A Practical Guide to Substation Testing Using IEC 61850 Mode and Behavior

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Abstract—**IEC 61850 is a standard for integrated protection and control systems around the world and has been recently gaining momentum in North America. There is a growing need to verify the successful implementation of this technology when performing commissioning and maintenance in substations. IEC 61850 Edition 1 introduced several methods of intelligent electronic device (IED) testing intended to help overcome the challenges encountered when testing in the field. However, Edition 1 only describes a general approach to IED testing and does not clearly specify requirements for implementing its testing methods. Therefore, when Edition 2 was published it provided more descriptive methods of testing as well as more clarity about how to use them; however, in doing so it increased its complexity. There are still some issues of incompatibility that could affect interoperability and produce unexpected results, such as the simultaneous use of Edition 1 and Edition 2 devices or devices with other protection protocols.**

This paper discusses two of the most important IEC 61850 Edition 2 test features: Mode Control (widely referred to as "Test Mode") and Simulation. The paper first briefly describes the test features in Edition 2 and then illustrates the applications and guidelines for these features in depth, including potential pitfalls. Finally, the paper provides examples related to various utility domains as a practical guide to help the reader make informed choices on how to use these test features, independently or combined. The use cases include asset additions, commissioning, and multiowner systems.

I. INTRODUCTION

Creating a standard that works across many application domains is a challenge that requires dedicated time and effort to accomplish. The IEC 61850 standard was conceived with the purpose of unifying the communications protocols between protective devices. This was meant to solve a breadth of interoperability problems, where any one asset could communicate with another assuming they could both interpret IEC 61850 protocols. However, the length of time and diversity of effort put into creating this standard resulted in an unfortunate side effect: the insufficient explanations of use published with the IEC 61850 testing methods introduced a great deal of complexity to the standard. The first edition of the standard pioneered many solutions to various problems of automation, one of which was being able to test a protective scheme logic. Testing supervisory control and data acquisition-based (SCADA-based) automation schemes with IEC 61850 devices uncovered ambiguity surrounding how to meet the standard's complex requirements. This ambiguity led to engineers developing and integrating devices that were not actually interoperable, undermining the purpose of having a standard in the first place.

II. CROSS-STANDARD TESTING

Companies have been experimenting with integrating IEC 61850 devices in tandem with the evolution of the standards, such that when commissioning and testing of these devices began, the depth of device-interoperability problems was exposed. Device manufacturers developing products did so using their own interpretation of the IEC 61850 standards. The interoperability issues resulting from the complex and ambiguous nature of the standards required discussion and deliberation between users and manufacturers to solve. Later, these issues and their solutions would be incorporated into the second edition of the standard; however, while these discussions were happening, a few utilities made investments into existing Edition 1 standard systems. Due to the unlikelihood of replacing admittedly expensive devices, the reality today is that Edition 1 devices endure in utilities systems, even though they and Edition 2 devices are not guaranteed to be test-interoperable, which is all due to the original ambiguity surrounding testing using Manufacturing Message Specification (MMS), Generic Object-Oriented Substation Event (GOOSE), and Sampled Value (SV) signals as first described in IEC 61850.

Edition 1 of this standard introduced the concept of testing relays using two different methods. The first method is by sending and receiving signals with the GOOSE message test bit set to either TRUE or FALSE [1]. The second method was by changing a logical device or logical node's Mode, which was defined as: On, Test, Blocked, Test/Blocked, or Off [2]. Unfortunately, an unintended consequence of using this terminology was the escalating overuse of the term "test," which was used both for the GOOSE test bit and for a device's Mode value. In both cases, test signals are sent to a device. For example, Fig. 1 shows Wireshark's GOOSE dissector—which still uses Edition 1 nomenclature—in which the simulation bit is referred to as "test." Wireshark's GOOSE dissector test field should be "Simulation" under Edition 2 [3].

"Test Mode" was coined in the Edition 2 standard in specific reference to Mode control and Behavior [4]. However, users of equipment were already using the phrase "Test Mode" to specify any time the unit went into a test state. "Test Mode" could refer to any number of different testing conditions including proprietary manufacturer-defined testing states, GOOSE parameter test = TRUE [1] (renamed "Simulation" with Edition 2), or Mod.stVal/Beh.stVal = TEST, as described in Table I. Due to this added complexity, assumptions should not be made when reading or using the term "Test Mode."

Fig. 1. Wireshark's dissector for GOOSE messages. The dissector still uses the Edition 1 standard nomenclature to describe the Simulation bit.

TABLE I
IEC 61850 EDITION 1 GOOSE MESSAGE DEFINITION
SHOWING THE TEST BIT [4]

Parameter Name	Parameter Type	Value/Value Range/Explanation
DataSet	ObjectReference	Value from the instance of GoCB
AppID	VISIBLE STRINGS	Value from the instance of GoCB
GoCBRef	ObjectReference	Value from the instance of GoCB
T	EntryTime	
StNum	INT32U	
SqNum	INT32U	
Test	BOOLEAN	(TRUE) test | (FALSE) no-test
ConfRev	INT32U	Value from the instance of GoCB
NdsCom	BOOLEAN	Value from the instance of GoCB

GOOSE Data [1..n]: **Value** parameter type depends on the common data classes defined in IEC 61850-7-3. The parameter shall be derived from GOOSE control.

Despite the name change of the GOOSE message test bit, with some manufacturer devices it is still possible to test systems that operate with a mix of Edition 1 and Edition 2 devices [1] [5] [6]. IEC 61850-7-1 defines the handling of simulation signals via the Sim.Oper.ctVal in the logical node physical device (LPHD) [7]. As it is explained in Fig. 2, setting the device to handle simulated GOOSE or SV signals means that only signals with the Simulation bit set to TRUE should be processed.
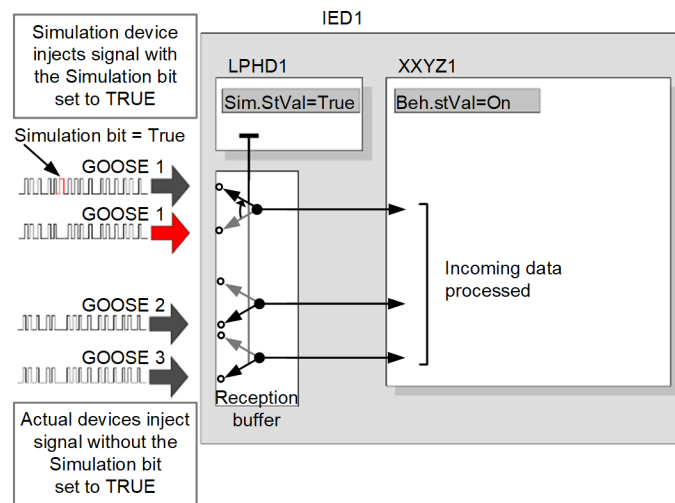

Fig. 2. Device under test receiving and processing signals with the Simulation bit set to TRUE [7].

