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Hardware-In-The-Loop (HIL) Simulation-based Interoperability Testing Method of Smart Sensors in Smart Grids

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***Abstract*—Smart sensors in smart grids (SG) can provide real-time data and status of electrical power grids (EPG) for monitoring, protection, and control (MPC) applications to improve the reliability and resilience of EPG. However, there are major challenges for smart sensor data interoperability in SG, such as optional functions and implementations based on different interpretations of the standard. Interoperability modeling, testing and certification, and measurement and assessment methodologies help achieve and assure interoperability. This paper proposes a hardware-in-the-loop (HIL) simulation-based interoperability testing method for smart sensors in the closed-loop MPC use cases of EPG. In this testing method, a smart sensor, as hardware or device under test (DUT), is plugged into the closed-loop MPC application simulation of EPG to test its interoperability with the rest of the simulation system. A HIL simulation-based interoperability test case of IEC 61850-9-2 merging unit (MU)-based smart sensor is used to illustrate how the testing method works. This testing method not only tests how to exchange information between an MU-based smart sensor and the simulated protective relay (PR) but also tests how the PR can use the information from the smart sensor for MPC applications. Smart sensor users and manufacturers can use this testing method to develop testing systems to help achieve interoperability and, ultimately, plug-and-play of smart sensors.**

Index Terms*—Device under Test; Hardware-in-the-Loop; IEC 61850-9-2; Interoperability Testing; Merging Unit; Monitoring, Protection, and Control; Real-Time Simulation; Smart Grid; Smart Sensor.

I. Introduction

Wide-area monitoring, protection, and control (MPC) systems use phasor measurement units (PMUs)-based smart sensors to attain real-time situational awareness of electric power grids (EPG) operations aiming to improve reliability and resilience [1-4]. Hundreds of thousands of smart sensors supplied by different vendors and deployed in EPGs could employ different interfaces and communication protocols that could present a major interoperability challenge for smart grids (SGs). International Electrotechnical Commission (IEC) 61850 defines communication networks and systems for power utilities [5] to support MPC applications in EPGs. Standardizing sensor interfaces can improve interoperability, but there may still be challenges if the sensors implement different optional functions of the standard and have implementations based on different interpretations of the standard. Interoperability modeling [6], testing and certification [2-4, 7, 8], and measurement and assessment help achieve and assure smart sensor data interoperability. Interoperability profiles can help accelerate the development of testing and certification programs to improve interoperability by defining a subset of a given standard or set of standards on which stakeholders have agreed to focus their efforts [8].

The IEEE defined interoperability as the ability of two or more systems or components to exchange information and to use the information that has been exchanged [9]. In the NIST Smart Grid Framework and Roadmap for Interoperability Standards, "Interoperability is the capability of two or more networks, systems, devices, applications, or components to exchange and readily use information securely, effectively, and with little or no inconvenience to the user" [8]. Interoperability testing can be used to verify if two or more devices, or systems implementing the same standard are interoperable [2-4], [10]. Interoperability testing not only verifies information exchange but also verifies information use. Some existing interoperability testing methods of smart sensors focus on testing the exchange of information between a smart sensor and its client [4, 7], not validating if the client can use the information exchanged. The physical equipment, devices, or controllers can be inserted into real-time simulations to test, validate, and verify their performance and interoperability [11]. One of the most effective ways to test the interoperability of devices under test (DUTs) or commercial products is to place them in a simulated environment to check and verify interoperability [12]. The testing idea mentioned above is defined by IEEE P2004 as a hardware-in-the-loop (HIL) simulation-based testing method, which provides best practices for the use of the HIL simulation-based testing method for electric power apparatus and controls [13].

