Transformer overload protection using wireless communications

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Abstract

The .growing number of Distributed Energy Resources (DER) connected to power systems, among other challenges, can lead to an overload condition on the distribution substation transformers. Bidirectional power flow, alternating charge/discharge states at each DER site, remote and rural DER locations all make substation transformer overload protection difficult. In the Pacific Gas and Electric (PG&E) system this can occur where large (20MVA) distribution connected DER's are installed, along with smaller aggregate DER's are continually interconnecting on the distribution feeders.

This paper presents a transformer overload protection scheme based on wireless communication between the head end station and multiple DER sites. IEC 61850 GOOSE messages are used to communicate Ramp down and Trip signals, as well as DER state and status information. The scheme uses directional overpower (32) elements to supervise overcurrent (50) elements. Custom logic was developed to support selective ramping down and tripping of DERs operating in the detected overpower direction only.

Wireless mesh communication was chosen due to its ability to reach remote DER locations without building a wired communication infrastructure, accompanied by the sufficient reliability and security of its operation.

Scheme design, including protection elements, logic and communication configuration are discussed. Test results for the proof-of-concept (POC) system are included, covering communications, protection and custom logic. The benefits of applying wireless communication assisted transformer overload protection scheme are summarized.

1. Introduction

There have been instances where Pacific Gas and Electric (PG&E) distribution transformers have the potential to overload due to large and growing number of interconnected Distributed Energy Resources (DERs), which could be located at several different locations. PG&E wanted to develop a scheme to detect transformer overload and trip the contributing to the overload DER location(s) selectively. Single line diagram of the envisioned by PG&E solution is shown on Figure 1.

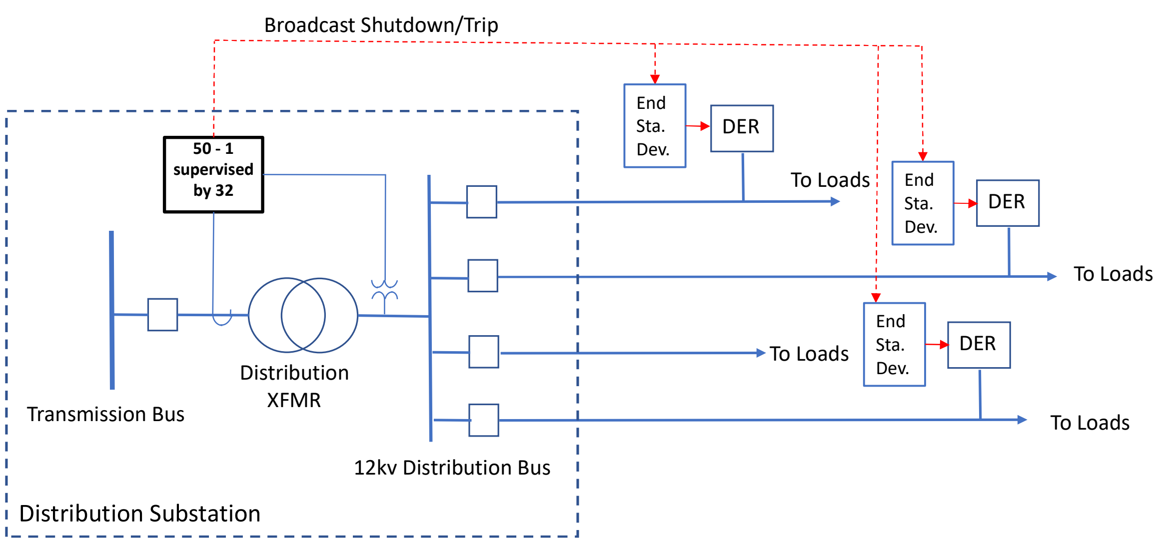


Figure 1. Single line diagram

The overload is detected by monitoring transformer High Voltage winding current. Trip signals must reach DER stations reliably, and latencies within 2 seconds are acceptable. Wireless communication with point-to-multipoint or mesh architectures were preferred. Use of a wireless method utilizing a single headend device that communicates with multiple remote devices would greatly reduce cost and complexity. A simple and universal package for installation at DER stations was preferred with main scheme logic executed at the headend substation. Existing PG&E design standard methodologies and test practices to be followed by the new scheme.

As a first step to test the validity of the considered approach, a radio assessment was performed for one area of PG&E system. A circle with a radius of 5 miles around a distribution substation was assessed, where real and hypothetical DER sites were located. Report brought positive results, stating that the minimum number of radio repeaters, if any, will be sufficient in that area.

To tackle the overall task of solution development a cooperative engineering approach was chosen. Specifically, it was decided to jointly develop a proof-of-concept (POC) system with at least two end DER stations and conduct its testing in PG&E laboratory.

2. Proof-of-concept development

The overall solution concept was conceived during numerous technical meetings, its summary is presented on Figure 2.

