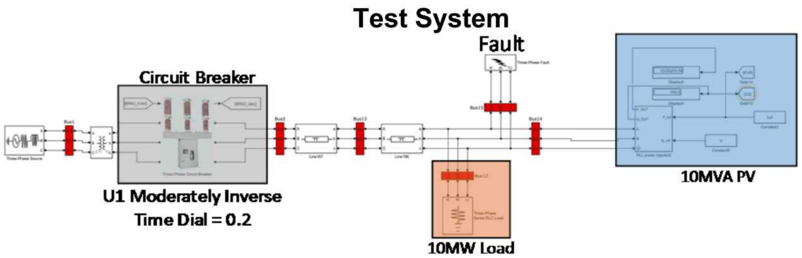
Component	Update Rate
State Estimation	Up to 60 Hz update rates
Feeder Protection	Estimation Based Protection (EBP) operating on two sampled values at a time. Time response depends on sampling rate; typically, < 1 ms.

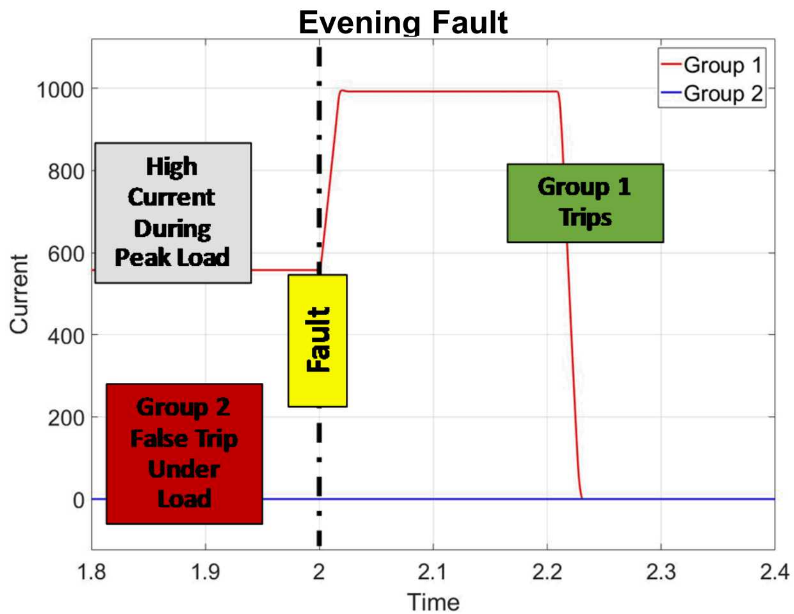


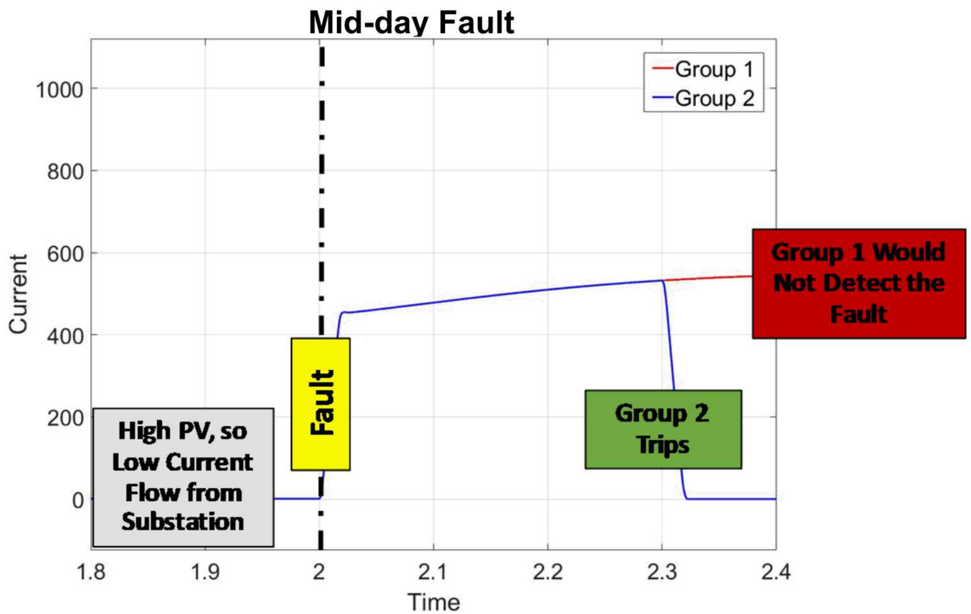


Adaptive Protection

- Protection settings may have to be modified when conditions change (reconfigurations, load transfers, islanding of a microgrid, etc.)
- As an example, high penetrations of PV may require different protection settings
  - Relay Setting Group 1: 51P Pick-up = 420 A
  - Relay Setting Group 2: 51P Pick-up = 150 A





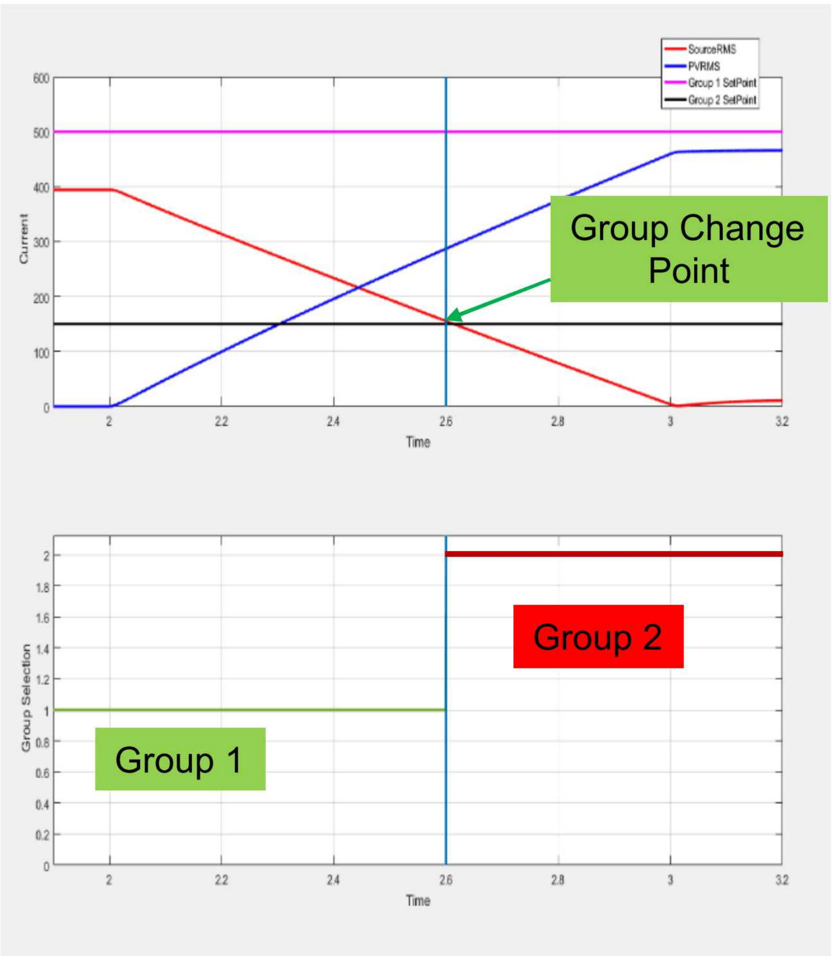


- Setting Group 1 works well with little solar production
- Setting Group 2 cannot work in the evening, trips during peak load

