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Protection of Inverter-Based Systems

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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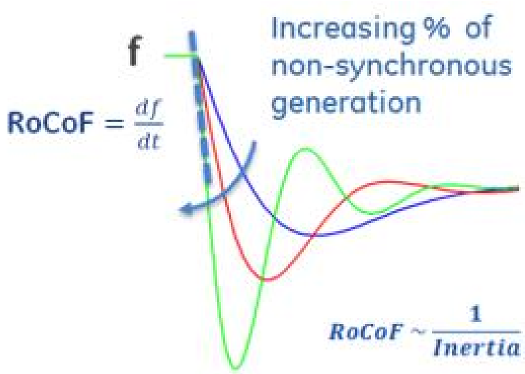
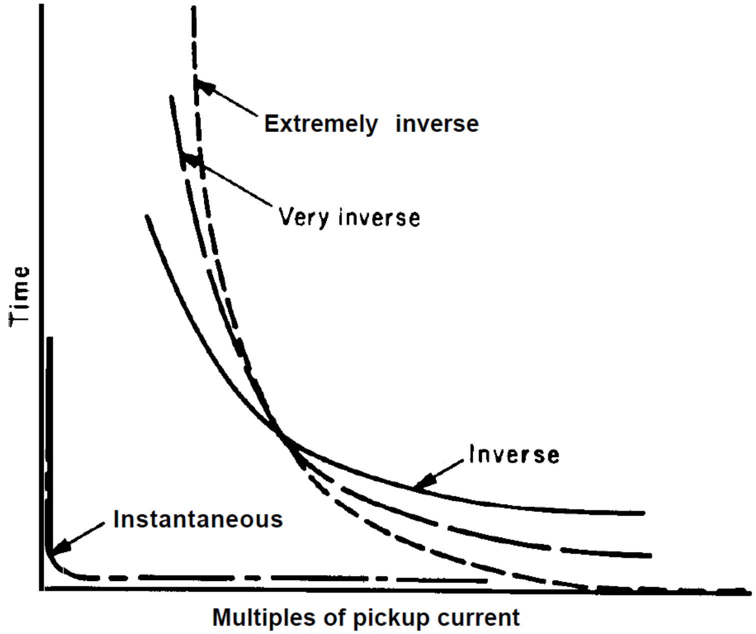
Power System Protection

- The protection system is designed to maintain safe and reliable service
  - Rapidly remove the fault and minimize the disconnection of customers
- Conventional power system protection design may not work for high penetrations of inverter-based resources (IBR)
- 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*



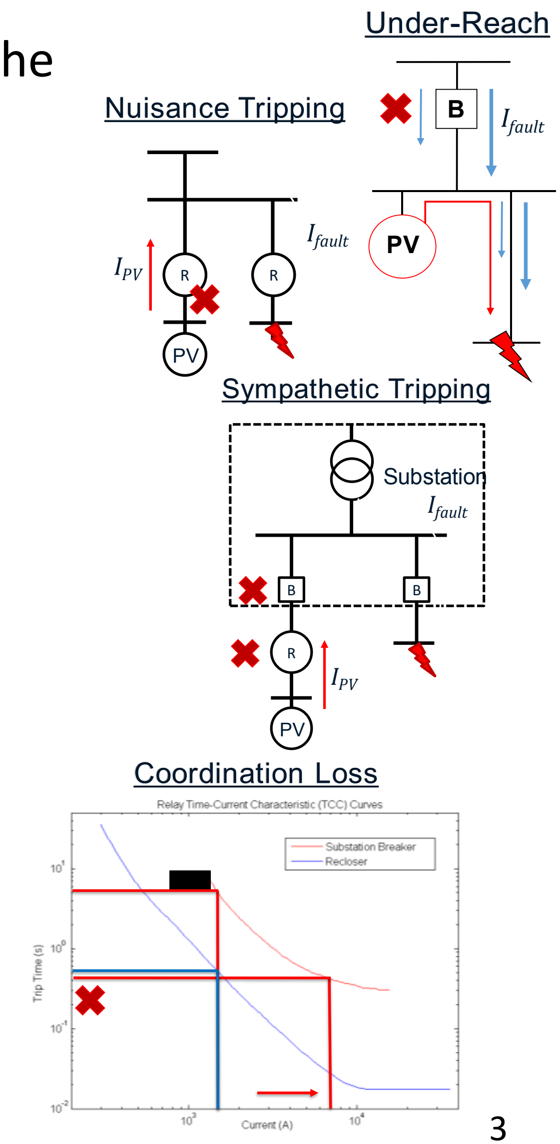


Inverter-Based DG Impacts on Protection

The legacy distribution protection was not designed for the presence of inverter-based distributed generation (DG)

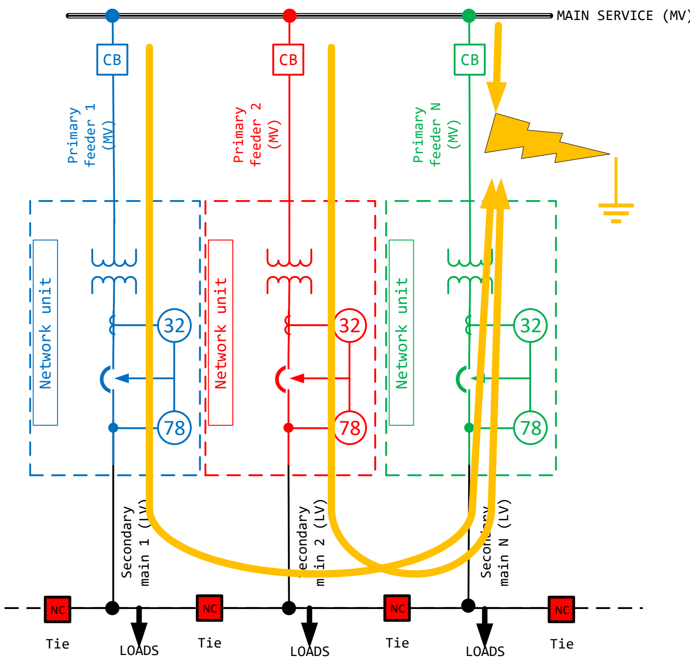
Common Protection Issues and Impacts:

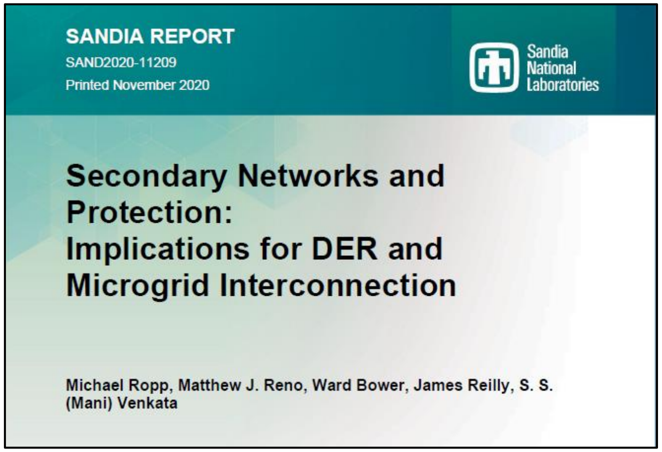
- ✓ Reverse power flow and multiple injection points of fault current
- ✓ Loss in coordination between protection devices
- ✓ Relay desensitization
- ✓ Transfer trip strategies
- ✓ Anti-islanding detection
- ✓ Open-phase detection
- ✓ Interconnection transformer winding configuration and grounding
- ✓ Load rejection transient over-voltage



Impacts on Secondary Network Protection

- Downtown meshed low-voltage networks fed from many network units provide increased reliability and efficiency
- Fault on the medium-voltage or in the transformer are fed through the secondary network, so network protectors are used to very quickly trip on reverse faults
- Network protectors are designed to not allow reverse power flow, which presents challenges for interconnection of DER or microgrids

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Secondary Networks and Protection:
Implications for DER and Microgrid Interconnection

