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Implementation of an IEC 61850 Sampled-Value-Based Line Protection Scheme for a 132 kV System †

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Abstract

The paper details the implementation and experimental validation of an IEC 61850-9-2 sampled value (SV)-based distance protection scheme for a 132 kV transmission line. Instead of conventional analog interfaces, we propose a scheme that uses a digital process bus to stream time-synchronized voltage and current measurements from instrument transformers to protection relays. A laboratory-scale setup was developed, in which an SEL 401 merging unit samples currents and voltages injected by an OMICRON CMC 356 and publishes them as SV messages to an SEL 421 distance relay. This work demonstrates how IEC 61850-9-2 can be practically applied to modernize transmission line protection and enhance overall grid reliability and resilience.

Keywords: sample values; IEC 61850-9-2; SEL 421 relay; SEL 401 MU; GOOSE; digital substation

1. Introduction

1.1. Background

Reliable, high-speed transmission protection is vital for maintaining grid stability and mitigating fault impacts. Conventional distance protection relies on analog voltage and current measurements; however, as networks become more complex, the accuracy and response times of these traditional methods are becoming increasingly limited. To address these constraints, the IEC 61850-9-2 standard [1] introduces sampled values (SVs), enabling the delivery of high-resolution, time-synchronized digital measurements directly to protect and control devices [2]. This paper is arranged as follows: the Introduction is given in Section 1; Section 2 details the evolution of substation automation; Section 3 outlines the IEC 61850 Standard Protocols; an overview of distance protection schemes is given in Section 4; the simulation results are given in Section 5; and the Conclusions are provided in Section 6.

1.2. Conventional Substation

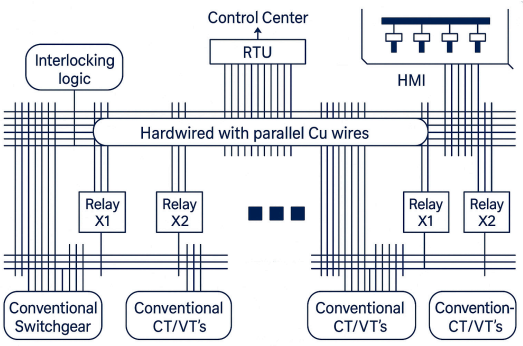
Historically, conventional substations relied on direct wiring of copper cables from instrument transformers in a switchyard to the analog input terminals of protective relays and digital fault recorders located in the relays [3]. In conventional substations, automation systems operated in isolated segments. Monitoring, protection, and metering functions were handled by a dedicated set of devices, primarily using hardwired connections and instrument transformers [4]. Figure 1 presents the conventional substation automation system and its modern successor, which is discussed below.

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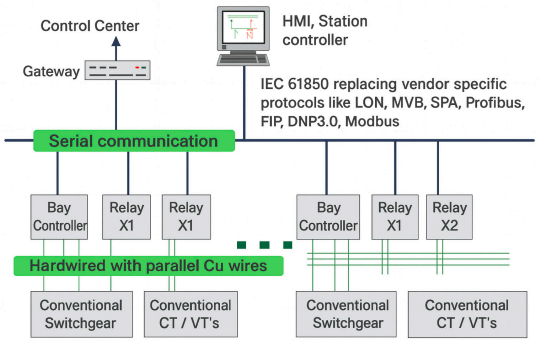
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(**a**) Conventional substation—island of automation.



(**b**) Modern substation with a station bus.

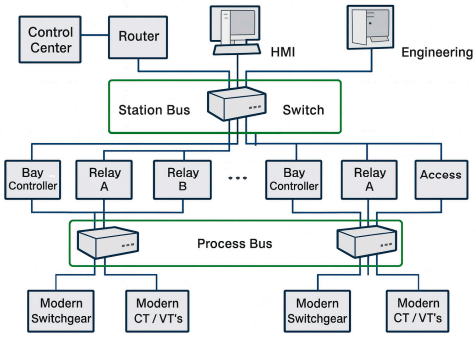
Figure 1. (**a**) Conventional substation—island of automation. (**b**) Modern substation with a station bus.

