UNIVERSIDADE FEDERAL DO PARANÁ

GUILHERMME JOSÉ LISBOA DOS SANTOS

PERFORMANCE ANALYSIS OF TRANSFORMER DIFFERENTIAL PROTECTION (87T) BASED ON SAMPLED VALUES

CURITIBA

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Orientador: Prof. Dr. André Augusto Mariano

Coorientador: Prof. Dr. Mateus Duarte Teixeira

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RESUMO

A norma IEC 61850 e o barramento de processos se tornaram o padrão para sistemas de automação em subestações no mundo todo, redefinindo como os Sistemas de Proteção, Controle e Automação (PACS) são projetados. A aplicação do barramento de processos representa a utilização de *merging units* como um elemento de digitalização entre equipamentos primários e relés de proteção. Este novo componente no sistema de proteção pode introduzir tempo adicional para eliminação de faltas na cadeia de proteção. Para esta dissertação, o objetivo é analisar o impacto destas alterações na cadeia de proteção. Foi utilizado um ambiente de testes para avaliar uma proteção de transformador em uma condição tal que permitisse quantificar o desempenho do transformador em cenários específicos: *i)* diferentes topologias de *merging units*, com uma ou duas *merging units* publicando *SV streams*, mais uma condição com uma simulação híbrida, com um enrolamento de transformador medido digitalmente e outro convencionalmente; *ii)* com *streams* de *sampled values* considerando um ou dois ASDUs, como especificado nas normas IEC 61850-9-2LE e IEC 61869-9 respectivamente; *iii)* O volume de tráfego de rede, levando em conta o uso de VLANs para limitar as mensagens que são entregues as portas ethernet do IED de proteção, variando de todas as mensagens publicadas na rede, para apenas as necessárias, mais um caso adicional onde todos os dispositivos desnecessários foram desconectados. Todos os testes foram realizados com um relé de proteção adicional conectado em paralelo com o digital, para gerar os resultados exatos necessários para comparar aplicações digitais e convencionais. Para todos os casos de teste, uma mala de testes foi utilizada para gerar a falta diferencial trifásica. Os resultados dos testes identificaram um desempenho melhor para topologias híbridas ou com duas MUs do que com uma MU. A aplicação medida com uma ASDU encontrou tempos de trip mais rápidos do que com duas ASDU. A comparação relacionada a tráfego de dados confirma seu impacto no desempenho da proteção, onde uma rede com tráfego leve apresentou resultados melhore que em testes com volume maior. Finalmente, a comparação geral entre todos os testes com proteção com barramento de processos e convencional resultaram em resultados levemente mais rápidos para a proteção convencional. Ainda, todos os testes realizados com merging units atenderam as normas referidas para desempenho de proteção, bem como todos os resultados estão alinhados com aqueles apresentados nas publicações utilizadas como referência.

Palavras-chave: IEC 61850. Barramento de Processos. Proteção Diferencial de Transformador. Sampled Values. Subestação Digital. IEC 61869-9

ABSTRACT

IEC 61850 and process bus have become the standard for substation automation systems worldwide, redefining how Protection, Automation, and Control Systems (PACS) are designed. The application of process bus represents introducing merging units as the digitization element between the primary switchgear and protection relays. Such new component in the protection system can induce additional time in the overall protection chain for fault clearance. For this dissertation, the objective is to analyze the impact of such changes in the protection chain. A test environment was utilized to evaluate a transformer protection in such a condition that allowed to quantify its performance for certain scenarios: *i)* different merging unit topologies, with either one or two MUs publishing SV streams, plus another condition with a hybrid simulation, with one transformer winding digitally measured and another conventional one; *ii)* with sampled values streams considering one or two ASDUs, as present on IEC 61850-9-2LE and IEC 61869-9 respectively; *iii)* The network traffic load, by taking into account the usage of VLANs to limit the data that is delivered to the ethernet ports of the protection IED, ranging from all the published messages in the network, to just the necessary ones, plus an additional case where all unnecessary devices were disconnected. All tests were performed with a conventional protection relay connected in parallel to the digitized one, to generate the exact results necessary to compare digital and conventional applications. For all test cases, a relay test set was used to generate a three-phase differential fault. Test results have identified better performance for topologies with hybrid or two MUs then with one MU. The measured application with one ASDU had faster trip times then the one with two ASDU. The comparison related to network traffic shows the impact of it on protection performance, where a light network traffic load resulted on better results than the tests with more load. Finally, the overall comparison between all tests with process bus and conventional protection give the conventional protection a slight better overall result. Still, all test results with merging units have complied with the referred standards for protection performance, as well as the results are aligned with those found on reference papers.

Keywords: IEC 61850. Process Bus. Transformer Differential Protection. Sampled Values. Digital Substation. IEC 61869-9

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LIST OF ABBREVIATIONS

ANSI	American National Standards Institute
ASDU	Application Service Data Unit
CID	Configured IED Description
CT	Current Transformer
FAT	Factory Acceptance Test
GGIO	Generic Process I/O
GNSS	Global Navigation Satellite System
GOOSE	Generic Object-Oriented Substation Event
GPS	Global Positioning System
HSR	High Seamless Redundancy (IEC 62439-3)
ICD	IED Capability Description
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers
IRIG-B	Inter-range Instrumentation Group-B
IT	Instrument Transformer
LAN	Local Area Network
LPIT	Low Power Instrument Transformer
MMS	Manufacturing Message Specification
MU	Merging Unit
NCIT	Non-Conventional Instrument Transformer
PACS	Protection, Automation and Control Systems
PPS	Pulse per Second
PRP	Parallel Redundancy Protocol (IEC 62439-3)
PTP	Precision Time Protocol (IEEE 1588)
RSTP	Rapid Spanning Tree Protocol
SCADA	Supervisory Control And Data Acquisition
SCD	Substation Configuration Description
SCL	Substation Configuration Language
SSD	System Specification Description
SV	Sampled Value
UPC	Protection and Control Unit (*Unidade de Proteção e Controle)*

VLAN	Virtual Lan Arena Network
VT	Voltage Transformer
XML	eXtensible Markup Language
87T	Transformer Differential Protection (ANSI)

CONTENTS

1 INTRODUCTION

1.1 CONTEXT

Protection, Automation, and Control Systems (PACS), as the digital component present in substations and other elements of power systems, have been a paradigm shift, with the adoption of IEC 61850 standard's process bus.

One of the main elements of such disruption in regards of deploying process bus is the replacement of purely copper-based analog measurements connection from the switchyard to the protection devices located in control rooms. Such application is now replaced by digitized sampling, based on IEC 61850 sampled values (LEITLOFF, KURTZ, LADRIERE, CAYUELA, & BRUN, 2018). The sampled values are transmitted through ethernet networks from either Low Power Instrument Transformers (LPITs) or Merging Units, installed close to the primary equipment in the switchyard, to the protection and control devices, now called Intelligent Electronic Devices (IEDs).

There are numerous advantages to be considered in such innovation, naming only a few of them here: (OLIVEIRA & ARCON, 2019)

- Construction cost reduction (smaller amount of copper cables, installation time);
- Higher system monitoring capacity with additional monitorable data generated; and
- New supervision resources and testing tools.

On the other hand, the innovative technology adds new stages in entire protection chain. Starting from the analog measurement stage, which originally were transmitted directly through copper from current and voltage transformers (CTs and VTs) to protection devices, now are converted into sampled values and published on ethernet networks to the IEDs.

Still from the switchyard to the control room, status signals from primary equipment as circuit breakers and disconnect switches are transmitted using a different communication protocol, the Generic Object-Oriented Substation Event (GOOSE) and similarly, have additional steps between the main equipment and the protection devices. Trip signals, from protection devices to circuit breakers by long copper cable, are replaced by GOOSE transmission from IEDs to merging units (CIMADEVILLA & SANTIAGO, 2018).

1.2 MOTIVATIONS

IEC 61850 station bus, deployed in control rooms, is a reality in many countries. Process bus remains as the next threshold to be crossed, as protection requires absolute high trip speeds to ensure primary equipment safety and system stability (MASON).

A protection system, by definition, is a scheme composed by one or more equipment, and other devices designed to perform one or more protection functions. They are composed by one or more protection devices, instrument transformers (current and/or voltage), copper cables, trip circuits and, where necessary, communication systems. (LISBOA, 2020).

A protection chain based on sampled values and GOOSE differs from the conventional protection design by the addition of new elements, such as digital communication, and consequently additional delays through packet encoding and decoding (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016). In order for a protection function to operate, whether it is conventional or digitized, it must comply with relevant standards, as those described on the IEC 60834-1 Teleprotection equipment standard (IEC 60834-1, 1999), meanwhile for GOOSE and sampled values transmission one may consider what's described on Part 5 of the IEC 61850 standard.

For a case such as transformer differential protection, the practical conditions where it will be deployed are relevant for the definition of the appropriate protection. In case of protection based on sampled values, the solution's complexity exceeds the conventional definition of CTs and VTs connection to protection devices, because other solutions related to process bus are necessary (LISBOA, 2020).

Among project criteria, it is necessary to consider ethernet network design, choosing the most appropriate architecture (with redundancy based on RSTP, MSTP, PRP, HSR), plus time synchronism (IRIG-B or PTP), merging units composition (number and location of the devices, or even the sampled values transmission standard (61850-9-2LE or 61869-9), as described on (LISBOA & KENZO, 2019).

In literature, among several works presented for transformer and line protection tests, many of them lacked real merging units available, not one with IEC 61869-9, one of the first commercially units available were used on the tests performed for this dissertation.

In addition to that, network concerns were shared on the previously mentioned publications, evaluated network environment as close as possible to real case.

1.3 OBJECTIVES

1.3.1 General

The main objective of this research, focusing specifically a transformer differential protection, is to obtain specific results to determine if a process-bus based protection complies with relevant standards for protection devices, plus how it compared to conventional protection devices.

1.3.2 Specific

Perform the analysis of the impacts on protection performance, when varying relevant elements to the proper application of IEC 61850 sampled values for process bus-based transformer protection.

Tests will be performed varying three specific elements:

a) **Quantity of Merging Units (Topology):** The merging units' topology can be organized with:
   - two devices, one for each transformer winding;
   - with one unit that will be responsible for acquiring current measurements for both windings;
   - or hybrid, where one measurement will be performed directly by the protection device, and the second one will be digitized (measured through a Merging Unit).

b) **Ethernet network traffic load**: The ethernet network where all IEC 61850 data signals will flow, can be set with the most recommended design considerations, with an structured data transmission where all GOOSE and sampled values multicast messages are restricted only between the publishers and subscribers; it can also be stablished without such recommended organization, risking to overload the devices present in the network and consequently face performance delays; or just have a lightly loaded network traffic, not being able to influence protection relays performance.

c) **Sampled values configuration**: comparing different orientations on how IEC 61850-9-2LE and IEC 61869-9 standards define the sampled values data stream are published.

1.4 STRUCTURE

This dissertation is structured in five chapters, including the introductory one, and the additional ones are organized as described below.

Chapter 2 consists of literature review, encompassing an introductory overview on IEC 61850 and the evolution of substation automation, the background of the standard adoption and major concerns on its application coupled with solutions for such concerns. The additional part of this chapter will focus on transformer protection, relevant standards for protection and how IEC 61850 can impact it. This chapter will include an extensive review of significant publications related to experiences around protection tests performed with process bus, not only for transformer function but others also.

Chapter 3 will focus on cementing the challenges created by replacing conventional protection devices with process bus applications, and on its second part it will describe the laboratory environment that was put together to perform the necessary tests that were executed.

Chapter 4 delivers the test results obtained for all objectives listed (both general and specific) and discusses their interpretation. Comparisons for all test results for process bus variations and conventional protection are put on display.

Chapter 5 addresses the conclusion of the dissertation and suggests future research topics.

2 LITERATURE REVIEW

2.1 SUBSTATION AUTOMATION EVOLUTION

The IEC 61850 standard, especially with process bus application, offers a complete revolution on how protection, automation, and control systems (PACS) are deployed.

The evolution on substation protection, is led by a very conservative market, where solutions that are proven have the preference over innovative technologies. Copper-based connection between primary devices and protection relays have been the same for several decades.

Legacy systems, since protection systems have existed, relied on that. From (MASON, 1956) up to (ZIEGLER, 2005), protection-oriented publications focus on such structure, not considering if the protection device was electromechanical or digital.

The first revolution on protection systems came with the deployment of the application of microprocessor-based protection devices (LARSON, FLESCHSIG, & SCHWEITZER, 1979), and later the rise of automated substation Protection, Automation, and Control Systems (PACS), until here mostly based on serial communication protocols.

Such environment gave birth to several vendor-proprietary systems, which led power utilities to restrictive situation, and a first generation of open standard communication protocols have arisen, such as IEC 60870-5-101/103/104 (DE MESMAEKER, BRAND, & BRUNNER, 2005), plus other ones such as Modbus and DNP 3.0. Other approach has led to develop gateways that allowed some level of interoperability.

Only when EPRI and IEC joined forces to create an interoperable standard, IEC 61850 was the output of such effort. (HOHLBAUM, HOSSENLOPP, & WONG, 2004).

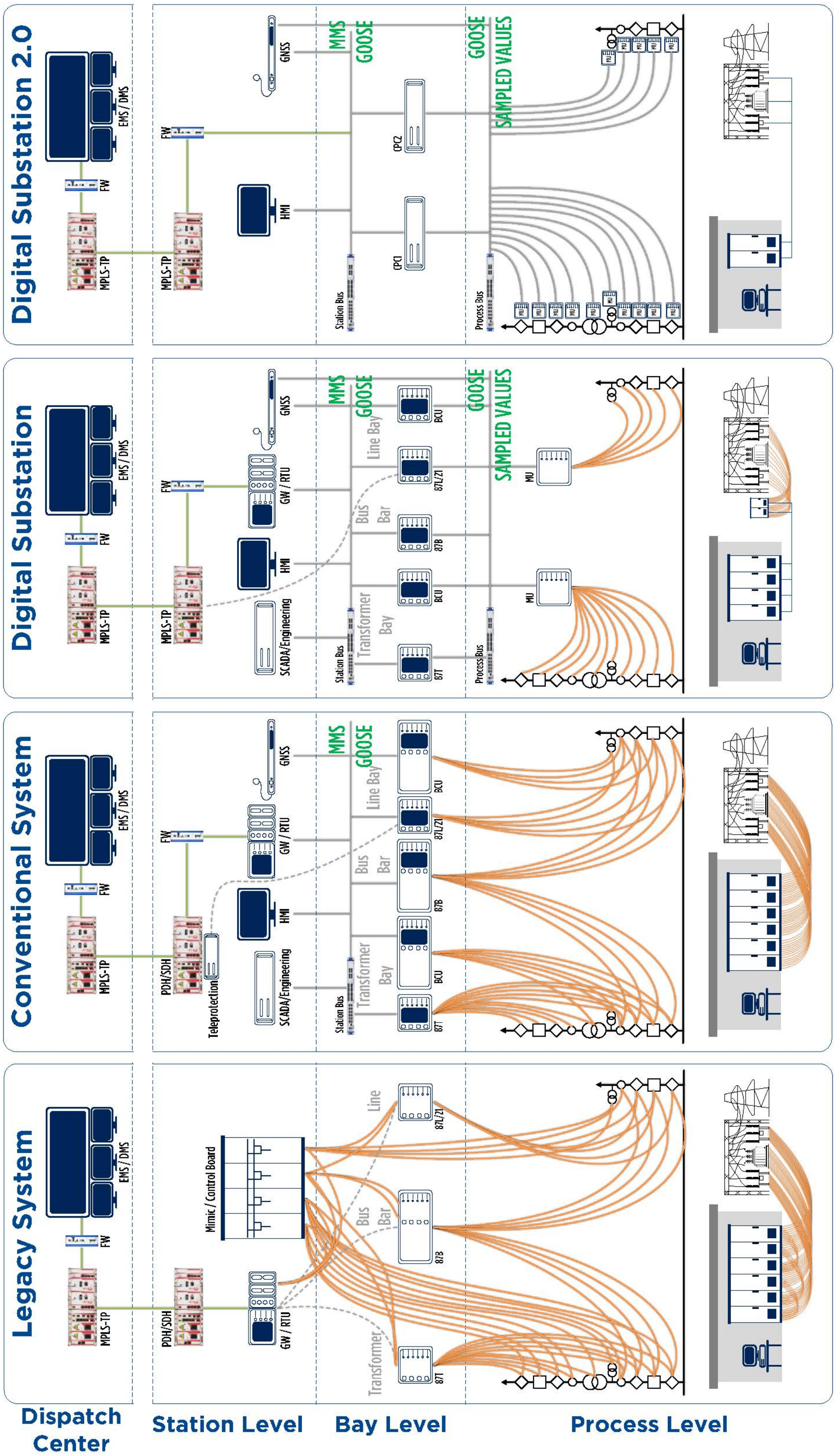
This standard not only allows the beforementioned interoperability between vendors, but also focuses on replacing the ancient method of connecting the switchyard to the control room with copper now with a digitized process bus, analog to what other industries have done for a long time.

The main drivers for such copper replacement are known as Generic Object-Oriented Substation Event (GOOSE) and sampled values. The first being a direct replacement to binary data, used for equipment status, interlocking and trip commands, whereas the latter is the digital version of measured analog current and voltage signals, sampled on a high rates enough to be used for protection functions (LEITLOFF, KURTZ, LADRIERE, CAYUELA, & BRUN, 2018).

