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Hardware-in-the-loop Testing of Line Differential Protection Relay Based on IEC 61850 Process Bus

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Abstract

The term *digital substation* refers to the process of managing operations between intelligent primary devices and distributed Intelligent Electric Devices (IEDs) interfaced with a highly secure communications network. The process bus is the first part of the interface between the primary instruments (such as the current and voltage transformers and protection devices) and is an important part of digitalization. This paper describes a method for constructing an interface between measurement instruments and protection devices based on the IEC 61850 standard. Two scenarios are considered to examine the performance of the power system protection in a transmission line between two substations. Both a conventional and an IEC 61850-9-2 (sampled values) approach are implemented to feed the measured values to the protection devices. Trip signals are then also sent to the circuit breakers using IEC 61850-8-1 (GOOSE message). Comparing this method with conventional technology, the outcomes for the digital substation are more accurate and reliable thanks to the rapid reaction of protection devices and the speed at which the trip signal is received. The new process bus method has been tested by implementing a hardware-in-the-loop platform, consisting of a real-time simulator (OPAL-RT eMEGAsim), StandAlone Merging Units (SAMUs), and line differential protection.

1 Introduction

In a digital grid, all analog interfaces are digitalized and data is shared through a communication system in the substation. Digitalization allows measuring and collecting data using smart transformers and switchgear, which continuously transmit data to the communication bus. A process bus capable of interfacing with data from the equipment (e.g protection relays, control, and monitoring devices) is thus the main requirement for a digital substation. As flexibility and reliability are the main goals of implementing a digital substation, any analog values received in the process bus from the primary equipment (e.g., CT and VT) should be converted to sampled values (SVs) and fed to IEDs through a communication network.

Data models and message format based on the IEC 61850 standard are used to digitalize I/Os of the integrated devices. The IEC61850 standard entitled "Communication Networks and Systems for Power Utility Automation" is used for communications networks because it allows easy configuration and maintenance of the future digital substation. One of the major feature of the IEC 61850 communication network is to implement a publish–subscribe model of data transfer. Any device supporting IEC 61850 standard can then connect to the network and interface with other devices. When a device or application is added to the network, a message is published in the system and can be received by subscribers anywhere on the network [1].

On the other hand, a power network's protection system is vital to ensuring reliability and security. Selective, reliable, rapid protection functions can act to isolate only the part of the network which is faulted as rapidly as possible, leaving the rest of the network operating stably. Moreover, transmission lines are an important part of the power system, conventionally protected by differential protection. This protection function involves subtracting the total current leaving the protection zone from the total current entering it: under normal conditions, when there is no fault inside the zone, this difference will be zero. A nonzero difference implies that a path for current flow was not included in the calculations, and thus that there is a fault [2].

Here, to transmit the measured values by CT and VT (current and voltage) and to feed them to protection relays, IEC61850-9-2 (Sampled Values) is used in the process bus. The trip signal generated by the protection relays is then sent to a circuit breaker through IEC61850-8-1 high-speed peer-to-peer Generic Object Oriented Substation Event (GOOSE) messages. To implement this method, merging units (MUs) are required for the interface between the CT/VT and protection relays, unlike in conventional hardwired protection systems [3]. The main objective of this paper is to study process bus capabilities and performance using a real-time simulator (RTS), and to compare the conventional arrangement of data transmission with that used by modern technology employing merging units and the sampled values protocol. Here, a hardware-in-the-loop real-time simulation platform has been developed on the basis of Opal-RT (eMEGAsim simulator) and ABB relays (Differential relays), and IEC 61850 protocols are used for communications and data exchange.

The paper is organized as follows: implementing of the project which consist of HIL platform, the configuration of communication system, power system modeling and detail of two different scenarios are presented in Section 2. In Section 3, a simulation study is presented to evaluate the fault and trip signal processing. Finally, the paper is concluded in Section 4.

2 Implementation of the Project

2.1 *Hardware-in-the-loop Real Time Simulation Platform*

To test and compare the performance of the new process bus based protection solution against traditional approach, a hardware-in-the-loop platform was developed. The laboratory setup consists of a real-time simulator (OPAL-RT eMEGAsim), two amplifiers, two sets of standalone merging units (SAMUs), and two line differential protection IEDs (ABB RED670). To execute the platform, the following steps must be considered hierarchically [4].

