A Novel Maintenance Mode for IEC 61850 Digital Secondary Systems to Improve Protection Availability

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***Abstract*—In high-voltage substations, configurations such as double-bus double-breaker, breaker-and-a-half, and ring bus are commonly used because they provide reliability and operational flexibility in terms of equipment maintenance and network switching. Two breakers are used to feed a network element (e.g., a line, transformer, or capacitor bank) in these bus configurations. In a conventional substation, a line intelligent electronic device (IED) physically measures the current flowing through each breaker and calculates the total line current by summing two breaker currents. Line-protection functions like distance (PDIS) and directional overcurrent (PTOC) are executed using total line current and line voltage. During circuit breaker (CB) maintenance, test switches are opened to isolate the IED from the breaker under maintenance. The line is fed from the second CB and line-protection functions remain available during the maintenance period. In IEC 61850-based digital secondary systems (DSS), breaker currents are digitized by merging units (MUs) before they are subscribed by protective IEDs. When an MU fails or the communication link breaks, a DSS IED selectively disables protection functions that use analog signals from the failed MU. During maintenance, an MU installed in the breaker cabinet might be powered down. The loss of MUs will result in the unavailability of protection functions during maintenance tests and impact the overall reliability of an IEC 61850-based DSS.**

This paper describes a novel maintenance mode for IEC 61850-based DSS IEDs to keep protection functions enabled during maintenance. It describes in detail how the maintenance mode can be implemented using the IEC 61850 standards. Use cases and benefits of all three maintenance mode components are provided. The proposed solution is intended to improve protection availability and assist in maintenance testing of an IEC 61850-based DSS.

I. Introduction

The Bulk Electric System (BES) includes critical generation and transmission system elements that have significant impact on system reliability. Faults on BES elements can lead to widespread outage, system instability, or cascading failures. The critical nature of the BES requires its design and operation to be reliable, secure, and economical. In North America, the BES is planned, operated, and maintained as per North American Electric Reliability Corporation (NERC) system performance criteria. The reliability of the BES is normally measured by determining the performance of all power system elements and their ancillary systems. Protection systems, which are considered ancillary systems, are critical to maintaining the level of reliability required for the BES.

Redundant BES elements and protection systems ensure reliability, increase system stability, maintain end-user satisfaction, and aid in maintenance. Double-bus double-breaker, breaker-and-a-half, and ring bus configurations are popular in high- and extra-high-voltage (HV) substations. These bus configurations provide both reliability and operational flexibility [1]. The network elements (e.g., transmission line, feeder, transformer, capacitor bank, or generator) in these bus configurations remain in service when a breaker, a current transformer (CT), or a bus is under maintenance. The added cost of the redundant breaker and the bus is needed to provide the high availability of those network elements.

Protection system reliability depends upon both dependability and security. For protective IEDs, dependability is the ability to trip for in-zone faults while security is the ability to refrain from tripping for out-of-zone faults. Redundant protection systems, typically referred to as System A and System B, are installed to improve dependability, which in turn improves reliability [2]. The redundant protection systems allow for IED maintenance without a network element outage, and it ensures continued operation when the primary protection system fails. For critical remedial action schemes, voting schemes, typically consisting of three primary IEDs from different manufacturers, are used to improve security.

To maintain the BES reliability, NERC has established some standards and requirements for primary equipment and protection systems maintenance. The objective of a maintenance test is to detect in-service failures of components, wiring, interfaces, communications, or unwanted changes of settings or configuration. These periodic tests were developed to verify that, once placed in service, the protection and control system continues to operate correctly. Some of these tests are calibration tests to verify that individual components are operating within its specification. This type of test is especially vital for the components susceptible to degradation or other changing characteristics due to aging and wear [3].

When a primary element (e.g., breaker, CT, potential transformer [PT], or bus) is under maintenance, network elements are fed from redundant sources. In a conventional substation, analog and binary signals from these elements are isolated from the protection system by opened test switches. A binary input is directed to the protection system to inform it that a primary element is under maintenance. Once the signals are isolated, any maintenance activities on the primary element have no impact on the protection system. Both System A and System B protection systems are available during maintenance tests. The overall reliability of the protection systems remains intact.

In an IEC 61850-based digital secondary system (DSS), merging units (MUs) digitize analog and binary signals from primary elements. These MUs are typically installed in the field cabinets. Protective IEDs, which are typically installed in a control house, subscribe to MU data and execute protection functions. Protection functions' availability depend upon MU data quality and the communication channel's health. If a communication link fails or invalid data are received, then protection functions are disabled. Unlike a conventional substation, the physical isolation between the primary element and the MU is not always possible in an IEC 61850-based DSS. When primary equipment or an MU is put under maintenance, the MU might be powered down. The loss of an MU will result in the unavailability of protection functions that depend upon analog signals from the MU. Unavailability of protection functions during maintenance tests lowers the overall reliability for an IEC 61850-based DSS.

In this paper, a novel maintenance mode for an IEC 61850-based DSS is proposed to improve protection availability during maintenance. Section II describes maintenance workflow for both conventional substations and DSSs and discusses the impact on protection unavailability for the DSS. Section III describes the possible manufacturer-specific and IEC 61850-based solutions to improve protection availability during a maintenance period. The challenges of these solutions are also discussed in this section. The proposed maintenance mode and its benefits are discussed in detail in Section IV. Finally, Section V presents our concluding remarks.

II. Maintenance and Impact on Protection Availability

Malfunctioning protection systems can lead to major power system outages and widespread cascading events. Routine maintenance of primary equipment and protection systems is important to maintain the BES reliability. Maintenance programs are important in uncovering equipment problems and hidden failures before they become urgent. As a result, NERC and other regulatory agencies require asset owners to conduct and maintain records of periodic maintenance activities. For example, NERC requires maintenance on circuit breaker (CB) trip coils at least once every six calendar years. Similarly, it requires a maximum maintenance interval of 12 calendar years for monitored microprocessor-based protective IEDs [4] [5]. Most utilities follow their own maintenance schedule, which is typically five to six years.

There are many factors that may prevent a CB from interrupting fault currents. Some common causes for the failures are loss of tripping power, dc battery failure, shorted trip circuit, incomplete breaker mechanism travel, faulty components that are needed for the interruption, or if the dielectric material in the interrupter is out of specification or contaminated [6]. The breaker's internal faults may lead to explosions and fires. Due to the significance of breakers within the substation, preventive maintenance intervals are developed based on manufacturer guidance and best practices for both external and internal maintenance [7]. According to [8], CB reliability decreases with increasing voltage levels. It cites a mean time between failure (MTBF) of 83 years for breakers used between 300 kV and 500 kV. For breakers used at voltages between 63 kV and 100 kV, the MTBF increases to 364 years. Hence, real-time monitoring and periodic maintenance of CBs are critical for station reliability.

