

VIRTUAL COMMISSIONING OF AN IEC 61850-BASED SUBSTATION AUTOMATION SYSTEM THROUGH AN INTEGRATED ENGINEERING WORKFLOW

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Abstract: This paper proposes a structured IEC 61850-based engineering methodology for virtual commissioning of digital substations by integrating protection engineering in DIGSI 5, virtual validation using SIPROTEC DigitalTwin, and SCADA preparation in TIA Portal. Unlike conventional approaches, the proposed methodology unifies protection configuration, communication engineering, and supervisory interface in a single workflow. The methodology is evaluated using protection scenarios that assess the consistency of protection logic, relay operation, and supervisory visualization. The results demonstrate that the proposed workflow can effectively verify the coordinated development of protection and automation components before hardware deployment, reducing dependence on physical equipment during the early engineering stages.

Keywords: Virtual Commissioning, Substation Automation, IEC 61850, DIGSI 5, TIA Portal

INTRODUCTION

Power systems are undergoing a digital transformation. The main goal is to improve flexibility and reliability while supporting the integration of advanced automation. Traditional substations rely on isolated protection and control devices, interconnected through hardwired communication. Modern digital substations require fast and reliable communication. Today, protection, automation, and monitoring functions must operate together in an integrated system rather than separately [1]. The development of the IEC 61850 communication standard has significantly changed the design of modern digital substations. IEC 61850 provides standardized communication and data modelling, based on the Substation Configuration Language (SCL). This enables interoperability between Intelligent Electronic Devices (IEDs) from different manufacturers [2]. IEC 61850 introduces high-speed communication services, allowing for reliable real-time data exchange over Ethernet networks. As a result, the IEC 61850 communication standard has become the foundation of modern substation automation systems, leading to standardized communication and engineering workflows for protection, automation, and supervisory control applications [3]. This creates the need for frameworks capable of integrating and validating protection and automation systems within a virtual environment before practical use.

Generic Object-Oriented Substation Event (GOOSE) messaging is one of the crucial services defined by IEC

61850, enabling high-speed exchange of data between IEDs. By supporting exchange of protection and control information, GOOSE improves response times and reliability of digital substations [4]. However, commissioning of protection and automation systems depends on hardware and dedicated testing equipment. Existing relay testing methods are accurate, but they are often expensive and time-consuming. This can be a limitation during early development stages and system upgrades. Improper configuration of protection logic makes the system more vulnerable to faults and disturbances, increasing engineering costs [5]. However, existing studies primarily address individual aspects of virtual commissioning, such as protection engineering, Programmable Logic Controller (PLC) validation, Digital Twins, or Supervisory Control and Data Acquisition (SCADA) visualization. In comparison, a unified methodology that integrates these activities into a single IEC 61850-based workflow has received significantly less attention.

To address these challenges, virtual commissioning is used as an effective approach for validating protection and automation systems before field deployment. Virtual environments allow engineers to simulate the behavior of protection and automation logic without a complete physical installation. These approaches support system validation, simplified troubleshooting, and more flexible testing [6]. In this context, Siemens DIGSI 5 and TIA Portal provide complementary environments for protection configuration, PLC programming, and system visualization [7], [8]. Their integration enables

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coordinated development of protection, automation, and SCADA applications in a virtual substation. This paper proposes a structured engineering methodology for virtual commissioning by integrating protection engineering in DIGSI 5, virtual validation using SIPROTEC DigitalTwin, as well as PLC programming and SCADA preparation in TIA Portal. The main contribution of this work lies in the development and evaluation of a structured methodology for virtual commissioning of IEC 61850-based substation automation systems. A unified workflow is developed that integrates DIGSI 5, SIPROTEC DigitalTwin, and TIA Portal in a single engineering process. Unlike previous work that primarily focuses on individual engineering activities, the proposed methodology integrates protection engineering with virtual validation and SCADA within a unified workflow intended for verification of a digital substation at early stages.