The power system (two power substations, transmission line, and other components) is modeled using Simulink and eMEGAsim/Artemis toolboxes and a model uploaded to OPAL-RT simulator. Two CTs are modeled to measure the line current; these are located at each end of the line. Since the simulator outputs the CT measurements as analog voltage signals, two amplifiers are employed to convert these signals into currents, via the appropriate scaling. As mentioned in Section 1, this research is novel in implementing a communications network based on IEC61850 in process bus—i.e., GOOSE messaging (IEC 61850-8-1) and sampled values (IEC 61850-9-2). In this platform, IEDs (RED 670) are connected to the simulator in two ways: via analog/digital signal channels and via IEC 61850-communication system. Three different faults were used to determine the functionality of these IEDs. The current is measured at both substations and sent to IEDs (ABB RED 670) through amplifiers in analog form, and also through the SAMUs which forwards them in SV format to IEDs (analog signal → SAM600 → switch → fiber optic cables→ IEDs). The trip signal from the IEDs is then send back to simulator in two forms, as digital inputs (from trip contacts of the IEDs) and GOOSE messages (IEDs → fiber optic cables → switch → Opal).

2.2 *Test System Modelling*

The modelled power system is a transmission line that connects substations 1 and 4 with a branch line containing only load (usually referred also as tapped load). A single-line diagram of the power system is shown in Fig.1. Substation 1 assumed to have a swing bus generator (G1) and Load 1 is supplied from Substations 1 as well. Substation 2 has not any generator or load and it is simply a *transmission switching substation*. Substation 3 is the load substation which supplies Load 2 and in this case study a variable load is also added to this substation. Substation 4 is modelled as PQ bus and the power flow is defined by its phase angle.

Power system parameters are tabulated in Table 1. To provide a realistic fault signals, three different test cases is consider in the research. In these cases, both IEDs receive the value of the current through measurement from CTs, which are installed at each end of the line (besides substations #1 and #4) as shown in Fig. 1. Two faults as indicated by F#1 and F#2 in Fig. 1 and one load variation at substation 3 have been considered as study cases to evaluate the response of the relays and delays in communication system. The characteristics of faults and load variation are presented in Table 2. The power system is modelled in Matlab Simulink, compiled and loaded to the OPAL-RT simulator with RT-Lab interface software. The power system runs in real time. Voltage and current measurements are provided as analogue outputs by means of digital to analogue conversion (DAC) interface card. The analogue signals have been used in this case study in two different arrangements as described in Section 2.4.