This revolution also encompasses a data-modelling structure that offers multiple advantages on specification, design, installation, commissioning, operation, and maintenance (HOHLBAUM, HOSSENLOPP, & WONG, 2004)

The FIGURE 1 represents the evolution of substation automation systems, from legacy electromechanical systems, passing on to conventional systems, up to the now called digital substations, and even introducing another variation of the newer iteration, here named digital substation 2.0 by the author.

FIGURE 1 – Substation automation evolution with IEC 61850



SOURCE: (BELDEN, 2023)

In the following sections, we present several works related to its application, focusing on transformer protection.

2.2 IEC 61850 PROCESS BUS

2.2.1 IEC 61850 Adoption

By 2008, when the first IEC 61850 installations were being deployed, only with station bus, the impression was that there was a migration from developments focused on solutions developed by manufacturers (proprietary communication standards), to the at-the-time new international standard (HOSSENLOPP, CHARTREFOU, THOLOMIER, & BUI, 2008).

More than 15 years later, the adoption of station bus, using MMS and GOOSE in the control room is already usual around the world. The next step, application of process bus and sampled values is on the rise (COELHO & LIMA, 2019) and (LISBOA, 2020). Currently, digital substations are already considered one of the building blocks for smart grids (APOSTOLOV, 2020), also described as a reality, being at the heart of the major trends in power grids: decentralization, decarbonization and digitalization (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020).

The so-called term digital substation, intrinsically connected with the utilization of IEC 61850, is one where all analog interfaces, such as current and voltage measurement, as well as other equipment status and alarms, plus control points are converted to digitized data directly at their source. The main driver for all structured data flow is the IEC 61850 standard. it enables its flow and interoperability between devices and systems from different vendors (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020).

More recently, it has been confirmed that digital substations are still being introduced, with many pilot projects (LEITLOFF, et al., 2022). A first generation was deployed in UK, France and Canada (HOSSENLOPP, CHARTREFOU, THOLOMIER, & BUI, 2008), and another relevant batch of examples are a pilot project in Norway, which started in 2017 (HURZUK, LOKEN, PEDERSEN, & NORDENG, 2020), an extensive pilot project in Scotland, where multiple architectures and merging unit multi-vendor interoperability was tested on a 275 kV substation (MOHAPATRA, et al., 2020), a comprehensive study in France (LEITLOFF, et al., 2021), and an industrial substations (FLEMMING, RESCHKE, SCHNEIDER, ORTIZ, & NEUMEIER, 2021). A collection of these and other relevant pilot projects around the world was published (LOKEN, APOSTOLOV, & LEITLOFF, 2020).

The first 500kV substation project in the world took place in Brazil in 2019 was developed (OLIVEIRA & ARCON, 2019). Other cases were developed in Brazil with 500 kV substations (LELLYS, FONTINHA, & OLIVEIRA, 2019), and pilot projects with lower voltage levels (FORONI JR., BRANDÃO, & HOKAMA, 2019). The previous publications were developed by the main manufacturers of IEDs, and there were also studies developed by system integrators (LISBOA, 2020).

2.2.2 Advantages of IEC 61850

The application of IEC 61850 standard offers significant advantages, when compared to conventional copper-based substations, it can offer advantages on both green field and retrofits, due to its flexibility for design (CROSSLEY, et al., 2011) and (SHARMA, NGUYEN, KUBER, & BARADI, 2021), and can offer improvements on reliability, security, and efficiency (APOSTOLOV, 2020).

When introducing the standard, one of the first significant advantages is the copper cable reduction, listed on multiple instances (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2013), (YANG, CROSSLEY, WEN, & WRIGHT, 2014), (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016), (LEITLOFF, KURTZ, LADRIERE, CAYUELA, & BRUN, 2018), (COELHO & LIMA, 2019), (LELLYS, FONTINHA, & OLIVEIRA, 2019) and (APOSTOLOV, 2020). On some real project publications, the reductions were even quantified, with significant reductions, over 30km of cables. (LISBOA, 2020). In a simple analogy, several copper connections are replaced by on optical fiber pair. (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2013), (OLIVEIRA & ARCON, 2019). Financial analysis of the costs, solely focused on the PACS investment for CAPEX, were published (LISBOA & KENZO, 2019).

The reduction of copper cables does not only translate to their overall quantity, but also to the covered distances of the ones that remain. As cables connecting the CT to the MU will be significantly shorter than the ones the usually connect CTs to IEDs in control/relay rooms, this translates into reduced CT saturation risks. (COELHO & LIMA, 2019). In addition to that, LPITs used for high voltage systems, based on optical fibers technology, have construction characteristics that eliminate entirely the risks of saturation (BASSAN, et al., 2021).

Still in the field of CT risks elimination, other advantages that come with the digitization of analog signals are the elimination of hazardous secondary CT signals in the control room, mitigation of CT explosion risks and reduced SF6 usage, resulting into environmental advantages. (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2013), (YANG, CROSSLEY, WEN, & WRIGHT, 2014), (OLIVEIRA & ARCON, 2019) and (LELLYS, FONTINHA, & OLIVEIRA, 2019).

There are other significant gains on environmental matters. The substation footprint can be reduced (driven by smaller cable trays, smaller control room sizes, reduced panel dimensions) (LELLYS, FONTINHA, & OLIVEIRA, 2019), oil-insulated instrument transformers can be replaced for optical equipment (LPITs), allowing to gather advanced diagnostics and additional analytics data from their assets and make decisions on such data remotely and faster. (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020)

It is important to emphasize that the lifetime spam of primary equipment (power transformers, switchgear) is around 40 years, whereas secondary systems, encompassing protection and control devices, have shorter lifecycles, being replaced more often. IEC 61850 based solutions are designed to optimize the replacement of the secondary systems (YANG, CROSSLEY, WEN, & WRIGHT, 2014).

On a wider perspective, there are significant technical advantages for all stages on a PACS design, when applying IEC 61850, ranging from engineering, operation all the way up to maintenance (OLIVEIRA & ARCON, 2019) and (LELLYS, FONTINHA, & OLIVEIRA, 2019). It also encompasses reductions on commissioning time, and shutdown/intervention duration on expansions and maintenance activities (OLIVEIRA & ARCON, 2019) and (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020).

On the area of project design, the application of IEC 61850 can result in simplified documentation and improved protection schemes (OLIVEIRA & ARCON, 2019). On the same documentation-related subject, there are efforts to create efficient methods for properly create methods to develop proper documentation for GOOSE messages (DA SILVA, 2019)

Standard documents also need to be reviewed to contemplate new digital elements, such as the protection single line diagram, where the CT connections, now only linked to MUs, must somehow represent that this information will be transferred to IEDs. (LISBOA, 2020). Additional documentation necessary for network design, and relevant to improve PACS monitoring for network, GOOSE and SV status. (LISBOA & KENZO, 2021).

In addition to all that, the standard offers a completely new method to design Protection, Automation, and Control Systems (PACS), based on a top-down approach, which starts with the IEC 61850 data modelling for all protection functions and its data flow, on both station and process bus. Such method is already being considered by power utilities (ALEXANDRINO, 2021).

Finally, developments with additional concepts that the IEC 61850 standard can propose have started to appear, and in the Power Distribution a concept called Centralized Protection and Control (CPC), where multiple protection relays can now be centralized into a single computing platform have its first experiences being shared, as (ALEIXO, et al., 2023) and (HEMMER, MELENHORST, & WOERTMAN, 2023) have presented in Europe. In Brazil, these applications have already been published also (OLIVEIRA, SYLVESTRE, & SYRIO, 2023).

In terms of protection functions, the IEC 61850 has already been the solution for a wide-area protection system (LELLYS, 2023), and is already been tested in tandem with packet-based Multiprotocol Label Switching – Transport Profile (MPLS-TP) telecommunication systems for line protection (OLIVEIRA, et al., 2023).

2.2.3 Adoption Resistance

Even with numerous advantages, there has been significant publications in the early adoption years focusing on its insecurity for application, even being described as years away from maturity (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014).

Later It has been stated that the application of process bus fascinates some members of the power systems community, and still leads to lack of confidence to others. The latter happens due to the fact of a paradigm shift, replacing a standard application for a new one (PEREIRA JR, et al., 2018).

The concerns reflected the challenges of introducing an innovative technology that is not familiar to the protection, automation, and control (PAC) specialist. (APOSTOLOV, 2020), and that the transition from wire to network infrastructure has raised doubts related to reliability. The key issues for conventional systems are wire damage and electromagnetic interference. The digitized technology has more concerns to address, such as equipment failure, network congestion, transmission errors, only to name a few. It requires protection engineers develop enough ethernet network knowledge to design and maintain networks that support the needs of a digital substation. (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020)

Finally, (DOLEZILEK, LIMA, ROCHA, RUFINO, & FERNANDES, 2020) published research comparing proprietary direct connection between MU and IED with IEC 61850 based dataflow from MU to IED, without even comparing with conventional devices solutions. Direct connection between MU and IEDs, without the usage of multicast GOOSE and SV eliminates future advantages of IEC 61850 process bus, leading to a conclusion to install IEDs on the switchyard.

Several studies have been published to address these concerns, proving that the technology is dependable and can be used as specified.

Other recent hot topics that could be used as justifiable means to explain resistance for acceptance of IEC 61850 utilization, can be centered around the work of (STEINHAUSER, 2023), who lists concerns on Precision Time Protocol (PTP) applications combined with Parallel Redundancy Protocol (PRP, IEC 62439-3). Plus, recent IT cybersecurity considerations, reflected on IEC 62351-3's orientation on encrypting all MMS, GOOSE and sampled values data on Substations. The primary concern relates to the additional delay on protection operation in terms of process bus, and consequent difficulties to monitor and evaluate substation automation systems, because of the network dataflow loss of visibility due to the suggested encryption. Yet, it is important to reinforce that this publication is not focused on means to refrain to apply this standard, but relevant topics to improve the standard.

2.2.4 Ethernet Networks

For the network concerns, challenges for process bus networks were listed by the time of early adaptations of IEC 61850 (HOSSENLOPP, CHARTREFOU, THOLOMIER, & BUI, 2008). Multiple factors must be considered, such as functionality of the substation PACS, importance of the substation to the entire power grid, sampling rates used, requirement for fault clearing times, PACS philosophy, and system architecture (distributed, centralized, hybrid). (APOSTOLOV, 2020). Most systems are hybrid (distributed protection, centralized HMI, disturbance and event recording, mixed interlocking).

Ethernet network performance has become more critical, as it is the platform where GOOSE and SV will navigate, so the design of the communication network may have a significant impact on the performance of the system (APOSTOLOV, 2020)

Bandwidth is a concern. Just like wire gauge is chosen based on current, link speed must be sufficient to the volume of data being transmitted. As most data is multicast, VLANs or multicast address filtering are used to control the dataflow. Latency is another additional concern. Long network paths and congestions add time to the transmission between publisher and subscriber. Designing the physical connections to ensure that the sender and receiver are as close as possible is the best way to minimize latency. Prioritization can also reduce latency, by using QoS (quality of service) can optimize priority packets to be transferred before less important data. (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020)

The IEC working group TC 57 has published a Technical Report, IEC 61850-90-4 TR – Communication networks and systems for power utility communication – Network engineering guidelines for substations, which should be considered for design of digital PACS, as it covers many aspects of communication in digital substations. It refers to the application of high availability redundant networks, based on PRP and HSR. (APOSTOLOV, 2020). Another publication categorized process bus traffic, by message sizes, rates, performance requirements (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014)

Several publications that focused on testing or design have targeted a segment of their research on tests for network performance, as the shift towards a higher usage of ethernet-based communication increases on the overall performance requirement of IEC 61850 communication systems (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016)

To confirm if the expected performance of devices would be acceptable, simulated network delays on single network have been performed with positive results (KATOULAEI, ADRAH, SANCHEZ-ACEVEDO, & HØIDALEN, 2021)

Different methods to generate network load have been used, such as with traffic simulator (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014) and OPNET network simulator (CROSSLEY, et al., 2011). Other case performed network overload tests, generating SVs with repeated SVID (YANG, CROSSLEY, WEN, & WRIGHT, 2014), and another approach used OPNET and OMNET to create latency (WU, HONETH, NORDSTRÖM, & SHI, 2015)

Focusing on larger applications, a network with seven switches was put together to verify the sampled values phase offset that it could generate, also testing different network architectures (star, ring), without any mention to PRP/HSR redundancies (CROSSLEY, et al., 2011). Other cases have specified which redundancy architecture they have applied, as some cases have used HSR (LEITLOFF, et al., 2016) and (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016)

Even if PTP synchronization is not a full object of this document, it is relevant to frame that such element is relevant for process bus, and its failure effect has been tested (WHITEHEAD, KANABAR, & HOSSEINZADEH, 2021).

Finally, there are tests with multiple IEC 61850-9-2LE streams on the network. ranging from 1 to 21 streams. Beyond 18 streams, average trip time increases, and protection failures were detected. At first, such structure has been assessed without any VLANs set. A second batch of tests was performed, this time with proper VLAN settings, and the result was that no protection failures were found, nor trip time increase (COELHO & LIMA, 2019).

2.2.5 Relevance for Network Design

The characteristics of an IEC 61850 network and its applications, firstly GOOSE and later Sampled Values, have translated into several publications where the network design is put into a position of main relevance.

On an IEC 61850-based substation automation system, the network data flow has characteristics to be reinforced: It does not change over time, as it is based on the substation design, operating requirements, and equipment. The only changes it will happen once it's operational are the substation retrofits and expansions, that will happen only because of significant modifications. (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020) In another words: once they're operating, the entire network dataflow will remain deterministic.

Within a process bus network, the traffic characteristics of GOOSE and PTP have small bandwidth consumption, as GOOSE has a heartbeat message cyclically published, and an increased rate when spontaneous messages are transmitted. One GOOSE message can range from 1 kbit/s when in steady-state and about 1 Mbit/s when bursts of data change take place. PTP in the format of power utility profile publishes one message each second, with a bandwidth consumption comparable to steady state GOOSE messages. One sampled value data stream, on the other hand, have a higher bandwidth consumption that ranges from 5 to 12 Mbit/s, constantly. With larger systems the overall data traffic will consume more bandwidth, which can affect network performance (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020) and (MOHAPATRA, et al., 2020)

As the tolerance for unavailability and system failures on PACS is as close to zero as possible, not only redundant protection devices are utilized, but ethernet networks also follow the same criteria. For that, full-redundant, seamless applications based on IEC 62439-3 (Parallel Redundancy Protocol – PRP – and High-Availability Seamless Redundancy – HSR) are used.

Different techniques have been considered for network shaping, focused on process bus. (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2013) considered the usage of MSTP to enable alternative paths for selected VLANs. This specific paper, however, does not consider PRP and HSR to achieve higher levels of network performance and redundancy.

Applications focused on detailing the physical network design have been published. (OLIVEIRA & ARCON, 2019) described a system designed with focus on high availability and redundancy, using PRP for station bus and HSR for process bus. It reinforced the value and importance of correct network design related to architecture and services related to it. Topics such as bandwidth, performance, availability, time synchronization must be evaluated. An extensive interoperability project has been executed in Scotland, and their different process bus architectures with PRP and HSR were evaluated (MOHAPATRA, et al., 2020)

Considerations of PRP networks or two completely separated main and backup systems, even with independent networks, with the conclusion that PRP architecture is the preferred solution have been described in some countries in Europe (HURZUK, LOKEN, PEDERSEN, & NORDENG, 2020)

Other cases have targeted solutions completely based on using PRP on process bus (LISBOA, 2020), and (WHITEHEAD, KANABAR, & HOSSEINZADEH, 2021) tested multiple network configurations, on process bus, ranging from PRP to HSR. On this publication, the station bus was always assembled as simple network.

Beyond a physical level, however, to achieve the best possible performance, network traffic management is required, most specifically for process bus. The flow of multicast messages must be restricted only to relevant devices for each multicast message. This will reduce the computation workload of protection relays, substation computers, and network switches. (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014) There are works with relevant suggestions about traffic prioritization and VLAN traffic segregation (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2013).

(LISBOA & KENZO, 2021) has described VLAN design considerations to optimize performance, leading to exclusive connections between publishers and subscribers for each bay and purpose (SV, GOOSE, trip, control, etc.), to assure optimal network traffic. Similar solutions were also suggested considering traffic segregation by applying different methods, such as physical segregation, VLAN filtering, and Multicast MAC-Address Filtering. (MOHAPATRA, et al., 2020)

Cases where the network design was the main subject have assessed the worst-case scenario of traffic, overloading the network with excessive numbers of data streams (YANG, CROSSLEY, WEN, & WRIGHT, 2014). Other publications have focused more on protection functions only, without configuration to prioritize neither GOOSE nor sampled values (SHARMA, NGUYEN, KUBER, & BARADI, 2021), and in other cases, no consideration for network traffic took place (ALMAS & VANFRETTI, 2013).

The complexity of designing a digital substation network is greater because all data traffics through the same physical network, in addition there are several protocols and more variables to be considered. This means that more care must be taken when engineering the network in digital substations. (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020)

It has been made clear that an engineering document addressing the communication network performance (latency, reliability, worst case analysis) is recommended (LEITLOFF, et al., 2022), and on several instances the IEC 61850-90-4 Technical Report has been cited and a relevant reference for the network design. It mentions average latencies per bridge hop and that the main influencing factor for latency are the frame size and other traffic's large packages (they'll influence on the overall performance as these packages will make a high priority package wait until the ethernet port processes the large package (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016).