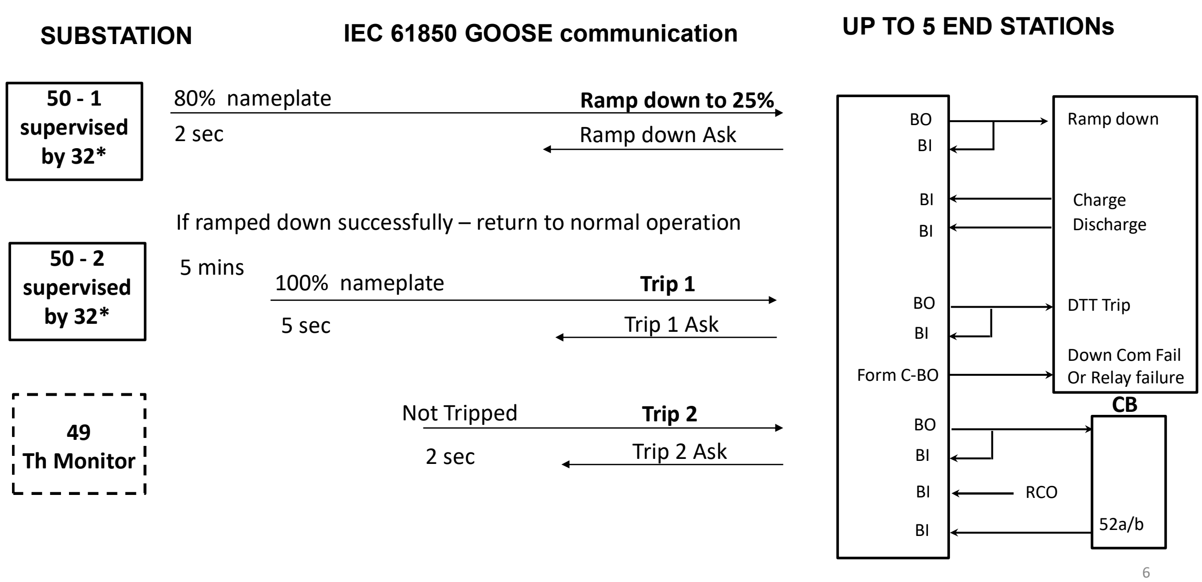


Figure 2. Overall solution concept

Scheme's operation is based on detection of bi-directional overpower condition, and ability of the substation device to ramp down and trip end devices contributing to the overload condition. The initial approach had all scheme intelligence executed in the substation headend device. However, to provide selective tripping, status of the end stations is required, specifically, an indication of charging or discharging state. Addition of these statuses made headend station logic dependent on the end stations statuses.

Timing wise, the idea was to utilize multiple timers, first to identify the initial overpower condition, then allow time for end device to act on ramp down command. If no action occurred, and overpower condition worsen, a direct transfer trip (DTT) signal, called Trip 1 in this scheme, is initiated. If DER does not trip on DTT, a second trip directly to the circuit breaker (CB), called Trip 2, is issued. Refer to Figure 3.

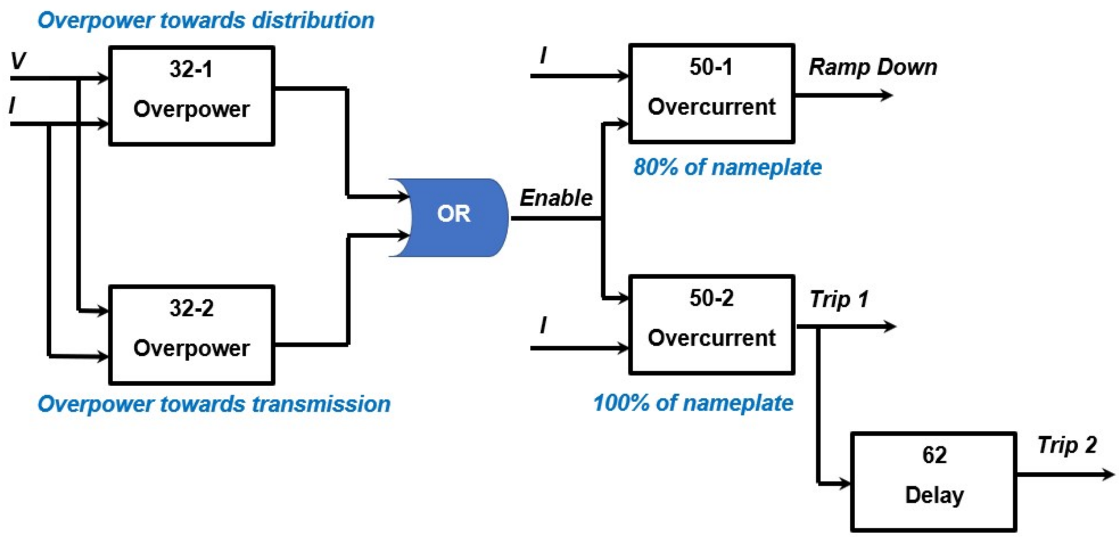


Figure 3. Protection logic

As the scheme is highly depended on communication, communication status is continuously monitored, and acknowledgement for each command and communicated back to the headend station. These acknowledgements are generated through a direct hardware loopback, as shown on Figure 2. Specifically, received Ramp down command, results in asserting an associated binary output (BO), which in turn is connected to binary input (BI) assigned for the Ramp down Acknowledgement signal, which is sent back to the substation. This provides communication health verification embedded into the scheme, as it basically tests communications integrity down to the binary output for each issued command.