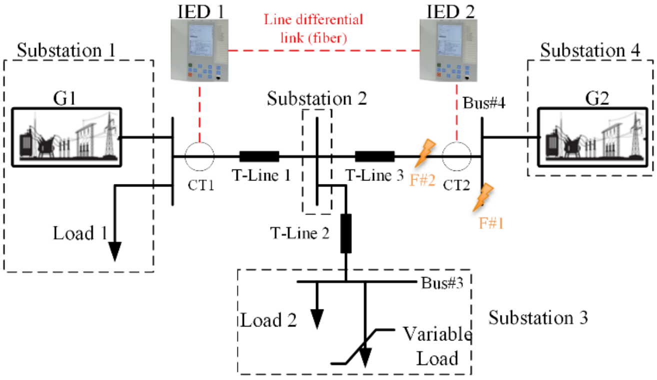


Fig. 1 Single-line diagram of the power system

Table 1 Power system parameters

Comp.	parameters	Comp.	parameters
G1	Bus type: Swing $V_{ph\text{-}ph}$ =119.46 kV Φ_{ph_a} = -27.50˚ R_{G1} = 8.20 Ω L_{G1} = 82 mH	Variable Load	Load type: Constant Z $V_{ph\text{-}ph}$ = 116.9 kV P_{L1} = 52.8 MW Q_{L1} = 39.4 Mvar
Load 1	Load type: Constant Z $V_{ph\text{-}ph}$ = 117.09 kV P_{L1} = 7.366 MW Q_{L1} = 0.175 Mvar	T-Line 1	R_1=0.19, R_0 = 0.38 Ω/km L_1=1.25, L_0= 2.75 mH/km C_1=6.08, C_0=5.84 nF/km *Length*: 6.6km
G2	Bus type: PQ $V_{ph\text{-}ph}$ = 118.73 kV Φ_{ph_a} = -35.06˚ R_{G1} = 17.62 Ω L_{G1} = 153 mH	T-Line 2	R_1=0.19, R_0=0.38 Ω/km L_1=1.25, L_0= 2.75 mH/km C_1=6.08, C_0=5.84 nF/km *Length*: 4.0 km
Load 2	Load type: Constant Z $V_{ph\text{-}ph}$ = 116.89 kV P_{L1} = 12.389 MW Q_{L1} = 0.378 Mvar	T-Line 3	R_1=0.10, R_0=0.46 Ω/km L_1=1.19, L_0= 4.91 mH/km C_1=9.60, C_0=6.03 nF/km *Length*: 12.3 km

Table 2 Characteristics of faults and load variation

Fault number	Fault type	Fault Inception angle	Fault Resistance
F#1	LLL	45˚	0.01 Ω
F#2	LLL	45˚	0.01 Ω
Variable Load (step change)	--	Minimum differential current (I_{dmin}) = 0.3Ib	I_{Load}≥1.5I_{dmin}

2.3 *Communication Configuration for HIL Execution*

In recent years, high-speed communications network have led to the development of power system protection, as well as wide-area control and monitoring to integrate these functions [5]. High performance, reliability, scalable, and greater security describe the role of the communication network in the modern grid [6]. In the HIL real-time simulation platform used here, system wide information—consisting of measured current and voltages—and the relay setting group are shared using an IEC61850 communication system. Generally, the required value is transferred to the relay in two ways, and the trip signal is also sent back in two ways; these communication methods are described in Section 2.4.

The communication-based technique for feeding the fault signal to IEDs utilizes SAMU and a product from ABB (SAM600). An SAM600 module interfaces the traditional analog current or voltage transformers, while the SAMU provides IEC 61850-9-2 functionality. The SAM600 package includes SAM600-CT, SAM600-VT, and SAM600-TS.

Four analog input measurement channels are considered for interfacing the conventional current and voltage transformers in the SAM600-CT and SAM600-VT respectively, which convert analog input values from the measurement cores (1A and 100–125 V AC settable, respectively) to a digital format transmitted over Ethernet, in line with IEC 61850-9-2. An SAM600-TS module provides communication redundancy and time synchronization [7].

To send the trip signal from the relays to the real-time simulator, a communication-based method relating to IEC 61850-8-1 (GOOSE messages) was used. To this end, a communication interface was created on the OPAL-RT side using different blocks to publish and subscribe to the signal. To publish and receive the signal, mac addresses and IDs should be defined in both IEDs (ABB RED670) and on the OPAL-RT side. The protection and control IED manager (PCM600) is used to set the IEDs, produce the .icd file, and check functionalities. Moreover, software such as Wireshark can be employed to monitor and analyze the status of the communication flow and data packets

2.4 Different Arrangements for Connecting the Protection Relays

Two different arrangement for connecting the protection relay to the simulator have been tested as described in the following:

2.4.1 Traditional Current Transformer: CTs and VTs are modelled as part of the simulation model. Simulated voltage and current measurements are provided as analog signals through DAC ports of the OPAL system. These signals are in the range of ±10V therefore before feeding these signals to the protection relays, amplifiers are used in order to amplify the signals to the range applied in protection relays. The signals simulates voltage and current measurement from real VTs and CTs respectively.

2.4.2 Stand-Alone Merging Unit (SAMU): The analogue signals are provided from simulator as explained in previous arrangement, representing simulated voltage and current measurement from physical VTs and CTs respectively. These signals are fed to SAMUs, which generates sampled values to be fed to the IEDs via the process bus (Ethernet connection). The arrangements are depicted in Fig. 2.

3 Results and Discussion

As mentioned in Section 2.1, to test the performance of the process bus approach, a hardware-in-the-loop platform was developed. The result of the test made are presented in the following.

