**76th Annual Conference
for Protective Relay Engineers
March 27-30, 2023**

Protection and Control Challenges of Low-Voltage Networks with High Distributed Energy Resources Penetration

Quanta Technology -
Zheyuan Cheng
Eric Udren
Juergen Holbach

Sandia National Laboratories -
Matthew Reno
Michael Ropp

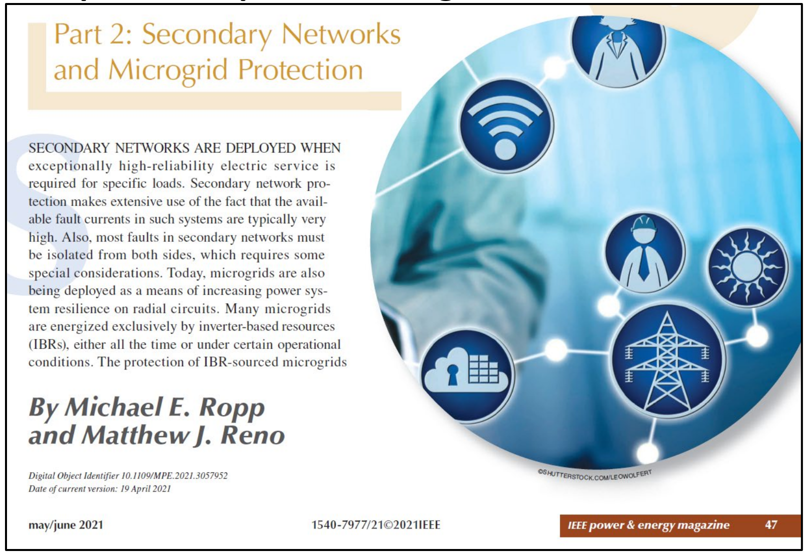
Agenda

1. Project overview – goals and steps – *Eric Udren*
    - Overview of Sandia-sponsored research programs
    - Overview of late-2020 utility workshop - research opportunities identified
    - Focus on challenge of DER and microgrids with LV networks
    - *Model-based simulation and HIL testing on RTDS®*
2. Research overview - integration of DER with LV networks – *Zheyuan Cheng*
    - *Model development*
    - *Findings on impact of DER on operation and fault protection*
    - *Proposed new solutions and solutions in use today*
    - *Continuing study plans*

Inception of research

- Sandia National Laboratories (SNL) and the US Department of Energy (DOE) are leading research into low-voltage (LV) secondary networks and spot networks serving high-density load areas.
  - What are industry trends and upcoming needs?
- Began study in 2020 - broad assessment of LV network issues and R&D opportunities
- 2021 to present - Focused on protection challenges with interconnection of DER and microgrids in LV networks.
  - Increasing penetration of clean energy
  - Increasing resilience with microgrids and backup generation during extreme weather events

IEEE Power & Energy Magazine
https://ieeexplore.ieee.org/document/9408478



Part 2: Secondary Networks and Microgrid Protection

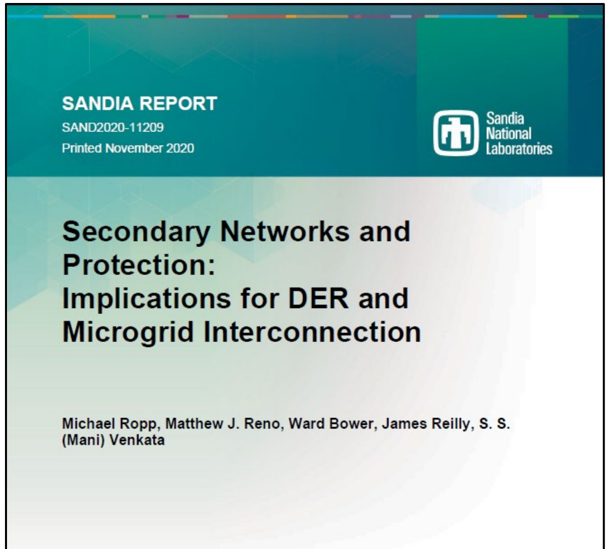
SECONDARY NETWORKS ARE DEPLOYED WHEN exceptionally high-reliability electric service is required for specific loads. Secondary network protection makes extensive use of the fact that the available fault currents in such systems are typically very high. Also, most faults in secondary networks must be isolated from both sides, which requires some special considerations. Today, microgrids are also being deployed as a means of increasing power system resilience on radial circuits. Many microgrids are energized exclusively by inverter-based resources (IBRs), either all the time or under certain operational conditions. The protection of IBR-sourced microgrids

By Michael E. Ropp and Matthew J. Reno

Digital Object Identifier 10.1109/MPE.2021.3057952
Date of current version: 19 April 2021

may/june 2021 1540-7977/21©2021IEEE *IEEE power & energy magazine* 47

Sandia Report SAND2020-11209
https://www.osti.gov/servlets/purl/1738874



SANDIA REPORT
SAND2020-11209
Printed November 2020

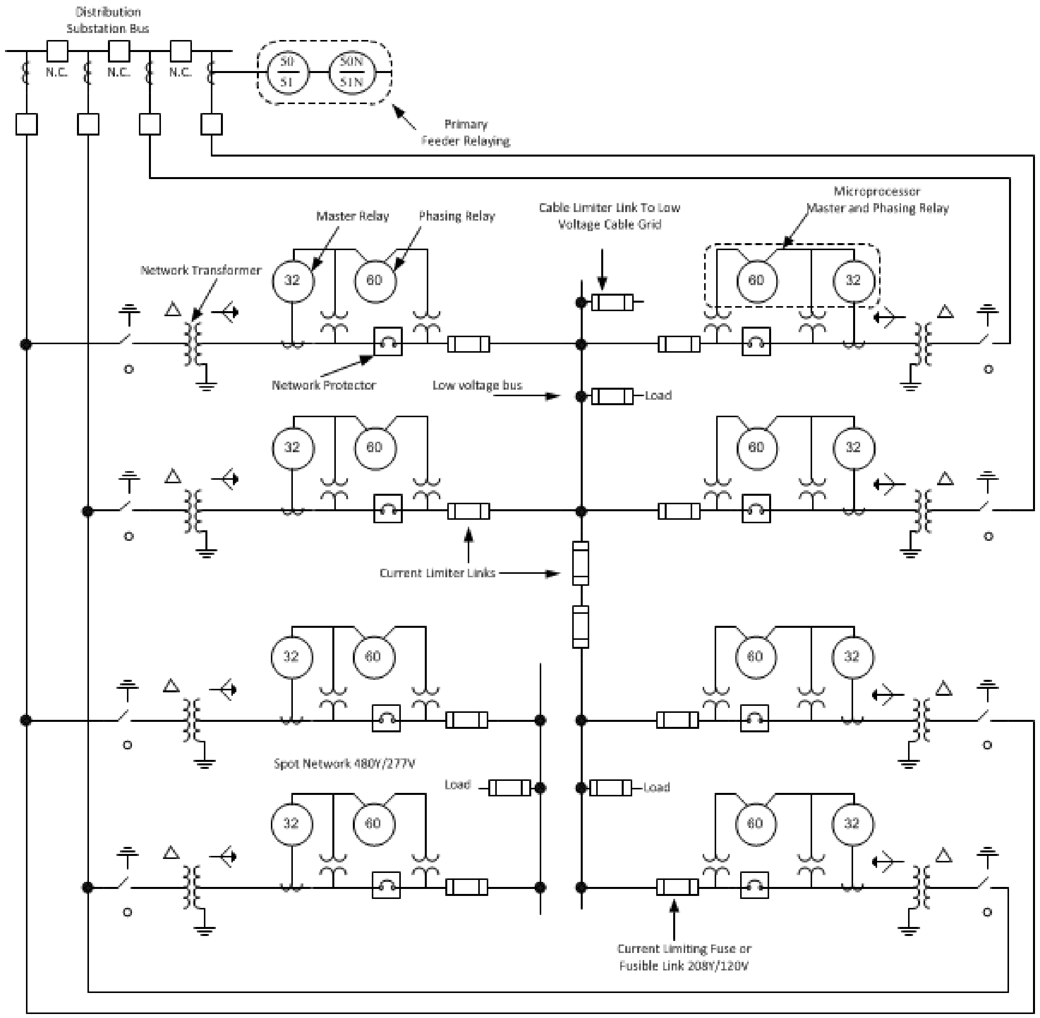
Sandia National Laboratories

Secondary Networks and Protection: Implications for DER and Microgrid Interconnection

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

Phase I Investigation

- Typical LV network:



From IEEE C37.108-2019

Objective:

- Assess electric utility experience and issues with low-voltage distribution network protection devices and systems.

Overview of LV grid and spot network design and fault/failure protection principles

Literature review:

- IEEE standards: C37.108-2002, C57.12.44-2014, 241-1990, P1547.6-2011, etc.
- Technical papers and reports from literature search

Interview of utilities using LV grid and spot network distribution:

- Consolidated Edison Company of New York
- PHI PEPCO
- Oncor Energy Delivery

Major Research Recommendations from Phase I Survey (1)

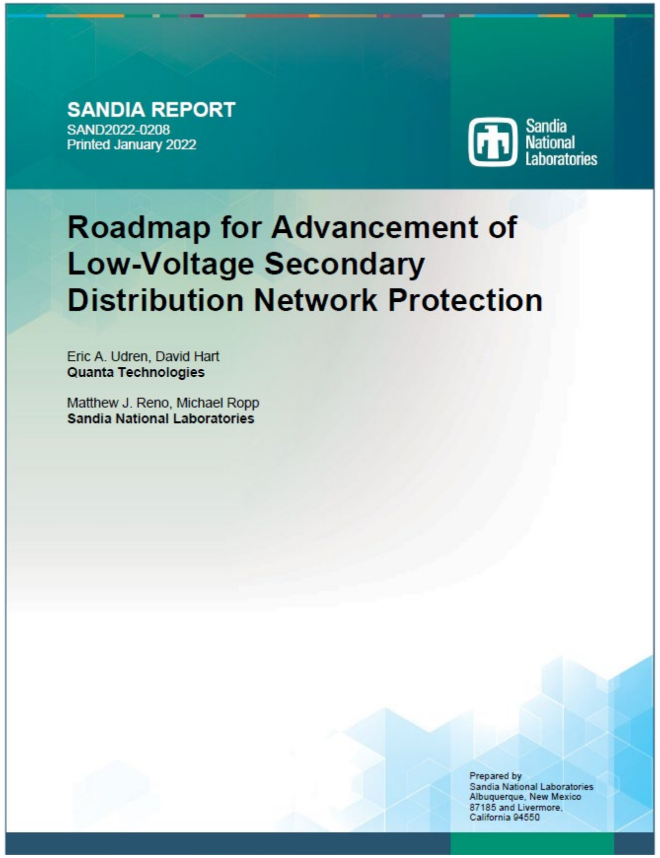
Notation – {importance or value; difficulty or cost] with H (high), M (medium), and L (low)

- [H;L] items are lowest hanging fruit.
- [H;M] items are worthy of early attention.

