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Advanced Protection for Inverter-Based Systems

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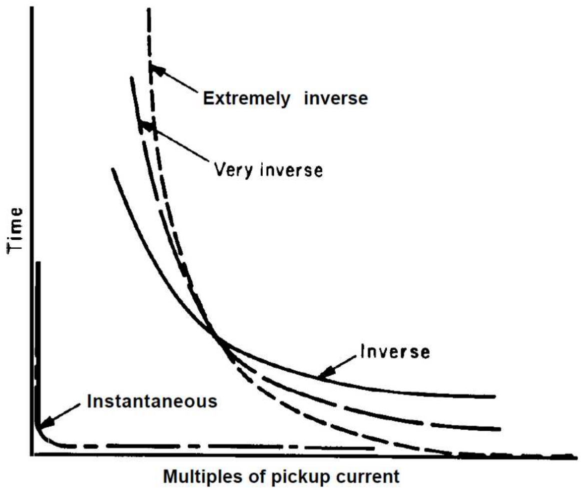
Power System Protection

- The protection system and equipment is designed to maintain safe operation of the grid and reliable service
  - Must rapidly and automatically disconnect the faulty sections of the power network
  - Minimize the disconnection of customers
- Conventional power system protection design may not work for high penetrations of inverter-based PV generation
- 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*

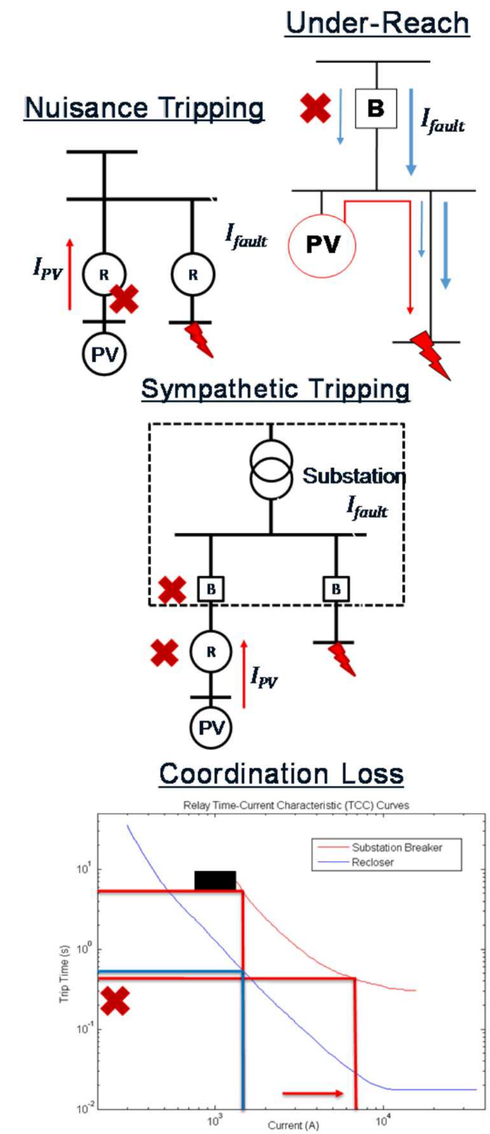


Inverter-Based DG Impacts on Protection

- The legacy protection was not designed for the presence of inverter-based DG

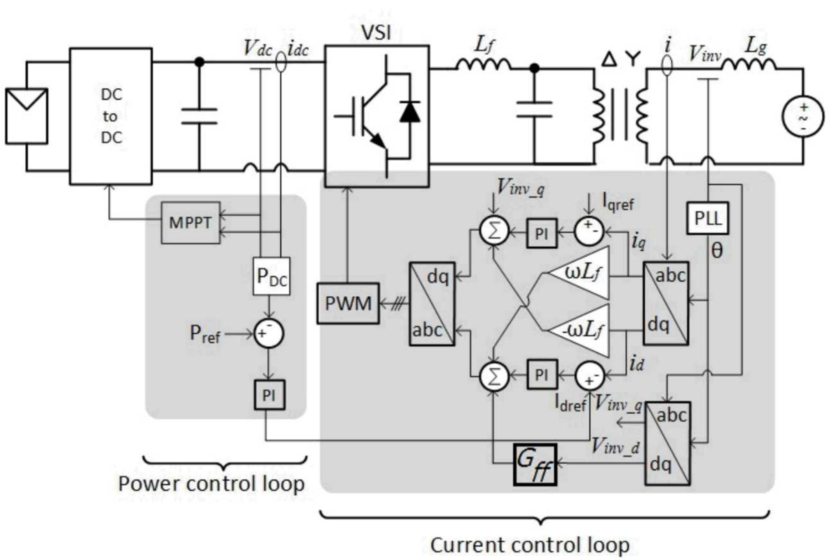
Common Protection Issues and Impacts:

- ✓ 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



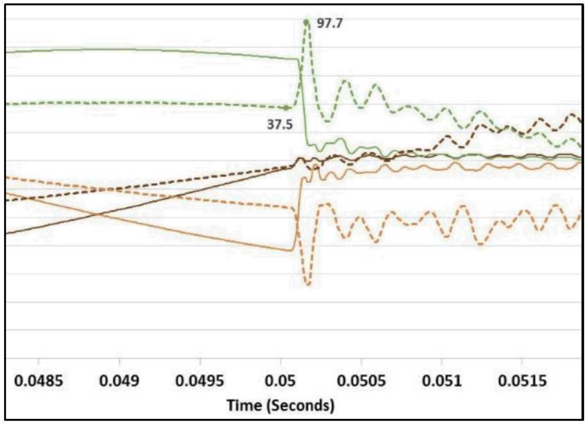
100% Inverter-Based System Protection Challenges