Protection-wise, the scheme uses two overpower elements (32), one per overpower direction, which supervise two instantaneous overcurrent elements (50). Main protection logic is shown on Figure 3.

Interestingly, this is the first time PG&E utilized a directional 32 element for this type of application. It is set conservatively at 50% nominal power. Refer to Figure 4 for protection settings for the 32 elements.

OpMode1	OverPower			
Power1	50.0	%SB	0.0	500.0
Angle1	0.0	Deg	-180.0	180.0
TripDelay1	0.01	s	0.01	6000.00
DropDelay1	1.00	s	0.01	6000.00
Hysteresis1	0.5	%SB	0.2	5.0

OpMode1	OverPower			
Power1	50.0	%SB	0.0	500.0
Angle1	180.0	Deg	-180.0	180.0
TripDelay1	0.01	s	0.01	6000.00
DropDelay1	1.00	s	0.01	6000.00
Hysteresis1	0.5	%SB	0.2	5.0

Figure 4. Directional overpower element settings: towards distribution and towards transmission

Two power flow directions towards distribution (when end stations are charging), and towards transmission (when end stations are discharging) are detected using angle settings differing by 180 degrees. The setting Angle1(2) gives the characteristic angle giving maximum sensitivity of the power protection function. For active power the set angle should be 0° or 180°. 180° should be used for generator reverse power protection. Directional overpower characteristic is shown on Figure 5.

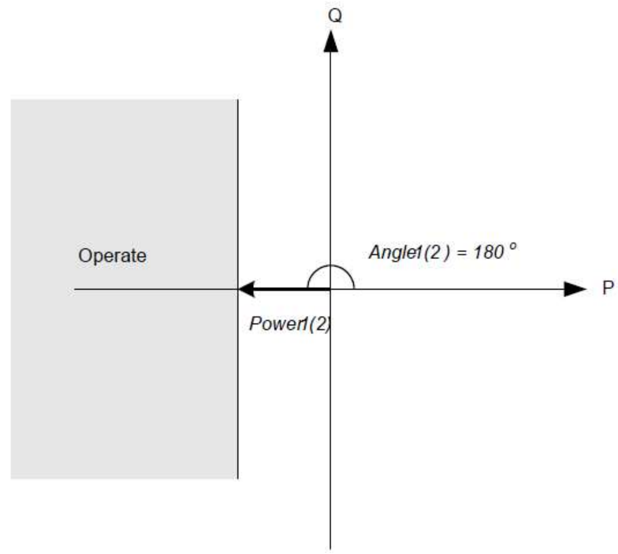


Figure 5. Directional overpower characteristic

Directional overpower (32) elements only supervise two instantaneous overcurrent (50) elements, see Figure 4, i.e., only enable the operation of 50 elements. The 50 elements, in turn, are set at 80% and 100% of transformer nameplate nominal current. If 80% of nominal current is present for 2 seconds and supervised by an overpower condition (in either direction) a Ramp down condition is initiated. 100% of nameplate current is supervised by an overpower condition and initiates a DTT or Trip 1 condition.

To follow PG&E test and maintenance procedures, trip separation is required for each end station. Various methods were thoroughly discussed, and a solution with multiple cut-out options was designed. Figure 6 shows logic implemented for trips isolation and maintenance testing. At the substation end, each end station can be Cut Out (disconnected or taken out of service) using a hardware pushbutton. Each DER station as well has a mechanical switch to physically isolate its trip circuit. This is called Remote Cut Out (RCO), use of RCO's is a standard PG&E practice.

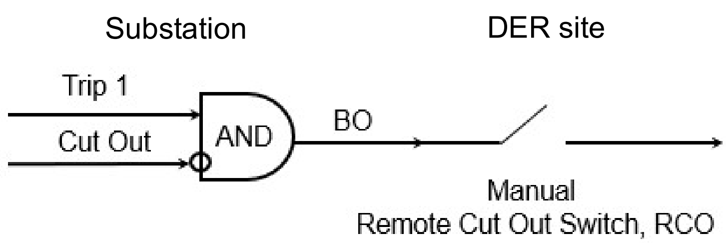


Figure 6. Trips isolation and maintenance testing

Ramp down, Trip 1, Trip 2 signals as well as Charge, Discharge and Breaker Status positions (52a/b) are all communicated as signals in IEC 61850 GOOSE messages over broadband mesh wireless network.

GOOSE stands for Substation Object Oriented Substation Event in IEC 61850 terminology.

Various devices were evaluated and considered for scheme design, including remote terminal units (RTUs), radios with combined input/output boards and protective relays. Protective relays were selected to maintain PG&E standards for electrical terminations, as well as keep scheme's devices uniformly the same. For the communication devices, wired Ethernet switch was selected for substation connectivity and dual frequency band radios for main wireless connectivity: with wireless gateway placed at the substation end, and radios placed at end DER stations.

The overall proof-of-concept system developed with two end stations is shown on Figure 7. It was purposely decided to keep this system completely isolated , and not connect it with field area network (FAN) being deployed at PG&E.

