

If You Cannot Test It, You Cannot Use It – IEC 61850 GOOSE System Designed With Testing in Mind

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Abstract—IEC 61850 Generic Object-Oriented Substation Event (GOOSE) systems can be designed in a manner that allows testing personnel to easily identify problems and verify system functionality. This paper provides procedures and guidelines for successfully designing and integrating GOOSE protection schemes while keeping the feasibility of initial commissioning and maintenance testing in mind. The paper addresses the following questions:

- How can GOOSE systems be designed to support testing?
- How can GOOSE systems be designed with expansion in mind?
- How should GOOSE signals be incorporated into drawing packages?
- What impact do settings modifications have on test validation?
- How can test engineers incorporate GOOSE system verifications into intelligent electronic device test procedures?

I. INTRODUCTION

Modern power system designs often incorporate IEC 61850 Generic Object-Oriented Substation Event (GOOSE) protection schemes. GOOSE messaging can be thought of as a virtual interconnection of signals that replaces wiring. Hardwired systems are physically verified, whereas GOOSE systems require virtual verification. Testing GOOSE systems presents a unique challenge when performing signal verifications. Revised engineering practices are required to efficiently modify settings, complete initial and maintenance testing, and expand the system. Without careful consideration of aspects such as drawing details and testing methodologies, migrating to a GOOSE system can be difficult and sometimes unsuccessful.

While the development of optimized GOOSE systems requires knowledge of virtual local-area networks (VLANs), MAC address filtering, and logical node names, many testing technicians do not feel comfortable analyzing Ethernet traffic or investigating managed switch configuration settings, for example. However, GOOSE systems can be designed to allow testing personnel to easily identify problems and verify system functionality.

The integration of GOOSE signal isolation methods for transmitting and receiving GOOSE signals must be considered prior to commissioning. Testing and expansion capabilities cannot easily be added to a system after the initial design, so

they must be considered during the initial design. If the Ethernet network and GOOSE protection scheme are properly designed and commissioned, future changes can be integrated and updates tested without the fear of invalidating previous functionality verifications.

This paper provides procedures and guidelines for successfully designing and integrating GOOSE protection schemes while keeping the feasibility of initial commissioning and maintenance testing in mind.

II. DESIGNING GOOSE SYSTEMS TO SUPPORT TESTING

A properly designed GOOSE system incorporates design philosophies that enable testing throughout the life of the system. Device GOOSE testing requires validation of both incoming and outgoing GOOSE signals. GOOSE transmit signals are broadcast across the Ethernet network, unlike unicast traffic. This makes GOOSE systems susceptible to virtual wiring mistakes. Systems should be designed to prevent and easily identify these virtual wiring mistakes. Additionally, GOOSE systems must be tested to determine that the system, not just the individual devices, functions as intended. If system functional testing is to be completed with portions of the system live, care must be taken to properly isolate the devices to protect against unintentional operations caused by testing processes. This section explores how to design GOOSE systems to prevent and identify virtual wiring mistakes as well as how to isolate devices for testing.

A. Identifying and Preventing Virtual Wiring Errors

A properly designed system must account for the possibility of subscription mapping mistakes. Fig. 1 shows that subscription mapping mistakes come in three forms: an unintended intelligent electronic device (IED) receiving the signal, the correct IED receiving the signal on the wrong virtual input, or the correct IED failing to receive the signal.

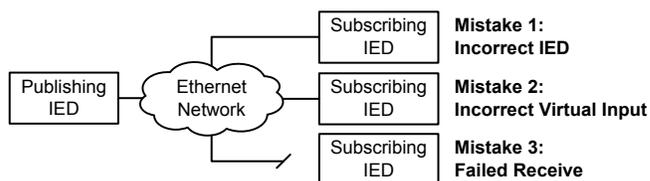


Fig. 1. Subscription Mapping Mistake Types

To prevent an unintended IED from receiving a GOOSE signal, software-defined and traditional managed Ethernet networks can limit the destination availability of a GOOSE transmit signal. One goal of GOOSE system network engineering is to define the allowable communications paths between IEDs. A device that does not subscribe to information contained within the GOOSE transmit signal should not receive the traffic. Not only does this help reduce the traffic burden on IEDs, it protects against incorrect IED subscription mapping errors.

One method to prevent messages from being received on the incorrect virtual input is to implement a logical subscription mapping pattern. A virtual input name typically does not have a readily apparent meaning. In order to easily review Configured IED Description (CID) files, received signals, and logic that involves GOOSE received signals, consistent subscription mapping patterns are helpful. For example, if each IED is assigned five virtual inputs per subscribed device and the first virtual input from each subscribed device is always the quality bit, GOOSE received elements must be supervised by the corresponding virtual input (the first, sixth, eleventh, and so on).

When designing subscription mapping patterns, one option is to group blocks of messages by data type. For example, there may be a block of data for the open or closed status of each breaker, each breaker's hot-line tag enabled status, or to indicate whether any breaker has an alarm asserted. This can be particularly useful when receiving the same data from all devices because it is simple to verify that subscribed logical nodes were received from all devices. Table I shows messages received by an IED, grouped by data type.

