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Low Voltage Network Protection Utility Workshop - Summary and Next Steps

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ABSTRACT

Increased penetration of Distributed Energy Resources and microgrids have fundamentally changed the operational characteristics of Low Voltage (LV) network systems. Current LV network protection philosophy and practice are due for a significant revamp to keep up with changing operating conditions. This workshop invites four of the major LV network users in the US to discuss the challenges they face today and the new technologies they have been experimenting with. In light of this workshop discussion, use cases for further hardware-in-the-loop testing efforts are proposed to evaluate new LV network protection solutions.

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EXECUTIVE SUMMARY

The workshop is a step for a research program in which Sandia National Laboratories (SNL) and Quanta Technology LLC (QTech) teams have been investigating the state of industry practice, needs, and opportunities in the application of protection, control, and monitoring of low voltage grid and spot power distribution networks widely used for serving concentrated loads in dense urban areas with high reliability.

Phase I of the project, carried out in 2020, has identified current practices and challenges for low voltage network protection and control via utility literature research, interviews, and inventions of the QTech and SNL investigators. The potential research directions going forward include a wide range of low voltage network topics including component design, instrument transformer improvements, protection schemes based on fuses and relays, telecommunications applications, device monitoring, and study of operating conditions.

This workshop is the kickoff event in the phase II research program. The workshop was hosted virtually via Microsoft Teams on 08/20/2021 from 9:00 am to 12:40 PM EST. Utility subject matter experts from Consolidated Edison Company of New York, Commonwealth Edison Company, Oncor, and PEPCO/PHI were invited to participate in this half-day workshop. In total 18 participants attended the workshop, among which 12 were from utilities. The workshop reviewed the key findings in the Phase I project work, the RTDS® testing concept, surveyed current low voltage network protection situations, challenges, and future testing needs. During the half-day workshop, four contemporary low voltage network challenges were discussed in detail:

1. Protection in low voltage networks penetrated by distributed energy resources (DER)
2. Voltage profile management in low voltage networks
3. Low voltage network fault location and fast clearing
4. Microgrid protection challenges

Among the research topics discussed, the project team decided to pursue the first and likely the most pressing issue that participating utilities are facing – DER-induced reverse real and reactive power flow issues. Other topics are reserved for future research efforts.

The remainder of the Phase II research efforts are dedicated to developing appropriate hardware-in-the-loop real-time digital simulation (RTDS) models of LV networks with DER including protective relay models, as well as procuring commonly used network protector hardware to benchmark and evaluate existing and proposed new protection schemes. The ultimate test goals in the Phase II research are:

1. Evaluate the impact of DER reverse real power flow on the existing protection schemes.
2. Assess the impact of smart inverter reactive power injection on the LV network protection.
3. Propose and benchmark new protection solutions that allow more DER P/Q back-feed without protection misoperations.

ACRONYMS AND TERMS

Acronym/Term	Definition
AMI	advanced metering infrastructure
CB	circuit breaker
ComEd	Commonwealth Edison Company
ConEd	Consolidated Edison Company of New York
CT	current transformer
DER	distributed energy resources
IBR	inverter-based resources
IR	infrared
LV	low voltage
NP	network protector
NT	network transformer
NU	network unit
PEPCO	PEPCO/PHI
QTech	Quanta Technology LLC
RTDS	real-time digital simulation
SCADA	supervisory control and data acquisition
SNL	Sandia National Laboratories

1. INTRODUCTION

1.1. Workshop Background

The workshop is a step for a collaborative research program between Sandia National Laboratories (SNL) and Quanta Technology LLC (QTech). The aforementioned teams have been investigating the state of industry practice, needs, and opportunities. The focus has been on the application of protection, control, and monitoring of low voltage mesh and spot power distribution networks that are widely used for serving concentrated loads in dense urban areas with high reliability. Increasingly, customers are connecting distributed energy resources (DER) to the low voltage network. This undermines the long-standing foundational assumptions upon which protection design is built [1]. Furthermore, low voltage networks and supply infrastructure occasionally suffer faults or misoperation that can black out major load centers, creating serious safety and public-impact consequences.

Phase I of the project in 2020 has identified current practices and challenges for low voltage network protection and control via literature review, utility interviews, and inventions of the QTech and SNL investigators [2]. The potential research directions going forward include a wide range of low voltage network topics including component design, instrument transformer improvements, protection schemes based on fuses and relays, telecommunications applications, device monitoring, and study of operating conditions.

This workshop is the next event in the research program. Along with a review of and feedback on findings so far, the workshop aims to gather specific and detailed experiences and needs. The discussion includes a major focus on modeling of low voltage networks, the distribution system that serves low voltage networks, component devices of low voltage networks, and integration of new elements such as inverter-based resources (IBR).

1.2. Workshop Attendees

QTech personnel; SNL personnel, as well as utility subject matter experts from Consolidated Edison Company of New York (ConEd), Commonwealth Edison Company (ComEd), Oncor Electric Delivery, and PEPCO/PHI (PEPCO) were invited to participate in this half-day workshop. In total, 18 participants attended the workshop. Among those in attendance were 12 utility participants. Table 1-1 below provides a detailed list of invited participants and whether they attended.

Table 1-1 Workshop attendance

Participants	Company	Attendance
Eric Udren	Quanta Technology	Yes
Juergen Holbach	Quanta Technology	Yes
Zheyuan Cheng	Quanta Technology	Yes
David Hart	Quanta Technology	Yes
Matt Reno	Sandia National Laboratories	Yes
Michael Ropp	Sandia National Laboratories	Yes
Christopher Jones	Consolidated Edison Company of New York	Yes
Jeremy Preas	Oncor Energy Delivery, Ft. Worth, TX	No
Ken Hanus	Oncor Energy Delivery, Ft. Worth, TX	Yes
Alexi Paaso	Commonwealth Edison Company, Chicago	No

Participants	Company	Attendance
Patrick Arns	Commonwealth Edison Company, Chicago	No
Marina Mondello	Commonwealth Edison Company, Chicago	No
Ayun Brown	Commonwealth Edison Company, Chicago	Yes
Najwa Abouhassan	Commonwealth Edison Company, Chicago	No
Boushra Soliman	PEPCO/PHI, Washington, DC	No
Scott Placide	PEPCO/PHI, Washington, DC	Yes
Robert Spelman	PEPCO/PHI, Washington, DC	Yes
Jacob Burlin	PEPCO/PHI, Washington, DC	Yes
Cesar Santamaria	PEPCO/PHI, Washington, DC	Yes
Bee Morton	PEPCO/PHI, Washington, DC	Yes
Jeffrey Chai	PEPCO/PHI, Washington, DC	Yes
Justin Bradfield	PEPCO/PHI, Washington, DC	No
Scott R Canning	PEPCO/PHI, Washington, DC	Yes
Jhonnal Daniels	PEPCO/PHI, Washington, DC	Yes
Alexander J Davis	PEPCO/PHI, Washington, DC	Yes

1.3. Workshop Agenda

The workshop was hosted virtually via Microsoft Teams on 08/20/2021 from 9:00 am to 12:40 pm EST. The workshop reviewed the key findings in Phase I of the project, the RTDS testing concept, surveyed contemporary low voltage network protection situations, general protection challenges, and future testing needs. Table 1-2 provides a detailed agenda of the half-day workshop. The full slide deck used during the workshop is attached in Appendix A: Workshop Slides.