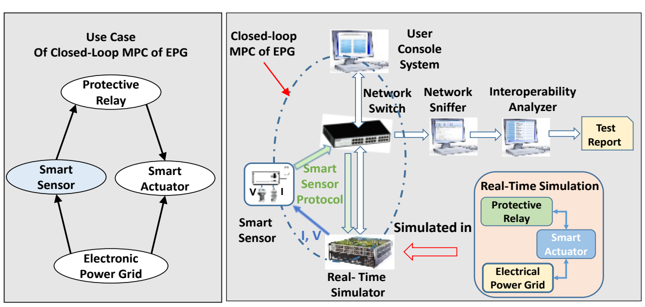
This paper focuses on HIL simulation-based smart sensor interoperability testing method for closed-loop MPC applications for EPGs. It is noted that this testing was performed using low voltages and currents and not the high voltages and currents normally found in power grids. Related work is described in Section II, and the HIL simulation-based interoperability testing method is provided in Section III. An interoperability test case for IEC 61850-9-2 merging unit (MU)-based smart sensors is described in Section IV, with a summary given in Section V.

II. Related Works

In recent years, HIL simulation-based tests have come into use in various applications or use cases in smart grids. For example, an implementation for IEC 61850 messaging on a real-time digital simulation was provided for differential protection tests, which provides a basis for HIL simulation-based testing for MPC applications [14]. A protective relay is considered as hardware in the test loop configuration to validate the performance of a proposed relay model by comparing HIL testing to standalone model testing [15].

In Microgrid, Wang et al, proposed a universal platform of HIL testing of microgrids for testing hardware controllers at the signal level and testing power inverter/converter at the power level [16]. An energy management controller as hardware in HIL for an electric vehicle integrated microgrid was introduced to validate the real-time operation of the controller and the cost optimization [17]. Based on use cases, a smart grid interoperability test methodology was described [18]. Interoperability between systems in a smart grid must be well specified in use cases that provide a basis for the specification of functional requirements, test cases, and interoperability profiles. The HIL simulation-based testing and validation of PMUs was applied for different use cases, including wide-area MPC, PMU compliance, and security based on IEEE C37.118.2 [19]. An IEEE standard C37.118-based co-simulation platform was presented for wide-area MPC to test network performance [20].

These HIL simulation-based testing methods mentioned above focused on testing protection schemes, conformance, and performance but they were not focused on testing interoperability. However, this paper focuses on the HIL simulation-based interoperability testing method of smart sensors for the real-time MPC use case.



(a) Components of closed-loop MPC of EPG. (b) Architecture of a HIL simulation-based interoperability testing method of smart sensors.

Fig. 1. A HIL simulation-based interoperability testing method of smart sensors in MPC use case.

III. HIL Simulation-based Interoperability Testing Method of Smart Sensors for MPC Applications

A. *Smart Sensor as a Hardware in MPC Application of EPG*

A closed-loop MPC use case of EPG shown in Fig. 1 (a) includes several components, such as a smart sensor, a protective relay (PR), a smart actuator or controller, and EPG. The MPC use case could be implemented as a real-time simulation, including all these components. However, the smart sensor component in the simulation could be replaced by a physical smart sensor as hardware. Therefore, the physical smart sensor, as hardware, can be plugged into the simulation of a closed-loop MPC use case and tested if it is interoperable with other components in the simulation of MPC applications.

B. *HIL Simulation-based Interoperability Testing Method of Smart Sensors in MPC Use Case*

Fig. 1 (b) shows the architecture of a HIL simulation-based interoperability testing method of smart sensors in the closed-loop MPC use case. This architecture consists of a smart sensor, a network switch, a user console system, a network sniffer, a smart sensor interoperability analyzer (software tool), and a real-time simulator that simulates a PR, a smart actuator or controller, and an EPG. In this case, the smart sensor is a hardware component in the MPC use case and is considered a device under test. The HIL simulation-based interoperability testing method defined here is to test and verify the interoperability between the smart sensor as a hardware component and the simulated protective relay in the closed-loop MPC application simulation based on the smart sensor standard communication protocol. When the smart sensor is plugged into the closed-loop MPC use case, it can measure analog voltage and current values from the power grid and provide the digital current and voltage values to the PR using a standardized smart sensor communication protocol through the network switch. By analyzing these current and voltage values, the PR can detect electrical faults and consequently send a control message to the smart actuator or controller that can open the circuit breaker accordingly to protect the power grid. Meanwhile, the network sniffer captures all network packets among the smart sensor, PR, and smart actuator communications. The smart sensor interoperability analyzer automatically analyzes and assesses the interoperability of smart sensors based on the network packet data collected in the test.