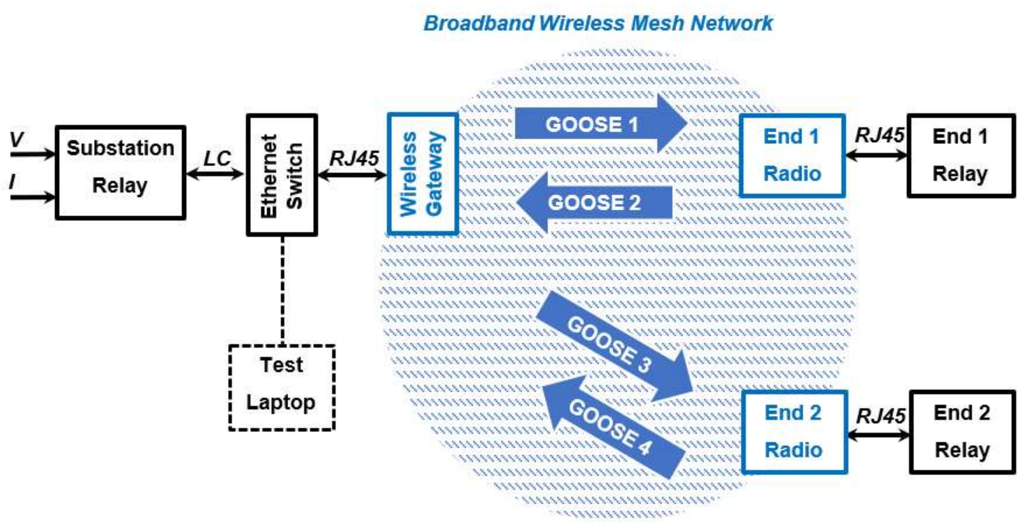


Figure 7. Developed proof of concept system with two end DER station

3. Proof-of-concept testing

The system was designed and engineered jointly, which is the best way to ensure that the end result actually meets the original request. The system was engineered remotely, due to world and travel situation at the time. It was tested in parts remotely for the same reasons.

Special test provisions were added to the scheme to support immediate out-of-box communication verification. LEDs were setup at station relay and end relays indicating right away the status of bi-directional communication, controlled by a single "Cut In" pushbutton per end station. This simplified testing and system delivery as it only took a few seconds to verify that communication is operational, right out-of-the-box.

The same mindfulness and planning discipline were exercised for testing the scheme itself.

3.1 Step 1

First, the overall scheme was tested over wired communication. Emulations of the Ramp down and Trip conditions were designed into the scheme to avoid the need for current and voltage injections. All conditions were successfully tested, with COMTRADE records captured and presented to PG&E team for acceptance. Timer durations were reduced to speed up the testing. Figure 8 shows wired test setup.

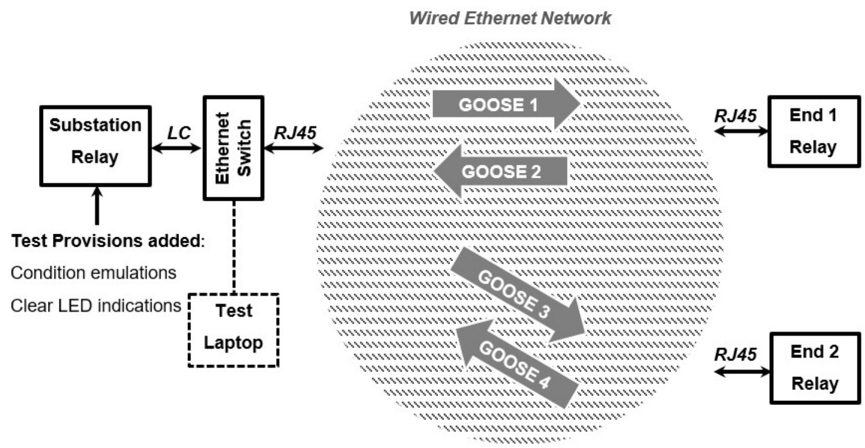


Figure 8. Wired system diagram

Figure 9 has a picture of the overall wired system and shows the embedded communication verification feature visible right upon initial system power up.