Table 1-2. Workshop Agenda

Topic	Presenter
Introductions: project and workshop goals	Eric Udren (QTech); Matt Reno (SNL)
Overview of Quanta 2020 Phase 1 work for Sandia National Labs • Overview of low voltage grid and spot distribution network operation • Issues and research opportunities identified	Eric Udren (QTech)
Attendees describe current situations, issues, interests, future needs, and directions for low voltage networks	All participants
Break	
RTDS® testing approach and modeling of components • Hardware-in-the-loop simulation • IBR modeling in RTDS	Zheyuan Cheng (QTech)
RTDS model topologies for low voltage networks with DER and with microgrids	Juergen Holbach (QTech)
Discussion and feedback on proposed modeling and research	All participants
Wrap-up and future engagements as identified	All participants

2. DISCUSSION OF LOW VOLTAGE NETWORK CHALLENGES

2.1. Definition of Low Voltage Network

The low voltage network referred to in this report is also known as a secondary network. Secondary networks are meshed power distribution systems that are often found in urban downtown areas and dense load centers. As its name suggests, low voltage networks operate at a low voltage level (120/208 V or 277/480 V). These low voltage networks have relatively high reliability because they are typically designed with redundant paths to the substation source. Generally, they are categorized into two types: (1) Low Voltage Grid Networks, and (2) Low Voltage Spot Networks. Figure 2-1 and Figure 2-2 present a typical low voltage grid network and a typical low voltage spot network respectively.

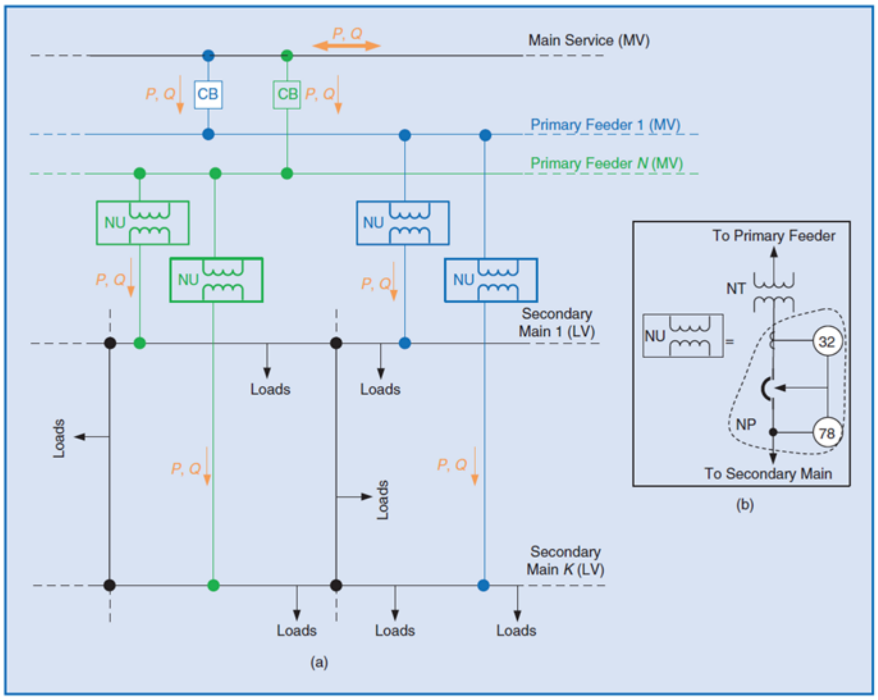

Figure 2-1. Typical Low Voltage Grid Network: (a) the network topology, showing the directions of the active (P) and reactive (Q) power flows, and (b) a network unit (NU). CB: circuit breaker; LV: low voltage; NP: network protector; NT: network transformer. [3]

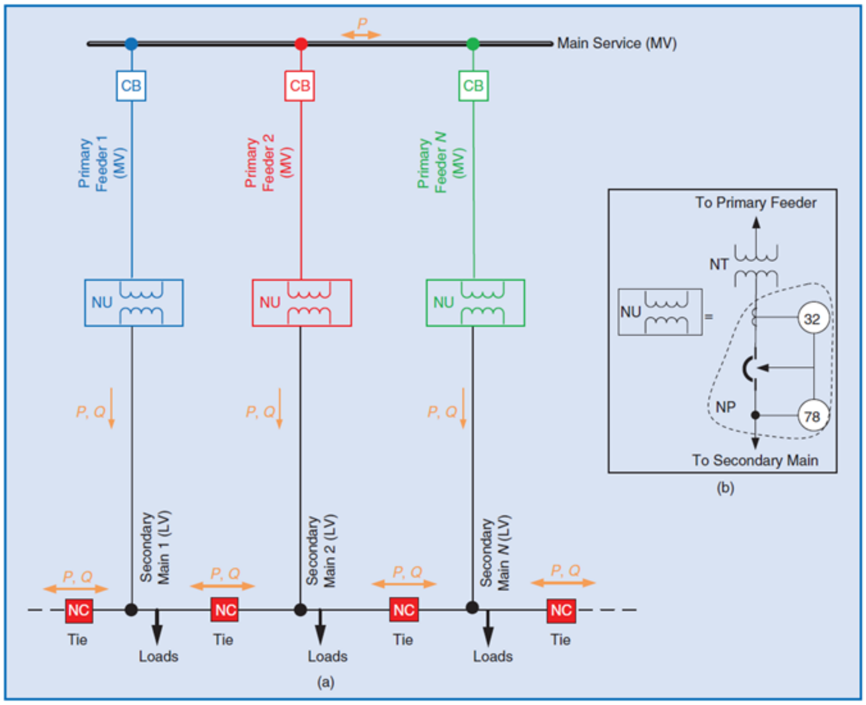

Figure 2-2. Typical low voltage spot network: (a) the circuit topology, showing the P, Q power flow directions, and (b) an NU. NC: normally closed switch. [3]

2.2. Challenge #1: Protection in Low Voltage Network with DER Penetration

One of the most frequently visited topics in the workshop is about the DER penetration in the low voltage networks. Participating utilities all reported growing integration of DERs. For example, PEPCO's recent renewable DER integration target is 10%. As more DERs are added to the low voltage network, the added generation could exceed the demand peak resulting in a back-feed of power to the primary feeder or main service. As depicted in Figure 2-3, when DER generation in the secondary low voltage network is higher than the load served, the reverse power flow through network protectors and main service circuit breakers.

The low voltage network with DER reverse power flow is one of the most challenging operating scenarios reported by the utility participants. Some current challenges reported by utility participants are:

- Preventing misoperation of protection devices when DERs are present.
- Reliably detecting DER back-feed and primary feeder faults.
- Implementing DER management system (DERMS) to operate and monitor large numbers of DERs.
- Leveraging DERs to reduce peak demands and avoid curtailment.
- Increasing DER hosting capacity for the low voltage network without impacting the protection and reliability.