The interoperability testing method presented here could be applied to any smart sensors in the closed-loop MPC use cases based on different smart sensor communication protocols, such as IEEE C37.118 PMU-based, IEC 61850-9-2 MU-based, IEEE 1815 outstation-based, and IEEE 1451-based smart sensors. All smart sensors, as hardware, could be plugged into the simulation of the MPC use case to test interoperability based on the specific standardized communication protocol used for testing. This testing method provides a platform to test the interoperability of smart sensors in the real-world closed-loop MPC use cases of EPG. See detailed descriptions of the IEC 61850-9-2 MU-based smart sensor test case below.

IV. Test Case: HIL Simulation-based Interoperability Test System of IEC 61850-9-2 MU-based Smart Sensors

A. *IEC 61850-9-2 MU-based Smart Sensors*

The IEC 61850-9-2 standard defines the Specific Communication Services Mapping (SCSM) for the transmission of sampled values (SVs) [21]. An IEC 61850-9-2 MU-based smart sensor consists of current transformers (CTs) and voltage transformers (VTs) connected to the MU to provide current and voltage input signals. The MU-based smart sensor samples one or multiple phases of the input AC signals and converts them to digital values, merging or aligning multiple phases together based on the synchronized timestamps. It then transmits the SVs to protection relays through networks based on the IEC 61850-9-2 standard protocol. MU-based smart sensors are used in substation automation systems for publishing these voltage and current data to multiple protective relays for protection and control applications.

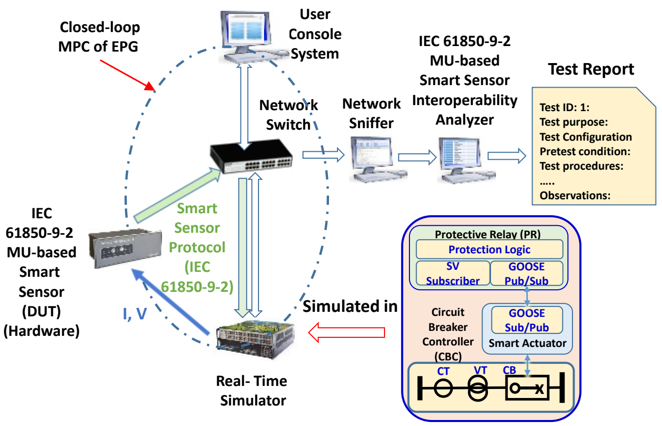


Fig. 2. A test case of an interoperability testing system of IEC 61850-9-2 MU-based smart sensors.

B. *HIL Simulation-based Interoperability Testing System of IEC 61850-9-2 MU-based Smart Sensors in the MPC*

Interoperability testing is the activity of proving that end-to-end functionality between (at least) two communicating systems is as required by the base standard(s) on which those systems are based [22]. The interoperability test for MU-based smart sensors is to verify that the communication or interaction functionality between the MU-based smart sensor and the PR is compatible with the IEC 61850-9-2 communication protocol and check if the MU-based smart sensor is interoperable with the PR. Fig. 2 shows a HIL simulation-based interoperability testing system of IEC 61850-9-2 MU-based smart sensors in an MPC use case for EPG. This system consists of an MU-based smart sensor, a network switch, a network sniffer, an IEC 61850-9-2 MU-based smart sensor interoperability analyzer, a user console system, and a real-time simulator for the simulation of an IEC 61850-based MPC. The user console system is the user interface of HIL interoperability testing. It displays data and control status, including the MU SV data, GOOSE data, protection relay status, control commands, and circuit breaker (CB) status. As shown in Fig. 2, a real-time simulation consists of an EPG with various faults, a PR with an overcurrent protective scheme, and a smart actuator or CB controller (CBC) to open or close the CB in the EPG. The SV subscriber in the PR continuously subscribes SV streams from the MU that gets analog voltage and current signals from the EPG via VT and CT, and the PR detects electrical faults based on data of SV streams, and then the GOOSE publisher in the PR will publish the GOOSE control message to the CBC. The GOOSE subscriber in the CBC subscribes to the GOOSE message and then opens or closes the CB of EPG. This simulation was implemented using an OPAL-RT OP5600 simulator **. Fig. 3 shows the three phases of analog voltages and currents from an EPG outputted to the MU-based smart sensor that, in turn, publishes SVs to the PR. As shown in Fig. 3, the I/O Group 1 Subsection A (16 analog signals from the simulator) connects the simulator with the MU. Channels 0-3 correspond to the three phases of analog voltage outputs and neutral, while channels 8-11 correspond to the three phases of current outputs and neutral, which are all applied to the MU. Fig. 3 also shows the GOOSE control command from the PR to the EPG on the left side of the power system module.

