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# The Implementation and Evaluation of Virtualized Protection Intelligent Electronic Devices into a Virtual Substation

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**Abstract:** This paper presents an investigation into the virtualization of substation protection IED functions using a sophisticated co-simulation environment that integrates virtual intelligent electronic devices (vIEDs) with a real-time power grid simulation. Anchored by the IEC 61850 protocol, this study constructs a virtualized IED framework, emphasizing the encapsulation of protection schemes using the example of different types of overcurrent protection within a containerized vIED. Using open-source software, this study aims to replicate the communication and functional aspects of physical IEDs. This study uses a co-simulation environment that couples virtualized network components with a real-time power grid simulation to validate the vIEDs against real substation hardware. Simulation results from induced short-circuit events confirm the operational congruence of the vIEDs with their physical counterparts, demonstrating their potential to serve as cost-effective and adaptable testbeds for substation automation. This paper concludes that virtualized IEDs represent a cost-effective, flexible alternative for substation automation testing, with future research directed towards increasing the functional complexity and real-world applicability of these virtual systems.

**Keywords:** virtual IED; IEC 61850; co-simulation; virtualization; overcurrent protection; IED



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## 1. Introduction

### 1.1. Background

Various considerations have been focused on digital substations and other power supply stations in recent years, such as functional enhancements, flexibility, and IT security [1–4]. In this case, standardized communication with real-time capabilities plays a major role and is explicitly introduced through IEC 61850. All functions are implemented through communication devices in the form of intelligent electronic devices (IEDs) and realize substation automation. Accordingly, the importance of simulative investigations of the communication infrastructure is constantly increasing, and various modeling approaches are being developed and published [5]. One promising approach is the virtual mapping of the OT infrastructure, or secondary equipment, and its coupling as part of a co-simulation with a power grid simulation to generate physical measurements. In this approach, the components of the communication network are implemented using virtual container instances. The power grid simulation supplies the process information, such as currents and voltages, via internally mapped merging units using IEC 61850 Sampled Values (SVs). Virtual IEDs (vIEDs) therefore receive process information as measured values and can, for example, feed control commands back into the power grid simulation as a protective function in the application. In this way, virtualization can be executed in parallel to the real-time power grid simulation at the same time, and a co-simulation of the substation automation can be established. This approach has already been presented in [6,7].

One goal of co-simulation is the simulative reproduction of substations in such a way that traffic and interactions in automation functions can be represented as realistically as possible. The simulated infrastructure should therefore resemble a real structure in

the field or laboratory to a certain extent to create a virtual testbed. For example, new functions could be integrated and tested in this testbed, or network traffic data could be made available for external monitoring systems, such as intrusion detection systems. From this point of view, reconstructing automation functions is essential. The basic features of these should be modeled to resemble a commercially used automation device up to a certain level of quality without having to set up these devices in the laboratory as hardware.

### *1.2. Motivation*

This paper explores the emerging domain of virtualizing protection IED functionalities within a virtual substation environment. This paper explicitly does not aim to develop productive IEDs and integrate them into real substations. Virtualization also has potential for application in the field, as shown, for example, in [5,8–10]. Our simulations should contain simplifications that reduce the complexity of vIEDs to keep simulated IEDs as lightweight as possible and to be able to integrate them into virtualization. In general, however, it is also possible to include very detailed representations of real IEDs in co-simulation. In this case, the simulation environment can serve as a substitute for a test environment for functional tests. To test entire system networks, however, simplified vIEDs are again useful, and they can be combined with very detailed IEDs. Complex testbeds based on the vIEDs presented here can be created using this approach. Such an approach can significantly reduce the expenses and costs of testing for manufacturers or integrators. In comparison to the existing literature on virtual IEDs [5,10–12], the focus here is neither on virtualization nor on time requirements, but rather on functional implementation for testing purposes. Enhancements in the area of vIED development can enable virtual protection assessments to be carried out, which can significantly reduce the time and effort required for factory acceptance tests (FATs) and site acceptance tests (SATs).

### *1.3. Objective*

Previous publications, such as [6,7], have mainly focused on the description and development of a virtual testbed system itself. In [4], in particular, the focus is on the development of the testbed in the form of a co-simulation in which virtual IEDs can be placed. This publication aims to present the procedure and an example of a vIED development that can be used in the testbed demonstrated in [4]. The primary objective of this publication is to implement and evaluate a virtualized protection IED within a virtual substation framework. In addition to the communication stack using libiec61850 [13], the focus is on abstracting IED functionalities, including various overcurrent protection schemes, within a containerized environment. To replicate functions such as vIEDs, templates that are as simplified as possible but still valid in terms of function are therefore required, which can be used to reconstruct substation automation in virtualization. This article presents a procedure and an implementation example of a protection IED for this purpose. This paper will show how the communication and function layer can be designed and implemented using open-source libraries based on the design specification for vIEDs from [6,14]. The mapping quality of the function will then be analyzed in Section 3. Therefore, the mapped protection function as a vIED will be compared with a commercial IED of the same protection function regarding the electrical behavior, i.e., the effect in the power grid simulation.