- **Overall LV network operation and protection needs and opportunities workshop. [H, L]**
  - **Transient simulation and test capabilities for LV networks and protection including HIL; DER and microgrid cases**
- Modeling and operational software and function workshop. [H, L]
- Study, specify, demo [H, M], then develop software tool and real-time distribution simulation modeling with LV networks.
- Study, specify, demonstrate [H, M], and then develop [H, H] operational management tool integration for distribution with LV networks.
- Develop integrated P&C specification - holistic architecture, design, and functional requirements:
  - Function list with high-level specifications; top-level architecture for an integrated, standardized P-C-M system based on IEC 61850 and Ethernet services. [H, M]; development and demonstration [H, H.

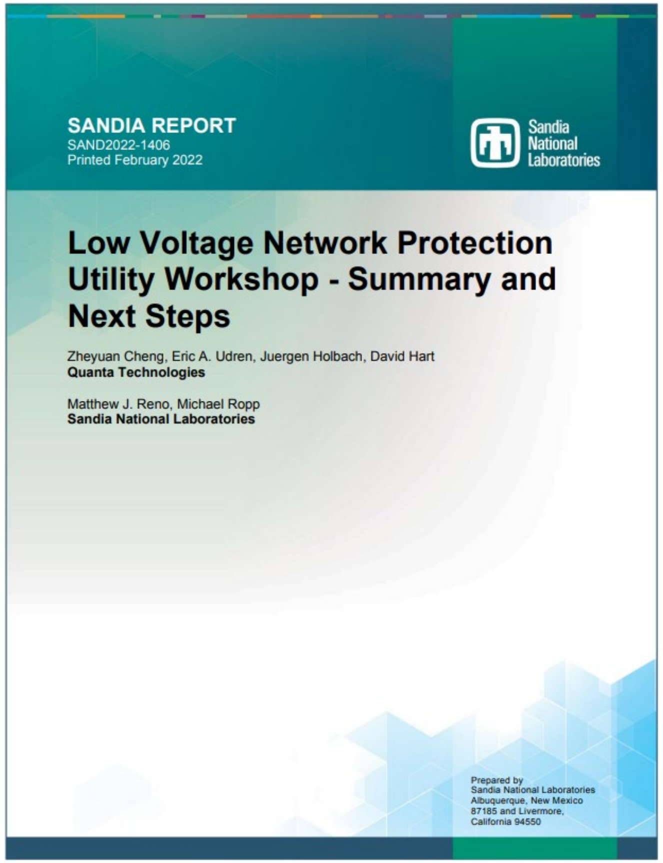
Major Research Recommendations from Phase I Survey (2)

- Electrical predictive apparatus monitoring signatures. [H, M]
  - Opportunity to detect LV and MV low-current and incipient faults, pre-fault degradations.
  - Related utility distribution arcing-fault product testing to date shows that security/false response is a challenge for that signature or pattern detection technology.
- Communicating ground fault detection CTs for LV differential schemes. [H, M]
- Low-cost SCADA communications technology. [H, H]
- Arc flash sensing by optical, IR/heat, smoke, CO detection means. [H, M]
- Investigation of stray voltage detection methods. [H, H]



Phase II Project Tasks

- Conduct workshop with key LV network users and industry suppliers, combined with study and invention by research team experts, to categorize network protector and distribution system modeling issues and behaviors to investigate in Tasks 2 and 3.
- Develop and program RTDS real-time simulation models of typical distribution system with LV networks.
- Conduct HIL testing of network relays and protectors in operating and fault scenarios.



Workshop in August 2020 reviewed utility user experiences and plans,
and listed challenges.

- Details in SNL report
- Major challenges…

Challenge #1: DER backfeed induced NP misoperation

Reported challenges

- Having trouble with DER reverse power flow causing protection misoperation.
- Cannot reliably distinguish DER backfeed from MV supply feeder faults.
- Need a better DER management system or DERMS to operate and monitor a large number of DERs.
- Need to leverage DER to reduce peak demands and avoid curtailment.

How can we increase DER hosting capacity of the LV network without impacting protection and service reliability?

Con Edison mitigation strategies

- Rate-of-change based detection: use backfeed rate of change settings in new relay design to distinguish slow changes in current during backfeed from sudden changes caused by faults.
- Substation transfer trip: Install transfer trip from MV feeder sub to network protectors; configure network protectors for reduced sensitivity to reverse flow; and let the MV distribution substation relay transfer-trip network protectors.

Challenge #2: Voltage profile management

Reported challenges

- DER smart inverters, e.g., with reactive power injection, could hurt voltage regulation.
  - Need more coordination between DER and voltage regulators.
- How to leverage inverter-based DER to improve the LV network voltage profile.
- Voltage profiles change over time, season, and weather. For weak-supply areas, it is difficult to manage the voltage profile.

Today's voltage regulation practice

- Con Edison reported typically use of fixed-tap network transformers
  - Taps can circumvent control coordination between the voltage regulator and smart inverter.
  - Tap positions need to be determined based on the actual voltage drops in the field.
- PEPCO uses network transformers with automatic tap changers.

Challenge #3: Slow clearing of secondary cable faults

Reported challenges

- Inability to detect and rapidly clear slowly developing cable faults is a huge problem. These faults do not present clear signatures.
- The visibility of the secondary low-voltage network is very limited. More weatherproof sensors and monitoring tools are needed to detect and locate secondary faults.
- Users need better real-time power flow models and tools for contingency analysis during faults.

Fault cause

- A frequent cause of slow-developing cable faults in New York City is corrosion associated with snow melting and road salt - approximately 3000 events per year.

Mitigation strategy

- Con Edison has deployed an infrared (IR) camera-based fault detection system to detect and locate hot spots caused by high loads and faults. These IR camera sensors are battery-powered and communicate to the operator via wireless communications.
  - One major drawback of IR camera sensor systems is the battery failure and replacement needs.

Challenge #4: Microgrid integration

Reported challenges

- How to coordinate between the microgrid tie-breaker and low-voltage network protection.
- What is the justification for creating a microgrid in this environment? The LV grid network already serves with extremely high reliability.
  - Microgrid can maintain service for major distribution outages, notably with BESS

In workshop participants' perspective, protection within a microgrid should be treated as a separate topic.

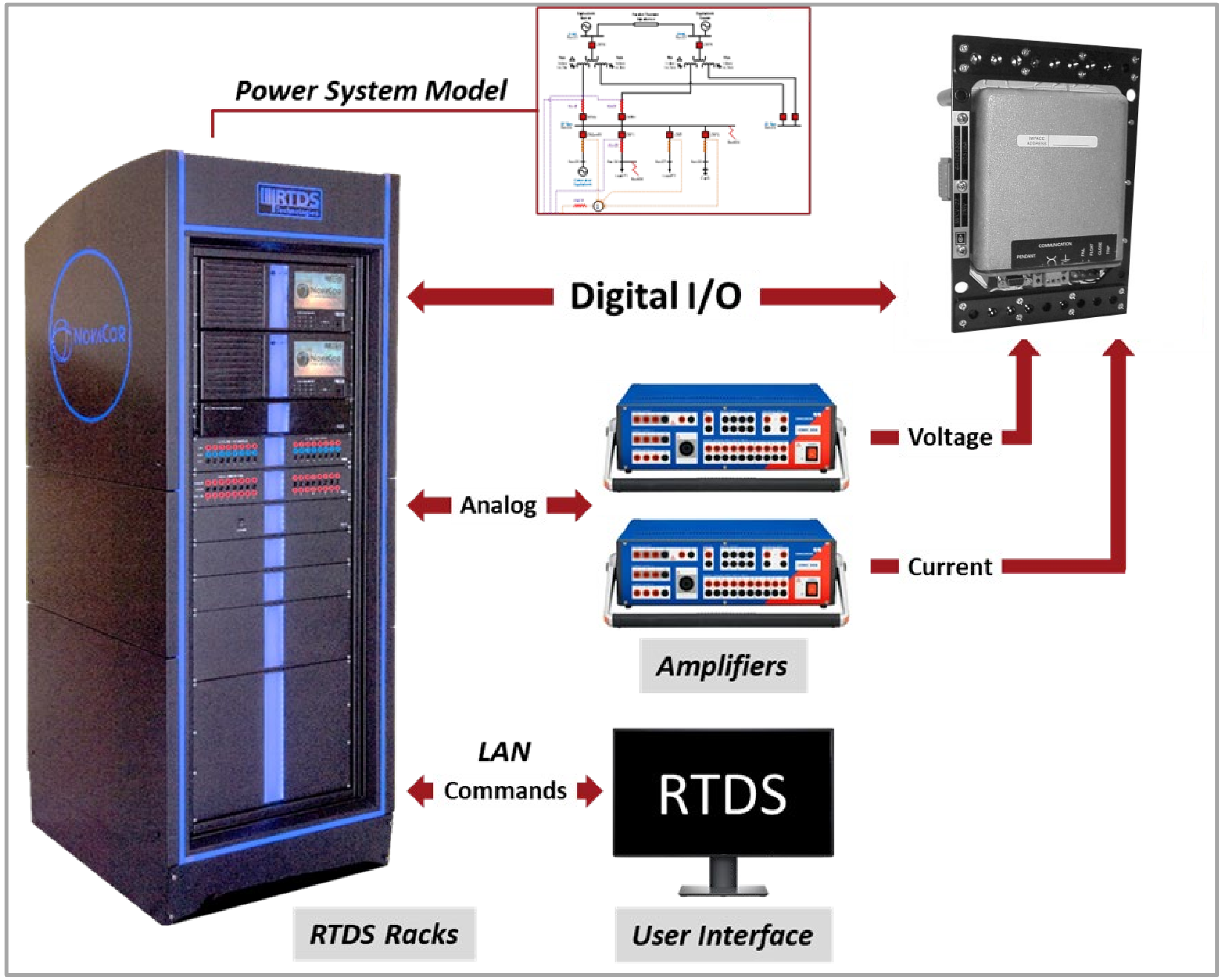
Common microgrid types in low-voltage networks

- Customer-site microgrid with one or multiple connection points to the low-voltage network - can maintain critical load service during a blackout.
- Microgrid with sizeable DER generation may be connected to the medium voltage primary feeder.
  - Can potentially supply multiple primary feeders and restore part or all of the low-voltage network

Key 2022-23 research topics driven by challenges - DER and microgrid impact

- Develop RTDS models for simulation of LV network with DER inside, MV connected grid, microgrids.
- Develop RTDS models for existing NP relays and new operating characteristics.
- Study relay response and security against misoperation for DER within the LV network.
- Study relay protection effectiveness for variety of fault situations and microgrid applications.
- What relay characteristics and behaviors support DER and microgrid integration?