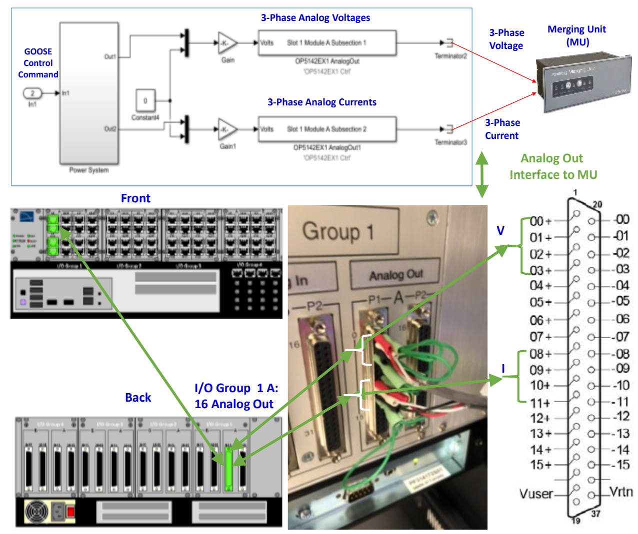


Fig. 3. Voltage and current analog I/O interface to a MU.

C. *Overcurrent Protection Test Case of EPGs*

The simulated EPG consists of a power source and a load, a circuit breaker, and an electrical fault. The power source voltage is set up as 11 kV based on the medium voltage range of 2 kV - 35 kV of a distribution grid, according to the IEEE 1623-2020 (1-35 kV) [23]. However, these voltage and current values from the simulated EPG need to be scaled down to lower levels before applying to the EPG analog voltage output board, which has an output range of up to 15 V. Since the EPG interface hardware can only output voltages, not currents directly, the simulated current outputs need to be converted from voltage to current values before applying them to the MU for samplings and measurements. Both the voltage and current outputs from the EPG are thus scaled down by a factor of 1/1,000 and 1/10,000, respectively, to suitable levels up to 15 V. They are measured by the MU for analysis by the protection logic. Therefore, the normal voltage values for the simulated currents at the output of the interface board after the scaling factor is applied is about 1.1 V. A 20-ohm resistor is used to convert the output voltages from the EGP into corresponding current values. After applying the scaling factor, the full-scale current output is 0.055 A. The preset overcurrent threshold is set at 0.12 A. The fault signal duration is 2 s, and the total test time is 5 s.

