ISEP INSTITUTO SUPERIOR DE ENGENHARIA DO PORTO

# Real-Time Quality Index Estimation for Redundant Sampled Values Streams in Digital Substations

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# Abstract

With the advancement of technology, electromechanical relays have evolved into Intelligent Electronic Devices (IEDs) and, as a result, protection relays have gained the ability to communicate. They not only provide equipment protection but also communicate with other devices and exchange information among themselves. Communication protocols bring many advantages and challenges. They reduce the amount of wiring needed to transmit information. Previously, a wire was required for each piece of information, but with communication protocols, a pair of wires is sufficient to convey various pieces of information. However, the knowledge required to implement this is significantly greater.

With the introduction of the IEC61850 protocol, the energy sector has established a communication standard for the entire segment. This protocol has brought interoperability among manufacturers, one of the numerous advantages it has over other protocols. Real-time information exchange occurs through specific protocols that are part of the IEC 61850 standard, ensuring higher data quality and availability.

Now, a customer is no longer bound to a single manufacturer, not having to replace all equipment when upgrading devices. This is because all devices are required to communicate following the established protocol. As Intelligent Electronic Devices play a critical role in substations, and many of their functions are critical and need to be executed at the right time, any development incorporated into the device has an impact on the entire product.

This thesis aims to develop a functionality for Protection Relays (IED). Currently, the treatment for SV's (Sampled Values) in the protection relay involves checking communication with the Merging Unit, which acquires and sends information to the protection relays. When the primary channel fails to transmit, the secondary channel takes over, informing the protection relay about the information that the first channel failed to send. If one channel fails, the other can provide the lost information and assume the primary communication.

For example, the channel 1 provides information as the primary channel. As soon as Channel 1 is interrupted for any reason, Channel 2 takes over, providing information to the protection relay. This is the decision-making method; when there is a total system failure, the other channel assumes control. The proposed functionality in this master's thesis aims to add intelligence to this selection method by suggesting ways to evaluate, quantify, and qualify the received information. It aims to determine which signal to use based on indicators, whether through Channel 1 (primary) or Channel 2 (secondary). This ensures better information for protection relays, allowing protection algorithms to take the correct actions as quickly as possible within their operating parameters.

It is through Sample Values that protection algorithms determine if there is a fault in the electrical network, becoming a highly critical component for the entire system with a direct impact on product performance in terms of quality, efficiency, and reliability.

**Keywords:** IEC61850-9-2, Sampled Values (SV), IEC61850-9-3, Precision Time Protocol

# Resumo

Com o avanço da tecnologia, os relés eletromecânicos evoluíram para os Dispositivos Eletrônicos Inteligentes (IED), e com isso, os relés de proteção ganharam a capacidade de se comunicar. Não apenas realizam a proteção do equipamento, mas agora também se comunicam com outros dispositivos e trocam informações entre si. Os protocolos de comunicação trazem muitas vantagens e desafios. Eles diminuem a quantidade de fios necessários para a transmissão de informações. Anteriormente, um fio era necessário para cada informação, mas com o protocolo de comunicação, basta um par de fios para transportar diversas informações. No entanto, o conhecimento necessário para implementar isso é significativamente maior.

Com a chegada do protocolo IEC61850, a área da energia estabeleceu um padrão de comunicação para todo o setor. Esse protocolo trouxe interoperabilidade entre fabricantes, sendo uma das inúmeras vantagens sobre outros protocolos. A troca de informações em tempo real ocorre por meio de protocolos específicos que fazem parte da norma IEC 61850, proporcionando maior qualidade e disponibilidade dos dados.

Agora, um cliente não fica mais preso a um único fabricante, não sendo obrigado a trocar todos os equipamentos ao realizar um upgrade nos dispositivos. Isso ocorre porque todos os dispositivos são obrigados a se comunicar seguindo o protocolo estabelecido. Como os Dispositivos Eletrônicos Inteligentes (IED) desempenham um papel crítico nas subestações, e grande parte de suas funções são críticas e precisam ser executadas no tempo correto, qualquer desenvolvimento que seja incorporado ao dispositivo tem impacto em todo o produto.

Esta tese tem como objetivo desenvolver uma funcionalidade para os Relés de Proteção (IED), hoje a tratativa para as SV's (Sampled Values) no relé de proteção é apenas se há a comunicação com a Merging Unit que está aquisitar as informações e a enviar para os relés de proteção, quando este canal deixa de enviar o canal secundário passa a informar ao relé de proteção as informações que o primeiro canal deixou de enviar a informação, quando um canal falha o outro consegue fornecer as informações perdidas e assume a comunicação principal.

Por exemplo, o Canal 1 está à fornecer informações como o principal, assim que o Canal 1 é interrompido por quaisquer razões o Canal 2 passa a fornecer as informações ao relé de proteção, sendo este o método de decisão, quanda há uma falha total do sistema é que o outro assume. A funcionalidade proposta nesta tese de mestrado é dar alguma inteligência a este método de seleção, propondo maneiras de se avaliar a informação recebida, quantificar e qualificar a mesma e determinar por estes indicadores qual sinal utilizar, se é o caminho pelo canal 1/principal ou canal 2/secundário, com isto garantido melhores informações aos relés de proteção para que os algoritmos de proteção tomem as ações corretas no menor tempo possível e o mais rápido possível dentro dos seus paramêtros de atuação.

São pelas Sample Value que os algoritmos de proteção determinam se há um defeito na rede elétrica ou não, tornando-se um componente de alta criticidade para todo o sistema,

com impacto direto no desempenho do produto em critérios de qualidade, desempenho e confiabilidade.

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# Chapter 1

# Introduction

## 1.1 Overview

Since the discovery of electricity, humanity has harnessed electrical energy for a multitude of purposes. As the demand for electricity grew, encompassing applications like heating, ventilation, and lighting, the need to generate more electrical power became paramount to accommodate the evolving array of functionalities that emerged over time.

Consequently, diverse power plants were established to meet the increasing demand. These included thermal power plants, hydroelectric plants, nuclear facilities, geothermal installations, combined-cycle plants, and others. In contemporary times, we have witnessed the advent of novel energy sources, such as wind, solar, tidal, biomass, and green hydrogen. Classified as renewable energies, these sources, along with hydroelectric power, offer a pathway towards planetary decarbonization, as they eschew reliance on fossil fuels.

However, these power-generating facilities often found themselves situated at a considerable distance from major consumers, specifically large urban centers. This spatial disparity necessitated the development of a means to efficiently transport the energy generated by these plants to the significant consumer hubs. This necessity gave rise to electrical substations, pivotal in facilitating the transmission of energy from power plants to end consumers, thereby playing a fundamental role in the entire energy cycle.

However, the introduction of electrical substations takes place, and while various types exist,here spotlight four specific substation categories here:

- Step-up substations: Positioned in close proximity to power plants, these substations serve the crucial function of elevating the energy voltage. This strategic placement aims to minimize losses attributable to phenomena such as Foucault currents and parasitic currents, ensuring the delivery of generated power with utmost efficiency. Given the substantial distances involved in transmission, the decision to increase voltage at this stage becomes imperative to effectively mitigate the mentioned challenges.
- Distribution Substation: Following the transmission of energy from remote areas at higher voltages to minimize losses, it becomes essential to lower the voltage before reaching consumers at safer levels. This leads to distribution substations, where the voltage is reduced, allowing for a more seamless distribution of energy within urban centers.
- Step-Down Substation: The step-down substation is the one located very close to the end consumer, operating at a lower voltage than in distribution, thereby reducing the risks to the individuals who utilize it.