Hardware-in-the-Loop (HIL) testing of LV network protector relays

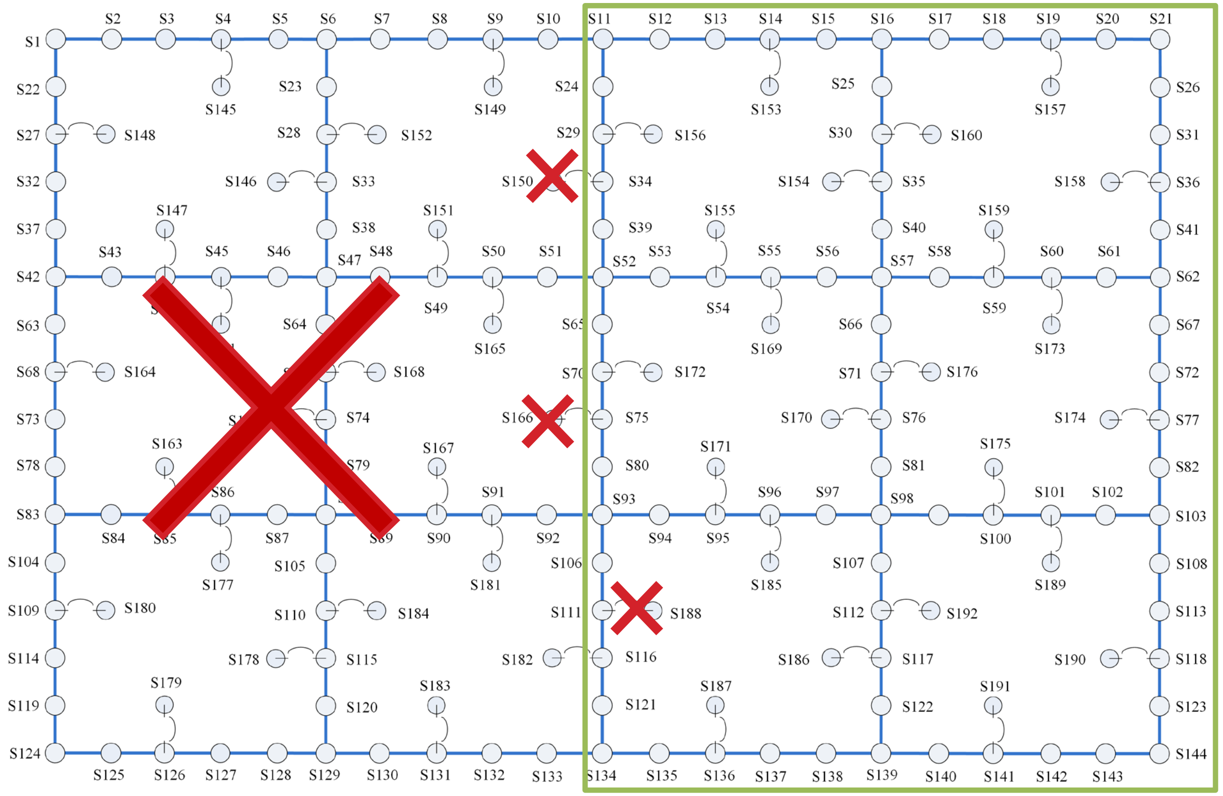


- Model LV network, vault apparatus, MV utility supply grid, virtual relay models, DER, microgrids
- Simulate in real time - normal service operation, load and DER variations and behaviors, faults and disturbances
- Test any combination of actual NP relay samples and virtual relays modeled within the RTDS
- Relay responses operate NP models and yield real-world network model response

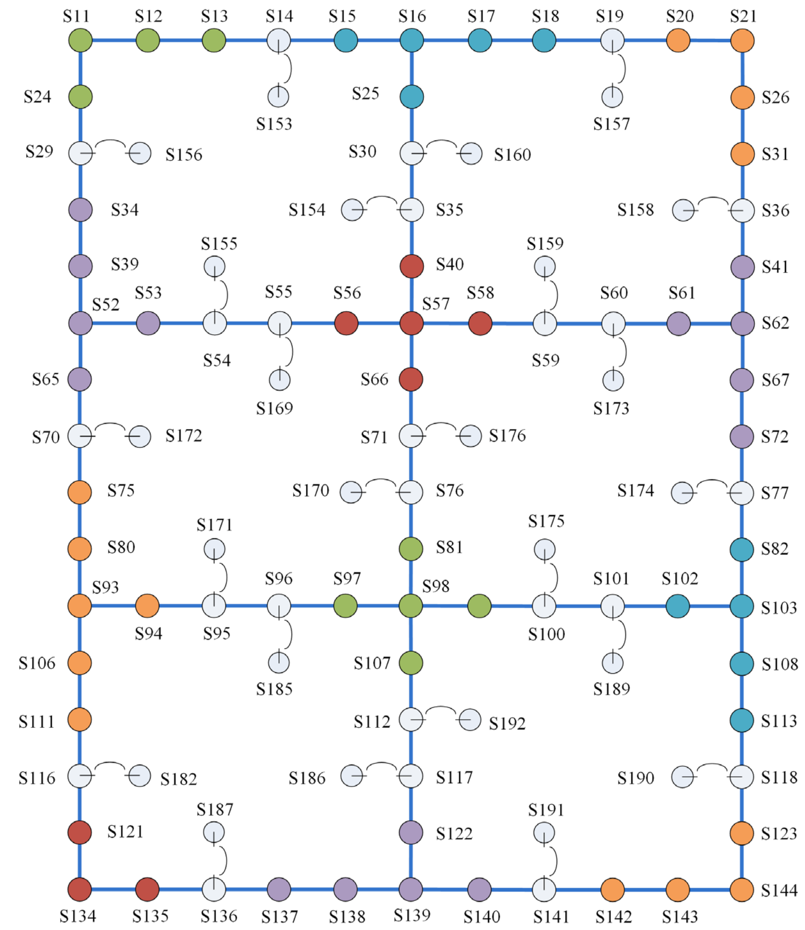
Low-Voltage Grid Network Model

Reduced IEEE LVTNS Model – Model Reduction

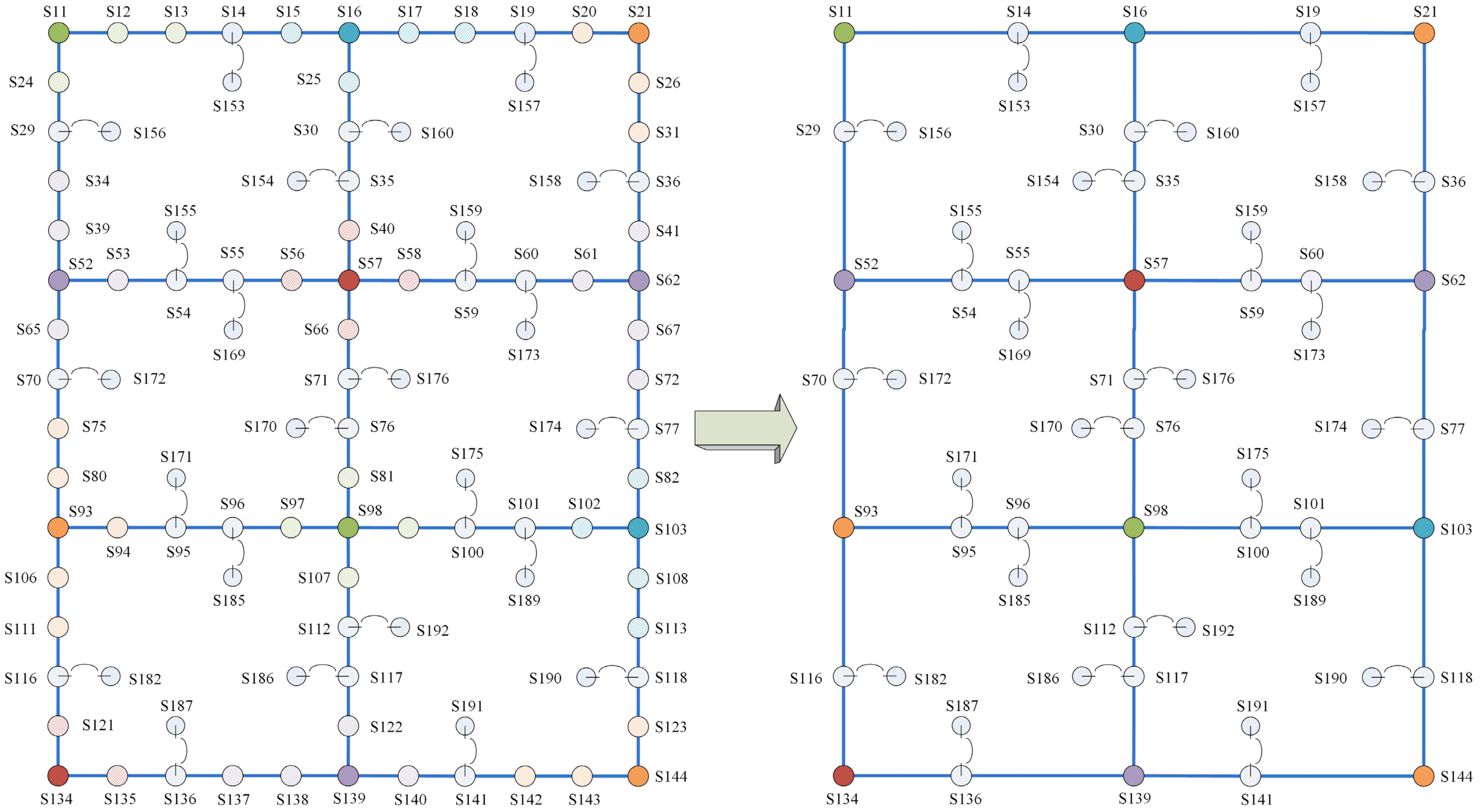
- Original Secondary Network



- Reduced Secondary Network
  - Removed left-hand side secondary network
  - Removed network XFMER on the "new" boundary

