Communication Networks for Protection and Control in Substations

ASAN MASRAF_ Report Article Research

Abstract:

Power substations play a crucial role in controlling and directing electricity flow from generation to demand, supporting Iraq and Kurdistan Region Government targets for grid stability, reliability,and reduced carbon emissions. As the demand for power increases, integrating renewable generation and low carbon technologies becomes essential. Interoperability, facilitated by theIEC 61850 data communication standards, is key to achieving fulldigital substations. This enables utilities to deploy new technologies seamlessly and manage Intelligent Electronic Devices efficiently. The National Grid in Kurdistan region has invested in digital substation technologies for almost over 20 years, with projects like AS³ and FITNESS demonstrating the benefits of IEC61850-9-2 process bus technologies. However, assessing the suitability of digital substation architectures under abnormal data network conditions remains a challenge. This research report article contributes by assessing network performance, evaluating data flow control methods, analyzing the impact of redundancy networks, and conducting experimental testing on protection and control schemes. The results provide valuable insights for KRG Electrical transmission utilities planning the rollout of full digital substations.

Chapter 1: Introduction

1.1 Substation Automation System

1.1.1 Development of Substation Automation System

The Substation Automation System (SAS) plays a vital role in enhancing the reliability of power transmission and distributionnetworks within substations.

The evolution of SAS began in the early 1980s, employing hardwired communication [1]. Figure 1-1 provides an overview ofthe conventional SAS, comprising a Remote Terminal Unit (RTU)and Human Machine Interface (HMI) at the station level, Bay Controller and Protection Relays at the bay level, and conventional switchgear and CT/PT at the process level. The primary focus of the conventional SAS is on integrating data acquisition, including current, voltage, switchyard status, and protection function data. However, the accuracy of these data points is not optimal. Additionally, reliance on analog signals transmitted through copper wiring results in a complex interconnection of devices, requiring extensive amounts of coppercable. This not only poses challenges in terms of accuracy but alsoleads to prolonged outages during maintenance or replacement activities, incurring significant costs.

Due to the growth and expansion of power networks, substation functionalities have evolved and integrated to ensure the normal and steady operation of the power system. To achieve this, multiple functions are consolidated into fewer devices for Substation Automation Systems (SAS) [3]. Microprocessor-based Intelligent Electronic Devices (IEDs) have been introduced and installed in substations, simplifying SAS and significantly reducing the amount of required copper wiring. Additionally, the widespread use of Ethernet technology, optic fiber, and Ethernet switches has enhanced the reliability, capability, and stability within SAS.

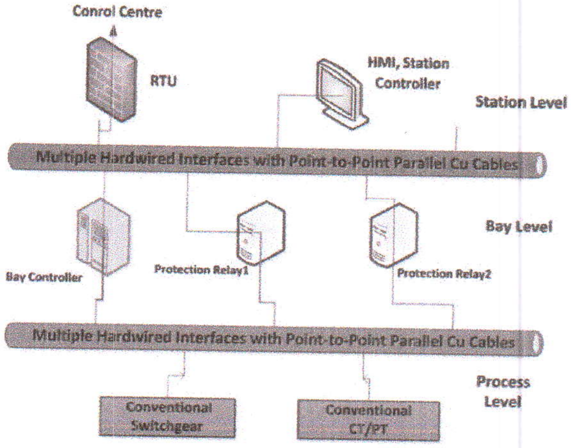


Figure 1-1 Conventional Substation Automation System [2]

In the past, various manufacturers employed proprietary communication protocols such as IEC 60870-5 [4], DNP 3.0 [5], MODBUS [6], Profibus, and Profinet [7] for communication between their IEDs. However, interoperability challenges arose due to different data formats and configuration languages, leadingto the need for protocol converters and complicating equipment maintenance and replacement in case of failures or expansions.

Recognizing this, the IEC 61850 standards were published in 2003, promoting interoperability between multi-vendor devices in SAS. These standards, applied to Merging Units (MUs), Circuit Breaker Controllers (CBCs), and IEDs, offer flexibility and benefits for power utilities and industries, enabling the confident deployment of new smart equipment, communication, and network technology applications. IEC 61850 standards address market demands for cost savings, extending substation equipment lifespan, and optimizing finances for replacement and maintenance. Moreover, these standards integrate wide-area monitoring and control flexibility into power systems, acceleratingthe integration of low carbon technologies.

The working principle of the IEC 61850 based SAS is shown inFigure 1-2

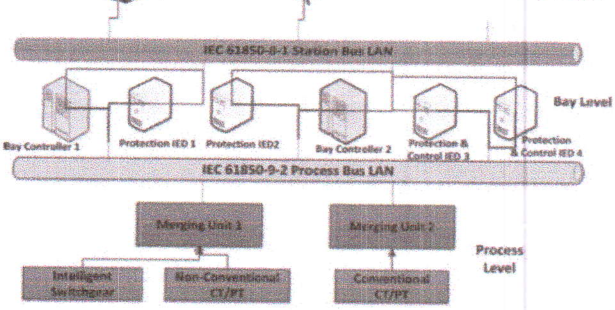


Figure 1-2 IEC 61850 Based Substation Automation System [2]

1.1.2 The Functions of Substation Automation

SystemTable 1-1 the Functions of SAS [8]

Type of Functions	Specification
Protection	➢ Bus bar and feeder protection
Control	➢ Open and Close the circuit breakers(CBs) and disconnectors ➢ Synchronization ➢ Interlocking
Monitoring	➢ Present the status of the CBs and disconnectors ➢ Show the fault type and location basedon the information from switchyard ➢ Visualization of the data flow in theSAS
Measurement	➢ *Measure the voltage and current fromCT/PT and* transfer to Sampled Values (SVs) via Merging Units (MUs) ➢ Measure more accurate data (voltagevalue and phase angle) by phase measurement unit for synchronization.
Alarming	➢ Give notice to operator of any abnormal condition of substation ➢ Avoid any extra issue of substationoperation.
Recording	➢ Record the data from IEDs. ➢ Fault record.

As can be seen from Table 1-1, the main functions of substationautomation system can be summarized in following aspects, (i)Protection, (ii)Control, (iii)Monitoring, (iv)Measurement, (v)Alarming and (vi)Recording.

1.2 Substation Challenges and Issues

1.2.1 Equipment Asset Maintenance and Replacement

Digital substations consist of primary equipment (e.g., CT/VT, circuit breakers) and secondary equipment (e.g., IEDs, bay controlunits). While primary equipment can operate for 30-50 years, IEDs have a shorter lifespan, requiring replacement every 5% annually in the UK [11]. Rapid technological advancements necessitatefrequent IED upgrades, causing prolonged outages and high expenses during installation, affecting power system reliability. [9]

1.2.2 Data Messages Delay and Loss

Message communication in substations involves time-critical messages (e.g., SVs, GOOSE) and non-time-critical messages (e.g., MMS). SV and GOOSE messages, critical for protection functions, face challenges with delay or loss, impacting process bus reliability. TCP/IP-based MMS messages introduce extra timedelay but enhance communication system reliability.

1.2.3 Vendor Interoperability

IEC 61850 standards aim to facilitate interoperability among IEDsfrom different manufacturers. However, despite compliance, interpretation differences exist. The engineering process involves System Configuration Description Language (SCL) files, leading to variations in proprietary communication protocols and tools.

Lack of a uniform standard for I/O interface modules complicatesinteroperability, requiring significant investment and maintenancefees for IED replacements. Manufacturers prefer developing substations based on their protocols for economic benefits. Figure 1-3 demonstrates the major electrical vendor's interoperability over the process level [13].

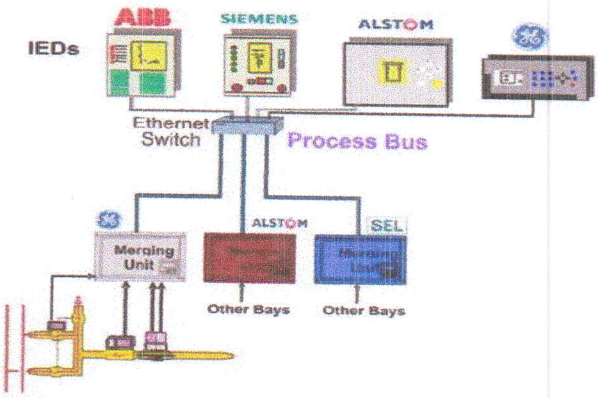


Figure 1-3 Multi-Vendor IEDs Interoperability Test on SubstationProcess Bus [13]

To improve interoperability, [14] has designed a vendor-natural system configuration tool. In the testing platform, the tool can directly configure the incorporated IEDs without employing vendor specific IED tools. The project in [15] has developed a visual configuration tool based on the Scalable Vector Graphics (SVG). The tool has a visual interface, which helps engineers configure the IEC 61850 based substation in an effective way. In[16], the integration of the SCL with the Open Platform Communications Unified Architecture (OPC UA) has been proposed to improve the vertical communication (i.e. the MMS Client/Server) performance.