1.3. Modern Substation

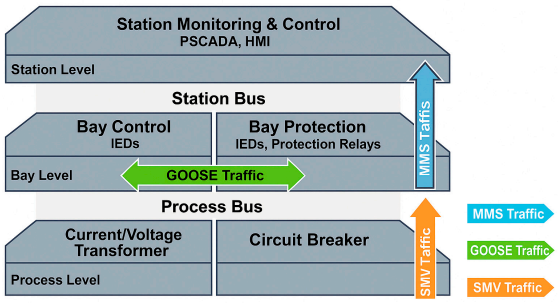
The introduction of modern substations, often referred to as Digital Substation 1.0, marked a significant advancement with the launch of the IEC 61850 Station Bus protocol in the 1980s, as indicated by the green "Serial communication" label in Figure 1b. This protocol replaced the legacy, vulnerable, and vendor-specific communication protocols that had previously been used to connect control centers [5].

1.4. Digital Substation

The IEC 61850 standard saw significant advancement in 2005 with the introduction of the process bus, which established a connection between the process and bay levels. This innovation truly marked the transition to digital substations. The process bus enables replacing traditional point-to-point copper wiring between IEDs, switchgear, and other devices with a secure, standardized fiber-optic communication system [2]. Figure 2a below depicts a fully digitalized substation automation system.



(**a**) Full digital substation.



(**b**) IEC 61850 substation communication architecture.

Figure 2. (**a**) Full digital substation. (**b**) IEC 61850 substation communication architecture.

2. IEC 61850 Communication Protocols

Within the IEC 61850 framework, digital substations utilize standardized protocols to ensure seamless data exchange and device interoperability. High-speed GOOSE messages and sampled values (SVs) facilitate real-time protection and measurement, while MMSs provide the communication necessary for monitoring and control functions. Figure 2b illustrates how these protocols are integrated to provide a reliable, high-performance architecture for modern grid or substation automation, as shown in Figure 2a.

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2.1. Manufacturing Message Specification (MMS)

The Manufacturing Message Specification (MMS) is a communication protocol defined in IEC 61850-8-1 and serves as the backbone of client–server communication in substation automation systems (SASs). It enables high-level messaging for monitoring, control, and data exchange between Intelligent Electronic Devices (IEDs) and supervisory systems, such as SCADA systems [3]. Within substation automation environments, the IEC 61850 MMS protocol is typically used in bay-level to station-level communication [6].

2.2. Generic Object-Oriented Substation Event (GOOSE)

Generic Object-Oriented Substation Event (GOOSE), as defined in IEC 61850-8-1, is used within substation automation systems [7]. It enables rapid, reliable message exchange between IEDs over a local ethernet network, making it ideal for time-sensitive operations such as protection schemes [8]. To maintain reliability without the need for acknowledgments, GOOSE messages are retransmitted in a predetermined pattern [9,10].

2.3. Sampled Values

Sampled values (SVs), also referred to as sampled measured values (SMVs), constitute a communication protocol specified in IEC 61850-9-2 that enables transmission of digitized representations of analog signals. It is primarily used to capture and communicate raw measurement data, such as current and voltage samples, within a substation automation system [7]. IEC 61850-9-2 LE (Light Edition) simplifies interoperability by limiting transmitted data to four voltage and four current values (three phases plus neutral) and setting clear sampling and synchronization rules.

2.4. Comparisons of IEC 61850 Protocols

Table 1 summarizes the key communication protocols defined by IEC 61850, highlighting their communication models, typical applications, and corresponding OSI layers.

Table 1. IEC 61850 protocols.

IEC 61850 Protocols	Communication Model	Typical Use	OSI Layer	Time Delay
MMS	Client/Server	SCADA monitoring/control	Application	ms to s
GOOSE	Publisher/Subscriber	Fast protection signaling	Datalink	<4 ms (real-time)
SMV	Publisher/Subscriber	Time-critical analog measurement	Datalink	<1 ms

3. Distance Protection Characteristics

Distance relays are commonly employed for transmission line protection by determining the impedance between the relay location and the fault point using local voltage and current measurements [11].

3.1. Impedance Relay

In distance protection, impedance estimation plays a foundational role in detecting and locating faults in transmission lines [12]. It involves calculating the apparent impedance between the relay location and the fault point using voltage and current measurements. This principle underpins various relay characteristics, including Mho and quadrilateral elements, which refine fault detection to meet specific system requirements. Distance relays are designed to respond only to faults within a defined protection zone [13].