Michael Ropp, Matthew J. Reno, Ward Bower, James Reilly, S. S. (Mani) Venkata

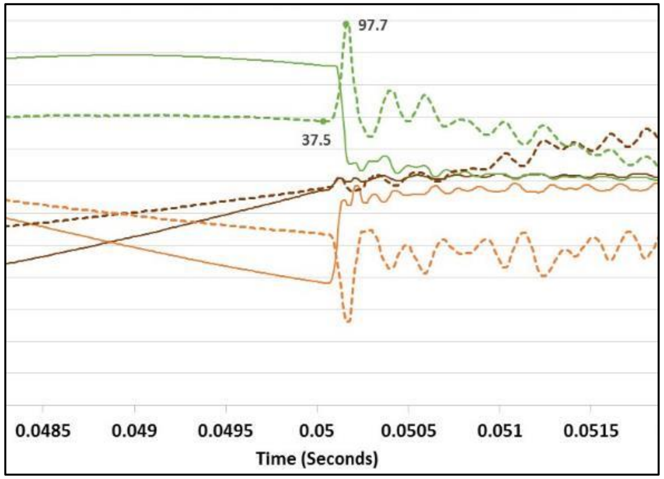
M. Ropp, M. J. Reno, W. Bower, J. Reilly, S. S. Venkata "Secondary Networks and Protection: Implications for DER and Microgrid Interconnection," Sandia National Laboratories, SAND2020-11209, 2020

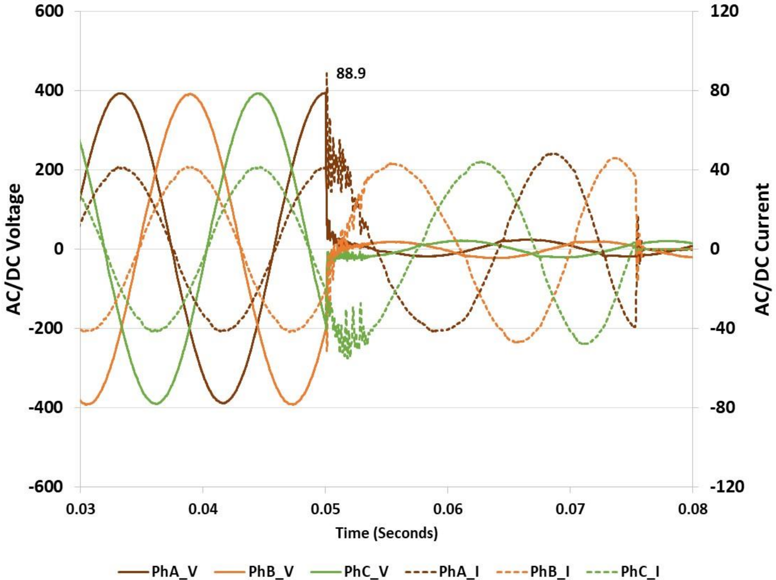
100% Inverter-Based System Protection Challenges

- 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

Inverter Short-Circuit Models

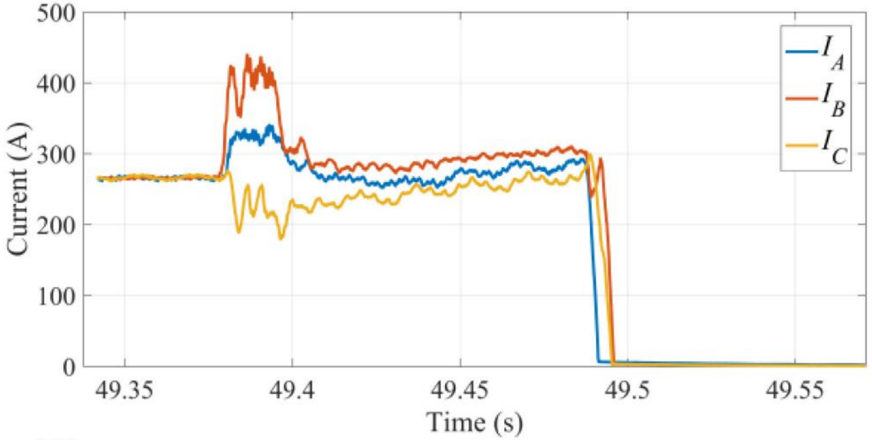
- It is important to have accurate models of inverters for dynamic studies and protection coordination
  - Initial spike (~0.1ms) depends on filter cap, system impedance, and pre-fault condition
  - Transients during control actions, lasting 2-8ms
  - Steady-state fault current based on the current limiter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

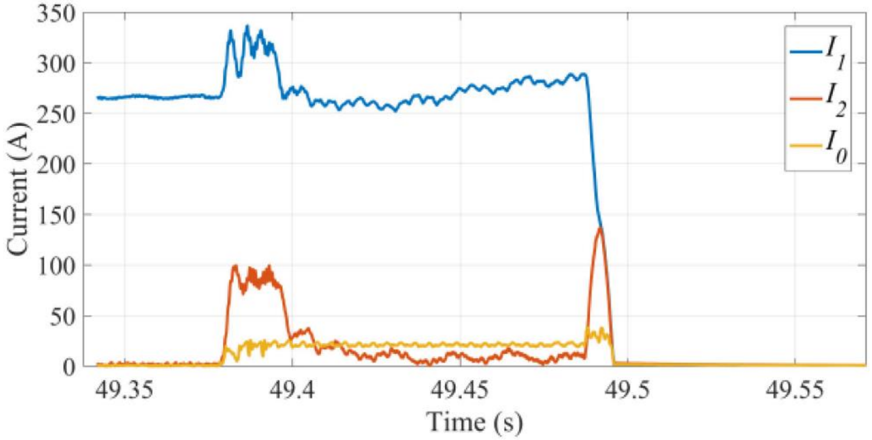




PV Plant Fault Characteristics

- Fault Phase B to Ground with PV at 0.71 pu power output prefault
- 22.5 MW PV system at 34.5 kV with wye-grounded/delta transformer





Two Key Periods Seen:

- Transient Period (1.5 cycles)
  - 1.1 pu phase current
  - 0.75 pu positive sequence current
  - 0.2 pu negative sequence current
  - <0.1 pu zero sequence current
- Steady-State Fault Current
  - 0.79 pu phase current
  - 0.75 pu positive sequence current
  - 0.03 pu negative sequence current
  - 0.06 pu zero sequence current

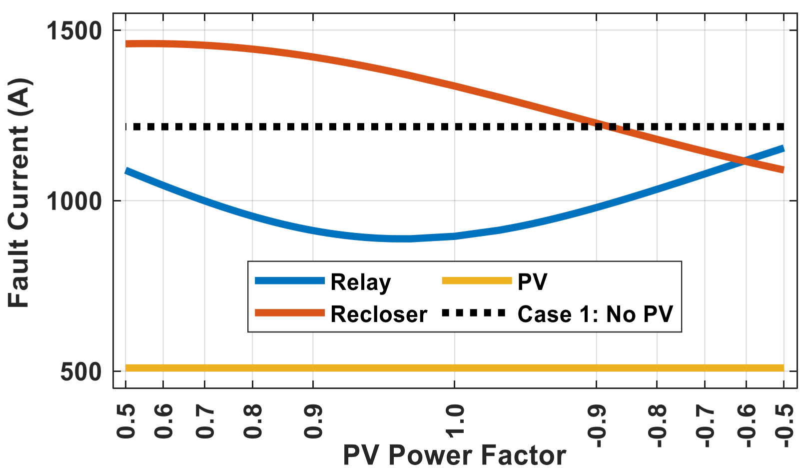
Conclusions

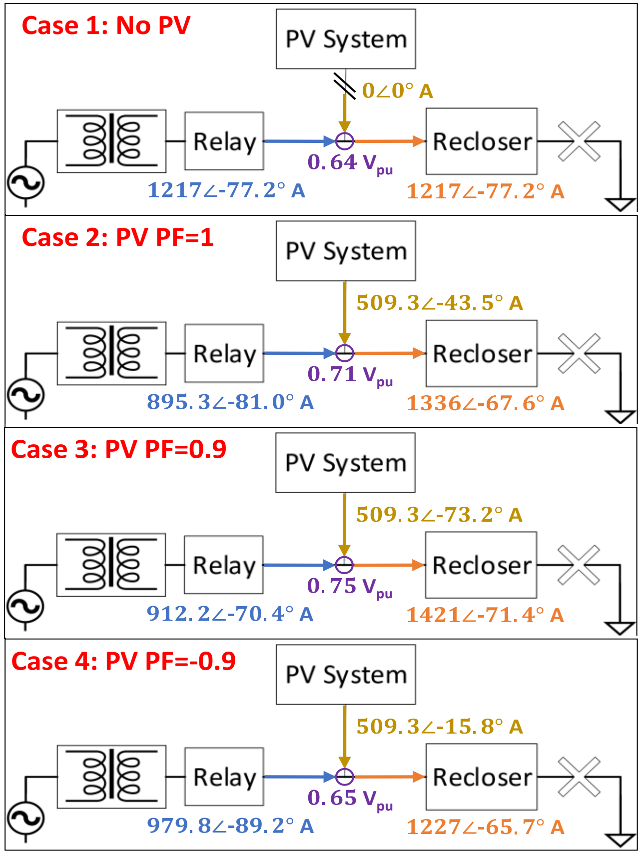
- Very little increase in inverter current during the fault
- No significant negative or zero sequence current injected

G. Kou, L. Chen, P. VanSant, F. Velez-Cedeno and Y. Liu, "Fault Characteristics of Distributed Solar Generation," in *IEEE Transactions on Power Delivery*, vol. 35, no. 2, pp. 1062-1064, April 2020.

