# Comparison of Processes for Testing, Commissioning and Maintenance Methods - Digital Versus Conventional Substations

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**Abstract**

This paper introduces protection engineers to the differences and similarities for testing, commissioning, and maintaining digital versus conventional substation protection and control schemes. IEC 61850 station bus and process bus solutions have become popular in modern digital substations. IEC 61850 standard employs digitized analog and control signals published and subscribed amongst relays/IEDs and merging units. Digital substation advantages include faster implementation with fewer errors, a more reliable and repeatable final product, and significant cost savings from efficiencies in design, testing/commissioning, and operation. This paper describes commissioning and maintaining process-bus/station-bus devices such as merging units, protective relays, and Ethernet network switches, and compares these with conventional (hardwired) protection and control schemes. Discussed are digital substation design and documentation methods, configuration testing/verification, factory acceptance tests, site acceptance tests, system testing/verification, periodic/maintenance testing and troubleshooting tools and methods.

## 1. Introduction

Digital substations involve the use of merging units (MUs) to connect to yard elements (CT, VT, 52, 89), digitizing the data, and communicating with relays/IEDs in the control house over a fiber optic Ethernet network. The Ethernet network providing this is called the "Process Bus". IEC 61850 analog data (SV or sampled values), known as IEC 61850 9-2 LE for "light edition", is published by the MUs on the Process Bus Ethernet network. Published sampled values are synchronized by IEEE 1588 Precision Time Protocol (PTP) in the Process Bus Ethernet network. The IEC 61850 9-2 LE profile for sampled values has a sampling rate of 80 samples/cycle. The dataset for IEC 61850 9-2 LE sampled values includes measurements for four currents (three phase and ground) and four voltages (three phase and auxiliary). High-speed messaging [IEC 61850 GOOSE (Generic Object-Oriented Substation Event)] is used for binary status and binary control (i.e., trip & close, etc.) in the Ethernet network via the "Station Bus". Inter-relay information used for interlocking, breaker failure, protection modification and other uses can also be performed over the Station Bus Ethernet network. Digital substations allow the elimination of inter-relay wiring using GOOSE messaging. The Process Bus and Station Bus can be separate Ethernet networks or same Ethernet network. Redundant process bus / station bus Ethernet networks can be employed for high availability and reliability. The benefits of digital substations are:

- Elimination of wiring runs from the yard elements to the control house relay panels
- Decrease in wire, terminations, trenching and conduit
- Decrease in engineering and labor associated with wiring and relay panels
- Large opportunity for standardization in design reducing engineering hours and construction time
- Large opportunity for standardization in testing and for additional monitoring capabilities

An example digital substation Ethernet network architecture with parallel redundancy protocol (PRP) is shown in Figure 1.

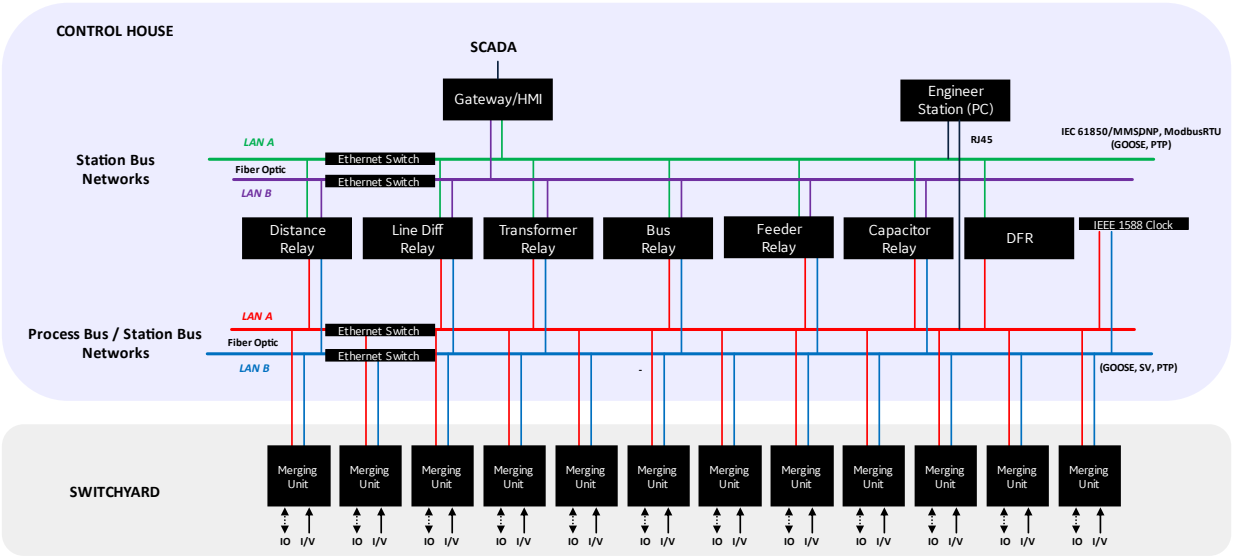
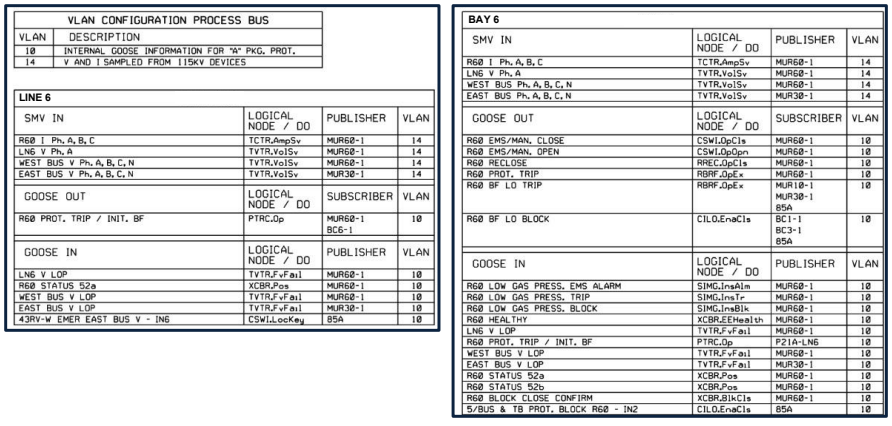