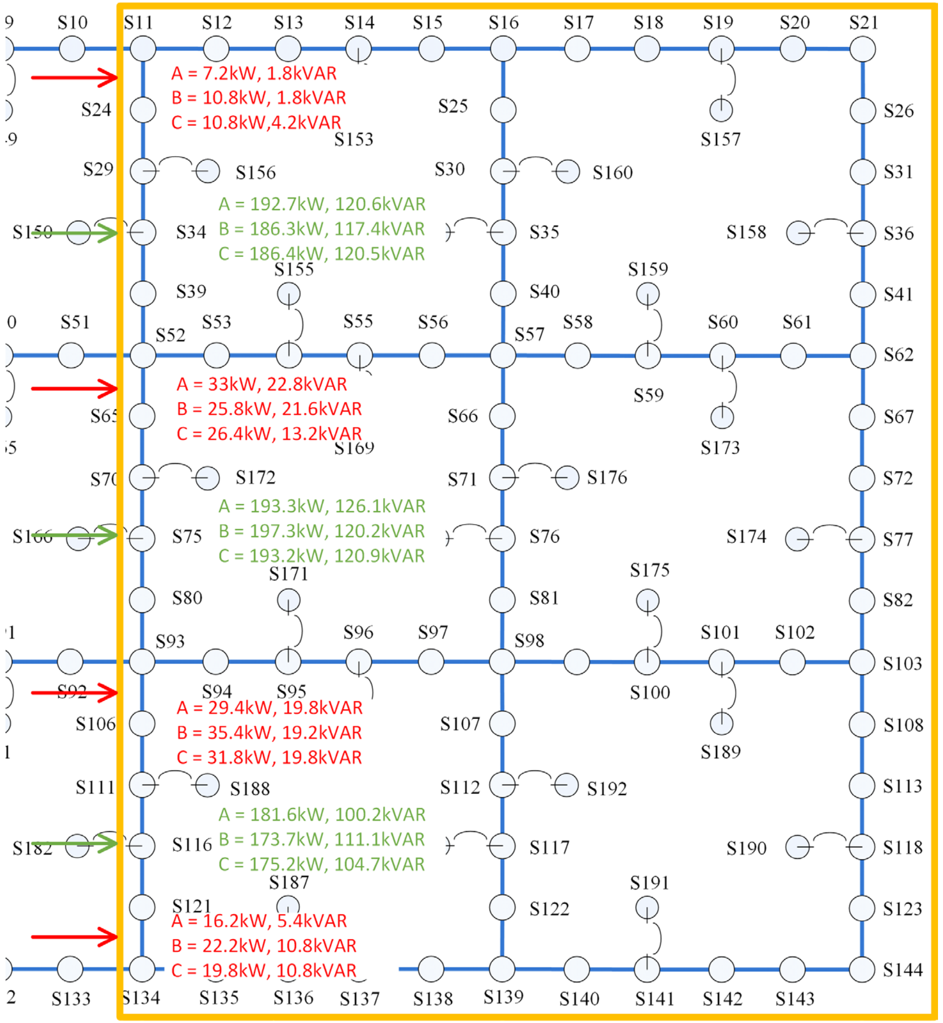


- Merge load buses to reduce total number of buses

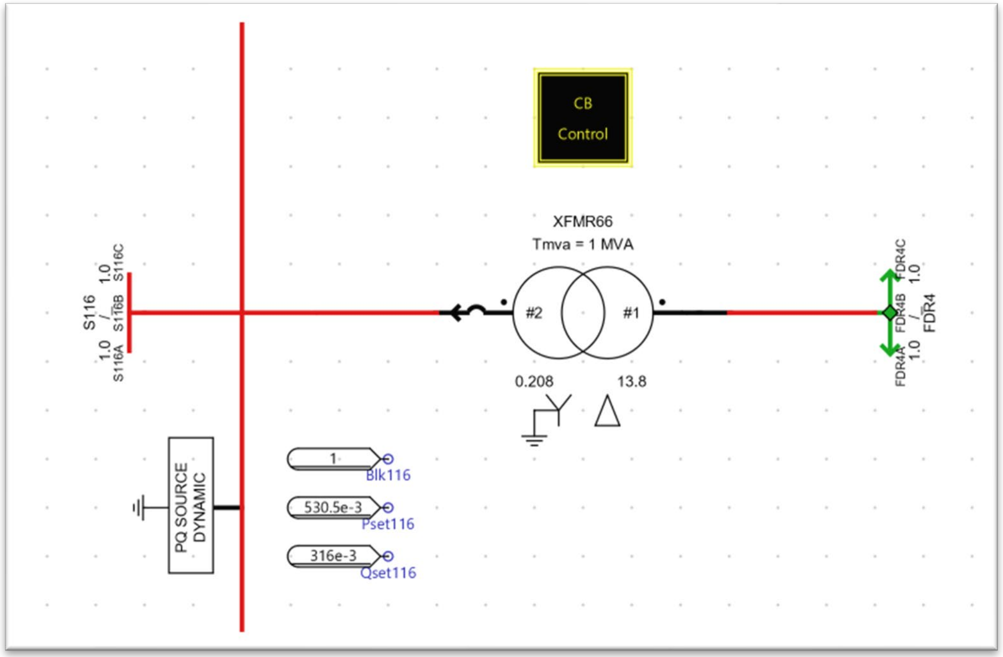


Reduced IEEE LVTNS Model – Model Reduction

- Current to be compensated
  - Cable current (red);
  - Network transformer current (green)

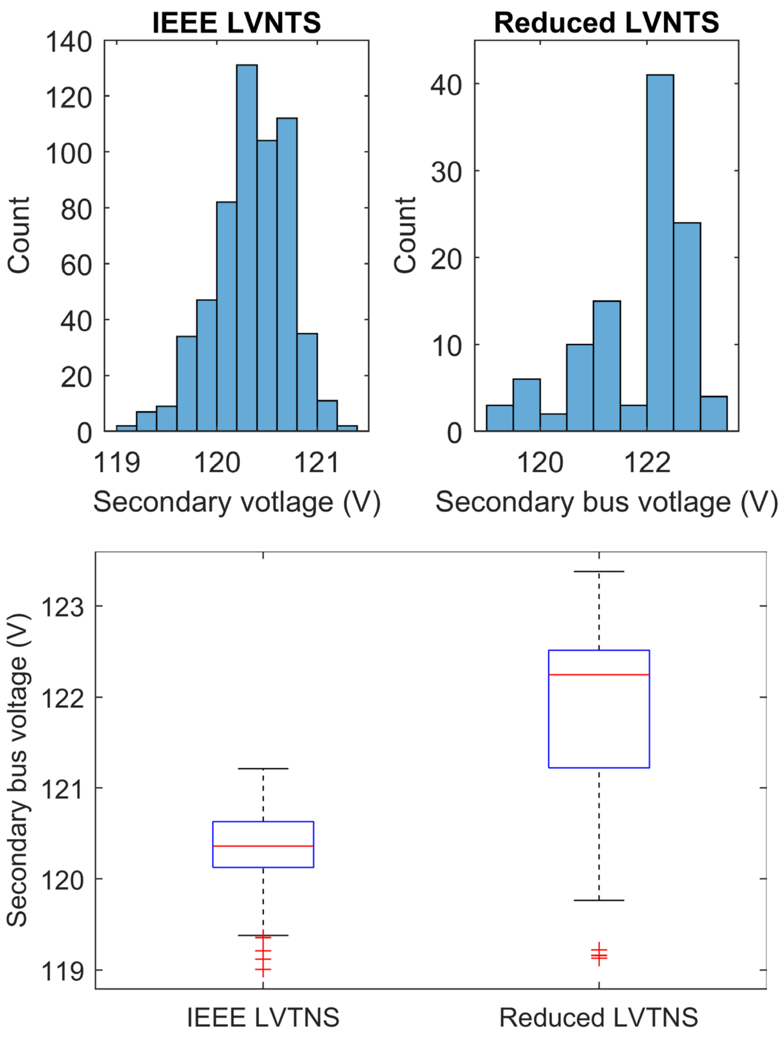


- Adding constant PQ sources
  - Adjust the load on edge nodes to compensate the power injection from cables, i.e., S11, S52, S93, and S134.
  - Add constant PQ sources to represent compensated power injection from network transformers