The proposed methodology is evaluated through representative protection scenarios to assess the consistency of protection logic, signal routing, and supervisory visualization within the developed virtual environment. The objective of this study is to investigate whether protection engineering, virtual validation, and SCADA visualization can be integrated into a single workflow, as well as to evaluate the protection scenarios used to verify the protection logic and supervisory visualization. The study identifies the benefits and current limitations of the proposed workflow in comparison with conventional commissioning approaches, establishing a foundation for future hardware-in-the-loop validation, quantitative performance evaluation, and interoperability studies involving IEDs from different manufacturers.

The following section of this paper reviews the existing literature on IEC 61850-based substation automation, virtual commissioning, and digital twins. Section III presents the proposed methodology, including protection configuration in DIGSI 5, virtual validation using SIPROTEC DigitalTwin, and SCADA development in TIA Portal. Section IV outlines the implementation and validation results of the developed protection and automation workflow. After that, Section V discusses the obtained results, compares the proposed methodology with related studies, and identifies limitations and opportunities for future development. Finally, Section VI summarizes the main conclusions of the research.

1. LITERATURE REVIEW

The transition from conventional substations toward digital substation automation has been largely driven by the adoption of the IEC 61850 communication standard. Unlike traditional hardwired communication, IEC 61850 introduces standardized object-oriented information models, high-speed Ethernet communication, and a unified process based on the SCL. These features enable interoperability between IEDs from different manufacturers

while simplifying engineering, maintenance, and future system expansion [3], [6], [9]. In addition to improving interoperability, IEC 61850 supports communication through GOOSE messaging and Manufacturing Message Specification (MMS), allowing protection and control information to be exchanged with low latency and high reliability [4]. Studies have consistently shown that these capabilities improve the flexibility and performance of digital substations compared to conventional communication architectures [3], [9], [10]. In addition to communication performance, recent studies indicate the importance of secure GOOSE communication. Reda et al. [11] demonstrated that although GOOSE messaging satisfies the strict latency requirements of protection systems, it remains vulnerable to cyberattacks if appropriate security mechanisms are not implemented. These findings indicate that digital substations require both standardized communication and secure validation during the commissioning process. However, most existing research concentrates on communication performance, protocol implementation, and interoperability. Less attention has been given to the integration of protection configuration, automation, and SCADA visualization in a unified virtual environment.

Virtual commissioning has become an important approach for reducing the dependence on hardware during the development of industrial automation and power systems. Instead of validating control logic only after installation, virtual commissioning tests automation sequences, communication, and system behavior before field deployment. This reduces commissioning time and minimizes engineering costs associated with configuration errors detected during physical testing [5], [12]. Recent studies show that the combination of virtual models with PLC simulation environments provides an efficient platform for verifying automation logic without implementing complete physical installations. Delgado Sobrino et al. [12] demonstrated the integration of Tecnomatix Plant Simulation with S7-PLCSIM Advanced and TIA Portal, showing that virtual commissioning can significantly improve the early validation of PLC control strategies. Similarly, Melo et al. [5] proposed an IEC 61850-based off-site methodology that enables remote validation of protection, automation, and control systems while reducing the need for extensive on-site commissioning activities. Although these approaches demonstrate improvements in engineering efficiency, they primarily focus on PLC validation or communication verification. The coordinated engineering of protection relay configuration, IEC 61850 communication, and SCADA visualization within a unified engineering methodology remains largely unexplored. The integration of protection systems with PLC-based automation and SCADA has become an important research topic as modern substations constantly evolve toward fully digital architectures. While protection relays are primarily responsible for detecting and isolating faults, PLCs and

SCADA systems provide supervision, visualization, alarm management, and operator interaction.

Consequently, several studies have investigated the coordinated operation of these components within substation automation systems. Elsayed and Mohamed [13] demonstrated that integrating distance protection with SCADA control improves relay adaptability under varying network conditions, resulting in a more reliable protection performance. Similarly, Faryal et al. [14] developed a laboratory platform based on PLC and SCADA. The platform combined protection, monitoring, and automation functions into a single control environment. Their results confirmed that integrating PLC programming with Human-Machine Interface (HMI) and SCADA improves operational flexibility while simplifying fault monitoring and system supervision. Although these studies demonstrate the practical benefits of PLC and SCADA integration, they primarily consider conventional laboratory or hardware implementations. The coordination between protection relays, IEC 61850, PLC, and SCADA in a virtual engineering environment has received limited attention in the existing research.