1.2.4 SAS Network Performance Evaluation:

Delays or losses in data packets, especially time-critical ones likeSVs and GOOSE, significantly impact overall substation networkperformance. IEC 61850 Part 5 outlines end-to-end time delay allowances for different message services, clarifying speed and priority.

Reliability and capability challenges persist, as standards alone don't solve detailed issues like data packet flow and queuing delayvariations.

1.3 Iraq/KRG AS3 and FITNESS Solutions:

Substation secondary systems (SAS) offer opportunities for functionality improvement, evolving from electromagnetic to micro-processor-based IEDs with Ethernet capability. Shortened life cycles of micro-processor-based protection devices necessitatefrequent maintenance and replacements, posing challenges during long planned outages.

The introduction of IEC 61850 standard aims to enhance the reliability, availability, and interoperability of IEDs, leading to various digital substation projects for demonstrating maintenancecosts, lifecycle, and interoperability. National Grid's AS³ projectproposes a flexible, reliable, and long-life substation, while FITNESS project assesses functionality and interoperability for multi-vendor IEDs using HSR and PRP redundancy networks.

1.4 Motivation:

Designing two independent process buses improves AS³

architecture's reliability, but data flow analysis for complex bay solutions and assessing AS^3 architecture's capability performanceare pending. FITNESS project, utilizing HSR and PRP redundancy protocols, lacks a thorough investigation into maximum device integration and time-critical message latency.
Simulation and experimental tests aim to evaluate digital substation architectures' stability, functionality, and operation limitations under various faulty components and power network faults. The results can optimize substation architecture designs andmaximize benefits during implementation.

1.5 Aim and Objectives

The aim of the project was to assess suitable and reliable substation data communication networks and minimise their impact on a protection and control scheme functionality and performance. To achieve the aim, the *following objectives wereconsidered:*

- Conducting critical literature reviews and identifying thegaps between the academic researches and industry applications for future deployment of a full IEC61850 based digital substationwhich led the project motivation.

- Establishing data message types based on IEC61850 standard and formulating message equations to be used for thesubstation data network performance studies.

- Modelling and implementing a typical IEC61850 basedProcess Bus (PB) simulation model for the assessment of the maximum equipment integration hosting capability based on theswitches used for the data exchanges capability.

- Modelling and implementing a typical IEC61850 basedStation Bus (SB) simulation model for the assessment of the maximum number of bay's hosting capability based on the switches used for the message exchange capability.

- Proposing and implementing the use of typical data flowcontrol methods to minimise the impact of stochastic storming data and avalanche data on the time critical messages in both process buses and station buses.

- Modelling and implementing two typical data networkredundancy network topologies based HSR and PRP simulationmodels and assessing the impact of the data network faulty equipment on the protection and control functionality and performance.

- Setting up experimental test bed in the laboratory and conducting the tests and analysis for the impact of the different faulty equipment scenarios in the real configured HSR and PRPdata network on the protection and control functionality and performance.

1.6 Knowledgeable Contributions

Three key contributions in the research report are summarized asfollows:

1. Communication Network Hosting Capability Analysis:

- Focuses on quantifying communication network hostingcapability under various redundancies.
- Addresses limited studies on the impact of storming data,avalanche data, and data flow growth on network equipment hosting.
- Contributes three generic redundancy models and a methodology for analyzing network data flow capability.
- Results contribute to National Grid's substation networkconfiguration and FITNESS project reports.
- Published related papers.

2. Impact of Data Flow Control on P&C Time-CriticalMessages:

- Quantifies the impact of different data flow controlmethods on time-critical messages like GOOSE.
- Formulates a Poisson queuing equation based onIEC61850 for representing GOOSE messages.
- Implements three data flow control models using OPNETand confirms suitable methods ensure network data flow performance for protection and control functions.

3. Experimental Assessment of Network RedundancyArchitectures:

- Addresses the lack of real-life impact studies on faultycomponents and power network conditions in digital substations.
- Designs a virtual digital substation test bed with RTDS,two vendor equipment, and configurable Ethernet switches.
- Conducts case studies on the impact of different networkredundancies on vendor equipment performance.
- Contributes a data analysis methodology based on Q-Qmethod for validating experiment data and conducting statistical analyses.

Chapter 2: Literature Review

2.1 Introduction:

This chapter provides essential background information on digitalsubstations. It covers IEC 61580, substation bus messages, and explores redundancy technologies for enhancing communication network reliability. Recent data flow management studies are discussed, followed by a summary and commentary on relevant research results.

2.2 IEC 61850 Communication Standards:

Overview of IEC 61850:

Originating in the early 1990s, efforts were made to design a versatile substation architecture promoting multi-vendor interoperability. UCA versions 1.0 and 2.0 laid the foundation, and in 2004, IEC 61850 was defined for real-time data exchangein substations.

IEC 61850 is a fundamental communication technology for smartgrids, offering clarity on data format and configuration language.The standard has been widely implemented, with research institutions globally contributing to its application.

IEC 61850 Parts Overview:

Part 1: Introduction and structure of the 10 parts.

Part 2: Glossaries used in the standard.

Part 3: General requirements for digital substation deployment.

Part 4: Focuses on projects related to process near automationsystems.

Part 5: Standardizes communication between IntelligentElectronic Devices (IEDs).

Part 6: Describes a unified substation configuration language.

Part 7: Encompasses communication service modeling,principles, and information models.

Part 8-1: Describes specific communication service mapping toManufacturing Message Specification (MMS).

Part	Title
1	Introduction and overview
2	Glossary
3	General requirements
4	System and project management
5	Communication requirements for functions and device models
6	Configuration description language for communication in electrical substations related to IEDs
7	Basic communication structure 7-1: Principles and models 7-2: Abstract communication service interface (ACSI) 7-3: Common data classes 7-4: Compatible logical node classes and data classes 7-5: IEC 61850 – Modeling concepts
8	Specific communication service mapping (SCSM): Mappings to MMS and ISO/IEC 8802-3
9	Specific communication service mapping (SCSM): Sampled values over ISO/IEC 8802-3
10	Conformance testing

Part 9-1 and 9-2: Explain communication between merging units,IEDs, and the mapping for Sampled Values (SVs) transmission.

Part 10: Covers technologies for testing and assessing communication services' performance.

IEC 61850 establishes a unified communication protocol, ensuringmulti-vendor interoperability and proposing a reliable, flexible substation communication network and architecture.

2.2.2 Function Hierarchy

Figure 2-1 illustrates the interface model of IEC 61850 based digital substation. IEC 61850 Standard has divided the substationautomation system into three different levels:

1) Station level, 2) Bay level and 3) Process level. And two buses:
1) Station bus and 2) Process bus from top to bottom respectively.The functionalities of SAS are specified in IEC 61850, including protection, control, monitoring, recording and communication applications. These functions are realized on different devices at different levels of the substation [19].

Process Level: Switchyard equipment is installed at process level,including current transformer, voltage transformer, disconnector, and circuit breaker, etc. All primary equipment is hard wired withcopper cable. Real-time analogue signals will be sent by these devices to process bus which contain instant measurement information about current and voltage, as well as the status of the circuit breaker.

Bay Level: Bay level is located between the process bus and station bus, and consists of protection and control IEDs for each bay. IEDs are connected with the process bus through optic fibersfor metering, trip recorder and protecting propose. Protection andcontrol data can be delivered to station level and process level; information between different bays can also be exchanged.

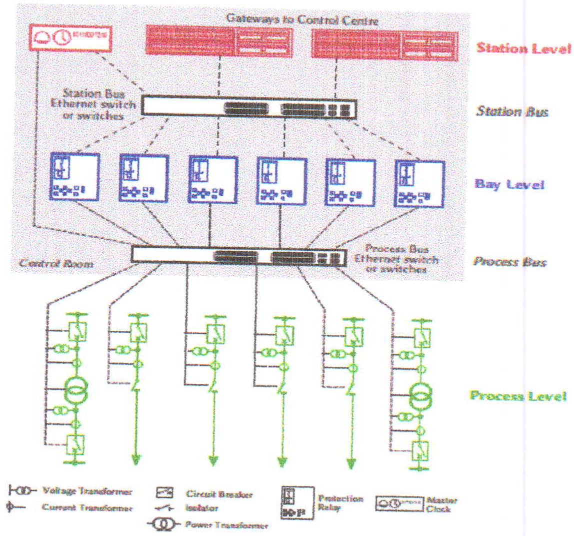


Figure 2-1 Interface model of IEC 61850 [20]

Station Level: The functions at station level will influence the equipment operation within the substation. It helps the substationto send data to the control center for scheduling or execution.
Station level also has other functionalities, including real-time substation monitoring and human-machine interface (HMI) system. Additionally, station level receives the data from other bays to prevent protection function failure. When a fault occurs,and the circuit breaker fails in the local bay, the circuit breakerscan be tripped in other bays.