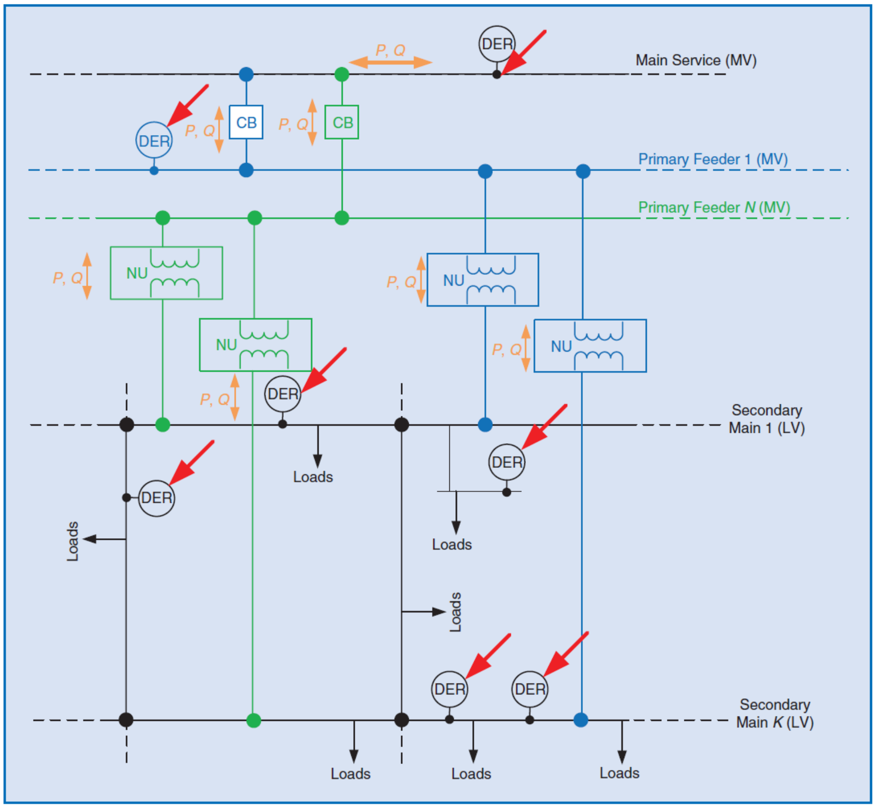

Figure 2-3. A low voltage grid network with DERs added (indicated by the red arrows). The DERs are larger than the loads served, and thus the power flow through the NUs can now be bidirectional under normal operating conditions, as indicated by the P, Q arrows. [3]

Two novel protection practices for avoiding maloperation of protection devices in the presence of DER-induced reverse power flow, as reported by ConEd, are:

1. Rate-of-change based detection: Use rate of change settings to distinguish slow changes in current during back-feed (rapid change is the fault).
2. Substation transfer trip: Install transfer trip capability on network protectors; configure network protectors in an extremely insensitive mode; and let the substation relay transfer trip network protectors.

According to ConEd's experience, the first rate-of-change method is not perfect, as it may have gaps and may misoperate for external transmission faults. Additionally, setting the rate-of-change threshold can be a case-by-case task for different low voltage networks. Although these two practices are currently used in ConEd's system, neither is optimal.

Currently, the low voltage networks with high DER to load ratios are usually set up as spot networks. The grid networks, such as those in New York City, have less DER penetration. However, the DER penetration in grid networks is likely to increase in 5-10 years.

2.3. Challenge #2: Voltage Profile Management in Low Voltage Network

Another challenge is voltage regulation. Significant DER back-feed could cause serious voltage profile issues, such as overvoltage and fluctuation, which will in turn put stress on voltage regulators in the low voltage network. Nowadays, advanced smart inverter functions, e.g., droop control, constant power, current, and voltage control modes, become readily available due to earlier standardization efforts such as IEEE 1547-2018 [4]. If used intelligently, these newly added functionalities may provide more flexibility or even solve some of the voltage profile management problems. Some current challenges reported by utility participants are:

- Reactive power injection from DER smart inverters could negatively impact voltage regulation. Additional coordination between IBRs and voltage regulators is needed.
- IBRs associated with DERs need to be leveraged to improve the low voltage network voltage profile.
- For weaker areas, it is difficult to manage the voltage profile. Voltage profile changes over season, time, and weather must be considered.

As for voltage regulation practice, ConEd reported that they typically use fixed tap network transformers, whereas PEPCO uses network transformers with automatic tap changers. The control coordination between the voltage regulator and smart inverters can be circumvented if fixed tap network transformers are used across the low voltage network. However, the tap positions need to be determined based on the actual voltage drops in the field that typically correlate to distance to the substations and seasonal voltage profile.

An interesting observation related to voltage control is reported by ConEd. Based on their experience, conservation voltage reduction generally allows higher DER reverse power flow.

2.4. Challenge #3: Low Voltage Network Fault Location and Fast Clearing

One of the most pressing issues the invited utilities face is the detection and fast clearing of low voltage network faults. Generally, the protection philosophy dictates that the network protectors trip for any reverse currents. Secondary networks are primarily protected using passive devices such as fuses and cable limiters. The lack of sensing devices in the low voltage network makes the fault location difficult if not impossible. Additionally, the fault currents on the fuses are usually very high and the fault is usually burned clear, which could cause smoke, fire, or even explosion hazards. Some current challenges reported by utility participants are:

- The detection and fast clearing of slowly developing cable faults is a huge problem. The signatures of this type of fault are not fully understood.
- 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.
- Standard power flow models and tools for contingency analysis during faults are challenging to compute in real-time.

According to ConEd's experience, the common cause of the slow-developing cable faults in New York City is the corrosion resulting from brine used to melt snow on city streets. Slow developing cable faults events occur approximately 3000 times per year in New York City. To address this pressing issue, ConEd 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 operate on battery and communicate to the operator via wireless communication such as LTE cellular networks. So far, this IR camera system has been delivering satisfactory fault detection and location performances. However, one major drawback of this IR camera sensor system is the battery replacement. Currently, approximately 50% of the IR camera sensors are not operational due to a dead battery.

Participating utilities reported a similar low voltage network CTs placement practice where the SCADA connected CTs are strategically at major nodes of the low voltage network to monitor the load current. It is also common for utilities to leverage the measurements from network transformers and advanced metering infrastructure (AMI) to monitor the load and fault currents.

In terms of low voltage fault clearing, ConEd has been deploying medium voltage interrupters to sectionalize low voltage networks. These sectionalizing devices provide great flexibility for fault clearing and service restoration.

As for contingency analysis, PEPCO reported that the lack of real-time power flow models significantly limits their ability to determine the power flow quickly and accurately in the cable and lines during contingency. Having a real-time power flow tool would also help to estimate load, voltage, current, and other necessary states for the low voltage network during normal operation. The availability of such state information would improve the visibility. There may be a good research opportunity to develop a real-time power flow tool that uses system model data, AMI data, and field measurements.

During the discussion of secondary cable faults, PEPCO has mentioned research challenges and opportunities in the topic of predictive cable faults and failure analysis. Some research work has been done to develop data-driven methods to identify cable failure signatures and precursors.

2.5. Challenge #4: Microgrid Protection Coordination

As part of the low voltage network, microgrids have been frequently developed to harness DERs and provide extremely high reliability to customers [5]. Microgrid protection by itself is a very complex and intriguing research topic [2],[6]. From the workshop participants' perspective, the protection within the microgrid should be treated separately in general. The coordination between the microgrid tie-breaker and low voltage network protection is of interest to this study.