Figure 1 - Digital Substation Ethernet Network Architecture with PRP

## 2. Digital Substation Design and Documentation

The building blocks of a digital substation are the MUs, Ethernet network switches and relays/IEDs. The wiring of the switchyard MU cabinet(s), which are the currents/voltages/IO interfaces to the yard equipment, can be standardized and become a module that is repeated for various installations (i.e., breaker or transformer). The wiring of the substation control house relay/IED panels are reduced to DC control power and fiber optic Ethernet communications. The Ethernet network switches in the control house become the "digital terminal blocks" for the digital substation allowing IEC 61850 sampled values data and IEC 61850 GOOSE messages to be shared/distributed amongst the switchyard MUs and the control house relays/IEDs. In the design of a digital substation, a publisher / subscriber table is useful and important in mapping IEC 61850 sampled values data and IEC 61850 GOOSE messages amongst the switchyard MUs and the control house relays/IEDs. Figure 2 shows example of a publisher / subscriber tables for IEC 61850 sampled values data and IEC 61850 GOOSE messages. These publisher / subscriber tables are similar to a conventional substation wiring table. Some utilities are placing publisher / subscriber information on their drawings.



VLAN CONFIGURATION PROCESS BUS

| VLAN | DESCRIPTION |
|---|---|
| 10 | INTERNAL GOOSE INFORMATION FOR "A" PKG. PROT. |
| 14 | V AND I SAMPLED FROM 115KV DEVICES |

**LINE 6**

| SMV IN | LOGICAL NODE / DO | PUBLISHER | VLAN |
|---|---|---|---|
| R60 I Ph. A, B, C | TCTR.AmpSv | MUR60-1 | 14 |
| LN6 V Ph. A | TVTR.VolSv | MUR60-1 | 14 |
| WEST BUS V Ph. A, B, C, N | TVTR.VolSv | MUR60-1 | 14 |
| EAST BUS V Ph. A, B, C, N | TVTR.VolSv | MUR30-1 | 14 |
| **GOOSE OUT** | **LOGICAL NODE / DO** | **SUBSCRIBER** | **VLAN** |
| R60 PROT. TRIP / INIT. BF | PTRC.Op | MUR60-1<br>BC6-1 | 10 |
| **GOOSE IN** | **LOGICAL NODE / DO** | **PUBLISHER** | **VLAN** |
| LN6 V LOP | TVTR.FuFail | MUR60-1 | 10 |
| R60 STATUS 52a | XCBR.Pos | MUR60-1 | 10 |
| WEST BUS V LOP | TVTR.FuFail | MUR60-1 | 10 |
| EAST BUS V LOP | TVTR.FuFail | MUR30-1 | 10 |
| 43RV-W EMER EAST BUS V - IN6 | CSWI.LocKey | 85A | 10 |

**BAY 6**

| SMV IN | LOGICAL NODE / DO | PUBLISHER | VLAN |
|---|---|---|---|
| R60 I Ph. A, B, C | TCTR.AmpSv | MUR60-1 | 14 |
| LN6 V Ph. A | TVTR.VolSv | MUR60-1 | 14 |
| WEST BUS Ph. A, B, C, N | TVTR.VolSv | MUR60-1 | 14 |
| EAST BUS Ph. A, B, C, N | TVTR.VolSv | MUR30-1 | 14 |
| **GOOSE OUT** | **LOGICAL NODE / DO** | **SUBSCRIBER** | **VLAN** |
| R60 EMS/MAN. CLOSE | CSWI.OpCls | MUR60-1 | 10 |
| R60 EMS/MAN. OPEN | CSWI.OpOpn | MUR60-1 | 10 |
| R60 RECLOSE | RREC.OpCls | MUR60-1 | 10 |
| R60 PROT. TRIP | RBRF.OpEx | MUR60-1 | 10 |
| R60 BF LO TRIP | RBRF.OpEx | MUR10-1<br>MUR30-1<br>85A | 10 |
| R60 BF LO BLOCK | CILO.EnaCls | BC1-1<br>BC3-1<br>85A | 10 |
| **GOOSE IN** | **LOGICAL NODE / DO** | **PUBLISHER** | **VLAN** |
| R60 LOW GAS PRESS. EMS ALARM | SIMG.InsAlm | MUR60-1 | 10 |
| R60 LOW GAS PRESS. TRIP | SIMG.InsTr | MUR60-1 | 10 |
| R60 LOW GAS PRESS. BLOCK | SIMG.InsBlk | MUR60-1 | 10 |
| R60 HEALTHY | XCBR.EEHealth | MUR60-1 | 10 |
| LN6 V LOP | TVTR.FuFail | MUR60-1 | 10 |
| R60 PROT. TRIP / INIT. BF | PTRC.Op | P21A-LN6 | 10 |
| WEST BUS V LOP | TVTR.FuFail | MUR60-1 | 10 |
| EAST BUS V LOP | TVTR.FuFail | MUR30-1 | 10 |
| R60 STATUS 52a | XCBR.Pos | MUR60-1 | 10 |
| R60 STATUS 52b | XCBR.Pos | MUR60-1 | 10 |
| R60 BLOCK CLOSE CONFIRM | XCBR.BlkCls | MUR60-1 | 10 |
| S/BUS & TB PROT. BLOCK R60 - IN2 | CILO.EnaCls | 85A | 10 |

Figure 2 – Example Digital Substation Publisher / Subscriber Tables

Configuration/setting templates for MUs can be created and standardized for a digital substation. Likewise, configuration/settings template for the various relays/IED can be created and standardized for a digital substation protection and control scheme. The GOOSE IDs (or GO IDs) and sampled values IDs (or SV IDs) used for the MUs and relays/IEDs will change in the standard configuration templates based on the information in the publisher / subscriber table for the particular digital substation design.