While the term for controlling this simulation was updated for clarity, its use has not changed. This means Edition 1 and Edition 2 relays should be able to send and process simulated and actual signals as prescribed by the IEC 61850 standard. Unfortunately, the same is not true for testing relays via Mode control and Behavior.

The Edition 1 standard introduced the Mode and Behavior features with the following states: On, Blocked, Test, Test/Blocked, and Off. Specifically, IEC 61850-7-4 defines each Mode and Behavior with a corresponding value [2]. However, the wording in the table (as described in Table II) is vague enough that any of a variety of meanings can be assumed. For example, Test Mode can describe multiple logics such as function active, outputs generated, reporting flagged as test, function operated, but results are indicated as test results, etc. [2]. "Reporting flagged as test" is particularly ambiguous because there are different bits for different things: there is the test bit for simulated GOOSE messages, and the quality.test bit for Mode. Table II does not differentiate between these values, so any manufacturer could have, and did, set either bit in Test Mode. GOOSE, SV, and MMS handling were not differentiated in the Edition 1 table, leading to more ambiguity and individual interpretation, culminating in a generation of Edition 1 devices that are infrequently interoperable with each other, let alone with Edition 2 devices.

Even though the Edition 2 standard addresses this with better defined descriptions and instructive methods, Edition 1 devices are still used in the field today and are part of larger, mixed systems that still require testing. Section VI of this paper outlines a solution to this issue.

Mode and Behavior	Value
ON (enabled) Function active Outputs (to process) generated Reporting (to client) Control services (from client) accepted Functional (process related) data visible Configuration (capability) data visible (Normal state)	1
BLOCKED Function active No outputs (to process) generated No reporting Control services (from client) rejected Functional (process related) data visible Configuration (capability) data visible (Process is passively supervised)	2
TEST Function active Outputs (to process) generated Reporting (to client) flagged as test Control services (from client) accepted Functional (process related) data visible Configuration (capability) data visible (Function is operated but results are indicated as test results)	3
TEST/BLOCKED Function active No outputs (to process) generated Reporting (to client) flagged as test Control services (from client) accepted Functional (process related) data visible Configuration (capability) data visible (Function is operated in Test Mode but with no impact to the process)	4
OFF (disabled) Function not active No outputs (to process) generated No reporting (to client) Control services (from client) rejected Functional (process related) data not visible Configuration (capability) data visible (Function is inactive but shows its configuration capability)	5

Industry practices dictate that when testing an in-service device, a clearance must be requested [8] and a device or system must be isolated from the rest of the system before testing [9]. With a traditional hardwired system, test switches provide a physical and visible isolation point, allowing engineers another method of confirmation. However, in IEC 61850, devices that are virtually connected via digital message exchanges provide logical isolation instead of a visible open point.

In order to mitigate some of the ambiguity of the Edition 1 standard, some utilities implemented a supervisory bit that was set via a front-panel interface or pushbutton. If this bit was set, a light-emitting diode (LED) or other indication on the front panel could indicate to the technicians that the relay was isolated from the rest of the system. This bit was included in the GOOSE message and indicated to subscriber relays that the device was in a test state.

The improvements to the standard introduced in Edition 2, which provided the mechanism for setting Mode/Behavior via an MMS client, would allow a device to be either isolated or set

to Mod.stVal = Test/Blocked using an MMS control. However, if the human-machine interface (HMI) in the substation was not an MMS device, or if it was a DNP3 or Modbus master, then the device would not be able to be put into Test, Blocked, or Test/Blocked Mode, as neither DNP3 nor Modbus masters would have access to the IEC 61850 data model.

Other challenges arise when there is no local HMI to signal a device to go into the desired mode. The standard does not provide a mechanism for changing Mode without the MMS client interface, but utilities will nonetheless need a method by which to put a device into different modes for testing. To resolve this problem, there are devices that have been made available that can control an intelligent electronic device (IED) mode without an MMS client.

III. CFE AND THE SUBSTATION AUTOMATION SYSTEM STANDARD

The largest utility in Latin America, Comisión Federal de Electricidad (CFE), has developed a specification that describes the general requirements for the application of the substation automation systems (SASs) in electrical installations, based on the IEC 61850 standard for the supervision, control, and operation of apparatus and auxiliary systems [10]. Requirement documents describe the need for use of all substation system protocols beyond just IEC 61850. This means protocols such as DNP3 and others must be taken into consideration when planning for in-system tests. Fig. 3 illustrates this type of system.
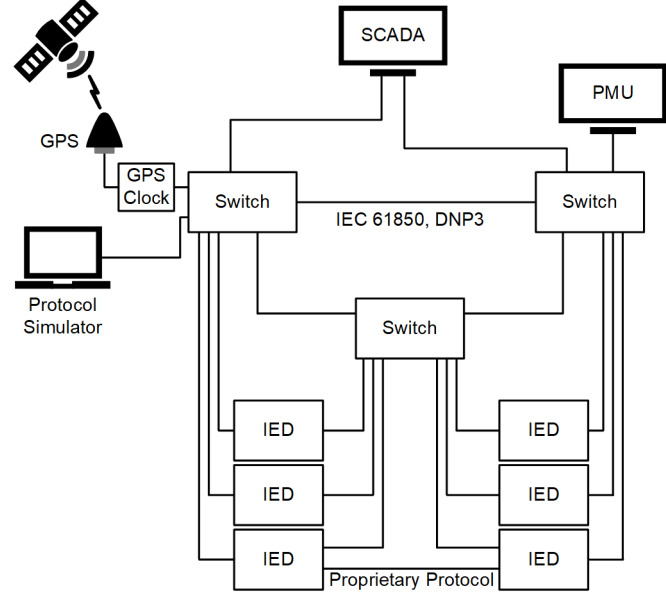

Fig. 3. High-level communications architecture for an SAS.

IV. CFE AND OTHER UTILITY TEST MODE IMPLEMENTATIONS

Utilities are combining virtual and hardwired techniques to protect their assets. GOOSE messages are proving reliable in communications-assisted protection [11] and thus are becoming broadly accepted as a replacement for hardwired signals [12]. The use of communications-assisted protection schemes has been present since the first edition of the

IEC 61850 standard, and they were used long before it was decided to standardize the way substations could be digitally tested with the inclusion of the Mode/Behavior in Edition 2.

A. Traditional Testing

Substation testing can be divided into two main stages: commissioning and in-service substation testing. During commissioning, the substation is in a grid-disconnected state, in which devices such as current transformers (CTs) or voltage transformers (VTs) are not connected to the electrical grid. Commissioning provides the engineers freedom to test everything without creating unwanted operations within the system or interruptions in the power. After commissioning, the substation is connected to the electrical grid and put in service. This paper will not address commissioning needs and instead will focus on in-service testing.

Once in service, any testing or additional modification is subject to the utility's clearance procedures. Unlike during commissioning, the ability to test has now been reduced to specific subsets of bays or IEDs in the substation. In-service substation testing has two main goals: first, to successfully confirm that the programmed functions in the IED work correctly and guarantee the integrity of the substation; and second, to prevent undesired operations during testing such as tripping a breaker or a group of breakers, accidentally enabling or disabling interlocks, or the unexpected closing of relay outputs [13].