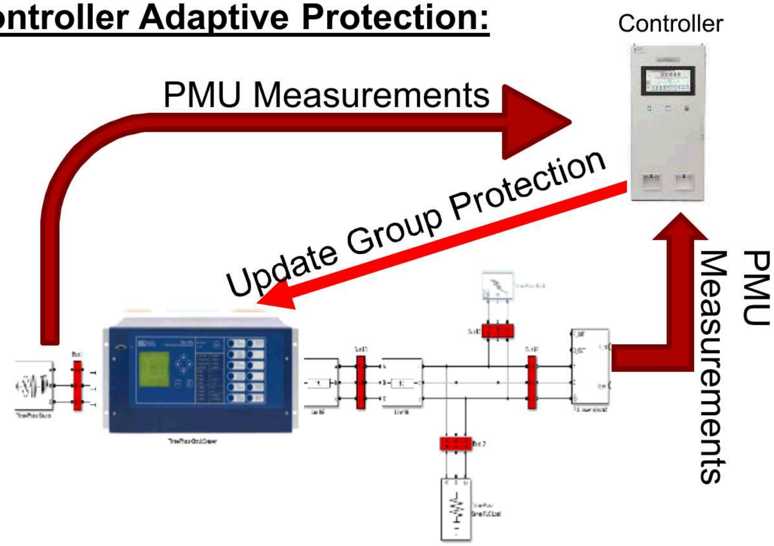
- Setting Group 2 works well with high solar production
- Setting Group 1 cannot work with high solar because of the reduced fault current seen at the substation

Adaptive Protection Demonstration

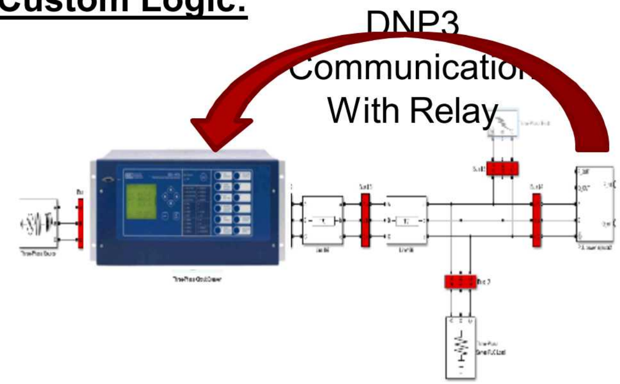
Demonstrated in HIL, communication with relay to change setting groups



Controller Adaptive Protection:

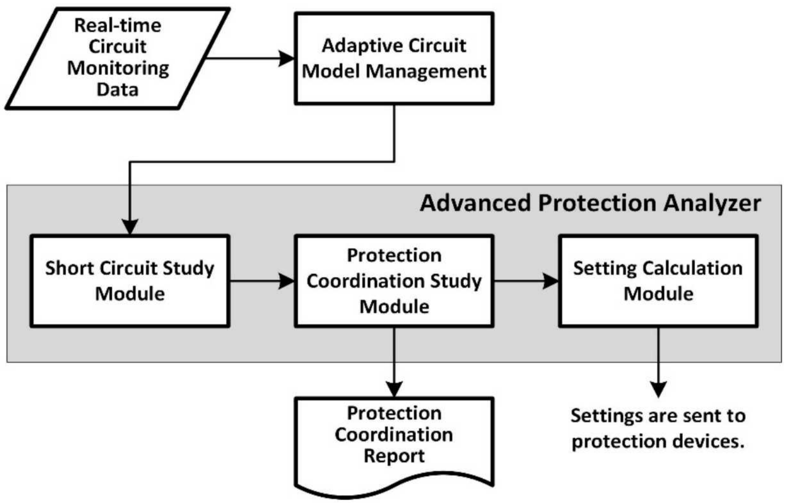


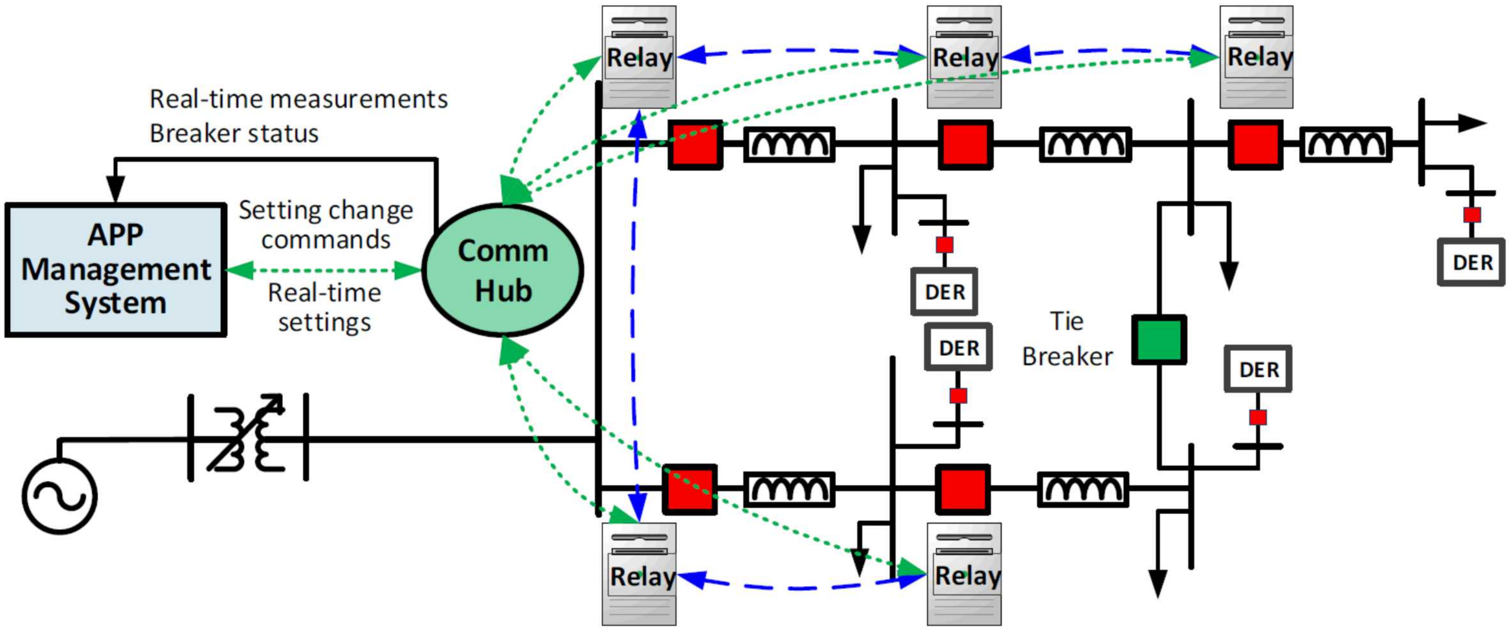
Relay Custom Logic:



Adaptive Protection

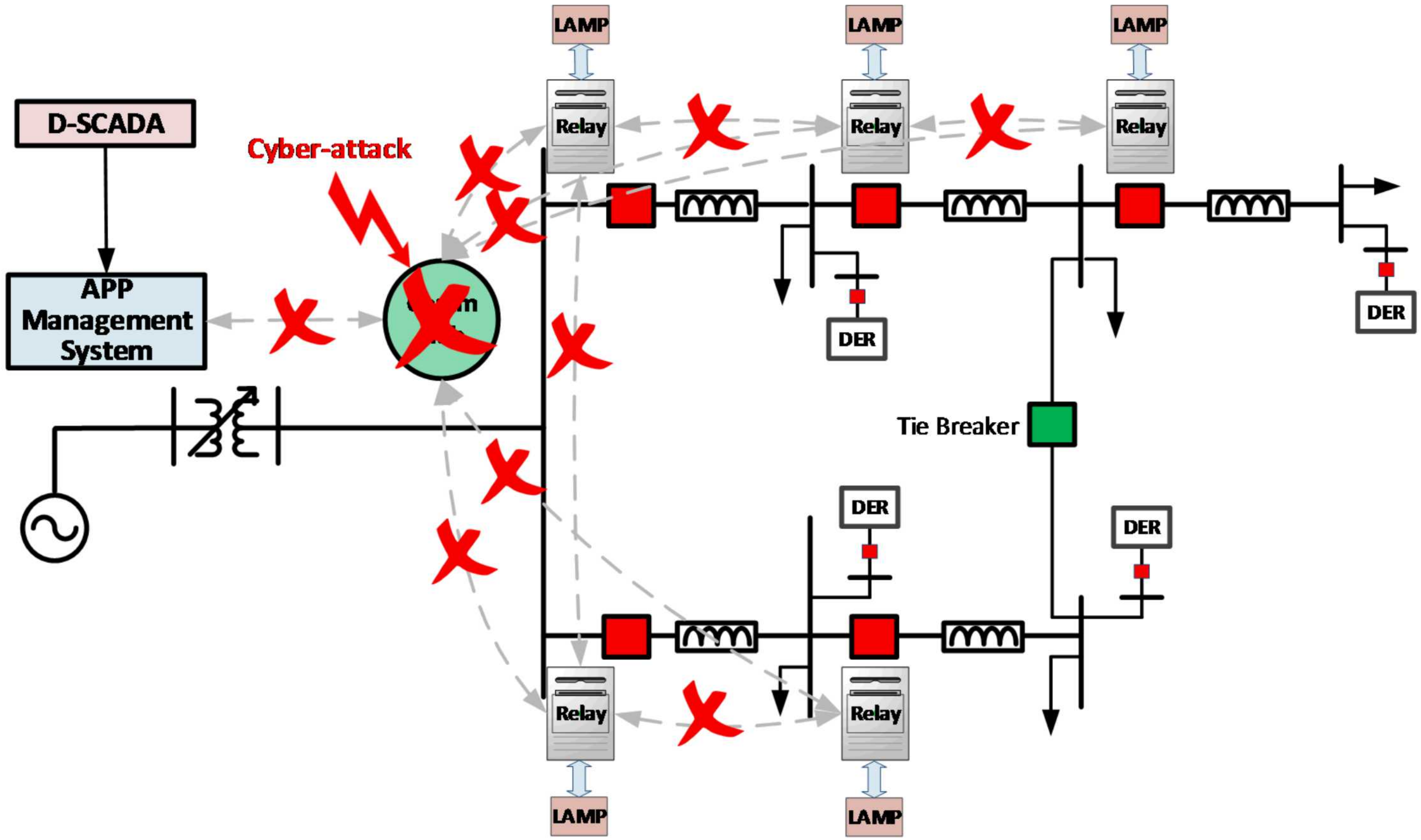
- Can be programmed ahead of time (logic-based adaptive protection)
- Or settings can be intelligently determined and selected in real-time to communicate





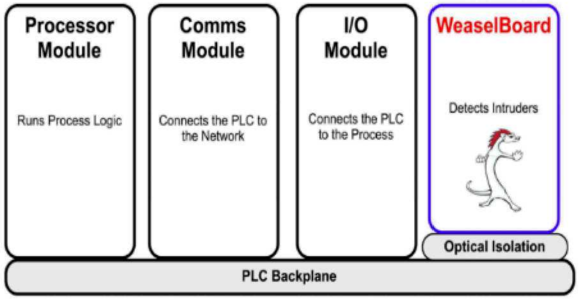
Communication-free Local Adaptive Modular Protection

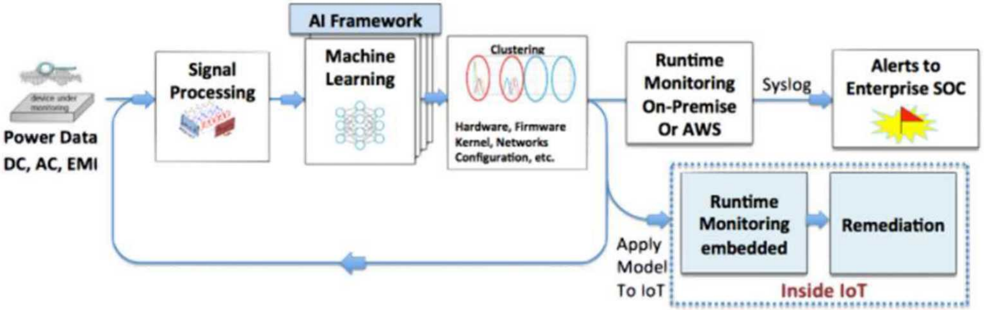
- Objective: To guarantee the reliable operation of protection system under extreme events when communication network is outaged.



Cyber Security for Protection

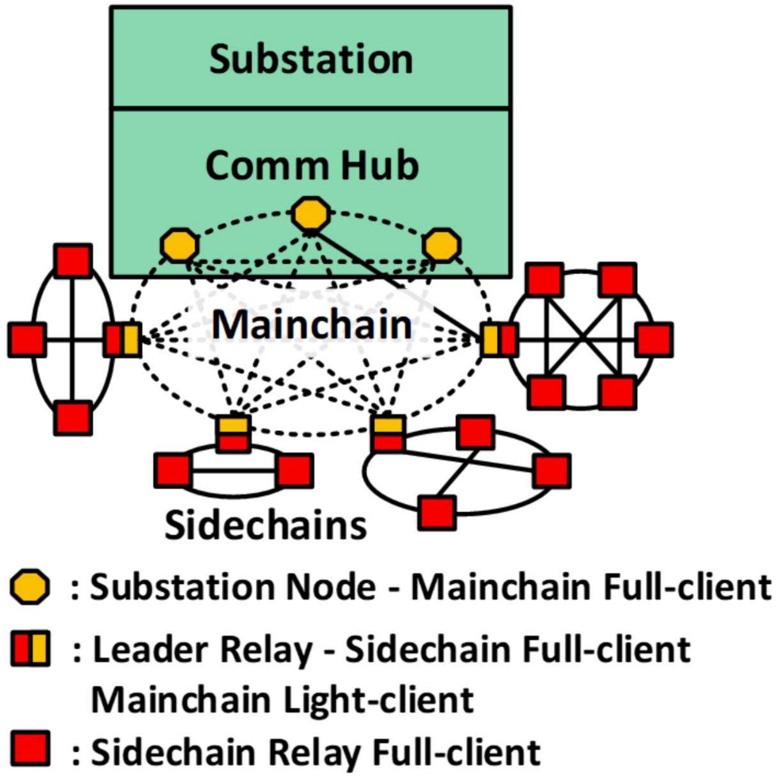
- Cybersecurity is a key challenge to making protection settings adaptive
- Cybersecurity of **power system protection** in general is very critical to the reliability of the bulk power system.
- Presently, the prevalent measures being incorporated include firewalls, intrusion detection systems (IDSs), and security gateway devices (SEL 3620)
- Improve cyber security posture of the protection with layered approach, pair device-level solutions with network defense such as intrusion detection systems (IDSs) and firewalls
- Working with SEL to detect cybersecurity vulnerabilities and improve security on their gateways





Blockchain-based Communication for Adaptive Protection

- Blockchains relies on a purely distributed, peer-to-peer (P2P) networking topology
- Advantages:
  - The P2P architecture improves the scalability of the adaptive protection system
  - The decentralized nature removes the single point of failure or contamination, enabling direct secure communication among IEDs
  - The consensus mechanism prohibits any alterations on the blockchain ledger resulting to data integrity and authenticity