Another option is to group GOOSE messages by publisher. Each block should be large enough to include all necessary subscriptions for any of the IEDs. Consider the example substation shown in Fig. 2, with two sources, two tie breakers, and many feeders. The substation uses GOOSE messaging for a permissive arc-flash (AF) tripping and fast-bus (FB) blocking scheme. (This example will be referenced throughout the paper as the example substation.)

Table II depicts the subscription pattern for this substation. Notice that every IED has the same pattern for the received GOOSE messages. Table II depicts the actual messages received by the Tie 2-3 IED. Other breakers, such as the feeder breakers, may not subscribe to all of the messages used by the tie breakers, but the receipt pattern remains the same. This organization method can be particularly useful during testing because there is consistency in the structure of GOOSE messages in each IED to be tested.

TABLE I
EXAMPLE SUBSCRIPTION PATTERN ARRANGED BY DATA TYPE

GOOSE Word Bit	From Device	IED Word Bit	Description
VB001	SG2W1	IN102	SG2 pressure OK
VB002	SG3W1	IN102	SG3 pressure OK
VB003	SG4W1	IN102	SG4 pressure OK
VB004	SG5W1	IN102	SG5 pressure OK
VB005	SG6W1	IN102	SG6 pressure OK
VB006	SG7W1	IN102	SG7 pressure OK
VB007	SG8W1	IN102	SG8 pressure OK
VB008	SG9W1 (future)	IN102	SG9 pressure OK
VB009	Spare		
VB010	Spare		
VB011	SG2W2	LT02	SG2W2 hot-line tag
VB012	SG3W2	LT02	SG3W2 hot-line tag
VB013	SG4W2	LT02	SG4W2 hot-line tag
VB014	SG5W2	LT02	SG5W2 hot-line tag
VB015	SG6W2	LT02	SG6W2 hot-line tag
VB016	SG7W2	LT02	SG7W2 hot-line tag
VB017	SG8W2	LT02	SG8W2 hot-line tag
VB018	SG9W2 (future)	LT02	SG9W2 hot-line tag
VB019	Spare		
VB020	Spare		
VB021	SG2W2	ENABLED	SG2W2 relay enabled
VB022	SG3W2	ENABLED	SG3W2 relay enabled
VB023	SG4W2	ENABLED	SG4W2 relay enabled
VB024	SG5W2	ENABLED	SG5W2 relay enabled
VB025	SG6W2	ENABLED	SG6W2 relay enabled
VB026	SG7W2	ENABLED	SG7W2 relay enabled
VB027	SG8W2	ENABLED	SG8W2 relay enabled
VB028	SG9W2 (future)	ENABLED	SG9W2 relay enabled
VB029	Spare		
VB030	Spare		

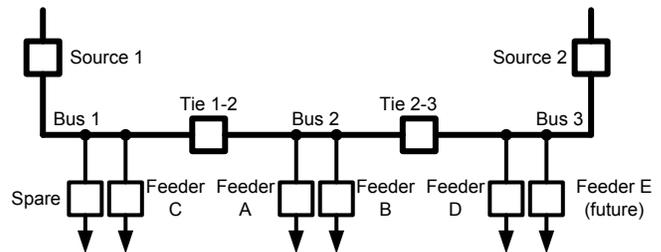


Fig. 2. Example Substation Layout

In either subscription mapping structure, value is gained by having a pattern to follow when creating and reviewing CID files. Inconsistencies are easier to identify in a pattern than in a random arrangement of messages.

TABLE II
EXAMPLE SUBSCRIPTION PATTERN ARRANGED BY SOURCE

GOOSE Word Bit	From Device	IED Word Bit	Description
VB001	Tie 1-2	n/a	Communications failure
VB002	Tie 1-2	LT10	Test mode enabled
VB003	Tie 1-2	SV02T	AF pickup
VB004	Tie 1-2	SV11T	FB block
VB005	Tie 1-2	LT18	AF lockout trip
VB006	Tie 1-2	LT20	FB lockout trip
VB007	Tie 1-2	(unused)	Breaker closed
VB008	Spare		
VB009	Spare		
VB010	Spare		
VB011	Source 2	n/a	Communications failure
VB012	Source 2	LT10	Test mode enabled
VB013	Source 2	(unused)	AF pickup
VB014	Source 2	(unused)	FB block
VB015	Source 2	LT17	AF lockout trip
VB016	Source 2	LT19	FB lockout trip
VB017	Source 2	SV28T	Breaker closed
VB018	Spare		
VB019	Spare		
VB020	Spare		
VB021	Feeder A	n/a	Communications failure
VB022	Feeder A	(unused)	Test mode enabled
VB023	Feeder A	SV02T	AF pickup
VB024	Feeder A	SV11T	FB block
VB025	Feeder A	(unused)	AF lockout trip
VB026	Feeder A	(unused)	FB lockout trip
VB027	Feeder A	(unused)	Breaker closed
VB028	Spare		
VB029	Spare		
VB030	Spare		
VB031	Feeder B	n/a	Communications failure
VB032	Feeder B	(unused)	Test mode enabled
VB033	Feeder B	SV02T	AF pickup
VB034	Feeder B	SV11T	FB block
VB035	Feeder B	(unused)	AF lockout trip
VB036	Feeder B	(unused)	FB lockout trip
VB037	Feeder B	(unused)	Breaker closed
VB038	Spare		
VB039	Spare		
VB040	Spare		
VB041	Feeder D	n/a	Communications failure
VB042	Feeder D	(unused)	Test mode enabled
VB043	Feeder D	SV02T	AF pickup
VB044	Feeder D	SV11T	FB block
VB045	Feeder D	(unused)	AF lockout trip
VB046	Feeder D	(unused)	FB lockout trip
VB047	Feeder D	(unused)	Breaker closed
VB048	Spare		
VB049	Spare		
VB050	Spare		
VB051	Feeder E (future)		Communications failure
VB052	Feeder E (future)		Test mode enabled
VB053	Feeder E (future)		AF pickup
VB054	Feeder E (future)		FB block
VB055	Feeder E (future)		AF lockout trip
VB056	Feeder E (future)		FB lockout trip
VB057	Feeder E (future)		Breaker closed
VB058	Spare		
VB059	Spare		
VB060	Spare		