During traditional testing, a test blade is inserted into the panel's test switch. This isolates the IED from the rest of the system, shorts the secondary circuits of the CTs, opens the VT signals, and blocks the breaker trip and any other trip signals by opening the electrical circuit between the IED contact outputs and the trip coils. A transmission line protection panel is shown in Fig. 4, with six test switches installed at the bottom of the panel. One test switch is for the primary protection, two test switches for each terminal in the backup protection, two test switches for each terminal in the bay controller, and the last test switch for a revenue meter.

Fig. 4.   Transmission line protection panel with installed test blocks at the bottom.

With the breaker trips blocked, the protection and automation routines can be executed in the tested device without provoking an unwanted operation. The testing results are validated and approved by analyzing the sequence of events (SOE) recorded in the IED, which, if the test is successful, demonstrates that the IED logic, protective function, and output contacts operate correctly.

B. Digital Testing

Testing methods for virtual wiring differ significantly from testing hardwired devices. As in traditional testing, the isolation of devices is required, but, instead of physical isolation, digital blocking is now needed. Testing procedures for digital exchanges should validate the correct configuration and operation of the relays and guarantee that the two main goals previously described are achieved.

Testing these digital exchanges was not adequately addressed by IEC 61850 until the release of Edition 2 in 2010. Prior to that, utilities used a heuristic approach that included the use of Boolean equations as interlocks as a way to provide physical isolation. Fig. 5 and Fig. 6 show ways of creating a blocked action using IED internal logic solutions. Utilities started calling this new approach Test Mode [13], which over time introduced the confusion that Edition 2 terminology attempted to clarify [4].

PLT01S := NOT IN101 AND NOT PLT01
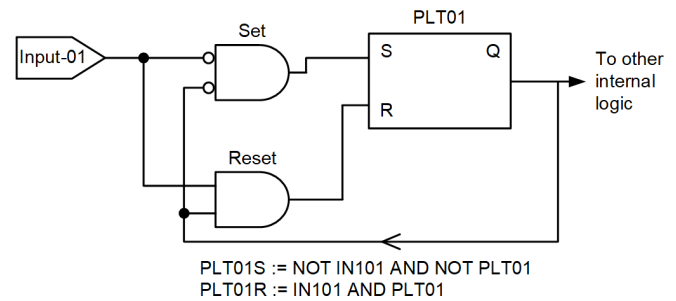PLT01R := IN101 AND PLT01

Fig. 5.   Using internal IED protection latch (PLT01) logic to set and reset the Test Mode.
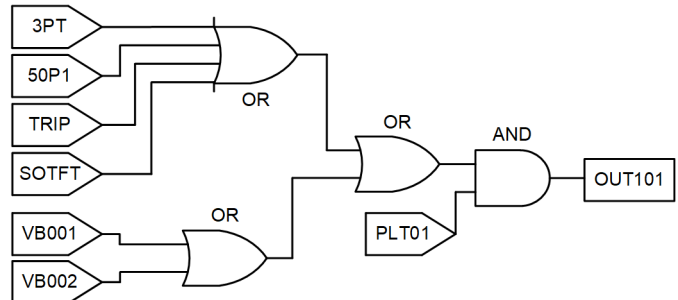

Fig. 6.   Logic used to lock the closing of an output contact (OUT101) in the IED to prevent undesired operations during the Test Mode.

This Test Mode consists of a series of Boolean logic equations that have been programmed into the IED and that will evaluate a condition before an internal logical variable is set or an output contact is allowed to operate. This isolation method does not rely on reserved fields (LPHD.Sim.stVal = TRUE, or Simulation mode), the Mode/Behavior of the IED, or on the possibly ambiguous value of Quality fields. As a result, this Test Mode can be used regardless of the implementation of IEC 61850 in other devices in the substation, and interoperability between devices is possible. Conversely, this method can be overly complicated, leaves room for error, and may not be supported in all IEDs.

The Test Mode may be enabled by a pushbutton located on the front panel of the IED, an internal control bit, or with a test switch blade that drives an input of the IED. In turn, an internal logical protection latch (PLT) will be controlled based on the

state of the input signals. The output of the PLT will be set to TRUE when the IED is in Test Mode. Fig. 5 illustrates a simple logic diagram to put the relay into Test Mode by inserting a test blade into the IED test switch.

The PLT output can be used for several tasks, one of which is turning on an LED on the front panel, warning the user that the relay is in Test Mode [8] [9]. It is included as a supervisory element in each protection and output contact logic equation to prevent unanticipated trip execution or closure. The Test Mode will block any physical trips, regardless of whether the IED operates as a result of a protective function or if it receives a trip command over a GOOSE message. Fig. 6 shows an output contact logic that is used to block the closing of the contact.

The implementation of this isolation method is time consuming because each IED is required to be programmed and configured with the corresponding logic and GOOSE subscriptions. Further, as the hardwiring is virtual, the mapping of GOOSE messages to each subscriber and the assignment of the Test Mode variables to the protection logic makes this method prone to errors and misconfigurations, as previously mentioned.

Overlooking the effort that must be put into the Test Mode setup, implementing this isolation method as part of the initial network design and before commissioning will increase the testing and expansion capabilities of the system after it is commissioned and put in service.

Once the configuration is finished, it will provide the end user with a certain level of freedom when testing. The Test Mode ensures that unwanted operations, such as false trips, do not occur because the protection and automation logic is restricted, and the output contacts do not operate when the IED is in a blocking configuration. Once configured, IEDs are isolated and the system is ready for live system testing without the need for clearances that require the system to go offline. The integration of GOOSE messages with protection, automation, and control systems acts as a complement to or replacement of hardwired signals with the current isolation method. Test Mode has been widely accepted and tested, all while demonstrating the implementation and utilization of IEC 61850 in transmission substations around Mexico [10] [11] [14].

V. THE NEW ERA OF IEC 61850 MODE CONTROL AND BEHAVIOR

A. The Future of Substation Digital Testing

IEC 61850 Edition 2 provides an improved, yet still overly complex, explanation of the preferred testing terms and methods, and it specifies how IEDs should operate based on both the Mode (Mod) and the Behavior (Beh). The revised approach defines a standardized method of isolation that reduces, but does not completely eliminate, the need for complex logic equations in the IEDs that had been necessary for isolation in Edition 1 IEDs.

Before the release of Edition 2, IED manufacturers interpreted the standard inconsistently, which contributed to interoperability problems and allowed greater odds of device misoperation. These issues contributed to confusion in testing devices, leading to widespread non-confidence in the standard

and the mostly experimental adoption of IEC 61850 devices. Edition 2 clarifications, which explain how Mode is controlled, improved the effectiveness of conformance testing and provided utility personnel with confidence that the testing scenarios in the standard had been addressed.

The improved implementation of Mode control and Behavior testing features include the standardization of GOOSE message processing [15], the operation of output contacts [15], and the setting of flags for the data within GOOSE messages [16]. Table III explains how the output contacts of the IED will behave according to the Behavior value of the IED [15]. Table IV explains how the IED will process data in a GOOSE message according to its stVal Quality value [15].