- Switching Substation: This facility is designed to interconnect supply circuits operating at the same voltage level. It allows for the segmentation of circuits, facilitating the power on of shorter sections, and enabling a more flexible and efficient distribution of electrical power.

Figure 1.1 is a simplified diagram illustrating the path from the power plant to the end consumer [1].

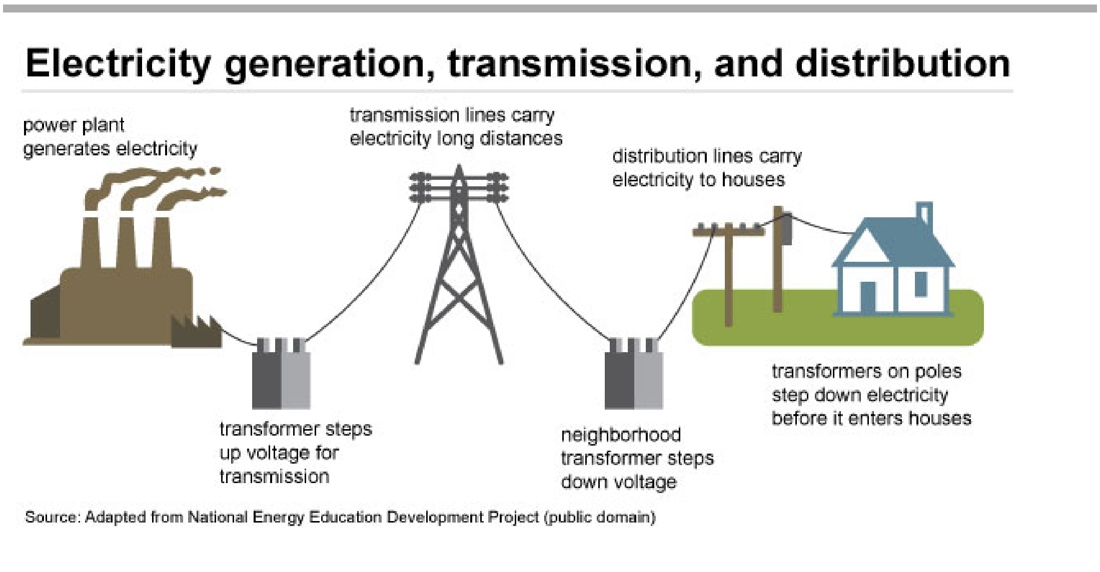


Figure 1.1: Electricity Generation, Transmission, and Distribution Pathway
(Image credits: U.S. Energy Information Administration)

## 1.2 Digital Substation

Electric power substations play a fundamental role in the entire cycle of electric energy and its transformations. Simultaneously, as we witness several generating sources converting energy, such as hydroelectric (water turbines), thermal (steam turbines), combined cycle (gas turbines and steam turbines), wind (wind energy), solar farms (solar energy), among others into electric energy, numerous consumers draw upon this produced energy. The absence of an energy storage location underscores the substantial importance of substations. Without them, meeting the extensive demand and need for electric energy would be impracticable, hindering economic growth and the development of industries, businesses, and even entire countries. Today, every facet of operation, from mega-factories to simple light bulbs, relies on electric energy.

Substations facilitate the extended reach of energy to diverse locations, enabling a direct connection from the generating source to consumers. Serving as the link between generation and consumption, substations categorize the electric energy chain into four major divisions: electric energy generation, electric energy transmission, electric energy distribution, and electric energy consumption. These processes start with High Voltage (Generation), increases to Very High Voltage (Transmission), goes to Medium Voltage (Distribution) and when finally reaches the consumer is Low Voltage (Consumers).

[1] https://www.eia.gov/energyexplained/electricity/delivery-to-consumers.php

The evolution of electric substations has embraced new technologies, as preventive maintenance, predictability of problem occurrences, fault alerts, backyard equipment switching, and visualization of currents and voltages. Follow these advancements are electromechanical protection relays, monitoring and safeguarding against electrical faults in backyard equipment. Backyard equipment, including high-voltage circuit breakers, switches, capacitor banks, reactors, transformers, and transmission lines, retains the basic concept from the 1990s but now has features enhanced performance and added functionalities due to technological advances.

Electric power systems within a substation can be categorized into four levels:

- Level 0 - Backyard Equipment: Encompassing all devices responsible for transmitting energy from the power generation station to customers, premises—factories, public lighting, residences, hospitals, data centers, etc. These devices are responsible for the entire energy transmission.
- Level 1 - Electrical Protections: Formerly known as Intelligent Electronic Devices (IED), these devices have replaced the need for multiple protection relays, executing various protection functions, such as overcurrent, overvoltage, and transformer differential, within a single device and add the communications possibilities.
- Level 2 - Supervisory Control and Data Acquisition (SCADA): SCADA systems communicate with IEDs to acquire data, including readings of currents and voltages, facilitating the supervision of the entire substation and remote operation of backyard equipment.
- Level 3 - Control Center: This centralizes information from multiple substations, commanding them in a manner conducive to the grid and handling functions inherent to Level 2. Typically used by those overseeing the distribution of electrical energy throughout a country, it ensures a balanced load throughout varying consumption periods.

Over the years, substations have evolved to the concept of a digital substation. Even today, it is a very current topic, as we have very few digital substations in the world. With evolution, we moved from having less 'smart' equipment to having every device becoming more 'intelligent'.

The concept of a digital substation involves seamless communication between devices across all levels, minimizing the need for electrical wires and favoring optical fiber as the primary means of information exchange. Devices communicate with each other, enabling actions such as a trip originating from an IED communicating with a circuit breaker via the network to address a fault identified by the IED. This is achieved through a message called Generic Object-Oriented Substation Event (GOOSE), and the circuit breaker itself triggers the operation through the GOOSE protocol, exemplifying the digital substation concept. While the world still faces limitations in fully embracing the digital substation concept, notable progress has been made at Level 0, particularly with the introduction of Merging Units. These units perform analog acquisition of current and voltage sensor data and inform other devices digitally on the network.

This marks another step towards the digital substation concept, where only this equipment is connected to the sensors, and a single optical fiber connects to a switch to publish information from the respective sensors. Today, there is no longer a need to connect wires to the electrical protection panel, connect the IEDs to the same network as the Merging

Unit provides the necessary information to execute electrical protection algorithms, including protection against overcurrent and overvoltage.

## 1.3 Research Motivation and Context

With the advent of the IEC61850 standard in the energy sector, emerging as the definitive standard for the entire industry, facilitating essential interoperability among diverse equipment from various manufacturers, ensuring reliability, real-time responsiveness, and resilience over time. Fueled by a deep passion for the field of electrical energy, I have devoted my professional journey to this domain.

Presently, I am actively contributing to the improve of Intelligent Electronic Devices (IEDs), developing a solution wherein the device possesses decision-making capabilities. This involves choosing, through the IEC 61850-9-2 Samples Values protocol, which sample provided by the Merging Units to employ in the algorithms of the protection device. This endeavor allows me to amalgamate my extensive experience in commissioning electrical substations, particularly in conducting primary and secondary tests with a focused emphasis on secondary evaluations.