Advanced Inverter – Protection Impacts

- Because the inverter 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 due to power factor or volt-var controls
- 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

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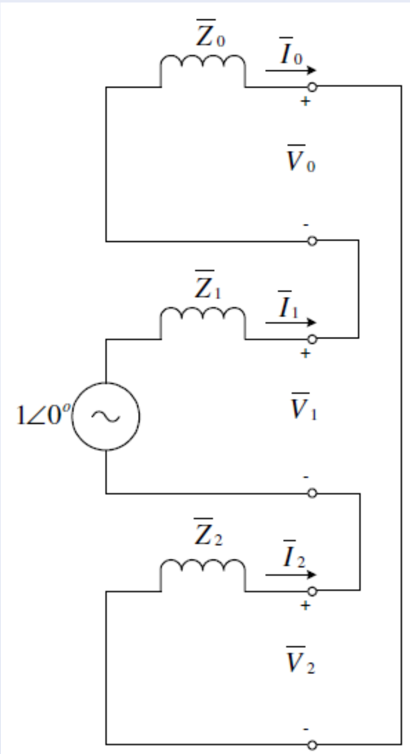
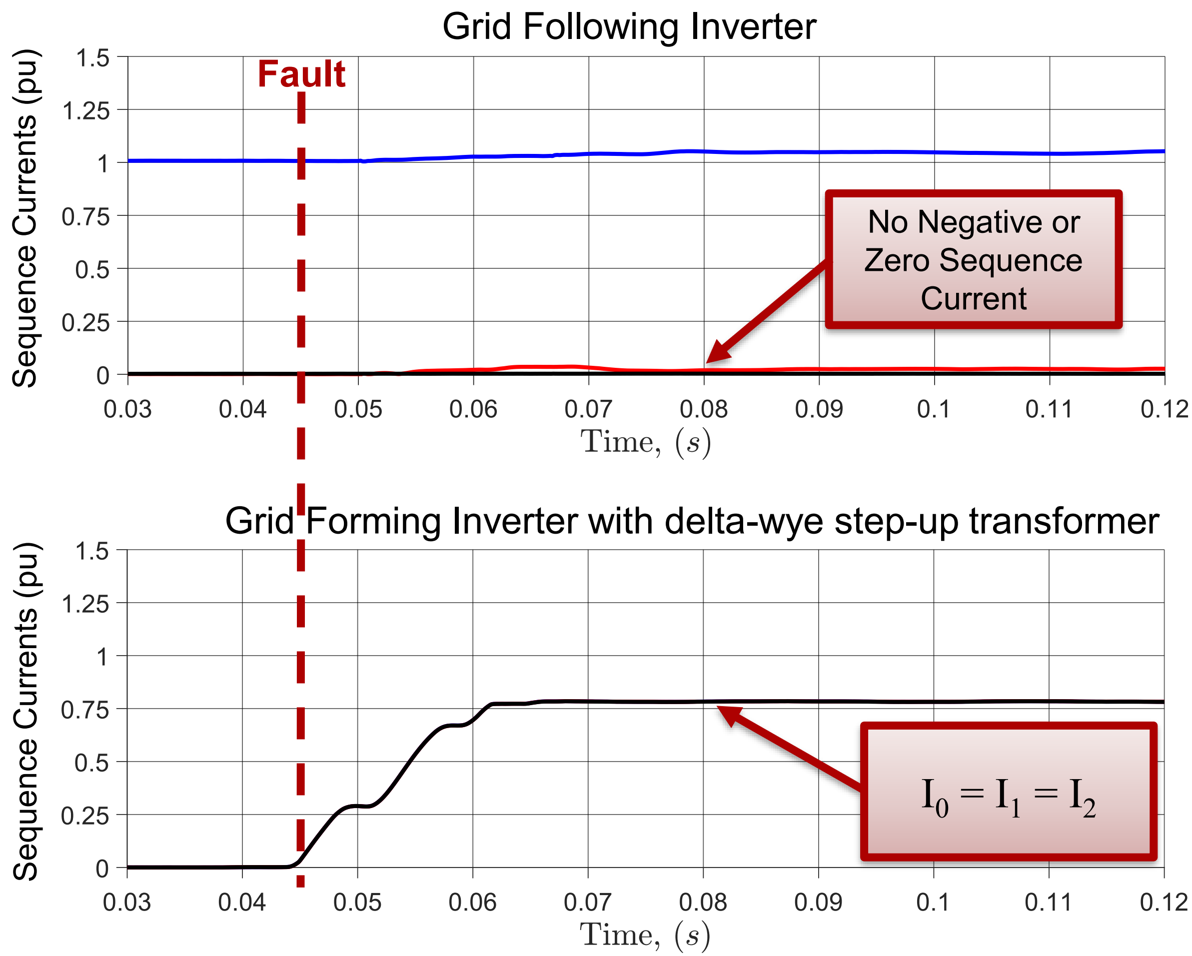
Single-Line-to-Ground Fault Diagram