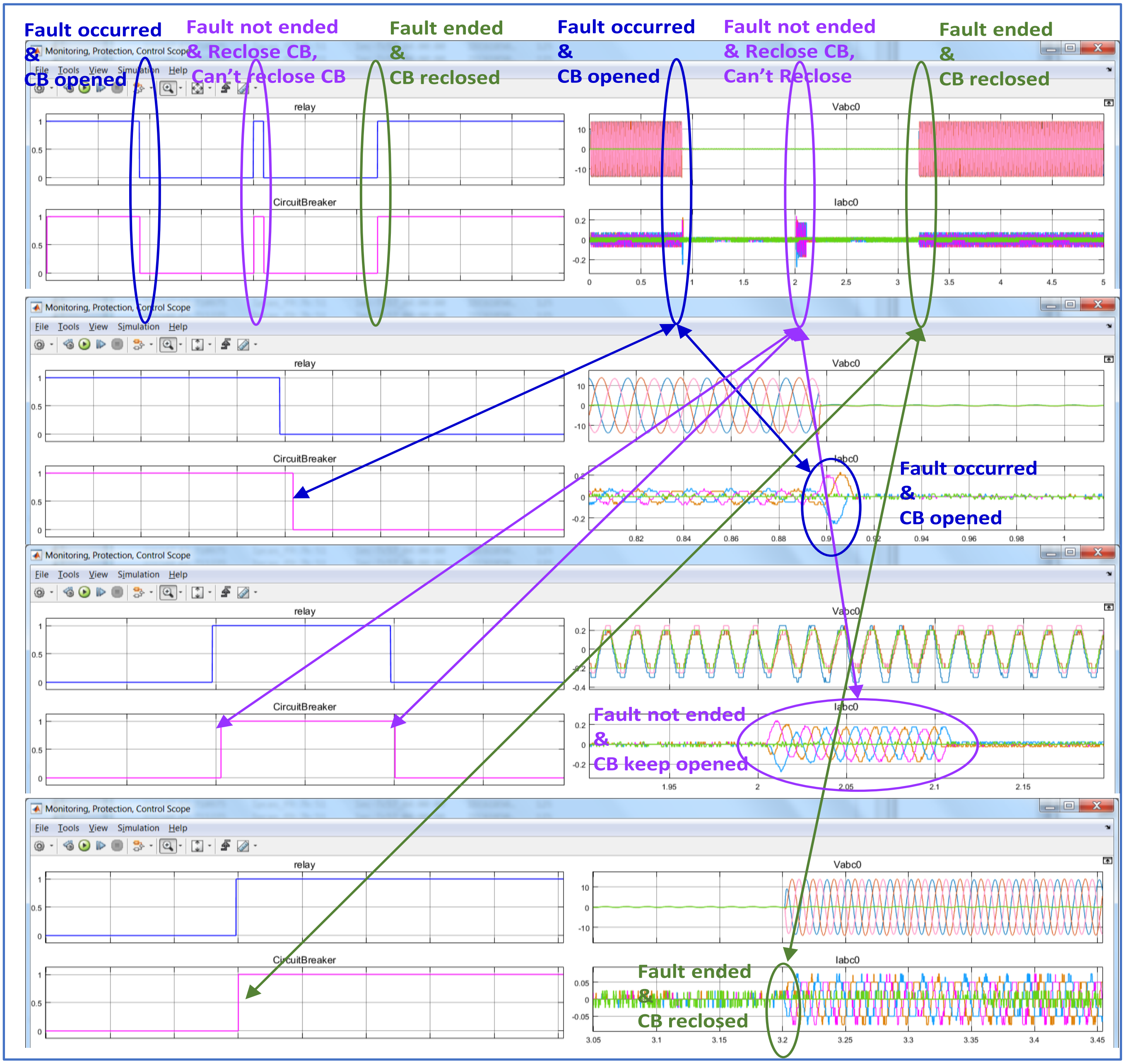


Fig. 4. Screenshot of overcurrent protection results.

The overcurrent protection logic of the PR was designed and developed based on some control parameters, including over-current threshold, breaker operating delay time, breaker reclose delay time, and reclose attempts. The PR continuously subscribes to SV streams from the MU, compares the three-phase current values from the SV data against a pre-set threshold and sends a command to the CBC to open the circuit breaker if the threshold is exceeded. If any phase current value exceeds the threshold, the status of the PR becomes "0" or "false", and the PR sends a GOOSE message to the CBC. After the CBC receives the GOOSE message ("0" or "false"), it opens the CB. After the breaker reclose time delay, it sends a command to the CBC to reclose the CB and checks if each phase's current value still exceeds the preset current threshold. If so, it commands the CBC to re-open the CB. The CB is controlled based on the protection logic developed. Initially, when the CB is closed, the PR status is "1". The breaker reclosing delay time of the CB depends on many factors, such as voltage levels, CB type and characteristics, electrical fault type, time duration, protection relay performance, and IEC 61850 SV and GOOSE network communication latency. According to the IEEE C37.04-1999, the minimum reclosing time of a circuit breaker is set to 0.3 s [24], and the maximum number of reclosing attempts is set to 4 based on standard industry practices [25].