The insights gained from my pursuit of a Master's degree in Critical Computing Systems are seamlessly integrated into this tangible development. The aim is to enhance a critical functionality of IEDs, positioning these devices as the cornerstone with the most critical actuation power within an electrical substation. This commitment ensures optimal response times while steadfastly adhering to the foundational principles of electrical protections and the four pillars of electrical protection:

- Reliability: The likelihood of a component, equipment, or system meeting its intended function under specified circumstances, while avoiding unnecessary operations during routine system operation or in the presence of faults outside its protection zone.
- Sensitivity: The capacity of the protection system to respond to abnormalities in the designated operating conditions, selectively isolating only the portion of the system experiencing a fault, while allowing the rest to operate normally.
- Selectivity: The ability to completely isolate the faulty element and disconnect the smallest possible portion of the system by operating associated breakers.
- Speed: The commitment to minimizing the impact of faults and the risk of instability, quantified by the time between fault occurrence and the opening command of the circuit breaker issued by the relay or IED.

## 1.4 Research Objectives

The ongoing digital transformation of electrical substations has given rise to a crucial component known as the Merging Unit. This sophisticated equipment plays a pivotal role in the modernization of substations by facilitating the acquisition of data from current and voltage transformers. Its primary function is to read and process these values, subsequently transmitting them through the IEC 61850-9-2 Sampled Values (SV) protocol.

However, a potential scenario arises where two Merging Units concurrently read data from the same current or voltage transformer. Both units then independently send Sampled Values over the Ethernet network, introducing a need for a decision-making mechanism within the Intelligent Electronic Device (IED). The IED, a key component in protection systems, must be endowed with the intelligence to discern and select the most optimal sample for deployment in its protection algorithms.

This research endeavor is dedicated to developing the necessary intelligence within the IED, ensuring it can autonomously evaluate and choose between the multiple samples provided by the Merging Units. By enhancing the decision-making capabilities of the IED, we aim to optimize the functionality and reliability of protection systems in digital substations, ultimately contributing to the overall efficiency and resilience of the power grid.

## 1.5 Research Contributions

This thesis introduces a significant contribution through the proposition of an algorithm designed to optimize the selection of samples from each current transformer and voltage transformer for individual electrical protection relays. These algorithms are instrumental in ensuring that electrical protection systems adhere to the four key principles of protection philosophy. Recognizing that the same Merging Unit may not yield optimal results for all protection relays, the effectiveness of the algorithm is contingent on various factors, including communication routes, the distance information travels, and potential network issues such as information overload, given the abundance of sampled values in the network. As such, the primary contribution of this thesis lies in the development of an algorithm capable of discerning the most suitable sample for consumption by the Intelligent Electronic Device (IED) in the network.

## 1.6 Thesis Structure

The current thesis is organized into four sections, with a plan to expand its content in the upcoming semester. Comprising only four chapters at present, Chapter 1 serves as an introduction to the thesis. It presents key concepts that elucidate the underlying idea and provide a comprehensive understanding of the thesis's objectives.

In Chapter 2, the idea is further explored, and fundamental concepts are explained. This includes the evolution of the network and equipment designed for information retrieval. The evolution of these elements is showcased, emphasizing the significance of this work in enhancing product quality and underscoring its crucial role in sustaining the integrity of electrical networks across numerous countries.

Chapter 3 is dedicated to developing the proposed approach to address the investigation outlined in this thesis. It discusses the architecture, development, testing, and implementation of the algorithm.

The final chapter of this thesis, Chapter 4, is responsible for detailing the methodology, research approach, evaluation of the thesis, and the timeline for all tasks that need to be completed.

# Chapter 2

# State of the Art

## 2.1 Introduction to Substation Automation System (SAS)

In the past, electrical grids faced serious limitations in terms of the employed technologies. However, in today's world, there is a notable increase and significant growth in digital communication technologies in terms of performance and reliability. To adapt to this evolution, Substation Automation Systems (SAS) are based on dedicated software embedded in hardware components. Additionally, SAS provides a straightforward way to control and monitor all equipment in the substation, both locally and remotely. Supervisory Control and Data Acquisition (SCADA) systems offer users a Human-Machine Interface (HMI) used to control, monitor, and protect devices. Moreover, SAS perform this control and monitoring in real-time, contributing to maximizing availability, efficiency, safety, and data integration, resulting in a significant cost reduction.

Furthermore, the IEC 61850 standard and its associated communication protocols are introduced, to be employed within individual substations and between substations. Consequently, the implementation of the MMS, GOOSE, and SV protocols allows for efficient control and monitoring, ensuring that the system is made more robust and future-proof.

Figure 2.1 is a simplified diagram illustrating the substation automation system. [1].

[1]https://docplayer.net/40767859-Lecture-5-substation-automation-systems-course-map.html

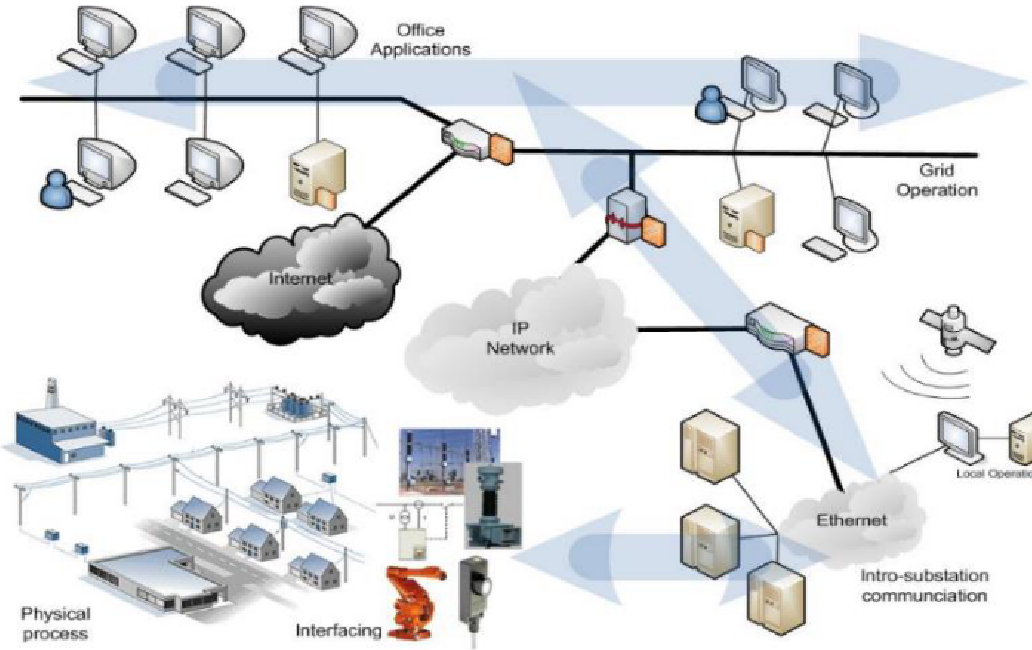


Figure 2.1: Design of Substation Automation Systems(Image credits: KTH, "Lecture 5: Substation Automation Systems")

## 2.2 Backyard System

The backyard system serves as the hub for all high-power apparatus, responsible for channeling energy from the power plant and facilitating its delivery to homes. It encompasses a range of critical devices, such as high-voltage circuit breakers, switches, voltage transformers for protection and measurement, current transformers for protection and measurement, high-voltage power transformers, capacitor banks, reactors, and synchronous compensators,devices that have gained increasing prominence in recent times. However, let's delve into the components found in any substation, as they will be detailed in the subsequent subsections.