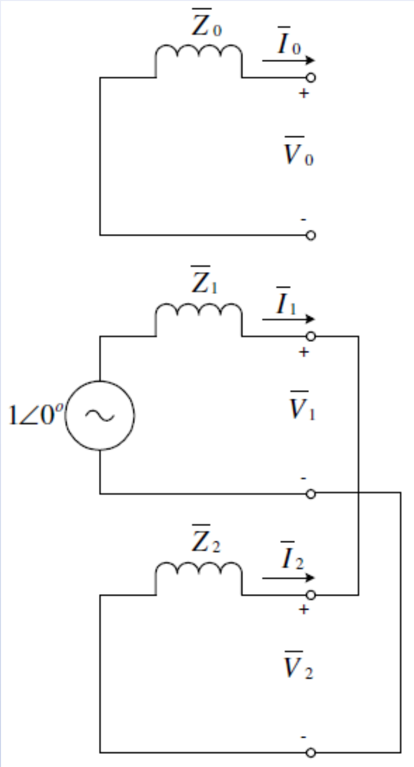
$$I_0 = I_1 = I_2$$



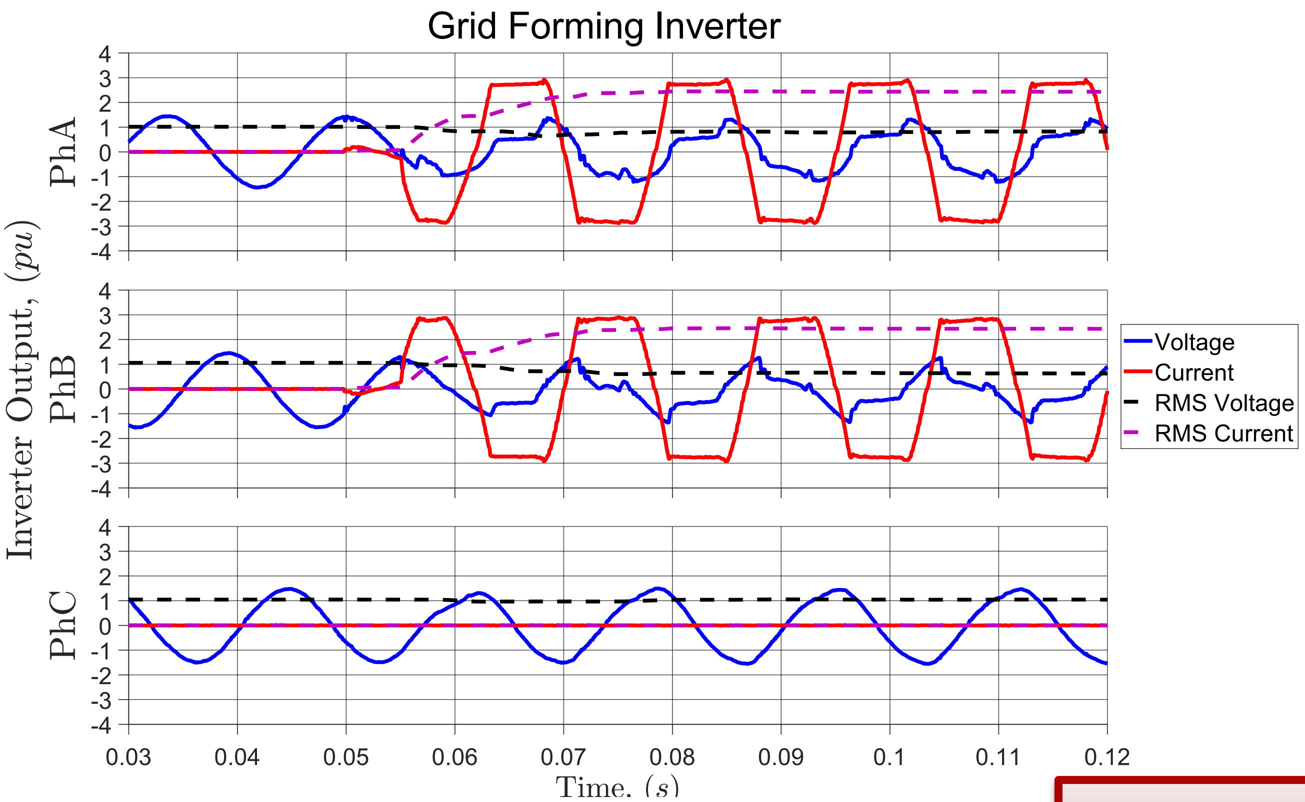
M. J. Reno, S. Brahma, A. Bidram, and M. E. Ropp, "Influence of Inverter-Based Resources on Microgrid Protection: Part 1: Microgrids in Radial Distribution Systems," IEEE Power and Energy Magazine, 2021.

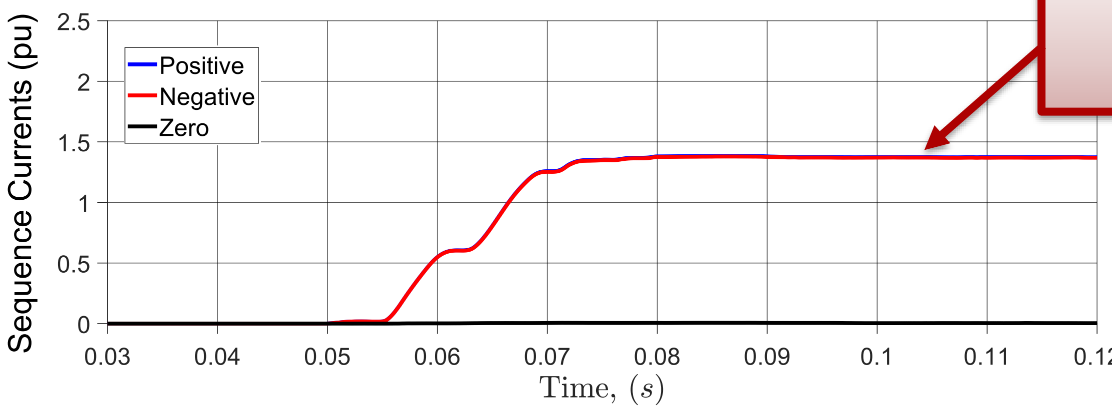
Inverter Tests – Line-to-Line Fault

Line-to-Line Fault Diagram



$V_1 = V_2$
$I_0 = 0$
$I_1 = -I_2$

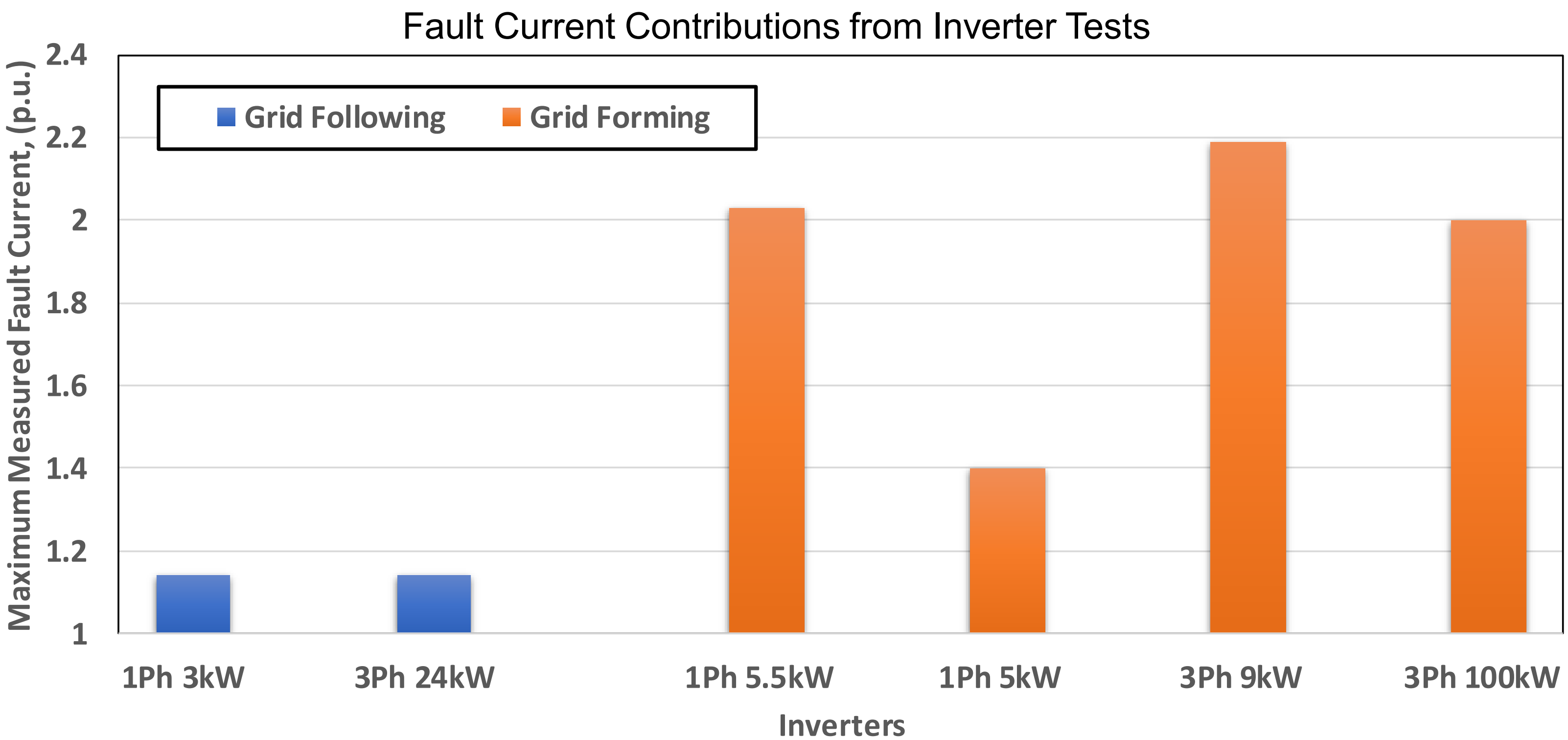




$I_0 = 0$
$I_1 = -I_2$

Inverter Tests - Fault Characterization

- Grid-following inverters (GFLI) generally have very low fault current contributions (1.1-1.2 of their rated current), but we are seeing this number increase
- Grid-forming inverters (GFMI) can deliver 2x the rated current for about 60 seconds