An organized mapping pattern also simplifies the task of verifying that transmitted messages are only received by the correct IEDs. Each IED should be configured to report all received virtual inputs to a centralized log. For example,

virtual inputs can be assigned to an IEC 61850 manufacturing message specification (MMS) report and collected by a data concentrator or supervisory control and data acquisition (SCADA) system. After a test, the centralized logs can be reviewed to ensure that only the expected IEDs asserted a virtual input.

In addition, a centralized log provides a place to identify whether there are any unreceived messages. Unreceived messages should also become apparent during functional testing.

B. Isolating Devices to Allow for Live System Testing

In an ideal situation, a substation where testing is executed is completely de-energized, giving the test engineer freedom to perform all testing without consequence. That is not a typical scenario, so a critical step before testing is to completely isolate the device or system being tested from its normal circuits and logic. Traditionally, there are test switches and cutout switches that make physical breaks in circuits to ensure that the tested device will not interact with the in-service equipment. However, GOOSE protection schemes cannot be fully tested by simply removing a device from the system and simulating the other devices with testing software. This approach does not verify whole-system functionality, mapping, and network configuration. Instead, the device should be left networked with the system and alternate methods should be implemented to isolate the device from interacting with live equipment.

All of the isolation methods presented in this paper use internal IED logic and do not rely on the test flag feature of the IEC 61850 protocol. This is advantageous because many of the optional features supported in IEC 61850 Edition 1, such as test flags, were not consistently implemented by IED manufacturers and therefore cannot be used on all devices. Standards committees focused heavily on clarifying, elaborating on, and defining the mandatory behavior for the testing capabilities provided by the protocol in IEC 61850 Edition 2 [1].

One method to prevent unintended operations during testing is to incorporate virtual test switches to qualify the logic before an output contact is allowed to operate [2]. This method uses local control bits to toggle the virtual test switches. One advantage of this method is that virtual test switches can be used for any internal IED logic, not just GOOSE messages. One drawback is that some relay technicians are more comfortable with the physical open point that a traditional test switch provides.

An alternate method uses two physical test switches wired to inputs on each IED to enable RX and TX GOOSE test switches [3]. The RX GOOSE test switch causes the IED to not act on incoming GOOSE messages, and the TX GOOSE test switch causes other IEDs to ignore received messages from the sending IED [3].

Another option is to implement a dual test mode configuration in the internal IED logic. To implement dual test mode, each device that has the ability to transmit or receive GOOSE messages needs the ability to be placed into test

mode. The test mode is enabled by a front-panel pushbutton, a local control bit, or with a test switch blade that controls an internal logical latch. Fig. 3 shows how this logic can be programmed if a pushbutton is used to enable and disable the latch. (Note that the logic shown in Fig. 3 is a simple way to implement the test mode enabling and disabling; be sure to consider whether supervision should be required to enable or disable the test mode. For example, you may want to ensure that test mode cannot be disabled if there is a standing trip.) An IED can display a message or have an LED lit to indicate when test mode is enabled.

Devices are programmed to subscribe to the IED word bits representing the test mode status of each device from which they receive messages.

Devices not in test mode will not act on GOOSE messages from other devices in test mode. Devices that are in test mode will act on GOOSE messages from other devices that are also in test mode.

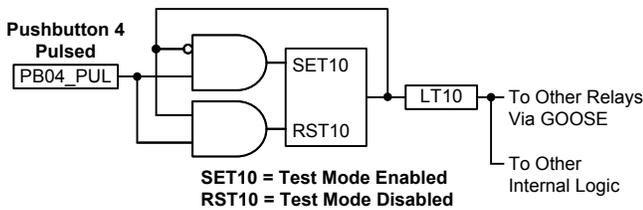


Fig. 3. Internal IED Logic for Enabling and Disabling Dual Test Mode

The “dual” in “dual test mode” indicates that there are two ways a subscriber treats received GOOSE messages depending on whether the publisher or both the subscriber and publisher are in test mode. Fig. 4 shows the internal IED logic for the dual test mode scheme as applied to one of the example substation IEDs.