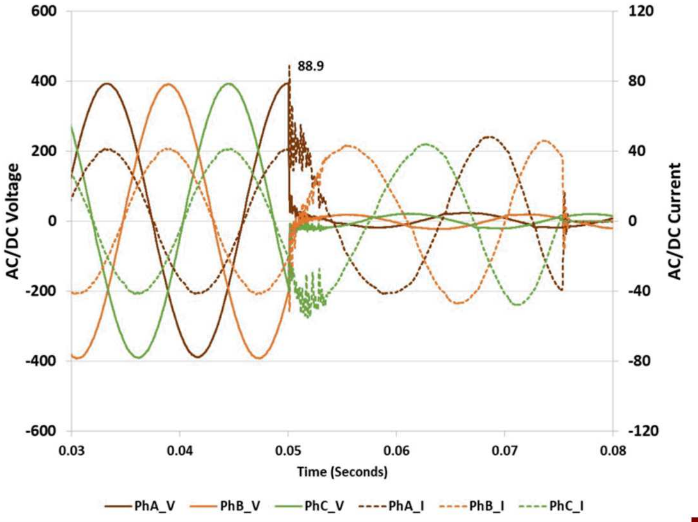
- 100% inverter-based systems present a new set of challenges for protection
- Inverters do not provide significant current during faults
  - Overcurrent protection schemes might not detect the fault
  - Fault currents can look similar to motor starts or inrush
  - With low fault currents, the fault currents are more sensitive to generation dispatch, complicating coordination



Inverter Short-Circuit Models

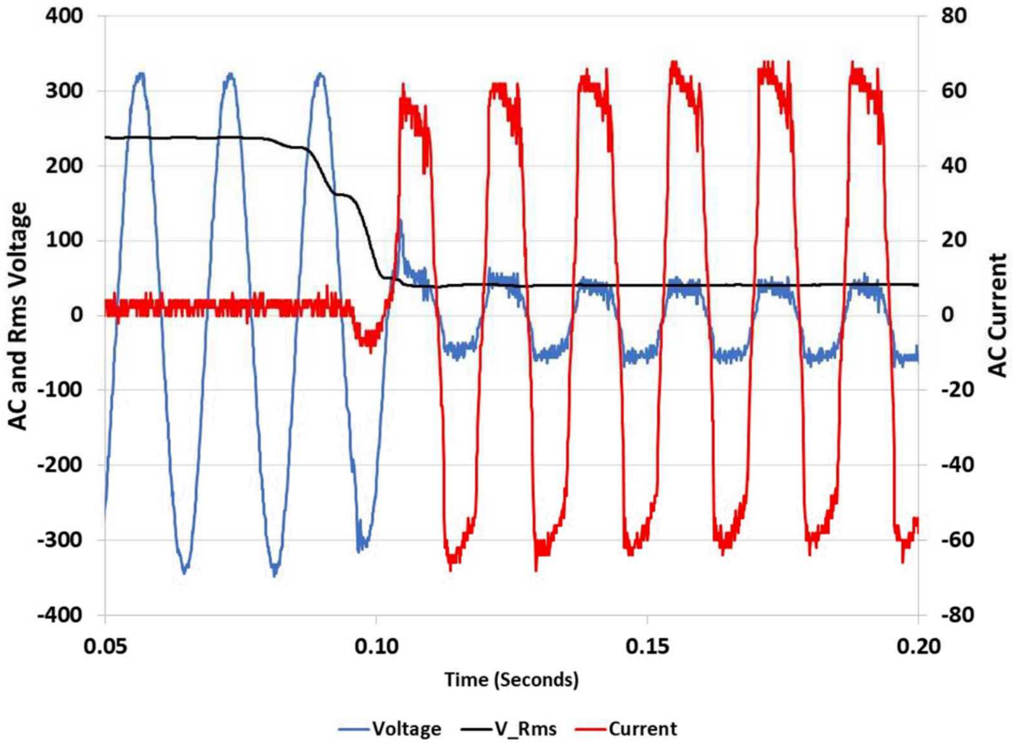
- It is important to have accurate models of inverters for dynamic studies and protection coordination
  - Initial spike (~0.1ms) depends on filter cap, system impedance, and pre-fault condition
  - Transients during control actions, lasting 2-8ms
  - Steady-state fault current based on the current limiter
- 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.