To fulfill such specific requirements on better integration between IEC 61850 systems and ethernet network switches, concepts on how to review switches design and settings procedures have been proposed by (LISBOA, 2021).

2.2.6 IEC 61850-9-2LE and IEC 61869-9

The creation of IEC 61850-9-2LE (Light Edition) was pushed by major manufacturers to define parameters and facilitate interoperability for sampled values (HOSSENLOPP, CHARTREFOU, THOLOMIER, & BUI, 2008), published in 2004 by UCA, as the original IEC 61850-9-2 had open statements, 9-2LE came to promote the expected interoperability (CIMADEVILLA & SANTIAGO, 2018).

There are significant differences on the implementations of both, related to sampling rates, and IEC 61850-9-2LE had different requirements for 50 and 60 Hz systems, time synchronization, dataset composition, samples per published message, among others. The original IEC 61850-9-2 standard did not have any of these definitions. The differences can be highlighted on TABLE 1

TABLE 1 – Comparison between IEC 61850-9-2LE and IEC 61869-9

	IEC 61850-9-2LE	**IEC 61869-9**
Sampling Rate	Protection: 80 samples/cycle Power Quality: 256 samples/cycle	Protection: 4800 Hz Power Quality: 14400 Hz
Dataset Composition	Fixed: 4 Current + 4 Voltage	Variable: 1 up to 24 analog signals
Time Synchronization	1 PPS	IEEE 1588 (Precision Time Protocol) (Power Quality Profile IEC 61850-9-3)
Samples per Message (ASDU)	1	Protection: 2 Power Quality: 6

SOURCE: (CIMADEVILLA & SANTIAGO, 2018)

The time synchronization requirement for IEC 61850-9-2LE was a major restriction element to turn process bus applications more common, as the deployment of 1 PPS time synchronization throughout substation switchyards was not practical. When PTP became a feature on merging units, even for devices compliant with 9-2LE, it is the moment when it was possible to see the rise of widespread IEC 61850 process bus cases.

IEC 61850-9-2LE was the focus of developments and available devices for process bus testing, as a significant portion of the available publications related to the subject only mention it, such as (CROSSLEY, et al., 2011), (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014), (LEITLOFF, et al., 2016), and (KATOULAEI, ADRAH, SANCHEZ-ACEVEDO, & HØIDALEN, 2021). These tests have either used sampled values simulation or merging units coupled with analog signal generators (test sets or real time simulators). (KATOULAEI, SANCHEZ-ACEVEDO, & HØIDALEN, 2022), evaluated it with a LPIT with Rogowski coil.

There are multiple examples of application of IEC 61850-9-2 LE on real case projects or pilot projects (LEITLOFF, KURTZ, LADRIERE, CAYUELA, & BRUN, 2018), (LELLYS, FONTINHA, & OLIVEIRA, 2019), (OLIVEIRA & ARCON, 2019), (HURZUK, LOKEN, PEDERSEN, & NORDENG, 2020), (MOHAPATRA, et al., 2020) and (FLEMMING, RESCHKE, SCHNEIDER, ORTIZ, & NEUMEIER, 2021).

Protection tests were performed using IEC 61850-9-2LE, such as (COELHO & LIMA, 2019), which used devices from a single manufacturer. In other cases, merging units from different manufacturers were used to confirm interoperability (YANG, CROSSLEY, WEN, & WRIGHT, 2014). One of the setbacks of what is described on IEC 61850-9-2LE is that it refers to time synchronization based on PPS. (SHARMA, NGUYEN, KUBER, & BARADI, 2021), as well as other publications mentioned before, have used PTP instead.

By 2016, IEC 61869 standard parts 6 and 9 were published, "Additional General Requirements for Low Power Instrument Transformers" and "Digital Interface for Instrument Transformers". The part 9 can be considered a substandard of IEC 61850-9-2 and a replacement for IEC 61850-9-2LE (CIMADEVILLA & SANTIAGO, 2018). Since its publication, it was already considered as the future default application for Sampled Values (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016). Others have described it simply as the best solution for Sampled Values (LEITLOFF, et al., 2022) and (WHITEHEAD, KANABAR, & HOSSEINZADEH, 2021).

Authors have described the most significant comparisons between both implementations, such as sampling rate, ASDUs, time synchronization. (CIMADEVILLA & SANTIAGO, 2018), (APOSTOLOV, 2020). One of IEC 61869-9 main advantages, the flexibility on the published signals instead of the fixed set of four current and four voltage signals, has been noted (DOLEZILEK, LIMA, ROCHA, RUFINO, & FERNANDES, 2019).

Another fact listed is that with IEC 61869-9 and 2 ASDUs per packet, the packets volume in the network for Sampled Values will be reduced by half when compared with IEC61850-9-2 LE (1 ASDU) (APOSTOLOV, 2020).

There are advantages of IEC 61869-9 for transformer protection, due to the before mentioned flexibility: it can either transmit all necessary current measurements on a single SV stream, saving network bandwidth (LISBOA, 2020).

Up to 2020, the SV communications were based on IEC 61850-9-2 LE profile, but it is expected to have it replaced by IEC 61869-9 (APOSTOLOV, 2020) . Some utilities already plan to use it (LEITLOFF, et al., 2021). The first publications in Brazil with IEC 61869-9 on a real case application have already been made (LISBOA & KENZO, 2021).

2.3 TRANSFORMER PROTECTION

2.3.1 Protection Relays

Protection Relays have a vital role in Power Systems, assuring optimized operation and minimizing the impacts of electrical faults. The extract below from (MASON, 1956), has a clear description of the function of protective relaying, and even though it was written over 50 years ago, it remains accurate:

> The function of protective relaying is to cause the prompt removal from service of any element of a power system when it suffers a short circuit, or when it starts to operate in any abnormal manner that might cause damage or otherwise interfere with the effective operation of the rest of the system. The relaying equipment is aided in this task by circuit breakers that can disconnect the faulty element when they are called upon to do so by the relaying equipment.
>
> Circuit breakers are generally located so that each generator, transformer, bus, transmission line, etc., can be completely disconnected from the rest of the system. These circuit breakers must have sufficient capacity so that they can carry momentarily the maximum short-circuit current that can flow through them, and then interrupt this current; they must also withstand closing in on such a short circuit and then interrupting it according to certain prescribed standards.
>
> (MASON, 1956), p. 3

Conventional protection relays have current measuring inputs of 1 or 5 A inputs, which will receive such measurements from the secondary circuits from conventional CTs (ZIEGLER, 2005), or via Sampled Values in case of digitized systems.

For Differential protection, in a simplistic description, Kirchhoff’s current law is applied, meaning that digitized current instantaneous values from all transformer windings may be compared at each sampling instant. For transformers, additional considerations such as magnetizing curve, harmonics, inrush and even windings ratio and transformer composition must be considered to determine the relevant parameters for accurate transformer differential protection. (ZIEGLER, 2005).

2.3.2 Protection Performance

The definition given for protection system, is that it is the complete chain of one or more equipment and other devices designed to perform one or more protective functions. These elements consist of protection equipment (one or more), instrument transformers (current and/or voltage), cables, trip (disconnection) circuits and, where necessary, communication systems (ZIEGLER, 2005)

About the general assumption that digital substations perform at the same level or even better than conventional systems, in terms of performance, there are considerations to review. (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016). Protection using merging units and sampled values differs due to the addition of new steps in the protection chain, such as ethernet network-based digital communication, which will generate delays due to reading and processing packets.

2.3.3 Trip Time Considerations

Power grids, especially the transmission segment, can be a highly regulated environment, depending on the country. Fault clearance and trip operation times can be among these requirements, which are complimentary to international standards for each location.

These guidelines can vary depending on the voltage level. In Australia and UK, the maximum permitted fault clearance times is specified ranging from four to six power frequency cycles. As the high-voltage circuit breakers operation can vary from two to three cycles, this will result on limiting protection relays operating time to a maximum between 40 ms and 60 ms (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014). In Brazil, the National Grid Operator (ONS) states that for all power transmission installations (230 kV or higher, plus additional specific environments) require that the complete time for fault elimination, including circuit breaker opening time through protection relays cannot exceed 100 ms (Operador Nacional do Sistema Elétrico (ONS), 2021).

For the protection relays themselves, IEC 60834-1 defines total clearance times, and trip time budget (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016). On the communication side, IEC 61850-5 defines the maximum transmission time for GOOSE and sampled values (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016), (WHITEHEAD, KANABAR, & HOSSEINZADEH, 2021), (OLIVEIRA & ARCON, 2019) (COELHO & LIMA, 2019) and (LELLYS, FONTINHA, & OLIVEIRA, 2019).

The previous statements reinforce the importance of proper network design to assure GOOSE and SV transmission performances are acceptable to maintain specified fault clearance times (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2013)

2.3.4 IEC 61850 Data Model

The IEC 61850 standard offers not only digital communication replacement instead of conventional copper cables. It encompasses a complete structure of object-oriented data model with proper semantics to design the PACS. There are multiple advantages for the entire PACS for such data modelling, as it can enable to have a simpler and more structured way of designing IEDs' IEC 61850 structure, and for example how to model a transformer IED and its protection functions. (APOSTOLOV, 2021). As such, an entire transformer has been modelled based on IEC 61850 data model (ALEXANDRINO, FLORES, GUGLIELMI FILHO, & TENFEN, 2022).

2.3.5 Transformer Differential Protection based on Process Bus

There are multiple protection functions and diverse ways to assess a protection relay. Focused on the central subject of this work, the following publications are the ones where process bus-based protection systems were evaluated.

For a transformer differential protection, (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014) evaluated two different faults, a high-voltage transformer winding three-phase fault, and a low-voltage winding phase-to-ground fault. Around one thousand faults were applied. This publication also compared trip operation times and GOOSE transmission for the trip signal. For these tests, two different analog sources were used: a Real Time Digital Simulator (RTDS) and an Omicron CMC 256-6 relay test set. No merging units were used, as the RTDS was the device publishing the IEC 61850-9-2LE SV streams.

(WU, HONETH, NORDSTRÖM, & SHI, 2015), on his experiment, also assessed transformer differential protection, based on A phase phase-to-ground fault. It compared a software-based merging unit to generate IEC 61850-9-2LE streams and compare it with a conventional device for the same protection function. For the conventional signal, the analog signal fault source was an unspecified amplifier.

(ALMAS & VANFRETTI, 2013), realized tests with an OPAL-RT real time simulator (which generated IEC 61850-9-2LE sampled values and controlled an analog amplifier), with trip signals for conventional cases sent directly from the IED to the OPAL-RT, without a merging unit. Three scenarios with different topologies were put together: a complete conventional topology, a hybrid (conventional and process bus), and a complete process bus. Three phase faults were applied for all scenarios. As a conclusion, it suggests that the system with merging units should the around 1ms faster than conventional systems.

A relevant transformer protection test was developer by (SHARMA, NGUYEN, KUBER, & BARADI, 2021), where different faults on a transformer were evaluated, focused on second harmonic, with five faults per case. Three different scenarios were created, with IEC 61850-9-2LE for sampled values streams.

(KATOULAEI, ADRAH, SANCHEZ-ACEVEDO, & HØIDALEN, 2021) focused on transformer protection with process bus, used MATLAB Simulink and generated fault cases to test three different merging units, generating IEC 61850-9-2LE sampled values, all with the same IED. The tests focused on measurement performance, accuracy, operating time performance, transient inrush, and saturation. An additional publication by the same author (KATOULAEI, SANCHEZ-ACEVEDO, & HØIDALEN, 2022), used the same structure to compare LPIT (with Rogowski coil), SAMU and conventional measurement.

2.3.6 Other Protection Functions evaluated with Process Bus

Among the pilot projects described on the study developed by (HOSSENLOPP, CHARTREFOU, THOLOMIER, & BUI, 2008), it has compared the performance of three different arrangements of line distance protection: a conventional protection, a conventional CT/VT interfaced with merging unit, and an optical CT/VT with built-in merging unit. All sampled values used IEC 61850-9-2LE, and the analog signals were generated with Omicron Test Sets.

(CROSSLEY, et al., 2011) created a line protection test environment, with relay test sets generating 9-2LE sampled values, comparing hardwired and SV injection.

Following the previous tests, a multivendor process bus was assessed by (YANG, CROSSLEY, WEN, & WRIGHT, 2014), focused on testing line protection, based on phase- to-ground faults. On each terminal, a different topology was used, one with process bus without merging units (sampled values generated directly), the other with conventional connections. The system had main and backup protections, with line differential protection as the primary one and line distance protection as the secondary. Omicron test sets were used to generate both analog and IEC 61850-9-2LE sampled values.

Another comparison between conventional and digital acquisition was published by (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016), focusing on total fault clearance times for IEC 61850-9-2LE sampled values. This specific case does not specify the protection function, nor the faults generated, just confirms that the total fault clearance times are aligned with overall specifications.

Two publications, (LEITLOFF, et al., 2016), and (LEITLOFF, KURTZ, LADRIERE, CAYUELA, & BRUN, 2018), combined the entire process of design, factory acceptance tests, and commissioning of LPIT-based protection system, for a transmission line bay, where both line differential and distance functions were tested. The LPIT injected 9-2LE-based sampled values streams directly on the HSR process bus network. The results were found successful, with significant feedbacks on LPIT testing due to challenges to generate primary inputs to stimulate the LPIT itself.

In a publication with a deeper focus on network challenges, (WHITEHEAD, KANABAR, & HOSSEINZADEH, 2021) created a test environment with a proprietary software designed as SV publisher, to generate network traffic, with a Doble test set with COMTRADE generated faults. The 9-2LE sampled values were used to evaluate an overcurrent protection function, focused on the IED behavior for failures of subscribed sampled values streams. The test had a Process Bus setup with three IEDs, one real merging and two or more virtualized ones. The focus was on SV generation and sampling in high volumes to identify the impact of multiple factors in the protection system in a controlled environment.

On a test focused on line differential protection, (PEREIRA JR, et al., 2018) used a Conprove test relay test set to generate over 260 faults. There were different fault scenarios, varying fault type, angle, and fault location. The tests compared conventional protection with process bus, with tests done separately. As the test did not have merging units, the test set generated 9-2LE SVs directly to the IEDs. Equivalent results for trip (0,9 ms difference) were found on both cases.

(COELHO & LIMA, 2019) performed tests on a 138kV line distance protection, using a real time simulator from RTDS. He created varied faults, as phase-to-ground faults inside the circuit, varying their location, resistance and angle, plus tested CT saturation and process bus data traffic, performing ten tests for each fault. The test environment had a conventional IED in parallel with another test set consisting of IED plus merging unit publishing IEC 61850-9-2LE, which translates into measuring a complete trip chain.

2.4 SUMMARY OF THE CHAPTER

This chapter has listed how IEC 61850 has become a cornerstone to enable a higher digitization level on power systems and substations, of which would not be possible without using process bus.

The chapter also lists the advantages for the adoption of process bus, and some of the arguments not to use it, with a considerable number of success stories of its deployment worldwide.

The performance of protection systems is influenced by various factors, including the equipment used, instrument transformers, cables, trip circuits, and communication systems. Digital substations are expected to perform at least as well as conventional systems, but it is stated the importance of proper ethernet networks design even at a logical level, to assure the necessary performance, by using VLANs and/or MAC filters, for example.

The differences between the first standard for sampled values publishing, IEC 61850-9-2LE, and the latest definition of it, IEC 61869-9, were described. Both topics, network design and different standards for sampled values, are some of the areas that the proposed tests will focus to confirm their impact on transformer protection.

The second section discusses transformer protection in power systems. It emphasizes the importance of protective relays in promptly removing faulty elements from the system to minimize damages and ensure effective operation. Protection relays issue trip commands to circuit breakers upon processing measurements from current transformers (CTs), acquired either directly via copper cables or through sampled values in digitized systems.

The definition of the entire protection chain, starting on primary equipment, such as instrument transformers and circuit breakers, are described. Standards for trip time requirements for fault clearance vary depending on the country and voltage level exist, and there are regional specifications also.

For example, in Australia and the UK, the maximum fault clearance time is typically limited to four to six power frequency cycles. The total clearance time for protection relays is governed by standards such as IEC 60834-1, while the transmission time for communication protocols like GOOSE and sampled values is defined by IEC 61850-5.

The IEC 61850 Standard provides a comprehensive data model for designing protection, automation, and control systems (PACS) in power systems. It enables a structured approach to modeling transformer protection functions and other components.

To complete the second part, all publications found that are focused on protection performance are listed, describing the main characteristics of each experiment. Numerous studies and experiments have evaluated transformer protection and other protection functions using process bus technologies. These evaluations have compared conventional systems to those based on digital acquisition, merging units, and IEC 61850-9-2LE sampled values. The tests have examined aspects such as fault detection, trip operation times, measurement performance, accuracy, transient inrush, and saturation.

As the objective of this research work, IEC 61850 and process bus have been assessed on different test environments and approaches on how to confirm its desired performance.

The review serves as a significant starting point to reinforce the relevance of the suggested tests. The test laboratory used for this publication was designed to use IEC 61869-9 instead of IEC 61850-9-2LE, but also being able to compare both standards to quantify if they would produce different results. Up to 2021, no commercial product with 61869-9 was available. The platform of this test was the first one in Brazil.

Related to the merging unit topology for transformer differential, it was possible to identify cases where assessments were done with two separate merging units, and hybrid topologies. However, no cases with a single MU were found. This also happens since all other tests used IEC 61850-9-2LE, which does not allow to concentrate all current measurements and sampled values stream into one single device and stream.