Recent advances in Digital Twin technology have expanded the possibilities for virtual configuration and commissioning of power systems. Digital Twins enable virtual representations of physical equipment. This capability supports simulation, testing, and system validation throughout the development cycle. Recent studies highlight that Digital Twins improve interoperability between multi-vendor systems, facilitate data exchange, and enable validation before physical deployment, reducing commissioning time, engineering costs, and operational risks [15]. More recently, Lopez et al. [16] developed a programmable Digital Twin platform based on IEC 61850 communication. This implementation integrated overcurrent protection, GOOSE, MMS-based monitoring, with experimental testing that demonstrated fast transmission times. The results further demonstrate the potential of Digital Twin environments for protection system validation. These capabilities have made Digital Twin technology an increasingly important component of modern substations and virtual commissioning practices inside those environments. However, while Lopez et al. [16] focused on development of a programmable digital relay, the coordination between protection configuration, PLC automation, and SCADA visualization remains less explored. Additionally, Bonetti et al. [17] demonstrated the potential of Digital Twin technology for protection engineering, testing, and virtual commissioning. Interoperability between different tools and the implementation of closed-loop testing were marked as crucial challenges for future development. The increasing adoption of Digital Twins corresponds to the transition toward virtual engineering in modern power systems. Most existing applications focus on asset management, predictive maintenance, or network operation.

However, considerably less attention given to integrating protection relay configuration, IEC 61850 communication protocol, PLC automation, and SCADA visualization in a single workflow. This creates an opportunity for virtual commissioning systems that effectively support coordinated development and validation of configured protection logic and automation systems in virtual substation environments.

Overall, the reviewed literature confirms that IEC 61850 has become the dominant communication standard for digital substations. Virtual commissioning and Digital Twin technologies have significantly improved system flexibility and reduced dependence on physical testing environments. Existing studies have demonstrated advances in communication performance, PLC validation, and SCADA integration. However, these topics are investigated independently in most of the studies. Limited attention has been given to frameworks that incorporate protection relay configuration, IEC 61850 communication, PLC automation, and SCADA visualization within a single virtual commissioning workflow. This gap provides the motivation for the engineering framework proposed in this paper.

2. METHODOLOGY

The proposed methodology is based on the development of an IEC 61850 framework for virtual substation automation [2]. The proposed workflow, illustrated by the diagram in Fig. 1, integrates protection, automation, and visualization layers in a single process, with a clear separation between protection engineering, virtual validation, and SCADA preparation.

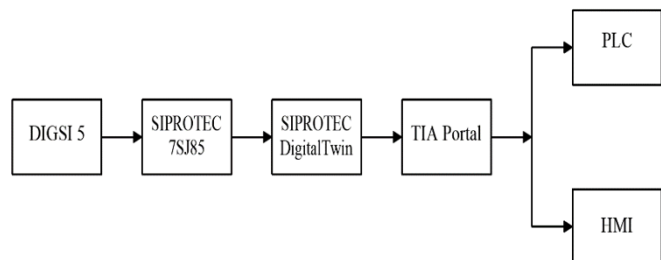


Figure 1: The proposed workflow for the virtual commissioning network.

Each stage of the proposed methodology provides necessary information for the next stage, enabling the entire workflow to be validated before physical deployment. In the first stage, the focus is on protection engineering in DIGSI 5, with the protection relay and communication model established. The second stage focuses on the necessary signals through information routing, enabling logical connections between protection functions to be formed. This is followed by the third stage that validates the developed protection model using SIPROTEC

DigitalTwin under simulated operating conditions. Finally, the methodology concludes with the preparation of the PLC-HMI communication architecture in TIA Portal, providing the basis for future SCADA integration and hardware implementation.

The first stage of the methodology begins with development of a secondary protection system for the 110 kV transmission line bay. The protected bay was modelled by defining the primary switching equipment and measurement points, including a circuit breaker (Q0), busbar disconnectors (Q1 and Q2), a line disconnector (Q9), and an earthing switch (Q8). The current transformer and the voltage transformer measure values for protection configuration in DIGSI 5.