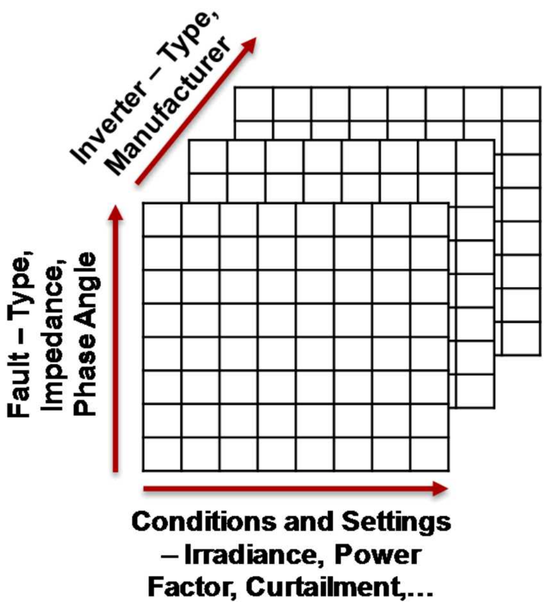




Inverter Fault Characterization

- 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

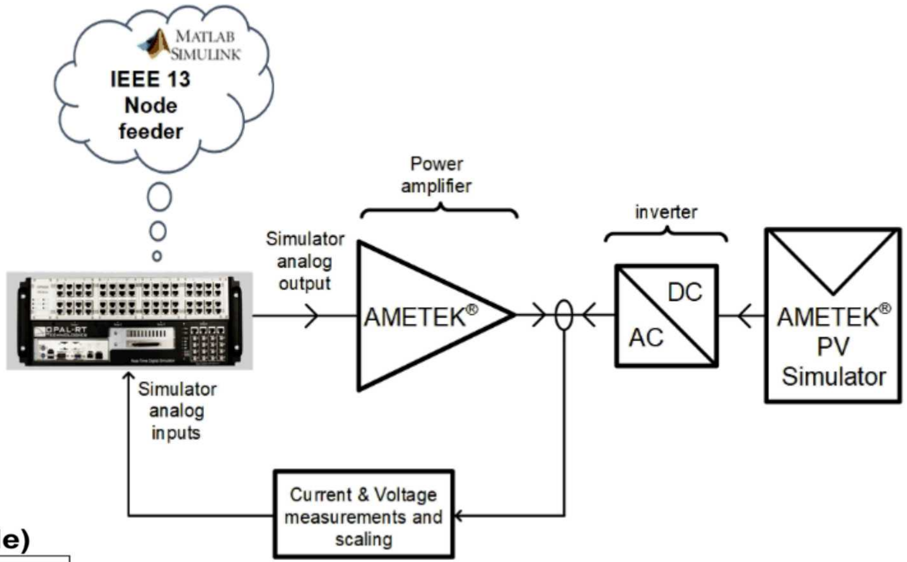


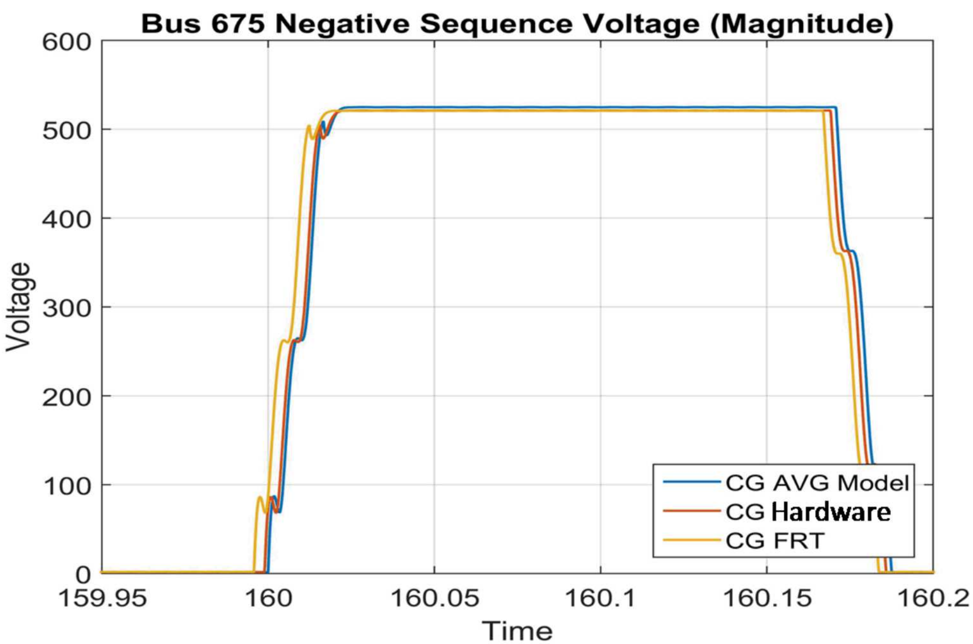


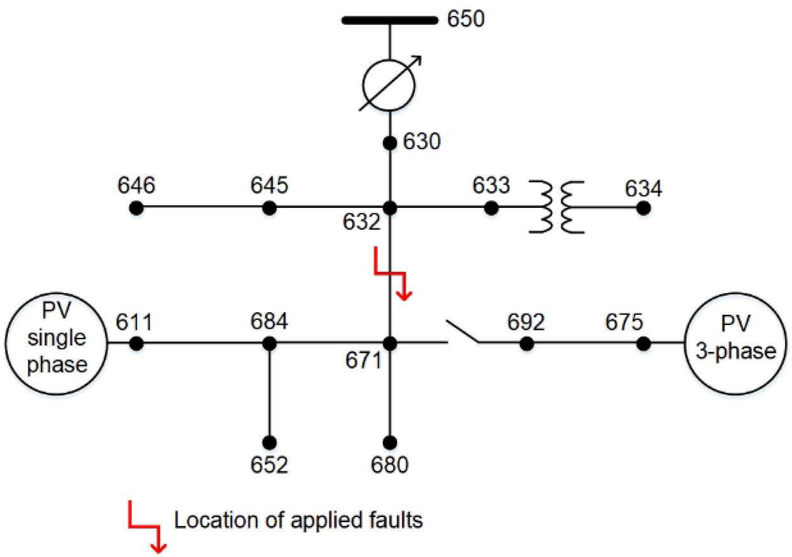
Hardware results from large test matrix of different inverters, faults, and settings

Testing Inverter Models Using HIL

- Validating inverter models to hardware results
- Opal-RT power HIL testing using same feeder and faults, testing models compared to hardware inverter response







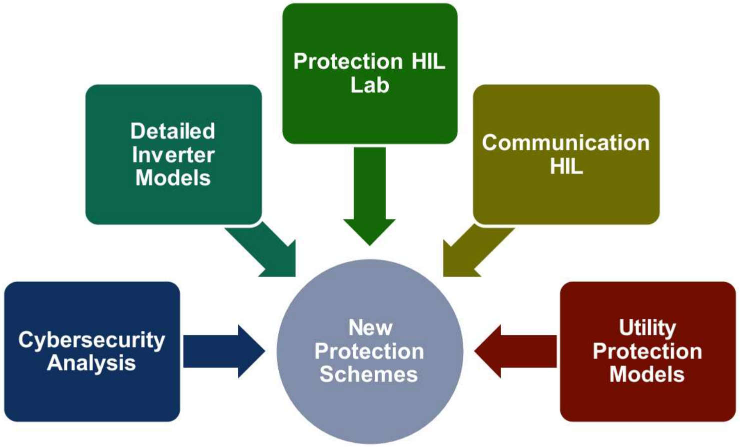
Inverter Protection Challenges

Other Protection Challenges Include:

1. Inverters do not provide zero sequence or negative sequence fault currents (depending on the controls)
2. 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?
3. 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