## 3. Configuration Testing/Verification

### 3.1 Lab Testing

Many electric utilities have protection and control (P&C) labs that they use to test and validate new protection and control schemes with their associated settings/configuration before the schemes are implemented into the field/substation. These labs use multiple sets of relay test sets to provide AC current and AC voltage signals to the equipment used in the P&C scheme under test. Trip control, close control and status for breakers / switches are often simulated by digital relay(s) or breaker simulator(s). Digital substations can be considered as a new P&C scheme and treated similar to a conventional P&C scheme with regards to the benefits of lab testing. This kind of testing is often called factory acceptance testing or FAT. An example digital substation lab is shown in Figure 3. IEC 61850 testing tools can be used during the lab testing to aid in validation of SV datasets, GOOSE messages and communication links of the digital substation P&C scheme. The FAT performs a complete test of the P&C scheme, including all protection element settings, logic, and configuration. The results of the lab/FAT testing for a particular digital substation P&C scheme are the following:

- Verification of the configuration template(s) for MU cabinet(s)
- Verification of the various relay/IED protection setting configuration templates
- Verification of the protection and control logic within and amongst the various relays/IEDs and MUs
- Verification of publisher and subscriber configuration of SV datasets and GOOSE messages of relay/IEDs and MUs
- Verification of Ethernet network switch configurations (such as VLANs and MAC address filtering)

Figure 3 – Example Digital Substation Lab

### 3.2 Digital Substation Merging Unit Testing

#### 3.2.1 Factory Acceptance Tests

For new digital substation construction, the MUs or MU cabinet should be factory installed by the substation equipment manufacturer (i.e., breaker manufacturer). A standard configuration should be loaded into the MUs that include generic/standard configuration of IOs, SV datasets and GOOSE messages that match the particular MU cabinet wiring design. Basic configuration testing/verification of the MU cabinet should be performed at the manufacturing site of the MU cabinet. The current/voltage/IO interface testing of a merging unit is similar to testing a conventional digital relay. These factory acceptance tests will verify the wiring to the merging unit is correct and the generic/standard configuration of the merging unit is correct for the particular P&C scheme for which the MU will be implemented. This MU testing uses a traditional method of injecting currents and voltages to verify the current/voltage analog measurements, verify digital inputs and output operation using standard relay testing tools. Similar to a conventional digital relay, the MU's interface software can be used to verify the current and voltage measurements and verify the states of the digital inputs and digital outputs being tested.

#### 3.2.2 Site Acceptance Tests

The specific configuration of IOs, SV datasets, GOOSE messages and current/voltage settings of each MU for a particular P&C scheme should be uploaded at site during commissioning / site acceptance tests (SAT) using the MU's interface software. The SAT of each MU will verify the specific configuration of the IOs, CT settings, PT settings, phase rotation, SV dataset(s) configuration and GOOSE messages configuration. The configuration of the SV dataset(s) and GOOSE messages of each MU can be confirmed by using IEC 61850 testing tools from relay test manufacturer during commissioning / site acceptance tests (SAT) and as needed during maintenance/troubleshooting. The IEC 61850 tools should be configured to subscribe to the data published by the MU and configured to publish control flags to the MU through GOOSE messages using the MU Substation Configuration Language (SCL) configuration file [i.e., Configured IED Description (CID) file or Substation Configuration Description (SCD) file]. IEC 61850 testing tools can benefit from the information contained in the SCL files to automate the creation of test cases and minimize manual configuration by the user. The MU's interface software can monitor the status of the GOOSE inputs subscribed by the MU and monitor the on-line/off-line GOOSE subscriber status of the subscribed GOOSE control blocks by particular MU being monitored. The MU's interface software can be used to verify the current and voltage measurements and verify the states of the digital inputs and digital outputs being tested. IEC 61850 testing tools can be used to read MU data, such as GOOSE states, measurements/SV data and GOOSE subscription status.

### 3.3 Digital Substation Protective Relay/IED Panel Testing

#### 3.3.1 Factory Acceptance Tests

As mentioned previously, the wiring of the substation control house relay/IED panels for a digital substation are reduced to DC control power for each relay/IED and fiber optic Ethernet network communications (station bus & process bus) for each relay/IED which greatly reduces the post assembly tests at the panel manufacturing site. The panel assembly tests are reduced to a power up test on each relay/IED and verification of relay self-test alarm contact prior to shipping assembled panel. The factory acceptance testing of each relay/IED generic P&C configuration should be done in the lab described in Section 3.1. It is not required to have any particular settings loaded in the relay/IED for the panel assembly tests to be performed, thus a basic/generic configuration file for the relay/IED is acceptable. It is assumed that only IO on the relay/IED is the self-test alarm contact and all IO come from the switchyard connected MUs. A traditional wired relay panel compared to a digital substation relay panel is shown in Figure 4.