### 2.2.1 Circuit Breakers

High-voltage circuit breakers play a crucial role in the operation and protection of electrical networks at very high, high, and medium voltages. They are electromechanical devices designed to interrupt the flow of electric current under abnormal conditions in the electrical network, such as short circuits and overloads. In the event of a network fault, the circuit breaker receives a signal from the electrical protection system detecting abnormalities. With this signal, the circuit breaker contacts quickly open to interrupt the electric current and extinguish the electrical arc generated when the contacts open, preventing damage to the network equipment.

Circuit breakers ensure the reliability of electrical power supply, with a focus on making electricity available to the entire network. High-voltage and very high-voltage circuit breakers are responsible for isolating detected faults in the system, preventing the spread of the defect to other parts of the network and thus avoiding widespread blackouts.

### 2.2.2 Switches

High-voltage switches play a pivotal role in the seamless operation of electrical networks at very high, high, and medium voltages. These electromechanical devices are intricately designed to isolate a section of the electrical system during normal operating conditions. When conducting maintenance on the electrical network, the switch opens a specific circuit segment, necessary for the safe and efficient execution of maintenance tasks. This ensures the well-being of maintenance personnel while simultaneously preserving the continuous operation of the electrical network.

In essence, very high, high, and medium voltage switches serve as integral components in power substations, offering a secure and dependable method for isolating designated sections of the electrical system. This isolation is essential for the maintenance of power system equipment, including transformers, circuit breakers, and capacitor banks. Importantly, this isolation process does not compromise the overall functionality of the substation.

### 2.2.3 Voltage Transformers

Voltage transformers play a critical role in electrical systems by providing precise voltage measurements for each phase of the circuit. Their primary function is to convert very high voltages into more manageable, general-purpose voltages like 110V. The utilization of lower voltages facilitates easier handling, both in terms of magnitude and the insulation required for compatibility with Intelligent Electronic Devices (IEDs).

Ensuring optimal signal quality is a key responsibility of voltage transformers. Their primary objective is to accurately replicate the high voltage in a lower voltage format, creating a precise replica with reduced values. This replication process is essential for utilizing the information in electrical protection (IED), enabling the analysis of network disturbances, and facilitating timely action in the event of a fault.

### 2.2.4 Current Transformers

Current transformers play a crucial role in electrical systems, offering precise current measurements for each phase of the circuit. Their primary function is to convert very high currents into more manageable, general-purpose currents, typically around 1A. This reduction in current values enhances ease of handling, both in terms of magnitude and the insulation required for compatibility with Intelligent Electronic Devices (IEDs).

Ensuring optimal signal quality is a paramount responsibility of current transformers. Their principal objective is to accurately replicate the high current in a lower current format, creating a precise duplicate with reduced values. This replication process is vital for utilizing information in electrical protection, enabling the analysis of network disturbances, and facilitating prompt action in the event of a fault.

## 2.3 Intelligent Electronic Devices (IED)

The electronic device (IED) formed by the set of units for data acquisition, processing, and transmission, located in substations, is generically referred to as a Remote Terminal Unit (RTU). At a given moment, it represented a significant evolution within a sector known for its conservatism in adopting new technologies, allowing remote control of substations by a central-level system, initiating the evolution of data transmission capacity through advances in telecommunications and the application of computers on a large scale. This enabled the expansion of the potential use of digital technology as a reality in substation environments( Rodolpho 2010).

With consolidated digital electronics technology, the first proposals for Integrated Protection and Control Systems emerged, using protection relays and control units based on microprocessors and memories, with intelligence at the equipment level for logic execution and automation, introducing the concept of IED. These devices enable the use of computer networks for communication via fiber optics between terminals and relays within the same substation. In addition, personal computers are used at the control and monitoring level of the substation ( Rodolpho 2010).

### 2.3.1 Protection Alghorithm System

Protection stands as one of the paramount functions within a substation or any power system. Its primary goal is to ensure the safeguarding of equipment and personnel, while also minimizing damage in the event of electrical faults, short circuits, or overloads. This critical function is inherently local, designed to operate independently if necessary, irrespective of the substation's automation system. Even though it seamlessly integrates into the automation system under normal conditions, the integrity and effectiveness of protection functions should never be compromised or restricted within any power system automation ( Rodolpho 2010).

### 2.3.2 Control System

Local control involves autonomous control actions that a device can independently perform, such as interlocks, switching sequences, synchronism verification, and others. In this context, human intervention is limited, and the risks of errors are minimized. Similar to protection, local control should continue to operate even if the automation system is compromised.

Remote control functions are related to substation control executed by SCADA software. Commands can be directly issued to devices managed remotely, such as opening or closing a circuit breaker. Relay settings can be adjusted either through the device itself or a computer equipped with manufacturer-specific software. Additionally, desired information can be collected from protection relays using the IEC61850 protocol via the Manufacturing Message Specification (MMS) protocol. This eliminates the need for human actions within the substation to perform switching operations, making these actions faster. Furthermore, the SCADA terminal provides an overview of the entire plant, offering insights into ongoing activities and status ( Rodolpho 2010).

### 2.3.3 Measurement

A range of information from a substation is collected and analyzed in real-time by the automation system for its proper functioning. The measurement system consists of:

- Electrical Measurements - voltages, currents, power, power factor, harmonics, etc;
- Monitoring Measurements of Equipment - such as transformer and motor temperatures;
- Disturbance Recorder - Recordings of disturbances for fault analysis.

This vast amount of information can assist in studies such as load flow analysis and planning for disturbances, in addition to being essential for protection and control functions Rodolpho 2010.

### 2.3.4 Monitoring

It is a sequence of events or part of the automation system with information that allows monitoring the state of the substation, such as equipment status, maintenance alerts, relay configurations, etc. This improves the overall system efficiency, enhancing the effectiveness of protection and control. These pieces of information are useful in fault analysis, determining what happened, when, where, and how it happened (location, time, and sequence)( Rodolpho 2010).

### 2.3.5 Communication Protocols

The significant progress in substation automation has led to substantial investments by major IED manufacturers aiming to provide differentiation in protection and control equipment for substations. This competition has also given rise to a large number of proprietary communication protocols, which, to some extent, generated undesirable results in terms of interoperability. Substations with a large number of IEDs are highly likely to have undergone growth, with the current topology not being the original one. In such cases, equipment from different manufacturers is often present, and when connected to a single network, they do not communicate as expected in the vast majority of cases.

