# Practical Experience Testing and Commissioning Digital Protection and Control Systems at EPCOR

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EPCOR Distribution and Transmission Inc. (EPCOR) is a regulated electrical subsidiary of EPCOR corporation which owns, plans and operates the electrical infrastructure in Edmonton and nearby area in the province of Alberta, Canada. EPCOR has been renowned for positioning themselves in the front line of technological advances in substation protection and control (P&C) as an early practitioner of IEC61850 based digital technologies. Their applications of IEC61850 date back to 2009 with the implementation of client-server communication in parallel with DNP3 for SCADA monitoring tasks. GOOSE messages were first attempted in a novel feeder protection upgrade project to trigger DFR functions in neighboring feeder protection relays. After numerous other small-scale GOOSE applications, a full-scale implementation of GOOSE for inter-device signaling was realized in 2020 in a green field substation project. In addition to standardizing on IEC61850 station bus applications, EPCOR completed and energized its first process bus installation in 2016 based on the 61850-9-2LE implementation guideline. The initial process bus project allowed for breaker fail, sync check and trip coil monitoring. Process bus applications at this site were expanded in 2018 to include transformer protection in the scope.

EPCOR has accumulated experience and valuable lessons while testing and commissioning digital P&C systems. Numerous conference papers in recent years have documented the digital testing methodology standardized by IEC61850. It is the intent of this paper to share practical aspects in system isolation, test injection, GOOSE interoperability, live component replacement, traffic monitoring and tracing and utilization of modern tools. Comparisons with conventional test methodologies would be remarked upon where applicable.

## 1. EPCOR's Background & IEC61850 Digital P&C Implementation

EPCOR, celebrating its 125 year history as Canada's first municipally owned utility, builds, owns and operates electrical, natural gas and water distribution networks, wastewater treatment facilities, sanitary and stormwater systems in Canada and the United States. EPCOR Distribution and Transmission Inc (EDTI), an operating company of EPCOR headquartered in Edmonton, AB, owns and operates 257 circuit kilometers of aerial transmission lines and underground transmission cables through 30 substations that form part of the Alberta Interconnect Electric System regulated by the Alberta Utilities Commission. EDTI also distributes electrical energy to customers in Edmonton through 19 distribution substations, 293 distribution feeders and approximately 5,950 circuit kilometers of primary distribution lines

EPCOR has been at the forefront of digital substation automation evolution. Through combinations of forward-looking leadership, nimble operating culture and talented technical resources they seize various opportunities to devise novel solutions leveraging new technologies of the time.

IEC61850-8-1 client-server reporting services were first utilized in 2010 in a green field substation project as an alternative to DNP 3.0, an experimental endeavor at the time when DNP 3.0 was the exclusive SCADA protocol of choice for substation automation. GOOSE messages were later applied in another novel feeder protection upgrade solution, which utilizes distance elements to reduce fault clearance time for close-in cable faults. GOOSE was applied in the solution to trigger station wide disturbance recording in all feeder IEDs, mimicking the functionality of a centralized disturbance recorder.

Maturation in IEC61850 technology comes with commercial advancement and proliferation of competing products and tools that propel digital evolutions in substation automation to a whole new level. EPCOR further expanded their applications of IEC61850 technologies in other green and brown field substation P&C system projects. The two most noteworthy are referenced below in detail.

### 1.1. Riverview Substation Full Station Bus Installation

A 240 – 25kV green field substation was approved for construction in late 2018. Detailed design & engineering of the SA System occurred in 2019 and the site was fully commissioned in early 2020. This is the first substation in which IEC61850-8-1 station bus communication are applied for the entire station automation assets, consisting of redundant power transformer, redundant 240kV transmission line, breaker management (breaker failure, sync-close and trip coil monitoring), and 25kV feeder protection devices. GOOSE messaging is applied for inter-device signaling to serve various protection and automation schemes with the goal of replacing conventional copper wiring between panels. Buffered/unbuffered report services are applied as means to transfer asset status from substation IEDs to the station data concentrator and HMI server, before reaching the corporate control center via DNP3.0. Control commands are sent to distributed remote I/O units, replacing the conventional, centralized RTU. Protection trip commands remain hard-wired to circuit breaker trip coils for this project. Key IEC61850 applications are summarized below:

GOOSE:

- Breaker failure protection: GOOSE messages are published by protection relays to the designated breaker management unit to initiate circuit breaker re-trip (BFI) and extended zone trip operations.
- Breaker failure transfer trip: breaker failure extended zone trip signals for circuit breakers of line protection zones are published to the redundant line protection IEDs for direct transfer trip (DTT) keying to isolate the remote line terminal.
- Line auto-reclose: GOOSE messages are published by Main B line protection to Main A counterpart to initiate auto-reclose sequence on selected transient line fault types. Only the auto-reclose function of line protection A is enabled.
- Transformer stub bus auto-restoration: GOOSE messages are published by transformer Main B and mechanical protections to Main A to initiate the bus bar auto-restoration sequence for transformer faults. The purpose is to start a series of commands, including resetting all circuit breaker lockouts and opening the transformer high voltage disconnect, to allow the control center to manually close the disrupted HV ring bus.
- DFR Trigger: A centralized DFR with IEC61850 capability are triggered from protection events throughout the station via GOOSE.