Inverter-Based System Protection

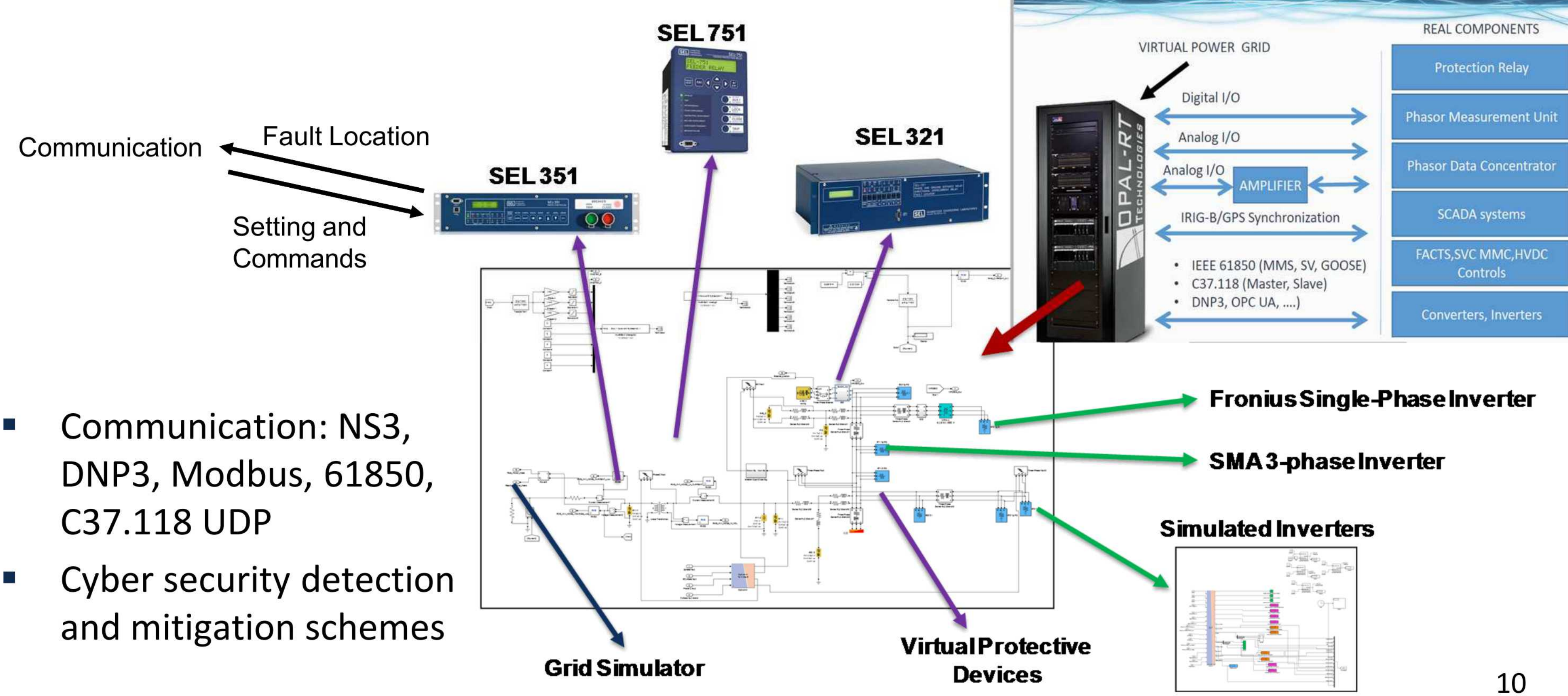
- For 100% inverter-based system protection:
  - Accurate short-circuit current models are needed
  - New protection schemes are required to detect faults
- Sandia is developing protection solutions for inverter-based systems:
  - Holistic approach to address the challenges of distribution system and microgrid protection under high penetrations of inverter-based DER
  - Using fast communication and time-synchronized measurements from multiple sensors for communication-based or wide-area protection
  - Develop fault location algorithms for microgrids and distribution systems with high DER penetration and tested algorithms in simulations and HIL



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

Protection PHIL Lab at Sandia

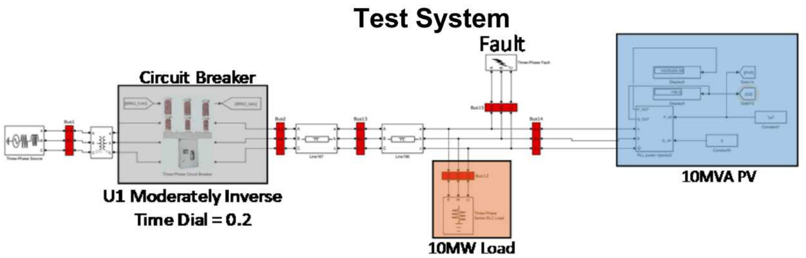
- Power hardware – inverters, PV simulator, grid-forming inverters, energy storage, controllable loads, Home/building/network EMS
- Demonstrated adaptive protection
- Grid-connected, off-grid and microgrid, and networked microgrid reconfiguration