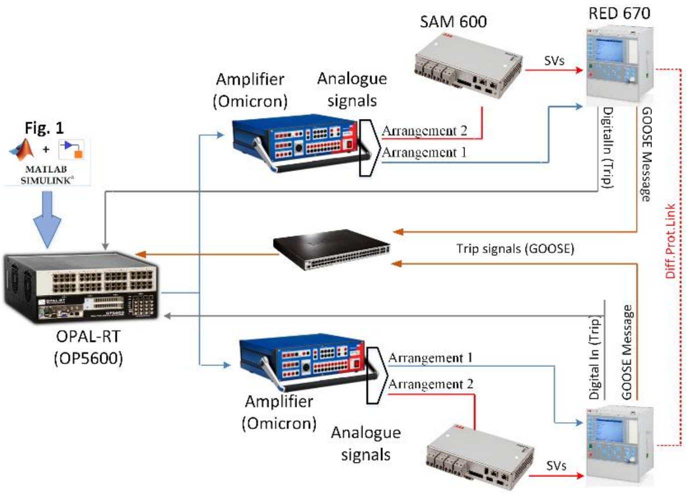


Fig. 2 Arrangements for connecting the studied cases

3.1 Fault Signal

Three events as those shown in Table 2 are simulated to occur at t_1=16s (F#1), t_2=19s (F#2) and t_3=22s (variable load, hereafter it is denoted as F#3). Each event lasts 1s and after 1s duration the event is cleared and system is working in normal condition until next the event happens. Fig. 3(a) shows the fault trigger signals as the F#1 starts at t=16s and ends at t=17s, time span [16-17s]. As it can be understood from Fig. 1, this fault is located outside protection zone of IED1 and IED2 therefore as it is shown in Fig. 3(b), F#1 is not detected by the IEDs. F#2 has time span [19-20s] and it has been located inside protection zone therefore as it is evident from Fig. 3(b) both IEDs have detected the fault. Third event, F#3 has different nature. It is not a fault but instead a step load variation. The minimum differential current in the IEDs is set to 30% of the base current. The load change is simulated so that the IEDs operate and trip signal is triggered as can be noticed from Fig. 3(b) although there is not any trigger fault signal at this point of time as can be seen in Fig. 3(a).

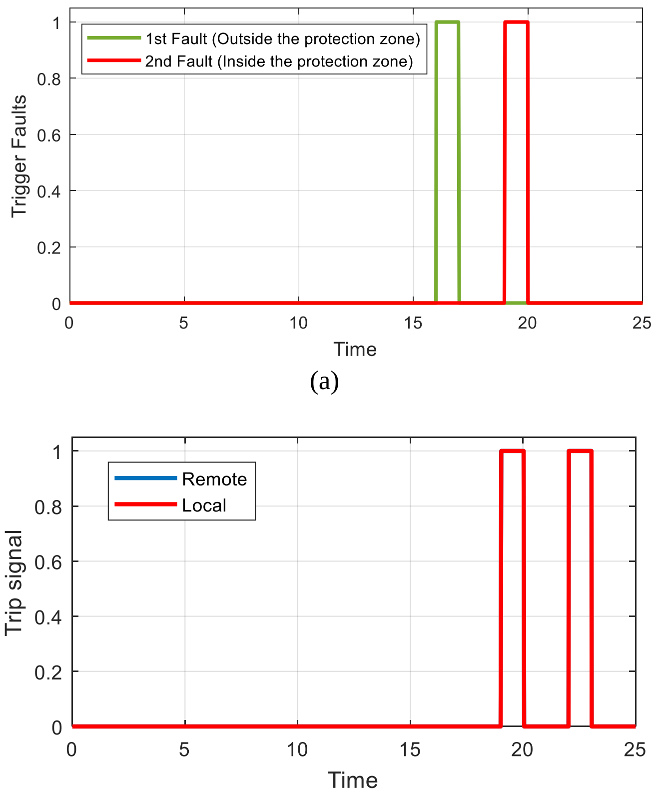
3.2 Trip Signal

The trip signals from IEDs are sent back to the real time simulator by two different means; traditional digital signal and the IEC61850-8-1 GOOSE message. The performance of these two methods has been investigated in two arrangements. Event F#1 is outside protection zone and therefore trip signal is not generated. Trip signal transfer speed is compared for F#2 and F#3.