Client/Server over MMS:

Buffered and un-buffered reports are implemented to transmit critical operation events, status and metering values to the central station data concentrator for communication with the control center, namely:

- Protection IEDs are configured to transfer major protection operation events and key equipment status such as breaker positions. Voltage, current and power measurements are transferred via un-buffered reports.
- For each protection panel a standalone remote IO unit compliant with IEC61850 is used to collect and report miscellaneous alarms and statuses such as relay watchdog contacts, breaker health and conditions, etc.

## 1.2. Woodcroft Substation Process Bus Pilot Installation

The Woodcroft Substation P&C upgrade was considered a major achievement at the time in the Utility industry. It was the first protection system upgrade project to adopt IEC61850-9-2LE process bus implementation guideline in Canada. Unlike Riverview described earlier, Woodcroft is a 72KV, brown field station, adding additional complexities in testing and commissioning aspects to the project. Protection upgrades are executed in phases for brown field stations so it is extra critical to minimize disruptions to protection schemes not included in the upgrade work. Two phases have been successfully completed in Woodcroft to date. The initial phase involved upgrades to breaker management units utilized for breaker failure, sync-check and breaker health monitoring applications. Transformer protections were added to phase two of the project, but only Main B protection was designed to subscribe and process sampled values to limit risks.  Vendor and product evaluation of the process bus technology commenced in 2014, detailed design of phase one occurred in 2015, and was fully commissioned in 2016.  Phase two of the upgrade was completed in 2018.

Station bus applications are fairly similar to those implemented in Riverview with the exception that transmission line protections were not included for GOOSE exchanges dictated by the phased upgrade schedule for brown field substations.  The ultimate phase would have all P&C assets upgraded to IEC61850 communication by mid-2020's. Figure 1 illustrates the ultimate layout in Woodcroft.

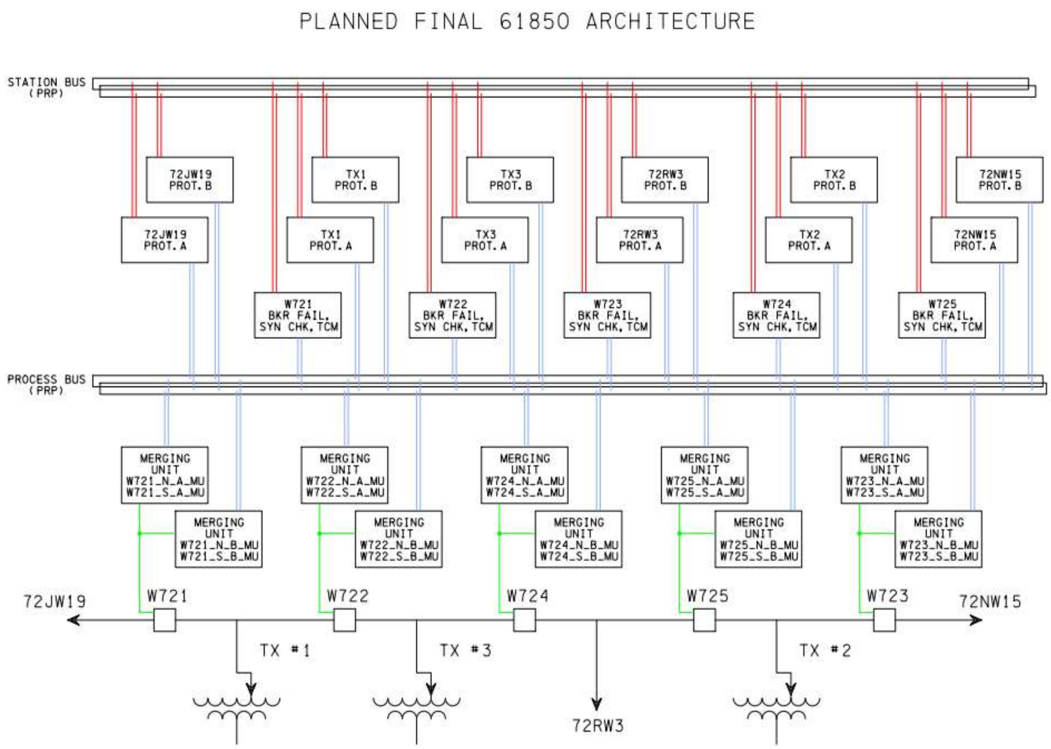


*Figure 1: Woodcroft Ultimate IEC61850 Configuration*

Process bus technology based on UCA Implementation Guideline, 61850-9-2LE, entails further digitizing analog signals from the current and voltage transformers close to the source by hardware located at the switchyard.  Commonly known as a merging unit (MU) or process interface unit (PIU), this hardware has similar analog terminals for CT and VT connections and in most commercial design today also comprises digital I/Os in the same enclosure to support binary signaling to/from the field. The digitized Ethernet packets, known as Sampled Measured Values (SMV) or Sampled Values (SV), are processed by protection IEDs similar to analog current and voltage inputs.  The process network is a dedicated Ethernet network employing parallel redundancy (PRP) to prevent any single point of network component failure, a critical requirement for sampled value transmission to ensure the same measure of dependability as conventional systems.  The key functionality of the process bus network is:

- Publish sampled values from merging units located in the switch yard onto the process network.  The streams of packets are subscribed and processed by different protection IEDs through vendor specific engineering procedures.
- Transfer binary values via GOOSE messages.  This includes both publishing signals such as CB positions and trip coil health collected via the digital inputs and subscribing critical trip, re-trip, and close signals from protection IEDs from the different P&C schemes. Figure 2 below displays the sample network architecture.