There are two types commonly seen microgrids within or connected to the current low voltage networks: (1) customer site microgrid that is connected to the low voltage network (may have multiple connection points), and (2) microgrid with significant DER that is connected to the medium voltage primary feeder. During an outage, the type-1 microgrids can disconnect from the rest of the low voltage network and restore on-site electric service. Whereas, the type-2 microgrid can potentially feed energy via the primary feeder and restore part of or the entirety of low voltage network.

3. PHASE II RESEARCH GOALS

3.1. Selected Use Cases

In this half-day workshop, four current low voltage network challenges were discussed. Each one of these topics is important and deserves its own comprehensive research investigation. Based on the feedback from the utility participants, the team decided to investigate the following two use cases in Phase II of the joint project "Advancement of Low-Voltage Secondary Distribution Network Protection" between QTech and SNL.

3.1.1. DER Back-feed

This proposed model is used to assess and investigate the impact of challenges #1, #2, and #4 summarized in Section 2. A DER back-feed conceptual use case is created and depicted in Figure 3-1.

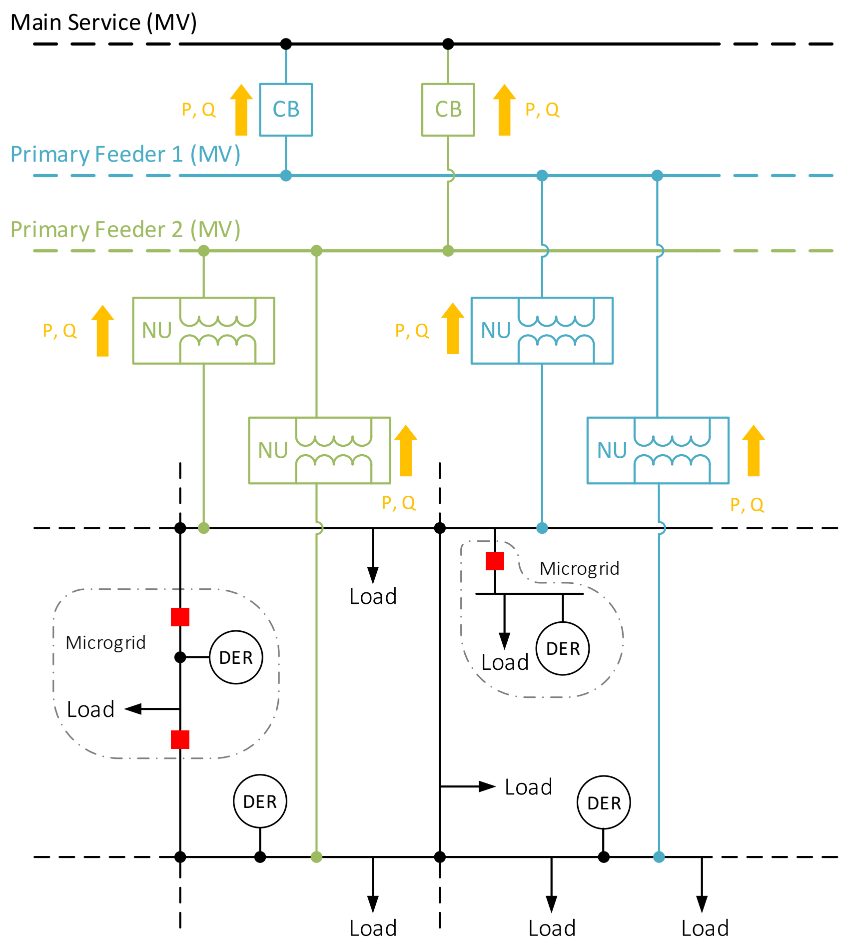

Figure 3-1. Selected use case #1: low voltage network with DER and microgrid back-feeding to the main service

In this first use case study, the project team aims to address the following three research problems:

1. How does the DER reverse real power flow impact the existing protection schemes?

2. How does the smart inverter reactive power injection affect the low voltage network protection?
3. How to allow more DER real/reactive power back-feed without compromising protection designs and system reliability?

3.1.2. DER/Microgrid as "Main Service"

To further investigate challenge #4 summarized in Section 2, a conceptual use case of DER/microgrid as the main service is created and depicted in Figure 3-2. During an outage, the DER/microgrid at medium voltage feeds part of or the entire low voltage network.

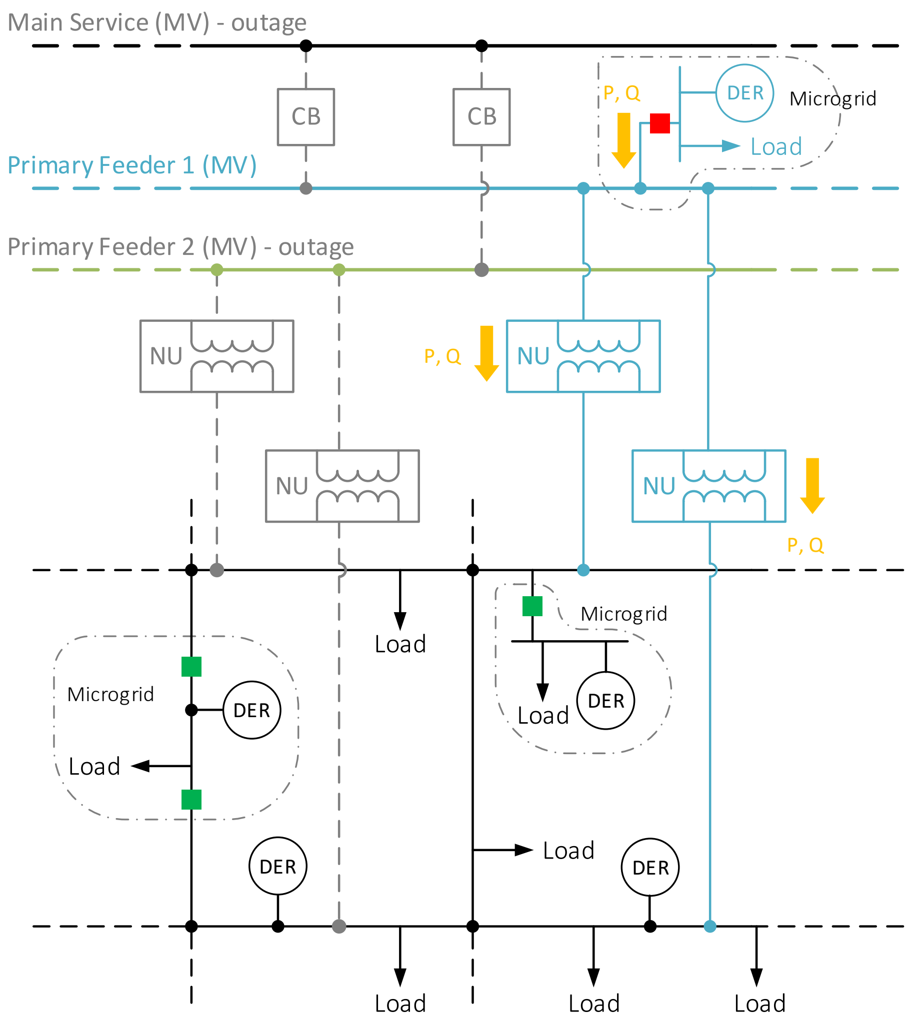

Figure 3-2. Selected use case #2: during an outage the DER/microgrid feeds the low voltage network

In this second use case study, the project team aims to address the following two research problems:

1. How does switching to DER/microgrid main source impacts the existing protection schemes?
2. How to enable DER/microgrid based service restoration to improve system reliability?