Different network traffic evaluation was performed, but mostly with traffic simulation devices and software. For this dissertation, actual merging units were used to generate all the network data. With that, the network design recommendations were taken into consideration and their influence on the protection operation will be shown.

Protection performance, for both transformer and line protection functions were assessed, but a transformer differential protection has not been tested with a complete protection chain (test set, merging unit, protection IED). The lack of MU in the process eliminates the necessary MU processing times for actual trip verification.

In addition to it, a conventional protection in parallel was employed to assure that the protection operation measurements are compared at the exact same moment and test conditions, which was not the case for most publications.

3 TRANSFORMER PROTECTION

This chapter will describe the impacts of replacing conventional copper-based connections with IEC 61850 process bus for a transformer protection and the relevant standards that guide the minimum acceptable results.

Later, it will explain the test structure available, the equipment used, and all the variations made on this environment, to generate the test results which are the focus of this work, verifying the impacts of different elements in the test results.

3.1 PROBLEM DESCRIPTION

Protection based on sampled values is different from the structure of conventional protection due to the addition of elements in the protection chain, such as digital communication, and consequently additional delays in the form of encoding and decoding packets (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016). For the actuation of a protection, conventional or with MUs, it must meet the times established in the standard, which as a reference are those provided for in the IEC 60834-1 standard (IEC 60834-1, 1999), while for the transmission of GOOSE and SV we consider the specified in the IEC 61850-5 standard (IEC-61850, 2003).

In the case of transformer differential protection, the practical conditions in which they can be applied are relevant for defining the protection solution. In the case of protections based on sampled values measurements, the complexity of the solution exceeds the conventional definition of connecting CTs, VTs and protection relays, since definitions related to the process bus are necessary (LISBOA, 2020). Among the design criteria, it is necessary to consider network architecture (RSTP, PRP, HSR), time synchronism (IRIG-B, PTP), composition of merging units (number of devices, their allocation), and sampled values transmission standard (IEC 61850-9-2LE or IEC 61869-9) (LISBOA & KENZO, 2019).

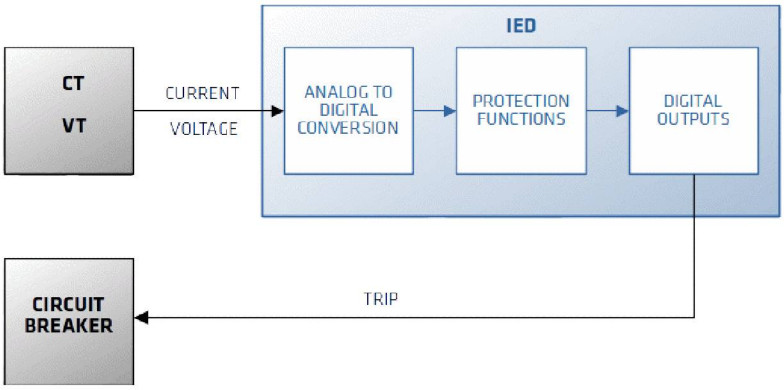
3.1.1 Protection System

A protective system, by definition, is an arrangement of one or more equipment and other devices designed to perform one or more protective functions. They are composed of one or more protection equipment, instrumentation transformers (current and/or voltage), cabling, disconnecting circuits (trip) and, where necessary, communication systems (ZIEGLER, 2005).

Due to the input of the digitalization element of analog signals and command to open circuit breakers (trip), whether NCITs or MUs, the protection based on the Process Bus requires signal transmissions through the ethernet network, not foreseen in fully copper-wired solutions.

Conventional IEDs, with reading of analogue signals, directly process the entire sequence of necessary elements between the measurement of current and voltage signals, up to the operation of the shutdown command digital output contact, as shown in FIGURE 2:

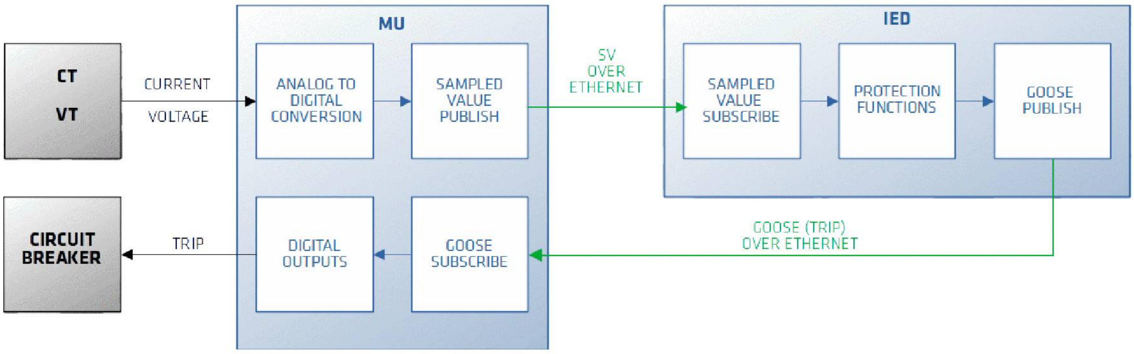
FIGURE 2 – Simplified sequence of reading, processing, and actuation of the protection IED



SOURCE: the author (2021)

The application using process bus, has additional steps, due to the transmission of analog signals from the merging unit to the IED, through sampled values, and the return of the shutdown command, via GOOSE, as represented in FIGURE 3.

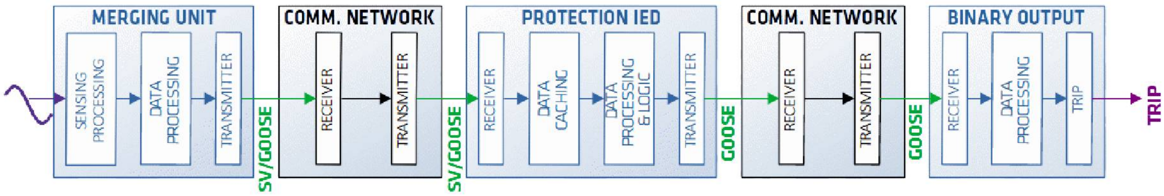
FIGURE 3 – Simplified sequence of reading, processing, and actuation of the protection IED using MU



SOURCE: the author (2023)

Another representation of such functional chain from CT/VT all the way until the binary output operation is represented on FIGURE 4 (LEITLOFF, et al., 2022)

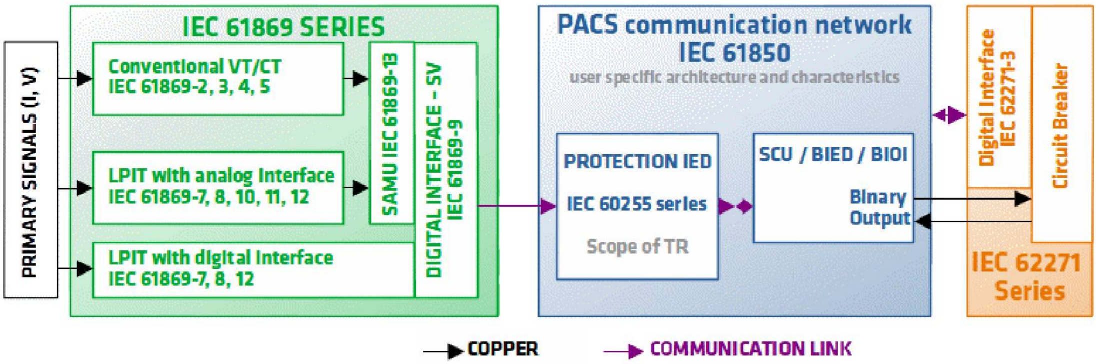
FIGURE 4 – Operate time of functional chain



SOURCE: Adapted from (LEITLOFF, et al., 2022)

Considering IEC standards, the same author (LEITLOFF, et al., 2022) has created FIGURE 5 that summarizes the interfaces between instrument transformers, protection devices based on IEC 61850, and even an additional reference to high voltage switchgear and control gear (IEC 62271-3)

FIGURE 5 – Digital interfaces of protection functions



SOURCE: Adapted from (LEITLOFF, et al., 2022)

3.1.2 Operating Times

3.1.2.1 Protection

In terms of protection actuation, the fault clearance time considers the time between the origin of the fault until the moment when it is physically cleared (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016). The IEC 60834-1 standard defines time window for fault extinction, according to the TABLE 2:

TABLE 2 – Total time to clear faults in power systems

Category	Time (ms)	What does it include
Fault Identification Time	10 ... 30	Analog input stage, protection algorithm execution
Relay Operating Time	0 ... 30	Trip decision, relay output contact operation
Trip Relay	n/a	Trip relay operating time
Primary Equipment Operating Time	30 ... 80	Circuit breaker trip coil, mechanical circuit breaker movement
Total	40 ... 140	

SOURCE: (IEC 60834-1, 1999)

In the analyzed protection system, we will check the first two elements of the chain: from fault identification to trip contact operation. The remaining parts (trip relay, primary equipment operating time) are not the scope of this work, as the process bus application will not interfere with them.

3.1.2.2 Data Transmission

The IEC 61850 standard provides classes of transmission time for data, classifying according to the application, as indicated in the TABLE 3:

TABLE 3 – Time requirements for data transfer

Class	Time	Example
TT0	> 1000 ms	File Transfer
TT1	1000 ms	Alarms
TT2	500 ms	Commands
TT3	100 ms	Slow Automation
TT4	20 ms	Fast Automation
TT5	10 ms	State Change
TT6	3 ms	Trips, Blocks, SVs

SOURCE: (IEC 61850-5, 2022)

In terms of transmission to protection functions, both GOOSE and sampled values messages are classified as TT6.

3.1.3 Transformer Differential Protection (87T)

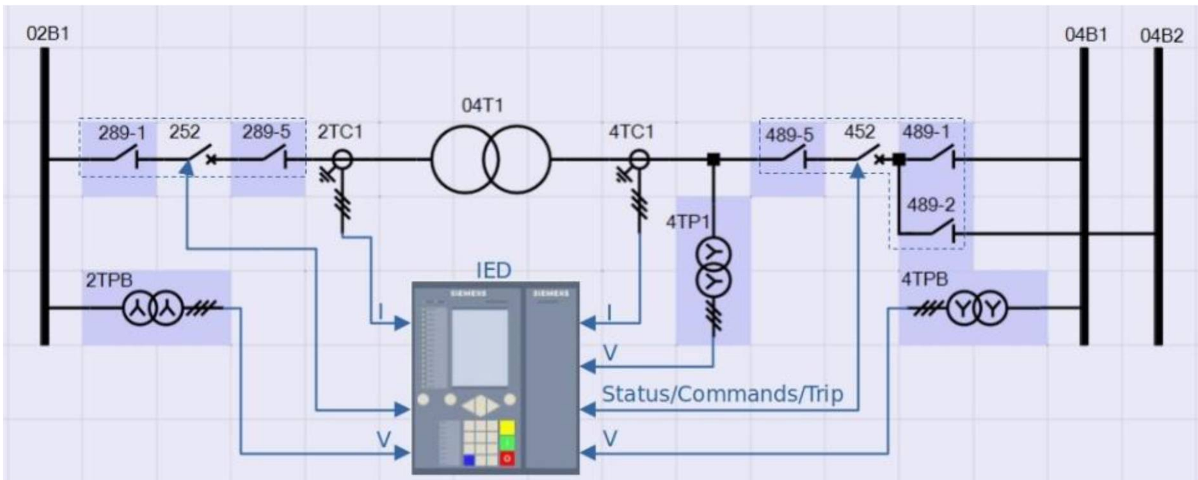
As previously presented, the arrangement of a differential protection can vary according to the protected element, and mainly in the case of solutions based on Sampled Values, which may have variations of solutions, with one or more MUs, or even hybrid solutions, where a part of the acquisition of signals will be done in a conventional way and another digital way.

For the specific case of this study, the considered transformer has two windings: a HV one and a LV one.

3.1.3.1 Conventional Protection

The conventional transformer differential protection is designed in such a way that the protection IED has the capacity to read current from all windings of the protected transformer element and eliminate its faults, according to the FIGURE 6:

FIGURE 6 – Conventional differential transformer protection

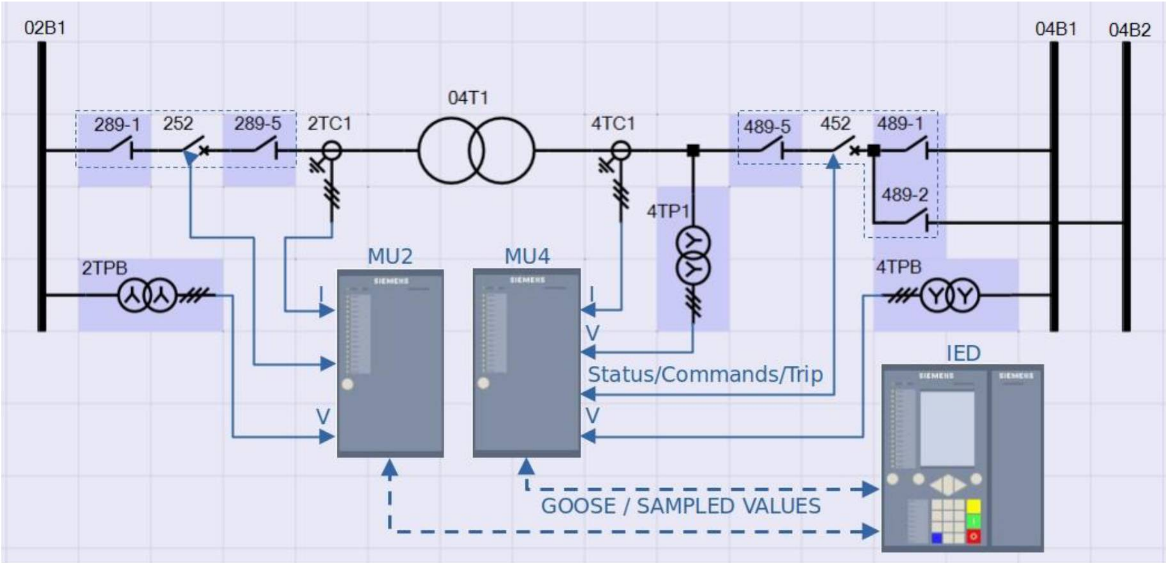


SOURCE: the author (2023)

3.1.3.2 Differential Protection with two Merging Units

The most common topology in the available references for process bus-based transformer protection, mostly due to the availability only of IEC 61850-9-2LE. This specific topology consists of deploying one merging unit per transformer winding. The FIGURE 7 shows this system configuration.

FIGURE 7 – Transformer differential protection with two merging units

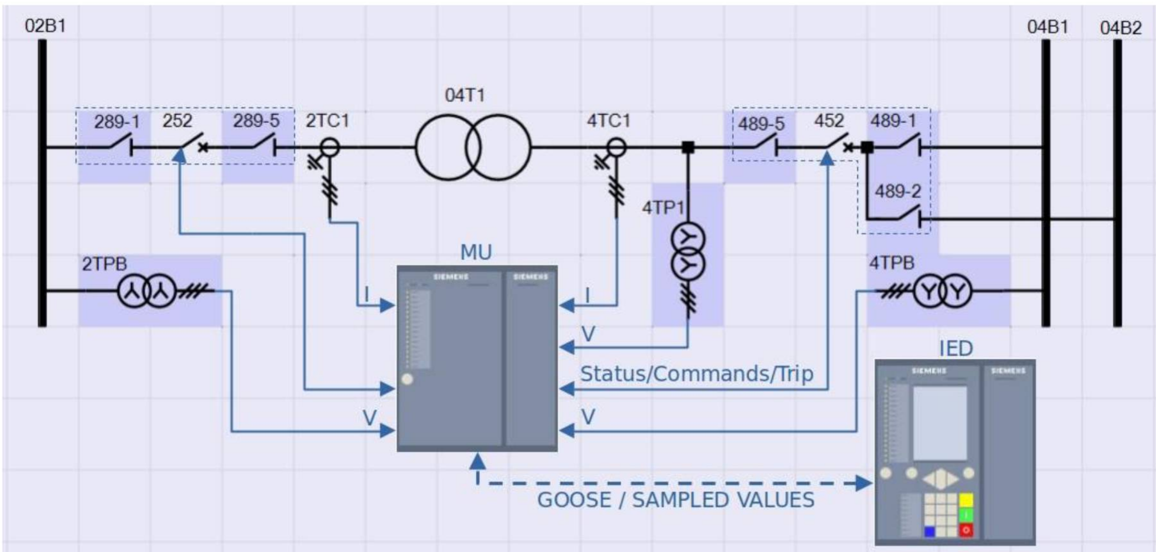


SOURCE: the author (2023)

3.1.3.3 Differential Protection with One Merging Unit

With the development of devices complying with the IEC 61869-9 standard (IEC 61869-9, 2016), a possibility of greater flexibility of analogue signals within a sampled values stream has become possible, as it supports transmission from 1 to 24 analogue signals. This new format allows the application of a single MU for the entire differential protection of a transformer, as shown in FIGURE 8.