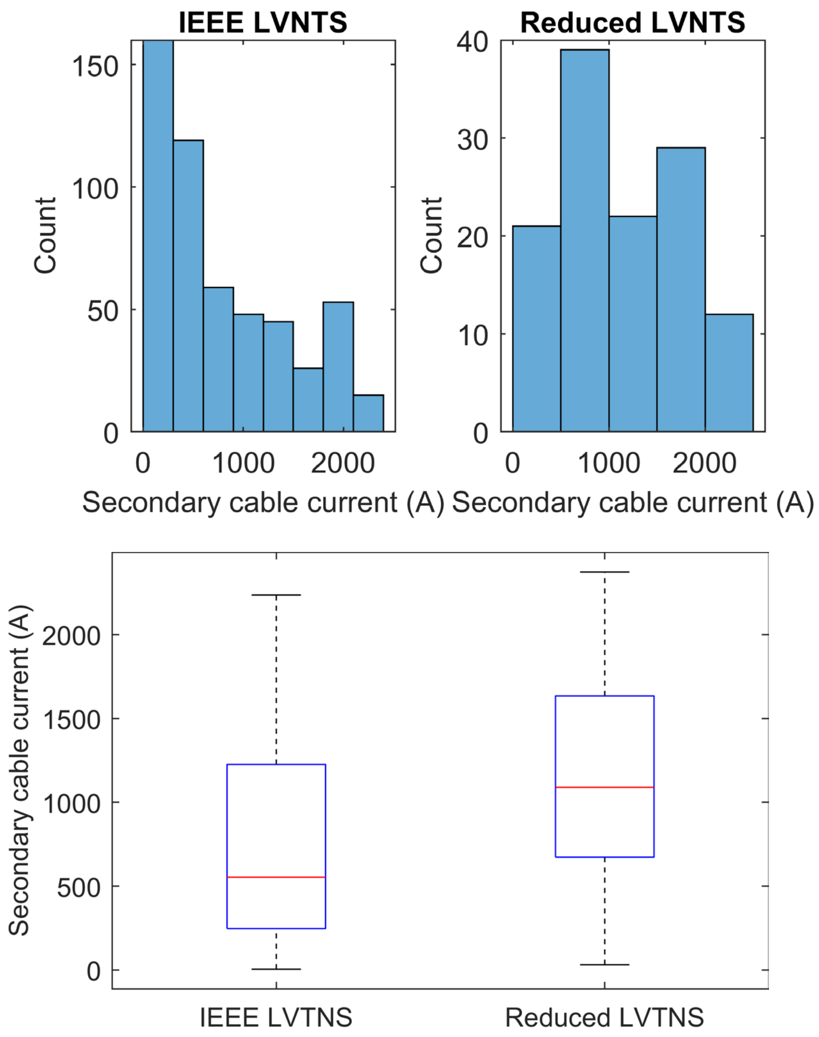


Reduced IEEE LVTNS Model – Model Validation

- Statistical comparisons with original IEEE LVTNS



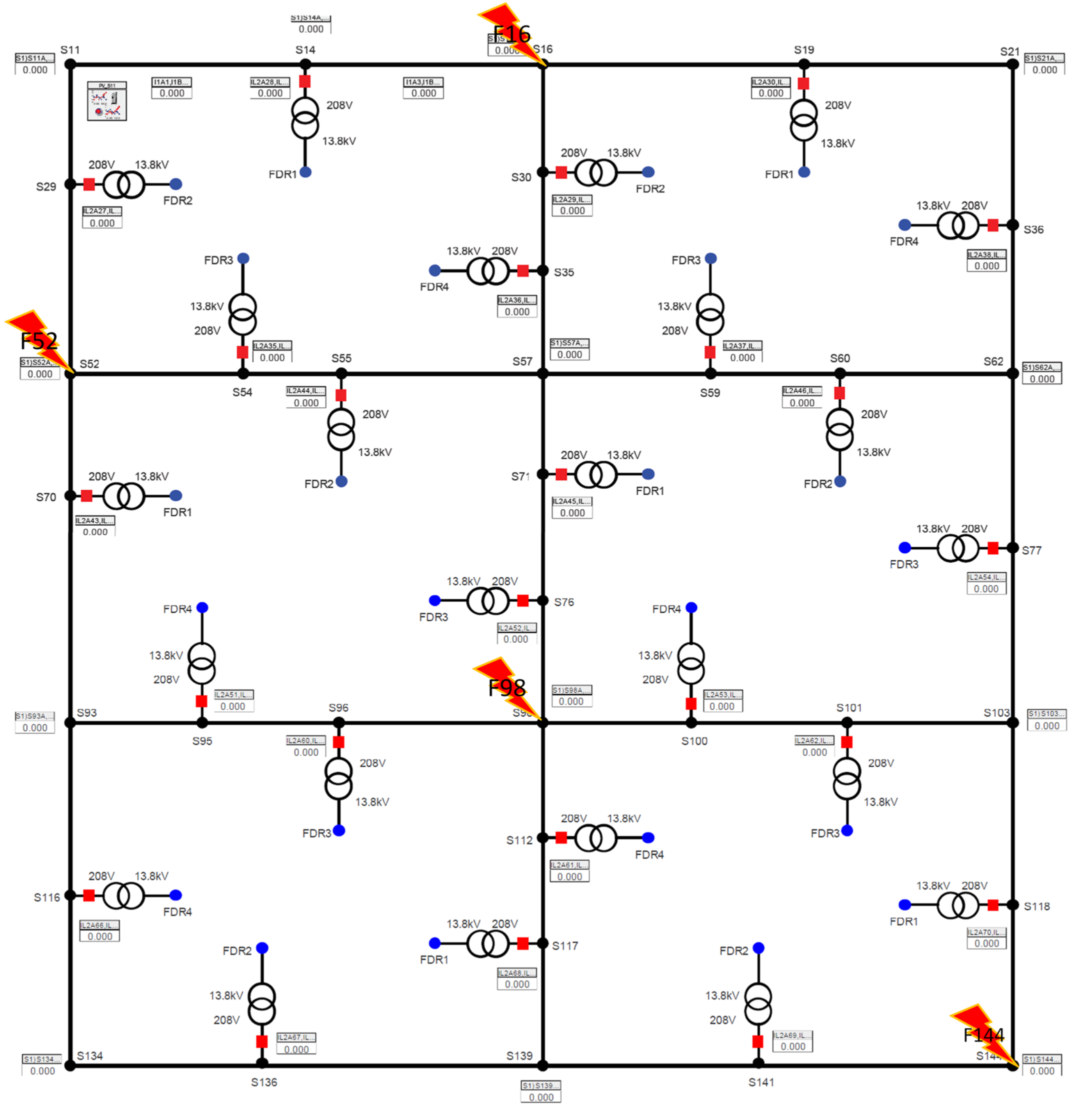
Voltage



Current

Reduced IEEE LVTNS Model – Model Validation

- Spot check locations



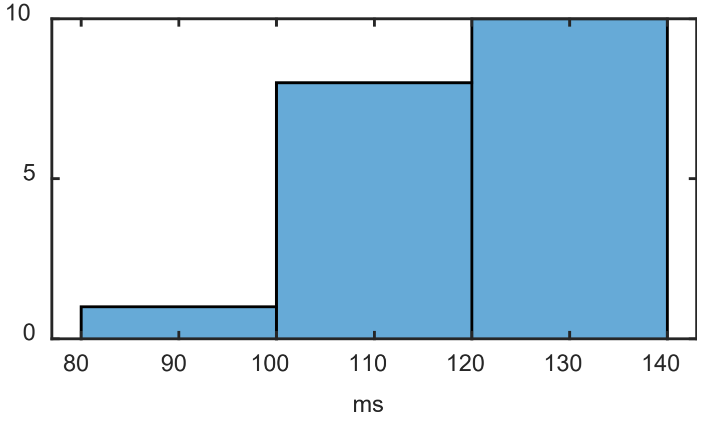
- Comparison with OpenDSS
  - Can achieve very close match with OpenDSS
  - One expected exception: S52
    - OpenDSS models original IEEE LVTNS in which S52 is a "middle bus", whereas RTDS models S52 on a boundary
    - S52 RTDS simulation results are on the same scale as other boundary buses, e.g., S16
    - S98 RTDS simulation results are on the same scale as "middle buses" in OpenDSS, e.g., S52

Location	1Ph Fault Current (A)			2Ph Fault Current (A)			3Ph Fault Current (A)			Comment
	OpenDSS	RTDS	%Error	OpenDSS	RTDS	%Error	OpenDSS	RTDS	%Error	
S16	78976	79904	1%	101044	99171	2%	121630	118252	3%	Good match
S52	123304	85418	31%	158422	103374	35%	193457	119716	38%	Expected
S98	123389	125831	2%	157966	155933	1%	192699	189080	2%	Good match
S144	49269	49477	0%	64188	63230	1%	76679	76467	0%	Good match

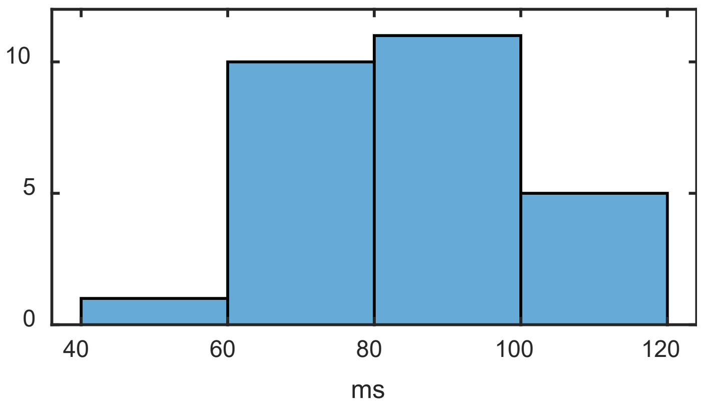
Network Protector Relay Model

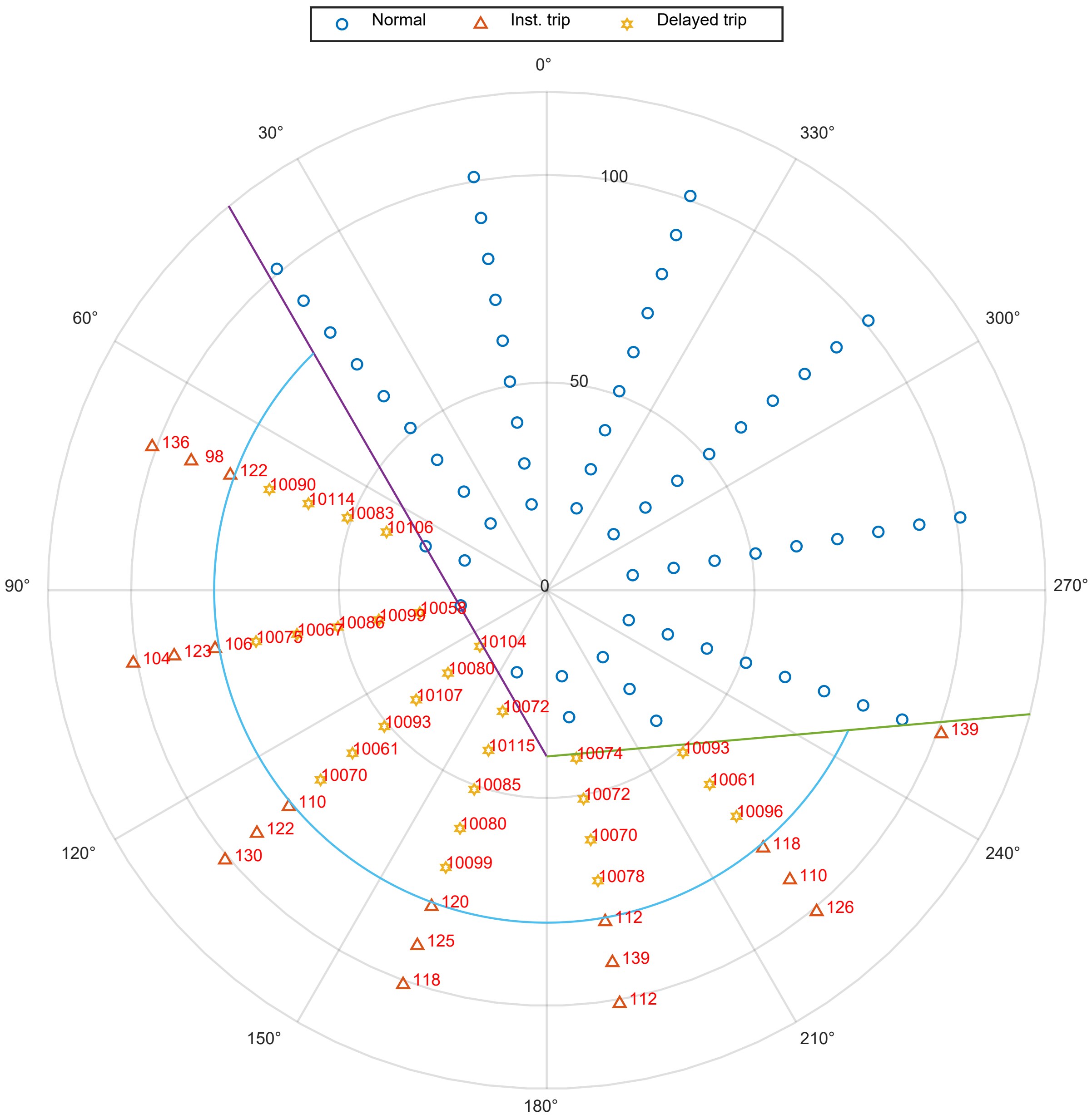
HIL Simulation – Reverse Trip Probing

- Average inst. trip time: 119.4947 ms



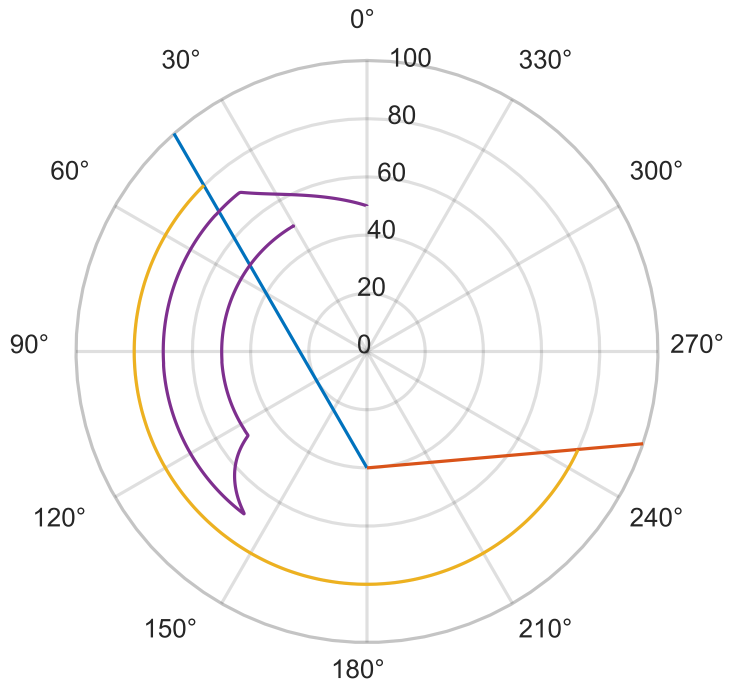
- Average delayed trip time: 10sec + 84.7407 ms