When two breakers are used for each network element, it allows continuity of service when a single breaker, a CT, or a bus undergoes maintenance. Both System A and System B protection systems should be available to protect the network element. This is the case for a protection system in a conventional substation with hardwired connections; however, for a DSS, both protection systems might not be available.

A. Conventional Substation

Fig. 1 shows the connections between instrument transformers and protective IEDs in a conventional substation for a double-bus double-breaker configuration. Only System A IEDs are shown. Separate breaker failure IEDs are used for each breaker. The Line 1 IED measures the current flowing through both breakers. It also measures the line and bus voltages for line protection and synchronism check. The Bus 1 IED measures the current flowing out of all CBs connected to Bus 1. Similarly, the Bus 2 IED protects the bus by measuring the current flowing out of all CBs connected to Bus 2.

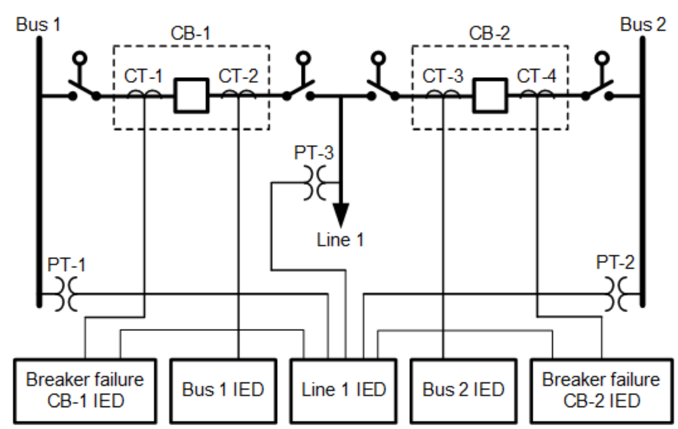

Fig. 1. IED connection for a double-bus double-breaker configuration.

Various protection functions available in a line IED are depicted in Fig. 2. The IED calculates the total line current by summing two breaker currents. Line-protection functions like distance (PDIS), out-of-step blocking (RPSB), and directional overcurrent (PTOC) are executed using total line current and line voltage.

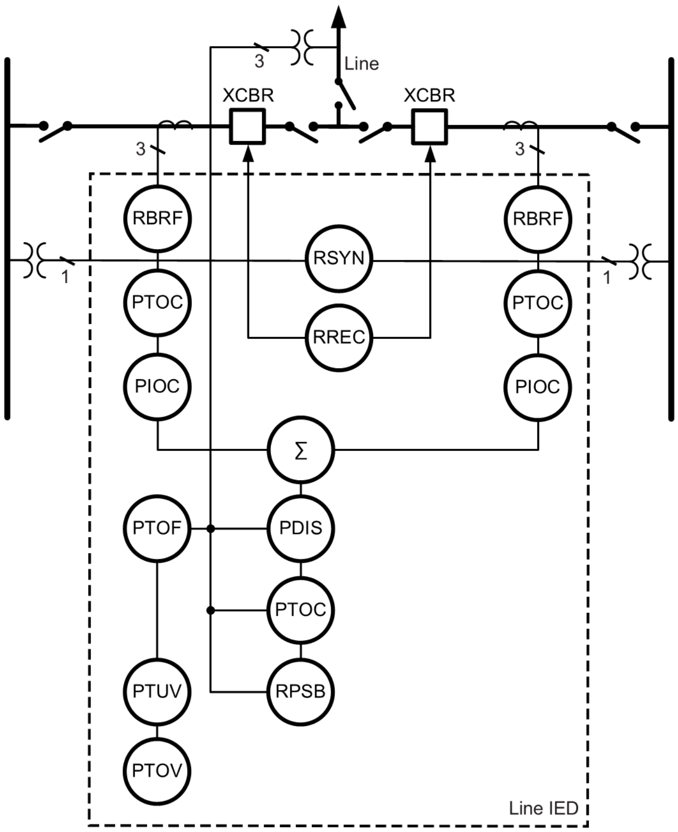

Fig. 2. Protection functions available in a Line IED.

When a CB or a CT needs maintenance, it is isolated from the bus and the line by opening a breaker followed by opening the disconnect switches. The test switches connecting the CB or CT to the IED are opened next. Once the test switches are opened, any maintenance activities have no impact on the IEDs. The line is fed from the second CB. The line current calculated by the IED is equal to the current measured by the second CT. The line-protection functions (PDIS, RPSB, and PTOC) remain available to protect the line. A rotary switch is usually installed in the IED panel to indicate breaker maintenance status to the IEDs. The switch output is connected to the IED binary inputs. That IED binary input is used to defeat breaker failure logic and reclosing logic for the breaker under maintenance. Line protection is available throughout breaker maintenance.

Like the line protection, bus protection is unaffected by CB maintenance. Once the test switches associated with the breaker under maintenance are opened in the bus IED panel, the bus protection remains available. Fig. 2 shows a transmission line as a network element. Instead of a line, it can be a power transformer fed from two breakers. Maintenance of a breaker, CT, or bus has no impact on the overall transformer protection. Except for the breaker-specific protection, all other protection functions remain available during the maintenance period for both System A and System B IEDs.

B. IEC 61850-Based Digital Secondary System

Fig. 3 shows multiple MUs and IEDs connected to a simplified process bus local area network (LAN) in an IEC 61850-based DSS. MU1 and MU2 are shown as installed in breaker cabinets. These MUs measure currents from CTs at either side of the breaker. These MUs also act as process-interface units between the breaker and the protective IEDs. Only System A's MUs, IEDs, and process bus are shown. For a system like this, normally there will be redundant System B protection and associated equipment (MU, IEDs, process bus).