Process Bus: It is used as a communication hub that transmits thedigital signal from merging units to IEDs as well as helping IEDs deliver instructions to plant equipment such as circuit breaker.

Station Bus: It not only exchanges data from station level and baylevel, but is also used for communication between different bays via the station bus.

2.2.3 Message Types:

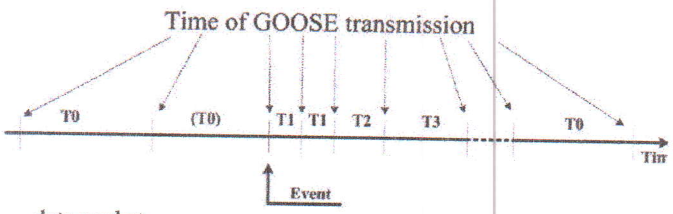
2.2.3.1 Sampled Value (SV):

- Defined in IEC 61850 part 9-2, SVs are generated in merging units (MUs) by converting analogue signals from non-conventional instrument transformers (NCITs)to digital signals.
- SVs carry fixed-length data packages containing voltage and current measurements from NCITs.
- The multicast capability of SVs enables forwarding the same data packets to multiple Intelligent Electronic Devices (IEDs), reducing Ethernet traffic significantly.
- SVs follow a subscriber/publisher structure, allowing a single MU to publish SVs to various subscribed IEDs, enhancing network availability and flexibility.
- Transmission of SVs occurs at specific predefined sampling rates, e.g., The frequencies utilized in the UK power system, 4000 Hz and 12800 Hz, correspond to the

standard 50 Hz frequency. This frequency standard is also employed in the power system of Iraq.SV messages occupy a substantial portion of the traffic bandwidth on the process bus's 100 Mbit/s Ethernet link capacity.

2.2.3.2 Generic Object Oriented Substation Event (GOOSE):

- GOOSE is a time-critical communication service with a subscriber/publisher mechanism, facilitating event-driven data transmission between IEDs.
- Operating over Ethernet layer 2, GOOSE messagesexclude Internet Protocol (IP) addresses and Transmission Control Protocol (TCP).
- Primarily used for forwarding trip signals, instructions, indicators, and alarms, GOOSE ensures swift exchange of information, enabling immediate status updates.
- Leveraging multicast capability, a single GOOSE message can serve various applications, publishing messages to different subscribed IEDs from one source.
- The size of a single GOOSE message varies, accommodating up to 1500 bytes of information in one



data packet.

Figure 2-2 GOOSE Retransmission Mechanism [21]

2.2.3.3 Client/Server Service and Benefits of IEC 61850:

2.2.3.3 Client/Server Service:

- Retransmission Structure of GOOSE Messages: Illustrated in Figure 2-2 per IEC 61850 Part 8-1, GOOSE messages are multicast in steady-state conditions with a specific frequency (T0) acting as a heartbeat.

- During events/fault injections, the retransmission interval shortens to T1 and gradually extends to T2 and T3. Once stability is restored, the retransmission time returns to T0.

2.2.3.4 Client/Server Service Model:

- Depicted in Figure 2-3, the client/server communication model mandates no new client requests until receiving corresponding server replies.

- Key data, such as fault records, event records, and measurement values, are exchanged in this model.

- IEC 61850-8-1 maps abstract objects and services to Manufacturing Message Specification (MMS) protocols of ISO9506, supporting complex naming and service models.

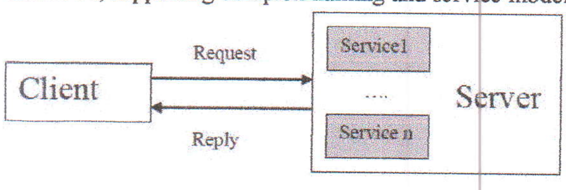


Figure 2-3 Client/ Server Service Scheme

IEC 61850-8-1 maps the abstract objects and services to the Manufacturing Message Specification (MMS) protocols of ISO9506 [45]. MMS has the proven implementation track recordthat can support the complex naming and service models of IEC 61850. MMS is used for real time data exchange and control within a station bus to achieve interoperability.

2.2.4 Benefits of IEC 61850:

- Realizing Multi-Vendor Interoperability: Standardized communication service classes and configuration language enable data exchange between different vendor equipment, fostering a competitive energy market.

- Simplifying Substation Design: Ethernet technology simplifies substation connection design, utilizing optic fibers to improve function hierarchy, reduce time delays, and enhance reliability.

- Minimizing Replacement and Maintenance Costs: Optical fibers facilitate easier installation and shorter configuration times. IEC 61850's system specification description (SSD) files and substation configuration language (SCL) streamline IED replacement and maintenance with minimal impact on power system operation.

2.4 IEC 61850 Based Substation Architectures:

- IEC 61850 minimizes or eliminates copper wire use in the substation's secondary side, introducing optic fibers for protection and control data transmission.
- Ethernet efficiently addresses data flow congestion for real-time requirements, with galvanic isolation achieved through optic fibers.
- While the standard doesn't specify substation architecture, varied designs exist based on communication function requirements of different powerutilities and manufacturers.

2.3.1 Generic Architecture

According to IEC 61850-7-1 [23], a generic IEC61850 standardsuggested substation architecture is shown in Figure 2-

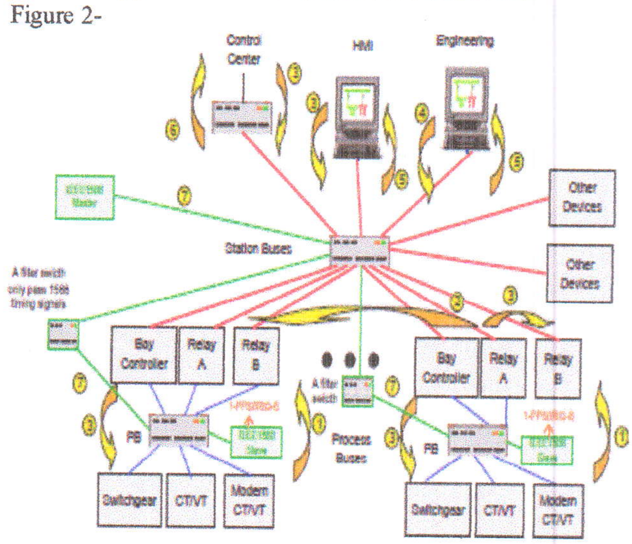


Figure 2-4 Overview of IEC 61850 suggested Architecture [23]

The data exchange flow by the communication of (numbers inbrackets in Figure 2-4):

1. IEC 61850-9-2 based SV exchange,

2. Fast exchange of I/O data for protection and control,

3. IEC 61850-8-1 GOOSE,

4. Engineering and configuration,

5. IEC 61850-8-1 MMS based client / server - monitoringand supervision,

6. IEC 61850-8-1 MMS based client / server - control-center communication,

7. IEC 61850-9-3 (IEEE 1588) time synchronization,

2.3.2 Architecture of Substation Secondary Systems

In order to develop a strategy and architecture for addressing the lifecycle issues of substation protection and control (P&C) assets,National Grid has set up the Architecture for Substation Secondary Systems (AS³) project. The project aims to develop a new architecture for substation secondary systems, which can provide a quicker, safer and easier approach for the installation and replacement of P&C equipment. The overview of AS³ architecture is shown in Figure 2-5 [24].