TABLE III
OUTPUT CONTACT OPERATION

Mode	Output Contact Behavior
On	Contacts operate on processed signals
Blocked	Contacts DO NOT operate
Test	Contacts operate on processed signals
Test/Blocked	Contacts DO NOT operate
Off	Contacts DO NOT operate

TABLE IV
PROCESSING GOOSE AND SV MESSAGES

Mode	q.Validity = Good q.test = FALSE	q.Validity = Good q.test = TRUE
On	Process as valid	Do not process
Blocked	Process as valid	Do not process
Test	Process as valid	
Test/Blocked	Process as valid	
Off	Do not process	

B. Use Case: The Transition From Handcrafted Equations to the Use of IEC 61850 Built-In Test Features

With the clarification brought by IEC 61850 Edition 2, users can consistently leverage the complex built-in features that the standard offers without needing to program complex logic equations to prevent misoperation during the testing of in-service substation assets. These built-in features are explained in depth in this section.

1) Simulation

The GOOSE control block contains a Simulation attribute which is set to TRUE for a simulated message. The S bit, inside the Reserved 1 section of a GOOSE protocol data unit shown in Fig. 7 [3], mirrors the Simulation attribute. This bit will be referred to as the Sim bit.

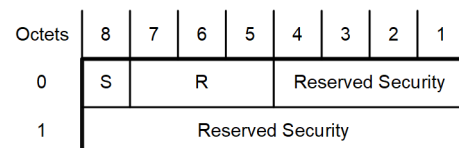| Octets	8	7	6	5	4	3	2	1
0	S		R		Reserved Security			
1	Reserved Security							

Fig. 7. The Simulate flag of a GOOSE message.

Simulation is the state where the IED is configured to process simulated GOOSE messages (LPHD.Sim.stVal = TRUE). With Sim.stVal = TRUE, once the IED receives a subscribed GOOSE message with the Sim bit set, the IED will stop processing the normal GOOSE message in favor of the simulated message. If the IED subscribes to other, nonsimulated GOOSE messages, it will continue to handle the other subscriptions as before. Only those simulated messages with the Sim bit set will be processed until the IED LPHD.Sim.stVal = FALSE [7]. Simulated GOOSE, normal GOOSE, and Sim bit set messages may all be present on the network. Simulation can be thought of as a replacement for a traditional test set that injects analog values and digital inputs into an IED. A device in Simulation mode will continue to process normal data if it does not receive a message with the Sim bit set. Therefore, a device in Simulation mode subscribing to multiple GOOSE or SV messages may process both simulated streams and actual streams simultaneously depending on the Sim flag of the published messages [7].

To allow an IED to process simulated GOOSE messages, the user needs to write a logical 1 (TRUE) to the LPHD.Sim.Oper.ctlVal that will set the LPHD.Sim.stVal = TRUE, indicating the IED is ready to receive simulated messages. Although the simulated GOOSE messages are typically sent from a test device or software, IED manufacturers may have implemented proprietary means by which to configure an IED to act like a simulation device and send simulated GOOSE messages to the network. For example, with a certain manufacturer's IEDs, the Simulate bit can be set by writing a logical 1 to the LPHD extended object, LN LPHD1.PubSim.Oper.ctlVal. It is necessary to mention that both the LN LPHD1.Sim and LPHD1.PubSim are test extensions and not present by default in a configured IED description (CID) file.

This feature will give users the opportunity to perform test operations on a subset of specific IEDs in an in-service substation without affecting the operation of any IEDs that are not involved in the test. As the IEDs that do not have the LN LPHD1.Sim.stVal=TRUE logic will ignore GOOSE messages with the Sim flag set, the chance that the IED will process any trip signals sent via GOOSE messages from the devices under test is low, therefore misoperation and false trips are possibly avoided without the need of any additional logic. Section VII describes how to use simulation when testing devices across both IEC 61850 editions.

2) Processing of an Item Contained in an Incoming GOOSE Message Based on the Quality Field Value

Each data item included in a GOOSE message should contain a bit-string that provides that item's Quality [16]. The Quality bit-string contains the following fields, described in Table V.

If a GOOSE message contains data that has q.Validity = Good and q.Test = TRUE, then the data item within that message is test data and should be processed by a device where Mode = Test or Test/Blocked. Refer to Table V.

TABLE V
BIT-STRING VALUES

Bits	IEC 61850-7-3		Bit-String	
	Attribute Name	Attribute Value	Value	Default
0–1	Validity	Good	0 0	0 0
		Invalid	0 1	
		Reserved	1 0	
		Questionable	1 1	
2	Overflow		TRUE	FALSE
3	OutofRange		TRUE	FALSE
4	BadReference		TRUE	FALSE
5	Oscillatory		TRUE	FALSE
6	Failure		TRUE	FALSE
7	OldData		TRUE	FALSE
8	Inconsistent		TRUE	FALSE
9	Inaccurate		TRUE	FALSE
10	Source	Process	0	0
		Substituted	1	
11	Test		TRUE	FALSE
12	OperatorBlocked		TRUE	FALSE

When the IED is put into Mode = Test or Test/Blocked, it will process GOOSE messages where the data have q.Test = TRUE set in the Quality string. If an IED is in Mode = On or Blocked and it receives data with q.Validity = Good and q.Test = TRUE, then the IED will process the data as if it were invalid. Therefore, putting an IED in Mode = Test should not affect an upstream device that is not in Mode = Test.

In testing devices that are virtually wired together through GOOSE, it can be difficult to provide a visible indication that a device has been isolated for testing when there is no MMS client to view the status of the Mode/Behavior or to change the mode of the IED. Modern test sets and test software may be able to access the data model and provide the Mode status; however, an indication on the IED could be used to provide the confirmation necessary to verify the IED has been isolated.

3) Behavior of Output Contacts of the IEDs Based on the Mode/Behavior Sent to the IED

Using traditional test methods, the test switch was sometimes used to provide isolation by opening the physical contact. To perform the test, relay logic was changed to use a spare output contact to verify the operation. In IEC 61850, when the Mode/Behavior = Blocked or Test/Blocked, the IED provides the required isolation by preventing the operation of the output contact.

As previously described in Table III, when receiving a control command via MMS or GOOSE processing logic, no output operation will be issued if Mode/Behavior = Blocked or Test/Blocked. The difference between these two is that if

Mode/Behavior is Blocked, incoming normal data (not test data) will be processed, but the output contact operation will be blocked. If the Mode/Behavior of a device is Test/Blocked, then incoming normal data and test data will be processed but the output contact will be blocked.

Using the blocked modes prevents undesired operations, such as the trip of a breaker or a group of breakers, or accidently tripping or closing relay outputs when testing relay logic. Because logic is still processed, but the output operation is blocked, utility personnel can examine the SOE recorder to confirm that the programmed functions in the IED work correctly and thus guarantee the integrity of the substation.