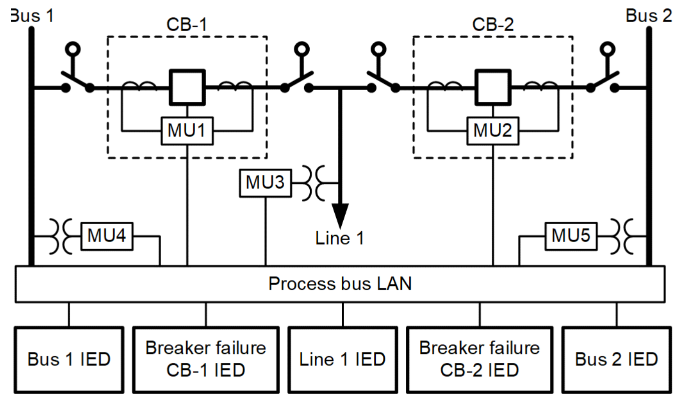

Fig. 3. Simplified IED connection diagram for a double-bus double-breaker configuration in an IEC 61850-based DSS.

In a DSS, IEDs receive CT, PT, and CB signals from MUs digitally via fiber-optic cables. Unlike a conventional IED, a DSS line IED can monitor the communication link of the connected MUs. When an MU fails or the communication link breaks, the DSS line IED selectively disables protection functions that use analog signals received from that MU. For the double-bus double-breaker configuration shown in Fig. 3, line-protection functions (e.g., PDIS and PTOC) are disabled when either MU1, MU2, or MU3 fails.

The line-protection logical device in Fig. 4 shows protection functions in a line IED that use line current [9]. If MU1 or MU2 is turned off for CT or CB maintenance, then the line IED declares communication loss and all line-protection functions are disabled. Even if the MU is online and switched to IEC 61850 Test, Test/Blocked, or **OFF** mode, the line IED, which is in **ON** mode, disables these protection functions.

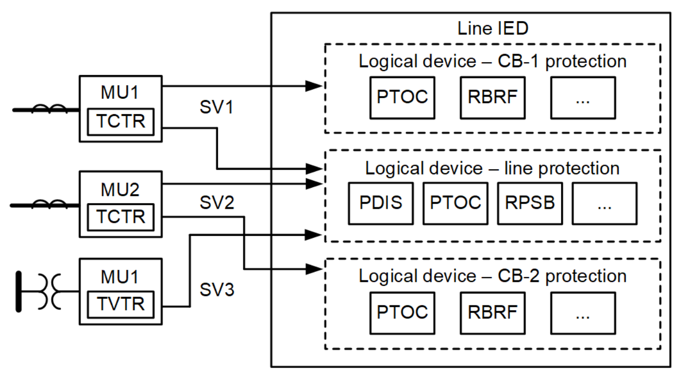

Fig. 4. Protection functions in a DSS line IED.

A bay controller IED for CB-2 subscribing to three sampled value (SV) streams from three different IEC 61850 TVTR logical nodes (LNs) is shown in Fig. 5. The synchronism-check function (RSYN) allows CBs to close if the corresponding phases across the open circuit breaker are within phase, magnitude, and frequency limits. The RSYN function compares two voltage signals, synchronism-check source voltage, and synchronism-check polarizing voltage. For a breaker-and-a-half configuration, the RSYN function can support up to two voltage signals for source voltage and two voltage signals for polarizing voltage for each breaker [10]. Fig. 5 shows MU6 and MU7 as two source voltages and MU5 as the polarizing voltage for CB-2. When MU7 is switched off for its own, bus, or PT maintenance, the SV stream is not available for RSYN function. As a result, RSYN control function is disabled. Even though the RSYN function can run a synchronism check using SV streams from MU5 and MU6, the absence of the MU7 SV stream disables the overall function.

The two examples described earlier show that certain protection functions are unavailable when primary equipment is under maintenance. The protection functions are also unavailable for some of the following cases:

- Primary equipment is in maintenance and requires power to the MU to be turned off.
- MU goes through its own maintenance test.
- MU undergoes a firmware upgrade.

In the last few years, optical instrument transformers (OITs) with digital interfaces have been deployed mostly in HV substations. These OITs have better accuracy, linearity, dynamic range, self-supervision capability and alarms, and compactness with superior safety in HV installations [11]. These OITs can be free-standing or integrated with primary switchgears. Integrated disconnecting CBs with optical current sensors are also available. The trend is to integrate existing MUs with new primary equipment. When the primary equipment is under maintenance, the integrated MUs are unlikely to be available to the IEDs. To keep protection functions available during maintenance, a separate mode is needed to indicate the maintenance status of primary equipment. In the next section, we explore some of the existing solutions to tackle this challenge.

III. Existing Solutions

A. Manufacturer-Specific Solution

Most IED manufacturers provide some sort of current and voltage source selection logic in their IEDs [10] [12] [13]. The logic allows the IED to switch from one current or voltage source to an alternate source following substation reconfiguration. For example, if a substation has a main breaker and an alternate breaker, the current source switching logic will acquire line currents from the alternate breaker during main breaker maintenance. Similarly, for a line energized by bus voltage transformers, voltage source can be switched from Bus 1 to Bus 2 when Bus 1 is de-energized. When two breakers are used for a line or a transformer, the logic calculates the line current by summing two currents. If a breaker is out for maintenance, then the line current is calculated using current from the remaining breaker in operation. Normally, Boolean logic is used for source selection.

For the system shown in Fig. 3, when MU1 is switched off for CB-1 maintenance a binary input is provided to the Line 1 IED, breaker failure CB-1 IED, and Bus-1 IED. When the Line 1 IED receives this input, it uses the source selection logic to remove CB-1 current from the line current. Similarly, when CB-1 is not available, the Bus-1 IED will remove this breaker from its bus-differential protection system. When IEDs from multiple manufacturers are used in a substation, these manufacturer-specific solutions add complexity to implementing logic consistently.