*Traditionally wired relay panel* *Digital substation relay panel*

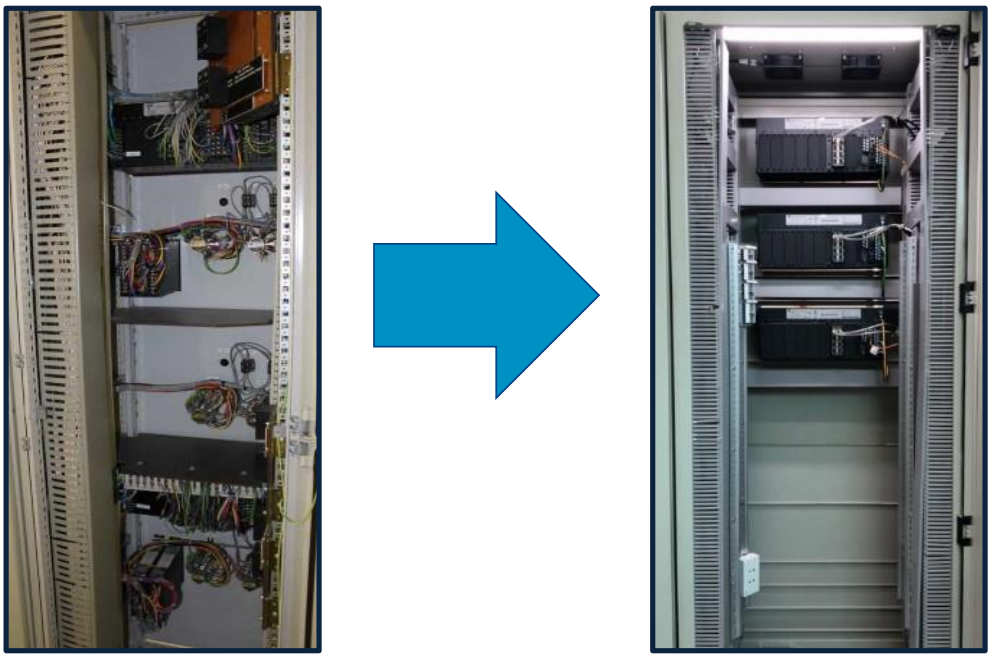


Figure 4 -Traditional Wired Relay Panel vs. Digital Substation Relay Panel

### 3.3.2 Site Acceptance Tests

The specific configuration for protection and control elements, SV datasets and GOOSE messages of each relay/IED for a particular digital substation P&C scheme should be uploaded at site during commissioning / site acceptance tests (SAT) using the relay/IED's interface software. This specific configuration could also be uploaded to each relay/IED at the relay panel manufacturer. The factory acceptance testing of each relay/IED configuration template should be done in the lab described in Section 3.1. The SAT of each relay/IED will verify the specific configuration of the CT settings, PT settings, phase rotation, SV dataset(s) configuration and GOOSE messages configuration. The configuration of the SV subscription(s) and GOOSE messages publishing/subscription(s) of each relay/IED can be confirmed by using IEC 61850 testing tools from relay test manufacturer during commissioning / site acceptance tests (SAT) and as needed during maintenance/troubleshooting. For validating the SV/GOOSE mappings, the IEC 61850 testing tools should be configured to simulate the data being subscribed by the relay/IED and to subscribe to the messages being published by the relay/IED. The IEC 61850 tools should use the relay/IED SCL configuration file (i.e., CID or SCD) for configuring the test. The relay/IED's interface software can be used to monitor the status of the GOOSE inputs subscribed by the relay/IED and monitor the on-line/off-line GOOSE subscriber status of the subscribed GOOSE control blocks by particular relay/IED being monitored. The relay/IED's interface software should be used to verify the current and voltage measurements simulated by the IEC 61850 testing tools or directly from the various connected switchyard MUs. Alternatively, the IEC 61850 testing tool can also be used to read the relay/IED data (GOOSE states, measurements/SV data, SV/GOOSE subscription status) through the process bus / station bus Ethernet network.

## 4. Digital Substation System Testing/Verification

Commission testing of a substation verifies that the protection system is installed correctly, all the devices are operating correctly and that the devices are configured correctly for the application. Commissioning a digital substation is more efficient than commissioning a conventional substation because the testing can be done in parts

or modules and IEC 61850 tools are available. The MU cabinets and relay/IED panels can be commissioned separately. Most of the testing is already done as part of lab testing or factory acceptance tests (FAT) previously described in Section 3. The lab and factory acceptance tests of Section 3 tests have proved the particular digital substation protection and control scheme and have individually tested the main components of a digital substation such as the MU cabinets and relay/IED panels. IEC 61850 testing tool can be configured to read MU or relay/IED data (GOOSE states, measurements/SV data, GOOSE/SV subscription status) and simulate SV/GOOSE data of MU and/or relay/IED on process bus / station bus Ethernet network.

A general commissioning process for a digital substation is shown in Figure 5. This process has five (5) basic steps with many steps already covered in previous sections.

- ***Factory acceptance tests (FAT) of each MU.*** These factory acceptance tests will verify the wiring to the merging unit is correct and the generic/standard configuration (IOs, SV datasets and GOOSE messages) of the merging unit is correct for the particular P&C scheme for which the MU will be implemented.
- ***Factory acceptance tests (FAT) of each relay/IED.*** These factory acceptance tests perform a complete test of the P&C scheme, including all protection element settings, logic, SV dataset(s) configuration and GOOSE messages configurations.
- ***Site acceptance tests (SAT) of each installed MU.*** These site acceptance tests of each MU will verify the specific configuration of the IOs, CT settings, PT settings, phase rotation, SV dataset(s) configuration and GOOSE messages configuration.
- ***Site acceptance tests (SAT) of each installed relay/IED.*** These site acceptance tests of each relay/IED will verify the specific configuration of the CT settings, PT settings, phase rotation, SV dataset(s) configuration and GOOSE messages configuration. The site acceptance test should also verify that each relay/IED is subscribing to the correct SV datasets, subscribing to the correct GOOSE messages, all subscribed SV datasets are on-line and all subscribed GOOSE publishers are on-line. These SV and GOOSE checks of all relay/IEDs in a digital substation can be performed using IEC 61850 testing tools (analysis of SCD file and network traffic).
- ***Final system checkouts.*** These system checks consist of exercising the switchyard breakers by performing a trip and close check using the front HMI of each relay/IED in control house, which verifies the particular relay/IED operates the correct breakers. The system checks should Verify particular relay/IED has correct SV analog data from each switchyard MU using IEC 61850 testing tool or by injecting currents and voltages at MU using relay test set.

Using the specific project MU configurations (if available) and specific project relay/IED configurations (if available) during factory acceptance tests (FAT) is best and will reduce site acceptance tests (SAT). Specific project settings/configuration of MUs and relay/IEDs, and specific communication (SV and GOOSE) mappings could be tested at FAT. This would reduce on-site work to fiber optic Ethernet cabling to primary equipment, confirmation of SV/GOOSE configuration/mapping using IEC 61850 testing tools (analysis of SCD file and network traffic) and final system checks.

The described digital substation commissioning process can be modified or adjusted between new substations and the retrofit of existing substations.