Microgrid Fault Location

Faults in microgrids exhibit different characteristics –

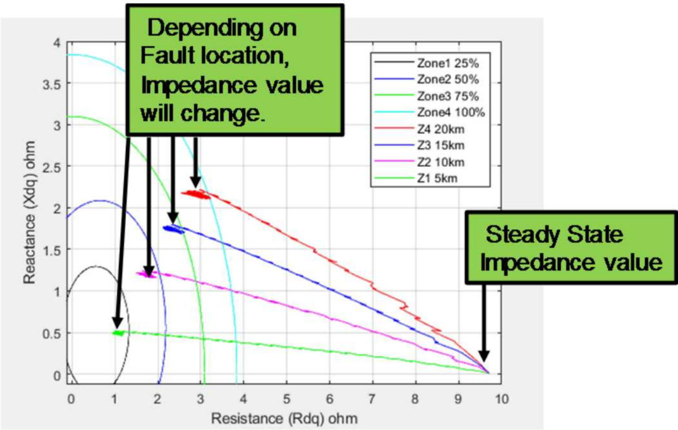
Making traditional protection schemes not suitable

- Shorter electrical distances due to smaller scale systems, especially compared to vast, sprawling transmission systems.
- Ability to dramatically change configuration (e.g., islanded mode vs. grid-connected mode)
- Inclusion of DERs that can impact system significantly with their variation/output

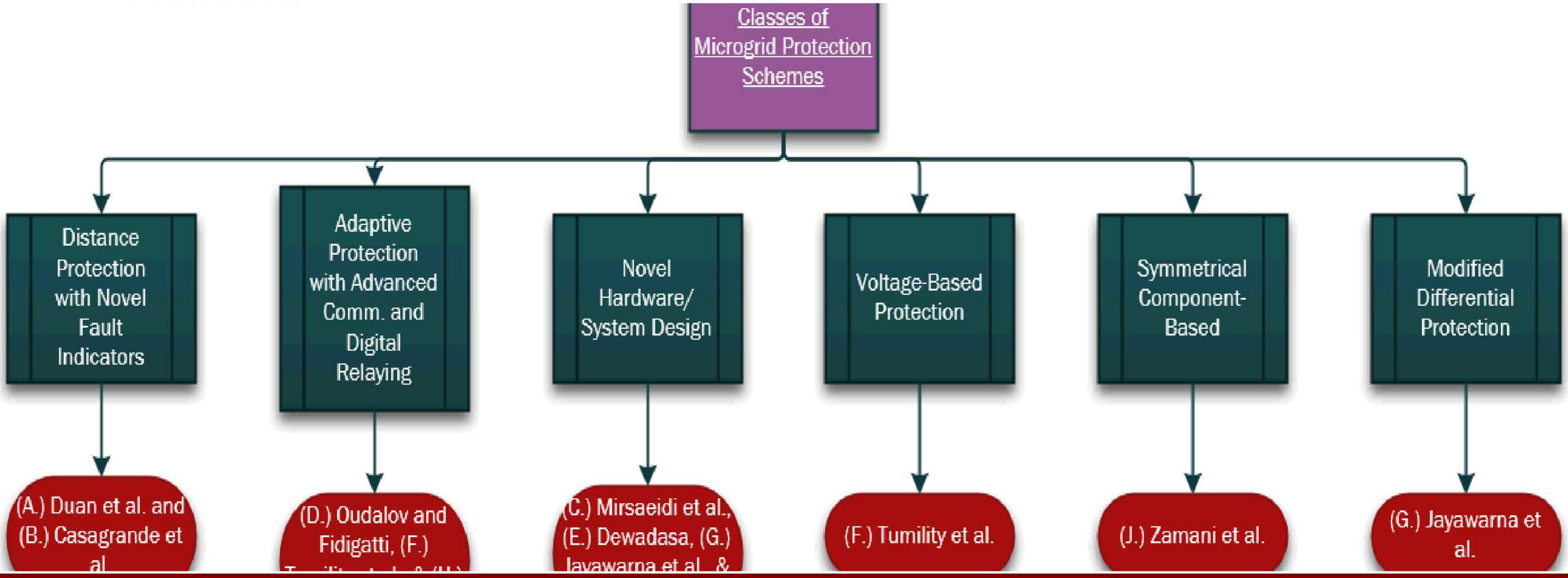
We are testing the impact of high DER penetration on existing utility fault location methods and developing new communication-assisted fault location algorithms

Fault Detection and Location Algorithms

- We are testing the impact of high DER penetration on existing utility fault location methods and developing new communication-assisted fault location algorithms



- Sandia report in collaboration with ORNL: “Microgrid Fault Location: Challenges and Solutions”

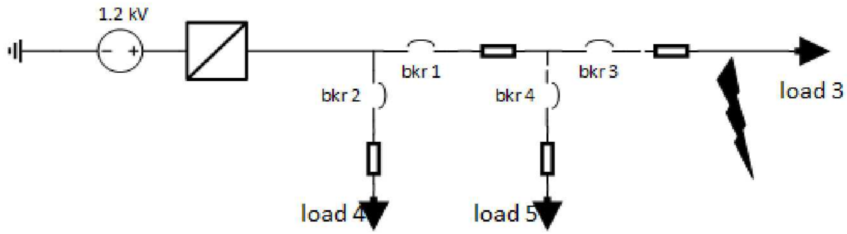


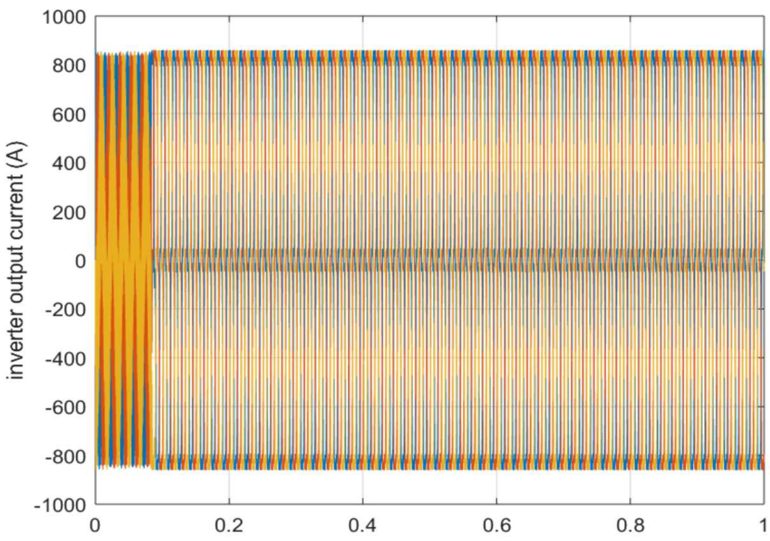
Fault Location by Increasing Fault Current

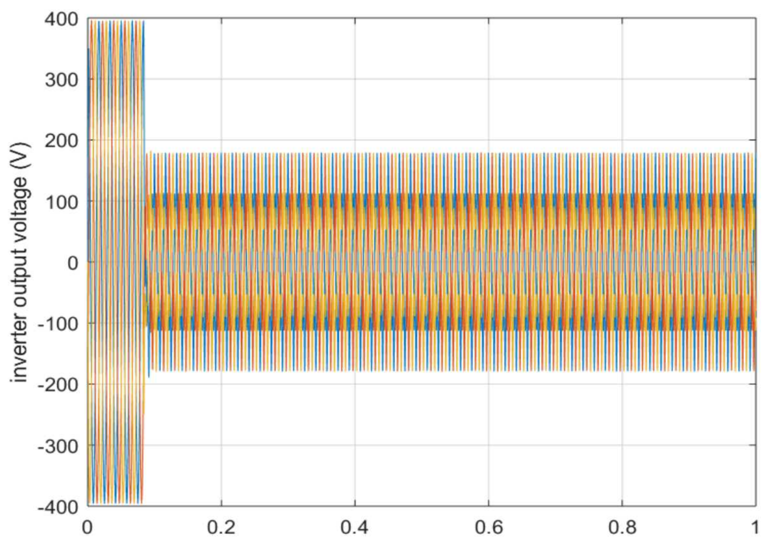
- Problem: Purely inverter-sourced systems have low fault current due to the inverter controls. Coordinating overcurrent protection is difficult without available fault current.
- Instead of changing protective equipment, it is possible to add energy storage units in parallel for fault current
  - Flywheel/Synchronous condenser
  - Supercapacitor
- Both the supercapacitor and the flywheel (synchronous condenser) are sized to approximately deliver a constant 1 MW for 0.5s.
  - $J \geq -\frac{2P_{energize}\Delta t}{(\alpha^2-1)\omega_{nom}^2}$ for the flywheel
  - $C \geq -\frac{2P_{energize}\Delta t}{(\alpha^2-1)V_{nom}^2}$
  - Flywheel: $\mathrm{J} = 0.8443\ \mathrm{kg\ m^2 @ 12000RPM}\ (21.2318\ \mathrm{kg\ m^2}$ @ 60 Hz)
  - Supercapacitor: $C = 0.2315\mathrm{F@2.4kV}$