For this test case shown in Fig. 4, the over-current threshold is set to 0.12 A, the breaker reclosing time to 0.1 s, the breaker reclose delay time to 1.1 s, and reclose attempts to 2 times, respectively. Fig. 4 shows a screenshot of the testing results for over-current protection, including the fault signal of 2 s duration, protective relay status, circuit breaker status, and current and voltage waveforms. When the three-phase electrical faults happen, the current spikes develop, and the voltages fall to zero. When the current values are greater than the preset threshold, I_{th}, of 0.12 A, the PR trips, and it sends a GOOSE message to the CBC. Then the CBC opens the CB to isolate the fault from the EPG to protect the power grid. When the reclosing time of 1.1 s has elapsed, the PR sends a GOOSE control message to the CBC to reclose the CB. However, the CB couldn't be reclosed because the current value still is greater than the threshold. After a second reclosing time of 1.1 s has elapsed, or the fault has ended, and the current values are less than or equal to the threshold, the CB will be reclosed. After all that, the current and voltage go back to their normal values. Fig 4 shows the entire fault event processes, in which the CB's status changes based on the GOOSE messages, including closed (1, true), opened (0, false), reclosed (1, true), reopened (0, false), and reclosed (1, true).

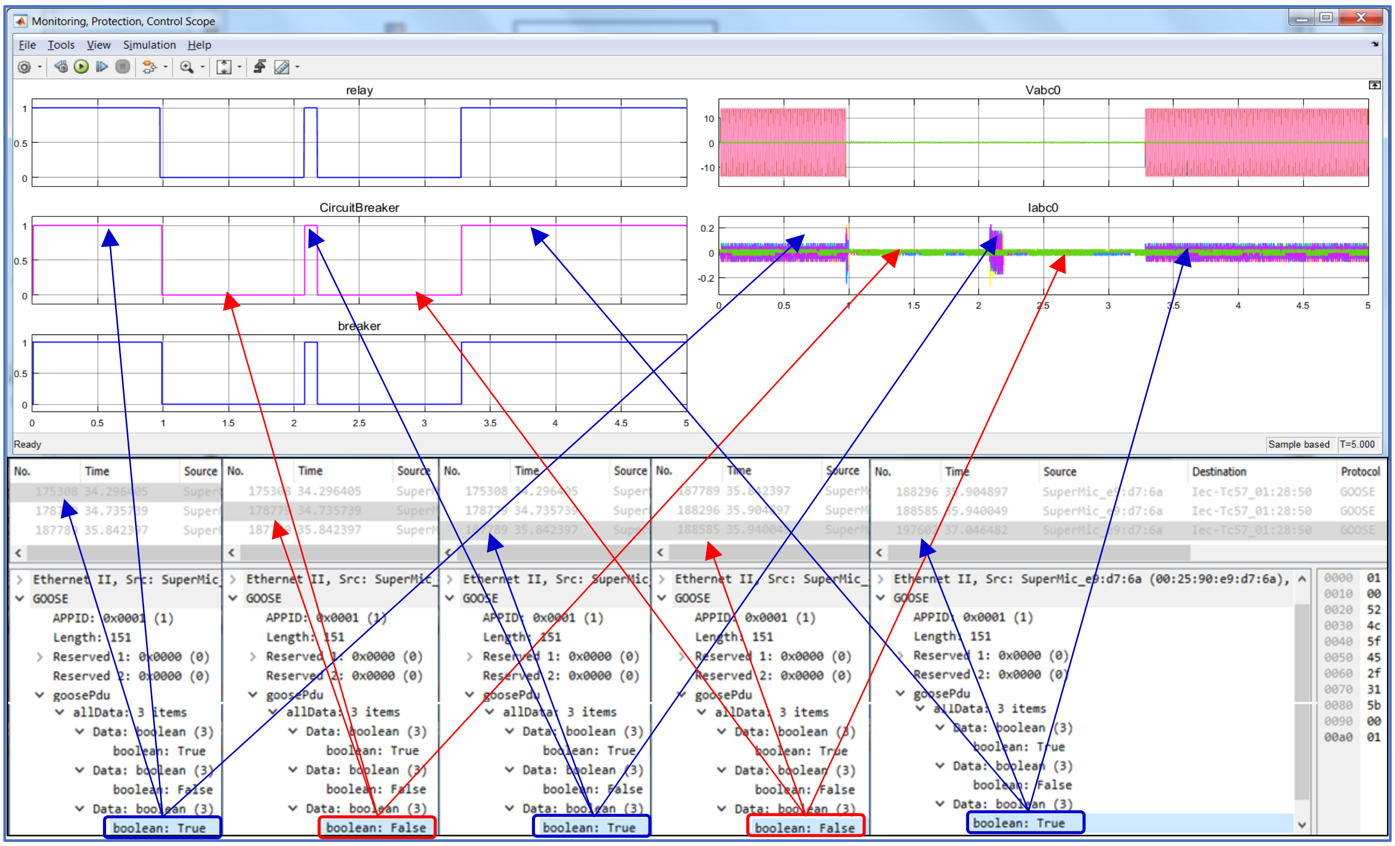


Fig. 5. Screenshot of overcurrent protection GOOSE control commands to open and close the circuit breaker.

Fig. 5 shows over-current protection control sequences based on the GOOSE control command messages to open and close the CB. There are two GOOSE messages (false or 0) to open the CB and two GOOSE messages (true or 1) to reclose the CB. This testing result has demonstrated that smart sensor voltage and current data or information have been exchanged from the MU-based smart sensor to the PR, and the information can also be used by the PR to open or close the CB for protection and control of EPG. This means that the MU-based smart sensor is interoperable with the PR based on the IEC 61850-9-2 standard and works with the PR by monitoring the three-phase current and voltage values in the closed-loop MPC applications.

D. Interoperability Analyzer for IEC 61850-9-2 MUs