## 2. Materials and Methods

### *2.1. Virtualization Framework and Containerization*

A co-simulation was designed and presented for various use cases, such as failure analysis or functionality testing, where it is possible to implement virtual components or IEDs and to feed them with power grid information from a separate simulation. The published co-simulation thus enables the communication level of a substation to be mapped using the IEC 61850 standard based on SDN virtualization. For this, vIEDs are essential for the inclusion of station functionalities. Mapped virtual IEDs can be communicatively connected to each other in network virtualization and exchange information. By coupling

virtualization with a power grid simulation, entire network scenarios can be simulated, and virtualized IEDs can be fed with measured values from the simulation. IEDs can therefore implement various automation functions of the station automation and feed control commands back into the power grid simulation [6,7]. The structure of the co-simulation is shown in Figure 1.

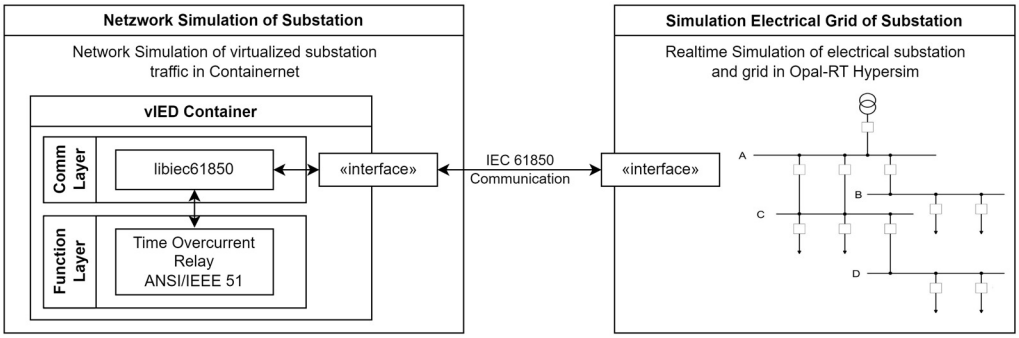


**Figure 1.** Co-simulation structure including proposed vIED layout with two separated layers.

The co-simulation is therefore based on the implementation of vIEDs in virtualization, the construction of a network consisting of several vIEDs, and coupling with a power grid simulation including the associated interfaces. Accordingly, a basic design of a structure of vIEDs was presented in [6]. An implementation of a vIED has two layers—a functional layer and a communication layer. In previous studies like [6], only highly simplified functions of the station automation were integrated into the co-simulation. These were mainly used to prove the functionality of the co-simulation. More extensive implementations and comparisons with real IEDs are still pending and will be introduced in this paper.

In the context of implementation, it is beneficial to avoid complex, commercial systems. Instead, this work focuses on basic protection functions, which are combined with an open-source communication stack. Additional management, configuration, and parameterization services, on the other hand, are not considered as they do not contribute to the functional purpose. Accordingly, specifications for protection systems, for example, act as descriptions of the function implementations, and functional behavior can be simulated. In addition to the IEDs' process function, log clients or other traffic-causing services may have to be modeled for the formulated objective of the simulation, i.e., the provision of realistic network traffic. The focus of this paper, however, is exclusively on the process bus connection and implementation of the protection function. The two protection functions (PIOC and PTOC) investigated in this publication are implemented within separate containers but are hosted on the same virtualization platform. The implementation presented can subsequently be used as a kind of template to simulate a virtual infrastructure of an entire substation that is to include process functions. It is therefore sufficient to initially focus on the implementation of the process functions.

### *2.2. Abstraction of IED Communication and Functional Layer*

#### 2.2.1. Communication Layer: Implementation of Substation Process Bus Communication

As depicted in Figure 1, the fundamental architecture of the proposed vIED containers is partitioned into a communication layer and a functional layer, wherein the latter encapsulates, in our case, a substation protection algorithm. Before providing the specifics of the protective function implementation, it is beneficial to provide a brief overview of the implementation of the communication layer. The communication layer is instantiated through the libiec61850 communication stack, which is an open-source project retrievable in [13]. The initiation of the IEC 61850 data model employs the commercial ABB RED 670's Configured IED Description file (CID), which is utilized to derive the data model for the libiec61850 communication stack in an automated way. Consequently, the established interfaces, communication links, and data models of the vIED are aligned with those of

the commercial IED. The vIED, as explicated in this publication and specifically depicted in Figure 2, communicates through two channels within the Containernet network simulation, facilitating interactions with other IEDs or the RT electrical grid simulation. The channels discussed herein are typical for process bus communication in digital substation environments, entailing a highly sampled IEC 61850-9-2 Sampled Values (SVs) data stream. This SV stream, operating in multicast mode, transmits instantaneous values of three-phase current and voltage measurements from a substation feeder to the vIED. This data stream is crucial for the accuracy of digital substation simulations as it enables a detailed emulation of electrical signals but also creates a computational challenge.