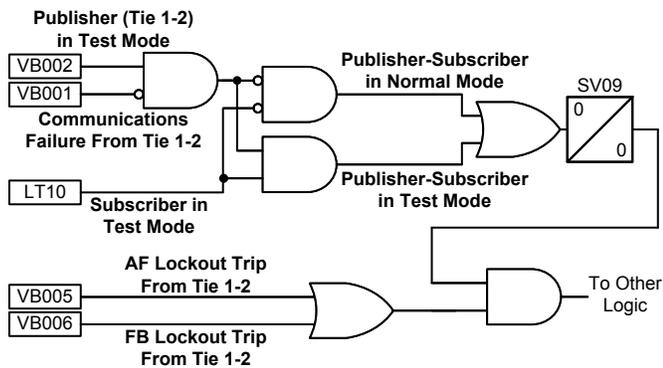


Fig. 4. Internal IED Logic for Processing Logic Using Dual Test Mode

When testing the interaction of two devices, the dual test mode option allows for messages sent between them to be processed as in normal system operation while not impacting other devices.

In addition to not relying on the test flag feature of the IEC 61850 protocol, another advantage of all of these methods of isolating the GOOSE signals is that they can be documented in logic diagrams. This allows the functionality to be easily viewed and understood by any engineer or relay technician regardless of whether they have advanced knowledge of the GOOSE protocol.

Before deciding which method to implement, consider the availability of IED features to enable or disable the virtual test switches or mode. Ensure that all IEDs have the necessary pushbuttons, inputs, or ease of toggling local control bits from the front panel.

No matter which test mode method is implemented, it is important that the entire system be consistently designed. Organization standards and quality control methods help ensure confident understanding of functionality expectations. Many organizations label switchgear and IEDs to remind testing personnel of isolation requirements prior to testing.

Lastly, in all methods, clearly document the use of the isolating features in the testing documentation. This is discussed further in Section VI.

III. DESIGNING GOOSE SYSTEMS FOR FUTURE EXPANSION

When planning a GOOSE system, it is important to consider future expansion. Planning this in advance saves on engineering time when components are added to the system and makes testing less burdensome. The first step, as described in Section I, is ensuring that a logical subscription mapping pattern is used.

When designing a relay panel, it is good engineering practice to leave spare terminal blocks for future growth. Likewise, when designing a GOOSE system, blocks should be reserved for expansion. If the subscription mapping is laid out by data type, space should be reserved for future equipment, such as SG9W1 in Table I. Additionally, space should be left for whole data sets. In Table I, GOOSE Word Bits VB031–VB050 (not shown) are reserved for future information that may need to be collected from the switchgear, such as the local/remote mode status. In Table II, where the mapping is arranged by source device, space has been reserved for additional information and for future feeders. When an organized mapping method is implemented, it is simple to identify new messages that an IED should subscribe to if additional equipment is added.

Another element that is important to consider is how new devices and messages required for system expansion will impact system testing. Refer to Section V for details on this topic.

IV. INCORPORATING GOOSE MESSAGING INTO DRAWING PACKAGES

It is well documented that as protection and control systems are modernized from electromechanical relays to microprocessor-based relays with internal logic and information transmitted digitally (as with IEC 61850 GOOSE systems), the need to modify drawing packages grows [3] [4] [5] [6]. Information that used to be obvious from the schematics is now hidden in internal IED logic or in GOOSE (or other digital) messages. It is critical to add information to drawing packages to show how GOOSE signals are transmitted and received to facilitate testing and troubleshooting.

A. Single-Line Drawings

The single-line drawing is the roadmap to understanding the electrical system. Noting the existence of a GOOSE scheme on the drawing alerts individuals working on the system that they need to consider how to isolate IEDs virtually, as well as physically, during testing. It is particularly important to note the existence of GOOSE schemes and to ensure proper isolation during testing when the schemes directly affect trip and close functionality.

One method of documenting GOOSE messages is described in [3]. For a transmission substation using a GOOSE scheme to simplify lockout circuits, dashed arrows labeled “G” are used to indicate when GOOSE messages are being transmitted or received by each IED. A separate arrow is used for each IED function that involves GOOSE messaging.

A similar method is shown in Fig. 5, where the functionality used in the IED indicates that a communications-based tripping scheme is enabled. This example simplifies the single-line drawing by noting the existence of the scheme but not including the details of which elements it affects. For additional details on how the GOOSE messaging is used, the logic diagram must be referenced.

Note that in both methods described, lines are not used to connect the communicating devices. This is because doing so complicates the single-line drawing. For example, Fig. 6 summarizes the GOOSE network required for the example substation. The number of lines that would be required in the single-line drawing would detract from other important information, such as current transformer (CT) and potential transformer connections.