Faced with the communication challenges between devices, standardized protocols have emerged with the goal of achieving the desired interoperability. In other words, these protocols aim to enable communication between devices from different manufacturers on the same network. Figure 2.2 displays some of the most commonly used protocols in substation networks ( Rodolpho 2010).

| Protocolo | Originalmente usado por | Velocidade | Princípio de acesso | Camadas OSI |
|---|---|---|---|---|
| MODBUS | Gould-Modicon | 19.2 kbps | Varedura cíclica | 1,2,7 |
| SPABUS | ABB (exclusivo) | 19.2 kbps | Varedura cíclica | 1,2,7 |
| DNP3.0 | GE-Harris | 19.2 kbps | Varedura cíclica[2] | 1,2,7[3] |
| IEC 60870-5 | Todos | 19.2 kbps | Varedura cíclica | 1,2,7 |
| MODBUS+ | Gould-Modicon | | Token | 1,2,7 |
| PROFIBUS | Siemens | 12 Mbps | Token | 1,2,7 |
| MVB | ABB | 1.5 Mbps | TDM | 1,2,7[4] |
| FIP | Merlin-Gerin | 2.5 Mbps | TDM | 1,2,7 |
| Ethernet + TCP/IP | Todos | 10 Mbps | CSMA/CD | 1-7 |
| LON | ABB (exclusivo) | 1.25 Mbps | PCSMA/CD | 1-7 |
| UCA 2.0 | GE | 10 Mbps | CSMA/CD | 1-7 |

Figure 2.2: Communication Protocols specifications.

## 2.4 Overview of IEC61850

IEC 61850 is an international standard for communication in substations and power utility automation. It defines a set of protocols and data models to enable the interoperability of devices within a substation, facilitating efficient and standardized communication for protection, control, monitoring, and automation purposes. Key features of IEC 61850 include:

- Data Modeling: The standard introduces a standardized way of modeling substation data, using a hierarchical structure known as the Common Information Model (CIM). This allows for consistent representation of information across different devices.
- Communication Protocols: IEC 61850 specifies communication protocols for substation automation, with an emphasis on Ethernet-based communication. It defines how devices such as protection relays, controllers, and meters exchange information using protocols like MMS (Manufacturing Message Specification) and GOOSE (Generic Object Oriented Substation Event).
- Sampled Values: Part 9 of the standard, IEC 61850-9, introduces Sampled Values, enabling the transmission of digitized analog values, such as voltages and currents, in a standardized manner. This is crucial for real-time protection applications.
- Configuration Language: IEC 61850 includes SCL (Substation Configuration Language), a standardized language for describing the configuration of devices and systems within a substation. SCL allows for the exchange of configuration information between different devices.
- GOOSE Messaging: Generic Object Oriented Substation Event (GOOSE) messaging is a key feature that allows devices to exchange critical information in a peer-to-peer manner, enabling faster and more deterministic communication for protection and control functions.
- Interoperability: The standard aims to improve interoperability between devices from different manufacturers, promoting vendor-neutral solutions and reducing integration efforts in substations.
- Engineering Process: IEC 61850 defines an engineering process that standardizes the design, configuration, and testing of substation automation systems. This helps ensure consistency and reliability in the deployment of automation solutions.

IEC 61850 plays a vital role in modern and optimal power systems by provide a standardized framework for communication and automation in substations. It enhances reliability, flexibility, and interoperability in the evolving field of power utility automation.

### 2.4.1 IEC 61850-1 - Introduction and Overview

This initial segment provides a comprehensive introduction to the entire IEC 61850 series, offering a foundational framework for communication within substations. It sets the stage for subsequent standards, establishing a cohesive context for the standardization of communication in substation automation systems ( Mackiewicz 2006).

### 2.4.2 IEC 61850-2 - Glossary

Part 2 meticulously defines the glossary of terms used throughout the IEC 61850 series. By ensuring a uniform understanding of terminology, this section fosters clear communication and interpretation of the standards among diverse stakeholders in the energy sector ( Mackiewicz 2006).

### 2.4.3 IEC 61850-3 - General Requirement

This section outlines overarching requirements for communication networks and systems in substations. Covering aspects such as performance, testing procedures, and documentation standards, it provides a robust set of guidelines for the effective implementation of IEC 61850 ( Mackiewicz 2006).

### 2.4.4 IEC 61850-4 - System and Project Management

Centered on system and project management, this section provides valuable guidance for the seamless orchestration of IEC 61850 within substation communication systems. It encompasses essential aspects of planning, execution, and documentation, contributing to the successful deployment of the standard ( Mackiewicz 2006).

### 2.4.5 IEC 61850-5 - Communication Requirements for Functions and Device Models

Part 5 plays a pivotal role by defining communication profiles for specific functions and device models in substations. This ensures seamless interoperability between devices from different manufacturers, facilitating their integration within substation automation systems ( Mackiewicz 2006).

### 2.4.6 IEC 61850-6 - Configuration Language for Communication in Electrical Substations

This segment specifies a standardized language for articulating the configuration of communication in electrical substations, particularly in relation to Intelligent Electronic Devices (IEDs). It streamlines the configuration process, enhancing consistency across diverge implementations( Mackiewicz 2006).

### 2.4.7 IEC 61850-7 - Basic Communication Structure

Establishing the fundamental communication structure for substation and feeder equipment, Part 7 provides a foundational framework. It defines essential elements necessary for communication within substations, fostering a standardized structure for various devices ( Mackiewicz 2006).

### 2.4.8 IEC 61850-8 - Specific Communication Service Mapping (SCSM)

Part 8 concentrates on specific communication service mappings, offering guidance for mapping diverse protocols used in substation communication. This ensures compatibility and smooth interaction between devices employing different communication protocols ( Mackiewicz 2006).

### 2.4.9 IEC 61850-9 - Specific Communication Service Mapping (SCSM)

Part 9 specifically deals with defining Specific Communication Service Mappings (SCSM) tailored for diverse protocols used in substation communication. It establishes a standardized framework to ensure compatibility and seamless interaction among different devices within substation automation systems. IEC 61850-9 is crucial for promoting interoperability and facilitating efficient communication among Intelligent Electronic Devices (IEDs) in substations by addressing the intricacies of various network layers ( Mackiewicz 2006).

### 2.4.10 IEC 61850-10 - Conformance Testing

Focusing on conformance testing, Part 10 establishes rigorous procedures and requirements to verify that devices and systems adhere to the IEC 61850 standard. This contributes to the reliability and compatibility of implementations by ensuring strict compliance through thorough testing processes ( Mackiewicz 2006).

## 2.5 IEC 61850-9-2 Sampled Values (SV)

This section discusses the evolution of the IEC 61850-9-2 protocols, tracing its development from its precursor in 2002, IEC 60044, to its current version, IEC 61850-9-2 Ed2, finalized in 2020.

### 2.5.1 IEC 60044-8/2002

Many in the industry are familiar with the IEC 60044 standard, a predecessor to the current IEC 61869 standard for instrument transformers. Part 8 of IEC 60044, dealing with electronic instrument transformers, introduced the concept of a "merging unit." This unit acts as a bridge between analog and digital signals, facilitating the conversion of analog network signals for use in digital Intelligent Electronic Devices (IEDs). Additionally, the standard introduced the idea of a data set, later utilized in IEC 61850 for network communication. Figure 2.3 illustrates the concept of the Merging Unit.[2]