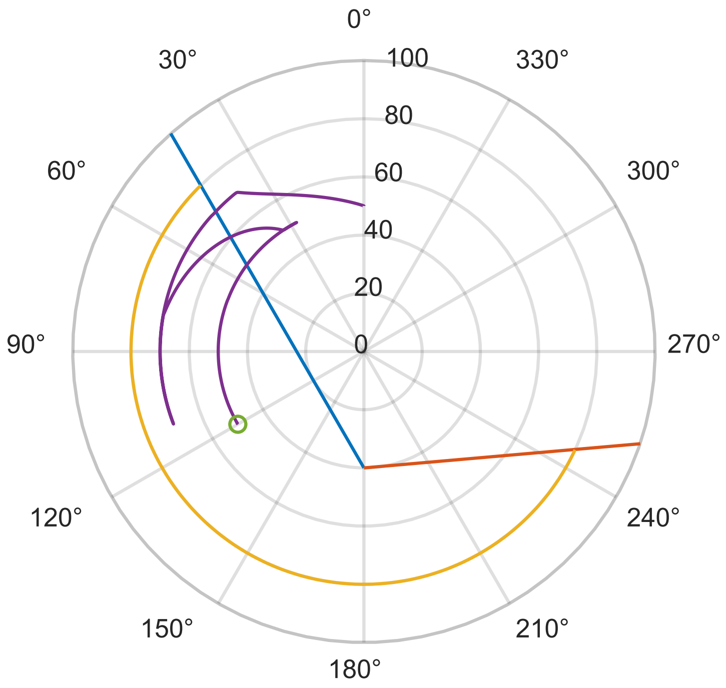


HIL Simulation – Reverse Trip Dynamic Tests

- In and out
  - Delayed trip timer got reset
  - No trip command is issued

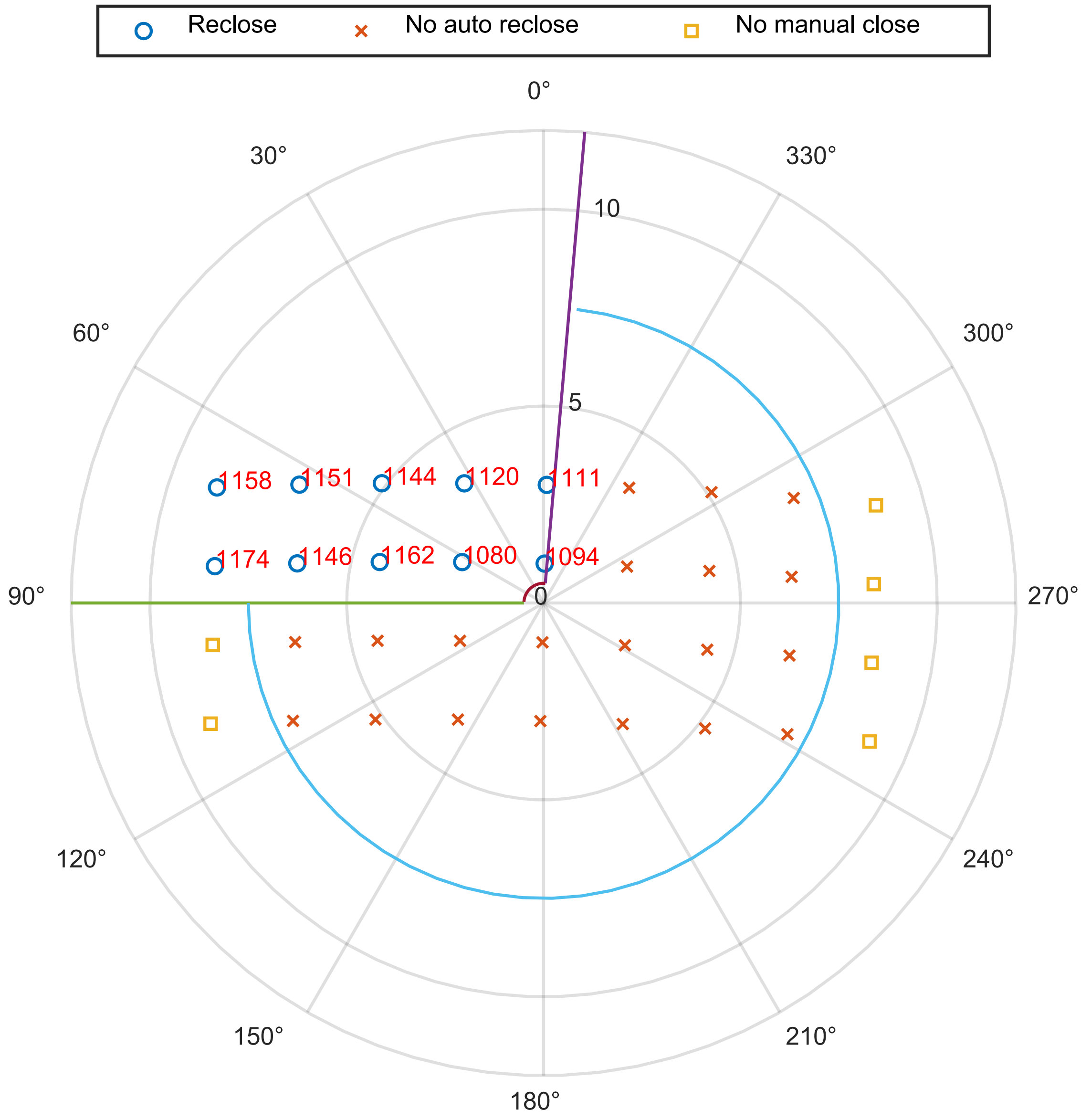


- In-out-in
  - Delayed trip timer got reset when current vector went out
  - Delayed trip timer starts when the current vector enters the trip zone the second time
  - Trip time:
    - 10.0856 sec (hardware) and 10.0840 sec



HIL Simulation – Auto Reclose Probing

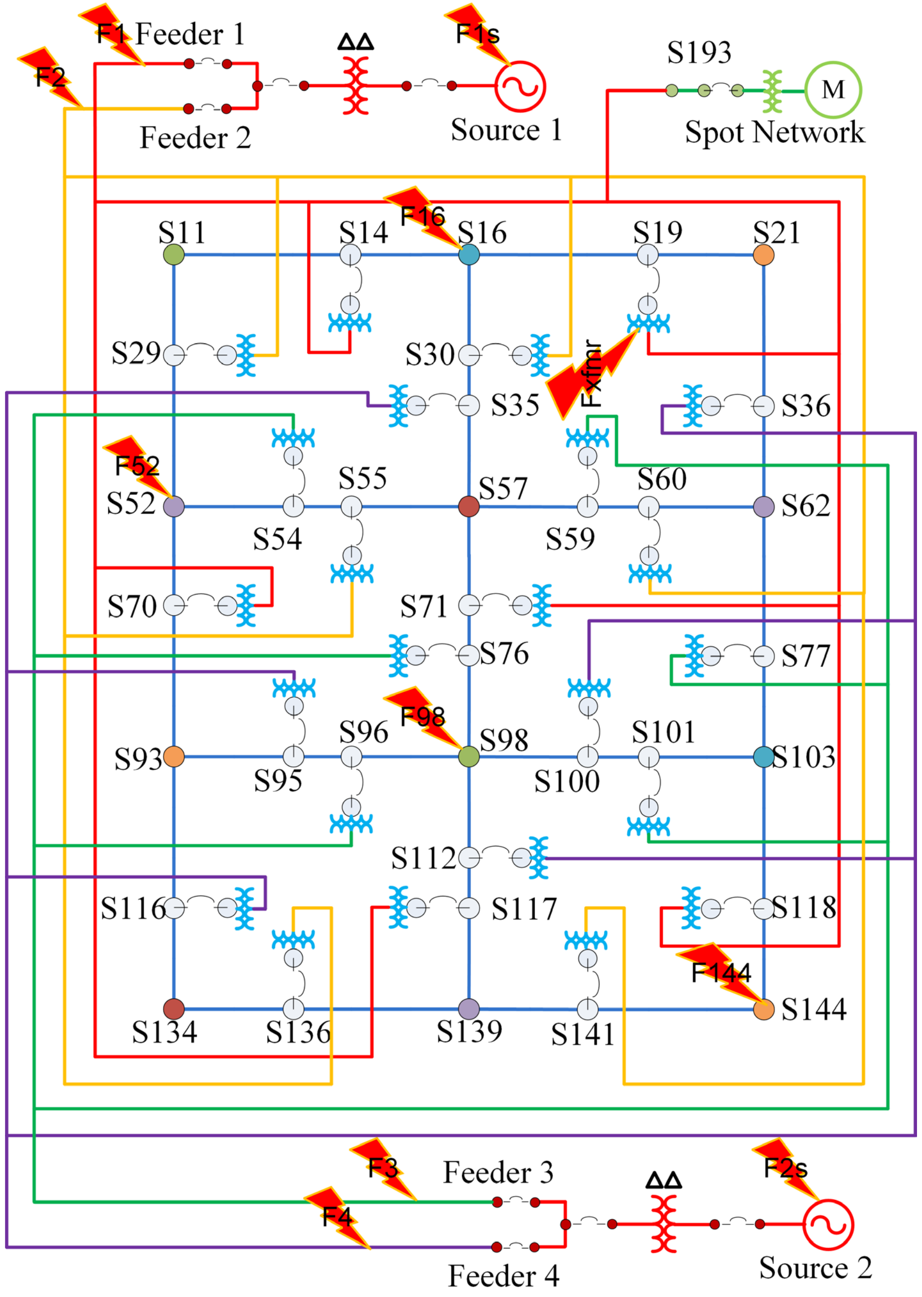
- Average auto reclose time: 1.133 sec
- If phasing voltage is outside of the block-auto-reclose zone, a trip signal is issued to prevent manual close operation. (Rolled Phase or Phase Reversal)