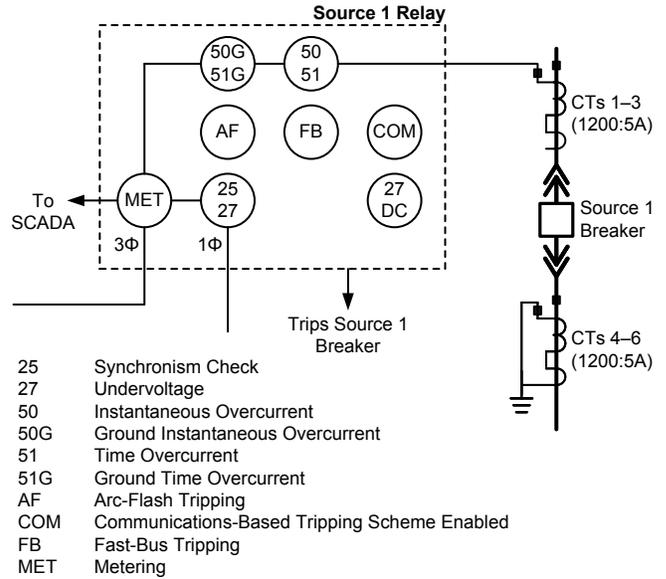


Fig. 5. Single-Line Drawing of Communications-Based Scheme

B. Communications Diagrams

Having a separate diagram to show the Ethernet connections between the IEDs and network switches aids in the system construction and troubleshooting [3] [5]. Port assignments, MAC IDs, VLAN IDs, and IP addresses should be shown on the communications diagram [3].

C. Logic Diagrams

Fig. 3, Fig. 4, and Fig. 7 provide examples of how GOOSE messaging can be shown in an IED’s logic diagram. The logic gate representation shows how the internal IED logic is

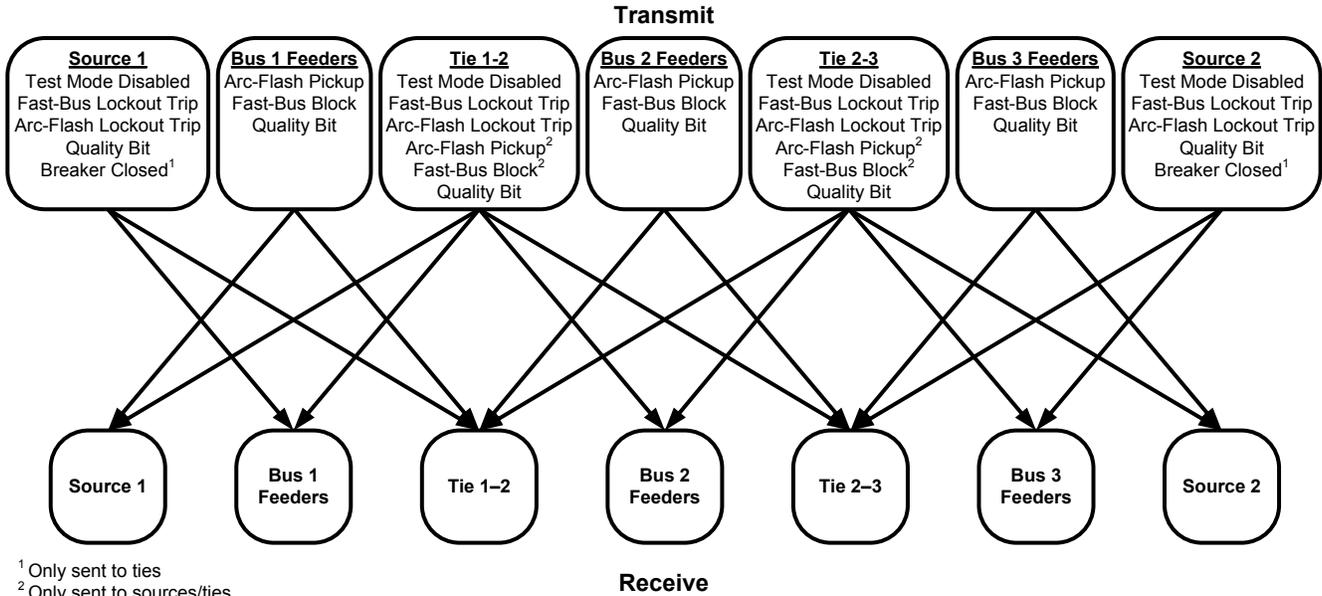


Fig. 6. Example Substation GOOSE Network

impacted by incoming information received via GOOSE messages. In addition, annotation is used to indicate where the data originate and if they are being transmitted to other IEDs. This method of graphical logic and/or supporting annotation is recommended in [4], [5], and [7].

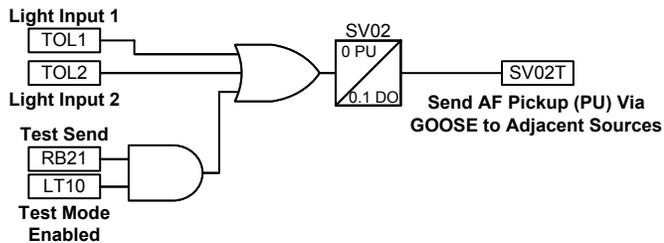


Fig. 7. GOOSE Messaging Incorporated Into Logic Diagrams

It is also useful to document the source and destination for each GOOSE message. It is standard practice to show all point-to-point wiring; similarly, all GOOSE connections should be shown.

This can be done in a chart format, as shown in Table I and Table II. Note that in these tables, the destination device is not explicitly listed because the table is specific to a single device. Value can be gained by organizing the lists by both subscription and publisher to aid in testing and troubleshooting. Reference [8] provides a clear example of documenting GOOSE logical connections.

Another option for showing the GOOSE connections between devices is an interdevice logic diagram, as described in [3]. In this type of diagram, the connections are shown graphically rather than as a list, which makes the diagram more like a schematic than a wiring diagram.