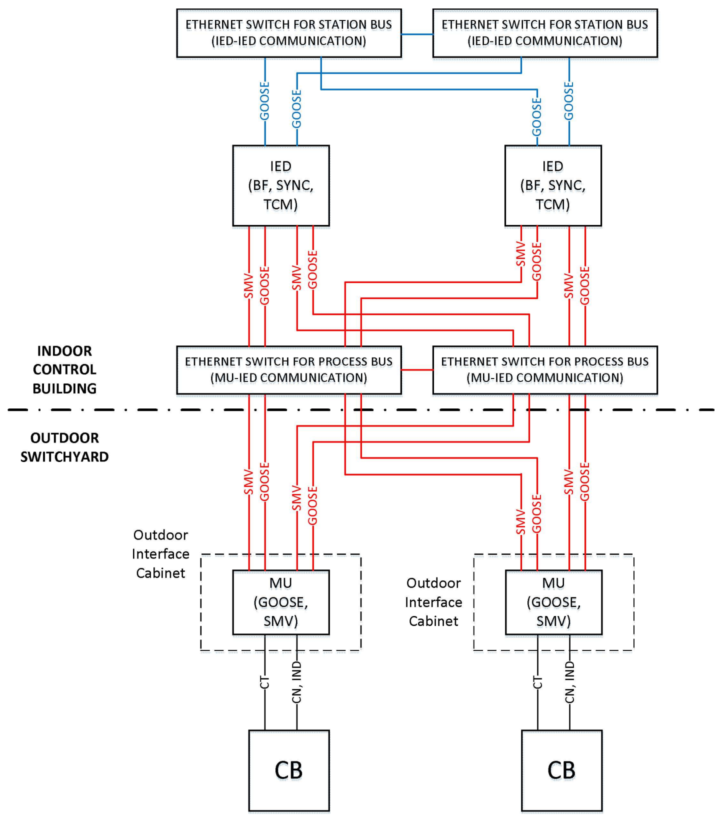


*Figure 2: Example IEC61850 Network Architecture*

## 2. EPCOR's Digital P&C System Testing Methodology

It is human nature for people to resist major changes outside their comfort zones.  This statement is especially true for P&C technicians who are responsible for constantly interfacing with live P&C systems to ensure the reliability of their operations.  Safe testing procedures for conventional copper P&C systems have been well established, trusted, and practiced for decades. The transition from copper wiring to digital signals challenges those deep-rooted routines and conservative mindsets, which hinder the advancement and adoption of 61580 technology. Through the efforts of standard committees, where equipment vendors and end users jointly collaborate to identify and fill the gaps for safe testing solutions and procedures in the Standard, we begin to see a wider acceptance of the technology supported by compliant test equipment and IEDs. Yet as a pioneer treading into this new realm over six years ago, some of the testing features that are known as standard today were not available or did not work as desirably. Moreover, transition of the mindsets of relay technicians to digital methodologies takes time. Training and constant exposures to digital systems are needed to develop proficiency and increase their comfort level in safe testing, operating and maintaining digital systems. After all, no one wants to fall victim to a new technology and takes blame for any undesired behavior because of it. This section documents EPCOR's elected testing and commissioning methodologies for the two digital upgrade projects, lessons learned from the commissioning experience, and visions towards future similar projects. Emphasis will be placed primarily upon experience attained from Woodcroft due to the additional challenges introduced by live work in a brown field environment.

### 2.1. Documentation

A conventional P&C design package is generally comprised of a single line diagram (SLD) showing the interactions and function allocations of P&C devices, DC schematics showing DC connections and I/O allocations per IED, AC schematics showing analog connections of each IED, and wiring diagrams showing the wiring of all components on a protection panel. The isolation points, with either isolating terminal blocks or test switches, are typically indicated on the DC schematic. For modern numerical IEDs, logic diagrams have also become an integral part of P&C documentation to highlight the applications of protection functions and customized logic implementations. When GOOSE messages are adopted to replace copper wiring between relays, a high-level representation of publisher-subscriber relationship between devices would be helpful to gain a quick insight into the impact of one device to others. A GOOSE SLD is created for this purpose as a guide for risk review and "virtual" isolation planning prior to conducting testing activities. GOOSE messages are also added to the logic diagrams in parallel to digital I/Os to show the roles they play in the protection logic. From the process bus standpoint, sampled values replacing conventional CT and VT analog wiring are documented directly on the SLD to indicate the source and destinations of different measurands. Lastly, a detailed document analogous to the conventional wiring list was created for each device participating in the 61850 networks, listing the full GOOSE and SMV data attributes published and subscribed to by an IED. The intent of furnishing the P&C design package with new digital information is to provide the field technicians a sense of familiarity and consistency so that locating information and cross- referencing signals can be carried out as closely to the conventional design as possible.