The IEC 61850 standard expects that an MMS client will be used to change the Mode/Behavior. Modern test sets that support IEC 61850 can access the data model and control the Mode; however, if this type of test set is not available to an IED, then a utility must find or invent other methods of testing, and the IED will be unable to report its Mode/Behavior value to non-IEC 61850 SCADA clients.

Some IEDs provide alternate means for modifying and indicating the value of Mode/Behavior. For example, dedicated logic equations can provide the means to set the IED into Test and/or Blocked Mode through a pushbutton or other input. In this example, SC850TM is a logic variable that can be used to set or reset the Test Mode. Similarly, SC850BM is a logic variable that can be used to set or reset the Blocked Mode. The logic below is an example of how the Mode/Behavior of an IED is selected through the use of the logic variables SC850TM and SC850BM, which in turn are controlled by the logic variables PTL02 and PLT03, respectively. Table VI illustrates the Mode/Behavior of the IED as a result of the state of the SC850TM and SC850BM logic variables.

SC850TM := PLT02
SC850BM := PLT03

TABLE VI
IED-SELECTED IEC 61850 MODE/BEHAVIOR

SC850TM	SC850BM	Mode/Behavior
0	0	On
1	0	Test
0	1	Blocked
1	1	Test/Blocked

By using this type of logic variable to illuminate front-panel LEDs, it provides the visible indication to the testers that an IED is in the expected mode for testing.

The value of Mode/Behavior is an enumerated number with a range of 1–5, defined in either the IED capability description or the CID file with the following corresponding values [17].

```
<EnumType id="Mod">
  <EnumVal ord="1">on</EnumVal>
  <EnumVal ord="2">blocked</EnumVal>
  <EnumVal ord="3">test</EnumVal>
  <EnumVal ord="4">test/blocked</EnumVal>
  <EnumVal ord="5">off</EnumVal>
</EnumType>
```

Another problem that may arise using Mode/Behavior is that other protocols, such as DNP3 or Modbus, have no way of reading the IEC 61850 Mode/Behavior; however, some device manufacturers provided means to report the Mode/Behavior status. For example, I850MOD is one manufacturer's named analog value in the IED that provides the current value of Mode/Behavior at the root logical device. The IED can report this value through other communications protocols, which supports readability beyond IEC 61850.

As IEC 61850 experimental adoption continues to grow, test procedures and methods will evolve. Utilities will need to learn to trust the status of digital signals as they previously trusted visibly open test switches. The visibility of Mode/Behavior in IEC 61850 testing methods can provide the reassurance that utility personnel seek.

VI. USE CASE: TESTING IN-SERVICE SUBSTATIONS WITH A MIXED INSTALLATION OF IEDS SUPPORTING IEC 61850 EDITION 1 AND EDITION 2

Due to the inconsistencies between the standardized and the non-standardized implementations among different IED manufacturers, there is a risk of provoking undesired operations when trying to perform digital testing in an in-service substation with a mixture of Edition 1 and Edition 2 devices.

Performing digital testing by using the Mod.stVal = Blocked or Mod.stVal = Test/Blocked in GOOSE messages between IEDs supporting both editions of IEC 61850 would produce unwanted operation by IEDs supporting Edition 1. These IEDs might process all the incoming GOOSE messages, regardless of the mode of the incoming message data. However, since the Sim/Test bit was standardized, this built-in feature can sometimes be leveraged to perform digital testing. This is the case because the name of the reserved bit changed, but not its location in the GOOSE message, which allows users to leverage simulated signals.

Consider the testing of a breaker failure scheme for Line 2 in an in-service substation with two lines, as shown in Fig. 8. As part of an upgrade project for Line 2, a new breaker failure relay (outlined in bold) is added to this line. All IEDs in Line 2 are new and support the Edition 2 standard, while all IEDs in Line 1 are older and support Edition 1.

Testing the Line 2 breaker failure scheme, assuming that no additional data are exchanged between Edition 1 and Edition 2 relays through proprietary protocols or communications, requires a certain series of steps, described as follows.

1. A test blade is inserted into the corresponding test switch for both the line protective and breaker failure relays.
2. The Line 2 line protective relay Mode/Behavior is set to Mode/Behavior = Test/Blocked.
3. The Line 2 line protective relay is set to publish simulated GOOSE messages to the network.
4. The Line 2 breaker failure relay is set to Mode/Behavior = Test/Blocked.
5. The Line 2 breaker failure relay is set to accept simulated GOOSE messages in the network.

6. The Line 2 breaker failure relay is set to publish simulated GOOSE messages to the network.
7. All IEDs in Line 1 remain in service with no additional configuration.
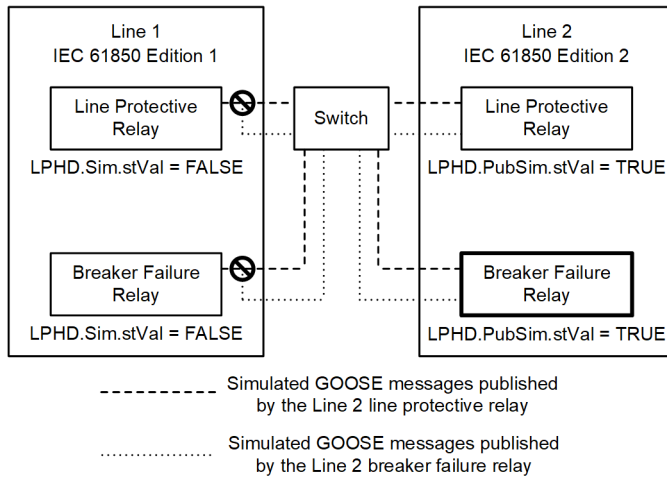8. All protection routines are executed as normal with the use of a test setup.

Fig. 8. Using Simulation as a way to perform digital testing in in-service substations with a mixture of IEC 61850 Edition 1 and Edition 2 IEDs. Each device in Line 2 is accepting and processing GOOSE messages from the other.

Setting the Mode/Behavior = Test/Blocked in both Line 2 relays will direct them not to close any output contacts as long the Mode/Behavior = Test/Blocked, providing the required physical isolation from other devices. This will also direct the IEDs to process all data items inside the GOOSE messages that contain the Quality attribute Test = TRUE and Mode = On.

Setting LPHD1.PubSim.stVal = TRUE in both Line 2 relays will direct them to set the Sim bit, and then all outgoing GOOSE messages from these relays will be recognized as simulated from all IEDs in the network, as shown in Fig. 8.

Setting LPHD1.Sim.stVal = TRUE in the Line 2 breaker failure relay will direct the relay to process only simulated GOOSE messages that have the Sim bit set [3]. All remaining IEDs in the substation (i.e., Edition 1 IEDs in Line 1) will process only GOOSE messages with the Sim flag cleared and ignore all simulated GOOSE messages published by both IEDs in Line 2 [3]. Keep in mind that this will work only if the IEDs in the substation, which may have been made by different manufacturers, process the Sim/Test bit in the same way.