FIGURE 8 – Transformer differential protection with one merging unit

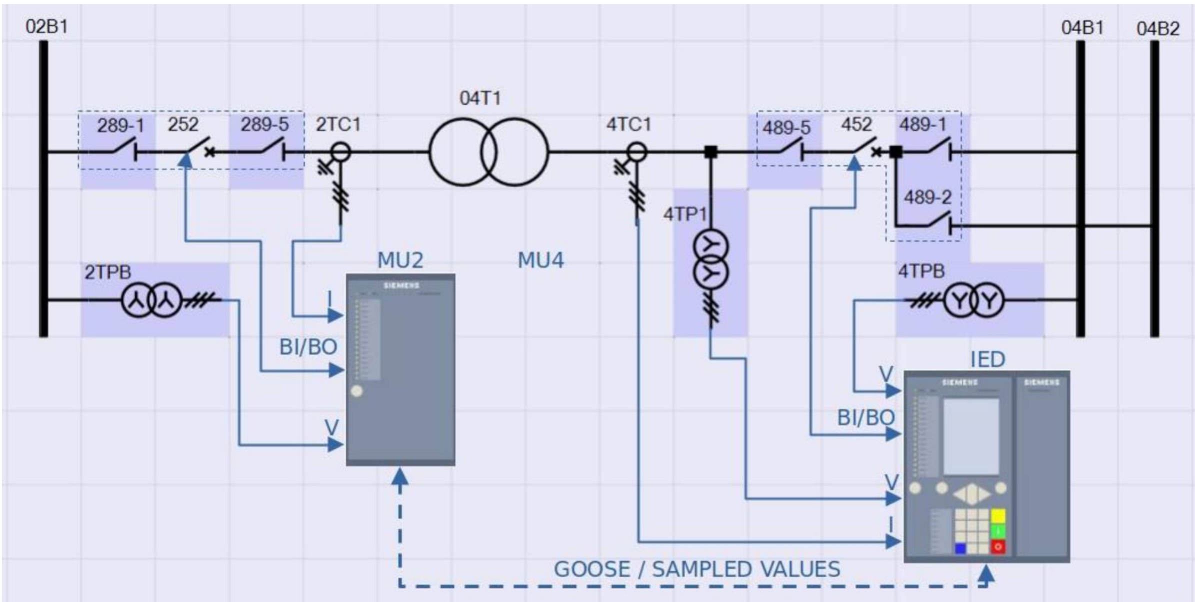


SOURCE: the author (2023)

3.1.3.4 Hybrid Differential Protection

When considering commercial and physical issues, the application of MUs for all windings of a transformer can become more expensive than others, as for example in the case of the existence of a tertiary winding, where the MV cubicle is installed close to the relay room, or even inside of it. In this situation, the cost of cables (short on length) will be much lower than the cost of an MU. If the IED has the capacity to receive both digitized signals and signals through cables, a hybrid alternative may be the best solution. The FIGURE 9 shows this configuration:

FIGURE 9 – Hybrid transformer differential protection



SOURCE: the author (2023)

3.2 TEST SETUP

For the tests that were performed, the applied protection IEDs were Siemens 7UT86 IEDs (and others from the same family comprising the rest of the substation), the merging unit models were Siemens 6MU85, network switches applied models were Hirschmann GRS1142 and Hirschmann RSP35 PRP redbox, plus GE RT430 time servers (GNSS) and Omicron CMC356 test set were used.

The topology consisted of two identical protection relays, one identified as UPC1, which was set as the process bus-based protection device, and the second one will be named from now on as UPC2. This second IED was wired as a conventional protection device, with all the analog signals acquired directly from the test set, through a series connection from the Omicron test set and the merging units.

The merging units used, identified as MUP1 and MUP2, will be utilized accordingly to each desired test topology. They will publish GOOSE and sampled values for the UPC1, and receive trip signals through GOOSE messages, which will issue a Binary Output signal that refers to circuit breaker trip command. This command will be connected to the test Set, to generate the measured trip times. For the hybrid configuration, UPC1 will also send a digital output signal directly to the test set, and UPC2 will always send similar signals to the test set.

An additional measurement has been created for both UPC1 and UPC2, where the transformer differential protection fault trip will generate a GOOSE message, whose times will also be measured by the test set.

3.2.1 Merging Units Topology

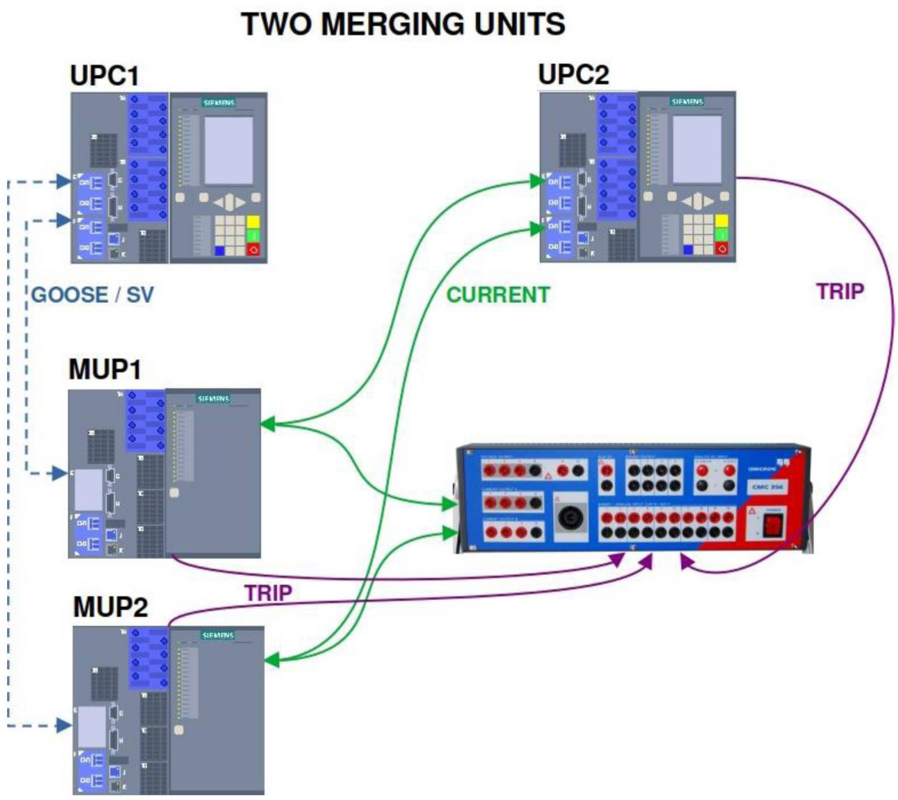
For the tests conducted, different arrangements were set up in a test environment, which simulated the three identified topology alternatives (one or two merging units, and hybrid). In all configurations, a conventional IED was connected in series to the merging units' analog inputs, allowing the comparison of each fault trip. The current signals were generated from a test set, which measured the actuation times of the trip signals of each device. The electrical connection of each setup is represented in the following figures.

3.2.1.1 Test Topology with Two Merging Units

The topology with two merging units, as shown on FIGURE 10, indicates the connection between the test set and two merging units (MUP1 and MUP2), and that these two three-phase current channels were later connected to a conventional protection device (UPC2). Both merging units published GOOSE and sampled values messages on the process bus network for UPC1 to process the transformer differential protection function. The sampled values signals were modelled reproducing the IEC 61850-9-2 LE standard, with four currents and four voltages per stream.

The UPC1 would later transmit GOOSE trip messages back to the MUs, which would then issue trip commands to the Omicron Test set. The UPC2 also sends trips commands, directly to the test set.

FIGURE 10 – Two merging units topology

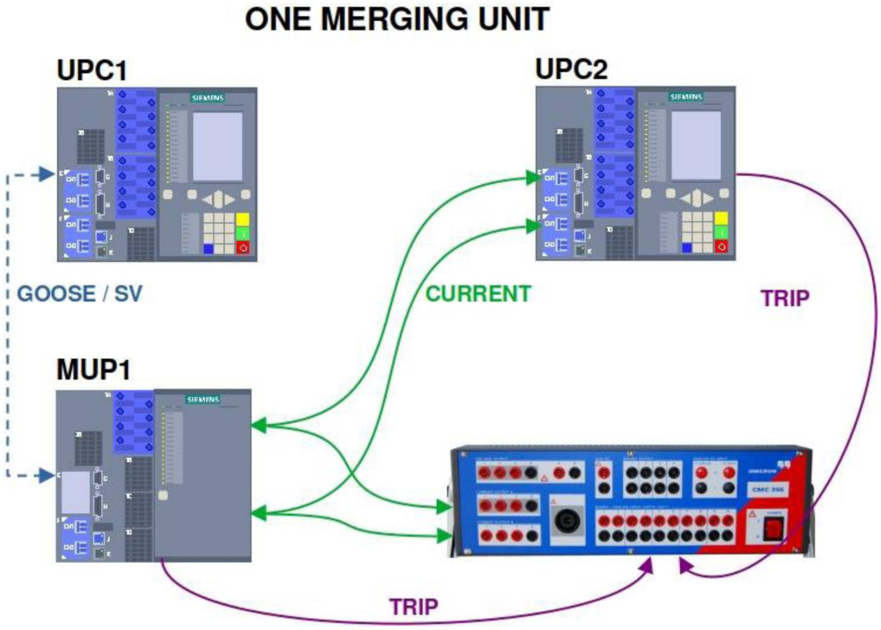


SOURCE: the author (2023)

3.2.1.2 Test Topology with One Merging Unit

On this case, the MUP1 has enough current Inputs to receive both signals and publish them on a single sampled values stream, based on IEC 61869-9. There are two GOOSE messages for trip, and different Binary Output signals on MUP1 for each trip binary output to be connected to the test set.
UPC2 topology remains the same. FIGURE 11 represents this topology.

FIGURE 11 – One merging unit topology

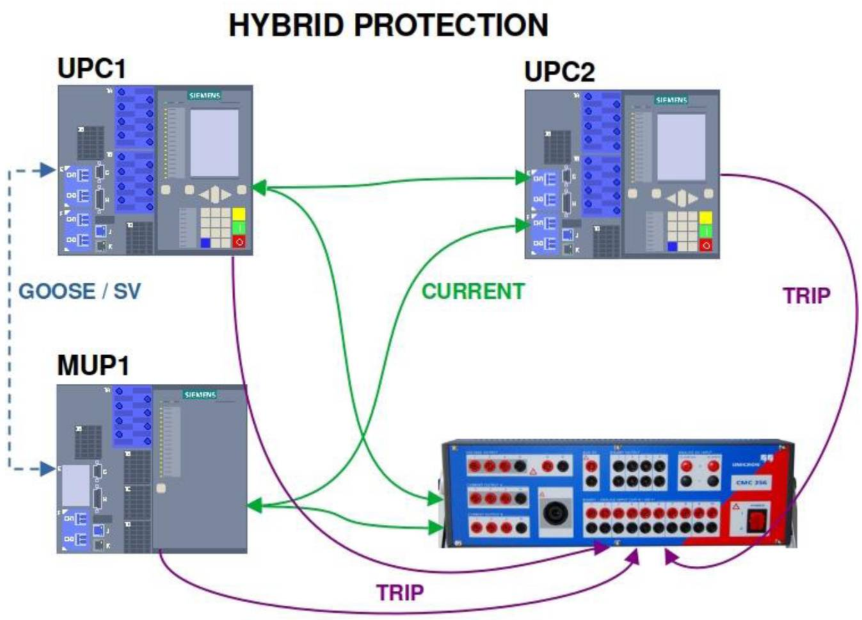


SOURCE: the author (2023)

3.2.1.3 Hybrid Topology

The FIGURE 12 indicates the connections made for hybrid tests, with the equivalent of one transformer winding being connected directly to the IED, and the other one digitized through a Merging Unit. UPC1 and MUP1 both issue one trip signal each to the test set.

FIGURE 12 – Hybrid topology

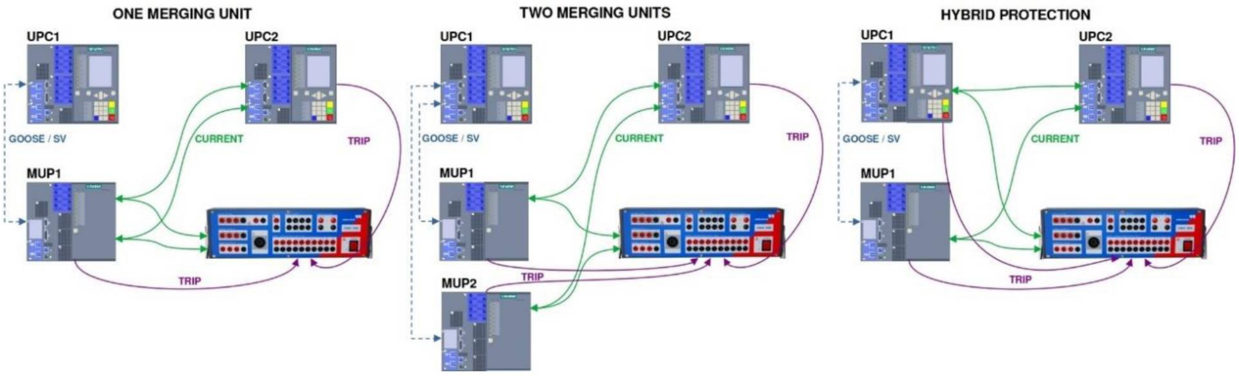


SOURCE: the author (2023)

As an additional information: all trip contacts, both in the UPCs and in the MUs, have the same actuation time characteristic, to ensure that the trip signals have similar expected behavior.

Finally, FIGURE 13 has all three topologies together, to provide faster comparison:

FIGURE 13 – All topologies



SOURCE: the author (2023)

3.2.2 Network Architecture

As the current protection system has a component of communication networks through which GOOSE and SV flow, considerations regarding the ethernet network of a protection need to be considered. For the process bus, as foreseen in the IEC 61869-9 standard, the time synchronization is done through PTP (Precision Time Protocol), based on the Power Utility Profile (IEC 61850-9-3). The ethernet network utilized for IEC 61850 communication, is the same utilized for PTP.

One of the objectives of the test carried out is that the cases are as close as possible to real applications, and therefore the ethernet communication network and its time synchronization were connected considering redundant networks, based on PRP (IEC 62439-3), and carried out within of a network of a digital substation project (LISBOA & KENZO, 2021).

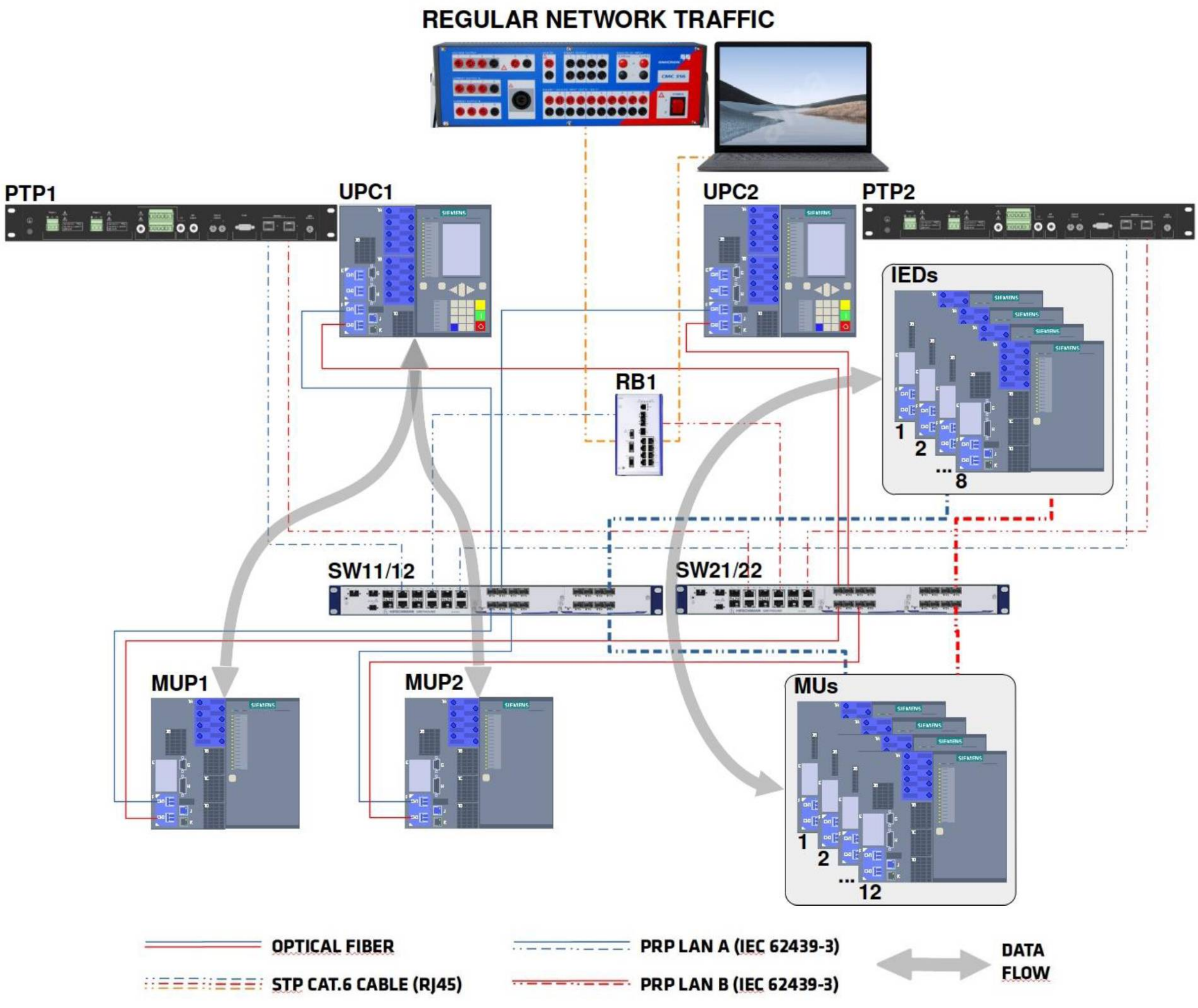
The project in question has a total of 8 IEDs and 13 merging units within the process bus network (LISBOA & KENZO, 2021). Recommendations considered both within the IEC 61850 standard and in other publications were applied (ZAPELLA, PIMENTEL, SILVANO, & HUNT, 2020). The GOOSE and SV messages were segregated into VLANs (Virtual Local Area Network), so that only the devices that publish and subscribe each message will receive the messages, generating a total of 36 VLANs.