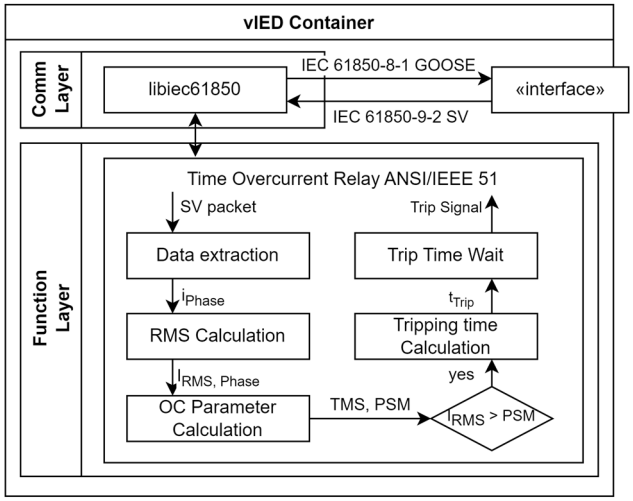


**Figure 2.** A detailed overview of the two layers of the vIED with the structured workflow of PTOC relay.

The evaluation of autoencoders based on the Clark-Park transformation, as presented in [15], could provide a possible remedy. In addition, the vIED communicates with the electrical grid simulation via the IEC 61850-8-1 GOOSE protocol, serving as a return channel. This latency-sensitive GOOSE channel is utilized for the rapid transmission of telegrams and actuation signals across the substation. In this scenario, the GOOSE channel is used to send a trip command to the feeder's circuit breaker within the real-time grid simulation. These described communication channels mirror those of the commercial ABB RED 670 IED.

#### 2.2.2. Reproduced Protective Functions

In this study, two different protection devices are reproduced in the function layer of the vIEDs. One is a time-overcurrent protection (PTOC), and the other is an instantaneous overcurrent protection (PIOC).

**Instantaneous Overcurrent (PIOC, ANSI/IEEE Code 50)**

- Within the domain of power system protection, instantaneous overcurrent relay, denoted by the ANSI/IEEE standard code 50, serves as a critical fundamental protection mechanism [16]. The principle of PIOC entails the immediate activation of the breaker trip once the current surpasses a preset pickup level. So, this type of protection is the most elementary form of overcurrent protection and is independent of the duration of the current excess. The PIOC delivers a nearly instantaneous response to current surges and transient spikes. The actuation time of the relay and the latency of the communication path are crucial elements, making it an ideal subject for investigations of virtualized IEDs. In our tests, the threshold value for triggering the PIOC (pickup current) is 200% of the base current. The load current is around 5.2 A.

**Time Overcurrent (PTOC, ANSI/IEEE Code 51)**

Time overcurrent protection (PTOC), represented by ANSI/IEEE Code 51, is a slightly extended protection against the overcurrent but also a critical component in power systems [16]. It involves a relay that initiates a circuit breaker trip based on the current magnitude and the duration of the overcurrent event. The tripping time of the PTOC is defined by a time–current characteristic curve, which is defined in various standards. In this work, we employ the Standard Inverse Curve (SIC), as defined by the IEC standard, for the time–current characteristic evaluation of the vIED and the commercial IED [17]. This also determines the parameters $\alpha = 0.02$ and $k = 0.140$ for calculating the curve. The following parameters were selected for the PTOC for the subsequent analyses: The pickup current $I_{Pickup}$ is 1000% of the base current. Here, too, the load current is approximately 5.2 A. The Time Multiplier Setting (TMS) is set to 0.1. These parameters were selected in accordance with the ABB IED specifications to ensure comparability. The following equation from [17] can be used to calculate the tripping time $t_P$ using the IEC Standard Inverse Curve:

$$t_P(I_{RMS}) = \frac{TMS \cdot k}{\frac{I_{RMS}}{I_{Pickup}}^{\alpha} - 1} \quad (1)$$

2.2.3. Function Layer: Implementation of Reproduced Protective Functions

This section aims to clarify the emulation of the overcurrent protection types using PTOC as an illustrative example. Figure 2 illustrates the general workflow of the overcurrent protection algorithm. The PTOC algorithm operates as a sequential process that initiates with the extraction of data from newly captured IEC 61850-9-2 SV packets. This step involves the extraction of current data, reflecting the instantaneous electrical conditions for each phase. Following data acquisition, the algorithm computes the root mean square (RMS) value of the current for each respective phase, which provides the basis for the operational decisions of the algorithm. The algorithm then progresses to the determination of PTOC-specific parameters, like the Time Multiplier Setting (TMS) or Plug Setting Multiplier (PSM), which are essential for the subsequent operational logic. The core of the algorithm's functionality is continuous assessment against the PSM threshold; when the RMS value of the current surpasses the PSM, the algorithm proceeds to calculate the tripping time. The appropriate tripping time is calculated based on the current's magnitude relative to the threshold and the Standard Inverse Curve (SIC), as defined in [17]. After computing the tripping time, the algorithm enters a state of conditional waiting during which it waits for the elapse of the calculated tripping time, all the while verifying whether the tripping conditions persist. If the conditions remain, the algorithm alters the data model within the libiec61850 communication stack, thereby triggering the transmission burst of GOOSE packets to the electrical grid simulation, and thus enacting a trip event.