3.2. Next Steps

To answer these research questions, the project team will develop appropriate hardware-in-the-loop RTDS models as well as procure commonly used network protector hardware to benchmark and evaluate existing and proposed new protection schemes. The next steps in the phase II research are:

1. Model low voltage network and devices
   a. Create a generic low voltage test system from IEEE low voltage test feeder
   b. Model NP in RTDS using published and validated protection function modules in RTDS
   c. Integrate the published inverter based resources (IBR) RTDS models with the low voltage network model
2. Reach out to vendors and utilities to procure 1-2 commonly used NP relays
3. Implement hardware-in-the-loop (HIL) testing using RTDS
   a. Setup the procured NP hardware and RTDS model for HIL testing
   b. Investigate the research challenges outlined in Section 3.1 for two selected use cases
4. Generate a final report that documents the study findings and proposes future research directions

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APPENDIX A. WORKSHOP SLIDES

QUANTA TECHNOLOGY

Advancement of Low-Voltage Secondary Distribution Network Protection Workshop

August 20, 2021

Sandia National Laboratories

Operated for the United States Department of Energy by National Technology and Engineering Solutions of Sandia, LLC.

Agenda

1. Introductions; project and workshop goals – *Eric Udren, Quanta Technology; Matt Reno, SNL*
2. Overview of Quanta 2020 Phase 1 work for Sandia National Labs – *Eric Udren, Quanta*
   - Overview of LV grid and spot distribution network operation
   - Issues and research opportunities identified
3. Attendees describe current situations, issues, interests, future needs and directions for LV networks – *All*

Break

1. RTDS® testing approach and modeling of components – *Zheyuan Cheng, Quanta*
   1. *Full simulation*
   2. *Hardware-in-loop simulation*
2. RTDS model topologies for LV networks with DER and with microgrids – *Juergen Holbach, Quanta*
3. Discussion and feedback on proposed modeling and research – *All*
4. Wrap-up and future engagements as identified - *All*

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Slide 2

Introductions

Quanta Technology:

- Eric Udren, Executive Advisor (Technical lead)
- Dr. Juergen Holbach, Senior Director (SME)
- Dr. Zheyuan Cheng, Senior Engineer (SME, PM)
- Dr. David Hart, Vice President, P&C

Sandia National Laboratories:

- Matt Reno, Principal Research Engineer (PM)
- Michael Ropp, Principal Research Engineer

Consolidated Edison Company of New York:

- Christopher Jones, Chief Engineer, Distribution Engineering

Oncor Energy Delivery, Ft. Worth, TX:

- Jeremy Preas, SCADA Engineering Manager
- Ken Hanus, SCADA Automation Engineer

Commonwealth Edison Company, Chicago:

- Alexi Paaso, Director of Planning
- Patrick Arns
- Marina Mondello
- Ayun Brown
- Najwa Abouhassan, Key Manager Engrg Standards

PEPCO/PHI, Washington, DC:

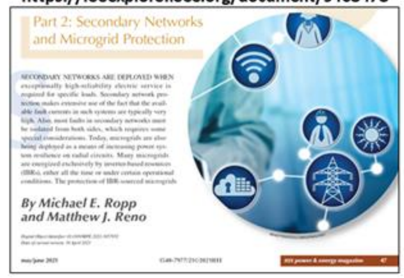
- Boushra Soliman
- Scott Placide
- Robert Spelman
- Jacob Burlin
- Cesar Santamaria
- Bee Morton
- Jeffrey Chai
- Justin Bradfield

Workshop introduction

Background

- Sandia National Laboratories (SNL) and the US Department of Energy (DOE) are leading research into applications and reliability of low-voltage (LV) secondary networks and spot networks serving high-density load areas, in support of electric utility industry trends and upcoming needs.
- Specific interest in addressing the protection challenges related to the interconnection of DER and microgrids in LV networks
  - Funding from DOE Office of Electricity Microgrid Program
  - Increasing penetration of clean energy
  - Increasing resilience with microgrids and backup generation during extreme weather events
- Began working with Quanta in 2020 for broad assessment of LV network issues and R&D opportunities

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



Sandia Report SAND2020-11209
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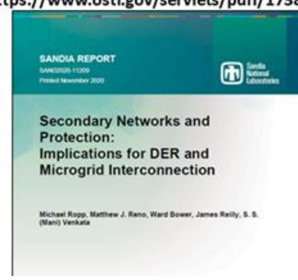

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Slide 5

Research objectives 1

Quanta Technology 2020 investigation:

- Assess experience with low-voltage (LV) distribution network equipment and systems including network protectors (NPs), network relays, and protection coverage.
- Review literature; gather current experiences and issues from a sampling of utility experts.
- Present a range of design ideas for improvements and additions
- Prioritize the list of recommended research and development topics.
- Research report draft circulated to workshop attendees.

SNL project leaders conducted separate parallel research into LV network DER and microgrid issues and research opportunities – SNL report SAND2020-11209.

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Research objectives 2

Quanta Technology 2021 investigation:

- Develop RTDS modeling of LV network equipment and surrounding system topologies for ongoing performance evaluations.
- Include hardware-in-loop (HIL) testing capabilities for NPs and relays in operating and fault scenarios.
- Initiate evaluation and testing of LV network protection and control including its MV supply systems.
- Initiate evaluation of impacts of increasing DER penetration in and around LV networks.
- Initiate evaluation of microgrid applications and scenarios in and around LV networks.
- Assemble, develop, or validate RTDS models:
  - NPs and relays
  - Inverter-based DER in normal operations and fault or switching conditions
  - Conventional LV network and MV distribution components in selected topologies.

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Workshop objectives

1. List operating scenarios for LV networks and measuring systems, including those with increasing DER and IBR that may impact network relays and LV or MV protection schemes to erode dependability margins or cause mis-operations.
2. List real-world operating and fault protection scenarios for which protection coverage may need improvement with a focus on increasing DER penetration.
3. Identify the status of industry capabilities for transient modeling of MV and LV interconnected distribution systems, in support of event simulation and hardware-in-the-loop (HIL) testing.
   - Review modeling requirements for accuracy and for suitability of HIL testing of network relays and equipment.
4. Review plans for RTDS® and HIL testing arrangements, including development of use cases and systems to model, for useful performance evaluations.
5. Additional topics according to interest or need and available time:
   - Steady-state or dynamic operational modeling for distribution system management and control performance.
   - Phasor-based fault study tools for protection coordination studies, including DER impacts.

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Overview of Quanta Technology 2020 Phase 1 work

Phase I Project Overview

Objective:

- Assess electric utility experience and issues with low-voltage (≤ 600V) distribution network protection devices and systems.