3.2. Mho Characteristic

Mho is one of the most used distance schemes. Figure 3 below shows the Mho characteristics, with three typical zones serving as reach settings operating at specific times. Zone 1 is generally set to cover 80% of the protected transmission line and operates instantaneously. Zone 2 extends to 100% of the protected line plus 50% of the shortest adjacent line, while Zone 3 covers the complete protected line, the second longest adjoining line, and 25% of the shortest remote line. The operating times are usually longer for Zones 2 (0.25–0.4 s) and 3 (0.6–1.0 s) [7].

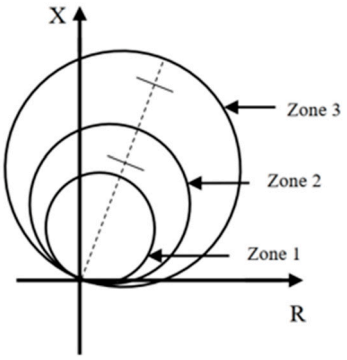


Figure 3. Mho distance characteristic on R-X resistance–reactance plane for three zones [7].

3.3. Quadrilateral Characteristics

The quadrilateral is also another commonly employed distance characteristic. It offers adaptable protection under high-fault conditions for both ground and phase faults. This makes it particularly beneficial for safeguarding phase-to-earth faults in short transmission lines, systems with ineffective grounding, and feeders with very high tower footing resistance [7]. The three typical zones of the quadrilateral characteristic are presented on the R-X plane in Figure 4 below.

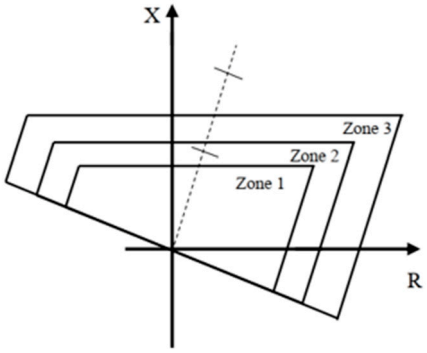


Figure 4. Quadrilateral distance characteristics on the R-X plane for three typical zones [7].

4. Project Key Component

Merging Unit–Sample Value Publisher

A merging unit (MU) is an Intelligent Electronic Device (IED) that digitizes analog measurements, mainly from conventional current and voltage transformers. It then publishes that data as a stream to the process bus at a predefined rate for capture by protection and control relays at the bay level. MUs merge (or combine) and perform time correlation of voltages and currents of the three phases (of a line), hence the name [7]. The connections from the instrument transformers to the merging unit are usually hardwired to the MU inputs.

5. 132 kV Line Protection Case Study

5.1. Power System Model

Figure 5 illustrates the distance protection scheme for the transmission line connecting Substations A and B used in the research. Primary protection is provided by Zone 1, which covers 80% of the line with a near-instantaneous delay of 0.04 s. To provide redundancy, Zones 2 and 3 extend the forward reach to 120% and 220%, respectively, with coordinated delays of 0.3 s and 0.8 s, respectively. Additionally, Zone 4 is configured in the reverse direction, covering 25% of the line with a 1.0 s delay, securing the bus against reverse faults.

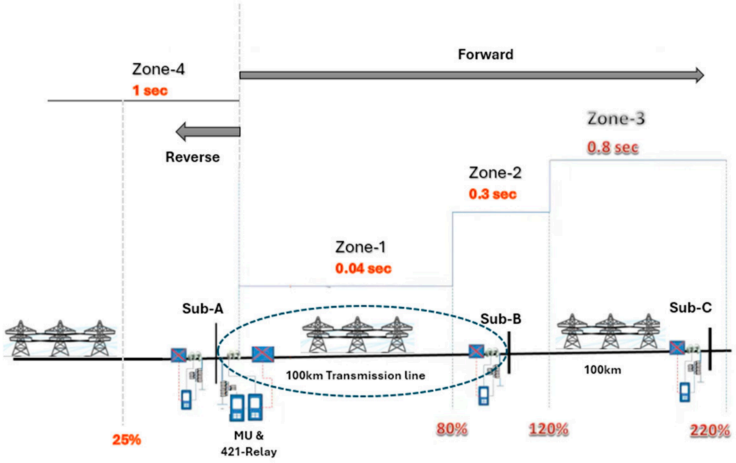


Figure 5. SLD of the modelled power system.