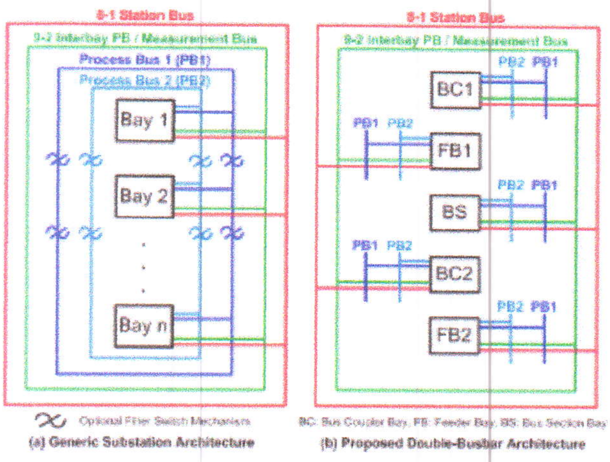


Figure 2-5 Overview of AS3 Architecture [24]

Figure 2-6 One of Bay in the AS³ Architecture
Details of AS3 Architecture and FITNESS Project:

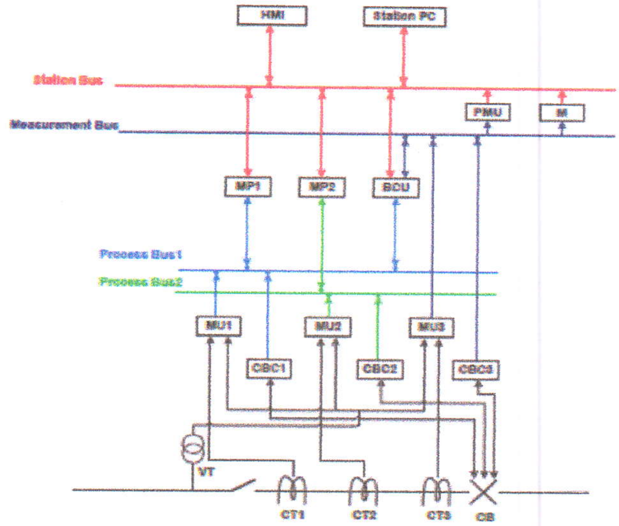
AS³ Architecture (Figure 2-6):

1. Ethernet Switching Ports: Standard ports between primary equipment and merging units (MUs), allowing offline installation of a replacement bay and quick switches between in-service and replacement equipment.
2. Two Independent Process Buses (PB1 and PB2):
- Enhances network communication redundancy.
- Prevents a single process bus failure from affecting IEDs'operation and control.
- Enables separate transmission of SVs and GOOSEs.
- Eliminates the need for Ethernet filters, reducing deviceinstallation and maintenance time.

3. Station Bus for Substation Automation:
- Connects Human Machine Interface (HMI) with IEDs forIEC 61850-8-1 MMS monitoring and control.
- Facilitates inter-bay GOOSE trip message delivery incase of circuit breaker failure.

4. Measurement Bus:
- Supports high-accuracy metering and circuit breaker(CB) synchronization.
- Connects to a bay control unit (BCU) for assessing SVstreams across bays.

5. Standard Bay Solution (SBS):
- Applies a standardized bay solution concept.
- Reduces interoperability issues between multi-vendorbays.
- Eases configuration integration for the entirecommunication system.



FITNESS Project Architecture (Figure 2-7):

- Deployed at KP (Kurdistan Power) Transmission's (KPT) Bazyan 400kVsubstation.
- Driven by interoperability and reliability among multiplevendors' equipment.
- Utilizes full digital substation architecture.
- Selects and configures 2 bays in the Bazyan substation tothe FITNESS architecture.

These architectural designs aim to enhance reliability, facilitateinteroperability, and streamline communication system configurations.

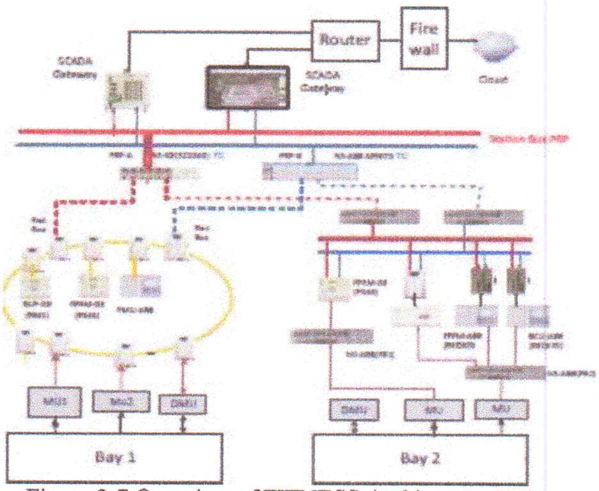


Figure 2-7 Overview of FITNESS Architecture [10]

The FITNESS architecture offers several key advantages:

1. **Ethernet Technology Implementation:** FITNESS employs Ethernet technology, reducing outage risks and providing a robust foundation for efficient asset replacement and load-related investments. The use of optical fibers enhances deployment speed, availability, safety, and controllability while minimizing costs compared to traditional designs.

2. **Redundancy Networks Integration:** Utilizing High-availability Seamless Redundancy (HSR) in the process bus and Parallel Redundancy Protocol (PRP) in the station bus (as illustrated in Figure 2-7), FITNESS ensures zero recovery time in the event of cable failure on the ring/star topology. This integration enhances substation reliability and expedites recovery.

3. **Multi-Vendor Interoperability:** FITNESS accommodates equipment from diverse manufacturers (GE and ABB), fostering multi-vendor interoperability. All devices adhere to the IEC 61850 configuration process, promoting seamless communication on both the station bus and process bus. This interoperability contributes to the development of new substations and expansions, benefiting operators and customers in transmission and distribution.

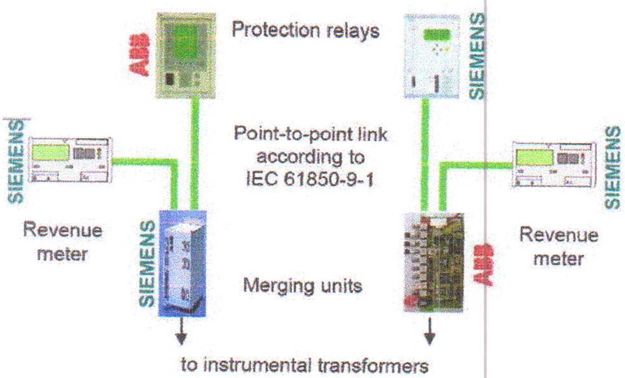


Figure 2-8 SIEMENS and ABB Interoperability Test Setup [25]

Several projects addressing vendor interoperability post IEC61850 releases include:

- In 2002, ABB and SIEMENS proposed an interoperability project, demonstrating synchronization and process bus interoperability. However, its impact onreal substation operations was limited due to technologyconstraints. Figure 2-8 shows the basic experimental setup which combines several electrical devices from ABB and Siemens respectively.

- TVA collaborated with GE, Siemens, AREVA, and ABBin 2005 for the "Bradley 500KV Substation" project. Despite aiming for a multi-vendor IEC 61850-based substation, challenges arose with private protocols and varied data formats, leading to slow progress and budget overruns.

- In 2013, five major electrical manufacturers initiated aproject evaluating GOOSE message communication reliability. The P2P and Client/Server communication models were explored, but full vendor interoperabilityremained elusive due to compatibility issues.

- Redundancy technologies, including Parallel RedundancyProtocol (PRP) and High-availability Seamless Ring (HSR) defined in IEC 62439, have been studied for optimizing network system reliability [26]. HSR technology, in particular, has demonstrated over 99.9973% process bus availability [27].

- Projects focusing on substation communication network performance assessment include [29-31]. The project proposed by five major electrical manufacturers in 2013 which are illustrated in Figure 2-9.

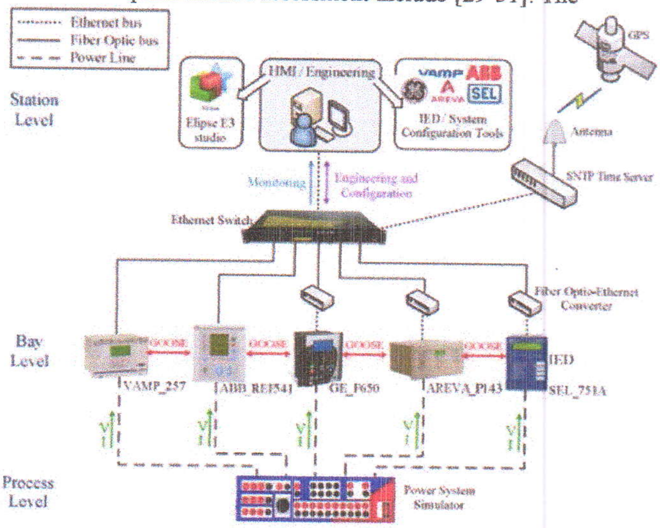


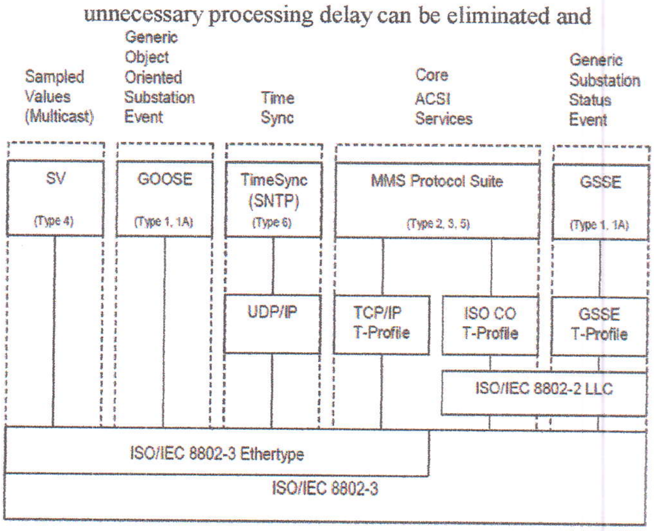
Figure 2-9 GOOSE Message Interoperability Tests [16]

2.4 Communication Systems for Digital Substation

2.4.1 Data Communication

Data communication can be implemented using OSI-7 layers stackmodel which is specified in IEC 61850 for data packets communication [32]. Three main types of message communicationstacks are illustrated in Figure 2-10. Seven different types of message service are proposed in the standard. And different services specify different communication time requirements.