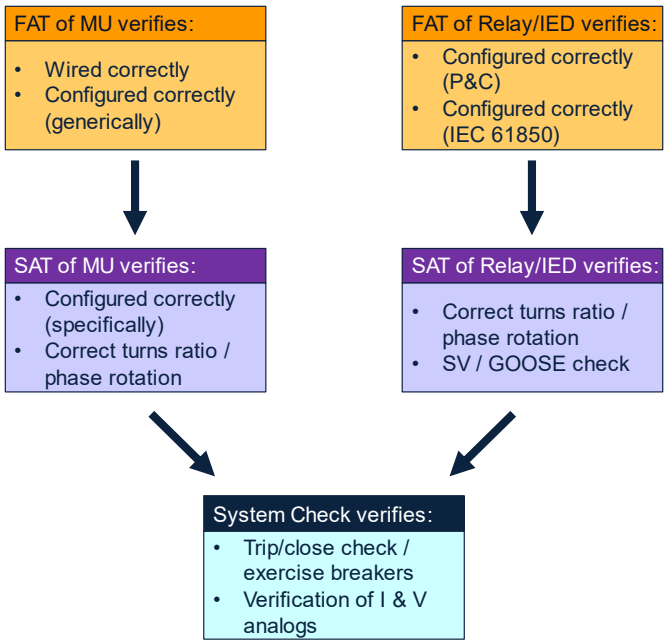



Figure 5 – Digital Substation Commissioning Process

## 5. Periodic / Maintenance Testing

Maintenance or in-service testing of a protection system proves the devices are still operating with defined performance parameters or when changes to the device configuration or protection element settings are made. For a digital substation, only the MUs may require regular maintenance testing. The relay/IEDs are a fully digital device with complete self-monitoring and does not require maintenance / periodic testing. However, the relay/IED may need maintenance testing if protection or control element settings are altered due to changing system conditions. The periodic testing of a digital substation verifies the settings in the relays/IEDs have not changed, the settings in the MUs have not changed, digital I/O of the MUs are operational, the analog measurements of the MUs are within specifications, SV dataset(s) and GOOSE messages configuration have not changed using IEC 61850 testing tool and SV and GOOSE communication links have not changed using IEC 61850 testing tool.

### 5.1 Out-of-Service Maintenance Testing

The MU is the digital to analog interface to the primary equipment and as such has all the physical I/O for the protection and control system. This physical I/O should be tested at regular intervals to ensure the MU is still operating correctly within desired performance parameters. Maintenance testing of a MU for either testing the output contacts or the analog inputs usually requires an equipment outage. This is to prevent undesirable operation during testing and to allow the exercise of the circuit breaker(s) if desired. There are three parts of the MU shown in Figure 6 that may require testing. The first is the MU output contacts, which must be tested to ensure they operate and energize circuit breaker operating coils. The second is the MU analog current and voltages inputs, where it is desirable to verify the measurements are working correctly. The MU's interface software can be used to verify the current and voltage measurements and verify the states of the digital inputs and digital outputs being tested. The third part is verification of the configuration of the IEC 61850 SV dataset(s) and GOOSE messages of each MU by using IEC 61850 testing tools from relay test manufacturer. The IEC 61850 testing tools should be configured to subscribe to the data published by the MU and configured to publish control flags to the MU through GOOSE messages using the MU SCL configuration file (i.e., CID or SCD). The MU's interface software can monitor the status of the GOOSE inputs subscribed by the MU and monitor the on-line/off-line GOOSE subscriber status of the

subscribed GOOSE control blocks by particular MU being monitored. Alternatively, the IEC 61850 testing tools can also be used to monitor this data from the process bus / station bus network.

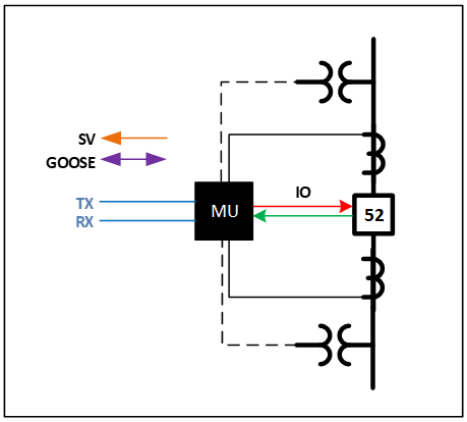



Figure 6 - Testing a MU

### 5.2 In-Service Maintenance Testing

In most digital substations, there will be redundant relay/IEDs and redundant MUs used for protection and control of a particular transformer, transmission line, capacitor bank or bus (an example is shown in Figure 7). With redundant protection and control schemes, one of the P&C systems (relay/IED and associated MU) could be put into various IEC 61850 test modes for in-service maintenance testing. Caution should be taken to isolate relay/IED or MU under test to avoid any accidental breaker trip or undesired exchange of IEC 61850 messages between IEDs due to the testing.

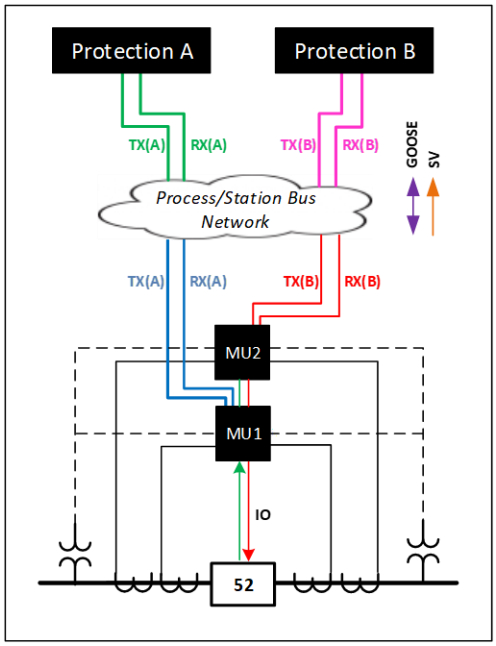



Figure 7 – In-Service Testing of Redundant P&C Systems

Edition 2 of IEC 61850 has two features that are available to accomplish isolation during testing, which are:

- **Capability to put a device/IED in test mode using the IEC 61850 data object mode (Mod), such as LLN0.Mod**. Based on the Mod value of a logical device, the resulting test-mode status is determined by the attribute behavior (Beh). IED manufacturers usually have a simple implementation with one Mod data object used to set the entire IED in test mode. Some typical values for the Mod data object (LLN0.Mod) are ON, TEST-BLOCKED and TEST. It is important that the quality of the data items of the GOOSE message, as shown in Figure 8, is configured in the device for the IEC 61850 data object mode (Mod) to function properly.
    - The ON mode is for normal in-service operation. P&C functionality and I/O functionality of the device are normal.
    - The TEST-BLOCKED mode allows for the device to be placed in a state where the device cannot negatively impact the power system or other parts of the substation automation system. This mode allows changing settings, loading new firmware, or changing communication connections. All IEC 61850 data published by the device in TEST-BLOCKED mode will be test data and will be processed but not used by the in-service devices in ON mode. All physical contact outputs of device are blocked when in TEST-BLOCKED mode. The test bit of the quality attribute of values sent via IEC 61850 services (SV and GOOSE) will be set to TRUE. The validity bit of the quality attribute of the data sent via IEC 61850 services (SV and GOOSE) will be set to GOOD.
    - The TEST mode ensures all IEC 61850 data published by the device will be test data and will be processed but not used by the in-service devices in ON mode. The test bit of the quality attribute of values sent via IEC 61850 services (SV and GOOSE) will be set to TRUE. The validity bit of the quality attribute of the data sent via IEC 61850 services (SV and GOOSE) will be set to GOOD.
- **Capability to use the simulation flag (LPHD.Sim) in subscribing device for IEC 61850 GOOSE and IEC 61850 sampled values**. The IEC 61850 data object LPHD.Sim serves as a switch between the messages coming from the real IEC 61850 devices in the system and simulated IEC 61850 messages coming from relay test sets or IEC 61850 testing tools. When device is in SIMULATION mode, received GOOSE messages and/or received SV data with the "simulation" flag/bit set are used in place of the normal messages in the subscribing device.

| SETTING | PARAMETER |
|---|---|
| TT6DataSet01 name | TT6DataSet1 |
| TT6DataSet01 shared by | |
| TT6DataSet01 Member1 | Master.GGIO1.ST.Ind001.stVal |
| TT6DataSet01 Member2 | Master.GGIO1.ST.Ind001.q |
| TT6DataSet01 Member3 | Master.GGIO1.ST.Ind002.stVal |
| TT6DataSet01 Member4 | Master.GGIO1.ST.Ind002.q |
| TT6DataSet01 Member5 | Master.GGIO1.ST.Ind003.stVal |
| TT6DataSet01 Member6 | Master.GGIO1.ST.Ind003.q |
| TT6DataSet01 Member7 | Master.GGIO1.ST.Ind004.stVal |
| TT6DataSet01 Member8 | Master.GGIO1.ST.Ind004.q |
| TT6DataSet01 Member9 | Master.GGIO1.ST.Ind005.stVal |
| TT6DataSet01 Member10 | Master.GGIO1.ST.Ind005.q |

Figure 8 – Example Device GOOSE Dataset

### 5.2.1 MU In-Service Test

In-service tests of MU could be performed using the IEC 61850 data object mode (LLN0.Mod). The steps for testing are:

1. Place MU into TEST mode. All IEC 61850 data published (i.e., SV data and GOOSE messages) by the MU will be test data and will be processed but not used by the in-service devices in ON mode.

2. Perform contact I/O and I/V analog injection using relay test set and associated MU test switches to verify digital I/O of the MU are operational and the analog measurements of the MUs are within specifications. Caution should be taken to isolate MU I/O under test to avoid any accidental breaker operation. Verification of the configuration of the IEC 61850 SV dataset(s) and GOOSE messages of MU can be performed by using IEC 61850 testing tools from relay test set manufacturer. The MU could be left connected to the process bus/station bus Ethernet network, since it is in IEC 61850 TEST mode, for IEC 61850 SV dataset(s) and GOOSE messages verifications by IEC 61850 testing tools.
3. After testing is complete, place MU into ON mode for normal in-service operation and re-connect to equipment using associated MU test switches.

### 5.2.2 Relay/IED In-Service Test

In-service tests of relay/IED could be performed using the IEC 61850 data object mode (LLN0.Mod) and simulation flag (LPHD.Sim). The steps for testing are:

1. Place relay/IED to be tested into TEST mode. All IEC 61850 data published (i.e., GOOSE messages) by the relay/IED in TEST mode will be test data and will be processed but not used by the in-service devices in ON mode.
2. Place relay/IED under test into SIMULATION mode so it will accept simulated SV and simulated GOOSE messages. A relay/IED in SIMULATION mode will use live process data for every subscribed SV dataset and subscribed GOOSE message until it receives simulated SV or GOOSE data (a message where the simulation bit is TRUE) for a specific message. Then for this message only, the device will only accept simulated data. Note the relay/IED under test is now in both TEST and SIMULATION mode.
3. Testing requires controlled data, so it is necessary to turn off all the live process data by simulating all the SV and GOOSE messages to the relay/IED under test. Depending on the IEC 61850 test tool used, this may require simulating SV and GOOSE messages one at a time to turn them all off, or this could be done in batches of SV and GOOSE messages. Testing is then performed by having the IEC 61850 testing tool simulate fault events, publishing simulated SV and simulated GOOSE messages, and verifying the protection element settings of the relay/IED under test.
4. Once the testing is complete, the following steps should be followed to place the device into normal operation:
    a. The Relay/IED under test is taken out of SIMULATION mode to only use live received GOOSE messages and live received SV data.
    b. The Relay/IED under test is returned to normal in-service operation by placing to ON mode.