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

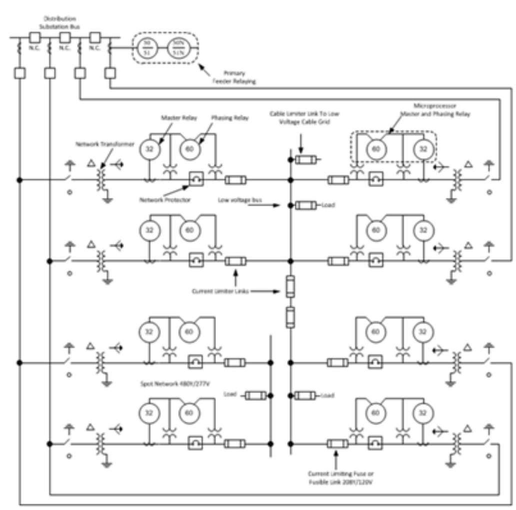
Literature review:

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

Utilities interviewed in the Phase I survey:

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

- Typical LV network:



From IEEE C37.108-2019

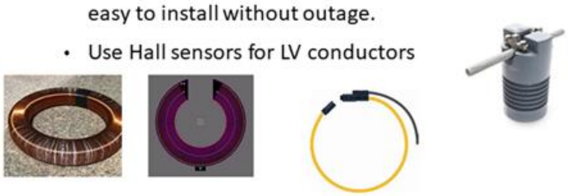
Technical explorations in Phase I Project Report (1)

Pre-publication Phase 1 Report draft supplied to attendees has freely explored topics and solutions, not all validated. What is interesting to study?

- Improvements to vault, network, and protector design
  - Improve the mechanical design and arc interruption mechanisms of the MV and LV breakers via low-maintenance design and better material use.
  - Develop monitoring capabilities for breakers and protectors that can identify mechanical malfunctions (e.g operation timing).
  - Improve the physical designs of the mechanism and vault such that they are less prone to be affected by harsh operating environments, e.g., flood, contamination, etc.
- Transformer protection
  - High-side fusing protection has undetected single-phase blow problems.
  - Distance relaying at the substation in modern versions may improve clearing speed, fault coverage at little additional cost.
  - Transformer differential protection with primary CTs and new output CTs
  - Reverse-looking distance relay can protect for transformer fault backfeed from the LV network.

Technical explorations in Phase I Project Report (2)

- Instrument transformers
  - Add new current measurements to the LV network to improve the fault detection and location capability.
  - Replace conventional iron-core CTs with Rogowski coils for better measurement accuracy and space-saving.
  - Use optical CTs to achieve better accuracy and weatherproof capability
  - Adaptations of line post sensor technology – easy to install without outage.
  - Use Hall sensors for LV conductors
- Fault clearing methods
  - Use vacuum interrupters for local 87T relays to achieve two-cycle fast clearing
  - Enable transfer-trip between local 87T relay and substation breaker.
  - Close a primary grounding switch to shunt fault current (controversial).
  - Use electronic fuses for transformer high-side protection to enable cross-trigger among phases.



Technical explorations in Phase I Project Report (3)

- LV network electrical fault-sensing methods
  - Add more measurement points on transformer neutral grounding connections and LV system grounding connections.
  - Used doughnut CTs to surround three-phase conductors and neutral return.
  - Develop LV network ground differential scheme with wireless or wi-fi like communications.
  - Analyze waveform signatures of arcing faults.
  - Identify waveform signatures of incipient failures and develop predictive fault identification algorithms.
- Non-electrical fault-sensing methods
  - Fault arc, optical fiber, or ultraviolet optical sensing.
  - Thermal or IR sensing.

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Technical explorations in Phase I Project Report (4)

- Communications opportunities
  - Install 87/87N protection around zones in network facilities and encompassing the connected LV network.
  - Install current differential 87L scheme on top of overcurrent schemes for speed, sensitivity and tolerance of DER arbitrary flow directions.
  - Replace protection and control wiring with integrated P&C design and optical fibers carrying IEC 61850 GOOSE/SV messaging and other P&C traffic.
  - Specify and demonstrate a secure protocol for utility owned or common-carrier Ethernet high-speed wide area network.
  - Specify secure communications for wireless differential schemes
  - Stream LV network measurements to SCADA system securely and efficiently
- Condition monitoring of protectors and circuit breakers
  - Use relay timing logic to catch slow breakers or protectors.
- Condition monitoring of protection system
  - Use built-in self-monitoring capabilities of microprocessor relays, in combination with heartbeat data communications among different relaying elements.
  - A condition-based maintenance program based on monitoring and alarming – include polling of configuration or settings of the IEDs by external monitoring system or SCADA - settings confirmed to be as intended and have not altered by field maintenance personnel.

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Technical explorations in Phase I Project Report (5)

- Steady-state operation of LV network with DER
  - Present schemes limit DER outfeed and risk tripping, but tolerance is increasing. Some adjustments of existing protection characteristics can tolerate DER production closer to the facility loading.
  - Inverters associated with DER must detect islanding conditions – loss of all utility supply – and shut down.
  - DER inverters should be able to ride through disturbances while disconnecting/blocking or reducing energy production for excessive backfeed.
- Engineering study software is routinely used for the analysis of fault coordination and non-fault operation of LV networks.
- The power electronic inverter systems supplied for DER generation and/or battery energy storage systems (BESSs) might be combined or functionally integrated into a new architecture for LV network control and protection, especially in a microgrid-capable design.

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Major Research Recommendations from Phase I Survey

- 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; external data sharing requirements; 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]; model platform of (2) is important.

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Major Research Recommendations from Phase I Survey

- 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]

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Summary of Phase II Project Tasks

- Engage in discussions and workshops 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 real-time simulations of typical distribution system sections in which low-voltage networks serve customer loads on a RTDS simulation platform.
- Conduct HIL testing of network relays and protectors in operating and fault scenarios with the RTDS simulation.
- Issue a final report of compiled results with recommendations for next steps.

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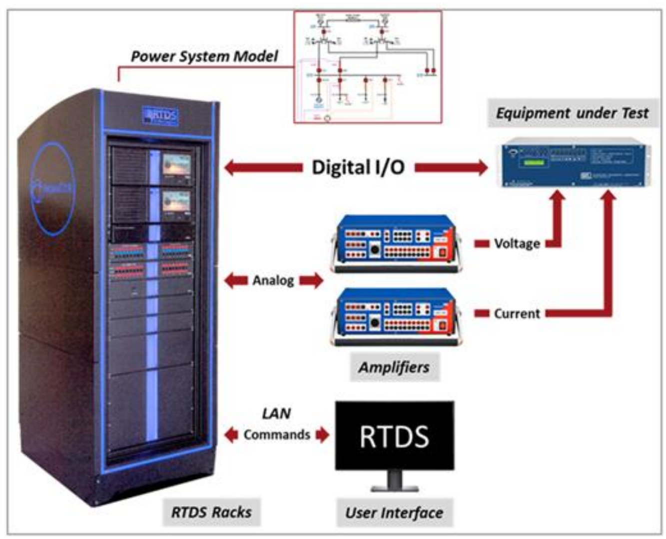
Participants' discussion of current experiences and issues; foreseen needs and new topics of interest