The resulting single-line diagram is the foundation for the protection configuration, communication, and signal assignment in the proposed system, as shown in Fig. 2.

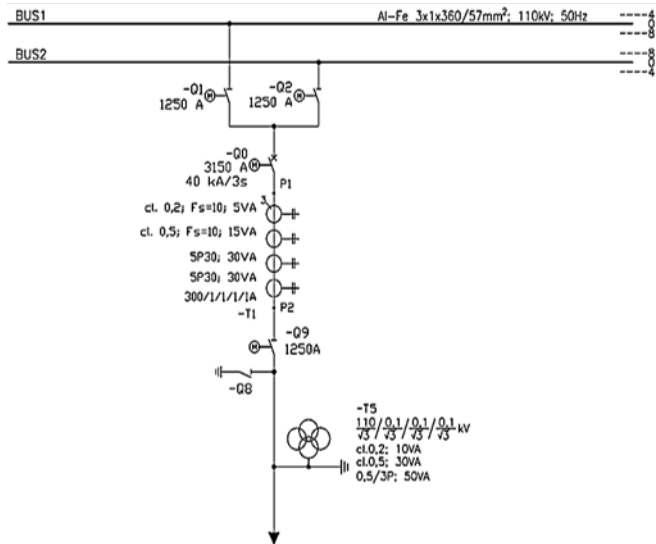


Figure 2: Single-line diagram of the protected transmission line bay.

The implementation begins with the development of the protection model in DIGSI 5 [7]. The SIPROTEC 7SJ85 protection relay was selected because it supports overcurrent protection, IEC 61850 communication, and modular hardware configuration. Protection engineering was performed using the relay platform configured according to IEC 61850 Edition 2. The relay model included the protection, communication, and hardware modules needed for the proposed workflow [2].

After the protection model was configured, signal assignment was performed through information routing in the second stage of the methodology. This was used to associate protection functions with binary inputs, binary outputs, LED indications, event logs, and communication objects for protection and automation functions [7]. Binary inputs represented the operating states of the primary equipment, while binary outputs were assigned to trip

and close commands. Two independent trip outputs were associated with the circuit breaker to represent separate trip coils, making the breaker tripping more reliable. Protection trip commands were configured as unlatched outputs to generate trip pulses of short duration, while operational switching commands were configured as routed outputs to support switching operations.

General pickup and operate indications, together with the corresponding overcurrent protection stages, were assigned to dedicated LED indicators for local visualization. Switching operations were recorded in the Operational Log, while protection operations, disturbance records, and fault events were assigned to the Fault Log. Furthermore, communication objects were linked to the Continuous Function Chart (CFC) environment to enable interaction between protection functions, switching commands, and communication signals. The produced interlocking signals represent the final output of the overall control strategy [7]. The signal assignments, implemented throughout the information routing process, are summarized in Table I. This stage of the research establishes the structured protection and configuration model that serves as the input for the virtual validation and the SCADA preparation stages of the proposed methodology.

Table I: Main signal assignments implemented through the information routing process

Signal Category	Configuration	Engineering purpose
Binary Inputs (BI)	Circuit breaker, busbar and line disconnectors, earthing switch	Monitoring of primary equipment operating states
Binary Outputs (BO)	Trip Coil 1, Trip Coil 2	Unlatched trip commands
Binary Outputs (BO)	Circuit breaker and disconnector close commands	Routed operational switching commands
LED Indications	General pickup, general operate, 50/51 pickup and operate	Local visualization of protection operation
Operational Log	Switching operations	Recording of normal operating events
Fault Log	Protection trips, fault records, disturbances	Post-fault analysis
Continuous Function Chart (CFC)	Protection and communication objects	Integration of protection logic with communication and control functions

The third stage of the methodology focused on virtual validation of configured protection using the SIPROTEC DigitalTwin environment. A predefined SIPROTEC

7SJ85 relay model, available within the demonstration environment, was used for the validation process. The proposed framework was evaluated under simulated operating conditions [15]. The validation procedure involved modifying three-phase current and voltage values, changing binary input states, and observing the corresponding relay responses through the integrated HMI. Relay measurements, pickup indications, trip signals, and circuit breaker status were monitored to verify the consistency of the configured protection logic. The evaluation focused on verifying the consistency between the relay operating states and the indications displayed in the DigitalTwin interface. Particular attention was given to confirming the correct sequence of pickup indications, trip initiation, and circuit breaker status changes. The DigitalTwin demonstration provided a practical environment for validating the engineering workflow without relying on physical protection hardware, confirming the feasibility of the proposed virtual commissioning methodology.