IEC 61580 defines time critical message SV (Type 4) and GOOSE(Type 1, 1A) as high priority frames which are directly mapped to data link layer 2. These frames hold priority within all operating IEDs. Therefore, unnecessary processing delay can be eliminated and



message performance improved. On the contrary, MMS (Types 2, 3, 5) employs a client-server mechanism that is based onTCP/IP protocol, operating above the Ethernet layer. The details of different message communication principles will be provided inthe next subsection.

Figure 2-10 Message Communication Stack [32]

2.4.2 Requirements of Data Communication

The system time delay is an important indicator to reflect the performance of substation communication network, which is defined in IEC 61850-5[12]. The message time delay consists of the total time it generated in source IED and it is then collected bythe destination IED within the communication network. As Figure2-11 shows, three layers in the IED transmission stack are considered, including Ethernet layer, TCP/IP layer and applicationrespectively.

The time delay of communication service is a crucial index to indicate the reliability and availability performance of a substationcommunication system. Figure 2-11 shows the principle of message transfer time which is defined in IEC 61850 Part 5 [17]. The transfer time is counted from the data packets generated in thesource device (MU, IED, HMI) to the data collected by a destination device through the substation communication network.

As Figure 2-11 shows, the time delay will be issued in three different stages for data packet transmission, and the time delayfor each stage are presented as follows:

- Stage 1: Time delay in the sending end device $Ta = Tsa + Tst + Tse$
- Stage 2: Time delay in the communication network(Optical fibers, Ethernet switches) Tb

Stage 3: Time delay in receiving end device $Tc = Tda + Tdt + Tde$

Therefore, the end to end (ETE) time delay of the data packet canbe concluded as T = Ta + Tb + Tc

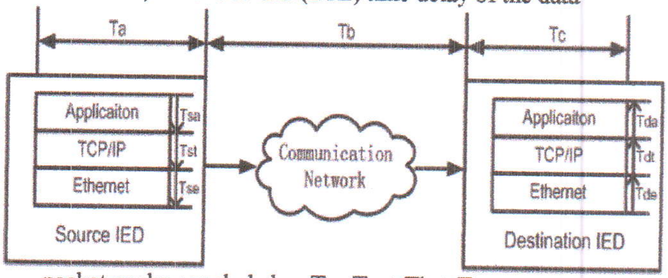


Figure 2-11 Principle of End to End Time Delay

The time requirements for communication services are provided inTable 2-2. The bandwidth and maximum transfer time of each communication service is specified as well. The message time requirements are based on their applications in the substation. For instance, the sampled value and GOOSE message are time critical messages while MMS are non-time critical messages. It can be concluded that the overall time delay of the substation communication network should be below 3ms to avoid any data delay and loss to ensure the normal operation of the substation [33].

Table 2-2 Time Requirements for Different CommunicationServices [33]

Message Type		Communication Service Applications	Max. Delay (ms)	Bandwidth
1	GOOSE	Fast messages	10	Low
1A	GOOSE	Trip messages	3	Low
2	MMS	Medium speed messages	100	Low
3	MMS	Low speed messages	500	Low
4	SV	Raw data messages	4	High
5	MMS	File transfer functions	1000	Medium
6	Time Sync	Time synchronisation messages	10	Low
7	MMS	Command message	1000	Low

2.4.3 Data Network Topologies

Some topologies are implemented within the IED 61850 based substation architecture, including star topology, ring topology. Theworking principle, advantages and disadvantages of these two main topologies are discussed.

2.4.3.1 Ring Topology

Figure 2-12 presents the serval Ethernet switches that are connected with point-to-point links within a close loop to deploy ring topology. The data packets are propagated circularly in the ring from node to node to ensure each switch node can handle thesame information.

Ring topology can bring a reliable communication network for traffic transmission. In case of failure of any one of the optical fibers on the ring, the data packet can be transmitted in reverse direction to ensure the protection functions can be realized to dealwith the fault.

However, due to the long distance of data transmission in ring topology compared with star topology, there is a long-time delay for messages, especially for time-critical messages. This will impact the operation of the substation when a fault occurs. Additionally, since more Ethernet switches are used in the ring, it is more costly than star topology.

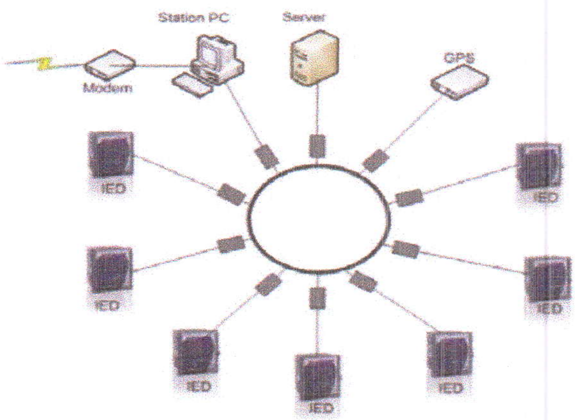


Figure 2-12 the overview of Ring Topology Network [34]

2.4.3.2 Star Topology

Figure 2-13 shows a typical star topology network. The devices atdifferent levels are connected with a central Ethernet switch directly. The central Ethernet switches help to transfer the data packets in the communication network.

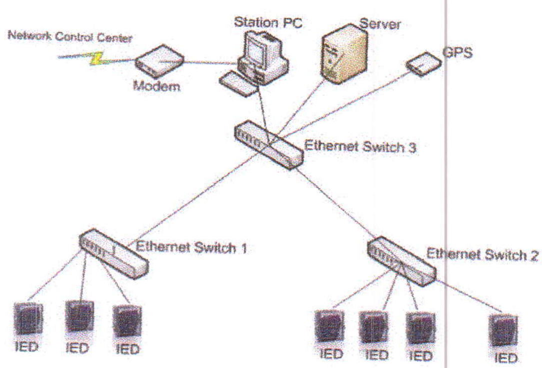


Figure 2-13 the Overview of Star Topology Network [34]

It is easy to add or replace the equipment in the star topology network with minimal impact on the operation of the network. And a faster transmission time can be provided since the data packets need a short distance to the destination compared with thering topology network. Therefore, data security can be improved in that the data do not need to cross the entire communication network [35].

However, as all devices are connected with central Ethernet switches, the failure of any central Ethernet switch will disrupt theoverall substation operation. Therefore, the reliability of the star topology will be reduced.

Table 2-3 Recovery Time Requirement for different Communication Services [38]

Communication Service	Message Type	Communication Recovery Time Requirement (ms)
SCADA to IED	MMS	400
IED to IED (interlocking)	GOOSE	4
IED to IED (reverse blocking)	GOOSE	4
Busbar Protection (tripping)	GOOSE	0
MU to IED	SV	0

2.4.4 Data Network Redundancy

Network redundancy is critical for power utilities and manufacturers, addressing communication service recovery needs.Beyond ensuring resilience during network failures, the objective is to manage outage times during equipment modifications [36]. Modern protocols like High-Availability Seamless Redundancy (HSR) and Parallel Redundancy Protocol (PRP), outlined in IEC 62439-3 [37], have replaced older protocols like Rapid Spanning Tree Protocol (RSTP) due to their inability to provide the requiredzero recovery time in digital substations.

Two seamless network protocols, High-Availability Seamless Redundancy (HSR) and Parallel Redundancy Protocol (PRP) aredefined in IEC 62439-3 [37] to deliver zero recovery time for thecommunication network in case of any single failure (e.g. Fiber, IEDs or MUs).

2.4.4.1 Communication Recovery Time

Assessing network redundancy impact on Protection and Control (P&C) involves considering communication recovery time between two services, a crucial performance indicator. As per the IEC61850 standard [38], specified recovery times vary for different communication services, with critical messages like GOOSE for busbar protection requiring zero recovery time, necessitating redundancy routes for uninterrupted communication.