V. IDENTIFYING THE IMPACT OF SETTINGS MODIFICATIONS ON TEST VALIDATION

Thorough commissioning testing validates all system settings. However, a GOOSE system's functionality can be impacted by several types of settings modifications. Understanding the impact of settings modifications helps prevent undesirable system behavior. Settings changes related to network settings, IED logic changes, and GOOSE CID files require different forms of retesting.

A. Network Changes

Because GOOSE traffic is multicast, the configuration of software-defined and managed Ethernet networks can impact the distribution of signals. Network traffic engineering can change the way packets are transported on the network and, therefore, represents a failure mode. For example, a network that is configured to allow VLAN ID 10 to egress Ports 4, 5, and 6 on a switch might undergo settings modifications that prevent VLAN ID 10 from egressing Port 6. This mistake would cause the subscribing IED to stop receiving the virtual signal altogether. After making network-related system changes (even a physical cable connection), the quality of all message subscriptions must be validated.

The most common error caused by network changes is messages not arriving at their destination. This causes the message to expire and the message quality to go bad (i.e., the

message is never received). Each time a GOOSE message is published, the IED calculates the time-to-live (TTL) value and includes it in the GOOSE message. TTL is a multiple of the maximum amount of time before the multicast message will be repeated by the same publisher. Subscribing IEDs use this TTL value as their time-to-wait (TTW). TTW is the time that a subscribing IED considers the GOOSE data valid. In the quiescent state, the IED publishes a TTL equal to twice the maximum time setting; during a data change sequence, the TTL is three times the maximum time setting. This avoids nuisance alarms caused by the nondeterministic nature of Ethernet. This also allows for some variation in delivery time but still indicates a problem after a delay of multiple publication intervals [9].

In general, errors associated with network configuration changes can be detected by the subscribing IED. The GOOSE protocol builds in error codes, described in Table III, for detailed diagnostics. Different IED manufacturers have different ways to monitor and implement logic using these quality flags. Additional visibility can be achieved with engineering access, front-panel indications, or SCADA statuses and alarms.

TABLE III
GOOSE MESSAGE ERROR CODES

Message Statistic	Error Code
Configuration revision mismatch between publisher and subscriber	CONF REV MISMA
Publisher indicates that it needs commissioning	NEED COMMISSIO
Publisher is in test mode	TEST MODE
Received message is decoding and reveals error	MSG CORRUPTED
Message received out of sequence	OUT OF SEQUENC
Message TTL expired	TTL EXPIRED

Network changes can also be made in the individual IEDs. Mistakes such as loading default network settings parameters into an IED are possible. A strict adherence to processes that verify GOOSE signal quality after any settings change helps reduce risks.

B. IED Logic Changes

Modifications to IED logic settings can impact GOOSE published signals. If the logic changes only affect the internal IED logic and not the transmitted GOOSE messages or CID files, then the change can be tested to the point of transmission. In other words, the receipt of the message does not need to be confirmed again. If the IED word bits being transmitted are changed or if new messages are added (and therefore CID files updated), the messages should be tested from transmission to receipt. The creation and upkeep of logic details in diagram form can make the risks associated with logic changes more apparent.

Consider the following changes at the example substation. If another light source is added to the feeder whose logic is shown in Fig. 7, the SV02 logic will change but the outgoing message will remain the same. No changes are required to the CID file, and no additional testing is needed in the IEDs that

subscribe to that message. This is something to consider during logic development as well. When future expansion is possible, consider ways to structure the logic in this manner so that future testing is minimized.

In the example substation, if a new feeder was added to Bus 3, Table II shows that VB041, VB043, and VB044 would need to be sent to the adjacent sources (Tie 2-3 and Source 2). This would require CID file changes and testing of message transmission from the new feeder IED as well as receipt by the Tie 2-3 and Source 2 IEDs.

C. CID Changes

Subscribing IEDs depend on the exact configuration details of published messages. Modifications to the content of published messages require all subscribing IEDs to be updated. Security measures in software and IEDs can alert users to potential issues. Updating the revision number within the CID file flags a configuration revision mismatch error code within the subscribing IED. Alternatively, configuration software can present a graphical warning, such as the one shown in Fig. 8.

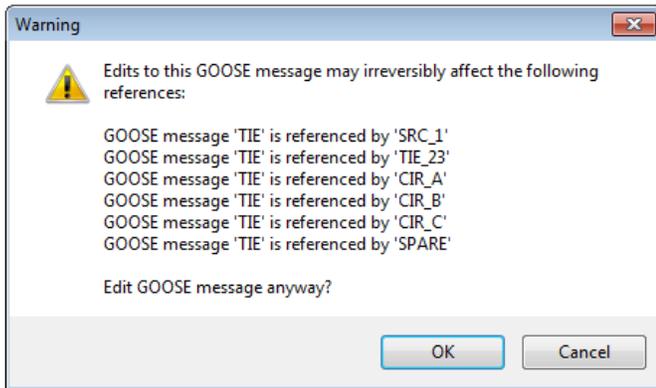


Fig. 8. GOOSE Transmit Message Edit Warning

After updating the content of a published message, the transmitting and all receiving IEDs must be tested for functionality impacts. Confidence in system functionality can be improved by creating checklists or test plans [10].