The final stage of the proposed methodology focused on the preparation of the SCADA integration architecture in TIA Portal [8]. A SIMATIC S7-1200 PLC and a TP900 Comfort HMI were selected to represent the automation and visualization layer of the virtual substation. A PROFINET communication network was established between the PLC and the HMI to define the communication structure of the proposed SCADA system. Furthermore, protection indications, switching commands, measurement values, and device status information were identified for future signal mapping between the DIGSI 5 engineering model, PLC variables, and HMI objects. The developed system architecture provides the practical foundation for future hardware implementation and runtime verification.

The prepared PLC–HMI communication architecture is presented in Fig. 3. The established PROFINET connection defines the communication path between the SIMATIC S7-1200 PLC and the TP900f0 Comfort Panel HMI, providing the practical foundation for future mapping of protection indications, switching commands, measurements, and status information originating from the DIGSI 5 protection model.

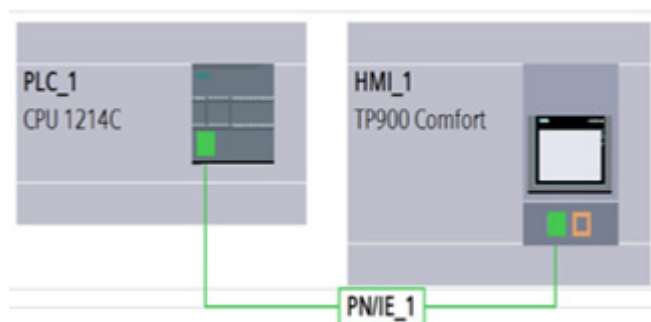


Figure 3: Prepared PLC–HMI communication architecture in TIA Portal based on a PROFINET network.

The proposed engineering methodology therefore integrates protection relay configuration, virtual validation, and the preparation of the SCADA communication architecture within a unified IEC 61850-based workflow. The implementation results and evaluation of the developed system are presented and discussed in the following section.

3. RESULTS

The developed protection model successfully represented the primary equipment of the protected line bay in DIGSI 5 engineering environment. The resulting single-line configuration provided an accurate representation of the circuit breaker, busbar disconnectors, line disconnector, earthing switch, and current transformer, enabling the implementation of IEC 61850-based protection functions.

The information routing process enabled the assignment of protection functions to binary inputs, binary outputs, event logs, and communication objects. Binary input signals represented the operating states of the primary switching equipment, while binary outputs were assigned to protection trip commands and operational switching commands according to their individual functions. The separation of unlatched protection outputs from routed operational outputs provided a clear distinction between protection actions and normal switching operations [7]. The developed system architecture demonstrated a consistent relationship between the configured protection and the corresponding relay control functions. The implemented signal assignments ensured that changes in simulated process variables were correctly propagated to the associated binary outputs. This demonstrates that the configuration established in DIGSI 5 can be consistently evaluated within a virtual validation environment prior to hardware implementation.

Furthermore, the structured organization of protection signals, event records, and communication objects provides a strong foundation for integration with higher-level automation and SCADA visualization systems. Following the completion of the protection stage, the configured engineering model was evaluated in the SIPROTEC DigitalTwin environment. By increasing the simulated three-phase current values above the configured protection threshold, the relay generated the expected protection response [15]. The configured trip output (BO 1.1) was activated, indicating that the relay issued a circuit breaker trip command, as shown in Fig. 4. The current magnitudes were at 1000 A in all three phases. The pickup threshold is at 200 A, meaning that the current exceeds five times the threshold. This resulted in protection pickup.