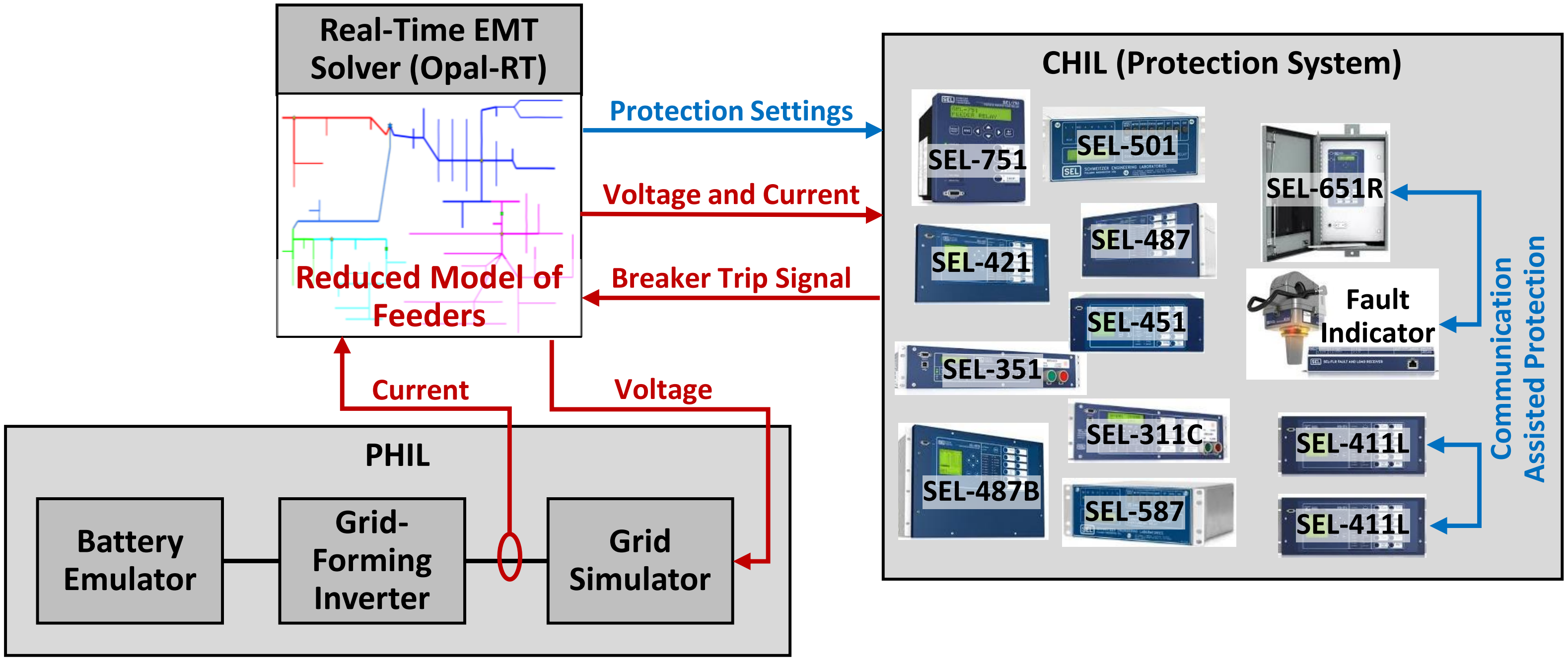


N. S. Gurule, J. Hernandez-Alvidrez, M. J. Reno, A. Summers, S. Gonzalez, and J. Flicker, "Grid-forming Inverter Experimental Testing of Fault Current Contributions," IEEE Photovoltaic Specialists Conference (PVSC), 2019.

Inverter-Based System Protection

- For inverter-based system protection:
  - Accurate short-circuit current models are needed
  - New protection schemes are required to detect faults
- Protection solutions for inverter-based systems:
  - Using fast communication and time-synchronized measurements from multiple sensors for communication-based or wide-area protection
  - Adaptive protection
  - Communication-free Local Adaptive Protection
  - Machine Learning Embedded in Relays
  - High-Frequency Fault Signatures

Protection Hardware-in-the-loop (HIL) Lab at Sandia

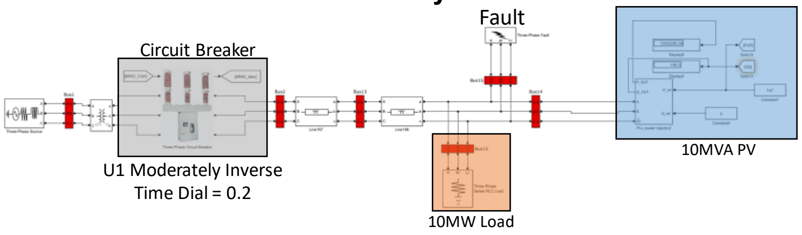


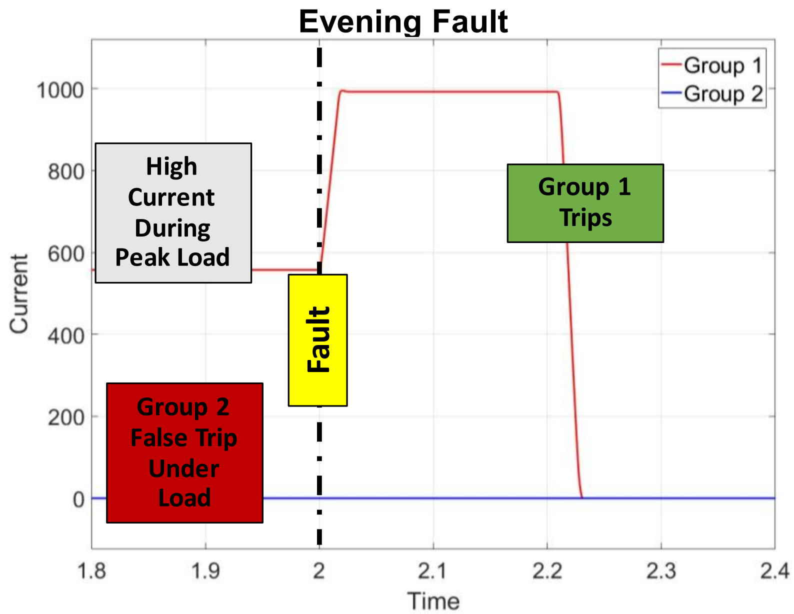
- Power hardware – inverters, PV simulator, grid-forming inverters, energy storage, controllable loads, Home/building/network EMS
- Communication: NS3, DNP3, Modbus, 61850, C37.118 UDP
- Cyber security detection and mitigation schemes

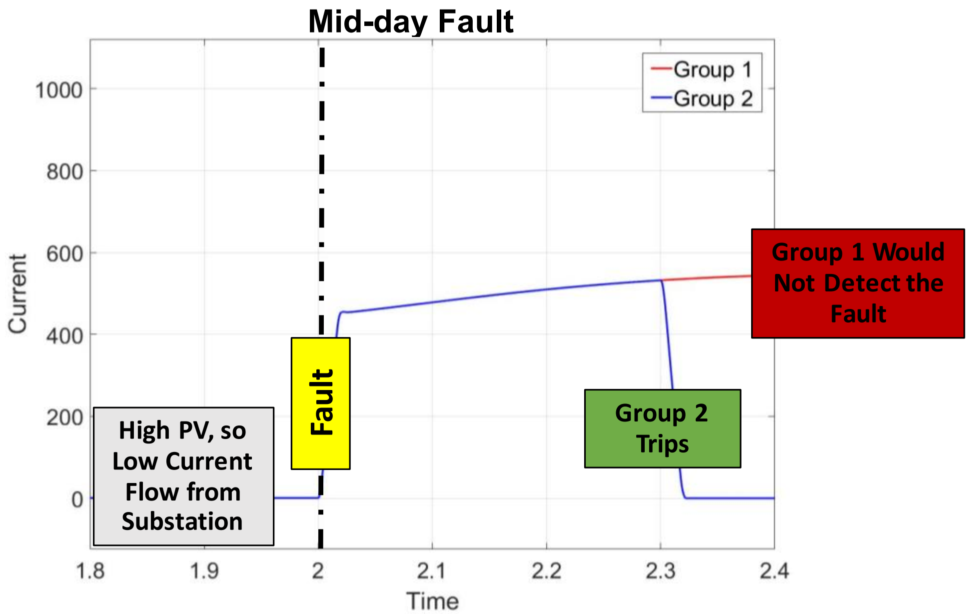
Adaptive Protection

- Protection settings may have to be modified when conditions change (reconfigurations, intermittency of renewables, 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