Considering these circumstances, the tests were conducted under three different network load conditions, presented as follows.

3.2.2.1 Regular Network Traffic

The configuration in this case was prepared as a normal design situation in a digital substation (VLANs filtering the GOOSE/SV circulation only for the devices that publish and subscribe to these messages). In this condition, the network load and behavior resemble conditions that protections via sampled values will be subject to. The network solution and its actual GOOSE/SV data flow is presented in FIGURE 14:

FIGURE 14 – Regular network traffic



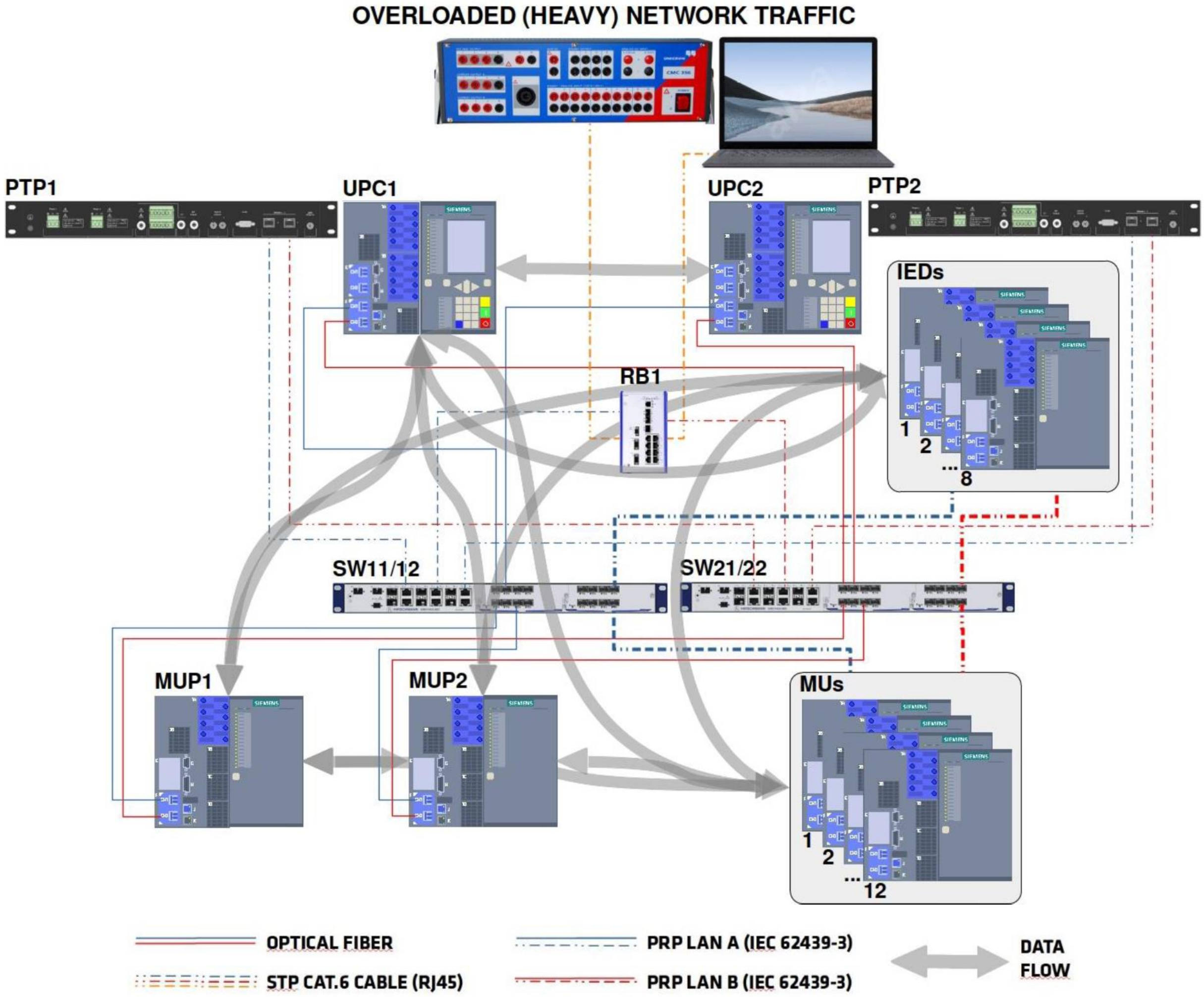
SOURCE: the author (2023)

As indicated, the flow of GOOSE and SV messages only occurs among the IEDs that subscribe to the messages, restricting the handling of packets to the switches in the network. The device named as “RB1” is the redbox, that enables the test set and the laptop to be connected to the PRP network.

3.2.2.2 Overloaded Network Traffic

The difference in this case is that the network does not have the correct routing settings for handling GOOSE and SV messages. No message is filtered on the switches via VLANs: the ports connected to the IED and the test MUs are part of all existing VLANs. This arrangement of such GOOSE/SV data flow is represented in FIGURE 15:

FIGURE 15 – Overloaded network traffic



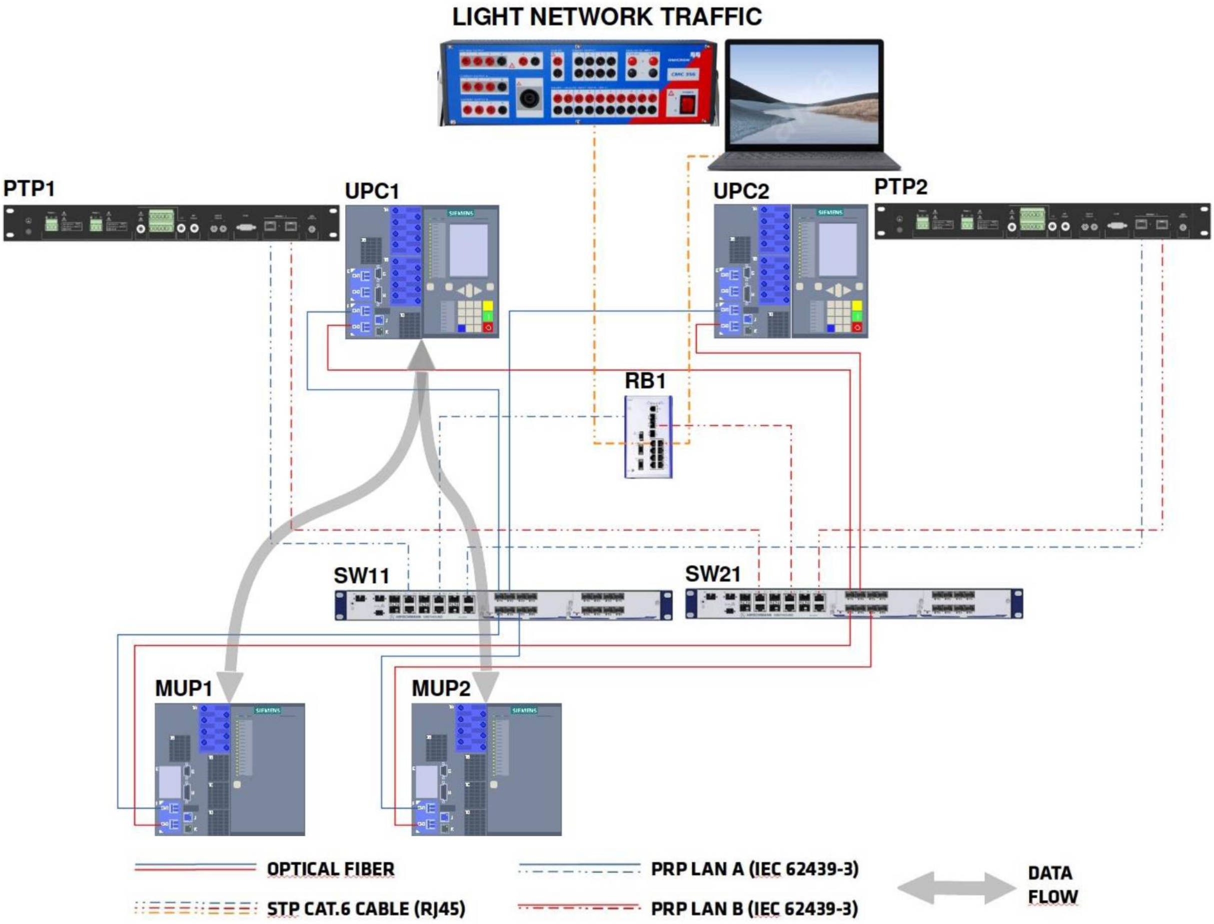
SOURCE: the author (2023)

3.2.2.3 Light Network Traffic

This test condition simulates a perfect environment for a process bus: a separate network only for the specific devices of a specific protection, without interferences of other devices from different bays. In the literature review, applications were found where a HSR (IEC 62439-3) network was set, even eliminating the need for switches, but still maintaining network redundancy (OLIVEIRA & ARCON, 2019)

For this test case, all devices not relevant for it were turned off. FIGURE 16 represents this test case:

FIGURE 16 – Light network traffic



SOURCE: the author (2023)

3.2.3 Sampled Values ASDUs (Application Service Data Unit)

One main difference between IEC 61850-9-2LE and IEC 61869-9 standards is the definition related to Application Service Data Unit (ASDU). The 9-2LE standard determines protection-related sampled values streams must publish one measured sample per published packet, which translates into 4800 messages per second, on a 60 Hz system.

The IEC 61869-9 standard, on the other hand, states that protection streams may have two measurements per message, which will translate on half of the published messages when compared with 9-2LE, with 2400 messages per second for a 60 Hz system.

Among the alternatives already presented for the transmission of sampled values, due to the flexibility generated, the use of the IEC 61869-9 standard was adopted as the solution for the final product of the system where the tests were performed (LISBOA, 2020). For measurement and protection applications, this standard defines the sampling rate of 4800Hz, regardless of the applied system frequency. Considering the standard recommendation of using 2 ASDUs (Application Service Data Unit, which contains a sample of all signals from an SV per unit) per packet sent, a total of 2400 packets are transmitted per second. TABLE 4 below represents these measurements, for the complete network available for testing:

TABLE 4 – Transmitted packets and bytes measured with one ASDU and two ASDU (network with overloaded traffic)

	1 ASDU					2 ASDU				
	% Packets	Packets	% Bytes	Bytes	Bits/s	% Packets	Packets	% Bytes	Bytes	Bits/s
Total	100.0	3.578.746	100.0	515.446.532	68M	100.0	1.821.223	100.0	463.791.405	61M
Sampled Values	99.9	3.573.532	87.3	450.154.462	59M	99.7	1.815.611	92.7	430.056.207	57M
GOOSE	0.1	4.368	0.2	823.977	109k	0.3	4.747	0.2	887.784	117k
Other Data	0.0	846	12.5	64.468.093	8.9M	0.0	865	7.1	32.857.414	3.9M

SOURCE: the author (2023)

When we compare the two configurations, we notice that with the use of ASDU configured as “2”, the reduction in terms of packets is representative (50.8%), but in terms of volume of bytes, the reduction is much smaller (10%).

All tests were performed with both settings, either one or two ASDUs.

The network traffic recorded above is the existing traffic for both cases described as regular and overloaded. The difference between both is the fact that the VLANs configured on the regular traffic limit the data that will be delivered to each IED/MU only to the subscribed GOOSE and sampled values streams. Therefore, the volume of data that the IEDs/MUs will be exposed will be the same as for the one on the light network.

For light network configuration, the volume of transmitted packets and data is registered in the TABLE 5

TABLE 5 – Transmitted packets and bytes measured with one ASDU and two ASDU (network with light traffic)

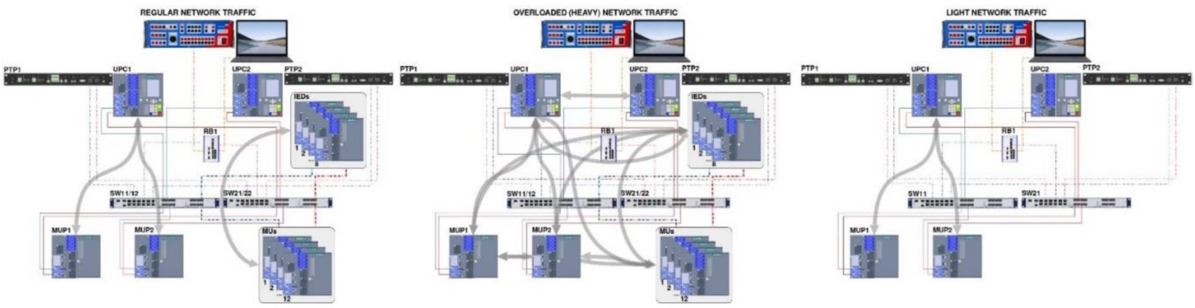
	1 ASDU					2 ASDU				
	% Packets	Packets	% Bytes	Bytes	Bits/s	% Packets	Packets	% Bytes	Bytes	Bits/s
Total	100.0	584.023	100.0	107.077.979	14M	100.0	432.955	100.0	139.407.631	18M
Sampled Values	98.3	574.042	87.4	93.568.846	12M	98.4	426.022	93.4	130.219.594	17M
GOOSE	0.5	2713	0.5	482.191	64k	0.5	2072	0.3	399.009	53k
Other Data	1.2	7268	12.10	13.026.942	1.9M	1.1	4.861	6.3	8.789.028	947k

SOURCE: the author (2023)

The traffic differences between the whole network represented on TABLE 4 and the one above has clear differences, especially on the amount of bits/s measured on each case. This is the amount of data that could reach each protection device and therefore require it to process them to perform its specified functions.

To complement this section, FIGURE 17 represents all network traffic configurations, to enable visualize their differences.

FIGURE 17 – All network traffic side-by-side



SOURCE: the author (2023)

3.3 PERFORMED TESTS

The tests conducted were centered on the same fault, a three-phase short circuit within the differential protection zone. 378 test cases were performed in total, split between the presented system configurations. The faults were applied simultaneously to an IED with digitalized signal acquisition (identified as UPC1), and another IED with conventional signal reading (UPC2).

For both IEDs, the test equipment monitored the actuation signal of function 87T (via GOOSE), the disconnection/trip signal sent to each breaker (via GOOSE) and, the actuation contacts of each protection chain to actual shutdown/trip command (via binary contact, powered at 125Vdc).

The FIGURE 18 below represents the recorded results of one of the tests performed (three-phase fault, one MU, normal network):

FIGURE 18 – Test results (from test set software)

Time Assessments: 01 in Teste UPC1 Digital 1

	Time Assessment									
	Name	Ignore before	Start	Stop	Tnom	Tdev-	Tdev+	Tact	Tdev	Assessment
1	UPC1 87T	FALTA 87T	FALTA 87T	UPC1 87T 0>1	30,00 ms	30,00 ms	30,00 ms	27,10 ms	-2,900 ms	✓
2	UPC1 Trip1 G	FALTA 87T	FALTA 87T	UPC1 Trip1 G 0>1	30,00 ms	30,00 ms	30,00 ms	26,10 ms	-3,900 ms	✓
3	UPC1 Trip2 G	FALTA 87T	FALTA 87T	UPC1 Trip2 G 0>1	30,00 ms	30,00 ms	30,00 ms	26,10 ms	-3,900 ms	✓
4	MUP1 Trip1	FALTA 87T	FALTA 87T	MUP1 Trip1 0>1	30,00 ms	30,00 ms	30,00 ms	30,70 ms	700,0 µs	✓
5	MUP1 Trip2	FALTA 87T	FALTA 87T	MUP1 Trip2 0>1	30,00 ms	30,00 ms	30,00 ms	30,50 ms	500,0 µs	✓
6	UPC2 87T	FALTA 87T	FALTA 87T	UPC2 87T 0>1	30,00 ms	30,00 ms	30,00 ms	26,00 ms	-4,000 ms	✓
7	UPC2 Trip1 G	FALTA 87T	FALTA 87T	UPC2 Trip1 G 0>1	30,00 ms	30,00 ms	30,00 ms	25,10 ms	-4,900 ms	✓
8	UPC2 Trip2 G	FALTA 87T	FALTA 87T	UPC2 Trip2 G 0>1	30,00 ms	30,00 ms	30,00 ms	25,10 ms	-4,900 ms	✓
9	UPC2 Trip1	FALTA 87T	FALTA 87T	UPC2 Trip1 0>1	30,00 ms	30,00 ms	30,00 ms	28,00 ms	-2,000 ms	✓
10	UPC2 Trip2	FALTA 87T	FALTA 87T	UPC2 Trip2 0>1	30,00 ms	30,00 ms	30,00 ms	28,30 ms	-1,700 ms	✓

SOURCE: the author (2023)

For the entirety of the test cases, the only deviation in the table above is related to the UPC1 Trip, where according to the configuration of the electrical connections (number of MUPs, or hybrid connection), the signals of the UPC1 trips were modified to a different source according to the tested topology.

4 TEST RESULTS

The test results have been reviewed based on the three major aspects considered: samples on each SV message (ASDU number), merging unit topology, and network traffic. Additionally, a full comparison between the digitized protection (UPC1) and the conventional one (UPC2), with all test results, is also available.