2.4.4.2 Rapid Spanning Tree Protocol (RSTP)

Rapid Spanning Tree Protocol (RSTP) is commonly used in ringtopology networks. The overview of the RSTP protocol is shownin Figure 2-14.

The working principle and function of the RSTP can besummarized as follows:

1. It can be assumed that the device linked with Ethernet switch D is the source IEDs for generating data packet, and the device linked with Ethernet switch E is the destination IEDs for receiving data packets. As shown in Figure 2-14, there are two separate routes for the traffic transmission in the ring network, the anticlockwise direction which is active: D→C→B→A→J→I→H→G→F→E, the clockwise direction which is inactive in normal operation: D→E. In normal operation, only the active route will be running for data packet transmission. And the inactive route is used for back up when a fault occurs (single Ethernet link failure).

2. When a single optical fiber fails or is disconnected in thering network, the backup route will be enabled for traffic transmission. It takes time to reconfigure the Ethernet switch to change the direction for data packet propagation. Therefore, data packet transmission will be delayed or even lost during device reconfiguration.

However, the data recovery time of RSPT protocol far exceeds therequirement for the IEC 61850 communication services based on industrial Ethernet real-time application [40].Therefore, manufacturers proposed some redundancy solutions based on ringtopology to shorten the recovery time and improve the reliability performance [41].

Optical Fiber Failure between I and J

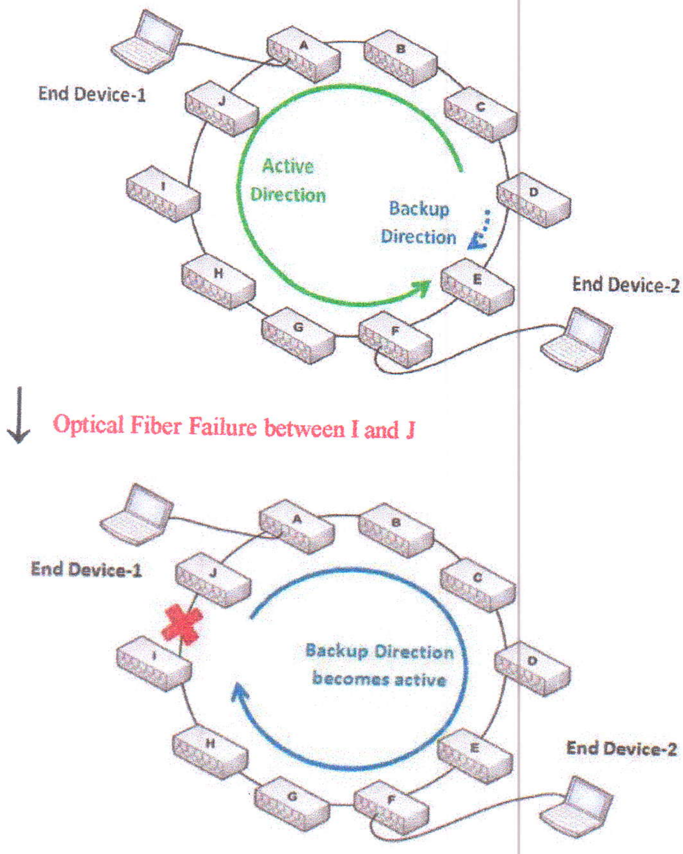


Figure 2-14 the Working Principle of RSPT Network [39]

2.4.4.3 Parallel Redundancy Protocol (PRP)

2.4.4.3.1 Overview of PRP Network

The basic concept of the PRP protocol is the equipment (MUs, IEDs) with PRP compatibility connected to two separate and isolated communication networks. Any data packets will be duplicated and published into both networks at the same time. However, the topology structure of two independent networks canbe different [42]. Figure 2-15 shows the overview of a typical PRPnetwork.

Figure 2-15 demonstrates the DANP (Double Attached Node using PRP), a PRP-compatible device with two independent interfaces. DANP distributes two identical frames (Frame A and Frame B) through isolated local networks (LAN A and LAN B) concurrently, with different transmission times due to route differences.

At the receiving DANP, equipped with dual interfaces, the first arriving frame is accepted, and the second is discarded. Failures or maintenance in one network do not impact frame transmission in the other, ensuring zero recovery time in the PRP network. Additionally, the switches deployed in the PRP network are standard Ethernet switches with no knowledge of PRP to transferthe PRP frames [36]; this is because PRP frames are normal Ethernet frames with additional PRP tags.

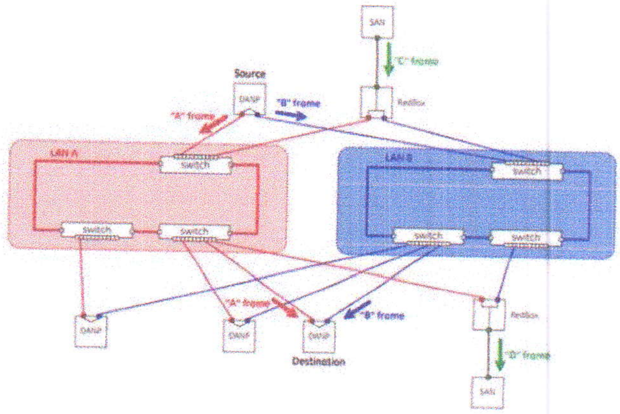


Figure 2-15 the Working Principle of PRP Network [43]

2.4.4.3.2 PRP Devices

As presented in Figure 2-15, different types of end node device areinstalled in the PRP network.

DANP (Double Attached Node using PRP):

Two separate traffic ports are configured in DANP which have thesame transmission abilities. DANPs are connected with two independent networks. However, in some special circumstances, itis possible to choose one of the ports for connection if there is only one LAN. The internal structure of the DANP is shown in Figure 2-16. The working mechanism of DANP is described below [44],

- Link redundancy entity is implemented in layer 2 (MAClayer) as Figure 2-16 shows.
- An instruction date from the network layer or that above (left red arrow) to generate two duplicated frames and send themto two separate transmit ports.
- Redundancy Control Trailer (RCT) is added into FrameA and Frame B in layer 2, which includes the frame sequence reference, the label of LAN A and LAN B and PRP tag.
- Once the first frame arrives at the destination device, theRTC will be removed in that frame to ensure the frame received by the network layer or the above layer (right red arrow) is standard Ethernet frame. And another frame will be discarded.
- In the send node and receive node, there is only one standard frame without redundancy mechanism in the layer 3 andupper layers.

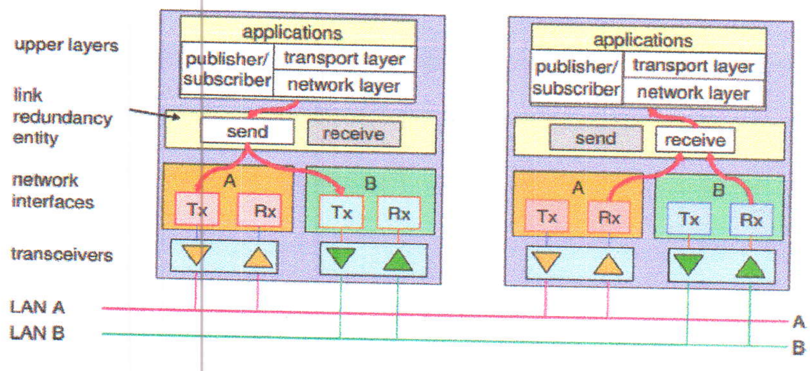


Figure 2-16 Internal Structure of DANP [45]

SAN (Single Attached Node) & PRP Redundancy Box (PRP Redbox):

In real industry applications, not many substation devices that support PRP protocol are considered as SAN. There is only one communication interface on the SAN. In order to connect with two independent networks, PRP Redbox is introduced to link between SAN and two networks. The working principle of PRP Redbox is presented in Figure 2-17. The function of Redbox is similar to the DANP to the PRP network. It receives the standard Ethernet frames from SAN and duplicates the frames. Then, theseframes are delivered into two different paths.

Figure 2-17 the Internal Structure of PRP Redbox [26]

2.4.4.3.3 PRP Ethernet Frame

Figure 2-18 shows the internal structure of PRP Ethernet frame.Redundancy Control Trailer (RCT) is placed into traditional Ethernet frames.

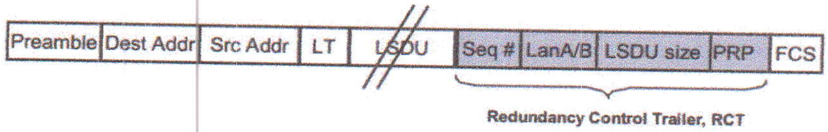


Figure 2-18 PRP Ethernet Frame [44]

RCT consists of sequence number, the label of LAN A and LANB, LSDU size and PRP suffix. The functions of each field are described below.