All of these protection routines can be executed at this time. No output contacts from the IEDs in Line 2 will be closed because the Mode is Test/Blocked, and any trip signals transmitted by GOOSE messages, either by the line protection or the breaker failure relays of Line 2, will be disregarded by all IEDs that are not set to receive simulated GOOSE messages. This setup provides the user with the confidence that no unwanted operations or false trips will be produced during testing.

Another option is to take advantage of the Simulation bit and Mode to test across editions. Edition 1 devices, which may or may not correctly block output contacts, are mixed with Edition 2 devices that can block output contacts. Setting Edition 2 IEDs LPHD.Sim.stVal = TRUE and Mode to Blocked will allow test signals with Sim bit set to be injected into the system, but which Edition 1 relays, whose LPHD.Sim.stVal = FALSE, will ignore. Fig. 9 illustrates this idea of using both test methods at once.
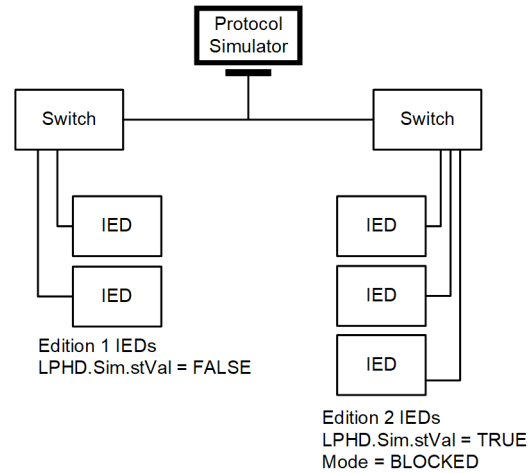

Fig. 9. System with both Edition 1 and Edition 2 relays using Sim bit and Mode for testing.

VII. USE CASE: TESTING A TRANSMISSION LINE PROTECTION SCHEME IN AN IN-SERVICE SUBSTATION WITH IEDs SUPPORTING ONLY IEC 61850 EDITION 2

The standardization in IEC 61850 Edition 2 ensures the uniform processing of GOOSE messages based on Mode/Behavior and Quality attributes. Thus, having a substation with all IEDs supporting Edition 2 makes the digital testing of an in-service substation easier than Edition 1 because all IEDs will process (or disregard) incoming GOOSE messages as explained in Table IV. This will ensure that no misoperation or false trips will be produced in the system as result of a misconfiguration on the IED, faulty logic, or IEDs from different manufacturers. This is essential when regional coordination councils or the specifications listed by some utilities recommend, or even mandate, that the primary and backup relays should be different in construction, protection algorithms, and even manufacturers.

Transmission lines are critical elements in the power grid. Because of this, transmission lines are rarely taken out of service. A line out of service translates into economic losses for both utilities and the industries that rely on that power, as well as an impact to the quality of life of individuals who rely on that electricity. As such, having trustworthy methods to test in-service live transmission lines is of utmost importance. The vision and effort that IEC TC57/WG10 has put into achieving substation testing in a live system without taking it out of service and putting the system offline, is now possible in the IEC 61850 Edition 2 release, although it is not perfect and does not address some points that are explained in Section VIII. Using the built-in features offered in this revision, in combination with a good panel design that provides physical isolation such as test switches, helps with testing in-service live systems.

The intention behind the built-in features of Edition 2 is to perform testing of the functions that protect the transmission line without disruption of service, as well as providing protection needed to clear any fault in the transmission line in the event that real failure occurs in the system.

Consider a traditional transmission line protection scheme, as illustrated in Fig. 10. Each end of the line contains four protective relays whose functions are explained in the following sections.
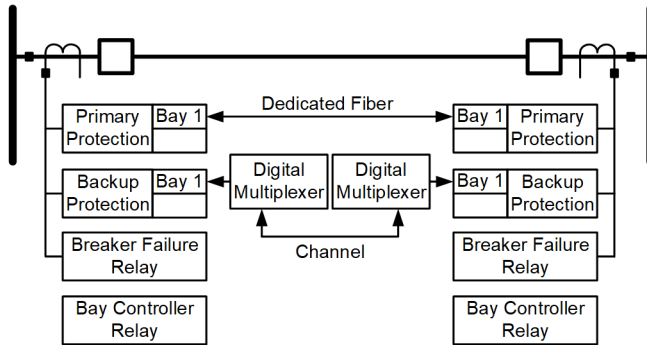

Fig. 10.   A traditional transmission line protection scheme.

A.   Primary Protection IED

The primary protection IED at the local substation exchanges differential data with the primary protection IED in the remote substation to achieve differential line protection (87L) by sharing the current measurements between the terminals of the line. The 87L communications run via a proprietary protocol. This protocol may allow the transmission of additional bits, such as the permissive overreaching transfer trip (POTT) or the direct transfer trip (DTT), to share with the differential line protection data. This feature helps to reduce additional communications equipment and hardwiring. Trip signals generated from the 87L, POTT, and DTT schemes are also published to the network via GOOSE messages.

The primary protection IED also exchanges data with other IEDs in the same substation using input/output contact signals. Protection schemes such as the breaker failure initiate (50BFI) and the reclosing initiate (79I) schemes are achieved by this method of communication. Similarly, trip signals, such as the 87L, POTT, and DTT operations, are also published to the network via GOOSE messages.

B.   Backup Protection IED

The backup protection IED serves as the distance and directional overcurrent line protection (21L/67L). The backup protection IED also exchanges protection data, such as POTT and DTT bits, using a proprietary protocol, usually through a communication multiplexer. The purpose of this communication exchange is to provide IEDs with faster trip processing, rather than relying on only the 21L/67L protective functions. Trip signals generated from the 21L, 67L, POTT, and DTT schemes are also published to the network via GOOSE messages.

Similar to the primary protection IED, the backup protection IED also exchanges data with other IEDs in the same substation to enable protection schemes, such as the 50BFI and 79I,

through input/output contact signals. Similarly, the 50BFI and 79I signals are also published to the network via GOOSE messages.

C.   Breaker Failure IED

The breaker failure IED serves as breaker failure protection (50BF). Unlike the primary and backup protection IEDs, normally the breaker failure IED does not exchange data with the other IEDs in other substations. However, trip signals such the 50BF and the trip to the lockout relay (86BF) are exchanged with other IEDs in the same substation through input/output contact signals. Similarly, the 50BF and 86BF trip signals are also published to the network via GOOSE messages.

D.   Bay Controller IED

The bay controller IED provides local control of breakers and disconnect switches of the bay to the operators. The bay controller may receive the statuses of alarms, apparatuses, breakers, disconnect switches, GOOSE messages, and interlocks, all signaling the bay controller to operate its contacts. The IED is programmed to handle these varied inputs.

To accomplish both the testing of each IED and its related protective functions, the Mode/Behavior will be changed only in the IED to be tested.

E.   Testing the Primary Protection (87L Function)

To test the 87L relays, IEDs at both ends of the transmission line are set to Mod.stVal/Beh.stVal = Test/Blocked. All the remaining IEDs in the scheme (21L/67L, 50BF, and the bay controller) remain unchanged (Mod.stVal/Beh.stVal = On).