Test System





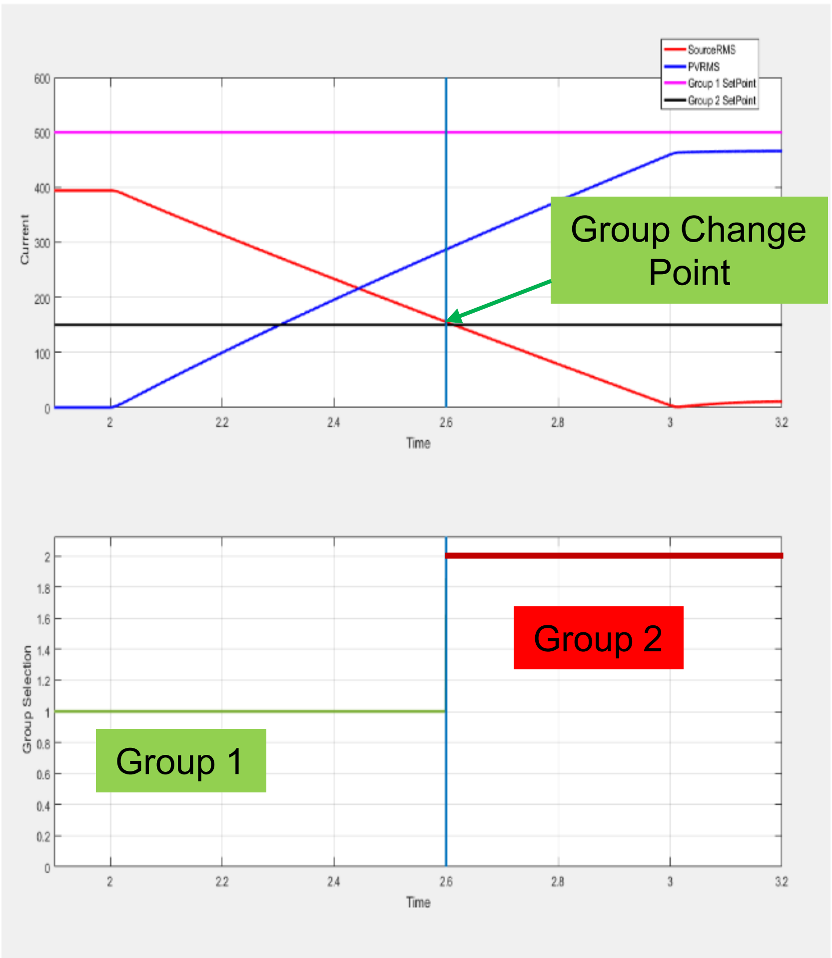


- Setting Group 1 works well with little solar production
- Setting Group 2 cannot work in the evening, trips during peak load

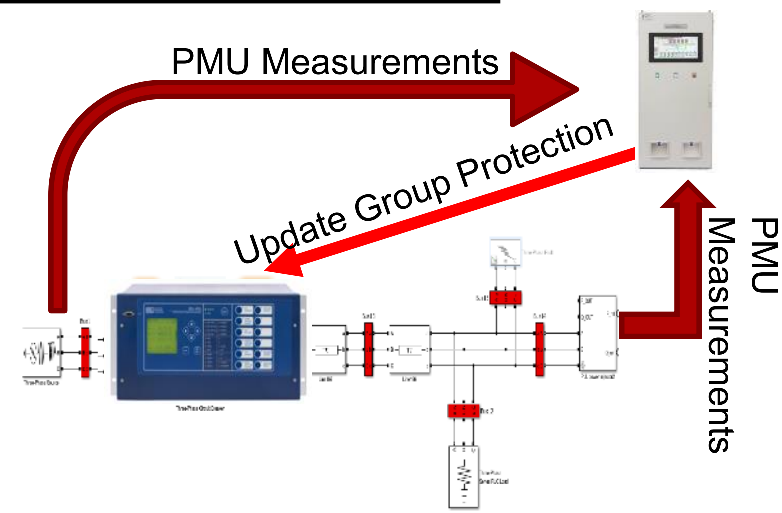
- Setting Group 2 works well with high solar production
- Setting Group 1 cannot work with high solar because of the reduced fault current seen at the substation

Adaptive Protection Demonstration

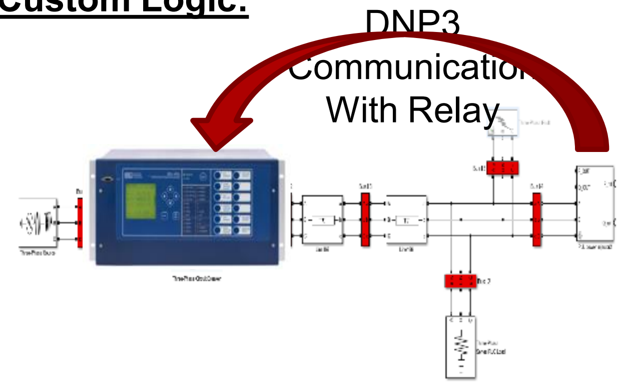
Demonstrated in HIL, communication with relay to change setting groups



Controller Adaptive Protection:

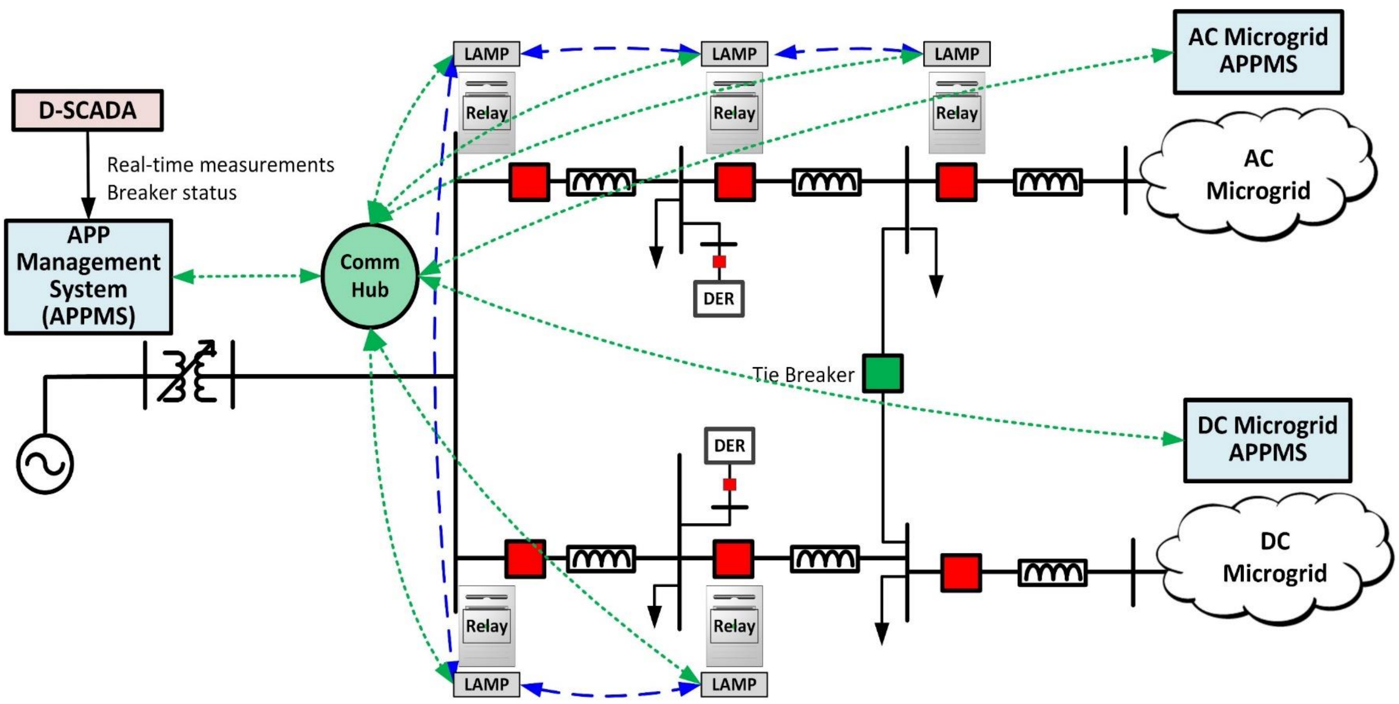


Relay Custom Logic:



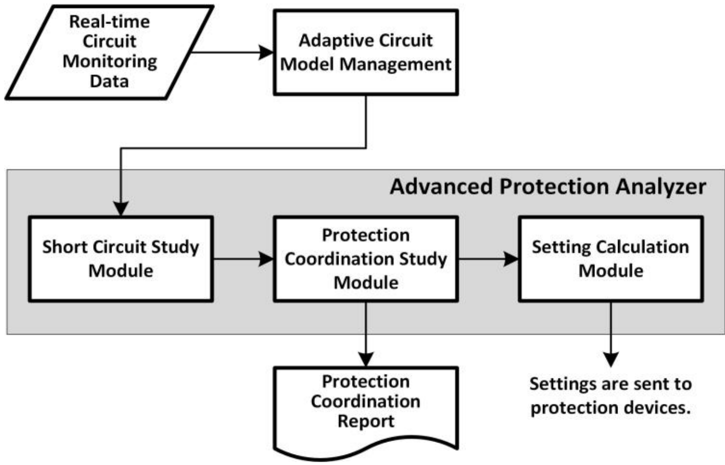
Adaptive Protection

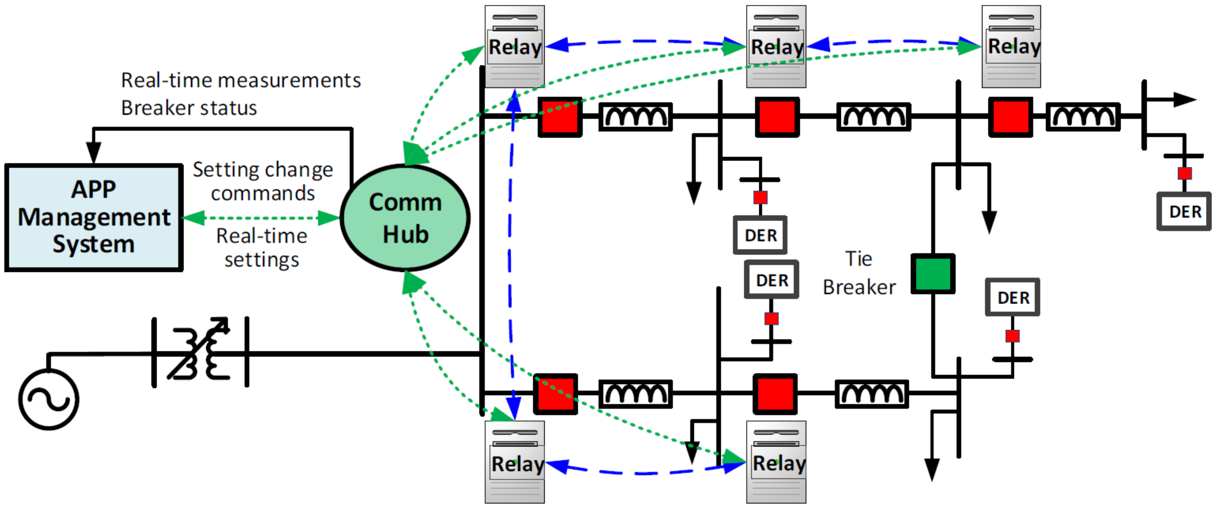
- Adaptive Protection Platform (APP) to adjust protection settings based on the grid configuration and state
  - Can be programmed ahead of time (logic-based adaptive protection)
  - Or settings can be intelligently determined and selected in real-time based on the current system state (switching, renewable generation, generator dispatch, etc.).



Optimal Adaptive Protection

- Settings can be intelligently determined and selected in real-time
- Given the system state, a detailed protection study can be performed testing all possible fault type, locations, and resistance (or a subset of salient faults) to come up with the best protection scheme

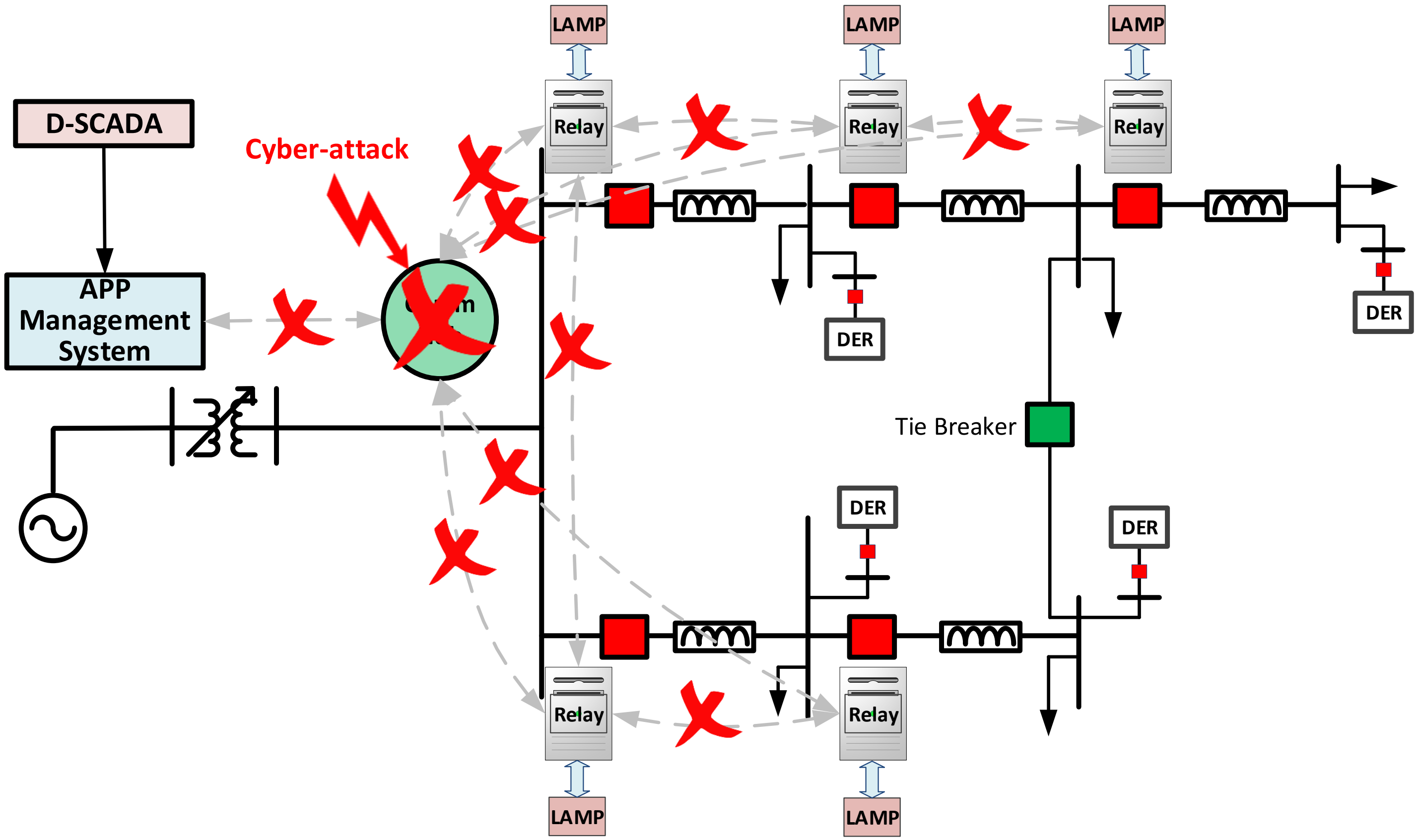




R. C. Matthews, T. R. Patel, A. Summers, M. J. Reno, and S. Hossain-McKenzie, "Per-Phase and 3-Phase Optimal Coordination of Directional Overcurrent Relays Using Genetic Algorithm," Energies, 2021.