When comparing the described PTOC algorithm of the vIED with those of commercial IEDs, one must consider potential simplifications and constraints. With the focus on simple integration, we focused on a basic version of PTOC, which is based on core principles of an overcurrent protection function. The PTOC module in commercial IEDs offers more extensions that can be configured as required. For example, the PTOC module in the compared ABB IED is called "Four step residual overcurrent protection" (EF4PTOC) and offers, among other benefits, four-stage protection with different operating current levels and time delays, a direction detection, blocking for harmonics, adjustable polarization, and special logic for parallel transformer switch-on processes. The algorithm workflow shown in Figure 2 is subject to certain reductions in complexity due to the proprietary and confidential nature of commercial PTOC algorithms. This prevents the full and comprehensive reproduction of a commercial PTOC algorithm in this study. Consequently, the PTOC algorithm, shown in Figure 2, only encapsulates rudimentary functionality, which may lead to less advanced fault detection and protection capabilities.

### *2.3. Evaluation Methodology and Scenario*

The testbed for the integration of the vIED and their functions is the real-time power grid simulation Hypersim, which provides the described I/O interfaces. Hypersim by Opal-RT offers a simulation of electrical circuits with a step width of 50 microseconds. This enables the precise modeling of dynamic electrical behaviors and transient phenomena within the power grid, which is critical for the evaluation and verification of power system responses and protective schemes [18]. To integrate the substation protection functions, it is necessary to model and simulate a section of the grid with a substation, complete with the necessary measurement outputs and controllable actuating elements (e.g., circuit breakers). Figure 3 illustrates a segment of the modeled substation, showing the arrangement of the two feeder branches.

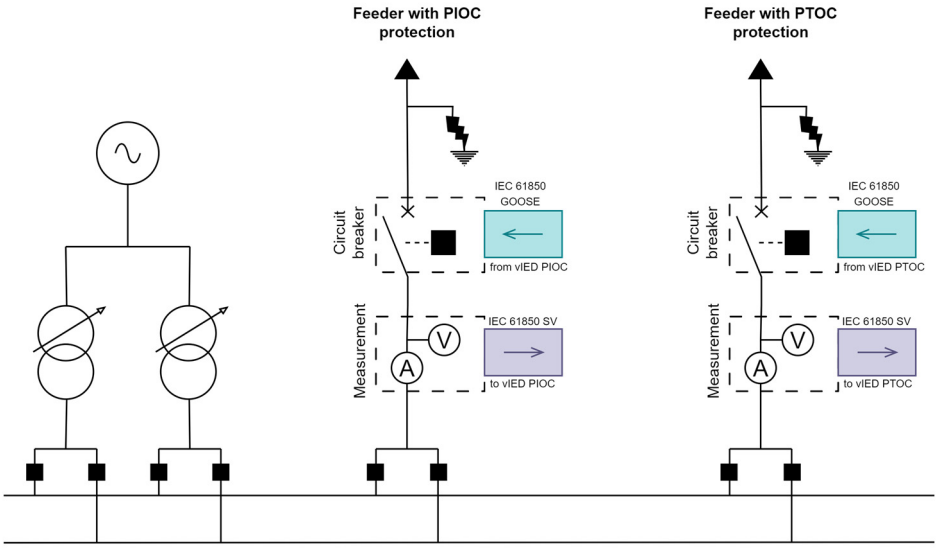


**Figure 3.** Extract of modeled substation with two feeder branches for protection function validation.

Each branch is designated for the testing of a specific protection function. Figure 3 also highlights the measurement points along each feeder where voltages and currents are recorded. These measurements are transmitted to the vIED via the SV protocol. Moreover, each feeder is equipped with a circuit breaker, which is actuated by the GOOSE protocol.

The validation scenario for the described vIED implementations involves a short-circuit event in the simulated three-phase electrical circuit. This typical event was chosen to test the reproduced IED functionality. The three-phase short circuit was generated at different simulation times and different feeders, as shown in Figure 3, to examine the IED's reaction und protection function individually. This allowed us to evaluate the response of the virtualized protection IEDs separately. Furthermore, this setup allowed for a comparison to be made between the response of the virtualized IEDs and their physical counterparts during a critical event in the power grid. The short circuit to investigate the behavior for the instantaneous overcurrent protection (PIOC) occurs at a simulation time of 4.0 s. For the time overcurrent protection (PTOC), the event starts at 6.0 s. The short-circuit currents are switched off by triggering the vIED protection function, which sends a GOOSE message to the grid simulation.