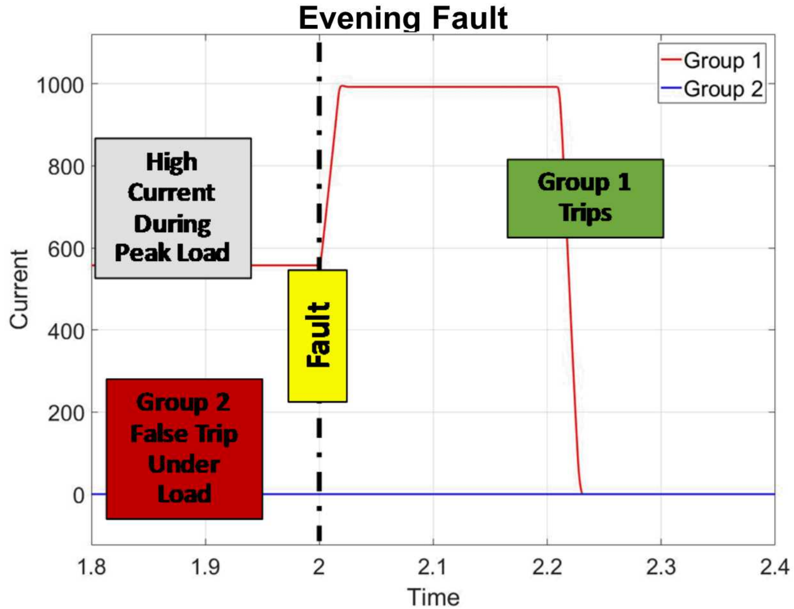


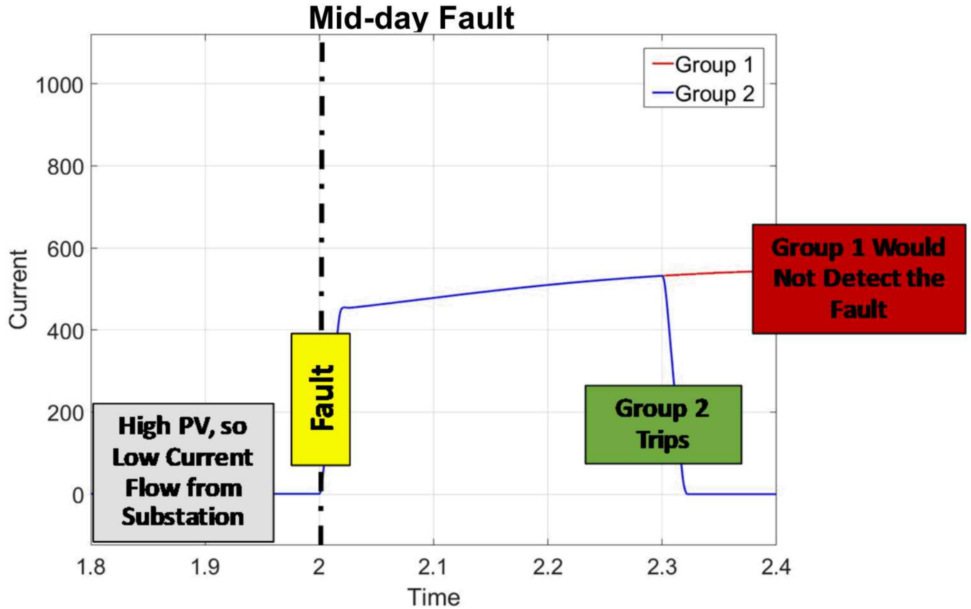
- Communication: NS3, DNP3, Modbus, 61850, C37.118 UDP
- Cyber security detection and mitigation schemes

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 = 800 A
  - Relay Setting Group 2: 51P Pick-up = 400 A





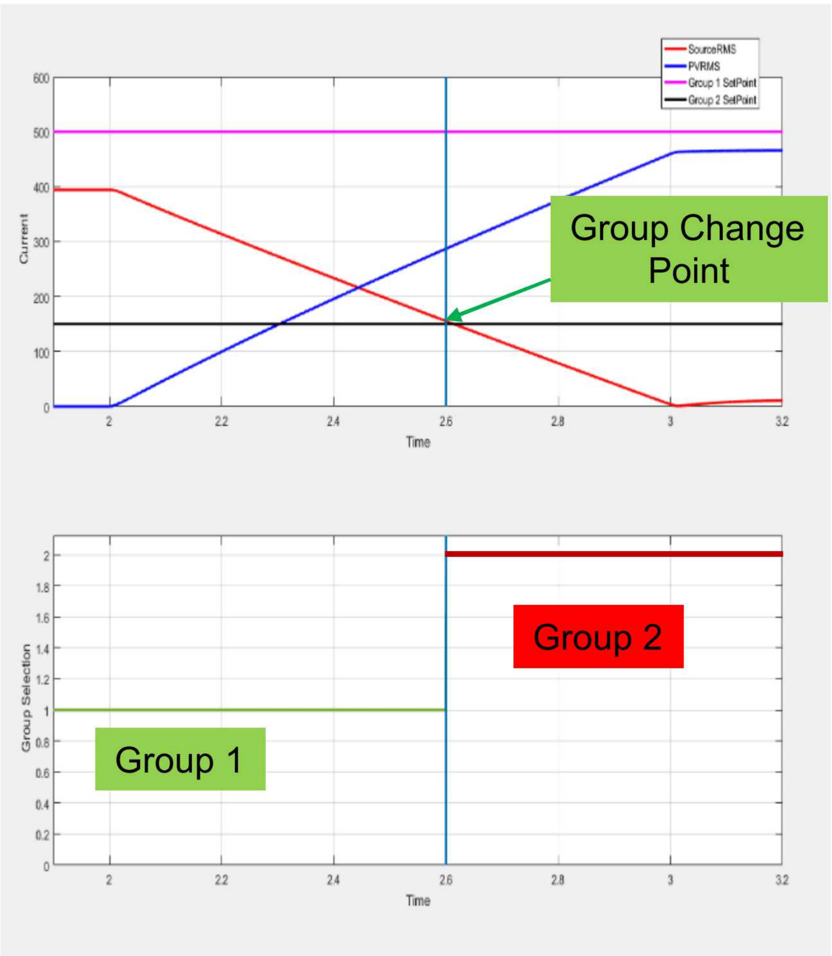


- Setting Group 1 works well with little solar production
- Setting Group 2 cannot work in the evening, trips during peak load