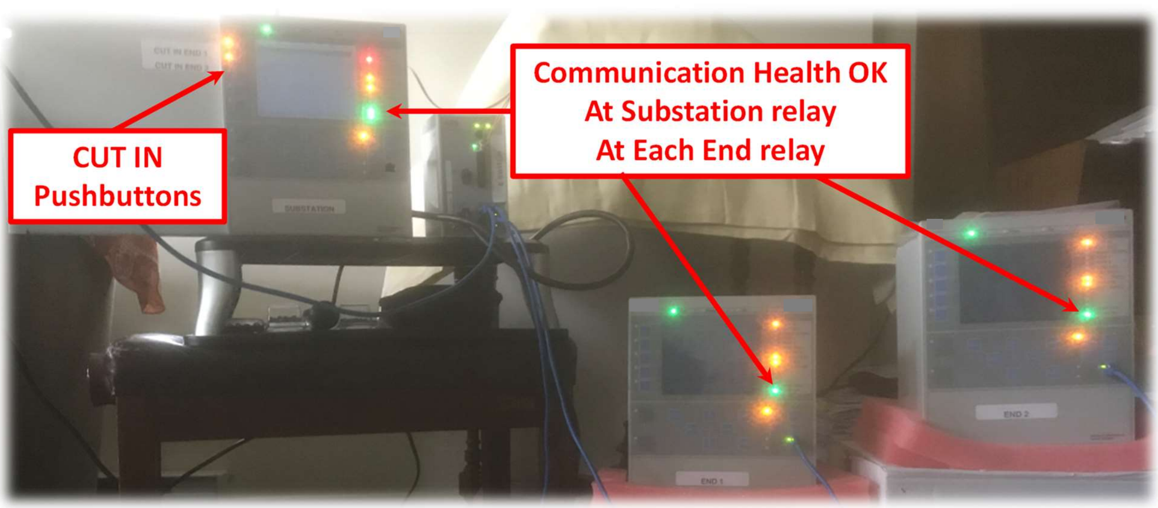


Figure 9. Wired system with embedded communication test feature

Figure 10 depicts a COMTRADE record showing Ramp down, Trip 1 and Trip 2 signals issued correctly with expected timing.

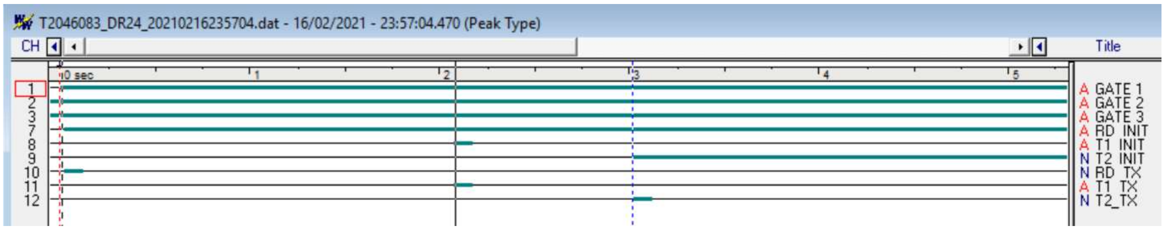


Figure 10. COMTRADE record capture showing Ramp down, Trip 1 and Trip 2 signals

This first testing Step was completed in April 2021 in Vancouver, BC, Canada.

3.2 Step 2

Second testing step was performed with wireless communication, instead of wired connections. Thanks to the embedded communication verification features clear and prompt indications were very helpful for this testing. A diagram of proof-of-concept testing with wireless connections is shown on Figure 11.

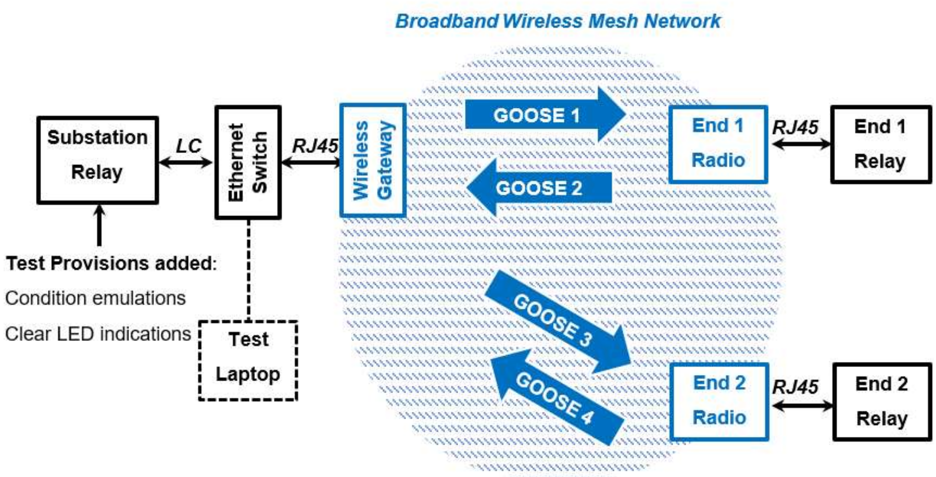


Figure 11. Wireless system diagram

A number of learning's came out of this testing step. These are summarized in lessons learned session. Testing step 2 was first completed in San Jose in May 2021, after which the whole tested POC system was delivered to PG&E, San Ramon laboratory. PG&E, in turn, confirmed the receipt of a functional system in June 2021, by verifying healthy bi-directional GOOSE communication right out-of-the-box. This embedded communication verification feature again was very useful and saved a lot of testing time. Figure 12 shows pictures of the setup with wireless gateway and radios.

Figure 12. Pictures of the wireless system setup

3.3 Step 3

The third step of testing was to test protection elements with current and voltage injections. A test set was used for these tests. Tests were performed by PG&E engineers in PG&E laboratory. Block diagram for these tests is shown on Figure 13.