### 2.2. Isolation

Conventional P&C design allows for a single zone of protection to be isolated, modified, tested, and restored without impacting other protection zones. Signals are isolated using test switches to provide visual proof of isolation. This tested-and-true technique is being challenged when transitioning to the digital realm. Modern IEC61850 compliant equipment supports virtual isolation commonly referred to as "test mode". A GOOSE message in test condition would be ignored by subscribing devices in normal operating condition, achieving isolation in a virtual sense. Adoption of Test Mode requires a full understanding and confidence with its automated blocking philosophy especially during live work environment because its operation is transparent by nature. To bolster the confidence of technicians running the tests, EPCOR engineering team designed a semi-automatic yet visual procedure leveraging the familiar test switches. Individual test switch blades were wired into relay digital inputs as usual and the open positions were programmed in the logic editor to block GOOSE messages from being published by the IED. There are multiple test switches assigned for blocking different GOOSE outputs. This measure is analogous to the conventional use of test switch to isolate digital outputs from the processes whiles also serving as visual indicators. One drawback of this practice compared to IEC61850 Test Mode was that the GOOSE attributes are blocked from updating their values altogether following an event, hence one would not be able to monitor the change in behaviors of the IED under test via this isolation method. As a compromise, the isolation zone will have to be extended to other devices subscribing to the GOOSE messages from the IED under test to allow selective restoration of the GOOSE test blades for monitoring purposes. The test blade design was used as the main isolating procedure during Woodcroft commissioning and subsequent live testing. It is envisioned, however, that the test switch design to be phased out in the next digital substation upgrade project following EPCOR gaining more confidence and experience learning and working with IEC61850 Test Mode in an offline, laboratory setting.

### 2.3. Injection and Simulation

Secondary injection from a test signal generator (test set) through the test switches into the IED under test is the standard method employed for conventional P&C testing to assess the operations of protection functions. For IEDs subscribing to SMVs over the process network, the same injections can be made directly into the MUs in the field cabinet. Direct injection testing with this method enables a complete loop test for the protection system, verifying correct operations from A/D conversion, metering accuracy, protection functions, customized logic, and trip contact performance. EPCOR prefers to conduct complete loop tests whenever applicable, but it is a hassle to have to move the test equipment out to the switchyard, set up, and make the connections. A solution was conceived during pre-commissioning to install the MUs temporarily on their detachable cabinet back panes inside the control building close to the protection panels and the network equipment. From there much more convenient injections can be made to the MUs. Only after major protection functional and scheme tests were completed the MUs were moved to switchyard for final installation.

A “virtual” injection technique, known as simulation, was used when minor changes made to protection settings and customized logic in the IEDs need to be re-verified, yet a complete system test isn’t deemed necessary. IEC61850 compliant test equipment is capable of publishing “simulated” SMVs on the network with user defined parameters. The protective relays would operate on the simulated values as if they are the real process values from the MUs, with one caveat, that the MUs publishing the real messages have to be stopped or simply removed from the process network to avoid packet conflict that would otherwise confuse the subscribing relays or cause them to malfunction. Nowadays an IEC61850 standardized test feature known as "Simulation Mode" offers a more elegant solution to the above. Nevertheless, virtual simulation of any kind offers an expedient alternative to verifying protection performances. Correct function testing from SMV simulation requires accurate time synchronization between the test equipment and IEDs using accurate time-sync protocols such as IRIG-B or precision time protocol (PTP) based on IEEE1588 V2.

GOOSE messages can also be simulated onto the network by importing the Substation Configuration Description (SCD) file into the test equipment. It was commonly used to force certain GOOSE inputs to the IED under test when triggering the actual protection elements publishing those messages isn't considered necessary.

2.4. Monitoring

Monitoring IED behaviors to assess its correct operations following either injection or simulation testing is a multi-faceted activity in a digital P&C system. For a copper based system, relay digital outputs are wired into the test equipment input ports and by sensing contact status changes, correct functional behaviors and performances can be ascertained. In a digital system the same results can be achieved by using IEC61850 supporting test sets subscribing to GOOSE messages published by the IED under test. The messages subscribed to are used by the test set to evaluate the different functional performance similar to hard-wired contact outputs.

The second monitoring aspect involves interrogating the actual bits of the digital packets on the network to ascertain the health and status of the messages on the network. With supporting scouting software running on a PC connected to the network, cryptic 0's and 1's are translated into friendly IEC61850 attribute values. For GOOSE and SMV messages that means one can immediately learn the status of Boolean attributes, analog magnitude and phase measurements and their respective quality values. Some software applications can present the messages in a graphical manner too, for example, allowing the user to co-relate breaker failure initiation and breaker failure extended zone trip events to verify the correct timing and performance. In MMS applications the test software can act as a legitimate IEC61850 client to receive buffer/unbuffered reports and send control commands to test the logic and configurations in the IEDs.