[2] https://www.linkedin.com/pulse/history-iec-61850-sampled-values-tibor-congo/

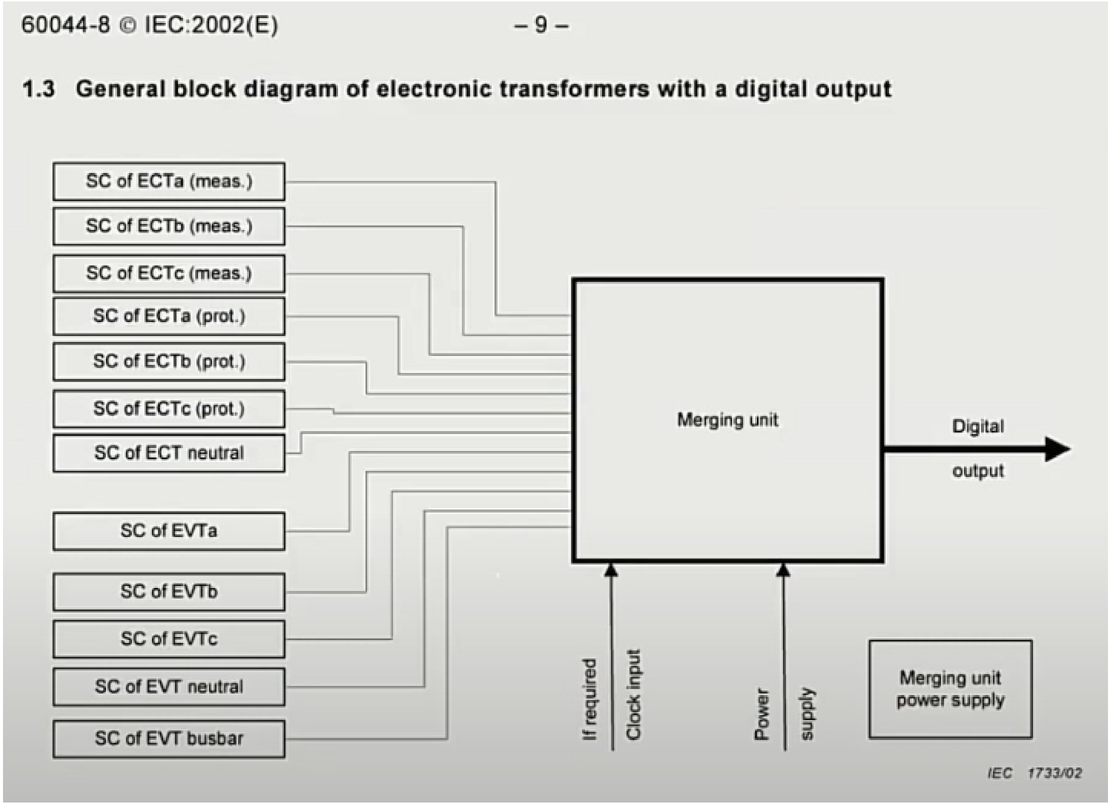


Figure 2.3: Concept of the Merging Unit.

### 2.5.2 IEC61850-9-1/2003

This marks the beginning of the protocol known today. However, it initially leaned towards a point-to-point communication model, resembling its predecessor IEC 60044. This approach lacked considerations for network applications, crucial for the interoperability that the protocol now provides. The concept of the Process Bus network, prevalent today, was not present during this period, causing delays in releasing the next version ( Tibor 2022).

### 2.5.3 IEC61850-9-2(Ed1)/2004

After correcting our course from a previous misstep, we are now embarking on a second significant stride towards the implementation of Sampled Values. At this juncture, the abstraction of the IEC 61850 standard is once again meticulously implemented. This service specification played a role in the IEC61850-7-2 standard and has now evolved into a standard within IEC 61850-9-2, precisely described and defined within the framework of Ethernet communication.

The data structure is characterized by its generic definition, and the communication process operates entirely independently. This implies that, in the future, we could seamlessly transition to another standard beyond Ethernet, tailored to the system's evolving needs. This flexibility is a testament to the power that abstraction brings. However, it's important to note that, thus far, the Ethernet protocol has been utilized and has consistently met the expected performance requirements.

In this revised standard, the noteworthy inclusion is the implementation of the process bus for Sampled Values, signaling a departure from the initial point-to-point communication approach. Here, to propagate Ethernet packets across the network, we leverage the existing multicast definition of the Ethernet protocol

I would like to highlight a widely embraced guideline employed by manufacturers in the development of Sampled Values, known as the UCA Implementation Guideline for IEC 61850-9-2. It's crucial to recognize that this is a guideline, not a standard( Tibor 2022).

### 2.5.4 IEC 61850-9-2 Ed2/2011

In this new edition, there were not many changes, mainly due to the fact that the energy industry was not significantly progressing in the adoption of this technology, even with lighter versions like IEC61850-9-2-LE. The reasons for this lack of progress are attributed to the skeptical nature of many protection engineers. They tend to be more conservative when it comes to supplying electrical power, sometimes justified by negative experiences in the field( Tibor 2022).

There were also some technical issues with Sampled Values (SVs) due to time synchronization. At that time, the most used protocol was SNTP, which allowed only millisecond precision. For SVs, higher precision in samples was needed. Additionally, there was immaturity in redundancy solutions in the network. Consequently, these two significant problems were only resolved later with the implementation of the following technologies:

- Time Synchronization - Precision Time Protocol (PTP): This protocol enables time synchronization via Ethernet with a timing error of less than 1 microsecond. Synchronization could now be achieved through the Ethernet network connection, eliminating the need for a separate network for time synchronization of merging units in the field.
- Redundancy - Parallel Redundancy Protocol (PRP): PRP operates with effectively two duplicated networks, resembling the approach adopted by service providers in the transmission of electrical energy networks. These providers often maintain redundant protection/control systems. The loss of service in one of these networks does not compromise functionality, as the parallel network continues to perform its communication functions without affecting the protection/control systems.
- High Availability Continuous Redundancy (HSR): HSR provides redundancy through a ring architecture. This is essentially the same ring architecture, where communication service continuity is maintained through the open ring, in case of service loss in any part of the closed ring. In both cases, specific hardware (and software) requirements must be met to consider the implementation of the solution. This is a fundamental element in the design of the Digital Substation.

For time synchronization, the adopted solution was the Precision Time Protocol (PTP). With a resolution below 1 microsecond, this was sufficient for SVs to be synchronized, making it possible to reconstruct the digital waveform into analog again and check for faults or network issues by IEDs. In terms of redundancy, two solutions were implemented: PRP and HSR, with PRP being the more widely used due to lower associated implementation costs and the assurance of redundancy( Tibor 2022).

### 2.5.5 IEC 61869-9/2016

The IEC 61869-9 standard is familiar to everyone using instrument transformers for other applications in the industry. This standard provided recommendations for measuring instruments, ranging from light versions to more demanding ones. The Figure 2.4 below summarizes this information. [3]

| Sampling Frequency | Samples per Packet | Packet Frequency | |
|---|---|---|---|
| 4000Hz (80SPC @ 50Hz) | 1 | 4000Hz | 9-2LE |
| 4800Hz (80SPC @ 60Hz) | 1 | 4800Hz | |
| 12800Hz (256SPC @ 50Hz) | 8 | 1600Hz | |
| 15360Hz (256SPC @ 60Hz) | 8 | 1920Hz | |
| 4800Hz | 2 | 2400Hz | New preferred |
| 14400Hz | 6 | 2400Hz | |
| 5760Hz | 1 | 5760Hz | 96SPC @ 60Hz |

Figure 2.4: Frequency regarding Sampled Values.

The information derived from the table indicates that protection functions use a sampling rate of 4800Hz at 60Hz and 4000Hz at 50Hz according to the IEC61850-9-2-LE version. When we talk about preferred streams, the sampling rates remain the same regardless of their use, such as protection, measurement, or power quality. This balance is achieved by adjusting the necessary samples per Application Specific Data Unit (ASDUs) per packet.