With both 87L relays' Mode/Behavior = Test/Blocked, no output contacts will be closed by these relays and the protection testing routines can be started. Any trip signals received (whether from GOOSE messages, over the 87L channel, transfer trips from other IEDs, or trips as the result of an induced fault by a test set) will be processed per manufacturer specifications, but no output contacts will be closed. Without the 87L relays closing the output contacts, no hardwired trip signals will be propagated to other IEDs. Trip signals published in a GOOSE message by the 87L relays will have the Quality (q) test field value set to TRUE. The published trip signals by the 87L relays will not be processed by other IEDs in the network; these trip signals will be discarded due to the .q field value mismatch. This physical and digital isolation will prevent the 87L relays and other IEDs from tripping the breaker.

Setting the 87L relays' Mode/Behavior = Test/Blocked, the following results are achieved:

- Transfer trips sent over the 87L channel will be received and processed on the other end, but no physical contacts will be closed at either end.
- Hardwired transfer trips will not be propagated to other IEDs because no contacts will be closed in the IEDs under test.
- Digital transfer trips, sent through GOOSE messages by the 87L relays, will be discarded by the subscribing IEDs that are not set to the same Mode/Behavior as the 87L relays.

- Any digital transfer trips sent over proprietary protocols by the 87L relays will be processed by the receiving IEDs, but no physical contact will be closed, preventing the trip of field breakers.
- The transmission line will be continuously protected by the 21L/67L relays during the testing of the 87L relays, providing the flexibility to test the required IEDs and not lose protection without decommissioning the line.

After the end of the test, 87L relays at both ends will be set to Mode/Behavior = On. This returns the relays to normal operation.

F. Testing the Backup Protection (21L/67L Function)

To test the 21L/67L relays, IEDs at both ends of the transmission line are set to Mode/Behavior = Test/Blocked. All remaining IEDs in the scheme (87L, 50BF, and the bay controller) remain unchanged (Mod.stVal/Beh.stVal = On).

With both 21L/67L relays' Mode/Behavior = Test/Blocked, no output contacts will be closed by these relays, allowing the protection testing routines to start. Like the 87L testing, received trip signals can be processed but no output contacts will be closed. Without the 21L/67L relays closing the output contacts, no hardwired trip signals will be propagated to other IEDs. Like the 87L relays, trip signals published in a GOOSE message will have the .q test field value set to TRUE. The trip signals published by the 21L/67L relays will not be processed by other IEDs in the network as these trip signals will be discarded due to the .q field value mismatch. This physical and digital isolation will prevent the 21L/67L relays and other IEDs from tripping the breaker.

Setting the 21L/67L relays' Mode/Behavior to Test/Blocked, the following results are achieved:

- Transfer trips sent over the proprietary communications channel will be received and processed on the other end, but no physical contacts will be closed at either end.
- Hardwired transfer trips will not be propagated to other IEDs because no contacts will be closed in the IEDs under test.
- Digital transfer trips, sent through GOOSE messages by the 21L/67L relays, will be discarded by any subscribing IEDs that are not set to the same Mode/Behavior as the 21L/67L relays.
- Any digital transfer trips sent over proprietary protocols by the 21L/67L relays will be processed by the receiving IEDs, but no physical contact will be closed, preventing the trip of field breakers.

After the end of the test, 21L/67L relays at both ends will set Mod.stVal/Beh.stVal = On, returning to normal operation.

G. Testing the Breaker Failure Protection (50BF Function)

To test the 50BF relay, the IED will set Mode/Behavior = Test/Blocked. All remaining IEDs in the scheme (87L, 21L/67L, and the bay controller) remain unchanged (Mod.stVal/Beh.stVal = On).

With the 50BF relay Mode/Behavior = Test/Blocked, no output contacts will be closed in this relay. At this point, the protection testing routines can be started. As before, any trip signals received via GOOSE messages will be processed, but no output contacts will be closed. Without the 50BF relay closing the output contacts, no hardwired trip signals will be propagated to other IEDs. Trip signals published in a GOOSE message by the 50BF relay will have the .q test field value set to TRUE, and the trip signals published by the 50BF relay will not be processed by other IEDs in the network; these trip signals will be discarded due to the .q field value mismatch. This physical and digital isolation will prevent the 50BF relays and other IEDs from tripping the breaker.

When setting the 50BF relay's Mode/Behavior to Test/Blocked, the following results are achieved:

- Transfer trips sent over a proprietary communications channel will be received and processed, but no physical contacts will be closed.
- Hardwired transfer trips will not be propagated to other IEDs because no contacts will be closed in the IED being tested.
- Digital transfer trips, sent through GOOSE messages by the 50BF relay, will be discarded by any subscribing IEDs that are not set to the same Mode/Behavior as the 50BF relay.
- Any digital transfer trips sent over proprietary protocols by the 50BF relay will be processed by the receiving IEDs, but no physical contact will be closed, preventing the trip of field breakers.

After the end of the test, the 50BF relay will be set to Mode/Behavior = On. This returns the relay to normal operation.

H. Testing the Bay Controller Function

It is common for the bay controller to be used only for the local and remote control of the IED bay and not as a protective device, meaning it does not trip the breaker directly. Due to this, the IED may only be tested using the controls from SCADA or from a local HMI in the substation.

To test the bay controller relay, the IED is set to Mode/Behavior = Test/Blocked. All remaining IEDs in the scheme (87L, 21L/67L, and the 50BF) are unchanged (Mod.stVal/Beh.stVal = On). One must consider whether the bay controller receiving the status of breakers, disconnect switches or any other interlocks via GOOSE messages. If so, all publishing IEDs servicing the bay controller will be set to the same Test/Blocked Mode/Behavior.

With the Mode/Behavior of the bay controller and any auxiliary relays set to Test/Blocked, no output contacts will be closed in these relays, meaning the control testing routines can be started. Any closing or opening signals of breakers or disconnect switches (via MMS, over an open communication protocol, over a proprietary communication channel or protocol, or via GOOSE messages) will be processed, but no output contacts will be closed. Without the bay controller relays closing the output contacts, no hardwired closing or opening signals will be physically issued. This physical and digital isolation will prevent the bay controller relays and other IEDs from opening or closing the breakers or disconnect switches.

Setting the bay controller relay's Mode/Behavior to Test/Blocked, the following results are achieved:

- Transfer commands sent over a proprietary communications channel or protocol will be received and processed, but no physical contacts will be closed.
- Digital transfer controls sent by the bay controller relay through GOOSE messages will be discarded by the subscribing IEDs that are not set to the same Mode/Behavior as the bay controller relay.

After the end of the test, the bay controller relay will be set to Mode/Behavior = On. This returns the relays to normal operation.

VIII. WARNINGS, CAVEATS, INCONVENIENCES, HAZARDS

Unfortunately, Edition 2 of the IEC 61850 standard does not consider that installed IEDs and substations use other communication protocols, both proprietary and open. Several issues that arise from this omission have not been addressed.