Network traffic monitoring is the third aspect that close attention needs to be paid during both design and commissioning stages. SMV data streams consume majority of network bandwidth in approximately 5 Mbps each. A 100 Mbps LAN caps the number of SMV streams to nineteen (19). Factoring into redundancy in MU design, that number could easily be surpassed for the ultimate development stage of Woodcroft. For that reason, EPCOR chose to implement IEEE 802.1q VLAN to manage and optimize layer 2 multi-cast traffic in both GOOSE and SMV. VLAN tagging prevents multi-cast messages from freely propagating to IEDs they are not intended for. With VLAN implementation each switch port receives an average of only three (3) SMV streams. Compared to SMV, GOOSE messages can consume bandwidth in the hundreds of Kbps range in message burst during an event, but most of the time network consumption by GOOSE is negligible. The VLAN table was developed to supplement existing documentation as a means of tracking VLAN assignments and used as a reference for efficient relay and switch traffic engineering and later as a troubleshooting aid. A dedicated hardware called network analyzer was used in the project to assess network conditions, assist in fault finding, and raise alarms when abnormal traffic patterns were detected.

Figure 3 depicts EPCOR's test equipment arrangement for test monitoring and analysis.

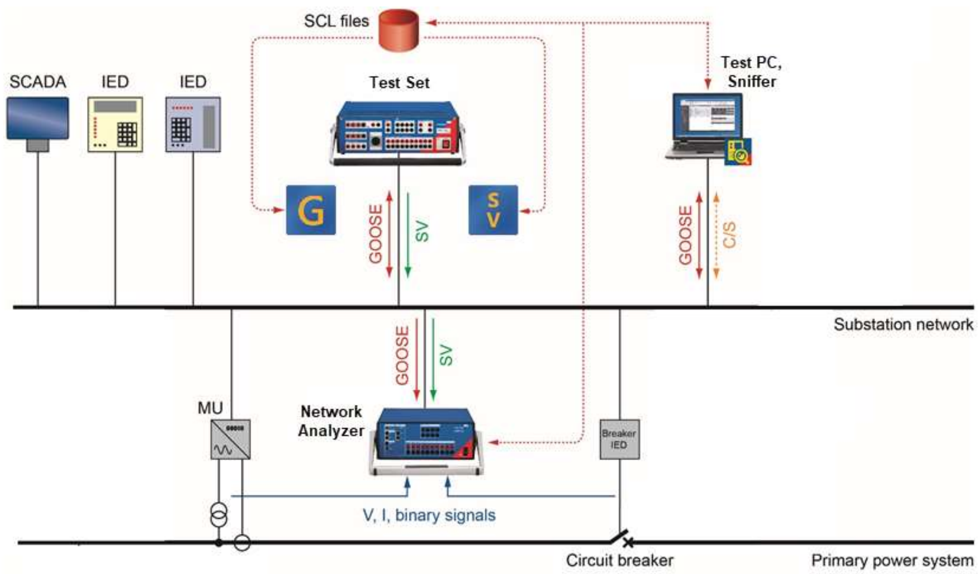


Figure 3: Network Monitoring and Analyzing Setup

2.5. <u>Summary of EPCOR's Commissioning and testing procedures</u>

EPCOR's commissioning and testing procedures utilizing the methods introduced in previous sections are summarized here. The test procedures are discussed for the three different stages in a P&C system life cycle. An overall summary of procedures will be provided last. The established procedures require no disconnection of wiring including network cables.

Pre-commissioning testing generally takes place offline in a laboratory environment to verify protection performance, customized logic and for IEC61850 upgrade projects, to also verify correct GOOSE communication and network configuration. For Woodcroft complete system tests from MUs to the IEDs back to MUs were performed ahead of the system outage window, which helped reduce the outage time otherwise required.

Commissioning activities generally require partial outages of the apparatus bays and circuit breakers to cut over new wiring and protection devices. During that interim the new protection panels and MUs will be installed in place and wired up according to design. Since adjacent bays might still be in service, isolation points must be carefully planned and determined to ensure no false operations could result from the testing activities. Because EPCOR considers BF protections as a secondary, backup protection scheme, it was considered acceptable to temporally block them all during the testing activities. During phase one of BF protection upgrades, all breaker management IEDs and MUs were isolated with blocking test blades. The IED that received the breaker outage at the time was free to unblock its GOOSE outputs selectively in order to perform end-to-end injection testing to verify both hard wiring, network connections and functional performance. In phase two of transformer Main B protection upgrade, similar concepts were followed with one transformer bay outage granted at a time. Out of security concerns it was decided to also block all breaker management IEDs to properly verify the network connection for applications such as BFI. Trip outputs of the associated HV MU were blocked as the main isolation point. Outage for the LV circuit breaker was needed to cut over the new LV MU cabinet.

Subsequent maintenance or ad-hoc testing of protection functions or logic can be supported by SMV and GOOSE simulation. Generally, no breaker or bay outage would be granted for this type of testing. An Isolation plan and risk assessment therefore needs to be carefully prepared prior to conducting any tasks. Different GOOSE outputs shall be selectively blocked and/or restored to allow monitoring of functional performance. Other IEDs subscribing to the SMVs being simulated on the network need to be blocked, too.

The high-level test procedures followed throughout the two phases with live elements in service are summarized below:

1. Study the standard SLD and GOOSE SLD to establish correct isolation points. For breaker failure function testing, extended devices have to be isolated.
2. Isolate trip signals to all circuit breakers to which the protection under test is associated. Trip signals were isolated from the MU cabinets.
3. Isolate the GOOSE outputs of the IED under test by opening the test switches.
4. Other IEDs subscribing to the same SMVs or GOOSE to be simulated need to be blocked. Simulate the virtual SMVs/GOOSE or use secondary injection to the MU to trigger the expected protection operations. Note that without aids from modern Simulation Mode of IEC61850 Ed.2, the source devices publishing the actual signals need to be blocked or stopped.
5. Selectively restore the GOOSE outputs of the IED under test to monitor the different functional performances.
6. The test set assesses the functional behaviors by subscribing to GOOSE messages published.