3.2.1 Arrangement 1, Traditional Current Transformer (CT):

Fig. 4 shows the results obtained from arrangement 1 where the voltage and current measurements are fed to the IEDs by means of analogue signals, as it simulates conventional substation. Generated trip signals by IEDs are sent to the simulator by means of; digital signal as it is fed to the simulator by means of digital input (denoted as Din hereafter) and GOOSE message. These signals are recorded inside real time simulator. The signals received from IED1 at substation 1 are shown in Fig. 4(a) and (b) for F#2 and F#3 respectively. It can be noticed that GOOSE messages are recorded 3-5ms faster

than the digital signals. It is possible to observe almost the same behaviour for the signals received from IED2 at substation 4 as those have been depicted in Fig. 4 (c) and (d) respectively.
One feature that can be noticed is the pulsations in digital signals due to the contact bouncing at digital outputs (mechanical switches) of the relays which is not present in the GOOSE message since its digital nature. In all cases, the GOOSE message is communicated faster.



(a)

(b)

Fig. 3 Fault (a) trigger signals (b) trip signals

3.2.2 Arrangement 2, Stand-Alone Merging Unit (SAMU):

Fig. 5 shows the results obtained from arrangement 2 where the voltage and current analogue signals are fed to SAMUs where those have been converted to sampled values and then communicated to the IEDs. The generated trip signals by IEDs are sent to the RTS by means of; digital signal and GOOSE message, similarly as with arrangement 1. These signals are recorded inside real time simulator. The signals received from IED1 at substation 1 are shown in Fig. 5(a) and (b) for F#2 and F#3 respectively. It can be noticed that GOOSE messages are recorded about 3ms faster than the digital signals. It is possible to observe almost the same behaviour for the signals received from IED2 at substation 4 as those have been depicted in Fig. 4 (c) and (d) respectively. The same observation as was noted with arrangement 1 can also be noted in this arrangement: in all cases the GOOSE message is communicated, in average about 3-4 ms faster than the digital signal. One reason behind this difference can be the electromagnetic circuit time delay (trip contacts at the relays) since normally an electromagnetic circuit needs about 3-4 ms to operation when it is energized.