- The standard does not address how IEDs whose Mode/Behavior is not Blocked or Test/Blocked would behave or operate when receiving a trip signal over other protocols from an IEC 61850 IED under test.
- The standard does not address how IEDs might behave when receiving commands from other protocols.
- Simulated GOOSE messages may direct data to functions that are not being tested.
- Devices may lose their isolation settings, whether from the IED losing power or being power-cycled during testing, and misoperate if the Mode/Behavior is not saved.
- Incorrectly setting the sequence of isolation may lead to unintended operation.
- Even if the Sim feature is standardized across Edition 1 and Edition 2, there may still exist a possibility that manufacturers had implemented this feature in a manner unlike what the standard prescribes. Due to this, users must consider how each installed IED will behave before proceeding to live testing.

- As the IEC committees change both the Behavior of IEDs and the processing of GOOSE messages with each revision [15], best practices suggest the proper design of GOOSE-assisted protection that includes the use of test switches to guarantee the safety of personnel and devices in the substation.
- The example provided here (the Section VII example of transmission line testing) will only work in protection schemes that use primary and backup protection. If one were to use this feature in protection schemes with no backup protection, it would become a true hazard risk. One IED must not be in a blocked mode because it must be able to operate contacts that protect the line. This is an issue because the setup will have only one end set to Mode/Behavior = Test/Blocked while the other end remaining set in Mode/Behavior = On. The end being tested will keep transmitting transfer trips over the communication channel, which will be processed by end units not blocking their output contacts, resulting in an undesired breaker trip.

These types of scenarios are not addressed in the standard but describe actual problems with current power systems. Understanding these shortcomings then falls to the end users, who, if they fail in that understanding, will then spend large amounts of time and money on IEC 61850 Edition 2, only to discover it does not meet all their real-world needs.

IX. CONCLUSION

Only through reducing its complexity will the IEC 61850 standard have the possibility of becoming a powerful tool for testing in-service devices. Until that time, this paper offers a few practical scenarios to using the standard. Even with the use cases outlined, this paper shows that there are rarely perfect environments for in-system testing. Systems will likely have multiple protocols controlling and reporting statuses. These protocols are developed even while those creating it cannot know every situation that every engineer and substation will face, meaning that only those most commonly reported are considered. IEC 61850 does refer to other automation protocols, but it does not define how to fully test a real-world system. This paper has endeavored to help outline practical and useful solutions and has addressed some of the areas the IEC 61850 standard does not cover.

X. ACKNOWLEDGMENT

XI. References

[1] IEC 61850-7-2, Communication Networks and Systems in Substations, Section 15: Generic Substation Event Class Model (GSE), Table 29, 2003.

[2] IEC 61850-7-4, Communication Networks and Systems in Substations, Section 6: Data Name Semantics, Table 9, 2003.

[3] IEC 61850-9-2, Communication Networks and Systems for Power Utility Automation, Section 5.3.3.4.4: Reserved 1, 2011.

[4] IEC 61850-7-1, Communication Networks and Systems for Power Utility Automation, Section 7.8.4: Test Mode, 2011.

[5] H. Pandzic, A. J. Conejo, I. Kuzle, and E. Caro, "Yearly Maintenance Scheduling of Transmission Lines Within a Market Environment," *IEEE Transactions on Power Systems*, Vol. 27, Issue 1, February 2012, pp. 407–415.

[6] IEC 61850-7-2, Communication Networks and Systems for Power Utility Automation, Section 18.2.3.1: GOOSE Message Syntax Table 43: GOOSE Message Definition, 2010.

[7] IEC 61850-7-1, Communication Networks and Systems for Power Utility Automation, Section 7.8.2: Multicast Signals Used for Simulation, 2011.

[8] Washington Administrative Code, WAC 296-45-335, Deenergizing Lines and Equipment for Employee Protection, 2019.

[9] IEEE Standard C37.233, IEEE Guide for Power System Protection Testing, 2009.

[10] Comisión Federal de Electricidad, *Sistema de Automatización de Subestaciones IEC 61850, Revisión 2* [Substation Automation System IEC 61850, Revision 2], 2018.

[11] V. M. Flores, D. Espinosa, J. Alzate, and D. Dolezilek, "Case Study: Design and Implementation of IEC 61850 From Multiple Vendors at CFE La Venta II," proceedings of the 60th Annual Conference for Protective Relay Engineers, College Station, TX, March 2007.

[12] T. Tibbals and D. Dolezilek, "Case Study: New Testing and Verification Practices for Virtual Wiring Among IEDs Via Ethernet Communications," proceedings of the 1st Annual Protection, Automation and Control World Conference, Dublin, Ireland, June 2010.

[13] D. Burkart, W. Edwards, A. Atalay, and S. Snuggs, "If You Cannot Test It, You Cannot Use It – IEC 61850 GOOSE System Designed With Testing in Mind," proceedings of the 70th Annual Conference for Protective Relay Engineers, College Station, TX, April 2017.

[14] N. Moreno, M. Flores, L. Torres, J. Juárez, and D. González, "Case Study: IEC 61850 as Automation Standard for New Substations at CFE, Practical Experiences," proceedings of the 12th Annual Western Power Delivery Automation Conference, Spokane, WA, April 2010.

[15] IEC 61850-7-4, Communication Networks and Systems for Power Utility Automation, Annex A, Table A.2, 2010.

[16] IEC 61850-8-1, Communication Networks and Systems for Power Utility Automation, Section 8.2: Mapping of Quality Common Data Attribute Type Specified in IEC 61850-7-3, Table 33, 2011.

[17] IEC 61850-6, Communication Networks and Systems for Power Utility Automation, Annex B, 2012.

XII. Biographies

Edson Hernández received his BS degree in Electronic Engineering from the Instituto Tecnológico de San Luis Potosí, Mexico in 2006. That same year, he served as an associate technician to the Instituto Potosino de Investigación Científica y Tecnológica (IPICyT) in the automation of laboratory processes and in the research and development of nanotechnology-based devices for the IPICyT Advanced Materials Division. In 2008, he joined Schweitzer Engineering Laboratories, Inc. (SEL) as an integration and automation engineer. Since then, he has designed, applied, and supported integration, automation, control, communications and network products for utilities around the world. He is currently a lead integration and automation engineer in SEL research and development, working in device integration, control and automation, communications protocols, secure communications, and cybersecurity.

Tovah Whitesell received her first three bachelor's degrees from the University of Washington in 2003, her master's degree from Washington State University in 2005, and her latest bachelor's degree from Washington State University in 2014. She joined Schweitzer Engineering Laboratories, Inc. in 2012 as a software engineer. Mrs. Whitesell is currently an engineering manager with the protection systems division helping develop automation solutions.

Karen Leggett Wyszczelski received her BS in Computer Systems Engineering Technology from the Oregon Institute of Technology in 1986. She worked at the Hanford Nuclear Reservation and at an industrial integration company before becoming a SCADA engineer at Grays Harbor PUD in Washington state. She joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2008 as an integration and automation engineer. She completed a master's degree in engineering management from Eastern Michigan University in 2019 and is currently an engineering manager in research and development at SEL.