### 2.6. Troubleshooting Experience

Troubleshooting a digital P&C system can be approached in a manner similar to a conventional system. The two practices generally follow the same concept, differing mainly in the tools used and the nature of the communication technology. As an analogy, to troubleshoot a relay input that fails to operate, one would first use a meter to check if the input terminal receives a positive voltage. This check verifies that the wiring path is continuous. Similarly, for an IED that fails to receive a GOOSE message, the first test would be to verify if the message is published on the network. Once checked out, then in both cases the next step is to investigate the IED internal configuration or network settings for the receiving error.

GOOSE communication operates on a publisher/subscriber relationship. Data attributes in a GOOSE dataset are published on the network for all recipients requiring the information to subscribe – an Ethernet technology called Multicast, a point to multi-point communication. The GOOSE dataset is encapsulated and controlled by the parameters specified in a GOOSE Control Block (GCB). Parameters such as MAC address, APPID, VLAN ID, and configuration revision are defined by the user to identify a particular message and control how that message will be transmitted. It is important to note that the publisher and subscribers' model of a GCB must match to ensure successful subscriptions.

EPCOR feels that for the majority of the time, GOOSE related issues are relatively straightforward to resolve. Using a network sniffing or scouting tool one can quickly determine whether GOOSE messages are on the network. If not, there could simply be a network connection issue such as a loose connection or a dirty fiber port. A ping test can verify this doubt. Should a ping test return with proper responses from the publishing device, then the issue could very well be with the Ethernet switch port configuration. A common Ethernet switch configuration issue is the misconfiguration of VLAN. Some IED vendors require entering the VLAN ID in HEX value while the switch interface requires decimal. This should be the first place to check. Of course, an incorrect port mirroring setup in the switch for the monitoring port could also result in the connected scouting software not able to detect the GOOSE messages. A more definitive test for verifying mismatched or wrong VLAN configuration at the Ethernet switch is by simulating the same GOOSE message with VLAN ID = 0 using a supporting IEC61850 test set. Ethernet frames with VLAN = 0 is known as priority tagged frames. The VLAN tags of priority tagged frames are stripped and ignored upon ingress to the switch port and the frames processed according to the priority tag appended. As the result, this type of frames will reach all switch ports unfiltered. It can be concluded that if the simulated GOOSE messages of VLAN = 0 are received by the subscribers it then most likely indicates some sort of Ethernet port configuration issue.

Another common cause of GOOSE subscription error is due to mismatch of GOOSE data model between publishing and subscribing devices. A mistake can easily happen during the engineering process when the copy of a GOOSE configuration file, typically in the form of substation configuration description (SCD), written to the publishing and subscribing IEDs are of different revisions. GCB parameters of the messages published on the network must match with the model running in the subscribing devices. An IEC61850 scouting tool has the capability of identifying the mismatched parameters by utilizing the SCL comparison feature between two SCD files online running in the IEDs, offline copies, or a mixture of both. Mismatches in the files are identified automatically by the tool. A manual comparison of the GCB parameters between the messages on the network and the SCD imported to the subscribers can be made using the network sniffing feature. If any mismatch is found it can be resolved by re-importing the SCD file and repeating the subscription configuration process again for the subscribers.

In addition to GOOSE data models, the data attributes quality such as validity and the TEST flag can also influence if the subscribing devices will process the data. There are also multiple ways the quality values can be verified. The most common method is to use the 61850 network sniffing feature to decipher the digital bits and bytes of the GOOSE message into IEC61850-7-3 defined quality information. Some vendor's IED Configuration Tools can also return real time quality values of subscribed GOOSE attributes directly. If a quality value is valid yet the expected operation does not occur, it typically suggests potential errors in IED application logic mapping.

Above troubleshooting tips for GOOSE applies generally to SMV as well. Most commercially available MU on the market today supports IEC61850-9-2LE UCA Implementation Guideline that standardizes the data model, data contents, and sampling rate to promote interoperability between vendors' IED products, making subscription of SMV more of a plug-and-play process with very minimum engineering steps. Modern 61850 scouting tools support features to sniff SMV packets to verify their control block parameters (SVCB) similar to GOOSE and can display them graphically as phasors or tabularly with information such as measurements, quality, and time sync. status. The most common reasons an IED would fail to subscribe to a SMV stream on the network is by mismatch of sampled value ID (SVID), APPID, and issues with time sync. quality between the MU and the IED that processes the SMV stream. Different vendors have ways to unblock or allow SMV subscription from loss of time synchronization for user selectable applications.

EPCOR engineers developed a visual GOOSE troubleshooting flow chart in Figure 4 below.