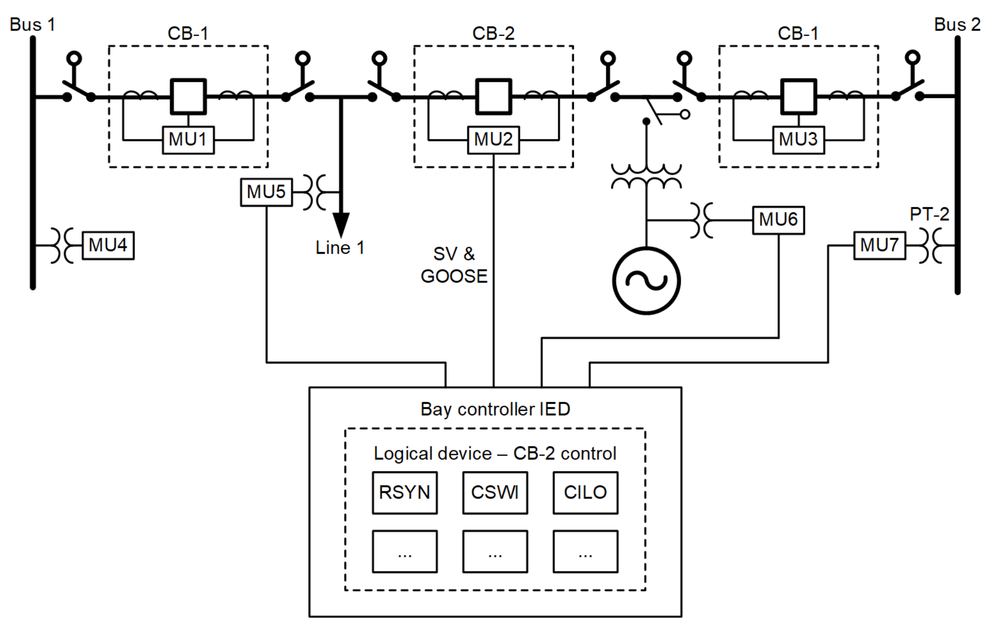

Fig. 5. Bay controller IED subscribing to multiple SV streams.

Some lines have line reactors connected to them. To measure the line current, the IED needs to add current signals from two breakers and subtract the line reactor current. The current summation logic with two CTs does not extend well for this case. Rather than using various manufacturer-specific solutions in each IED individually, a uniform solution to handle the loss of an MU during maintenance will help the protection engineers.

B. Existing IEC 61850-Based Solution

The following sections detail how testing mechanisms provided by IEC 61850 can be applied to the IEDs in the double-bus double-breaker configuration to keep protection functions enabled even when one of the MUs is switched off or is taken down for maintenance.

1) Using Simulation Mode

IEC 61850 Edition 2 provides a testing mechanism for DSS in the form of a Simulation Bit in generic object-oriented substation event (GOOSE) and SV messages. GOOSE and SV control blocks defined in IEC 61850 Edition 2 contain a Reserved 1 field in the GOOSE protocol data unit and SV protocol data unit, respectively. The structure of the Reserved 1 field, shown in Fig. 6, contains the S bit, which depicts whether the GOOSE or SV message is a simulated message or not [14] [15].

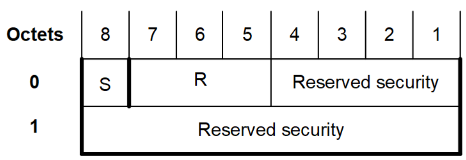

Fig. 6. Simulation Bit in Reserved 1 field.

The IED can be configured to process simulated messages by setting LPHD.Sim.stVal to **TRUE**. If the IED is not configured to process simulated messages (LPHD.Sim.stVal = FALSE), then any GOOSE or SV messages received with the Simulation Bit set will be rejected by the IED. Fig. 7 shows a conceptual diagram that illustrates the processing of simulation messages and normal messages when the IED is configured to process simulated messages (LPHD.Sim.stVal = TRUE) [16].

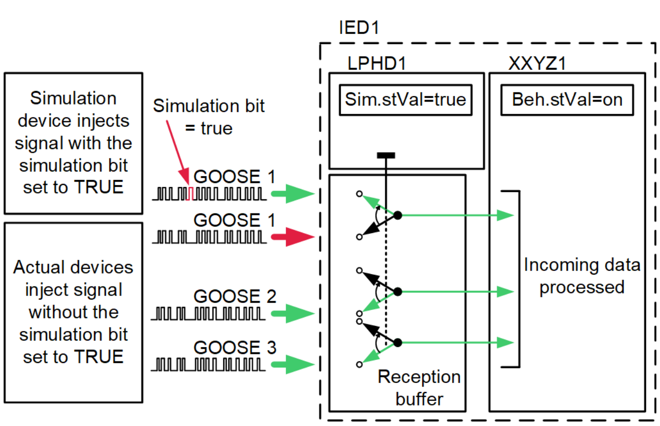

Fig. 7. Processing of simulated and normal GOOSE messages.

If the IED receives a GOOSE or SV message with the Simulation Bit set, then it will stop processing the normal GOOSE or SV messages and process the simulated message instead. If there are other nonsimulated GOOSE or SV messages that the IED is subscribing to, then it will continue to process those as normal. The IED stops processing the simulated GOOSE or SV messages when LPHD.Sim.stVal is set to **FALSE**. It shall then start processing the normal nonsimulated GOOSE or SV message for that subscription. This means that an IED in simulation mode can process normal GOOSE or SV messages as well as simulated GOOSE or SV messages simultaneously depending on the state of the Simulation Bit in the messages.

In the case of the double-bus double-breaker configuration illustrated in Fig. 1, let us look at the GOOSE and SV messages being received by the Line 1 IED. Fig. 8 shows the Line 1 IED receiving SV streams containing voltage information from MU3, MU4, and MU5. The Line 1 IED receives SV streams containing current information from MU1 and MU2. MU1 and MU2 also exchange GOOSE messages with the Line 1 IED to communicate breaker and disconnect status as well as control signals.

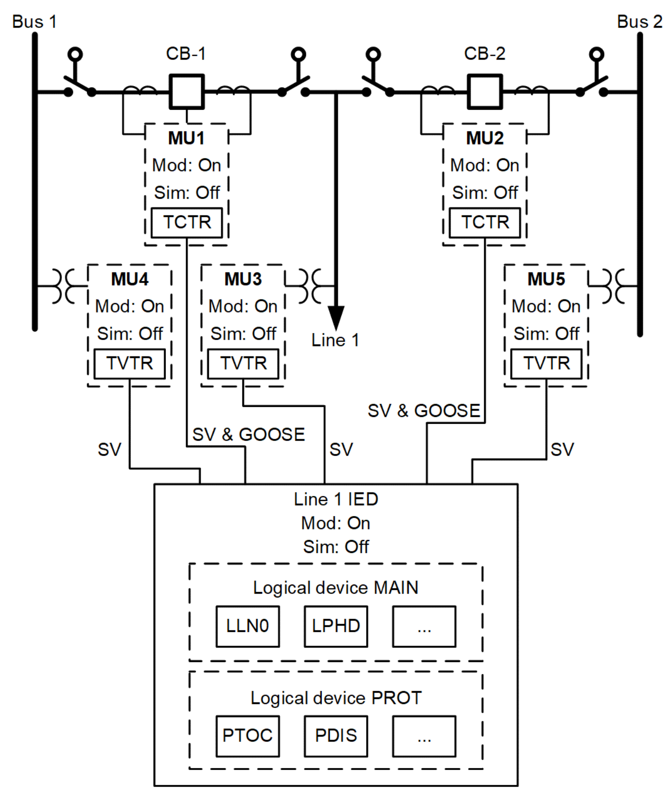

Fig. 8. GOOSE and SV subscriptions for Line 1 IED.