- Sequence number: The sequence number is incrementedonce the frame is duplicated in link redundancy entity. Thus, the destination device can identify the frame based on the frame sequence number.

- Label of LAN A/B: The label of LAN A/B can identify the transmission route of the frame. The fault will be detected when the frame with LAN A label is propagated into LAN B, andvice versa.

- LSDU size: The LSDU size is used to specify the PRP frame and standard Ethernet Frame, since the length of the RCT is6 bytes.

- PRP suffix: PRP suffix is the secondary identification forPRP frame in the network.

2.4.4.4 High-availability Seamless Redundancy (HSR)

2.4.4.4.1 Overview of HSR Network

As in the PRP protocol, the devices in the HSR network will sendtwo copies of the same frames into two separate routes simultaneously. However, these frames are propagated in the single network with ring topology structure. Figure 2-19 presentsan example of a HSR network.

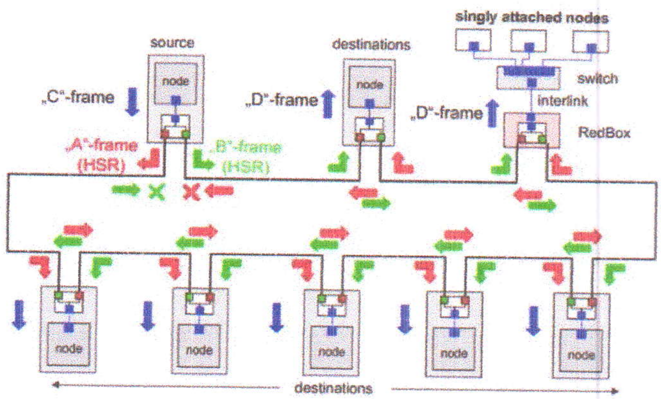


Figure 2-19 the Working Principle of HSR Network [46]

Figure 2-15 demonstrates the DANP (Double Attached Node using PRP), a PRP-compatible device with two independent interfaces. DANP distributes two identical *frames (Frame A and Frame B) through isolated local* networks (LAN A and LAN B) concurrently, with different transmission times due to route differences. At the receiving DANP, equipped with dual interfaces, the first arriving frame is accepted, and the second is discarded. Failures or maintenance in one network do not impact frame transmission in the other, ensuring zero recovery time in thePRP network.

Additionally, use of the standard switches is prohibited in the HSRnetwork as this may lead to endless frame circulation in the network and impact the operation of the network.

2.4.4.4.2 HSR Devices

The devices installed in HSR network are similar to the devices in the PRP network. However, the structures and specifications are alittle different.

DANH (Double Attached Node using HSR):

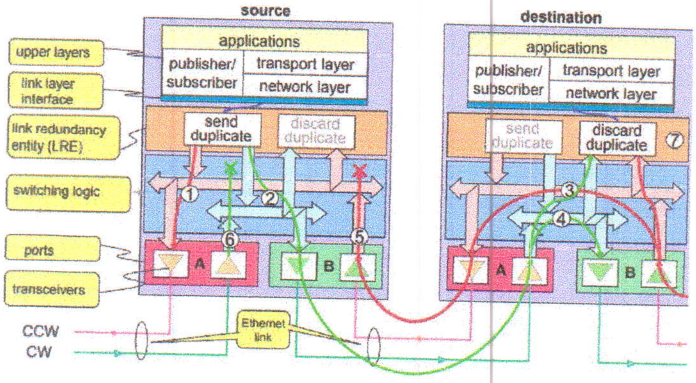


Figure 2-20 Internal Structure of DANH [47]

- Link redundancy entity is placed in layer 2 (MAC layer)which is the same as DANP.

- In source DANH, the message from the network layer or above is sent to link redundancy entity (left purple arrow) to generate two copies of identical frames with HSR tag, and forwardthem to Port A and Port B respectively at the same time.

- The switching logic module is implemented in DANH to transfer and forward the receiving HSR frame to the neighbouringDANHs on the ring network.

- At destination DANHs, the link redundancy entity willkeep and upload the first arriving HSR frame to the layer 3 and upper layers, and the HSR tag will be taken off by link redundancy entity before being uploaded. The second arriving HSR frame will be discarded here.

- The switching logic module in the source DANH will notforward and remove the HSR frame which is generated in this node.

SAN (Single Attached Node) & HSR Redundancy Box (HSRRedbox):

Unlike in the PRP network, the device which only has one Ethernet communication port is not allowed to be installed into theHSR network. These devices are not supported with HSR protocolcalled Single Attached Node (SAN). In order to realize the HSR

DANH is the device which supports HSR capability. Two identical ports (Port A and Port B with the same IP address andMAC address) are designed in DANH. The internal structure ofthe DANH is shown in Figure 2-20. The working principle of DANH is provided as follows: network with these devices, HSR Redundancy Box (HSR Redbox)must be deployed between the ring network and SAN. The internal structure of HSR Redbox is illustrated in Figure 2-21, andthe applications of HSR Redbox are similar to the DANH to HSR network. Switching logic module and link redundancy entity is developed in HSR Redbox.

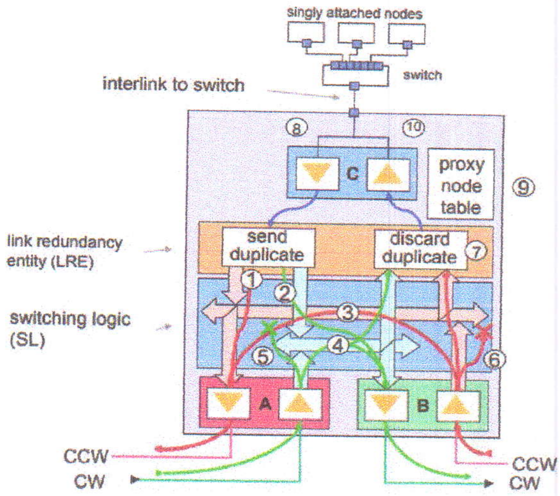


Figure 2-21 the Internal Structure of HSR Redbox [47]

2.4.4.4.3 HSR Ethernet Frame

The internal structure of HSR Ethernet frame is presented in Figure 2-22. A special HSR tag is introduced inside, based on astandard Ethernet frame.

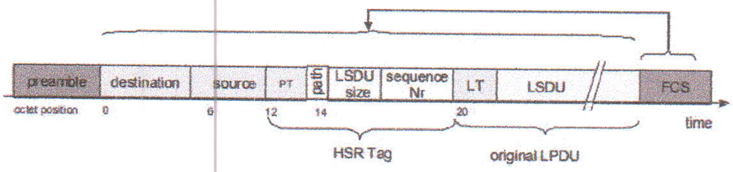


Figure 2-22 HSR Ethernet Frame [48]

HSR tag consists of the following four different sections [49],

- PT: This is the HSR Ethertype identifier to provide the unique identification for HSR frame in the ring network.

- Path: It is the route indicator for HSR frame (clockwisedirection or anti- clockwise direction)

- LSDU size: The size includes the section of the standardEthernet frame and the section of injected HSR tag.

- Sequence number: It will be incremented for each framegenerated from link redundancy entity based on HSR sequence numbering algorithm.

2.5 Data flow Management related work

2.5.1 Data Flow Simulation Tool

With the help of communication network simulation tools, substation automation systems based on real digital substations can be deployed without concern for underlying complex hardware constraints. There are a number of commercial communication network modelling tools available for the industry,such as NS-2, OMNeT++, Prowler, OPNET Modeller and etc [50].

NS-2 is discrete event simulation software based on Linux system[51]. And it is widely used for modelling sensor communication networks using C and C++ languages. Indeed, NS-2 does not provide complete device models and it can be developed by users.Thus, its reliability and stability are not guaranteed.

OMNeT++ is an open source tool that has strong features regarding operating system compatibility [52]. However, it facesthe same problem as NS-2. Due to a lack of defined communication protocols and proper network models, this software has been unpopular until now.

Prowler is operated in Matlab background. Thus, it provides several advantages compared with the other three tools, includingalgorithm optimization, better visualization and documentation capabilities that produce satisfying results quickly. Unfortunately,Prowler is still under development and a public-facing guideline and related documents cannot be provided by the manufacturer [53].

As for OPNET Modeller, it is the most mature software available for commercial use recently. And it is possible to create new hardware devices and communication protocols based on existing models in OPNET library which consists of several device modelsfrom manufacturers and various protocols [54]. Therefore, the network simulation results from OPNET are trustworthy.

Based on the comparisons and analysis above, OPNET Modeller is appropriate for assessing the SAS communication network performance in this project. There are several related works usingOPNET which will be discussed in the following section.