5.2. Power System Data

The values presented in Table 2 below are based on standard protection practices for the 132 kV overhead transmission line built with the ACSR (aluminum-conductor, steel-reinforced) cable, CT/VT ratios, and relay settings applied in the project.

Table 2. Power system data.

System Parameters	System Values
Nominal system line-to-line voltage	132 kV
Nominal frequency	1 A secondary
Protected line length	100 km
Primary pos. sequence impedance (Ω/km)	0.05 + j0.35 Ω
Primary neg. sequence Impedance (Ω/km)	0.15 + j0.90 Ω
Compensation factor	1.58∠−2.17°
PTR (potential transformer ratio)	132,000:110 V = 1200
CTR (potential transformer ratio)	800:1 A = 800

5.3. Lab Scale Implementation Setup

In the setup shown in Figure 6 below, the SEL-401 merging unit converts the secondary CT/VT signals injected by the OMICRON CMC356 (OMICRON electronics, Feldkirch, Austria) into sampled values (SVs) and publishes them on the process bus. The SEL-421 distance relay subscribes to these SV streams for phasor and impedance calculation, and when a fault is detected, it issues a GOOSE trip message on the station bus. Time synchronization for all devices is provided by the SEL-2488 satellite clock using Precision Time Protocol (PTP). A workstation on the station bus runs AcSELerator (version 1.15.5816.1142) and OMICRON Test Universe (4.20) for configuration and testing.

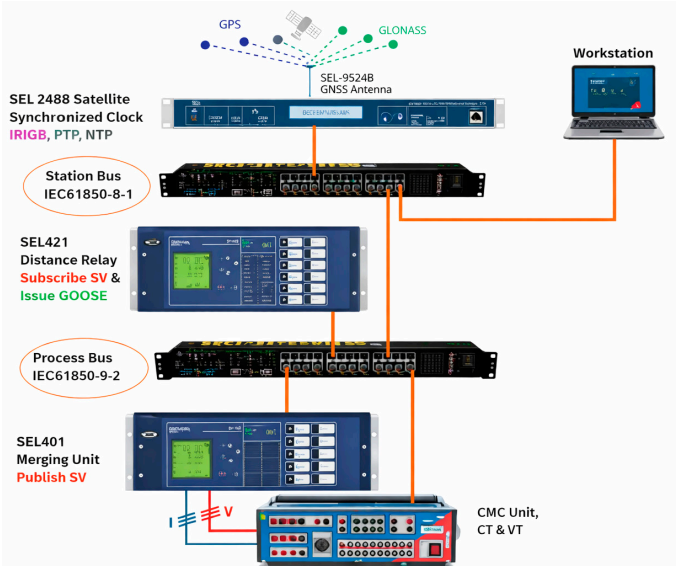
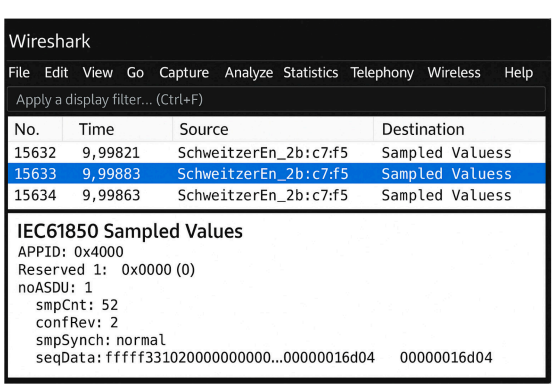


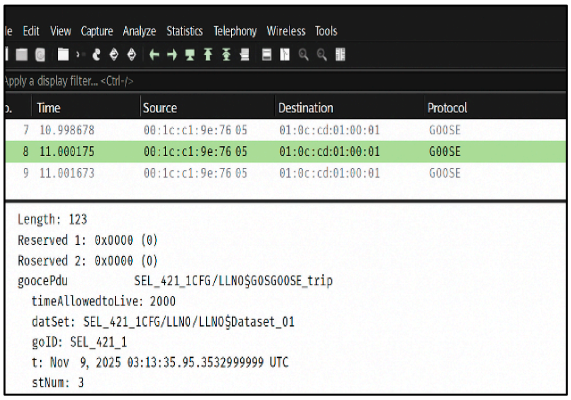
Figure 6. Lab-scale digital substation setup.