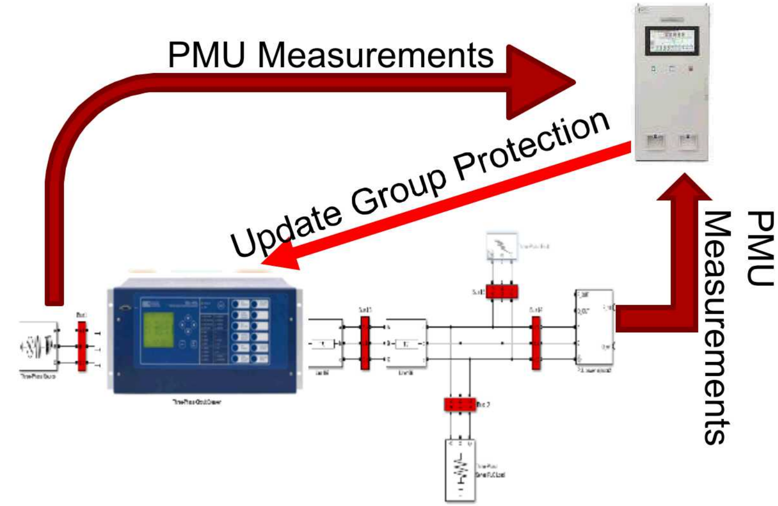
- Setting Group 2 works well with high solar production
- Setting Group 1 cannot work with high solar because of the reduced fault current seen at the substation

Adaptive Protection Demonstration

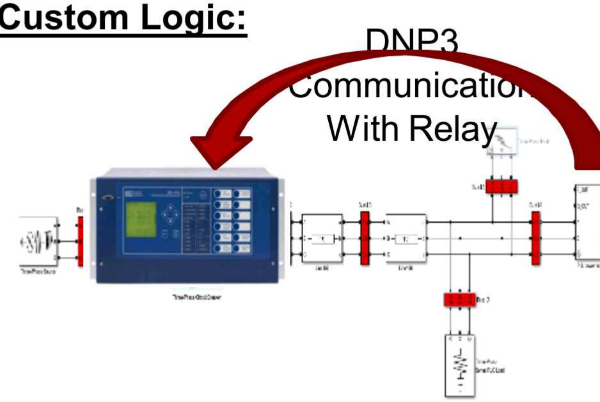
Demonstrated in HIL, communication with relay to change setting groups



Controller Adaptive Protection:

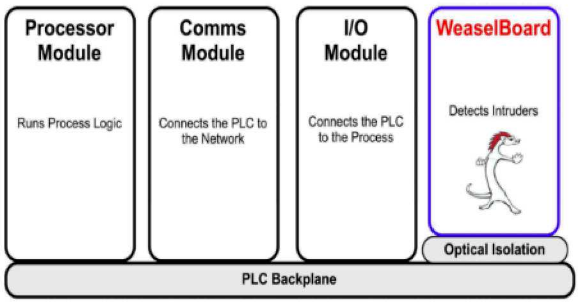


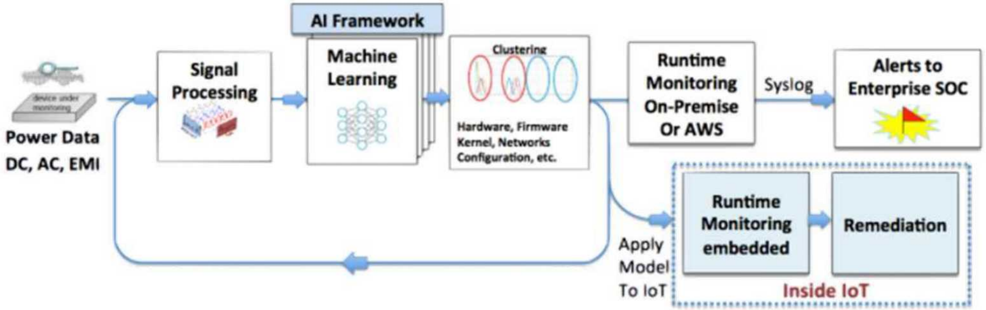
Relay Custom Logic:



Cyber Security for Protection

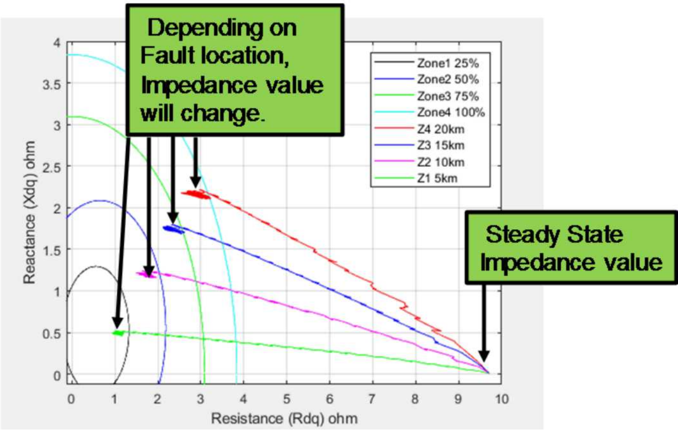
- Cybersecurity is a key challenge to making protection settings adaptive
- Cybersecurity of **power system protection** in general is very critical to the reliability of the bulk power system.
- Presently, the prevalent measures being incorporated include firewalls, intrusion detection systems (IDSs), 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