For all tests, a GOOSE message indicating that the transformer differential protection has identified a fault was measured, and it will be represented on the images and tables from this chapter as 87T. The relevance of this message is that it allows to identify the time difference between UPC1 and UPC2 for the first stage of IEC 60834-1, the fault identification time.

As the main objective of this study is to identify the whole protection chain performance, it is necessary to evaluate it with a deeper consideration the protection chain, including the fault identification time plus the relay operating time, as represented on FIGURE 4. The trip time was measured considering the time of the second trip signal issued from each device, as for a transformer differential protection, all windings of a transformer need to be disconnected from the power grid to assure that the fault has been cleared, so considering the last trip operation is necessary. The term “Last Trip” on all tables and figures of this chapter relates to that.

For the process-bus based protection, depending on the topology, three different devices could have been the issuers of this signal: MUP1, MUP2, or UPC1. On the conventional side, both signals were always operated by UPC2.

The values for “87T” and “Last Trip” on all tables are the averages found for each, while “Tmax” and “Tmin” are respectively the maximum and minimum operation times for each last trip during all tests. These two times, together with standard deviation for “Last Trip,” are graphically represented on the figures of this chapter.

4.1 MERGING UNIT TOPOLOGY

The variations of merging unit’s topology, as representing possible different use cases for process bus design, were the inspiration for these tests.

One merging unit generating all necessary sampled values for transformer differential protection, or with two merging units (as necessary if 9-2LE is applied), or even with a hybrid solution (with part of the current acquisition done directly on the IED and other via MUs), were the topologies utilized. The FIGURE 13 represents all three topology scenarios assembled on for such tests, and FIGURE 7, FIGURE 8 and FIGURE 9 represent the single line diagram for each process-bus topology.

TABLE 6 and represents the test results for such use case.

TABLE 6 – Test results for topology variations (in ms)

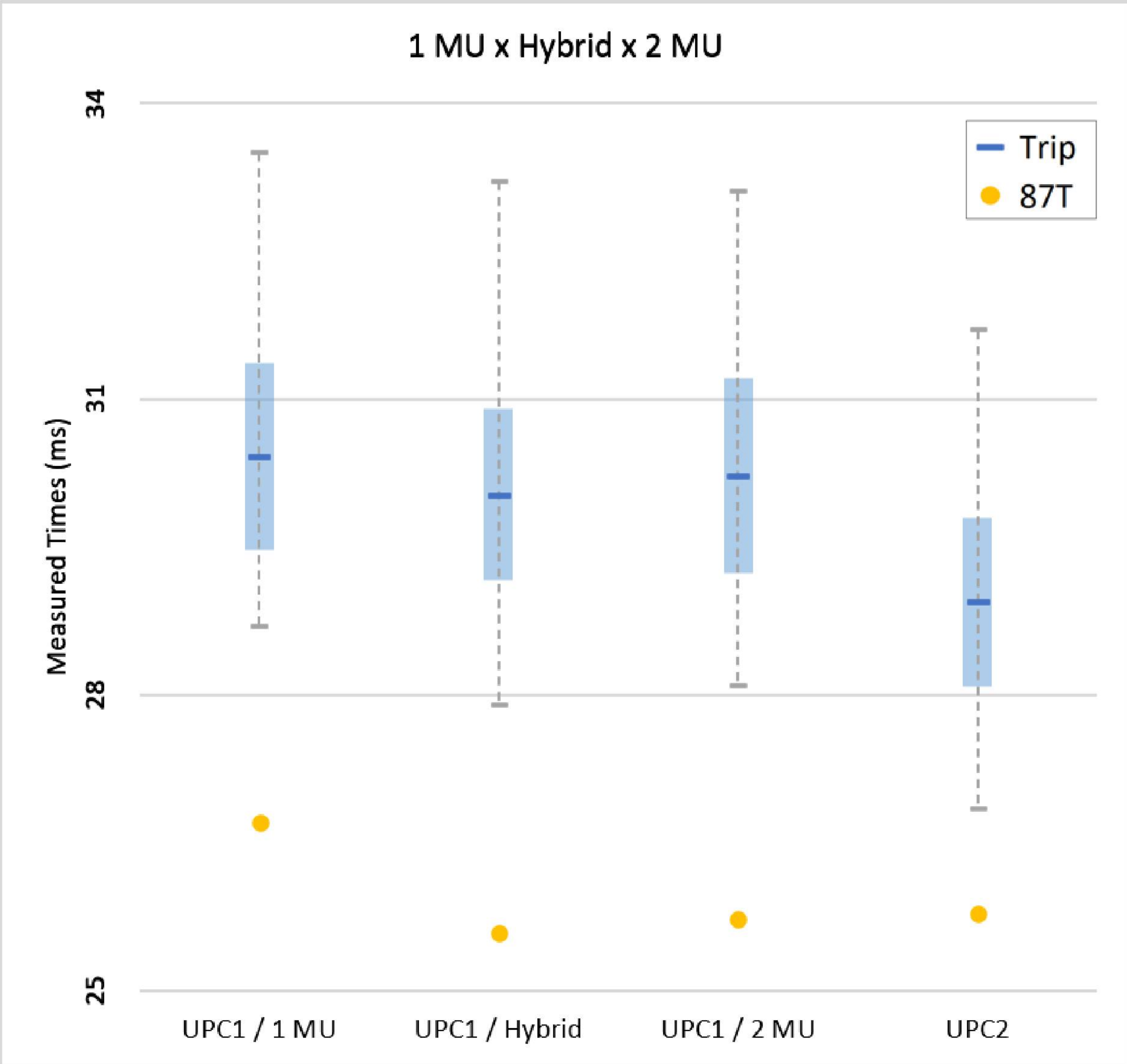
Topology	87T	Last Trip	Tmax	Tmin	dev
UPC1 / 1 MU	26.71	30.42	33.50	28.70	0.94
UPC1 / Hybrid	25.58	30.03	33.20	27.90	0.87
UPC1 / 2 MU	25.72	30.22	33.10	28.10	0.99
UPC2	25.78	28.94	31.70	26.85	0.86

SOURCE: the author (2023)

It is possible to identify that the fault identification (87T on the tables) stage for the process-bus based UPC1 for Hybrid and 2xMU topologies are both operating even faster than the conventional UPC2. The 1xMU UPC1 operation was 0.93 ms slower. The second measured time, the relay operating time, has an expanded difference between UPC2 and the others, as there is the GOOSE transmission time from UPC1 to its merging units, who will later have a digital output to operate. The UPC2 does not have the GOOSE transmission, and right after the fault is identified, the digital output will operate immediately. FIGURE 19 has the graphical representation of the test results above, where it is evident that the solution with one merging unit had a fault identification time above the other cases.

This figure and the following trip times comparison ones have the same structure. The term indicated as “Trip” refers to the average trip time, described as “Last Trip” on the tables. It is also displaying deviation times, plus the maximum and minimum trip times. The term “87T”, refers to the fault identification time. As the target of this dissertation is on the overall performance of a protection chain, the 87T was limited only to its average, to reduce the amount of information on the image.

FIGURE 19 – Trip times comparison for all three tested topologies



SOURCE: the author (2023)

4.2 MEASUREMENTS PER SAMPLED VALUES MESSAGE (ASDU)

The goal of this use case is to evaluate the impacts that IEC 61869-9 application could have, replacing IEC 61850-9-2LE, due to the differences on the number of measurements available on each SV stream.

The representation of the differences in packet count flowing through the network are represented on TABLE 4 and TABLE 5

TABLE 5 make it clear that the even if the sampled values proportion in relation to all other packets remains massive (over 99.7%), the total count with 2 ASDU is approximately half of the message count with 1 ASDU. Considering the sampling rates represented on TABLE 1, on a 60Hz system both IEC 61850-9-2LE and IEC 61869-9 standards will result on a 4800 samples per second. For a 1 ASDU application (9-2LE), this will translate into one SV message every 200 µs (0,2 ms). A 2 ASDU stream (IEC 61869-9) will result on an SV message every 400 µs (0,4 ms). This additional delay may represent additional time necessary for fault identification time, and therefore additional relay operating time. The theoretical 200 µs delay, on reality, has been measured as 380 µs, and such delay was similar on the relay operating time (Last Trip).

TABLE 7 has the test results for the ASDU variations. The fault identification time for the UPC1 with 1 ASDU was faster than UPC2.

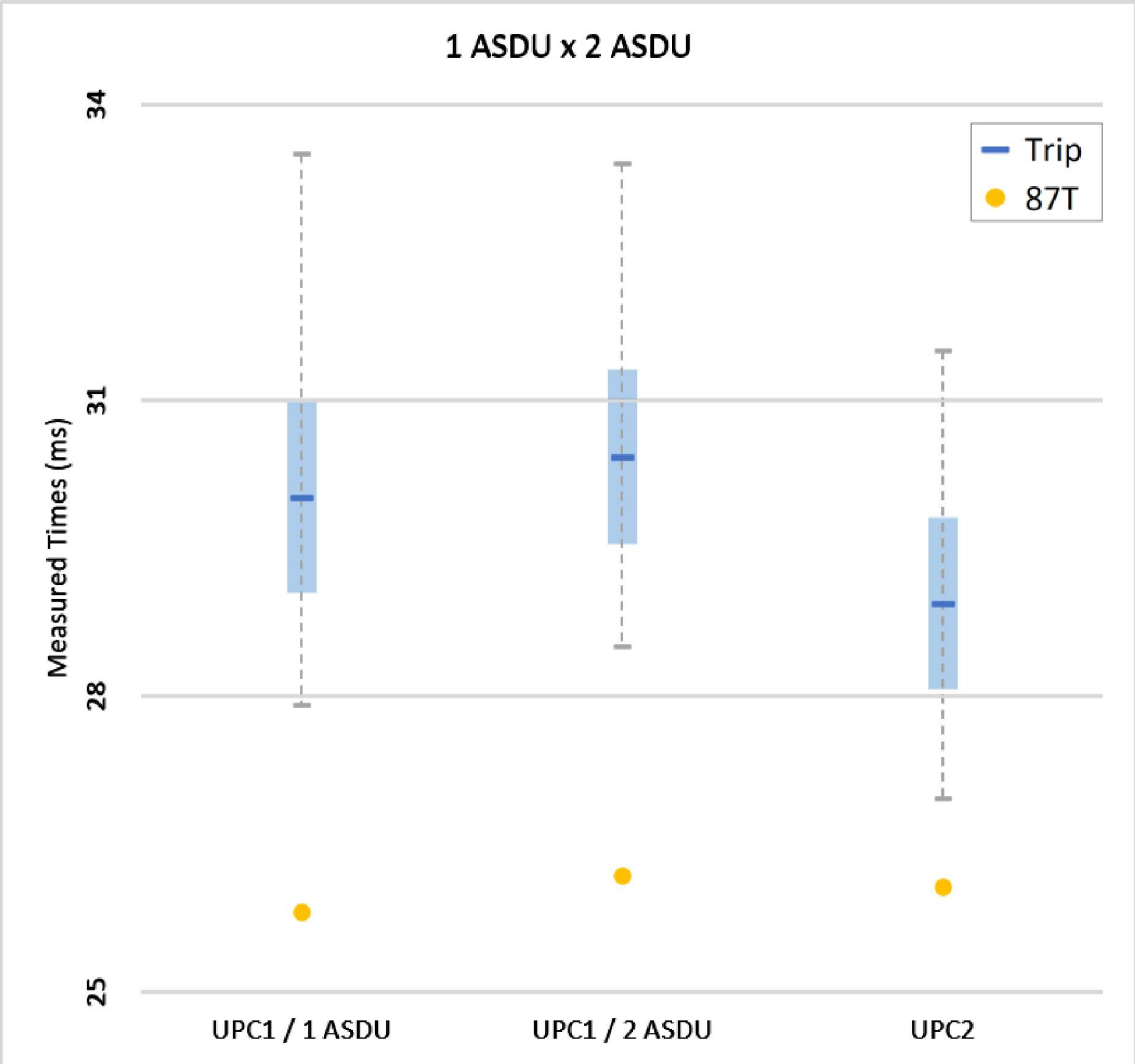
TABLE 7 – Test results for ASDU variations (in ms)

ASDU	87T	Last Trip	Tmax	Tmin	dev
UPC1 / 1 ASDU	25.81	30.02	33.50	27.90	0.98
UPC1 / 2 ASDU	26.19	30.43	33.40	28.50	0.89
UPC2	26.07	28.94	31.50	26.95	0.87

SOURCE: the author (2023)

FIGURE 20 represent the assessment results graphically.

FIGURE 20 – Trip times comparison for sampled values with 1 ASDU and 2 ASDU



SOURCE: the author (2023)

4.3 NETWORK TRAFFIC

As described on multiple publications on the literature review, concerns about the network traffic and how IEDs and MUs can respond to different network designs and traffic exist. This use case has focused on how a transformer differential protection would respond to network traffic exactly as it would face on a digital substation environment.

The representation of the differences in volume of data flowing through the network are represented on TABLE 4 (Overloaded Traffic) and on TABLE 5 (Light Traffic). The normal traffic scenario has the same network traffic as the overloaded scenario, but the VLANs set on the switches limit the data that will reach the UPC1 device to the same amount of data that is represented on the light traffic scenario. The switches are the ones that will have to process all the data flowing on the network.

For reference, the same network, when added two more sampled values streams, went over the actual 100Mb fast ethernet ports capacity of the devices, and went completely offline until these additional sampled values streams were removed from the network.

TABLE 8 represent the test results for such use case. It is possible to see a slight better performance of the normal scenario when compared with the overloaded assessment for fault identification (87T): 0,10 ms. The relay operation time (Last Trip) has the overloaded last trip 0,02 ms slower for normal traffic load.

The ethernet ports of the utilized devices have a very high throughput, meaning that they are optimized to handle overloaded traffic, to the point that they can ignore any network overloads to deliver the fastest possible GOOSE/SV response.

TABLE 8 displays the test results for such use case.

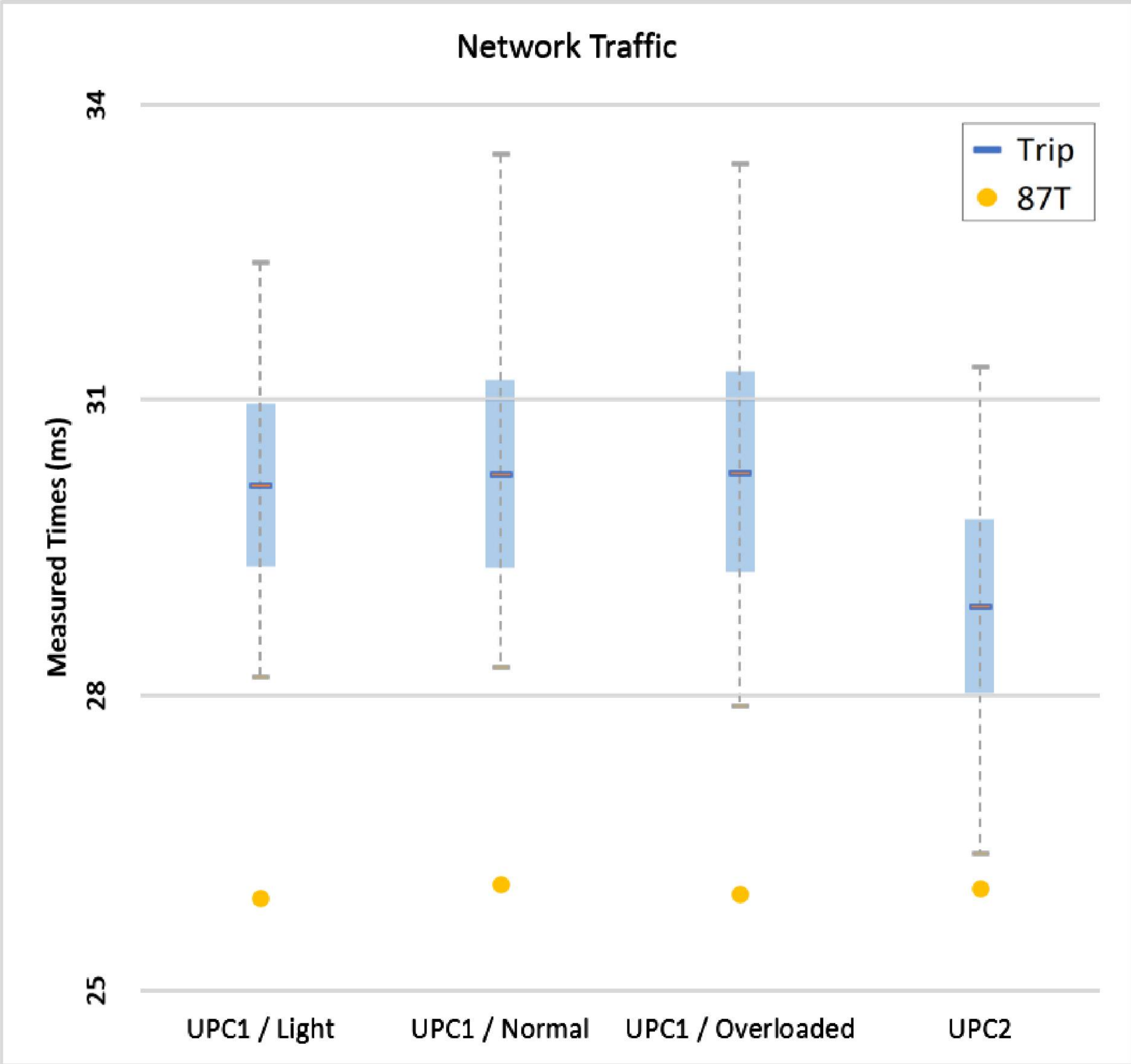
TABLE 8 – Test results for network traffic variations (in ms)

ASDU	87T	Last Trip	Tmax	Tmin	dev
UPC1 / Light	25.94	30.15	32.40	28.20	0.83
UPC1 / Normal	26.08	30.25	33.50	28.30	0.96
UPC1 / Overloaded	25.98	30.27	33.40	27.90	1.02
UPC2	26.04	28.91	31.35	26.40	0.88

SOURCE: the author (2023)

FIGURE 21 has the graphical representation of the assessment results.