HIL Protection Study – Impact Assessment and Mitigation Strategy

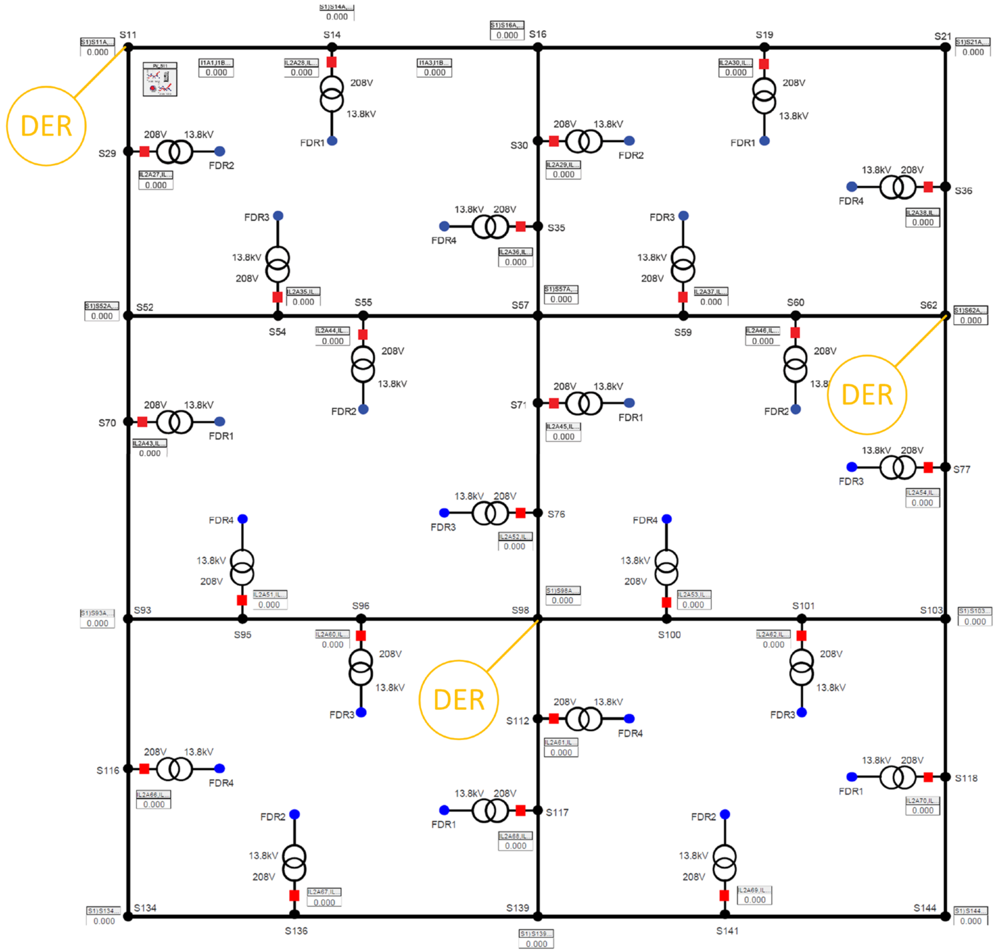
HIL Test Plan

- Fault locations
  - Secondary, primary (w reclose), source, and network transformer
- Fault types:
  - AG, AB, ABG, and ABC
- Fault inception angle:
  - 0°, 60°, and 90°.
- Fault impedance:
  - solid fault (1e-6 Ohm)
  - high impedance fault (30 Ohm) only for MV
- DER penetration levels:
  - 0% - 100%

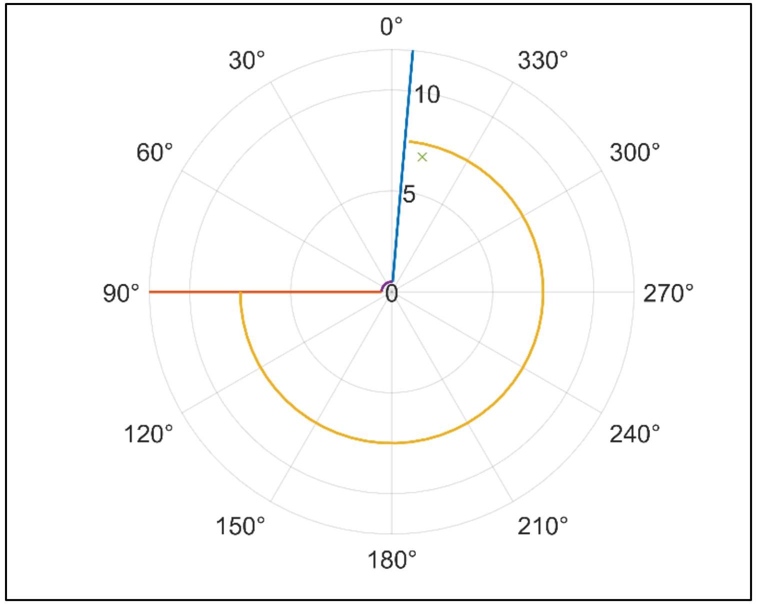


Scenario 1: Low-Voltage DER Backfeed

- DER locations
  - 3 aggregated DER to achieve up to 100% penetration

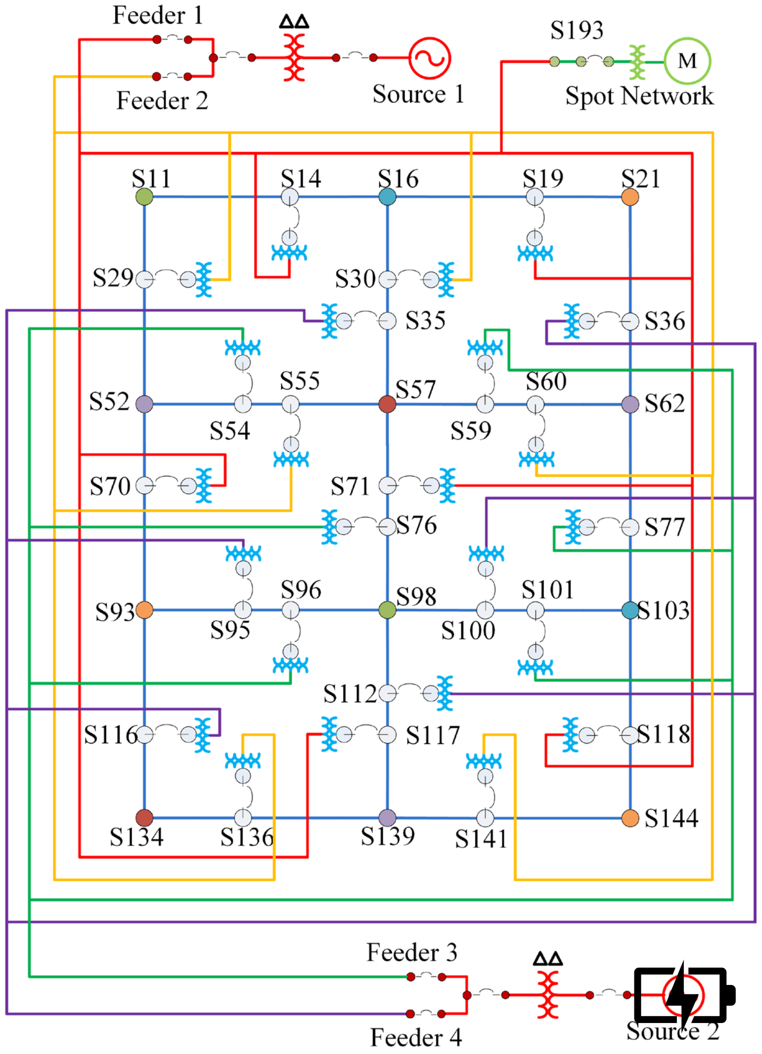


- Impact on reverse trip function
  - Three aggregated DER will cause considerable reverse power flow in nearby network transformers, hence, tripping nearby NP relays.
- Impact on auto-reclose
  - NP relays near aggregated DER cannot auto-reclose due to the leading network voltage.

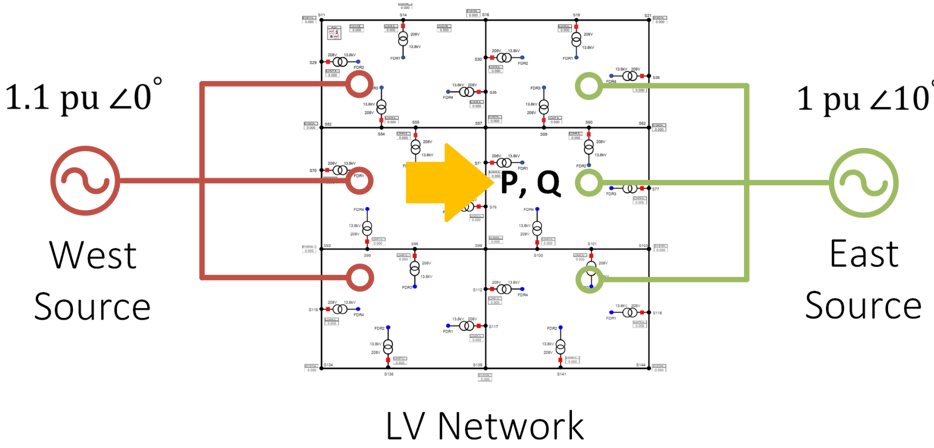


Scenario 2: MV DER Source

- DER penetration: 50% (6 MVA)
  - Temporarily lost utility source #1
  - Grid forming battery inverter at the source #2