If CB-2 is undergoing maintenance, then CB-2 and its associated disconnects will be opened so that maintenance activity can be carried out on the breaker. A test set, as shown in Fig. 9, can be used to simulate GOOSE and SV messages being sent by MU2. The simulated SV signals containing current signals will be forced to zero on the test set. The simulated GOOSE signals on the test set shall also be forced to zero or to values as deemed appropriate for the maintenance scenario. Next, the test set is connected to the process bus LAN. Since the Line 1 IED is not configured to process simulated messages (Sim: **OFF**), it will ignore the simulated GOOSE and SV messages being published by the test set and continue to process normal GOOSE and SV messages being sent by MU2 and other MUs it is presently subscribing to.

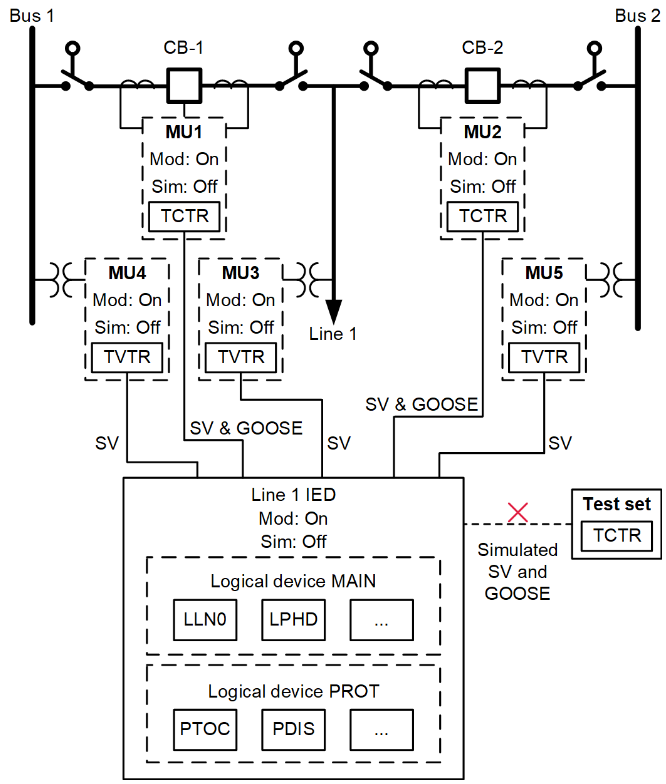

Fig. 9. Test set connected to the system.

The Line 1 IED is then put in simulation mode (LPHD.Sim.stVal = True), as shown in Fig. 10. Since the simulated GOOSE and SV streams being published by the test set are configured to be identical to the GOOSE and SV streams being published by MU, the Line 1 IED now starts processing the simulated GOOSE and SV streams being published by the test set and discards the GOOSE and SV streams being published by MU2. The Line 1 IED continues to process the normal GOOSE and SV streams being published by MU1, MU3, MU4, and MU5. Consequently, line-protection functions in the Line 1 IED remain enabled and continue protecting Line 1.

The user can now switch off MU2 or put it in **OFF** mode and continue maintenance on CB-2. Fig. 11 illustrates MU2 in **OFF** mode.

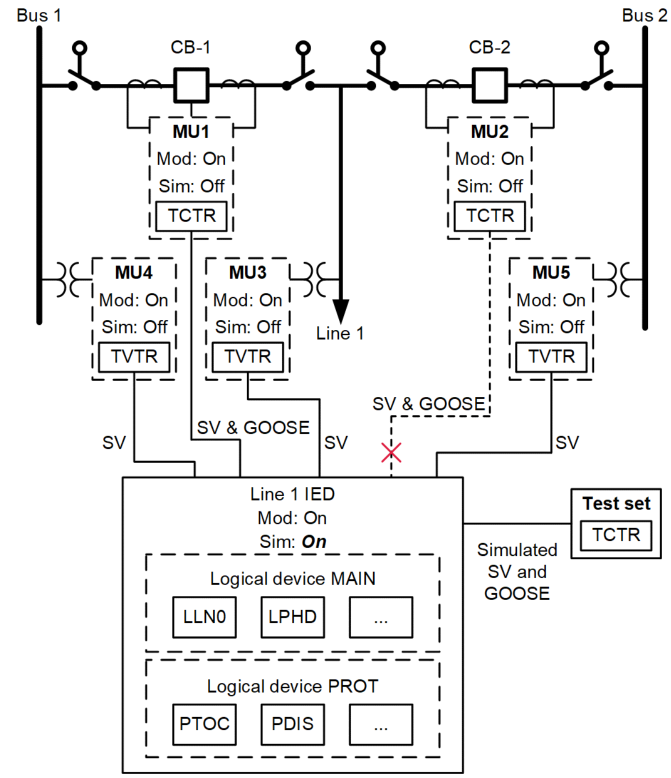

Fig. 10. Line 1 IED in simulation mode.