VI. INCORPORATING GOOSE SYSTEM VERIFICATIONS INTO IED TEST PLANS

In systems where each IED performs a particular and isolated task, test plans can be created on a per-device basis that focus specifically on the device under test. As systems continue to become more sophisticated within a networked environment, the approach to creating test plans and procedures should be even more specific and offer step-by-step instructions for the test engineer. Specific test plans are especially helpful when system engineering and testing are performed by multiple entities. By taking into account future additions and maintenance, test plans created for commissioning can be of value to other procedures in the future. Modern test sets offer GOOSE testing tools that can improve the overall commissioning process.

Properly crafting a test plan depends on the type of testing that needs to be executed. Testing scenarios that may be encountered include a new system where all primary equipment is de-energized, an existing system with a newly added piece of equipment that must be isolated from adjacent in-service equipment for testing, or an in-service system requiring maintenance testing to satisfy regulations or standards. Each scenario calls for different types of testing and different levels of GOOSE signal isolation.

A. Commissioning

During system commissioning, functionality needs to be completely verified from IED protective elements to specific schemes, and this testing needs to be documented. Keeping commissioning records is a good practice because, in the event that an unintended operation occurs, the records can be reviewed to determine if the whole system should be checked for something that was initially overlooked. In addition, keeping records allows future test plans to be improved.

The test plan should include at least two parts: the commissioning procedure and the test set plans. In some traditional systems, the commissioning document is more of a checklist than a procedure. Providing a step-by-step commissioning procedure that refers to specific test set plans can provide test engineers with confidence and end users with the verified functionality and documentation they require.

Consider a scenario in which the example substation system is new and the primary equipment is isolated such that the threat of accidental outages is eliminated. Many of the steps involved in commissioning this system are the same as in traditional systems without communication between devices. For instance, wiring is verified and protective elements are tested.

The first step that is unique to a GOOSE system is verification of the communication between devices. If communication errors are encountered, it is useful to break the system into smaller pieces for troubleshooting purposes [8]. After communication is verified, receipt of each specific message should be verified. This is analogous to testing functionality through an entire hardwired circuit.

Another typical step in the commissioning procedure is individual IED protective element testing. However, in a GOOSE system, it is likely that asserting protective elements will initiate the transmission of a GOOSE message. This is a good opportunity to validate the virtual isolation system in the IED logic. In the test procedure, list the steps required to configure the system so that all other sources and feeders are in service and testing this particular IED will not affect the in-service equipment. This same test plan can then be used in the future to incorporate new devices or for maintenance testing, and the testing technician will have full confidence that the steps documented to isolate the tested device are appropriate.

The commissioning procedure can then proceed from individual IED testing to scheme testing for the example substation's GOOSE-based fast-bus blocking and arc-flash tripping schemes. If the whole substation is out of service, this can be done without any device isolation.

B. In-Service Testing

In-service testing requires extra care to ensure that the equipment being tested does not interfere with in-service equipment. Consider testing for the addition of Feeder E on Bus 3 at the example substation. As in commissioning, one of the testing steps is validating the internal logic and protection elements in the Feeder E IED. The logic diagrams show that GOOSE messages will be sent from this IED, so a critical step in the test plan is to note how to isolate the new IED from the rest of the system. The following example test procedure describes how to isolate the IED using the dual test mode described in Section II, Subsection B:

1. Load settings into the Feeder E IED.
2. Verify IRIG-B and Ethernet connectivity.
3. Press the **{TEST MODE}** pushbutton on the IED front panel to enable test mode in the Feeder E IED. Verify that test mode is disabled on all other devices.
4. Load the new CID file into the Feeder E IED and the revised CID files into the Tie 2-3 and Source 2 IEDs.
5. Verify that there are no GOOSE message errors.
6. Use a IED test set to inject current to verify that each protective element trips appropriately. Refer to the relevant test set files to test 51P and 51G. Verify receipt of VB054 on the Tie 2-3 and Source 2 IEDs when the time-overcurrent elements are tested.
7. Test the arc-flash sensors. Verify receipt of VB053 on the Tie 2-3 and Source 2 IEDs.
8. Press the **{TEST MODE}** pushbutton on the IED front panel to enable test mode in the Tie 2-3 and Feeder E IEDs. Ensure that test mode is disabled on all other IEDs.
9. Open the trip cutout test switch on the Tie 2-3 IED.
10. Assert the arc-flash sensor on Feeder E while injecting current into the Tie 2-3 IED. Refer to the relevant test set files.
11. Confirm that the Feeder E IED receives VB005 from the Tie 2-3 IED and trips.
12. Disable test mode for all IEDs.

This is not an exhaustive test plan, but it contains enough detail to illustrate a few key points. Note the IED isolation in Steps 3, 8, and 12. By enabling dual test mode only in Feeder E, all other devices still receive GOOSE messages from this IED but do not process them in internal logic. Received inputs are logged in the IED's sequential events recorder (SER) for test validation and troubleshooting.