## 3. Results

### *3.1. Resulting Short-Circuit Currents*

The evaluation criteria include the design and accuracy of the virtualized protection schemes in emulating the tripping characteristics. As mentioned, the validation scenario for the described vIED implementation involves a short-circuit event in the simulated three-phase electrical circuit. The resulting fault currents for each vIED under the evaluation scenario are shown in Figure 4.

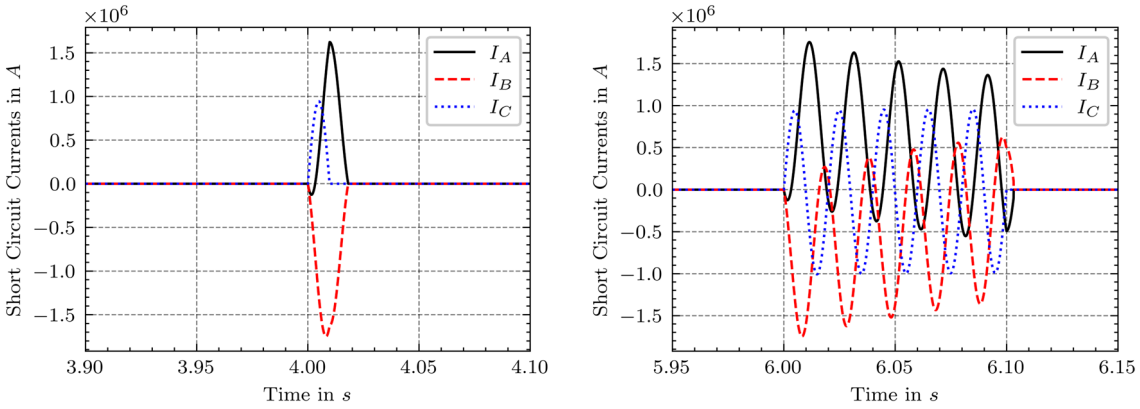


**Figure 4.** Resulting short-circuit currents when using implemented vIED PIOC (**a**) and vIED PTOC protection algorithm (**b**).

In both cases, the currents are switched off by the response of the vIEDs so that the critical event is cleared after a few milliseconds. Figure 4 also shows the intended difference in the reaction latencies between the two forms of overcurrent protective devices. The PIOC vIED operates with a rapid interruption of the fault current in immediate response to its detection. In contrast, the PTOC vIED exhibits a calculable temporal delay, extending over several 50 Hertz sinusoidal oscillations, before fault isolation is achieved. This corresponds to the intended functional purposes of the overcurrent protection types. Specifically, the PIOC is designed to extinguish the fault within the first sine oscillation to shield electrical equipment from peak currents and possible destruction.

### *3.2. Comparison of Tripping Times*

As mentioned, the benchmark for assessing the virtualized IED's performance is ABB RED 670 IED. In this section, we present the results from the comparison of a physical ABB protection IED and a containerized software approach that utilizes the same input and output data. The response of the virtualized IED to the three-phase short circuit is represented in detailed plots, which compare the tripping times of virtualized protection schemes with those of the physical ABB RED 670 IED. The tripping times of the two types of overcurrent protection based on the evaluation scenario are displayed in Figure 5.

The provided plots and the error measures in Table 1 show that the tripping times for the two overcurrent protection scenarios have a high degree of similarity with minor deviations. The plot on the left-hand side showcases the instantaneous overcurrent protection algorithm, where both the vIED and the compared ABB IED are triggered instantaneously. The absolute error for the tripping time is 0.21 ms. Conversely, the plot on the right-hand side demonstrates that the tripping times for both PTOC implementations display a high degree of uniformity. Both show a delay time slightly exceeding 95 milliseconds prior to the dispatch of the tripping signal to the circuit breaker. The relative error of the vIED tripping time to the commercial IED is 2.04%. The vIED is observed to trip marginally faster, which could be ascribed to minor computational deviations encountered during the tripping time calculation, perhaps due to varying RMS computation or the tmplementation of tripping

characteristic curves. Overall, Figure 5 shows that the vIED's operational characteristics are closely aligned with those of the compared commercial IED.