Fault Location by Increasing Fault Current

- Main inverter source in microgrid is limited during faults, so designated breaker/backups cannot detect and clear the fault
- Bus voltage dips drastically and waveform becomes distorted during sustained fault

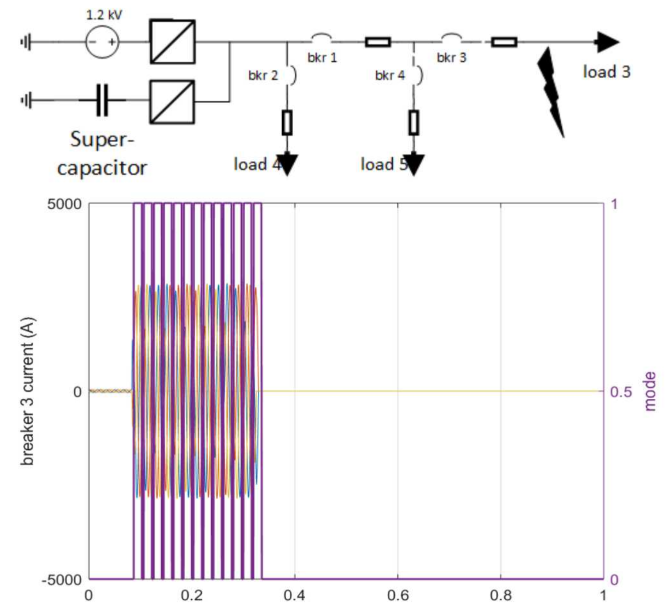


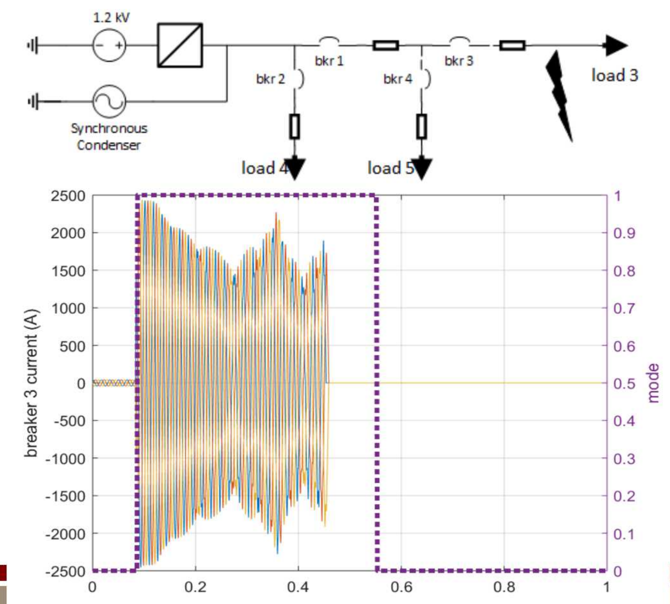




Fault Location by Increasing Fault Current

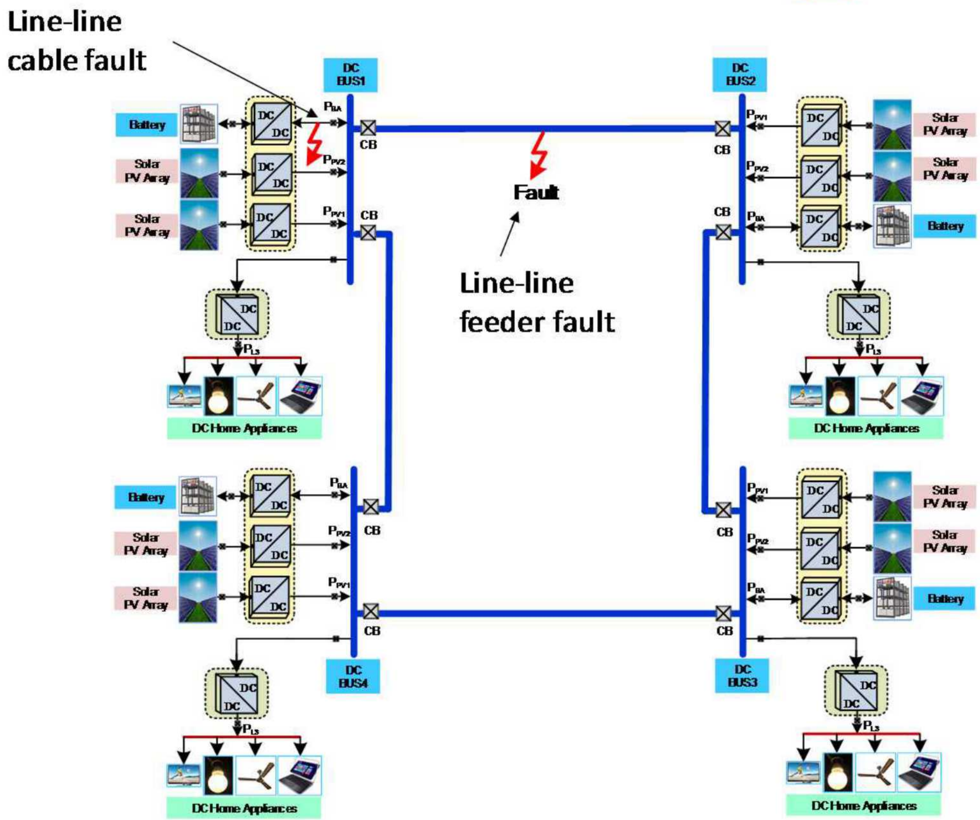
- Supercapacitor
  - Pros
    - Designated primary breaker clears fault successfully
    - Voltage waveform maintained with minimal distortion during fault
  - Cons
    - Additional auxiliary inverter for storage will exceed cost of original source inverter due to drastically increased current requirements
- Synchronous Condenser
  - Pros
    - Designated primary breaker clears fault successfully
    - No additional power electronics interface required
  - Cons
    - Voltage waveform highly distorted during fault
    - Maintenance cost for synchronous condenser

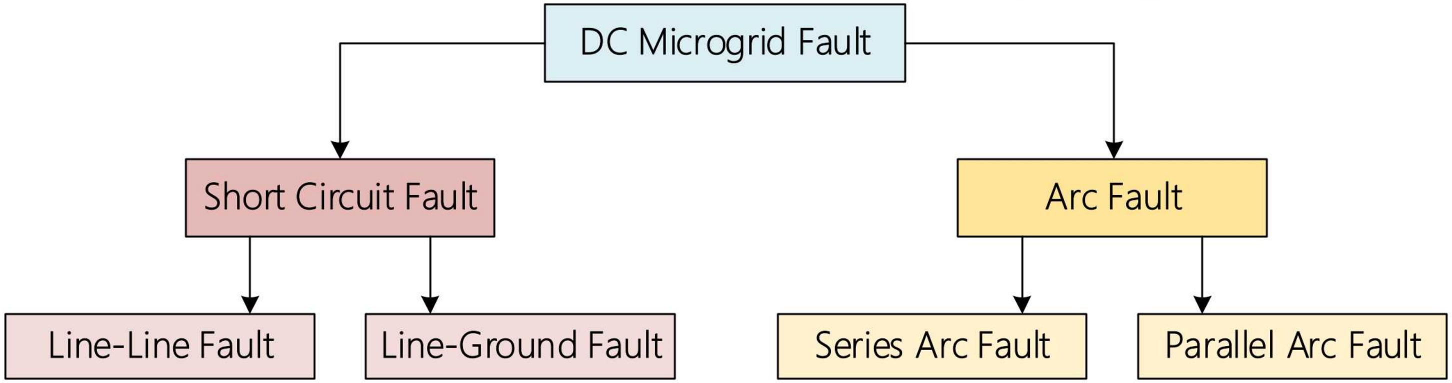




DC Microgrid Protection

Investigating protection system design for DC microgrids to address protection-related challenges of integrating DC microgrids to distribution systems