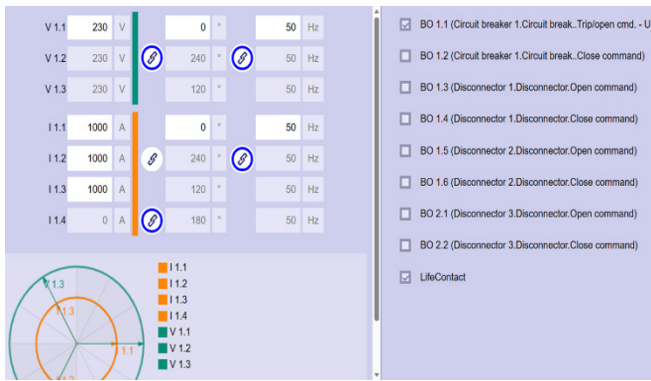


Figure 4: Circuit breaker trip command output activated in the SIPROTEC DigitalTwin environment.

Following the activation of the trip output, the relay HMI displayed the corresponding pickup indication together with the updated protection status. The measured current values and protection indications confirm the correct operation of the configured overcurrent protection functions under simulated fault conditions, as illustrated in Fig. 5.



Figure 5: Relay HMI response, displaying the inverse-time overcurrent protection pickup across three phases.

The resulting overcurrent conditions exceeded the configured pickup threshold, driving the relay logic into Inverse-T1 pickup state. The protection logic successfully issued a trip command by asserting binary output BO 1.1 (Trip/open cmd.), validating the functional mapping between the protection logic and virtual relay outputs. The relay successfully detected the overcurrent condition, activating the pickup indications for phases A, B, and C, whereas the earth-fault indication remained inactive at the start. The event window confirms the activation of the inverse-time 50/51 overcurrent protection, while the relay remained in the pickup state before issuing a trip command. Fig 5 illustrates the pickup stage immediately after the current of 1000 A initiates time countdown and turns the corresponding LEDs on.

As observed in Fig. 6, the Definite-T2 operate issues a circuit breaker trip command. Unlike inverse-time protection, definite-time protection operates after a defined interval. The recorded trip time was at 99 ms, while the pickup time was at 26880 ms, equivalent to approximately 26.9 s. This recorded time corresponds to the elapsed time between the pickup and operate events, which are stored in the relay event log.



Figure 6: Relay HMI response, displaying the definite-time overcurrent protection trip and pickup time.

The LEDs for pickup indication across phases A, B, and C are activated, as observed in Fig. 6. However, in addition to this, the HMI records the activation of the earth-fault protection pickup stage which can be attributed to small residual currents from other phases on. The obtained DigitalTwin results demonstrate that an increase in the simulated three-phase current resulted in the activation of the corresponding trip output, followed by the pickup indication displayed on the relay HMI. The observed sequence confirms the consistency between the protection logic, binary output activation, and operator indications in the virtual environment [15]. Consequently, the developed workflow enables verification of protection functionality before deployment on physical protection hardware. By combining DIGSI 5 with SIPROTEC DigitalTwin validation enables protection logic, signal routing, and relay behaviour to be evaluated without interrupting the operation of an existing substation.

This approach reduces the dependence on physical protection devices during the initial engineering stage, providing an efficient environment for configuration verification. Following the virtual validation stage, the methodology was extended to the SCADA preparation stage through the development of a PLC-HMI operator interface in TIA Portal [14]. The developed interface integrates a single-line representation of the protected line bay with protection status indicators, measurement values, circuit breaker status, and operator command functions, as shown in Fig. 7.

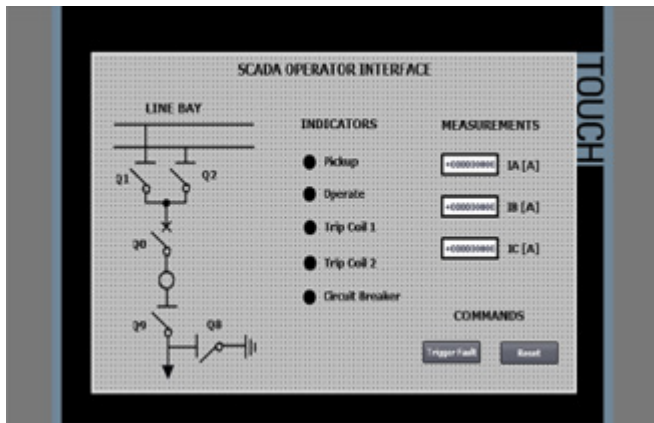


Figure 7: Proposed SCADA operator interface developed in TIA Portal.