Workshop break

RTDS® testing approach and modeling of components

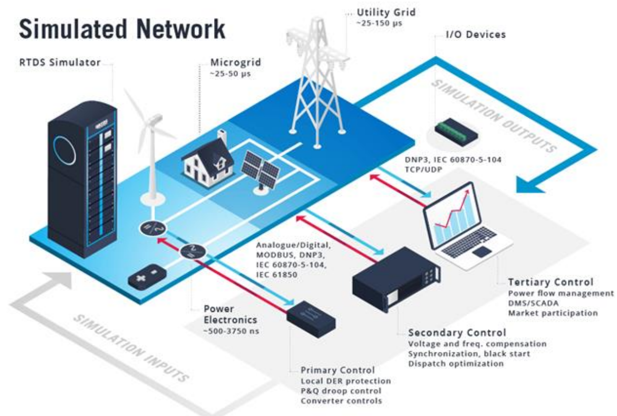
Quanta Technology's Raleigh RTDS Lab

- Quanta Technology RTDS Lab uses the state-of-the-art NovaCor RTDS test system
  - 6 cores allow the real-time simulation of 600 single-phase load units
  - 48 analog I/O channels can be streamed via amplifiers to external HIL to test complex P&C schemes
  - 80 digital I/O channels can be interfaced with external test unit
  - Network interface that supports IEC 61850, GOOSE, PMU C37.118, and generic TCP/UDP protocols
  - GPS time synchronization that supports IEEE 1588 PTP, 1 PPS, or IRIG−B

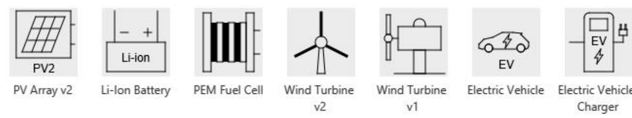


RTDS Modeling Capabilities

- Electromagnetic transient simulation of the distribution system and microgrid
- Detailed pre-built models for DER and power electronic converters
  - Solar
    - PV array/farm model with MPPT and Partial shading effect
  - Wind
    - Type I – IV wind turbine/farm models
  - Energy storage
    - Lithium battery, fuel cell, flywheel, and pumped hydro models
  - Electric vehicle
    - EV and charging station models with V2G control
  - Power electronics
    - Average and switching models for compensators, VSC, CSC, and MMC converters



Devices Under Test



HIL testing plan – LV network model

- Create a generic low voltage network model in RTDS
  - Type: Secondary grid network
  - With 1 main MV feeder and multiple MW primary feeders
  - With multiples LV secondary mains
  - With multiple network protectors (NPs)
    - Procure 1-2 physical NPs with relays from vendors or utilities
    - Additional NPs to be modeled and the models can be validated in tests

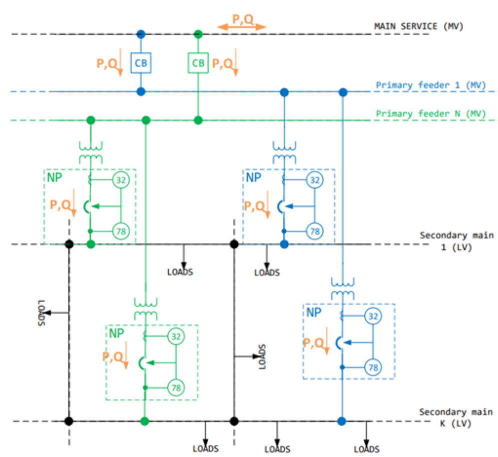


Figure 5. Secondary grid network with N primary feeders and K secondary mains, without DER. "NP" = Network Protector. "32" denotes directional power function; "78" denotes phase-angle relay. Directions of active power flow (P) are marked.

[SANDIA REPORT SAND2020-11209]

HIL testing plan – need for detailed DER model

- Unique challenges brought by IBRs
  - Limited fault current magnitude
    - Typically, 1.1-1.5 per unit
  - Control-determined current-voltage phase angle
    - Different behaviors in grid following and forming modes.
  - Different sequence components
    - Controller typically suppress negative sequence
  - Nonlinear fault current contribution
    - Flat-topped waveform throws off phasor calculation
- Impacts on the LV protection schemes
  - Overcurrent
    - Not enough fault current.
    - Difficult to provide enough sensitivity and selectivity.
  - Directional
    - Not enough negative sequence current to pickup asymmetrical faults.
  - Coordination
    - Impact tripping time and coordination between primary and backup overcurrent devices.

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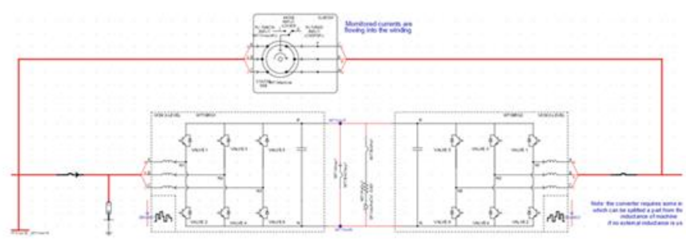
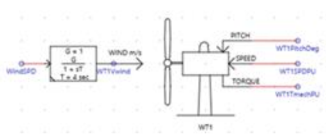
HIL testing plan – DER model (1)

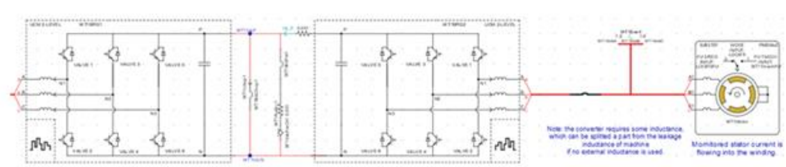
- Infuse the LV network with inverter-based resources (IBRs):
  - Wind turbines
    - Type 1-4
  - Detailed switching model: B2B inverter
  - Turbine model with active input for wind speed, pitch control, and power coefficients



Type-3 Model: Doubly Fed Induction Generator (DFIG)



Wind turbine model



Type-4 Model: Full Power Electronics Conversion

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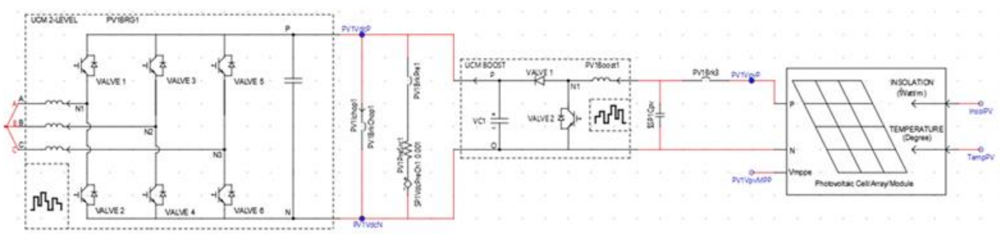
HIL testing plan – DER model (2)

- Infuse the LV network with inverter-based resources (IBRs):
  - Solar Energy
  - Detailed switching model
    - Boost converter with MPPT
    - Inverter model

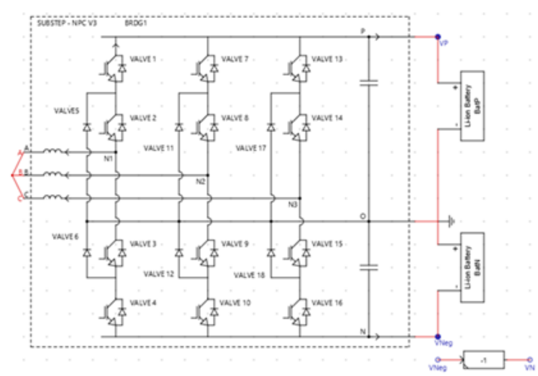
- PV array model with active input for insolation and temperature.
- Partial shading effects.
- Maximum power point tracking control



PV panel with MPPT control

HIL testing plan – DER model (3)

- Infuse the LV network with inverter-based resources (IBRs):
  - Battery Energy Storage
    - Lithium-ion battery model with temperature and aging effects
    - Other battery storage technologies: fuel cell, Flywheel, pumped hydro.
  - Detailed switching model: NPC inverter



Lithium-ion battery with NPC inverter

Discussion questions

- What are the typical network protectors used in your LV networks?
  - Vendors, models, specs, new features, etc.
- What are the protection schemes used in your LV network protectors?
- What type of coordination you would expect between the network protectors and secondary tie breakers (or microgrid breakers) if used?