6. Results

The results shown in Figure 7 below correspond to the sample values frames and GOOSE messages captured on the network via Wireshark.



(**a**) Sample values captured on the network.



(**b**) GOOSE messages captured on the network.

Figure 7. (**a**) Sample values captured on the network, (**b**) GOOSE messages captured on the network.

Tables 3 and 4 below present the performance of the SEL 421-7 distance relay during phase-to-phase and phase-to-ground fault tests conducted using CMC 356. Figure 8 below shows that the voltages of phases 1 and 2 in zone 1 drop during phase-to-phase fault testing.

Table 3. Results regarding phase-to-phase faults.

Zone 1 to Zone 4 Phase-to-Phase Faults					
Zones	**Impedance**	**t-norm**	**t-act**	**Dev**	**Results**
Zone 1	12.00 Ω	40.0 ms	31.90 ms	−20.25%	passed
Zone 2	25.96 Ω	300.0 ms	296.1 ms	−1.3%	passed
Zone 3	32.00 Ω	800.0 ms	835.6 ms	4.45%	passed
Zone 4	4.00 Ω	1.00 s	1.033 s	3.26%	passed

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Table 4. Results regarding phase-to-ground faults.

Zone 1 to Zone 4 Phase to Ground Faults					
Zones	**Impedance**	**t-norm**	**t-act**	**Dev**	**Results**
Zone 1	12.00 Ω	40.0 ms	33.50 ms	−16.25%	passed
Zone 2	24.84 Ω	300.0 ms	296.1 ms	−1.3%	passed
Zone 3	42.38 Ω	800.0 ms	840.1 ms	5.013%	passed
Zone 4	3.52 Ω	1.00 s	1.032 s	3.21%	passed

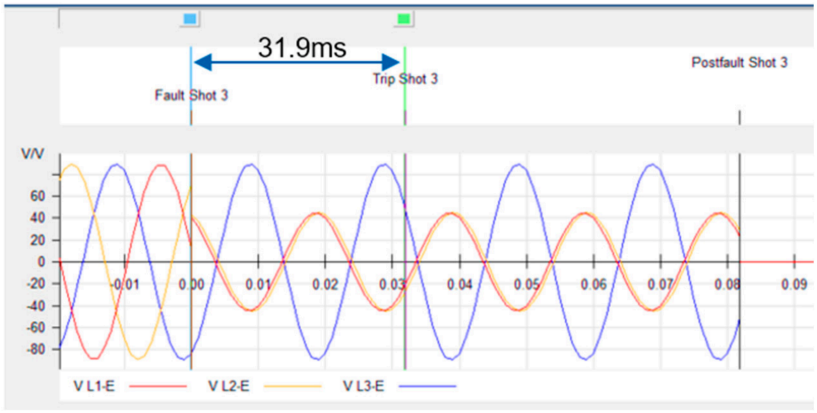


Figure 8. Zone 1 phase-to-phase fault.

Testing confirmed that the relay successfully detected and cleared faults across all four protection zones and that the measured operating times (t act) closely aligned with nominal values (t norm), with deviations remaining well within acceptable protection tolerances. The most notable variance was a −20.25% deviation in Zone 1 during phase-to-phase faults; this indicates faster-than-expected tripping, which is an advantageous characteristic for instantaneous primary protection. Other deviations ranged from −1.3% to +5%, demonstrating stable and predictable relay performance. These results validate the accuracy and reliability of the sampled value (SV)-based tripping architecture.

7. Conclusions

This study demonstrates a full, standard-based implementation of IEC 61850-9-2 sampled-value-based distance protection for a 132 kV transmission line using an SEL-401 merging unit and an SEL-421 relay. The laboratory configuration replicated a digital substation setup with a process bus for measurement exchange and a station bus for tripping through GOOSE. End-to-end testing verified interoperability and proper operation of the SV-to-GOOSE sequence. The measured performance closely matched the intended zone grading, and any minor variations were within normal tolerances, mainly due to detection latency, timing resolution, or communication delays.

Author Contributions: M.N.S. and S.K., conceptualization and methodology; M.N.S., software and validation; M.N.S., S.K. and M.N.S., formal analysis and investigation; M.N.S., resources and data; M.N.S. and S.K., editing, supervision, visualization, project administration, and funding acquisition; M.N.S. and S.K., writing, reviewing, and editing. All authors have read and agreed to the published version of the manuscript.

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