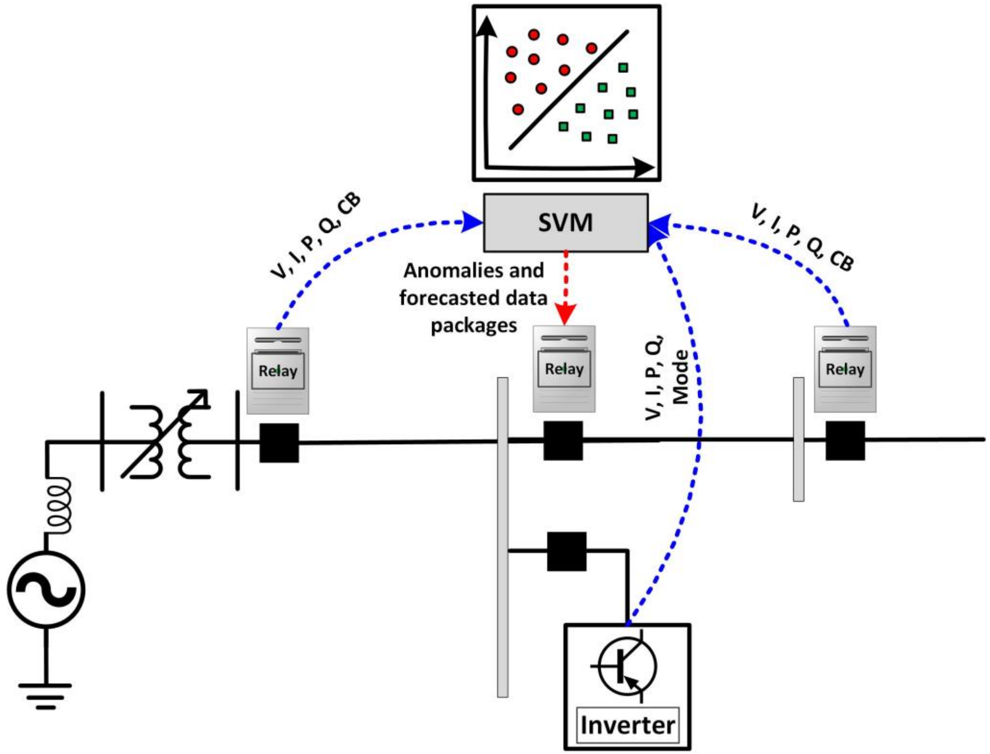
Communication-free Local Adaptive Modular Protection

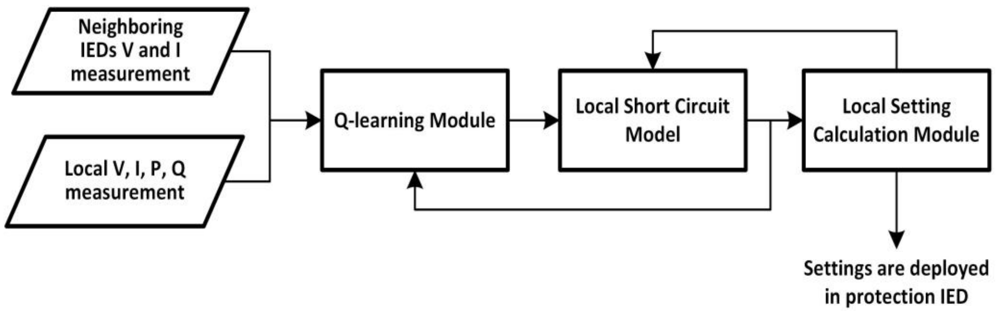
- Objective: To guarantee the reliable operation of protection system under extreme events when communication network is outaged.



Communication-free Local Adaptive Protection

- Ensures reliable communication-free operation
- Local learning at each relay of expected communication from other devices for the grid state
- Uses Q-learning to train the short circuit models in the local zone of protection for each relay
- Only takes action when the communication system is down or a cyber intrusion is detected

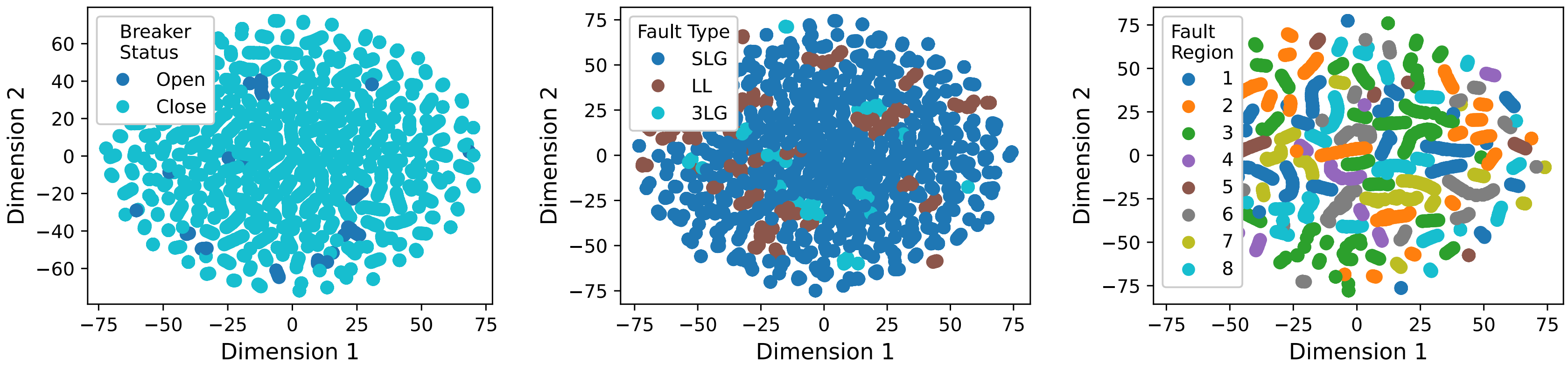




A. Rajendra-Kurup, M. Martinez-Ramon, A. Summers, A. Bidram, and M. J. Reno, "Deep learning based circuit topology estimation and fault classification in distribution systems", IEEE PES ISGT Europe, 2021.

Machine Learning Embedded in Relays

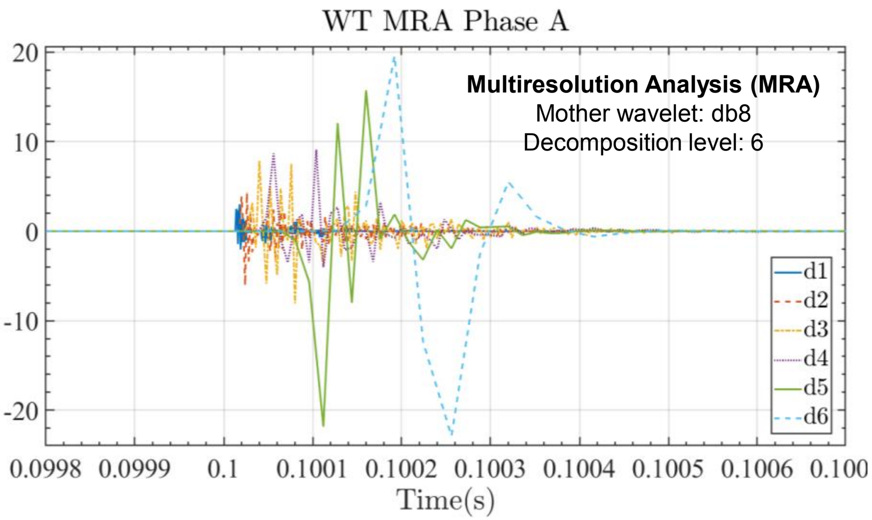
- Protection may be improved using machine learning
- Supervised machine learning trained with simulation data used to classify if there is a fault, fault type, and fault location.
  - Algorithm produces no false trips in yearlong testing with varying and dynamic loads, correctly detects and classifies all fault events
- Other machine learning applications for protection
  - Learning of system state, expected communication, and event detection
  - Online learning of line impedance, fault impedance, and inrush impedance
  - Learning circuit breaker timing and reclose times
  - Machine learning to detect incorrect settings or miscoordination



C. B. Jones, A. Summers, M. J. Reno, “Machine Learning Embedded in Distribution Network Relays to Classify and Locate Faults,” IEEE Innovative Smart Grid Technologies (ISGT), 2021.

High-Frequency Fault Signatures

- Most protection algorithms rely on detecting the response of the system to the fault based on the change in AC voltage and current magnitude and angle
- Using high-frequency measurements and traveling wave techniques, the fault signature itself can be detected instead of the system response
  - These methods are also faster, improving the stability in low- inertia systems
  - Detecting fault signatures does not rely on high fault currents
- Can combine the high-frequency point-on-wave measurements and AI to learn fault signatures



Conclusions

- At high penetrations of IBR, 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 studying the impacts of IBR on protection and designing advanced protection systems for IBR at many levels (low-voltage secondary networks, microgrids, distribution, and transmission)
- Hardware experiments provide validation data that is valuable for developing IBR models
- Real-time power hardware-in-the-loop (HIL) interfaces simulation with hardware such that the inverter models can be directly compared to the hardware response to the same signal
- HIL experiments can also test how the relay would respond in the field

QUESTIONS?

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