The developed HMI configuration demonstrates that the protection engineering model can be consistently transferred from relay configuration and virtual validation towards supervisory monitoring applications using a PLC–HMI environment. The communication established in TIA Portal provides the necessary foundation for future mapping of device status information from the DIGSI 5 protection model. Although complete WinCC Runtime execution could not be performed due to software licensing and administrative restrictions, the configured communication architecture, PLC logic, and HMI interface establish the basis for future implementation using physical SIPROTEC protection devices. Therefore, the obtained results demonstrate that the proposed methodology successfully integrates protection configuration, virtual validation, and SCADA preparation inside a unified IEC 61850-based workflow.

4. DISCUSSION

The obtained results demonstrate that the proposed methodology provides a feasible approach for integrating protection, validation, and SCADA preparation in a single IEC 61850-based workflow. Rather than focusing on individual engineering tasks, the proposed methodology establishes a structured sequence. The protection relay configuration, functional verification, and supervisory interface development are organized as consecutive stages. This organization enables engineering inconsistencies to be identified during early stages of virtual commissioning, reducing the dependence on physical protection equipment. The DigitalTwin validation confirmed that the configured overcurrent protection logic operated consistently under simulated operating conditions. Pickup and trip conditions are activated accordingly. The developed PLC-HMI architecture demonstrated the possibility of extending protection information towards supervisory monitoring. Although complete WinCC Runtime validation in TIA Portal could not be performed due to software

licensing and administrative limitations, the PLC logic, communication architecture, HMI tag configuration, and developed operator interface demonstrate that the proposed engineering model can be extended towards supervisory control and process visualization inside a digital substation environment.

The results are consistent with previous research on IEC 61850-based substation automation and virtual commissioning, while additionally demonstrating practical extensions. Kumar et al. [3] emphasized the importance of standardized communication, interoperability, and engineering processes enabled by IEC 61850, whereas Elbaset et al. [10] demonstrated the integration of protection and control functions through IEC 61850 communication within substation automation systems. Building on the methodology proposed by Melo et al. [5], which focuses on remote validation of protection, automation, and control systems, the proposed methodology incorporates SIPROTEC DigitalTwin for protection verification together with PLC–HMI preparation. Similarly, although Faryal et al. [14] demonstrated PLC–SCADA integration in a laboratory environment, the proposed methodology extends this concept by incorporating protection engineering and virtual commissioning in a single process. Recently, Thwe et al. [15] and Lopez et al. [16] highlighted the increasing role of digital twins in process verification, virtual testing, and commissioning activities. However, existing studies investigate the individual aspects of digital substations, including communication, protection, or virtual validation, rather than presenting an integrated system. In contrast, the proposed methodology combines them in a single process.

The developed SCADA operator interface complements this workflow by extending protection information to the supervisory level, directly supporting future supervisory monitoring and operator interaction. The proposed virtual commissioning workflow begins with protection relay engineering and continues with functional verification, concluding with preparation for supervisory control and visualization. As summarized in Table II, the proposed methodology extends previous studies by integrating protection relay, virtual validation, and SCADA preparation into a unified IEC 61850-based engineering process.

The resulting methodology provides a foundation for future hardware implementation while reducing engineering effort during the early stages of substation automation projects. From an implementation perspective, the proposed system workflow enables structured coordination of protection engineering, virtual validation, and SCADA development before incorporating physical equipment.