FIGURE 21 – Trip times comparison for different network traffic loads



SOURCE: the author (2023)

4.4 PROCESS BUS X CONVENTIONAL

The final comparison is the one considering all analyzed test results, but this time focusing the difference between the digital protection (UPC1), and the conventional one (UPC2).

TABLE 9 demonstrates the results, and it is visible that the fault identification time for a process bus-based transformer protection is faster than the conventional protection. The last trip binary output operation, as there are the GOOSE messages being transferred from UPC1 to merging units to influence the result of UPC1, but the main result is still under 0.30 ms).

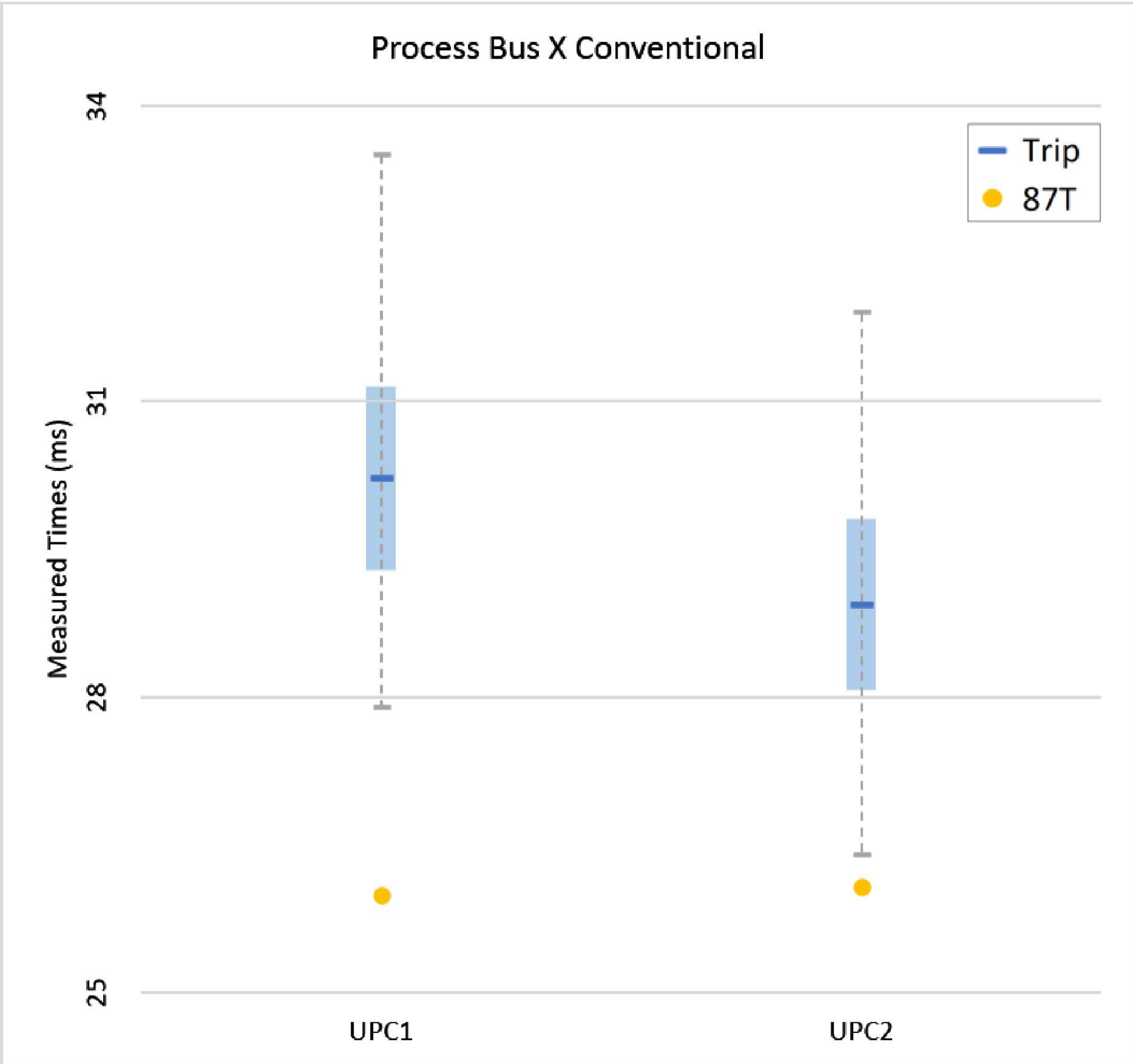
TABLE 9 – Test results: comparing process bus with conventional 87T (in ms)

	87T	Last Trip	Tmax	Tmin	dev
UPC1	26.00	30.22	33.50	27.90	0.93
UPC2	26.07	28.94	31.90	26.40	0.87

SOURCE: the author (2023)

FIGURE 22 has a visual depiction of the results found comparing a process bus-based protection and a conventional one. They cover all the results found on the previous assessments.

FIGURE 22 – Trip times comparison for process bus and conventional 87T



SOURCE: the author (2023)

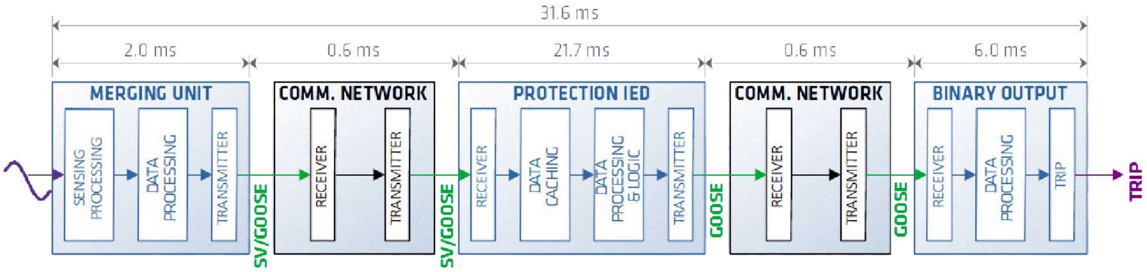
4.5 TEST RESULTS COMPARISON WITH OTHER PUBLICATIONS

Given the number of references for this dissertation, the most relevant ones were chosen for comparison of found results.

4.5.1 Performance considerations in digital substations (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016)

This publication compares the theoretical fault clearance time from standard times with the actual device performance times by the time it was published. The FIGURE 23 describes the standard times described for each element of the protection chain.

FIGURE 23 – Operate time of functional chain with standard times.



SOURCE: Adapted from (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016) and (LEITLOFF, et al., 2022)

As it can be seen, this author defined the expected time for total trip (Last trip on the test results of this dissertation) of 31.6 ms. The results shown on TABLE 9 are 30.22 ms.

In addition to that, the author states that with more recent devices, the trip time should be improved to 25.2 ms. Such result could not be found even for the fastest unique trip times, either with process bus or conventional applications. These results are listed below on TABLE 10

TABLE 10 – Results comparison with (MEIER, WERNER, & POPESCU-CIRTUCESCU, 2016) (in ms)

Fault Description	Last Trip Times
Author's results for process bus protection	30.22
Meier et al. clearance time with standard times	31.60
Meier et al. clearance time with recent devices	25.20

SOURCE: the Author (2023)

4.5.2 Software Merging Unit base IED Functional Test Platform (WU, HONETH, NORDSTRÖM, & SHI, 2015)

For this experiment, the authors have calculated trip time based on the trip binary output directly from the IED. When compared with the tests performed on this dissertation, it would be the equivalent of the "87T" signal.

The assessments performed have varied the angle and the Bias Current, over 24 different fault scenarios, and are represented on TABLE 11.

TABLE 11 – Time results from tests based on software-based merging unit (in ms)

Operate time (ms)		**Bias Current (per unit)**			
		0.5	**1**	**2**	**4**
Inception Angle (degrees)	**0**	26.7	26.2	27.0	26.2
	36	28.1	26.7	29.8	28.8
	72	27.9	29.2	28.9	29.6
	90	28.6	28.8	30.2	27.9
	108	28.8	29.3	28.9	29.1
	144	25.9	26.4	26.2	25.4

SOURCE: adapted from (WU, HONETH, NORDSTRÖM, & SHI, 2015)

Based on these results, it is possible to determine an overall average of 27.94 ms trip time. As shown on TABLE 9, the average found on the assessments for this dissertation, for all process bus-based trip times was 26.00 ms.

4.5.3 Performance Evaluation of Protection Functions for IEC 61850-9-2 Process Bus Using Real-Time Hardware-in-the-Loop Simulation Approach (ALMAS)

On this publication, the author has tested similar topologies to the ones used on this dissertation, but without merging units, therefore the equivalent times that need to be compared are the fault identification times, described as 87T. The test with a single merging unit was not evaluated on this paper, as it used IEC 61850-9-2LE for sampled values streams. TABLE 12 allows to compare both results side-by-side.

TABLE 12 – Results comparison with (ALMAS & VANFRETTI, 2013) (in ms)

Author description	87T	Tripping time	Almas et al. description
UPC1 / Hybrid	25.58	29.51	Primary, Secondary Both Hardwired
UPC1 / 2 MU	25.72	28.99	Primary SV, Secondary Hardwired
UPC2	25.78	29.60	Primary, Secondary Both SV

SOURCE: the Author (2023)

4.5.4 Testing IEC-61850 Sampled Values-Based Transformer Differential Protection Scheme (SHARMA, NGUYEN, KUBER, & BARADI, 2021)

This paper had similar scenarios of the previous one: a completely conventional application, an entirely digital topology (process bus-based), plus a hybrid topology. The test architecture did not have a merging unit, so trip times were measured since either from GOOSE or binary outputs originated by IED. TABLE 12 allows to compare these results with the ones from this dissertation.

TABLE 13 – Results comparison with (SHARMA, NGUYEN, KUBER, & BARADI, 2021) (in ms)

Author description	87T	Tripping time	Almas et al. description
UPC1 / Hybrid	25.58	27.48	Hybrid Transformer Differential (Scenario 3)
UPC1 / 2 MU	25.72	29.22	SV-Based Transformer Differential (Scenario 2)
UPC2	25.78	26.68	Traditional Analog Differential (Scenario 1)

SOURCE: the Author (2023)

4.5.5 System-Level Tests of Transformer Differential Protection Using an IEC 61850 Process Bus (INGRAM, SCHAUB, TAYLOR, & CAMPBELL, 2014)

This author has stated that the SV load has different impacts when the multicast destination is the same or different, proving that after 12 SV streams with the same multicast address, the response time starts to degrade. After 17 streams the results are alarming and from 19 onwards it is beyond acceptable levels.

As this publication has focused on proper data modelling and network design, such problematic results were not found. On the other hand, this paper tested SV stream count with different multicast destination ranging from zero to 18, without visible variation on the test results.

5 CONCLUSION

5.1 FINAL COMMENTS

Unlike other studies mentioned as reference in this study, the focus of this work was not to study specific protection functions, which for the scope of this work would relate to a multitude of different transformer protection functions and different fault cases, but the impact of variations related to sampled values structure and communication on protection. These variations are possibly to happen in real application cases in Protection, Automation and Control Systems, and their performance in these cases.

Variations were made regarding the analog signal reading format (one or two merging units, or even hybrid measurement), network load variations (network with several MUs, but organized in VLANs; without this organization of VLANs; or without this loading), and it was also varied the way the SV streams were composed (one or two ASDUs), and consequently the volume of packets circulating in the network.

It was confirmed that the digital protection, using sampled values, has actuation times above the conventional protection times, but still within the specification in standards. For IEC 60834-1, both fault identification and relay operation times still comply with the determined maximum times. The IEC 61850 transmission times for GOOSE and sampled values also were respected.

The advantages in design that IEC 61869-9 can provide in relation to IEC 61850-9-2LE, even more for transformer protection, where a solution with one single sampled values stream is possible. This solution, however, had a slower fault identification (87T) time, with 1.01 ms slower than a conventional protection. The hybrid scenario, with a combination sampled values and conventional measurements, has also been assessed and produced equivalent results to all other ones.

It was proven that the recommendation of the IEC 61869-9 standard to use two ASDUs per stream is valid, as the reduction of packets in the network is significant, but its overall trip time was increased by around 0.41 ms.

The average difference from conventional protection to the one based on process bus for fault identification time (87T) has the digital application faster by 0.07 ms. The relay operation time (Last Trip) had the conventional application faster by 1.28 ms. A relevant improvement on IEC 60834-1 could be to expand its operation times, to add considerations on the additional element that is the merging unit, and therefore consider one more time window in the whole protection chain.

The importance of the correct configuration of the PACS ethernet networks was confirmed, given the impact on trip times due to their variation. The IEDs used in the test are prepared to operate in networks with a large volume of data flow, as their delay in overloaded networks was very close to the normal network traffic load.

The results found are aligned with existing references on the subject, most specifically the test results that were performed for transformer differential protection, with different topologies, given the differences on the architectures and available equipment for each case. The behavior of well-designed network VLAN and proper data modelling with different multicast addresses also was confirmed.

In general, the entire set of test results prove that the bundle of technologies and standards necessary to deploy process bus are consistent enough to deliver a reliable solution, and that there are already available products in the market to put together a completely operational system.

5.2 FUTURE WORKS

Additional tests with new upcoming challenges can be executed to expand IEC 61850 confirmed capability as the main substation standard for Protection, Automation, and Control Systems.

Remaining on the domain of protection performance, as suggested by (STEINHAUSER, 2023), it is necessary to reproduce similar protection performance tests with encrypted IEC 61850 communication, as described on IEC 62351 standard. The encryption could create additional delays on the data transmission, and will require significant developments to enable communication monitoring, which currently is a quite simple task to achieve, because GOOSE and sampled values are both multicast messages. The outcome of such work is focused to confirm if under such encrypted environment, the protection chain can remain delivering protection operation below the maximum operation times required on international and regional standards. It may also deliver significant insights on how to approach testing encrypted IEC 61850 systems.

Another relevant study to be done relates to the replacement of bay-specific protection devices (as such ones used during this research) for centralized protection and control devices, as presented on (ALEIXO, et al., 2023) and (HEMMER, MELENHORST, & WOERTMAN, 2023). The additional step on such element is the fact that the amount of protection functions and data (GOOSE plus sampled values) gathered by one single specific device exceeds by far the input necessary for a single transformer differential relay. Just like the previous proposal, this one could also deliver performance results for CPC protection systems, plus suggestions on how to identify the limits each specific CPC solution, and its maximum capacity of protected bays, for example.

To assess multivendor merging units protection applications is another relevant work to be tested. This was one of the original goals of this research, but the issues to integrate two different manufacturers plus limited time available for tests at the factory environment have led to discarding this section of the originally expected scope. Elements such as bus bar protections (ANSI 87B) are very likely to take advantage of this application when positive test results are published.

In the same path of multivendor devices, another proposed follow-up research related to deep test and analysis of the implementation of the PTP profile for multivendor devices. Even if protection functions have not been evaluated, the PTP time synchronization based on IEC 61850-9-3 have been preliminary observed, as during the first tests performed with the tested system, there were occasions where different time synchronization behavior by the two available vendors could be verified. Upon first analysis, it was not clear if the power utility profile states exactly how the devices must behave and synch to a PTP Grandmaster, and which parameters of the PTP message must be relevant. The final comprehension of such issue could not be delivered and could be the scope of a future work.

Switching from transformer protection to line protection, there’s still room for additional testing on IEC 61850 application for transmission lines, with relevant questions to be answered comparing the performance of using regular GOOSE and sampled values through Telecommunication systems with the routable variations of such (R-GOOSE and R-Sampled Values). (LELLYS, 2023) has listed some experiences of these from a few years ago, but updated tests can be put in place. This make more sense when considering that there are many outdated telecommunication technologies still in place for Utilities (SONET, TDM, SDH), which are currently being replaced by Multi-Protocol Label Switching (MPLS), as suggested by (OLIVEIRA, et al., 2023).

Still related to line protection, when 5G/3GPP releases Ultra Reliable Low Latency Communications (URLLC), it will be relevant to confirm the actual performance of URLLC for both private and public networks, with their actual latency and jitter, to confirm if such deployment can be considered for power systems protection.

Related to ethernet networks, there are questions to be answered, as the reproduction of similar tests with different switch manufacturers to confirm that the assessments would have equivalent results. A different approach can be considered, comparing conventional ethernet networks performance and behavior with other network technologies, such as Software Defined Networks (SDN), Time Sensitive Networks (TSN), or even MPLS.

Finally, the data modelling part of the standard offers significant opportunities. As suggested on (LISBOA, 2021), being able to manipulate the data model that can enable to design and monitor accurately an ethernet network designed for a PACs will offer significant enhancements on how IEC 61850 systems are designed. To be able to integrate on a deliverable as the one achieved by (ALEXANDRINO, 2021) will offer another layer of solution optimization and standardization.

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