DC Microgrid Protection

Challenges for DC Protection

- Arcing
- No zero crossing
- Ground fault challenges - “neutral shift” due to common mode voltage

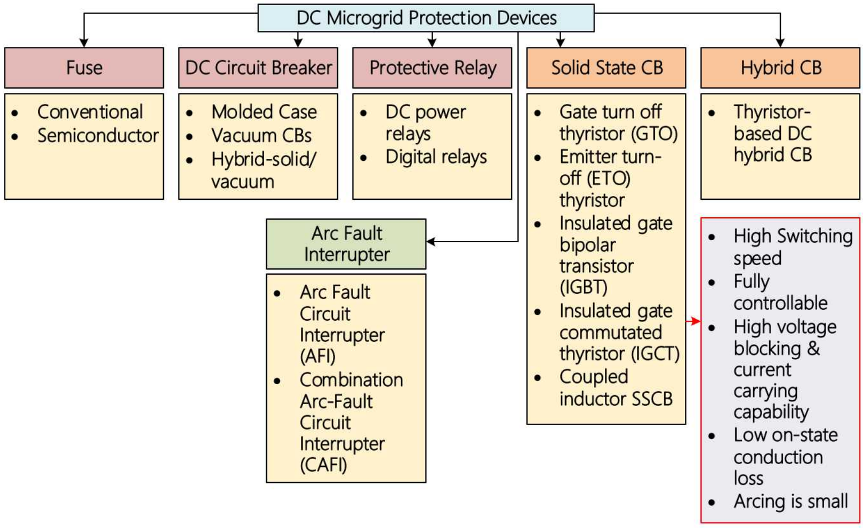
Enabled by recent advancements in wide bandgap solid state circuit breakers

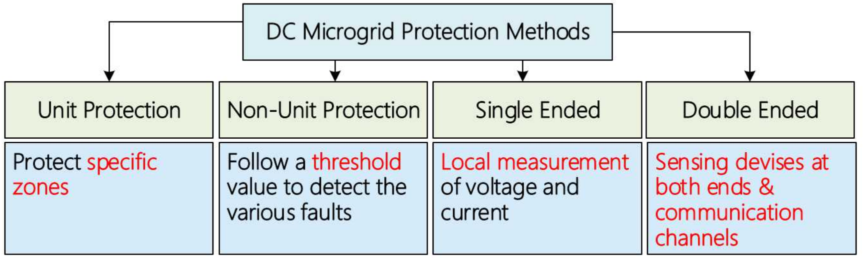
- High speed operation
- High voltage blocking capability
- High current carrying capability
- Low on-state conduction loss

Gaps & Research Needs

- Guidelines and standards
- Fast fault detection schemes
- Protection coordination and restoration

Published Sandia Report: “DC Microgrid Protection: Review and Challenges”



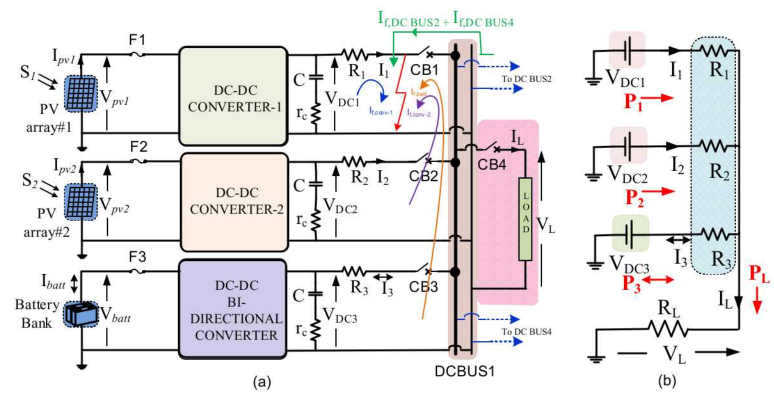


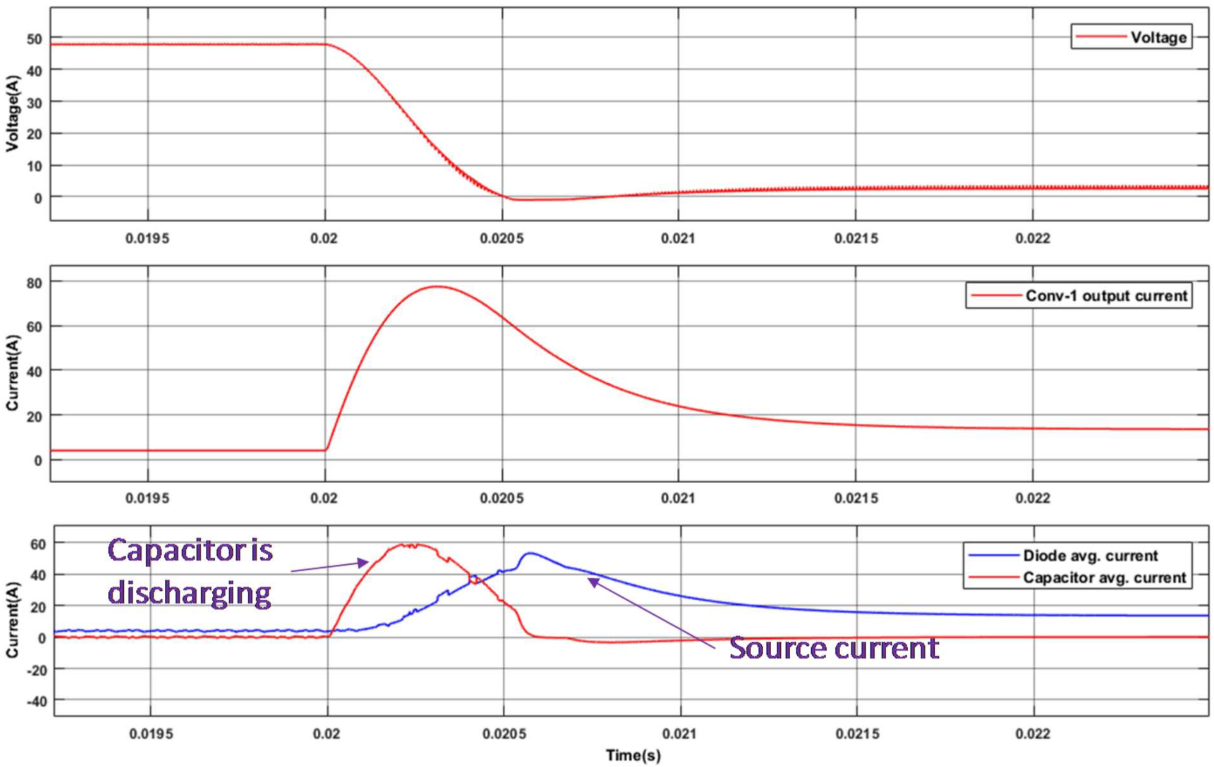
DC Microgrid Fault Detection Schemes

- Magnitude of voltage
- Magnitude of current
- Impedance estimation method
- Power electronic de-energization
- Power probe unit method
- Virtual Impedance method
- Differential current-based fault detection
- Transient-based fault protection
- Voltage derivative supervised current derivative protection
- Handshaking method
- Advanced fault detection techniques for PV arc, ground, and Line-Line faults