An example based on Figure 7 and the Relay/IED in-service tests of Section 5.2.2 would be:

a. Step 1: Place Relay/IED of Protection System B into TEST mode
b. Step 2: Place Relay/IED of Protection System B into SIMULATION mode
c. Step 3: Perform simulation of SV and GOOSE messages to subscriber Relay/IED of Protection System B using IEC 61850 testing tool
d. Step 5: Testing completed
    i. Remove Relay/IED of Protection System B from SIMULATION mode
    ii. Remove Relay/IED of Protection System B from TEST mode
    iii. Return Relay/IED of Protection System B to ON mode for normal in-service operation

An example automated test plan for in-service testing of relay/IED is shown in Figure 9.

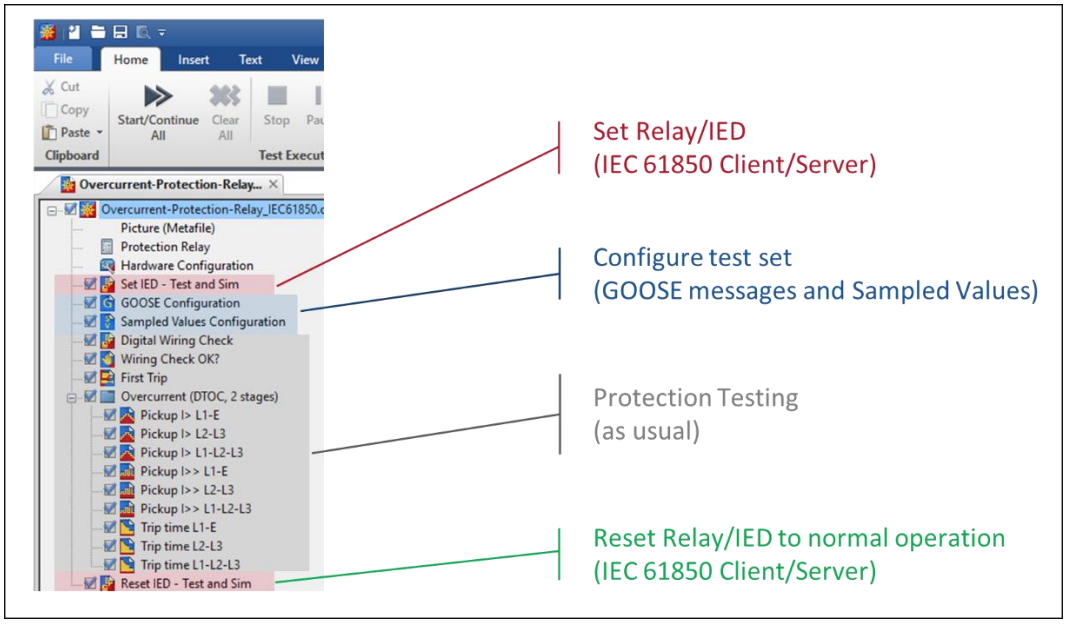



Figure 9 - Relay/IED In-Service Maintenance Test Plan

## 6. Troubleshooting Tools and Methods

Within IEC 61850, LGOS (logical node for GOOSE subscription) can be used for monitoring the status of GOOSE subscriptions in a device. Similarly, LSVS (logical node for sampled values subscription) can be used to monitor the status of SV subscriptions in a device.

A recommended commissioning and maintenance method for the digital substation is the use of HMI screens on relay/IED, substation gateway/HMI, or IEC 61850 testing/monitoring tools to show the on-line connection status of the following using LGOS and LSVS statuses:

- Relay/IED
  - On-line status of connected sampled value(s) from MU(s)
  - On-line status of subscribed MUs publishing GOOSE messages
  - On-line status of subscribed relays/devices publishing GOOSE messages
- Merging Units (MUs)
  - On-line status of subscribed relays/devices or MUs publishing GOOSE messages

With the above information readily available, the P&C technician can easily determine which device is off-line and take appropriate action. An example relay/IED status screen is show in Figure 10, which indicates an issue with merging unit (MU2).

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 453 TRIP PHASE A | 453 TRIP PHASE B | 453 TRIP PHASE C | 453 TIME OC FAULT | 453 INST OC FAULT | | | MU1 SV1 & SV2 ON-LINE |
| 496 TRIP PHASE A | 496 TRIP PHASE B | 496 TRIP PHASE C | 496 TIME OC FAULT | 496 INST OC FAULT | 496 RECLOSING READY | 496 RECLOSING LOCKOUT | MU2 SV1 & SV2 ON-LINE |
| 476 TRIP PHASE A | 476 TRIP PHASE B | 476 TRIP PHASE C | 476 TIME OC FAULT | 476 INST OC FAULT | 476 RECLOSING READY | 476 RECLOSING LOCKOUT | MU3 SV1 & SV2 ON-LINE |
| 486 TRIP PHASE A | 486 TRIP PHASE B | 486 TRIP PHASE C | 486 TIME OC FAULT | 486 TIME OC FAULT | 486 RECLOSING READY | 486 RECLOSING LOCKOUT | MU1 GOOSE ON-LINE |
| 466 TRIP PHASE A | 466 TRIP PHASE B | 466 TRIP PHASE C | 466 TIME OC FAULT | 466 INST OC FAULT | 466 RECLOSING READY | 466 RECLOSING LOCKOUT | MU2 GOOSE ON-LINE |
| BUS TRIP PHASE A | BUS TRIP PHASE B | BUS TRIP PHASE C | BUS PERCENT DIFF TRIP | BUS INST DIFF TRIP | BUS CT SAT DETECTED | BUS DIR FAULT DETECTED | MU3 GOOSE ON-LINE |

Figure 10 – Example Relay/IED Status Screen with SV and GOOSE Subscription States

There are several possible reasons for a commissioned relay/IED to show an off-line status for a subscribed SV dataset or GOOSE messages from a particular MU:

- Publishing device (i.e., MU) is not powered up
- Ethernet network switch issue
- Fiber optic cable / connector issue
- Publishing MU configuration (SV and GOOSE) has changed

A substation HMI can provide extremely useful communication information for a digital substation that can aid the P&C technician to identify Ethernet network hardware communication issues with various MUs and relays/IEDs. An example Ethernet network connection status screen for a digital substation is shown in Figure 11.