Classical LV grid network

Protection Philosophy

- The **primary feeder circuits** are protected from the utility side by standard instantaneous overcurrent and time-overcurrent devices (50/51/50G/51G), and from the network side they are protected by the reverse power function (32) in the network protectors.
- Faults in **network transformers** are isolated from the primary side by the primary circuit breaker using overcurrent, and from the network side either by the directional reverse-power function or fuses in the network protector.
- A fault in the **network protector** itself would be isolated by the primary circuit breaker on the primary side, and by fuses near the network protector on the secondary side.
- The **secondary mains in grid networks** are typically protected by cable limiters (fuses), and by the fact that fault currents are so high that faults tend to "burn clear".
- Faults in the **lowest, customer-serving levels of the system** are typically isolated by circuit breakers and other overcurrent-based devices.

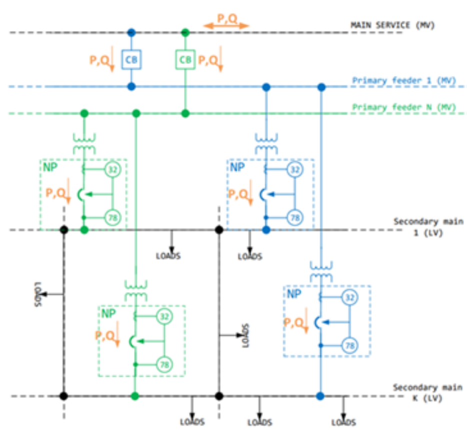


Figure 5. Secondary grid network with N primary feeders and K secondary mains, without DER. "NP" = Network Protector. "32" denotes directional power function; "78" denotes phase-angle relay. Directions of active power flow (P) are marked.

[SANDIA REPORT SAND2020-11209]

LV network with DER

Challenges

- Protection philosophy does not change with sufficient fault current provided by synchronous generators connected to the main service.
- If generation connected on main service is mainly provided by IBR, secondary fault may not be cleared due to low fault currents.
- Low load situation may export load and operate NP based on reverse power flow (32).

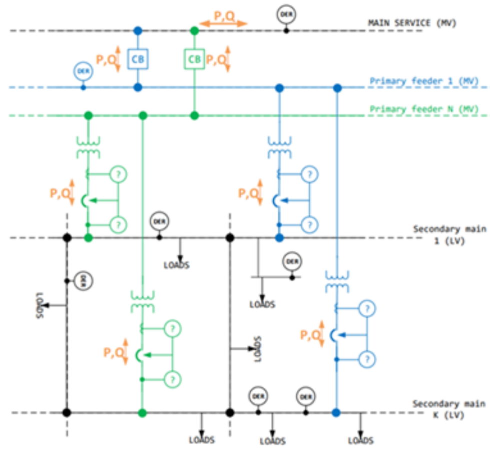


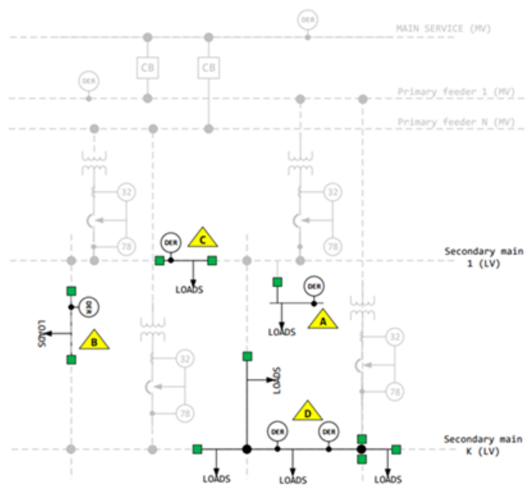
Figure 6. Secondary grid network with N primary feeders and K secondary mains, with DER. Directions of active power flow (P) are marked.

[SANDIA REPORT SAND2020-11209]

LV network with microgrids (1)

Challenges

- If the microgrid undergoes a closed transition when it leaves or returns to the utility grid, the microgrid protection must provide adequate short-circuit protection in both the on-grid mode, when fault currents are usually very high, and in the off-grid mode, when fault currents may be severely limited.
- Any section of a secondary network that is also inside the boundary of a microgrid must remain protected against short circuits. Cable limiters cannot work when the microgrid generation is based on IBRs due to the low fault current.
- This is especially important in Microgrid D where every fault within Microgrid D will cause the entire microgrid to black out based on lack of fault clearing means.

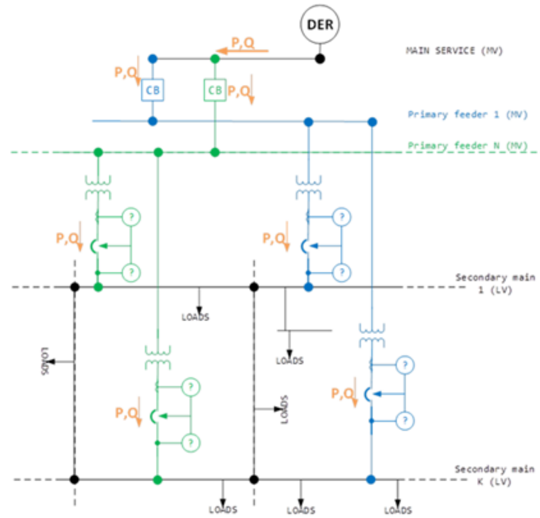


[SANDIA REPORT SAND2020-11209]

LV network with microgrids (2)

Challenges

- This shows the situation in which the DER is on the main service.
- The DER and LV network loads can form a microgrid with appropriate sectionalizing and load shedding .
- This example can represent a dense urban downtown LV network with severe space and emissions constraints, so that the only DER available is on the main service, removed from the constricted area.
- This configuration does not have all of the bidirectional power flows of DER in the LV network.
- Low fault duty in microgrid mode inhibits operation of conventional feeder and transformer protection, NP relays, fuses, and links. Arcing faults do not burn clear.



[SANDIA REPORT SAND2020-11209]

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Discussion of model topologies and use cases to simulate; Feedback on proposed modeling and research

Wrap-up and questions

- Did we get agreement on modeling for testing we foresee in the limited workshop time?
- Have we identified any group or subgroup continuing discussion needs?

If time allows:

Enquiry of the attendees on:

- Steady-state or dynamic operational modeling for distribution system management and control performance for planning, dynamic studies, operational analysis, contingency analysis…
- Adequacy of power-frequency fault study tools for protection coordination, including DER impacts.

Final observations and questions

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Thank you for supporting the workshop and project!

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