Simulating DC Microgrids and Faults

- Multiple types of DC generation, storage, and loads
- DC/DC converter models, controls, and power sharing

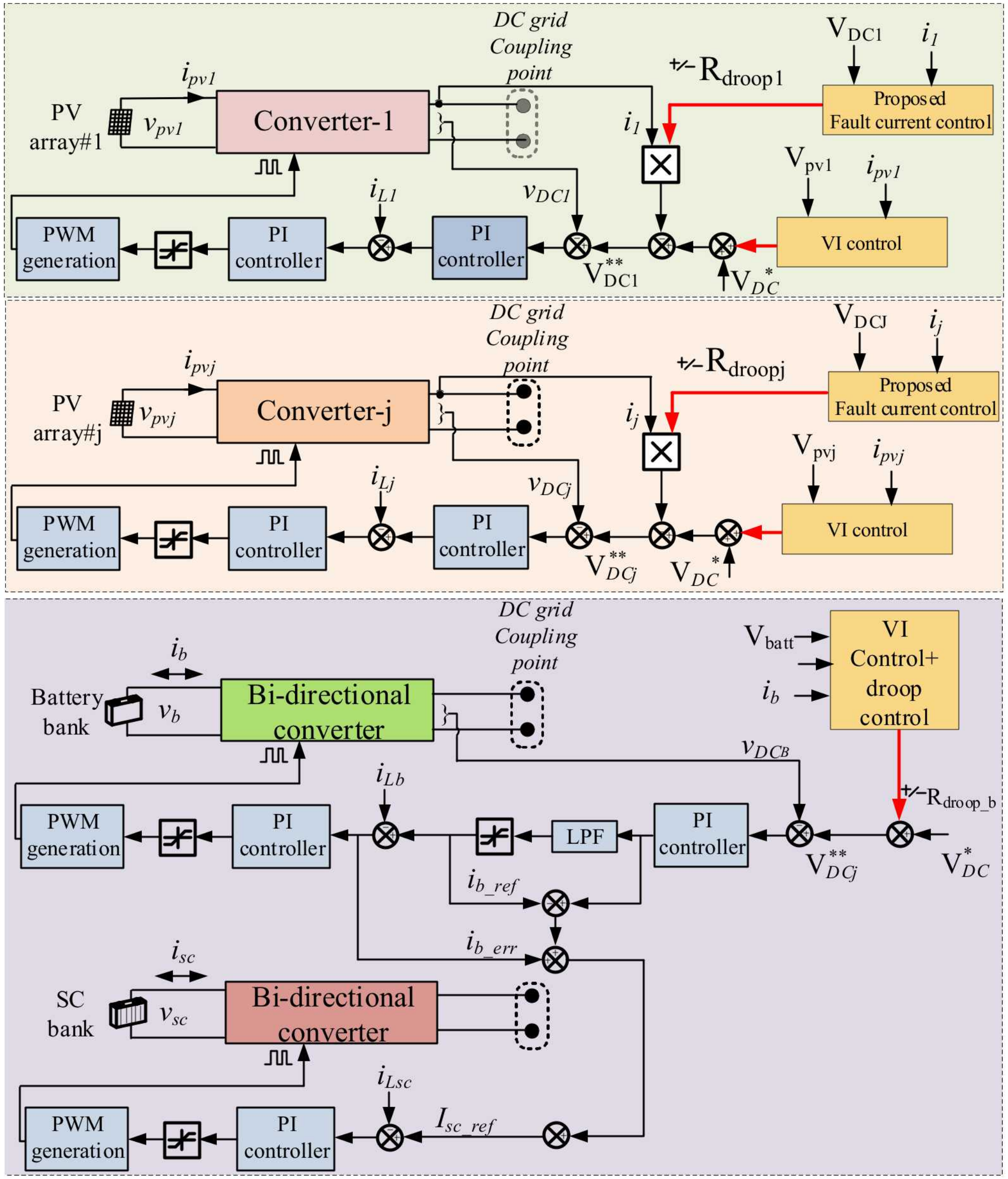




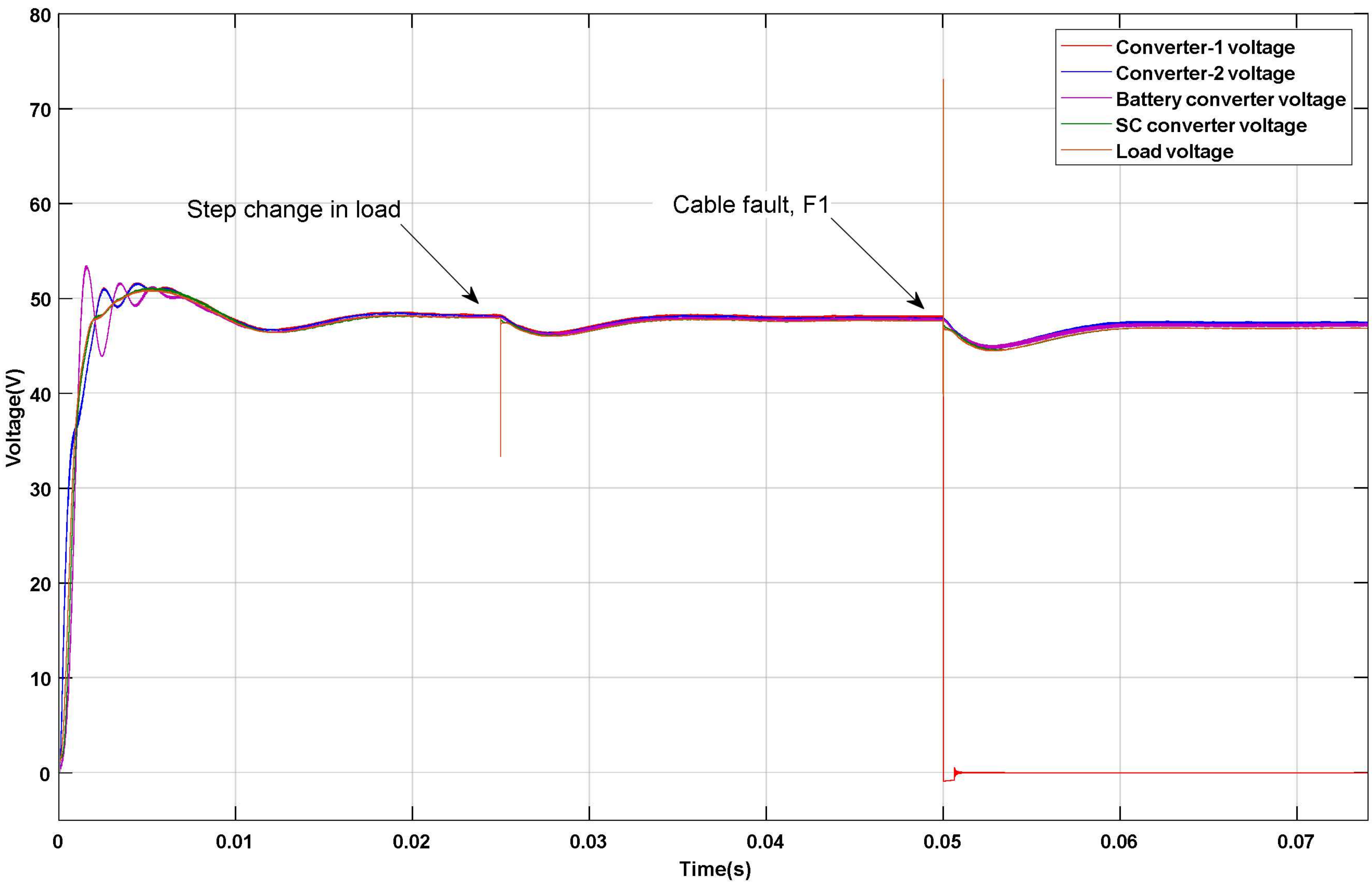
Fault Current Simulation of DC Microgrid