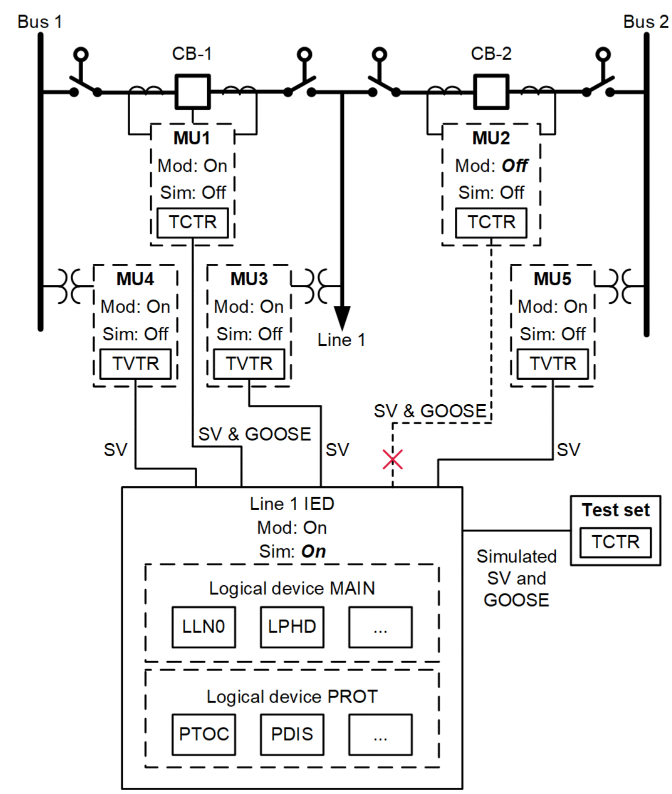

Fig. 11. MU2 in Off Mode

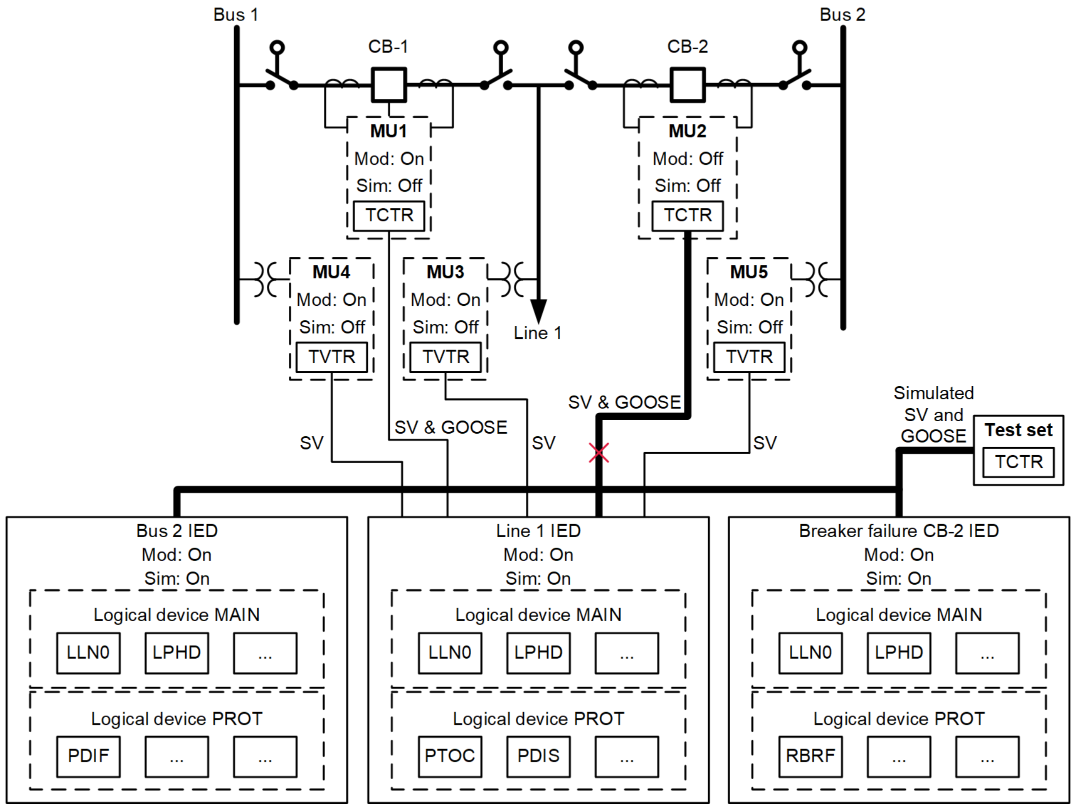

Fig. 12. IEDs subscribing to MU2 GOOSE and SV data.

However, GOOSE and SV messages being published by MU2 are also subscribed by the breaker failure CB-2 IED and the Bus 2 IED, as shown in Fig. 12. Consequently, to keep protection functions in these IEDs enabled, they will need to be configured to allow simulated messages, as well.

Additionally, there may be a redundant system in place. To ensure that the redundant system does not misoperate and remains available for backup in case the primary system fails, IEDs on the redundant system will also need to be put in simulation mode. This may require another test set to simulate GOOSE and SV signals being published by the backup MU.

2) Using InRef

IEC 61850 describes another testing mechanism in which LNs in the IED are allowed to switch between actual input signals and test input signals. Fig. 13 illustrates how the data can be switched from actual input signals to test input signals [17].

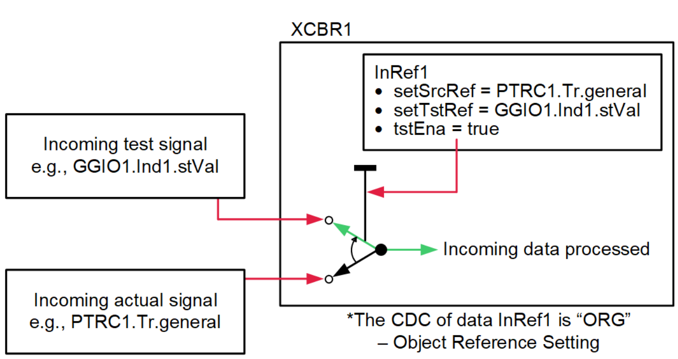

Fig. 13. InRef example for testing.

Each LN in the IED can define input signals to itself by including one or more InRef*n* data objects in the LN. The InRef*n* data object belongs to the object reference setting group's common data class as defined in IEC 61850-7-3 [18]. Each InRef*n* data object contains a *setSrcRef* data attribute that, in turn, contains the object reference of the actual input signal and a *setTstRef* data attribute that contains the object reference of the test input signal. Each InRef*n* data object also contains a *tstEna* data attribute that can be used to enable and disable the LN from processing data from the test input signal. When *tstEna* is set to **TRUE**, the LN uses the test input signal instead of the actual reference signal.

Fig. 14 illustrates protection functions and breaker failure functions in the Line 1 IED and the breaker failure CB-2 IED acquiring SV currents from IEC 61850 TCTR LNs in MU2. Fig. 14 illustrates only two IEDs consuming SV data from MU2 for representation purposes. In reality, there may be several more IEDs consuming SV data from MU2.

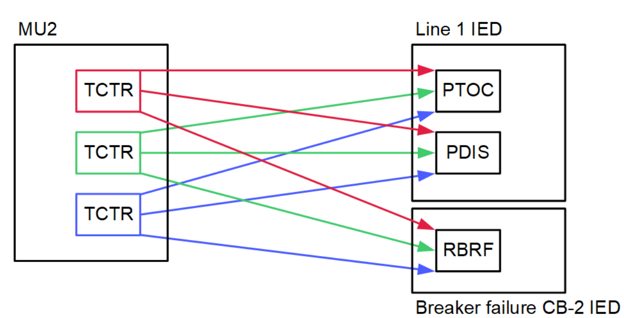

Fig. 14. SV messages between MU2 and the Line 1 IED and breaker failure CB-2 IED.