During the interoperability test, the network sniffer captures all network packets among the MU-based smart sensor, PR, and CBC communications and saves the packet data into a packet capture (PCAP) file that can be further converted into a packet details markup language (PDML) file. The MU-based smart sensor interoperability analyzer software tool we developed performs SV message analysis of the captured IEC 61850-9-2 data packets to determine the degree of MU conformance to standards and interoperability [26]. The interoperability analyzer can read and parse IEC 61850-9-2 packet data fields from a PDML data file and then automatically analyze the interoperability of IEC 61850-9-2 SV messages published by MUs based on the protocol knowledge. The interoperability analysis includes data analysis of the medium access control layer, link layer, and application layer of IEC 61850-9-2 SV messages. This tool can automatically analyze the type/length/value (T/L/V) of each field of the SV packet data. If the T/L/V for the field conforms to IEC 61850-9-2:2011, the analysis result of this field is true; otherwise, the result is false. For example, the smpCount is a counter of samples, for 80 samples/cycle SV stream, the range is 0~3999 for 50 Hz, and 0~4799 for 60 Hz electric power frequency. If the length of smpCount is two bytes and the value is in the range mentioned above, the analysis result of smpCount is true; otherwise, the result is false. Interoperability analysis details of the IEC 61850-9-2 SV protocol can be found in reference [27].

V. Summary and Conclusion

This paper describes a HIL simulation-based interoperability testing method of smart sensors in the closed-loop MPC of the EPG. An interoperability test case of IEC 61850-9-2 MU-based smart sensors is provided. As shown in Fig. 4 and Fig. 5, the interoperability test results show that the MU-based smart sensor is interoperable with the simulated PR because it can exchange IEC 61850-9-2 SVs information or message with the PR. Also, the PR understands and uses the SV information based on the IEC 61850-9-2 standard and then sends a control command to the CBC to open or close the circuit breaker to protect the power grid system. Based on this HIL simulation-based interoperability testing method, any MU-based smart sensors produced by different vendors could be plugged into this closed-loop MPC test case to test their interoperability based on the IEC 61850-9-2 communication protocol. Smart sensor users and manufacturers can use this testing method to develop interoperability testing systems to help achieve interoperability and, ultimately, plug-and-play of smart sensors.

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** No approval or endorsement of any commercial product by the National Institute of Standards and Technology is intended or implied. Certain commercial software systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

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