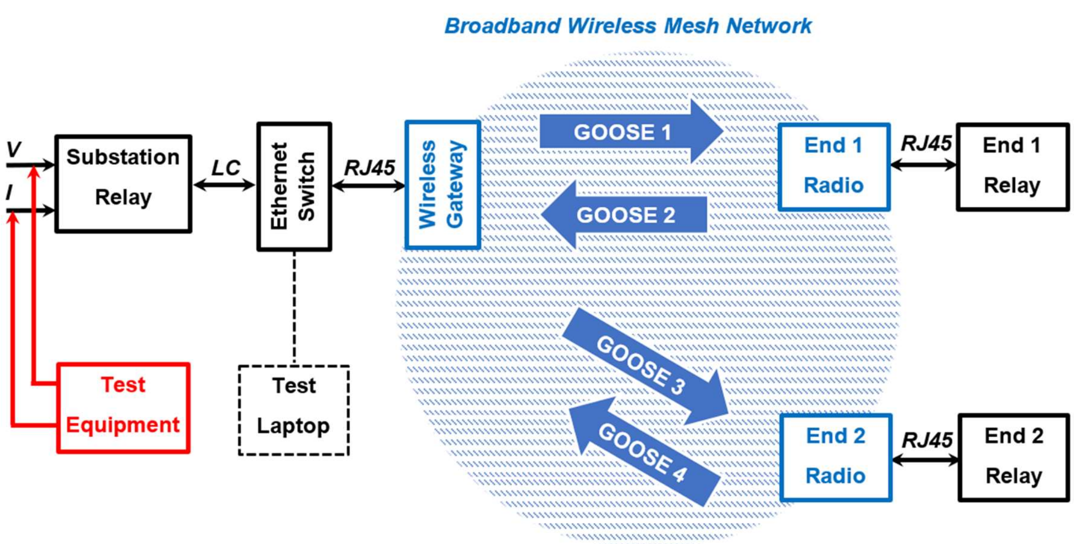


Figure 13. System setup used to test protection elements and the whole system

Various directionalities were injected to verify correct operation of 32 elements. Elements operated as expected. 50 elements operated as expected as well. This step was completed in October 2021, in a joint in-person testing session.

3.4 Step 4

The last Step 4 was focused on testing the whole proof-of-concept system, as its elements were successfully pre-tested prior. It was exciting to see the whole system in operation, behaving essentially as expected. Setup shown on Figure 13 was used to test the overall system. Figure 14 has pictures of the proof-of-concept system installed in PG&E laboratory.

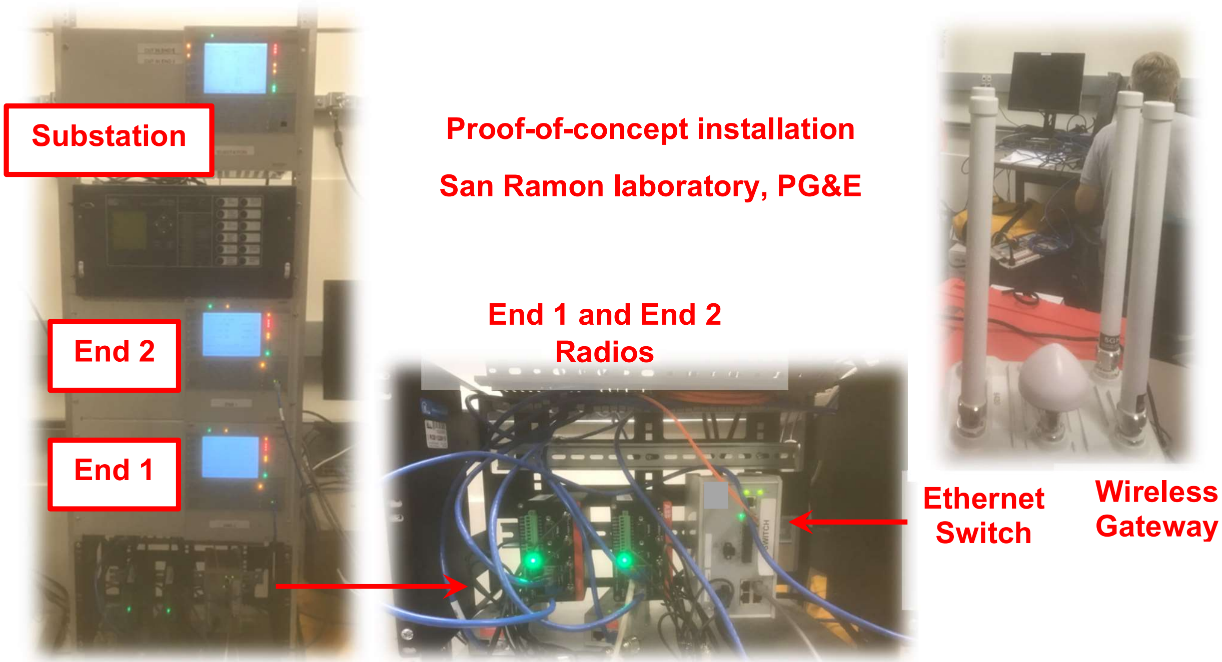


Figure 14.Proof-of-concept system installed in PG&E laboratory.

This testing step was successfully completed in November 2021, in an in-person testing session.