For simplification purposes, let us look at how the PTOC logical node in the Line 1 IED can be kept enabled even when MU2 is switched off or put in **OFF** mode. To keep the PTOC function in the Line 1 IED enabled when MU2 is switched off during CB2 maintenance, the Line 1 IED will need to subscribe to currents with a magnitude of 0 from a test device instead of the actual signals being received from MU2.

Fig. 15 shows MU2 containing three TCTR LNs corresponding to the three phase currents. There are three InRef data objects defined in the PTOC LN in the Line 1 IED. The *setSrcRef* data attribute in InRef1–InRef3 contains the object reference of the three phase currents received from MU2.

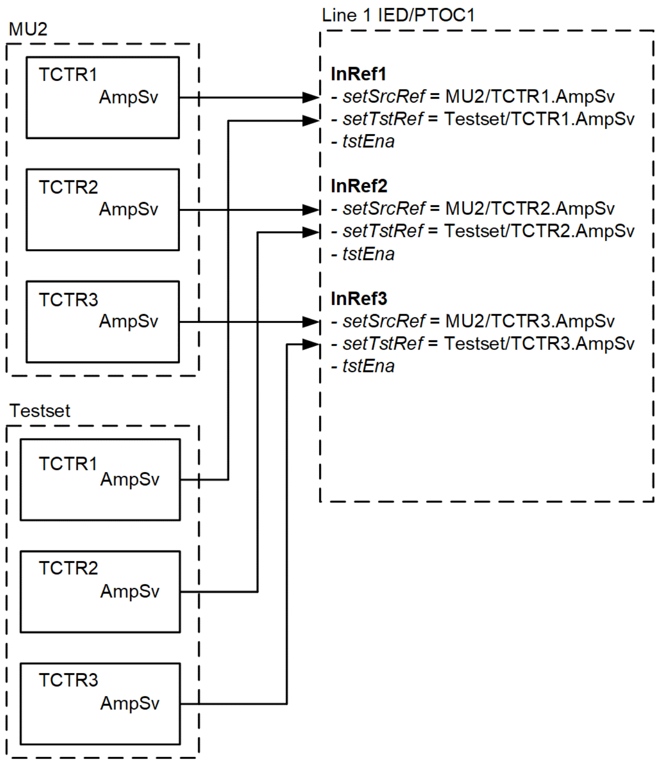

Fig. 15. PTOC LN using InRef.

Line 1 IED also contains three *setTstRef* data attributes that can be configured to contain the object reference of the test input signal that can be used during test scenarios. The *setTstRef* data attribute in InRef1–InRef3 contains the object reference of three phase currents being published by TCTR LNs in the test set. The test set is configured to publish SV currents with a magnitude value of 0. If CB-2 is undergoing maintenance, then CB-2 and its associated disconnects will be opened so that maintenance activity can be carried out on the breaker. Next, the *tstEna* data attribute in the three InRef data objects in the PTOC LN will be set to **TRUE**. The PTOC LN in the Line 1 IED now starts processing the data being published by the test set instead of the data being published by MU2. MU2 is then switched off or put in **OFF** mode. As a result, the PTOC line-protection function remains enabled and continues to protect Line 1.

The same steps will need to be repeated for all LNs in the Line 1 IED that use SV data being published by MU2. This process will also need to be repeated for all LNs in other IEDs that are subscribing to the SV data being published by MU2. Additionally, if there is a redundant system in place, then all LNs in all IEDs that use data from the backup MU will need to use test input signals from the test set. This may need another test set to simulate GOOSE and SV signals being published by the backup MU.

IV. Novel Maintenance Mode

As discussed in Section III, the solutions to keep protection functions available during maintenance can involve enabling source selection logic in multiple IEDs or using an external test set with simulation mode or InRef. These solutions are workarounds and do not address the problem at its source, i.e., there is no indication that an MU is in maintenance mode. Standard mode and behavior (on, blocked, test, and off) for LNs are defined in IEC 61850. This makes protection function testing consistent between IEC 61850-compliant IEDs from multiple manufacturers. Similarly, having a standard approach to indicate a maintenance mode in IEC 61850 will help consistent implementation between multiple IED manufacturers. This will eventually help users during maintenance in an IEC 61850-based DSS.

The purpose of the proposed maintenance mode (MM) is to keep protection functions enabled when an MU is unavailable during maintenance tests in a DSS. The proposed MM has three components.

A. Maintenance Mode in MUs

MUs are typically installed in the primary equipment cabinet in the switchyard. When any primary equipment undergoes maintenance, the MU associated with it is placed in MM. Once an MU is placed in MM, all IEDs subscribing to that MU will automatically receive the MU's MM state information. Next, the subscribing IEDs will force all signals (both analog and digital) received from that MU to go to zero. The signals are forced to zero even when the MU is switched off. This allows all subscribing IEDs to keep protection functions enabled when the primary equipment or the MU itself undergoes maintenance. The MM flag can be used in the protective IEDs to defeat breaker-specific logic like breaker failure and reclosing.

Fig. 16 shows how the proposed MM will be used in an IEC 61850-based DSS. Let us take a use case of CB-2 replacement. For this case, the user will open the breakers and disconnects and place MU2 in MM. The line IED will receive the MM flag and will force the GOOSE and SV messages received from MU2 to zero. All line-protection functions remain enabled and the IED keeps protecting Line 1. Similarly, a bus IED associated with Bus 2 will use the MM flag, force CB-2 currents to zero, and keep bus-differential zone protection running. The user can now switch off power to the breaker cabinet (MU2 is turned off) and start CB-2 replacement work. The MM is maintained in the subscribing IEDs even when the MU is switched off and when the subscribing IED goes through a power cycle, such as a diagnostic restart. Once the maintenance work is completed, the user can turn on MU2 and place it back in normal mode, i.e., switch off MM.

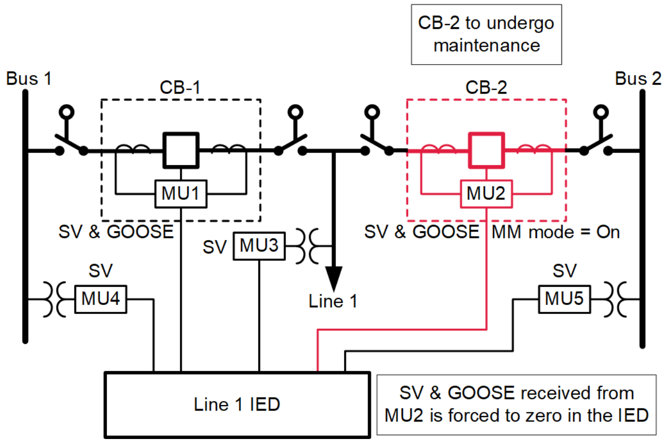

Fig. 16. MU2 placed in MM.