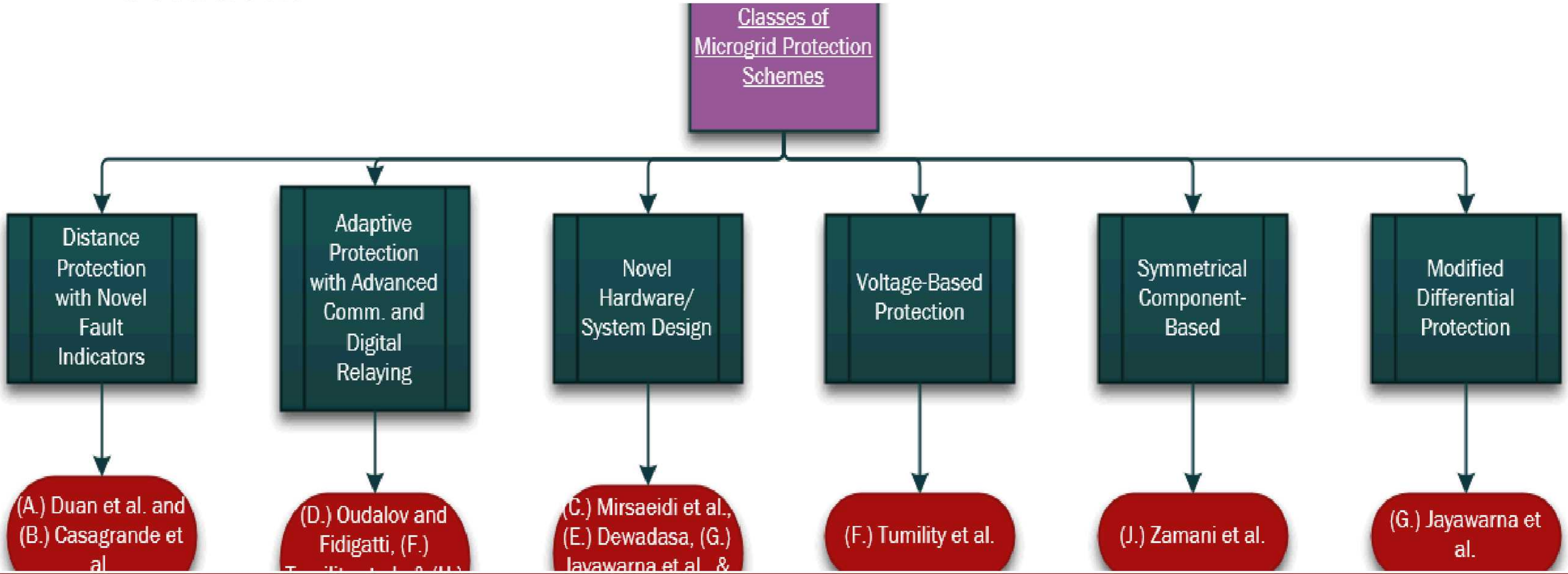


Fault Detection and Location Algorithms

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

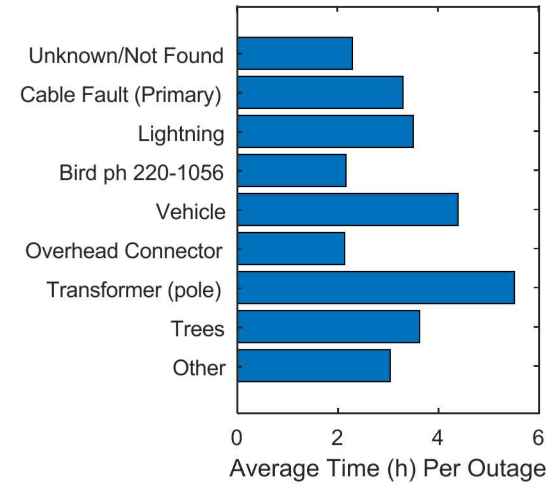


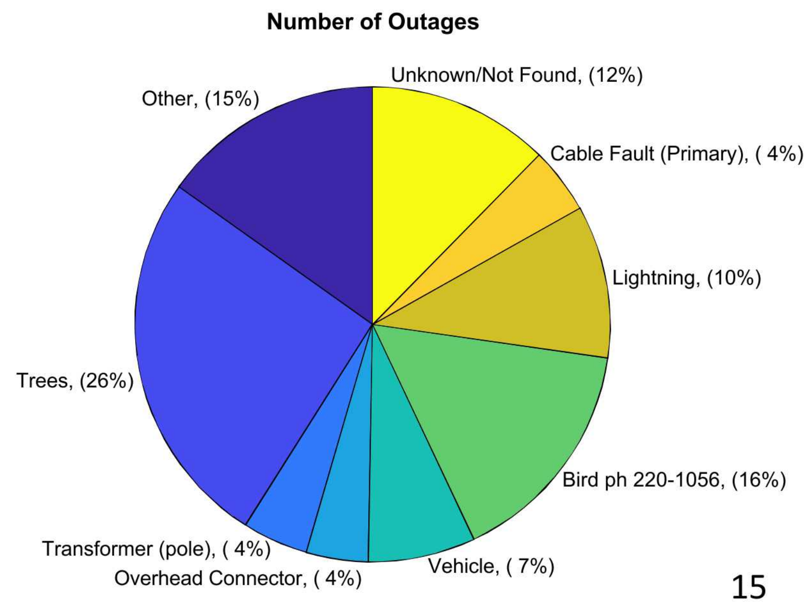
- Sandia report in collaboration with ORNL: "Microgrid Fault Location: Challenges and Solutions"

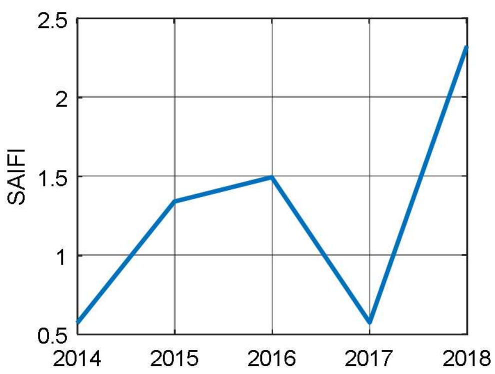


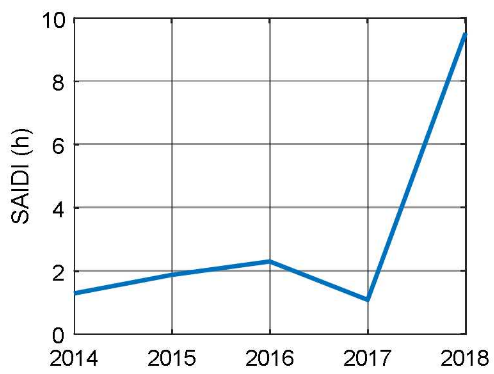
Optimal Protection Design

- Optimal placement of protective devices for improved reliability and reconfiguration
- Protection design constraints also feeds into design of networked microgrids
- Working on optimal protection design for PNM feeders based on historical outage data for frequency, outage time, customers impacts, etc.