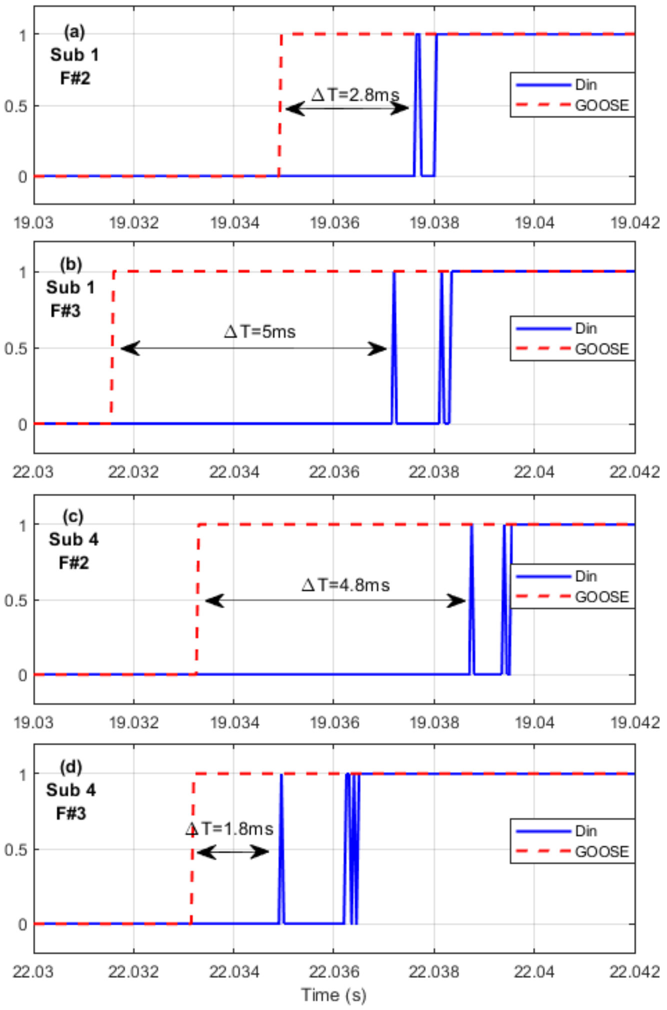


Fig. 4 Trip signals recorded in RTS (a) IED1, F#2 (b) IED1, F#3 (c) IED2, F#2 (d) IED2, F#3

4 Conclusion

This paper has presented a comparison between conventional and modern technologies of feeding measured values to IEDs and receiving trip signals. Two different scenarios have been considered for evaluating and comparing the alternative approaches, and a hardware-in-the-loop time simulation platform was utilized for both of them. The main outcome of the research was that the use of the IEC 61850 protocol in the process bus was recognized in most of the cases as a faster way to feed the measured current and voltage signals to the IEDs. Moreover, sending the trip signal from the IEDs to the circuit breaker (here in OPAL-RT) was investigated using two methods. The method based on IEC 61850-8-1 (using a Goose message) received the trip signal faster than the conventional method. This research was an initial step in analyzing the performance digital substation (including the process bus) and digital protection in the modern grid. Future work will consider a third alternative arrangement where the measured current and voltage at the measuring point (CT and VT) are converted to the sampled values in the simulator and then streamed through the communications network to the IEDs. In this way the resulting simulation setup enables the study of several potential problems arising in the practical implementation of digital substation. Currently, e.g. cybersecurity and time synchronization between two/multi streams of data is the most critical issues in digital substations and should be considered in future work.

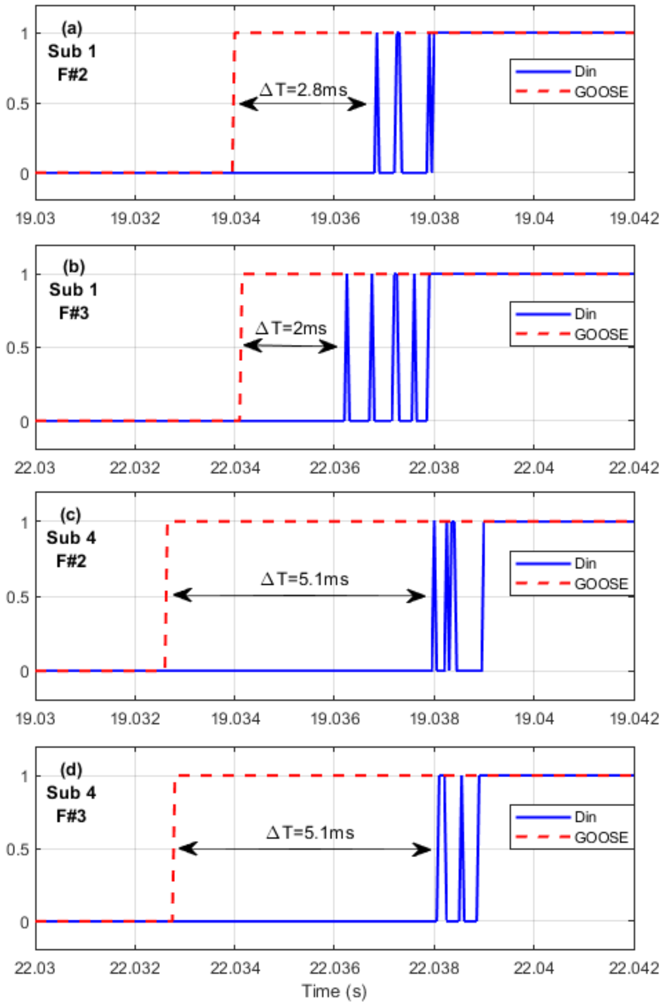


Fig. 5 Trip signals recorded in RTS (a) IED1, F#2 (b) IED1, F#3 (c) IED2, F#2 (d) IED2, F#3

5 Acknowledgements

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