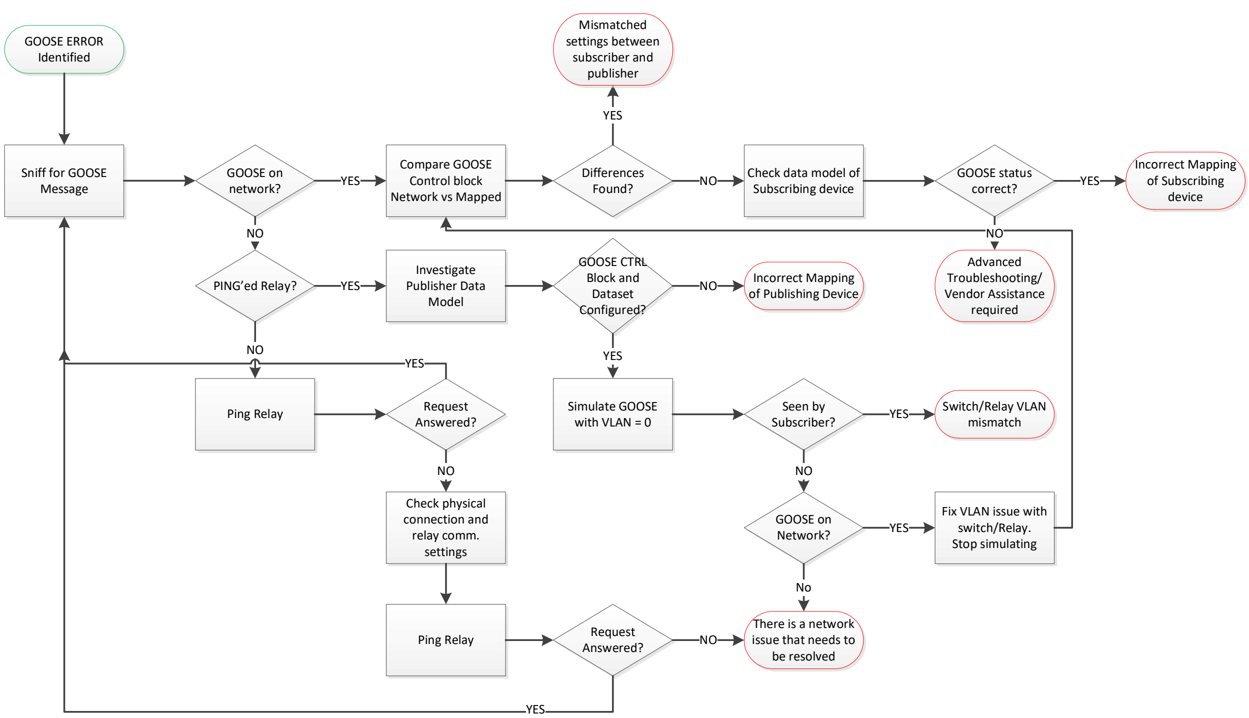


*Figure 4: GOOSE Troubleshooting Flow Chart*

## 3. Lessons Learned and Future Testing Design

### 3.1. IEC61850 Test/Simulation

One major lesson learned for the future is the adoption of true IEC61850 Test/Simulation features in the next similar process bus upgrade project. References [ 4] [5 ] [ 6] discusses the features in detail. To summarize, an IED in "Test Mode" publishes GOOSE and SMV messages with individual data attribute quality bit set to TEST. The messages will only be processed and executed by subscribing IEDs also in Test Mode. IEDs in normal service condition will ignore the messages. This mechanism is analogous to opening a test switch to block an input to the subscribing device. To block the contact operation of an IED (MU in this case) subscribing to a test message, the IED can be set to the "Test-Block" mode. With that the message will be processed but contact operations are refrained. This measure mimics opening of test switch blades to isolate tripping outputs.

"IEC61850 Simulation" is another concept that enables test equipment/software to publish "simulated" GOOSE and SV messages on the network with the Simulation flag set to TRUE. IEDs with their SIM attribute enabled (via a 61850 test client) can accept and process the simulated signals as if they are real and at the same time ignoring the real messages published by the MUs or other IEDs. This feature isolates the IED under test from the process signals and allows acceptance of test quantities to validate relay response and performance similar to conventional secondary injections. A correctly implemented simulation algorithm in the IEDs allows the IED under test to subscribe to the simulated messages while other IEDs in service will continue subscribing to the same signals from the real processes (MU or IED). IEC61850 Test/Simulation are designed to work in conjunction to accomplish the same convenience and security of conventional analog injections. Figure 5 below illustrates the concepts.