4. Lessons Learned

Most lessons were learned during testing that preceded system's delivery to PG&E. Most learnings were gained during integration or testing step 2 when wireless communication was used instead of wired. Specific learning's relate to testing and debugging abilities, as well as settings for wired and wireless communication devices.

4.1 Capturing GOOSE messages

Per IEC 61850 definitions, GOOSE messages are Layer 2 Ethernet messages with IEEE 802.1Q tags carrying Priority information only. No Virtual LAN(VLAN) information in included, in fact VLAN ID is equal to 0 in IEEE 802.1Q tags carried with GOOSE messages.

Such Priority only frames often processed differently by Ethernet switches and end devices: both can strip or modify the IEEE 802.1Q tags. To avoid tags removal, Ethernet switch had to be programmed as described in the next session. To allow capturing and viewing complete GOOSE messages with IEEE 802.1Q tags in place, Network Interface Cards (NICs) on the laptops had to be programmed in Windows Registry. Specific settings depend on NIC card vendor. Guidance on these settings is available on-line and was used to assist with this project's testing. Known tools, such as Wireshark, only display captured traffic, and if tags are already stripped by the NIC card, tags would never be shown.

Figure 15 depicts IEEE 802.1Q tag: these are 4 bytes inserted after source Media Access Control (MAC) address in an Ethernet frame.

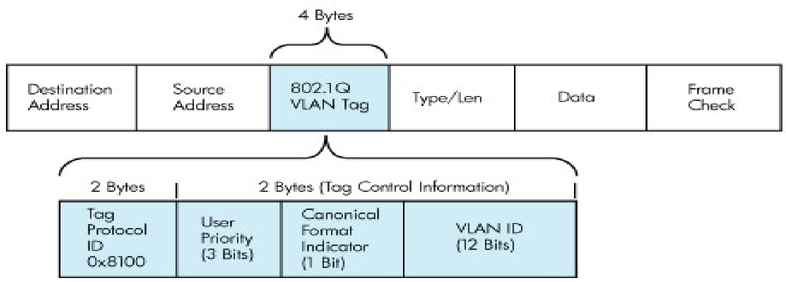


Figure 15. IEEE 802.1Q tag

Figure 16 shows an excerpt from an on-line guidance on how to enable NIC cards to accept IEEE 802.1Q tags, and its Uniform Resource Locator (URL).

> My sniffer is not seeing VLAN or QoS tagged frames. How do I fix it? **After changing the adapter registry setting in Windows*, you must restart Windows for the new registry setting to work**. The tagging frames get stripped out by the driver; however, making a registry change can be done in order to see the tags.
>
> https://www.intel.com › www › articles › ethernet-products
>
> My Sniffer Isn't Seeing VLAN, 802.1q, or QoS Tagged Frames

Figure 16. Guidance on configuring NIC cards to accept IEEE 802.1Q tags

4.2 Configuring Ethernet switch

During communication setup it was learned that default settings of Ethernet switch did not provide required connectivity. Specifically, the below default Ethernet switch settings had to be changed.

- Rapid Spanning Tree (RSTP), an Ethernet loop prevention protocol, had to be Disabled.
- Flow control had to be Disabled. This feature manages Ethernet traffic flow and limits it.
- To allow forwarding of Priority only GOOSE messages, a VLAN unaware mode had to be Enabled in a global setting. This is shown on Figure 17.