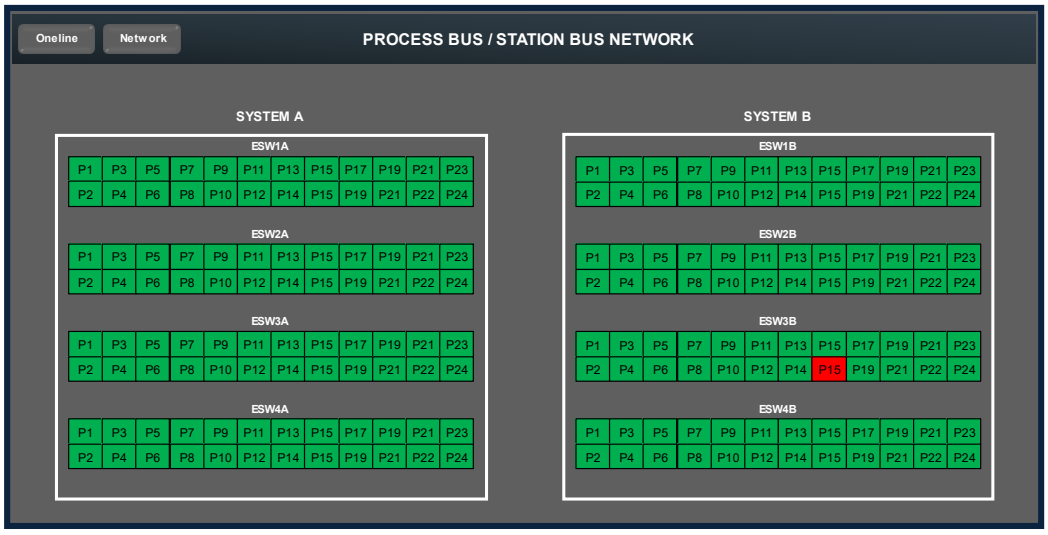



Figure 11 – Example Process Bus and Station Bus Ethernet Network Connection Status Screen

IEC 61850 testing tools are available to aid in all stages of a digital substation implementation and operation, such as design, lab testing, factory acceptance tests, site acceptance tests, commissioning, and maintenance. The IEC 61850 testing tool uses the System Configuration Description (SCD) file for the digital substation P&C scheme, which

contains all IED configurations (SV and GOOSE) and the communication configuration between relay/IEDs and MUs. After importing the SCD file into the IEC 61850 testing tool, the entire digital substation scheme can be visualized similar to a single line diagram or HMI as shown in Figure 12. The IEC 1850 testing tool can perform the following:

- ***Verification of communication links.*** The IEC 61850 testing tool can validate SV and GOOSE signals of each device and report communication links by accessing Ethernet network traffic and device MMS (Manufacturing Message Specification) connections. Issues can be identified, such as a GOOSE mismatch using control block settings, GOOSE publisher errors by sniffing the Ethernet network and comparing against SCD file, GOOSE subscription errors by verifying the LGOS states at each subscribing IED. As an example, Figure 12 shows a GOOSE subscription issue identified by the IEC 61850 testing tool due to a mismatch in the GOOSE configuration in one of the relay/IEDs.
- ***SV Dataset Simulation.*** The IEC 61850 testing tool can simulate and publish SV dataset(s), which mimics one or many merging units, for lab testing, factory acceptance testing or periodic/maintenance testing of a digital substation P&C scheme.
- ***Simulation/Publish of GOOSE messages***. The IEC 61850 testing tool can simulate GOOSE messages (both publisher and subscriber) of relay/IEDs or merging units for lab testing, factory acceptance testing or periodic/maintenance testing of a digital substation P&C scheme.
- ***Simulation of Relay/IED server functionality***. The IEC 61850 testing tool can simulate the relay/IED data model and associated SCADA (MMS) related services for lab testing, factory acceptance testing or periodic/maintenance testing of gateways, HMI, and SCADA systems.

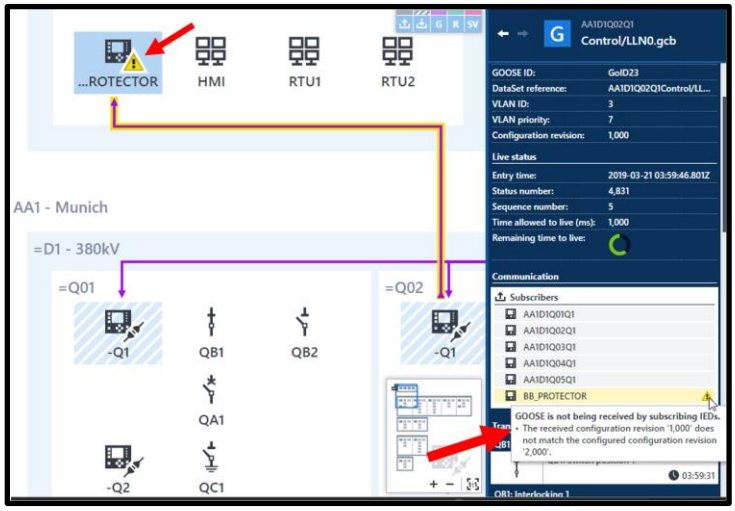



Figure 12 – Example Verification of Communication Links by IEC 61850 Testing Tool

## 7. Conclusions

Advantages of digital substation P&C system include faster implementation with fewer errors, a more reliable and repeatable final product, and significant cost savings from efficiencies in design, testing/commissioning, maintenance and operation. Documentation of a digital substation P&C design is important and aids in testing and operation. Efficient implementation of testing processes of a digital substation is achieved by lab testing, factory acceptance tests, site acceptance tests and system checks. Maintenance testing can be performed by placing the device/IED in test mode or test and simulation modes. IEC 61850 testing tools and the use of LGOS and LSVS aid in testing and troubleshooting a digital substation P&C scheme.

## 8. References

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## 9. Biographies

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