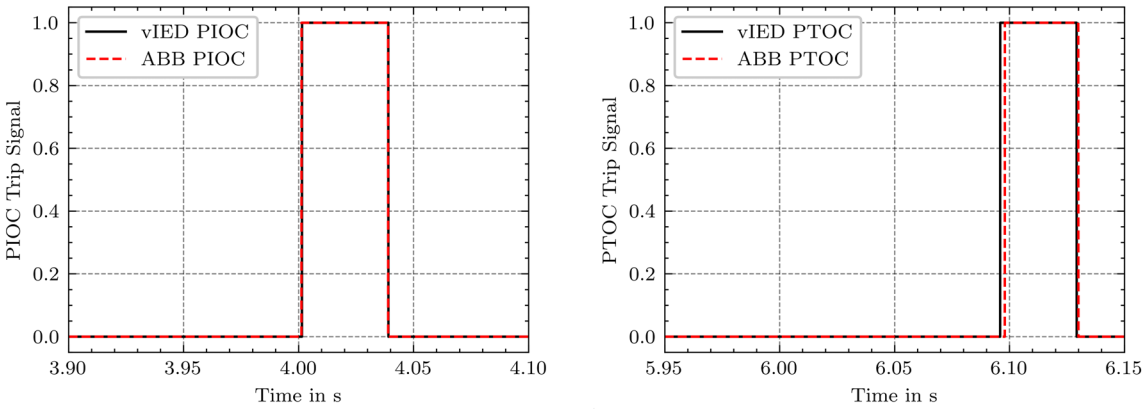


**Figure 5.** Resulting tripping times for described vIED approach and commercial ABB IED for PIOC (**a**) and PTOC protection algorithm (**b**).

**Table 1.** Comparison of total fault clearance times.

| Protection Function | PIOC | PTOC |
|---|---|---|
| vIED container | 1.50 ms | 95.95 ms |
| ABB RED 670 | 1.29 ms | 97.95 ms |
| Absolute Error | 0.21 ms | 2 ms |
| Relative Error | 16.28% | 2.04% |

For a more detailed comparison of the IED's performance, it is beneficial to look at the total fault clearing time across the two implementations. The software implementation of both the merging unit and the 61850 server also plays an important role in this context [19]. Accordingly, an analytical portrayal of the full fault clearing duration, as expounded in [19], is delineated in Figure 6.

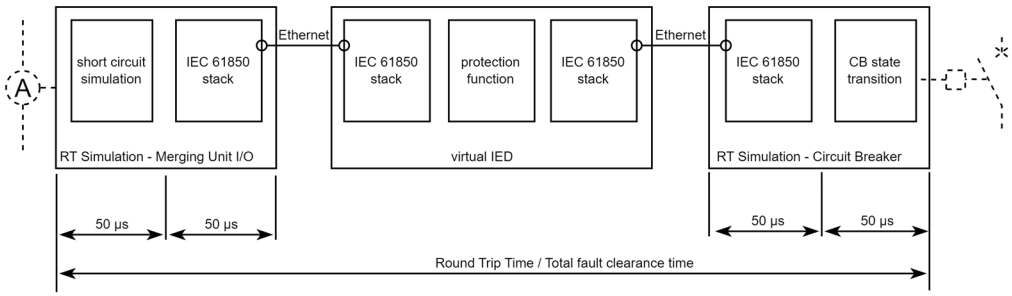


**Figure 6.** A breakdown of the total fault clearance time in digital IEDs.

Figure 6 shows the total fault clearing time, which encompasses the GOOSE packet transmission and additional computation and processing delays. The GOOSE packet transmission is restricted by the directive of IEC 61850-5 to a maximum of 3 ms for applications critical to protection schemes [20]. This guideline specifically addresses communication latency, and not the complete fault clearing process. The delays for computation and processing time includes, in this case, the delay caused by the I/O drivers of Hypersim (IEC 61850 software stack), as well as the selected simulation time step of the real-time simulation of the electrical network. In this study, both amount to one simulation step, which corresponds to 50 µs. In breaker operations in the field, the time taken to extinguish the arc and the mechanical tripping time of the circuit breaker are added to the fault

clearance time. These vary greatly depending on the arc extinguishing method (oil, FS6, vacuum, and air) and are not modeled and taken into account in the Hypersim model. Furthermore, the impact of network infrastructure, particularly Ethernet, on these processes has been modeled and discussed in detail in [21]. Table 1 shows the measured total fault clearance times.

## 4. Discussion

### *4.1. Interpretation of Results*

The presented results show the effectiveness of the implemented protection functions with coupling to the power grid simulation. The implemented short-circuit events within the power grid correctly trigger the implemented vIEDs, and these correctly trip the implemented switches. Pure process functionality is therefore proven. The comparison of the tripping times with the real protection systems also shows that the implementations are in a similar tripping time range. As expected, the PIOC function has a lower performance than the adequate real system from ABB. The simplifications made within the realization and implementation in a container may be possible reasons for this.

In contrast, the clearance time for the PTOC function for the vIED is lower than that of the real system. This can be due to implementation deviations between the systems and shows that the calculation basis for the waiting times or parameterization may be different. However, the rough time range is also very similar for the PTOC system.