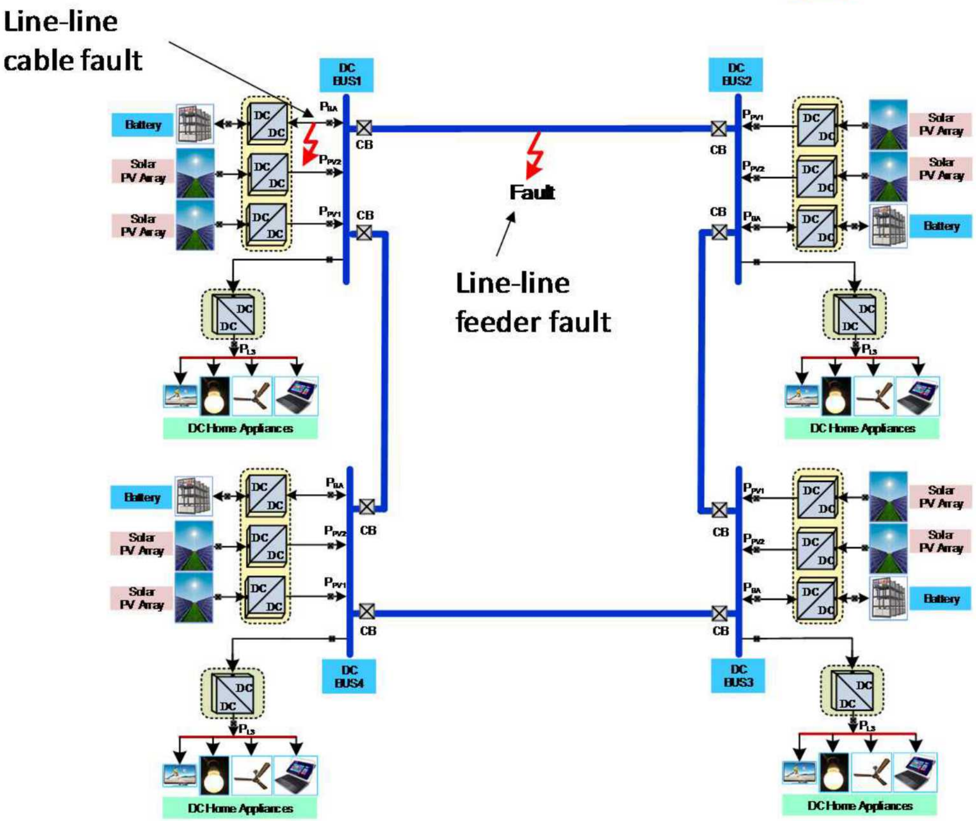


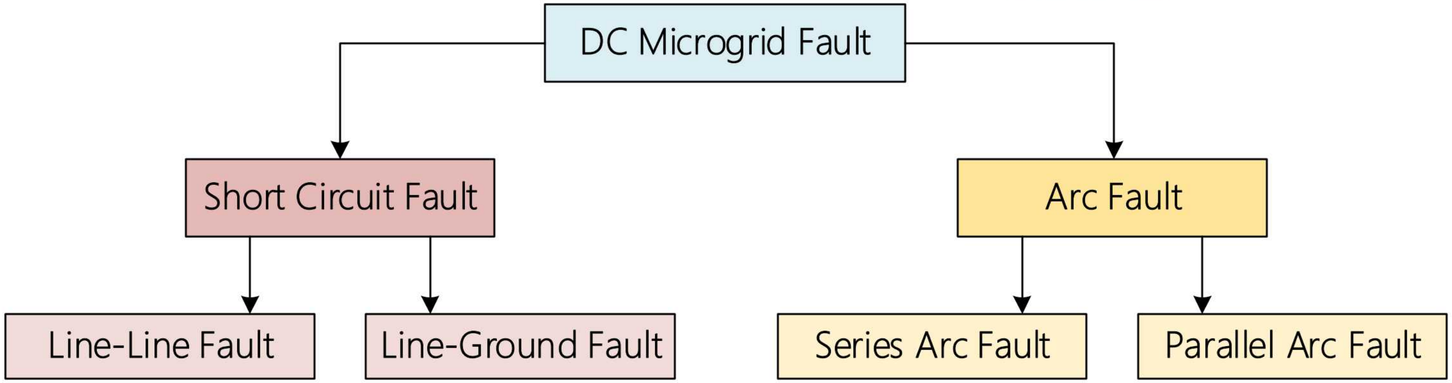




DC Microgrid Protection

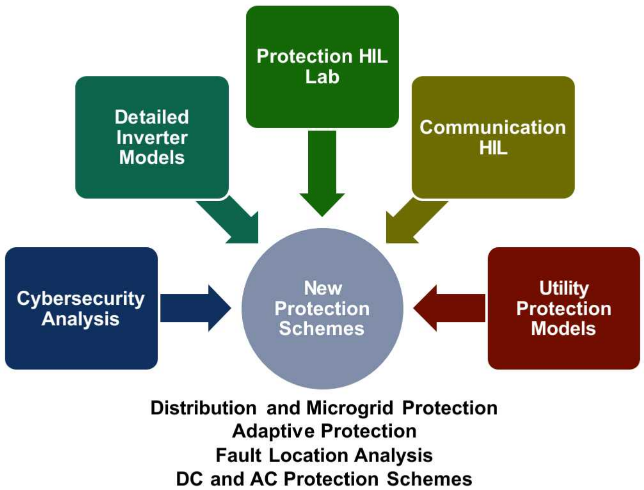
Investigating protection system design for DC microgrids to address protection-related challenges of integrating DC microgrids to distribution systems





Conclusions

- At high PV penetrations, or especially 100% inverter-based systems, conventional protection modeling and design is not sufficient
  - Accurate short-circuit current models are needed
  - New protection schemes are required to detect faults
- Sandia is developing Advanced Protection for Inverter-Based Systems
  - Holistic approach to address the challenges of distribution system and microgrid protection design with high penetrations of inverter-based DER
- HIL demonstration with inverters, relays, and communication is important



QUESTIONS?

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