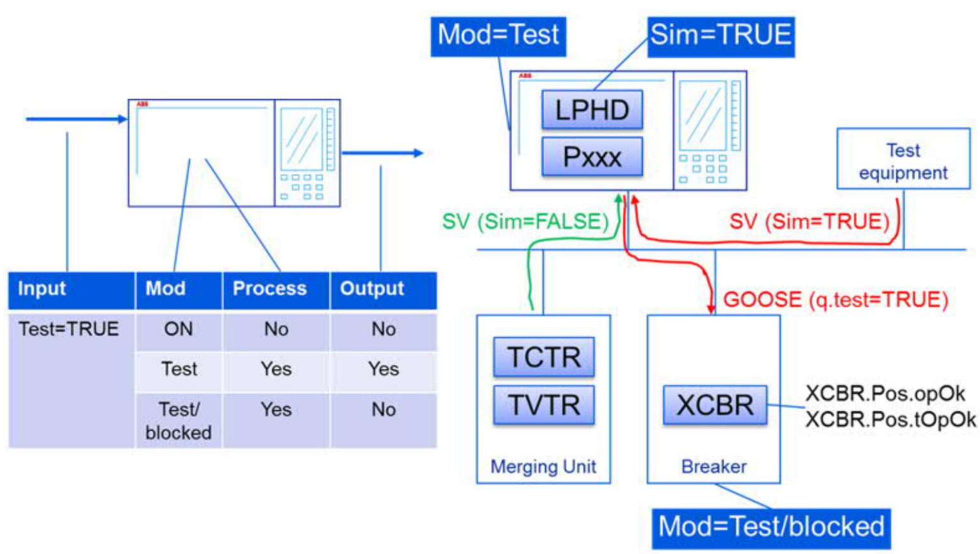


*Figure 5: IEC61850 Ed.2. Test and Simulation*

Taking the Woodcroft project again as an example, the benefits of applying IEC61850 Test/Test Block Mode will eliminate the need to block neighboring IEDs (including MUs) unnecessarily, thereby reducing protection outages and maintain a similar availability to the conventional testing technique. Application of Test Block also enables complete end-to-end tests up to the output contacts of the actuating devices. The benefits of applying IEC61850 Simulation eliminates the need to stop the real transmissions or remove other IEDs subscribing to the same messages from the network , and again, maintaining maximum protection availability during live test. These features were also designed to allow remote testing of IEC61850 SAS without having to send crew to site, at least for simple verification tasks.

In order to fully leverage the benefits mentioned above, a buy-in and confidence with the test/simulation feature set is imperative. Support is to be obtained from engineering and service management after fully learning and understanding the benefits of reduction in human errors in establishing isolation points and improvement in protection availability. Confidence with the procedures can be reinforced through hands-on training and most importantly, laboratory validation offline witnessed by all team members involved.

It is a vision that the feature set will be fully applied in Phase Three of Woodcroft P&C upgrade and future digital substation retrofit projects.

3.2. Live Replacement

A false operation of a transformer differential function took place approximately ten (10) months after the Phase Two relays were put in service. A current spike and distortion were clearly spotted on the oscillograph recorded by the relay disturbance fault recorder. The analog to digital converter in the MU was suspected to have caused the distorted waveform and the resulting operation. It is unknown to this day why a failed A/D hardware did not trigger a fail-safe action that blocks the protection functions in the IEDs subscribing to the SMV, but similar failures can happen in a conventional hard-wired IED, too, making this failure mode not unique to the process bus system. Nonetheless, a process bus system could be more prone to cause a wider outage for the benefit of material saving by subscribing multiple IEDs from the same MU. There is always the same trade-off between savings gained by consolidations and compromises to be made in protection dependability. Laboratory verifications with vendor support is necessary to obtain a clear understanding of all security features available in a process bus application. Sometimes, a firmware upgrade would be necessary to patch up any deficiency found. Because of the lesson learned out of this event, a design decision was reinforced to separate MUs supplying critical IEDs, such that adjacent transformer and line IEDs would not subscribe from the same MU. This practice also permits a similar degree of protection zone overlap as conventional schemes.

From the perspective of new MU installation, extreme caution needs to be made for working under live, in service environment. In EPCOR's live replacement procedure, the new MU was loaded with the as-left configuration and functionally tested in the lab environment prior to site installation. During installation all IEDs subscribing to that MU would have their

GOOSE outputs blocked. The IEDs can also be placed in Test Mode to ensure the most secure isolation. Once existing CT and VT leads were re-terminated, metering checks were performed on the relays. The new MU was monitored for a few days in the so called "soak test" before restoring the protections back to service.

Some MU vendors support a Test feature to support MU replacement in a live setting. Setting the MU in Test Mode, via either a binary input or via a setting, the published SMV streams would have their measurement quality switched to TEST. Following the same Test Mode concept, SMVs in Test can only be processed by IEDs that are also in Test or Test-Block mode. This feature enables live injection testing to the MU with controlled responses from selected IEDs only, eliminating the need to block other protections subscribing to the same SMV streams.

3.3. MU output isolation

Notwithstanding a minor oversight, the original design to physically isolate the hard-wired trip circuits was through isolating terminal blocks, not the common test switches, in Phase One for all 72KV MU cabinets. To maintain operating consistency and convenience going forward, test switches will be installed for future upgrade projects. In Phase Two the transformer low voltage MU cabinets were furnished with test switches to isolate the trip outputs.

## 4. Conclusions

This paper begins by exploring EPCOR's digital substation experience and then goes in depth to examine the design and methodology in place for testing and commissioning the two IEC61850 upgrade projects. In particular, the Woodcroft project with its multi-phased upgrade path, adoption of SMV communication, in an energized environment poses additional risks and challenges in testing and commissioning. Existing isolation, test injection, and troubleshooting methodologies are analyzed in detail. Future vision of adopting IEC61850 Test/Simulation features as the main isolation/injection technique is discussed with recommendations focusing on providing hands-on training and gaining support from the entire EPCOR team as the top priority. Lessons learned to date from the Woodcroft project will be applied to another process bus upgrade project in 2021. The performance and compliance of Main A protection to the standard will be examined then.

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