The IEC61869-9 standard mentions the use of configurable datasets. The IEC 61850-9-2-LE version simplified this by publishing 4 currents + 4 voltages for all datasets. While this approach was efficient, it lacked flexibility. Therefore, IEC61869-9 introduces flexibility in this regard, optimizing the implementation. However, this increased flexibility also brings greater complexity to data processing( Tibor 2022).

### 2.5.6 IEC61850-9-2 Ed2.1/2020

In this latest update, there was a small reinforcement of what was mentioned in the previous version. Here, a new field called SynchSrcID was introduced, which is used to specify the synchronization source of the merging unit. This new feature is one of the optional fields. In the IEC61850-9-2-LE version, there was only one field, but breaking free from the limitations of this version, now there are more fields to configure. Again, a note on what was mentioned above, it is essential to analyze configuration issues and implementation costs, as it will be more complex( Tibor 2022).

Below, the evolution of the standard will be demonstrated in Figure 2.5.

[3] https://www.linkedin.com/pulse/history-iec-61850-sampled-values-tibor-congo/

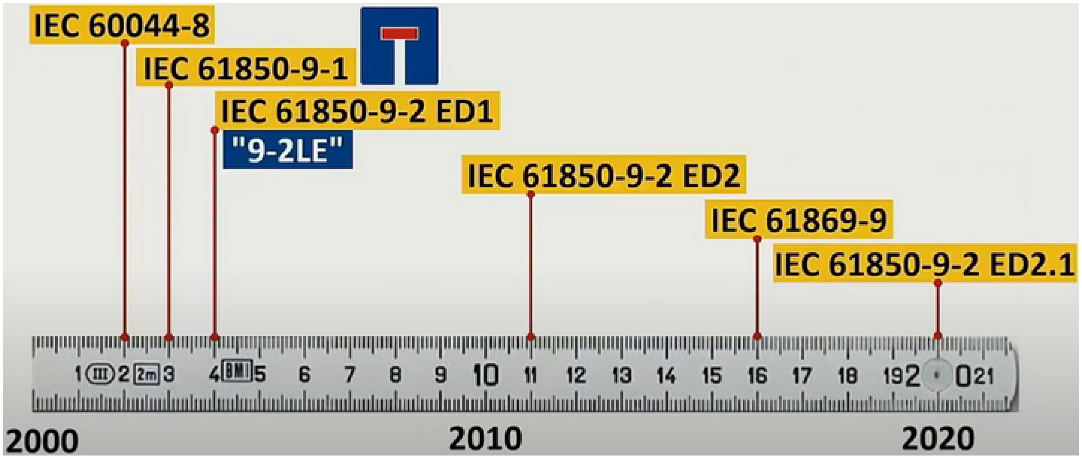


Figure 2.5: Evolution of IEC 61850-9-2

[4].

[4]https://www.linkedin.com/pulse/history-iec-61850-sampled-values-tibor-congo/

# Chapter 3

# Proposed Approach

## 3.1 Architecture of the Algorithm

The algorithm involves receiving two measurements from the same measuring sensor (Current Transformers or Voltage Transformers), providing redundancy in the data acquisition required by the Intelligent Electronic Device (IED) to process electrical protection algorithms. From a critical acquisition perspective, this approach is beneficial to address the scenario where one Merging Unit fails; the other Merging Unit can still send the data from that sensor. However, from the perspective of the IED, it needs to determine which of the two samples to use for running the protection algorithm to detect faults that may or may not occur based on the measurements received by the Merging Unit.

To address this issue, the proposed solution involves developing an algorithm that first monitors the Sampled Values messages (SVs), classifying them, and then delivering only the sample that is most well-qualified to run the protection algorithms. The architecture of this solution is akin to a switch, where two or more SVs from the same current or voltage transformer arrive, and the switch allows only the path of the best-qualified sample, discarding the others. Consequently, two SVs may arrive, but the protection system will only consider one SV with the best metric.

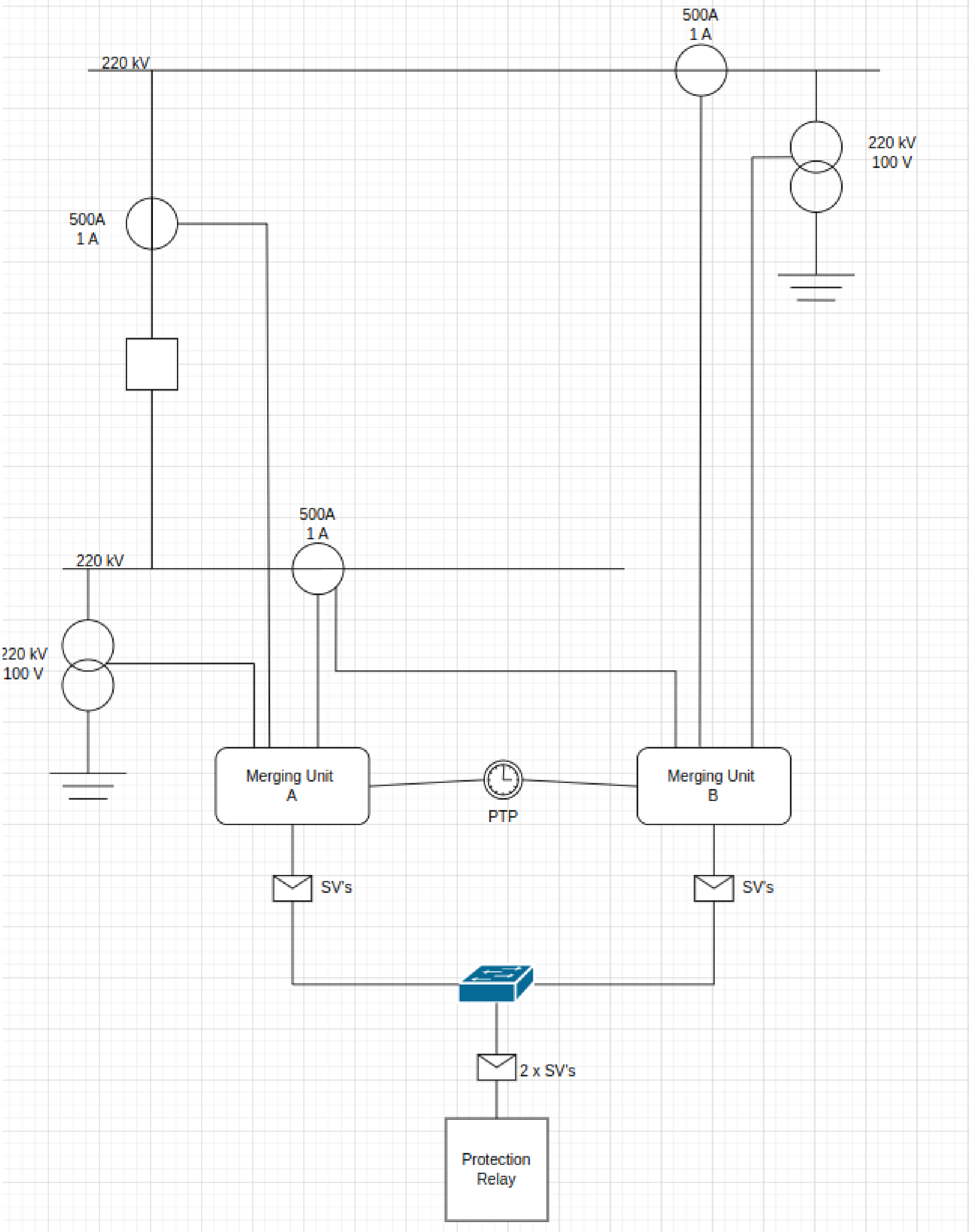


Figure 3.1: Simple Single Line Diagram (SLD) of Electrical Substation with SV's.