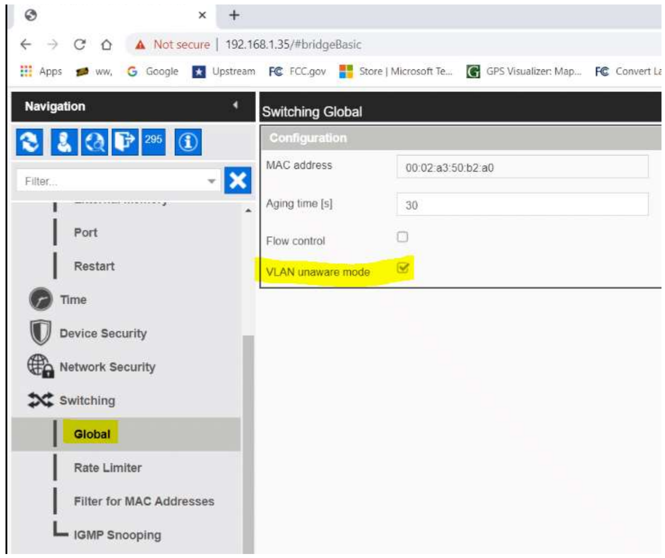


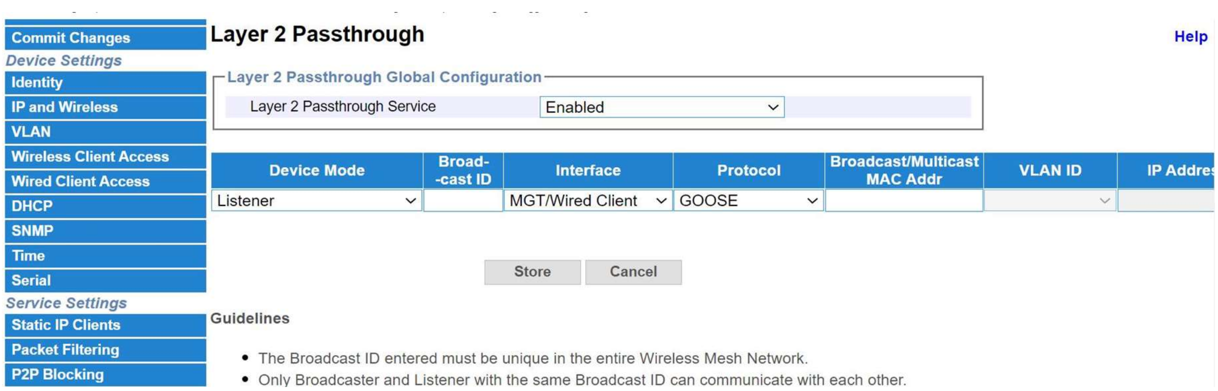
Figure 17. Ethernet switch setting that Enables VLAN unaware mode

4.3 Configuring Radios and Relays

While configuring wireless communication devices, it was learned that each GOOSE communication stream had to have its own unique destination MAC address. This was easy to arrange, and a dedicated multicast destination MAC address was assigned to each of 4 GOOSE streams used. This had to be configured for both wireless devices and the relays, which serve as publishers and subscribers to these GOOSE streams.

It should also be noted that wireless devices map Ethernet Layer 2 communication into secured IP stream. To forward Layer 2 Ethernet traffic, Layer 2 Passthrough mode has to be Enabled.

Wireless radios configuration is shown on Figure 18. All these destination MAC addresses are from the assigned MAC address range assigned to IEC 61850 GOOSE messages.



GOOSE Streams	Broadcast IDs	Destination MAC Address		
Substation to End 1	1	01:0C:CD:01:00:01	Substation (6420) = Broadcaster	End 1 (2420 – 1) = Listener
Substation to End 2	2	01:0C:CD:01:00:02	Substation (6420) = Broadcaster	End 1 (2420 – 2) = Listener
End 1 to Substation	3	01:0C:CD:01:00:00	End 1 (2420 – 1) = Broadcaster	Substation (6420) = Listener
End 2 to Substation	4	01:0C:CD:01:00:04	End 2 (2420 – 2) = Broadcaster	Substation (6420) = Listener

Figure 18. Configuration for wireless gateway and radios

4.4 Software Tools

While testing the solution, software debugging tools were found invaluable, along with embedded communication health verification and emulation features. Specifically, ability to test internal relay logic in real time was found to be very useful. Figure 19 shows an example of real-time debugging capabilities for internal relay logic.

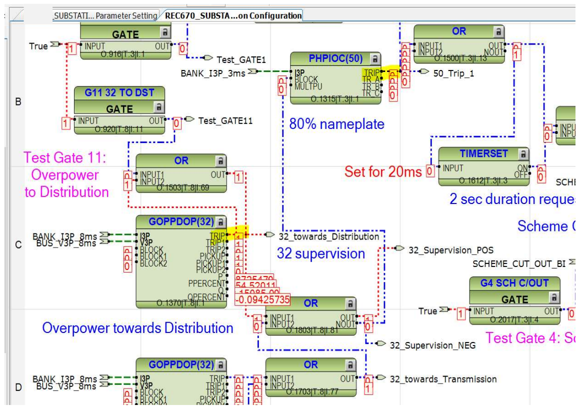


Figure 19. Example of real-time debugging of internal relay logic

Also, for communication -assisted schemes, capturing and decoding the actual communication-based signals is of critical importance. While tools like Wireshark do provide similar capabilities, specialized tools simplify the capture while providing a graphical real-time display of signals under test. Figure 20 shows an example of such tool depicting a signal in GOOSE message that is changing its state.

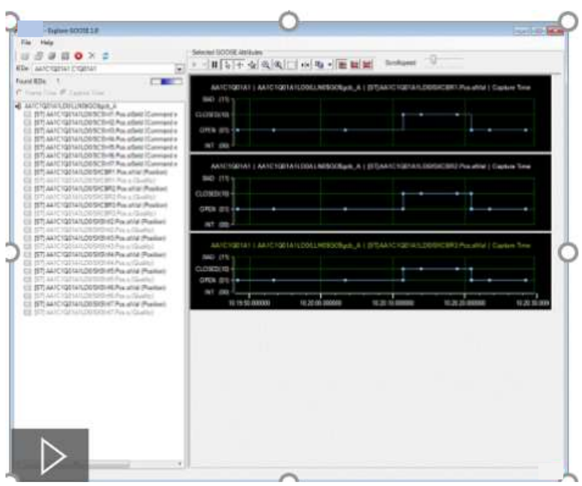


Figure 20. Software tool example showing changing signal inside GOOSE message

5. Conclusions

A solution to protect a transformer from overloading due to multiple connected DER sites was developed and tested in a cooperative and coordinated manner. Wireless communication was chosen to reduce cost and complexity. The concept was successfully tested in the lab simulating transformer overload conditions by applying overcurrent and varying directionality. Various lessons were learned. Use of this scheme has the potential to simplify DER installations where multiple DER sites are involved.