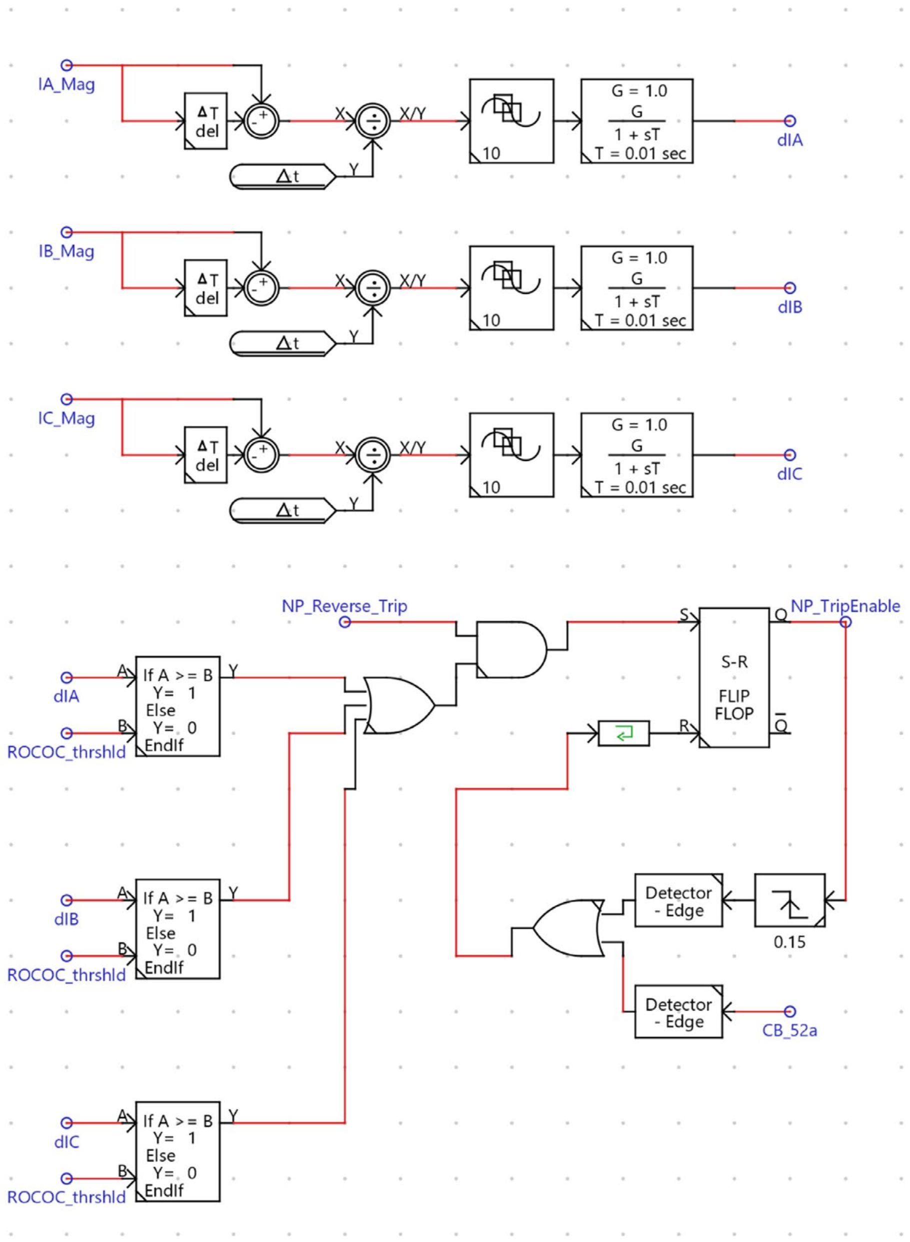
- Impact on auto-reclose
  - When restoring the parallel MV sources, phasing voltage is in the "no manual re-close" region (Rolled Phase or Phase Reversal)
    - lack of synchronization between the energy storage grid-forming inverter and the utility source



- Recommendations:
  - NP relay auto-reclose augmented with automatic synchronizer logic.
  - Add frequency nudge control input to grid forming inverter. (may need communication)
  - Discriminate healthy DER backfeed and unintentional power flow between MV sources

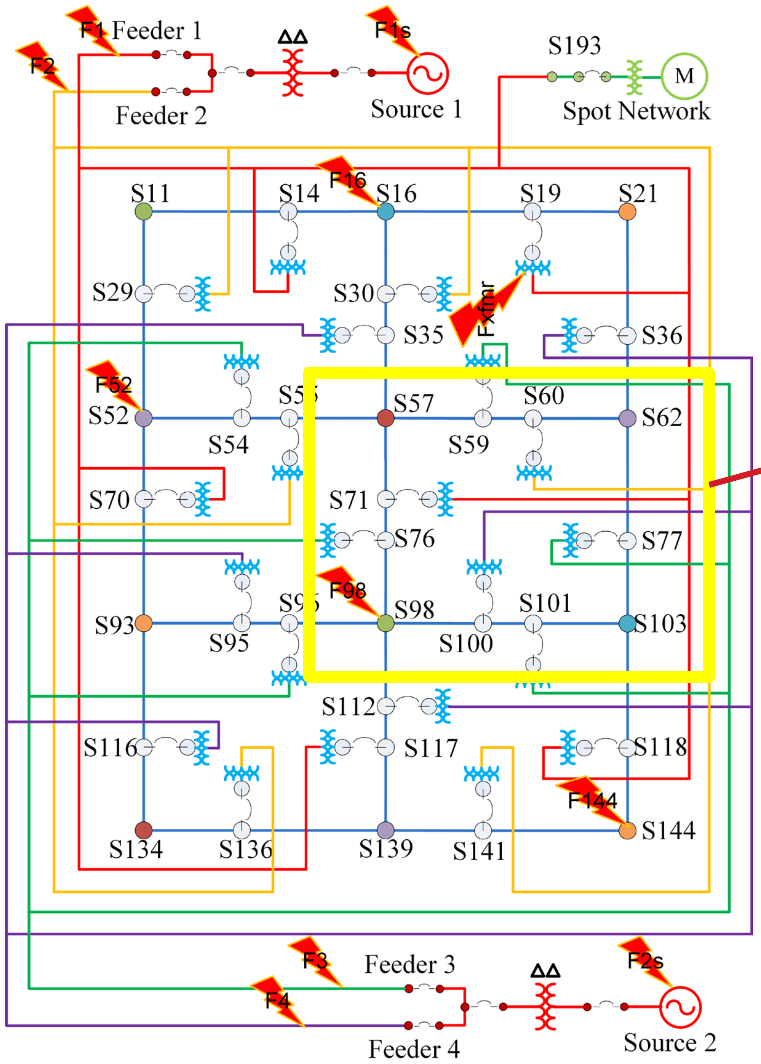
Rate-of-Change-of-Current (ROCOC) based Blocking Scheme

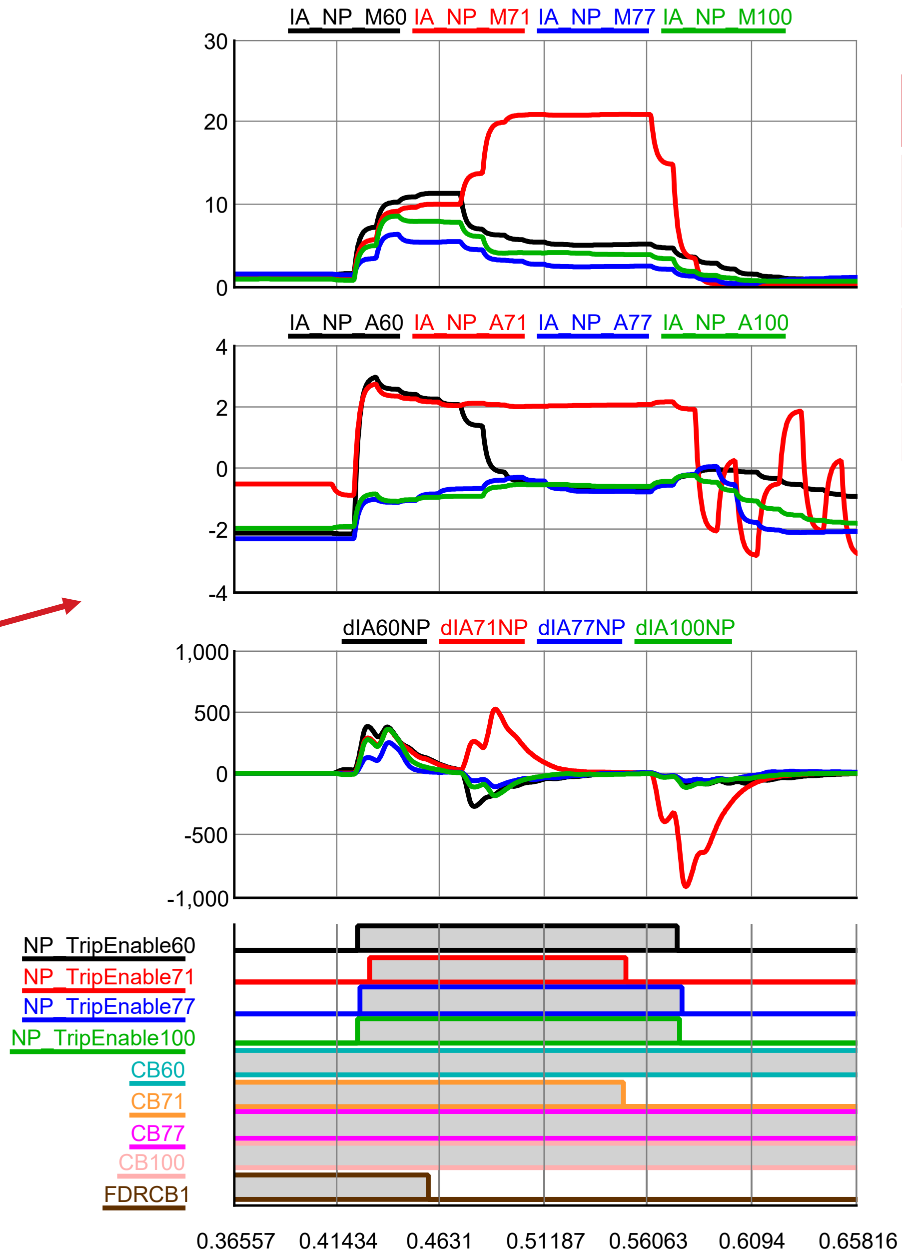
- Calculate derivatives of IA, IB, and IC phase current magnitudes
  - Filtering: time constant and moving average
- Design ROCOC threshold, impacted by:
  - Network apparent impedance (network-side path feeding fault), source impedance, DER penetration level, and fault resistance
- Supervise NP relay reverse trip
- Drop out by 150ms or reset by breaker 52a contact close.



Rate-of-Change-of-Current (ROCOC) based Blocking Scheme – Example

- DER penetration: 100% (13.5 MVA)
  - ABC Fault on feeder 1 – F1 location





FDR#	Label
FDR#1	71
FDR#2	60
FDR#3	77
FDR#4	100

Conclusions

Key takeaways – protection and operating issues

- Protection philosophy and relay characteristics in IEEE Standard Requirements for Secondary Network Protectors (IEEE Std C57.12.44™-2014) need to be revamped to accommodate DER and microgrids.
- To accommodate DER backfeed while remaining secure and reliable for faults on MV feeders, we recommend options for a rate-of-change-based blocking scheme.
- If NP relays allow reverse current for DER backfeed, MV sources can exchange power across the LV network. We must develop a protection scheme that can discriminate among reverse fault current, healthy DER backfeed, and unintentional power flow between MV sources.

Conclusions – research progress and plans

- This paper shares research results to date for today's low-voltage network protection experiences, challenges, and future testing needs, including insights from four major LV network users in the United States.
- The program has created a robust modeling platform for ongoing testing NP relays, inverter models, and control schemes in LV networks with DER and internal or MV-connected microgrids.
- This paper presents a methodology for creating a network protector relay digital twin via hardware-in-the-loop data generation and validation. The use of relay digital twins significantly reduces the hardware requirements and associated costs.
- 2023 research continues to study new relay models and relay characteristics to meet industry needs for reliable LV network operation with widespread DER penetration and microgrid deployment.

ACKNOWLEDGMENT

This article has been authored by an employee of National Technology & Engineering Solutions of Sandia, LLC under Contract No. DE-NA0003525 with the U.S. Department of Energy (DOE). The employee owns all right, title and interest in and to the article and is solely responsible for its contents. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this article or allow others to do so, for United States Government purposes. The DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan https://www.energy.gov/downloads/doe-public-access-plan.

Questions?

Dr. Zheyuan Cheng
zcheng@quanta-technology.com
(984) 500-8585

Eric A. Udren
eudren@quanta-technology.com
(412) 596 6959