By enabling dual test mode in the Feeder E and Tie 2-3 IEDs, the interaction of the Feeder E IED sending a message to the Tie 2-3 IED, the Tie 2-3 IED processing the message in its internal logic, and then the Tie 2-3 IED sending out a trip to all of Bus 3 via GOOSE messages can be seen without actually tripping any of the in-service feeders on Bus 3. All of this can be verified by reviewing the IED SER reports for receipt of the trip input. Note that if an actual event occurred on Bus 3 during the test, the trip cutout from the Tie 2-3 IED is open, so that breaker will not trip. However, because the Tie 2-3 IED is in test mode, a fast-bus block signal sent from it will be ignored and the next upstream source will be able to

trip just as quickly to clear the fault as Tie 2-3 would trip in a nontest scenario.

In the example test procedure, the received arc-flash pickup input is the same in both upstream devices because of planning put into the subscription mapping. When the fast-bus block and arc-flash pickup are sent in Steps 6 and 7, respectively, the upstream IED ignores the message because the publisher was in test mode but the subscriber was not. Lastly, the test set files are referenced in the plan for added clarity to the testing technician.

C. Modern Test Set Tools

Modern test set tools for GOOSE testing add value to the early stages of GOOSE system testing by mimicking other IEDs in the system. They do this by using a Substation Configuration Language (SCL) file and network parameters. During individual IED testing, the test set can assist in identifying CID file issues. Performing a point-to-point check with the test set, the IED under test, and the approved GOOSE virtual I/O list eliminates basic problems such as incorrect VLAN assignments and incorrectly assigned GOOSE publish and subscribe messages. If implemented during individual IED testing, the test set can find such variances to improve the efficiency and quality of the scheme testing. Eliminating errors from the start leads to minimal revisions of CID files for multiple IEDs, which prevents retesting of other schemes and the virtual I/O involved.

With the use of dual test mode or another virtual GOOSE message isolation procedure, a test set with GOOSE capabilities is not a critical piece of equipment for testing. These isolation procedures are useful when a test set with GOOSE functionality is unavailable or if testing technicians are not familiar with how to use such a test set.

VII. CONCLUSION

As more and more protection and control systems incorporate IEC 61850 GOOSE messaging, the design and testing of these systems must adapt. The basic concepts of designing and testing IEC 61850 systems are similar to those of traditional systems. Systems should be designed to prevent virtual wiring errors by using network engineering to limit the path of GOOSE messages and by developing logical subscription mapping layouts to identify and reduce mapping errors. GOOSE messages should be able to be isolated to prevent unintended operations during testing. GOOSE messaging should be clearly documented in drawing packages to assist in testing and troubleshooting and to provide the information necessary for system expansion. When GOOSE systems are updated, the changes need to be tested to confirm that the system still functions as intended. Well-documented test procedures help ensure thorough system testing.

Planning, documentation, thorough commissioning plans, and testing are key components of any properly designed system. While the fundamentals of protection system design have not changed, incorporating GOOSE messaging into a system requires an upfront understanding of the different design and testing procedures GOOSE systems require.

VIII. REFERENCES

- [1] W. Wimmer, "IEC 61850 Edition 2 and Engineering," *PAC World Magazine*, December 2014. Available: <https://www.pacw.org>.
- [2] S. Fulford and M. Thompson, "An Examination of Test Switches in Modern Protection and Control Systems," proceedings of the 34th Annual Western Protective Relay Conference, Spokane, WA, October 2007.
- [3] D. Vonada, G. Condict, J. Martin, J. Keeney, M. J. Thompson, J. Bariola, and D. Pool, "Case Study: Using IEC 61850 to Simplify Lockout Circuits in a 345 kV Wind Generation Integration Substation," proceedings of the 41st Annual Western Protective Relay Conference, Spokane, WA, October 2014.
- [4] J. Young and D. Haas, "The Importance of Relay and Programmable Logic Documentation," proceedings of the 62nd Annual Georgia Tech Protective Relaying Conference, Atlanta, GA, May 2008.
- [5] M. Thompson, "The Power of Modern Relays Enables Fundamental Changes in Protection and Control System Design (Build a Substation That Continuously Tests Itself)," January 2007. Available: <https://selinc.com>.
- [6] M. Thompson, "Substation Protection, Control, and Monitoring System Design." In *Modern Solutions for Protection, Control, and Monitoring of Electric Power Systems*, edited by H. J. Altuve Ferrer and E. O. Schweitzer, III, pp. 314–317. Schweitzer Engineering Laboratories, Inc., Pullman, WA, 2010.
- [7] S. Briscoe, G. Lewis, and M. Thompson, "Stanford University, Palou Substation Modernization Project," proceedings of the 31st Annual Western Protective Relay Conference, Spokane, WA, October 2004.
- [8] E. Atienza, "Testing and Troubleshooting IEC 61850 GOOSE-Based Control and Protection Schemes," proceedings of the 12th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2010.
- [9] T. Tibbals and D. Dolezilek, "Case Study: New Testing and Verification Practices for Virtual Wiring Among IEDs Via Ethernet Communications," proceedings of the Southern African Power System Protection Conference, Johannesburg, South Africa, November 2010.
- [10] K. Zimmerman and D. Costello, "Lessons Learned From Commissioning Protective Relaying Systems," proceedings of the 62nd Annual Conference for Protective Relay Engineers, College Station, TX, March 2009.

IX. BIOGRAPHIES

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