B. Forced MM in Subscribing IEDs

For the system shown in Fig. 16, if MU2 fails in the field, then it cannot be placed in MM. For this use case, the user opens CB-2 and the disconnects. Next, the user forces the subscribed GOOSE and SV messages from MU2 in MM in the line IED. The forced MM for each GOOSE and SV stream can be implemented using IED-specific logic. This process is repeated in each IED subscribing to MU2. The forced MM in subscribing IEDs allows protection functions to remain enabled while MU2 is being replaced. Once MU2 is replaced and operational, the user can clear the forced MM in the subscribing IED. The user can then close the disconnects and CB-2 to feed the line from both breakers.

C. Overriding MM in Subscribing IEDs

Fig. 17 shows MU2 placed in MM for the system described earlier and a second IED used for testing during the maintenance period. With CB-2 and the disconnects in an open state and MU2 in MM, the line IED protects Line 1 during maintenance. With MU2 in MM, both IEDs read the analog and binary signals published by MU2 as zero. Overriding MM in the test IED can be used to read the actual analog and binary signals published by MU2 during maintenance. This function will aid in the testing of a CT, CB, or MU during maintenance without affecting the Line 1 IED.

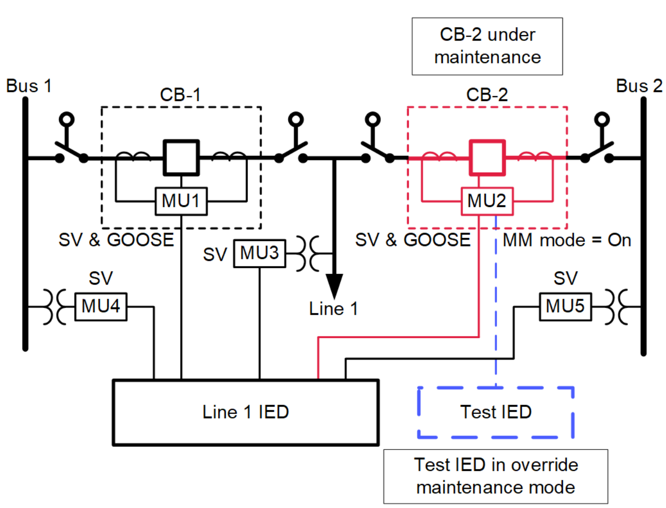

Fig. 17. Overriding MM in the test IED.

D. Proposed Implementation

MUs can publish both GOOSE messages and SV streams. When an MU is placed in MM, the outgoing GOOSE and SV messages should include the MM flag. IEC 61850-8-1 and IEC 61850-9-2 have defined two reserved fields in the GOOSE and SV frames to indicate different circumstances, as shown in Fig. 6 [14] [15]. Twelve of the sixteen bits are used for security, and the most significant bit of the Reserved 1 field is used to indicate a simulated message, as previously described. The subscribing devices use this Simulation Bit to determine if the incoming message should be processed based on its current simulation state (*LPHD.Sim.stVal*). The remaining three bits in the reserved field are yet to be defined by IEC 61850. If one of these bits is used to indicate that a publisher is in MM, then all of its subscribers will be aware that the MU is going to be unavailable, and logic within the subscribing devices can force the incoming values to zero and keep protection enabled. Then the MU could be taken out of service. This would simplify maintenance procedures and reduce the need for multiple test sets that may be required to provide simulated data to subscribers. Fig. 18 shows the proposal to use Bit 7 in Octet 0 of the Reserved 1 field to indicate whether the publisher is in MM or not.

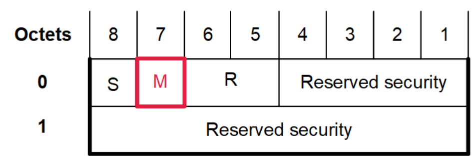

Fig. 18. Bit 7 of Reserved 1 field used to indicate MM.

A sample logic used to identify an MU in MM to the subscriber is shown in Fig. 19. When an incoming GOOSE or SV message has the MM flag set, the latch output is set. The subscriber identifies which MU is in maintenance and internally substitutes the MU data to zeros. The binary output of the logic can be used to disable certain protection functions (e.g., breaker failure or reclosing logic) and alarming. The latch maintains the MU MM even when the MU is switched off. The use case for forced MM and override MM were discussed earlier.

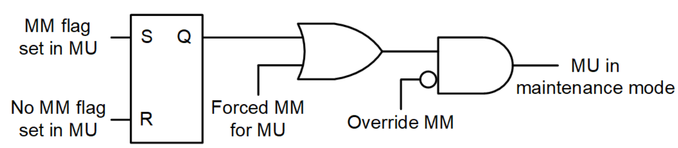

Fig. 19. MM logic in the subscriber.

V. Conclusion

Redundant power system assets and protection systems improve reliability and aid in maintenance. Maintenance of these assets is necessary to detect in-service component failures, unwanted wiring, and settings changes. As a result, NERC and other regulatory authorities mandate specific maintenance tests of these assets at regular intervals. In a conventional substation with redundant primary equipment, maintenance has no impact on protection functions. However, that is not the case for an IEC 61850-based DSS. When an MU is switched off during maintenance, some protection functions are not available. The unavailability of protection functions during maintenance tests lowers the overall reliability for an IEC 61850-based DSS. The proposed MM is developed to address this issue. If the proposal is implemented in the IEC 61850 standard, then it will provide a standard approach to handle MUs and IEDs in MM. The proposed MM improves protection availability in an IEC-61850-based DSS, which in turn improves system reliability.

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VII. Biographies

Arun Shrestha received his BSEE from the Institute of Engineering, Tribhuvan University, Nepal, in 2005, and his MS and PhD in electrical engineering from the University of North Carolina at Charlotte in 2009 and 2016, respectively. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2011 as an associate power engineer in research and development. He is presently working as a development lead engineer. His research areas of interest include power system protection and control design, real-time power system modeling and simulation, wide-area protection and control, power system stability, and digital substations. He is a senior member of IEEE and is a registered Professional Engineer. He is a member of IEEE PSRC and a U.S. representative to IEC 61850 TC 57 WG 10.

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