## 3.2 Development of the Algorithm

The algorithm development is based on the platform of Efacec's equipment, where a device driver will be created to incorporate this decision-making intelligence and achieve the shortest response time. As it is a critical function for the equipment, maximum performance is required to avoid any delays in samples that could impact the device's response and potentially hinder the operation of protections relays.

## 3.3 Test the Algorithm

The testing will take place in simulated environments at Efacec, enabling the simulation of SV message transmissions. I will analyze the outcomes of the device driver's actions, providing valuable metrics from the initial tests. This preliminary phase will precede the transition to physical equipment, allowing for further testing and integration within the actual product.

## 3.4 Implementation of the Device Driver in Efacec Equipment

The algorithm tests will be conducted within a controlled environment, and access will be provided to something very similar to Figure 3.1 for conducting the tests. The tests will be performed using EFACEC's own equipment with the addition of this device driver to enable the analysis of its performance and actual response. Verification of sample delays, selection of samples, and quantification and qualification of SV's messages will be carried out.

# Chapter 4

# Development Plan

## 4.1 Methodology

This chapter will describe the research methodology and the entire process of evaluating the objectives. In the 4.1 section, we provide an overview of the methods and tools that will be used throughout the development of the entire work. The 4.2 section outlines the approach to evaluating the project's progress and its results. Finally, in the 4.3 section, the roadmap to be followed for the entire development of the thesis is presented.

### 4.1.1 Research Approach

The development of the thesis is based on a feature to enhance the IED's decision-making method for selecting the SV samples that reach the device. This algorithm will be developed based on the information contained within the SV package itself and metrics. The manner in which it will be evaluated and classified will be determined during the thesis development, but the package parameters will dictate how it is classified and assessed. Below, I present 4.1 and 4.2 to illustrate the content that the SV message carries and the definition of the package fields. [1].

[1] https://www.typhoon-hil.com/documentation/typhoon-hil-software-manual/References/iec_61850_sampled_values_protocol.html

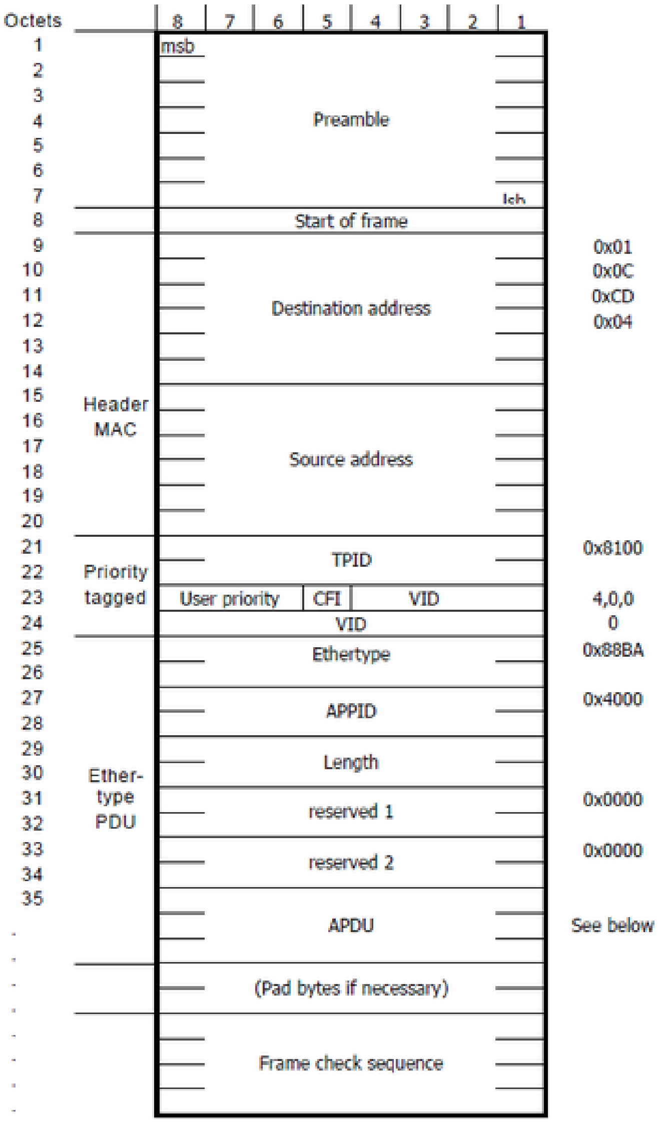


Figure 4.1: Content of the message Sampled Value (SV) precisa referenciar o site (Image credits: Typhoon HIL Documentation)

| Field name | | | Value | Description |
|---|---|---|---|---|
| Destination address 01:0c:cd:04:xx:xx | | | 00:00 - 01:ff | Destination MAC address |
| Source address | | | Defined by the sending device | Source MAC address |
| Priority tagged | TPID | | 0x8100 | Defines the 802.1Q protocol |
| | TCI | User priority | 1 - 7 | SV message priority: 4-7 is high priority; 1-3 is low priority |
| | | CFI | 0 | |
| | | VID | 0 - 4095 | Virtual LAN ID |
| Ethertype | | | 0x8ba | Defines the SV protocol |
| APPID | | | 0x4000 - 0x7FFF | Application ID |
| Length | | | | Message length |
| Reserved 1 | | | 0x0000 | Reserved field |
| Reserved 2 | | | 0x0000 | Reserved field |
| APDU | | | | Application Protocol Data Unit |

Figure 4.2: Description field of the Sampled Value (SV) precisa referenciar o site Image credits: Typhoon HIL Documentation)

### 4.1.2 Evaluation

The evaluation of this thesis will be based on the correct functioning of the chosen samples that best meet the specified requirements. It should be noted that the same merging unit may not always yield the best results for all protections. The Merging Unit is the equipment responsible for acquiring current and voltage data from current transformers and voltage transformers, which constitutes the main goal. However, we can break it down into three main parts: algorithm development, sample monitoring function, and selection of the best sample. Therefore, there are three main aspects that can be assessed throughout the course of the thesis.

### 4.1.3 Timeline

The progression of the thesis has been organized into distinct tasks aligned with the research goals and objectives. In Table 4.1, these tasks are detailed along with their respective durations, providing a clear roadmap to ensure timely completion of all essential activities.

| Activities | Jan | Feb | Mar | Apr | May | June | July |
|---|---|---|---|---|---|---|---|
| Research of articles | x | x | | | | | |
| Literature Review | x | x | | | | | |
| Development of Pré-Thesis | x | x | | | | | |
| Structure the Algorithm | | x | | | | | |
| Development of the Decision-Making Algorithm | | x | x | x | | | |
| Test of the Decision-Making Algorithm | | | | x | x | | |
| Write Thesis | | | | x | x | x | x |
| Conclusion and Results | | | | | x | x | x |

Table 4.1: Roadmap of activities

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