Looking at the various time components in Figure 6, the transmission time between two physical components comes to the fore, which is defined in IEC 61850-5 for various applications and types of criticalities. A maximum permitted transmission time of 3 ms applies here for triggering using GOOSE. Regarding the measured triggering time of the PIOC, the given setup is significantly shorter than this time. In [6,21], the transmission times were examined in more detail using the SDN infrastructure. In particular, [6] shows that the transmission times can be well maintained within the framework of the co-simulations with direct coupling. The same setup with the ABB system has a similarly low transmission time. Overall, the significant undercutting of the upper limit of the transmission time given by IEC 61850-5 can be explained by the direct coupling of the simulation to the protection system without any further intermediate network infrastructure. This can be explained by the fast communication stack used within the power grid simulator. We estimate this with a simple simulation time of 50 µs, as shown in Figure 6.

### *4.2. Advantages of Containerization*

Overall, the approach presented for abstracting the relevant IED functions and implementing them as container instances offers the possibility of setting up very flexible testbeds in an SDN environment. This container-based environment can be successfully coupled with the power grid simulation, and scenarios for function or communication tests can be used without a significant parameterization effort. The necessary creation of essential components as templates is the goal and is shown here using the PIOC and PTOC functions. This results in lightweight representations of the real IEDs, which demonstrably abstract the function well and thus have a certain mapping quality for different investigations. The template implementations can be built entirely on open-source components and emulate various functions.

Especially in comparison to real hardware testbeds, flexibility is greatly increased, and the financial burden of testbed creation is greatly reduced. Changing systems or infrastructures can therefore be simulated without changing the hardware setup.

### *4.3. Limitations and Future Work*

While this study confirms the viability of virtualized IEDs, it also identifies potential limitations and areas for future research, including the extension to more complex protection schemes and real-world testing scenarios. The implemented PIOC and PTOC represent a relatively simple range of functions. More complex systems, which are implemented in substations, can be considerably more complicated to implement to reproduce them as a template. Containerization also limits the computing resources that may be required for complex systems.

Further limitations have already been shown in the focus on the process function and the non-inclusion of other services, such as management functions. This limits the application of co-simulation to process behavior and the resulting network traffic.

Consequently, future work will focus on extending the functions within the virtual testbeds. Additional vIED templates will be developed and validated against real systems to be able to virtually simulate substations as holistically as possible. The aim is also to extend the functions of the individual containers, for example, to implement log functions. This means that a resulting testbed can also be integrated into monitoring systems, such as SIEM systems, with the aim of implementing IT attacks on virtual infrastructures. For this purpose, further services must also be validated to be able to evaluate the overall behavior of the vIEDs.

## 5. Conclusions

This paper successfully demonstrates the implementation and evaluation of virtualized protection IEDs within a virtual substation environment. The use of libiec61850 for communication abstraction, combined with the replication of overcurrent protection mechanisms, leads to a complete process representation of a protection IED. This results in the possibility of setting up virtual testbeds based on these vIEDs for various investigations. The containerized vIEDs presented in this study show good performance in terms of computing efficiency, which indicates that they could be capable of replicating the functionalities of physical IEDs. This clearly requires a higher degree of accuracy in the representation of the functional layer, which can be fulfilled by IED device manufacturers. Moreover, a containerized approach for IEDs offers significant advantages in terms of scalability by using automatic pipelines for the creation of vIEDs based on SCL descriptions. This allows for an efficient simulation of larger substation environments by simply deploying additional vIED instances. This could provide a flexible and cost-effective solution for testing and development purposes for IEDs. The implementations shown are necessary to create the processes within the substation automation and to couple these with the power grid simulation. Such a testbed requires extensive validation under various aspects to be usable for the intended functional and communication tests. For this reason, the validation of process capability in the context of co-simulation is included in this paper.

The results demonstrate the validity of the approach with the restrictions and limitations set out. Successful validation provides a basis for further work in the creation of vIEDs. In the future, these created templates should also be coupled with manufacturer-specific container instances of real IED applications. The virtual network offers great potential for testing the container instances extensively under different aspects and enriching the co-simulation.

By fully implementing the substation automation in the virtualization and coupling as part of the co-simulation, the goal of investigating dependencies between the power grid and the communication network is pursued. The implemented vIEDs make an essential contribution to achieving this goal.