Table II: Comparison of the proposed research methodology with existing studies

Aspect	Main approaches in the reviewed literature	Proposed methodology
Protection engineering	DIGSI or protection only	DIGSI 5 relay engineering
Virtual validation	Digital twin validation or simulation	SIPROTEC DigitalTwin
SCADA preparation	Limited or not included	TIA Portal PLC-HMI implementation
IEC 61850 role	Communication focus	Communication and engineering workflow
Workflow structure	Individual or partially connected activities	Unified, structured methodology
Demonstrated scope	Single protection, or automation task	Single-bay virtual commissioning

By separating relay configuration, functional verification, and supervisory interface preparation into separate stages, configuration inconsistencies can be identified earlier in the project lifecycle. The developed PLC–HMI architecture further demonstrates how protection information can be organized for operator supervision, enabling future hardware deployment, commissioning activities, and operator training. Consequently, the developed system contributes to reducing engineering effort and improving consistency during the development of IEC 61850-based digital substations.

Despite the encouraging results, limitations should be acknowledged. First, the implemented workflow was demonstrated using a single SIPROTEC d7SJ85 protection relay and a single protected line bay. Consequently, the scalability of the proposed approach for substations containing multiple bays, multiple protection relays, or multi-vendor IEC 61850 devices was not evaluated. Interoperability with protection relays from other manufacturers was not experimentally verified and therefore remains outside the scope of the present study. Furthermore, complete WinCC Runtime verification of the PLC–HMI implementation could not be completed due to software licensing and administrative restrictions within the available engineering environment. In addition, quantitative performance indicators such as communication latency, response time, and network loading were not experimentally evaluated and therefore remain important topics for future investigation.

Although the developed system was validated for a single protected line bay, its principles are not restricted to this configuration. Because of the standardized data models and communication services defined by IEC 61850, the proposed workflow can be extended to larger substation automation systems incorporating multiple bays, protection relays, and interoperable IEDs from different manufacturers, provided

that appropriate validation at system level is performed. Therefore, future research should focus on experimental validation using physical SIPROTEC protection devices together with quantitative assessment of communication performance, interoperability, and cybersecurity.

5. CONCLUSION

This paper presented a structured methodology for coordinating protection engineering, virtual validation, and SCADA system within an IEC 61850-based virtual commissioning environment. The protection model developed in DIGSI 5 represented the required protection functions, signal mappings, and communication objects, while validation using the SIPROTEC DigitalTwin environment confirmed the expected pickup and trip sequence of the overcurrent protection under a simulated three-phase fault condition.

In addition, the PLC logic, communication architecture, and operator interface developed within TIA Portal demonstrated the feasibility of extending the protection model towards supervisory monitoring and process visualization. The main contribution of the proposed virtual commissioning methodology is the coordination of protection relay engineering, virtual validation, and PLC–HMI preparation as consecutive stages rather than as independent activities.

This approach provides a practical basis for identifying configuration inconsistencies before physical implementation and has the potential to reduce dependence on protection hardware during initial engineering. However, complete runtime execution and communication between the virtual relay environment and the PLC–HMI system were not experimentally validated. Therefore, the implementation of physical protection devices, complete runtime integration, and the extension of the virtual commissioning workflow to substations with multiple bays and IEC 61850 devices from different manufacturers represent important directions for future development of the proposed methodology.

LIST OF ABBREVIATIONS

SCL	Substation Configuration Language
IED	Intelligent Electronic Device
GOOSE	Generic Object-Oriented Substation Event
PLC	Programmable Logic Controller
SCADA	Supervisory Control and Data Acquisition
MMS	Manufacturing Message Specification
HMI	Human-Machine Interface
CFC	Continuous Function Chart
BI	Binary Input
BO	Binary Output

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BIOGRAPHY

Vedad Mušović received his BSc degree in Electrical and Electronics Engineering from the Faculty of Engineering, Natural and Medical Sciences at International Burch University in Sarajevo, Bosnia and Herzegovina, in September 2024. His bachelor's thesis was titled Microcontroller-Based Smart Solar Tracking System. He is currently pursuing a MSc degree in Electrical and Electronics Engineering at the same institution. His academic interests include power system protection and automation, as well as control engineering and embedded systems. Since February 2025, he has been employed at Energoinvest d.d. Sarajevo as a Junior Engineer in the Engineering Department, within the Schematics Division. He is engaged in the design and development of technical documentation and electrical schematics for power engineering projects, primarily focusing on substations, protection and automation systems, both in Bosnia

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