DC Microgrid Protection

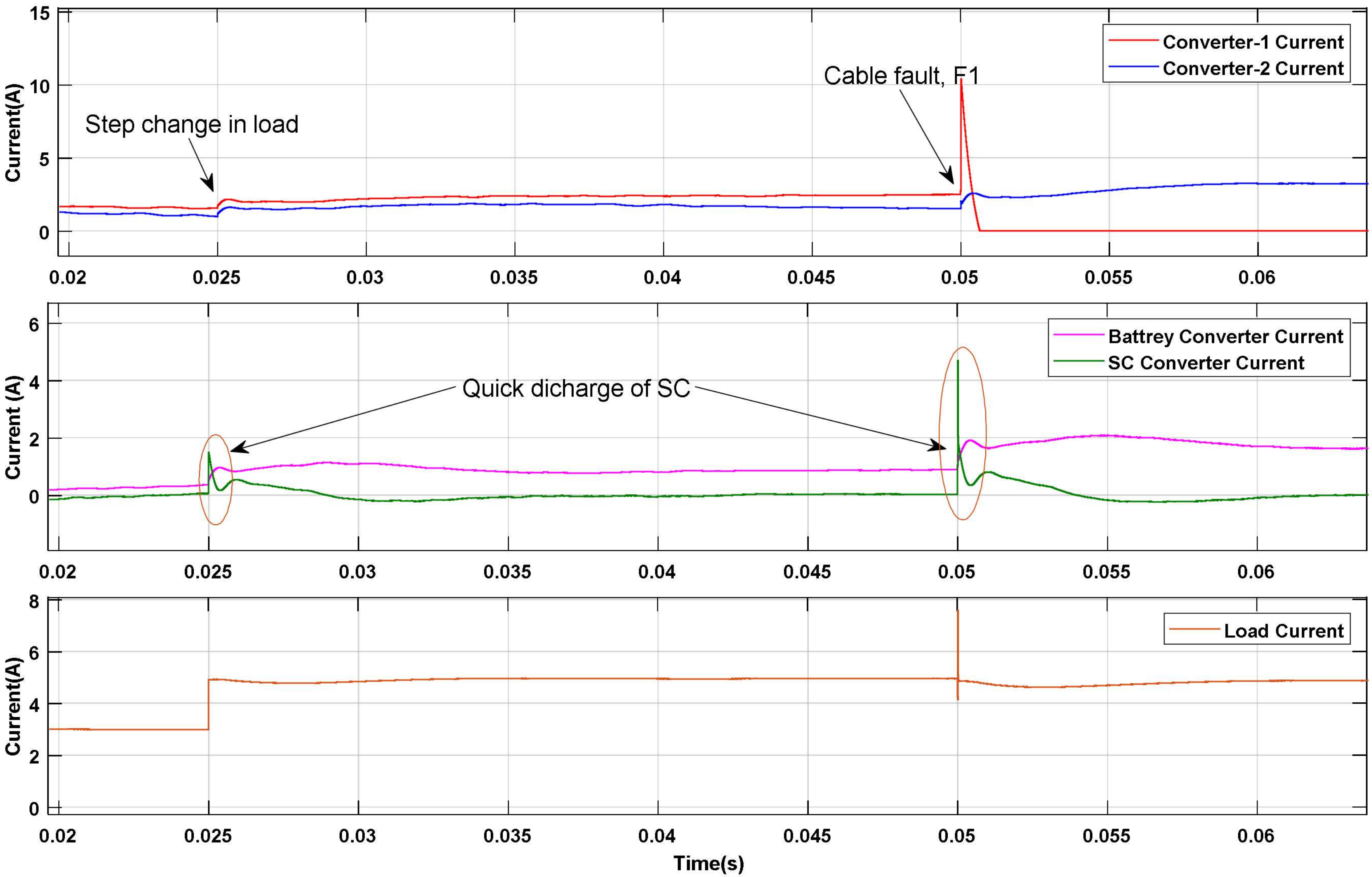
- Virtual inertia + droop algorithm to enhance the inertia of DC microgrid and maintain the DC bus voltage during transients and faults
- Super capacitor also used to stabilize the DC bus voltage during transients and compare the performance
- Improved energy management using hybrid energy storage systems



Load change at 0.025s and faults F_1 at 0.05s



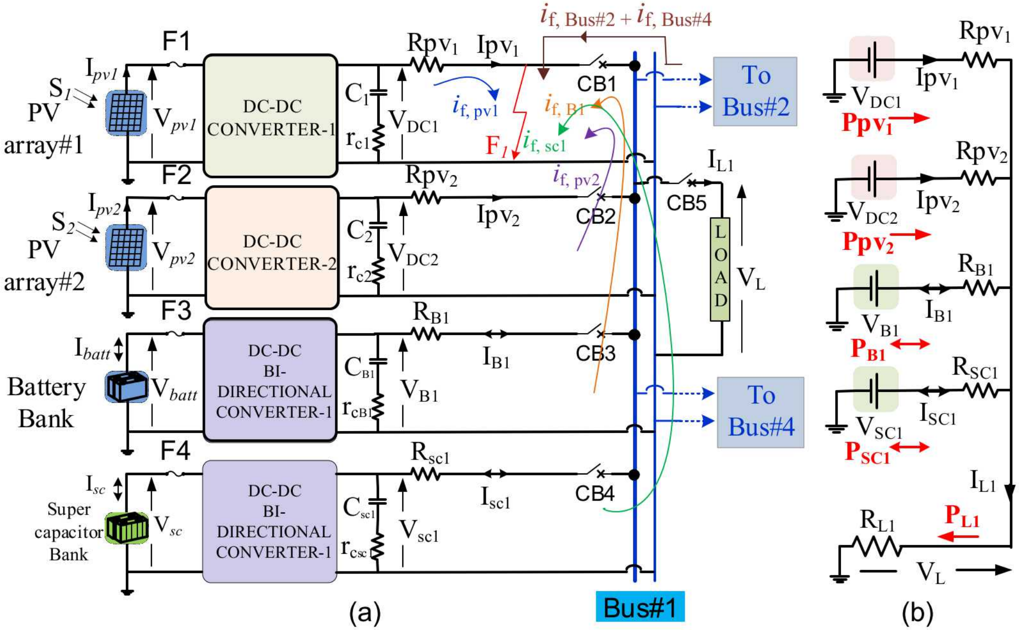
Load change at 0.025s and faults F_1 at 0.05s



New DC Microgrid Protection

Developing new converter controls for better DC microgrid protection

- Better control over converters output currents / input currents and the voltage during fault.
- Rate of change of converter fault current can be controlled
- Virtual inertia helps to smoothen the waveform during transients and faults.
- With di/dt algorithm, the converter-1 fault is detected very quickly



Project Significance

Innovative

- Developing new modeling and new microgrid protection schemes that will yield insights into local and wide area relaying philosophy with complimentary hybrid protection systems that are more resilient

High Impact

- Involvement in the IEEE Power System Relaying Committee (PSRC) to provide expertise and impact to standards and guides for microgrid protection
  - C30 Microgrid Protection has developed a “Microgrid Protection Systems” guide
  - C38 working group developing microgrid standards under 2030.12
- DOE Microgrid Protection Roadmap:
  - S. S. Venkata, M. J. Reno, W. Bower, S. Manson, J. Reilly and G. W. Sey Jr. “Microgrid Protection: Advancing the State of the Art,” Sandia National Laboratories, SAND2019-3167, 2019.
- Participating in DOE/WAPA Cybersecurity for Protection Relays Meetings

QUESTIONS?

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