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## References

1. Rehmani, M.H.; Davy, A.; Jennings, B.; Assi, C. Software Defined Networks-Based Smart Grid Communication: A Comprehensive Survey. *IEEE Commun. Surv. Tutor.* **2019**, *21*, 2637–2670. [CrossRef]
2. Fang, X.; Misra, S.; Xue, G.; Yang, D. Smart Grid—The New and Improved Power Grid: A Survey. *IEEE Commun. Surv. Tutor.* **2012**, *14*, 944–980. [CrossRef]
3. Huang, Q.; Jing, S.; Li, J.; Cai, D.; Wu, J.; Zhen, W. Smart Substation: State of the Art and Future Development. *IEEE Trans. Power Deliv.* **2017**, *32*, 1098–1105. [CrossRef]
4. Aftab, M.A.; Hussain, S.S.; Ali, I.; Ustun, T.S. IEC 61850 based substation automation system: A survey. *Int. J. Electr. Power Energy Syst.* **2020**, *120*, 106008. [CrossRef]
5. Wojtowicz, R.; Kowalik, R.; Rasolomampionona, D.D.; Kurek, K. Virtualization of Protection Systems—Tests Performed on a Large Environment Based on Data Center Solutions. *IEEE Trans. Power Deliv.* **2022**, *37*, 3401–3411. [CrossRef]
6. Rösch, D.; Nicolai, S.; Bretschneider, P. Combined simulation and virtualization approach for interconnected substation automation. In Proceedings of the 2021 6th International Conference on Smart and Sustainable Technologies (SpliTech), Bol and Split, Croatia, 8–11 September 2021; pp. 1–6.
7. Rösch, D.; Nicolai, S.; Bretschneider, P. Container-based Virtualization of an IEC 61850 Substation Co-Simulation Approach. In Proceedings of the 2022 10th Workshop on Modelling and Simulation of Cyber-Physical Energy Systems (MSCPES), Milan, Italy, 3 May 2022; pp. 1–6.
8. Torres, E.; Eguia, P.; Abarrategi, O.; Larruskain, D.M.; Valverde, V.; Buigues, G. Trends in Centralized Protection and Control in Digital Substations. *RE&PQJ* **2023**, *21*, 196–201. [CrossRef]
9. Kruger, C.; Narayan, A.; Castro, F.; Hassan, B.H.; Attarha, S.; Babazadeh, D.; Lehnhoff, S. Real-time Test Platform for Enabling Grid Service Virtualisation in Cyber Physical Energy System. In Proceedings of the 2020 25th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Vienna, Austria, 8–11 September 2020; pp. 109–116.
10. Wojtowicz, R.; Kowalik, R.; Rasolomampionona, D.D. Next Generation of Power System Protection Automation—Virtualization of Protection Systems. *IEEE Trans. Power Deliv.* **2018**, *33*, 2002–2010. [CrossRef]
11. Martinez, M.T.V.; Comech, M.P.; Hurtado, A.A.P.; Olivan, M.A.; Cortón, D.L.; Del Castillo, C.R. Software-Defined Analog Processing Based on IEC 61850 Implemented in an Edge Hardware Platform to be Used in Digital Substations. *IEEE Access* **2024**, *12*, 11549–11560. [CrossRef]
12. Manbachi, M.; Hammami, M. Virtualized Experiential Learning Platform (VELP) for Smart Grids and Operational Technology Cybersecurity. In Proceedings of the 2022 IEEE 2nd International Conference on Intelligent Reality (ICIR), Piscataway, NJ, USA, 14–16 December 2022; pp. 54–57.
13. Libiec61850. IEC 61850 Library. Available online: https://libiec61850.com/downloads/ (accessed on 18 September 2023).
14. Kabbara, N.; Nait Belaid, M.O.; Gibescu, M.; Camargo, L.R.; Cantenot, J.; Coste, T.; Audebert, V.; Morais, H. Towards Software-Defined Protection, Automation, and Control in Power Systems: Concepts, State of the Art, and Future Challenges. *Energies* **2022**, *15*, 9362. [CrossRef]
15. Kummerow, A.; Alramlawi, M.; Dirbas, M.; Nicolai, S.; Bretschneider, P. Clark-Park Transformation based Autoencoder for 3-Phase Electrical Signals. In Proceedings of the 2023 IEEE PES Innovative Smart Grid Technologies Europe (ISGT EUROPE), Grenoble, France, 23–26 October 2023; pp. 1–5.
16. *C37.2-2022*; IEEE Standard for Electrical Power System Device Function Numbers, Acronyms, and Contact Designations. IEEE: Piscataway, NJ, USA, 2022. [CrossRef]
17. *C37.112-2018*; IEEE Standard for Inverse-Time Characteristics Equations for Overcurrent Relays. IEEE: Piscataway, NJ, USA, 2019. [CrossRef]
18. OPAL-RT TECHNOLOGIES Inc. Hypersim Specifications. Available online: https://www.opal-rt.com/systems-hypersim/ (accessed on 11 March 2024).
19. Meier, S.; Werner, T.; Popescu-Cirstucescu, C. Performance considerations in digital substations. In Proceedings of the 13th International Conference on Development in Power System Protection 2016 (DPSP), Edinburgh, UK, 7–10 March 2016; p. 9.

20. *IEC 61850-5:2013*; Communication Networks and Systems for Power Utitlity Automation—Part 5: Communication Requirements for Functions and Device Models. International Electrotechnical Commission: Genf, Switzerland, 2013.
21. Rösch, D.; Bauer, T.; Nicolai, S.; Bretschneider, P. Delay modeling for virtualization-based Co-simulation of IEC 61850 substations. *J. Clean. Prod.* **2022**, *368*, 133179. [CrossRef]