2.5.2 Previous Work on Data Flow Modelling

End-to-end time delay is critical for assessing substation communication networks. Variations from IEC 61850 Part 5 standards can lead to the loss of crucial messages, emphasizing theneed for rigorous network modeling before deploying new devices.

Studies by T.S. Sidhu and Y. Yin [18, 55] used OPNET Modellerto assess substation automation systems, providing insights into time-critical message delays and guiding optimal network design.

In [56], OPNET Modeller evaluated substation automation performance with DER and DAS, offering valuable comparisonsof GOOSE messages under different scenarios for future smart grid construction.

VLAN technology in [57] and multicast filtering in a literature review [58] were explored to enhance the reliability of substationautomation systems, preventing message delays and losses.

Research [59, 60] utilized Real-Time Digital Simulator (RTDS) tosimulate power system primary side, assessing synchronization performance. This method will be adopted for simulation in the current project.

S. Kumar's study [61] focused on substation secondary system architecture, comparing the reliability of a single versus doubleprocess bus. Results highlighted the significant improvement insystem redundancy and reliability with the double process bus architecture.

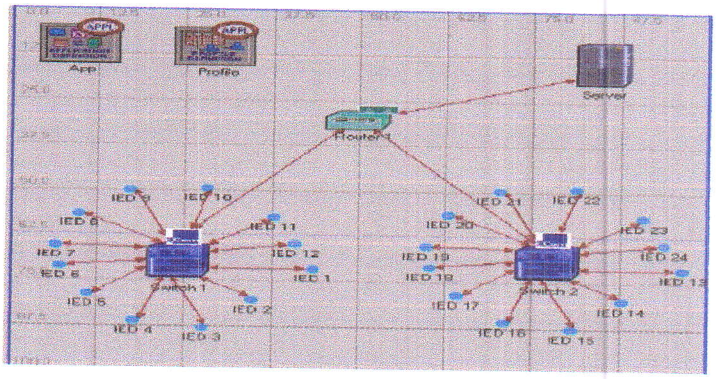


Figure 2-23 Double Process Bus Simulation [61]

2.6 Summary

International standard IEC 61850 has gained popularity around theworld in the substation automation system field. A detailed discussion of standard relevant research is given in the literature survey.

Different types of substation architecture are compared and discussed. IEC 61850 suggested architecture has been presented. National Grid AS³ project has proposed a more reliable and flexible IEC 61850 based architecture with two independent process buses and standard bay solutions. However, AS³ is rathercostly in terms of its complexity. HSR and PRP redundancy protocols are considered in FITNESS project to improve networkreliability and stability. The capability and functionality performance of FITNESS architecture need to be assessed. Someother industry architecture has been presented to improve the reliability and interoperability.

Several previous data flow works are discussed and all focus onsystem reliability and stability by utilizing communication network technologies such as PRP or HSR. Only a few of themhave considered multi-vendor IEDs interoperability. This is because most manufacturers follow their own proprietary communication protocols and tools to implement a digital substation. Additionally, it is hard for the configuration tool designed by each manufacturer to achieve compatibility and nomature technology has recently been developed

Chapter 3 Performance Assessment of Different NetworkRedundancies

3.1 Introduction

This chapter has 3 sections: (i) Network modelling: where three different process bus redundancy networks are modelled using a data communication network

simulation software tool, OPENT.
(ii) Results and analysis where system time delay, network bandwidth utilisation, the effect of single network component failure tests, and comparison studies between normal HSR andHSR with QR techniques, and (iii) Summary.

3.2 Network Modelling

The process buses with three commonly used redundancy communication networks and a minimum equipment requirementwith MP1 and MP2 for a protection and control scheme are modelled and simulated, respectively, using OPNET. They are shown in Figure 3-1, Figure 3-2 and Figure 3-3 respectively.

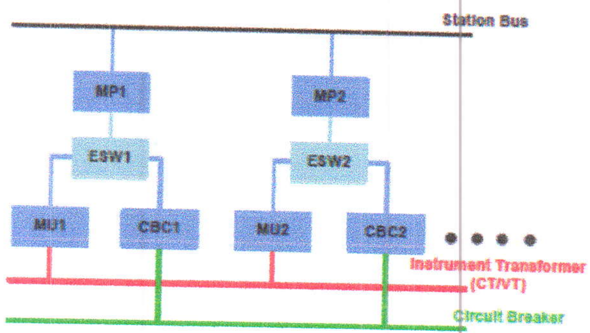


Figure 3-2 Overview of Two Independent Parallel Networks

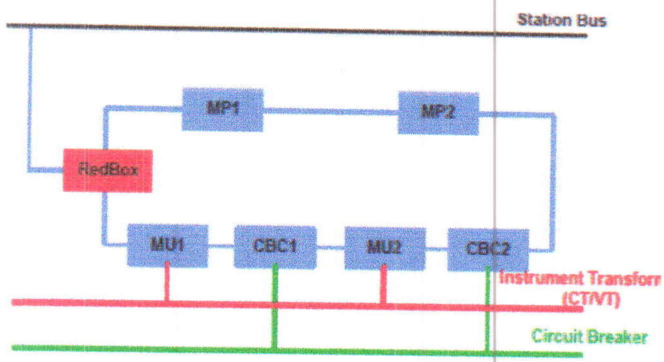


Figure 3-2 Overview of HSR Network

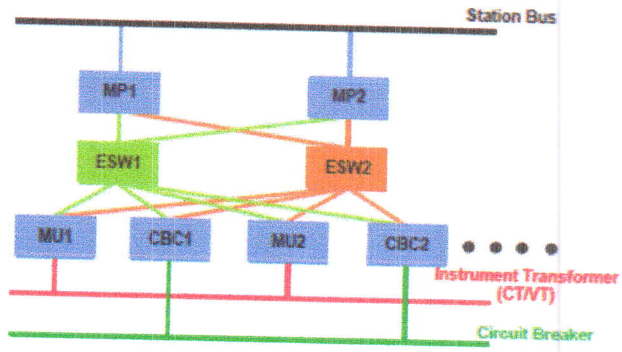


Figure 3-3 Overview of PRP Network

The proposed substation process bus configurations include twoindependent parallel star networks (Process Bus 1 and 2) for enhanced reliability. In case of failure in one network, the otheracts as a backup, improving the protection and control function.

The HSR process bus network forms a ring structure, providing two independent communication paths (clockwise and anticlockwise). Devices supporting Doubly Attached Node withHSR (DANH) enable HSR configuration, while Single AttachedNodes (SAN) require Redundancy Boxes (RedBoxes) for connectivity. Communication between HSR process bus and Station Bus necessitates a Redbox.

For high availability, two fully connected parallel star networks with PRP protocols are proposed. Duplicated message packets ensure protection and control function continuity. PRP network relies on Doubly Attached Node with PRP (DANP) devices, whiledevices lacking DANP function (SAN) require a RedBox for connectivity.

Multicast capabilities of Sampled Value (SV) packets facilitate simultaneous transmission to multiple IEDs, supporting periodic data sets with voltage and current information. Event-triggered messages are modeled as GOOSE messages, ensuring rapid circuitbreaker status updates. Table 3-1 details packet size and interval time for each message type.

Considering the data generated, Ethernet switches with a capacity of 100 Mbit/s are deemed suitable for simulation studies, accommodating the total data range from 9.24 Mbit/s to 12 Mbit/s.

Table 3-1 Message configuration in OPNET

Message Name	Source Devices	Packet Size (byte)	Interval Time (second)
Sampled Value	MUs	133	0.00025
GOOSE	MPs & CBCs	150-600	0.005

3.2.1 Modelling of a Single Star Network Process Bus

The two independent star networks in Figure 3-1 forming process bus 1 and 2 run separately without affecting each other, but they performs the same protection functions as MP1 or MP2. Thus, the single star network with MP1 was modelled using OPENT as shownin Figure 3-4.

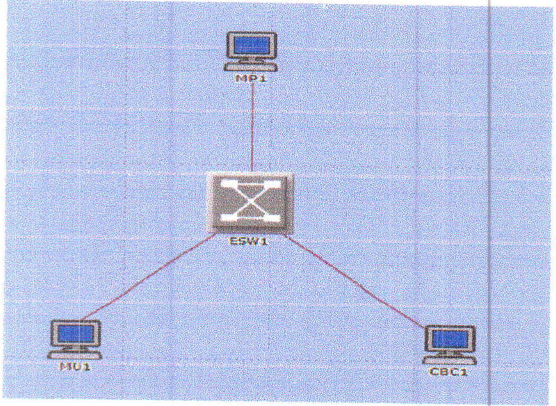


Figure 3-4 Single Star Network Modelling

As shown in Figure 5-4, MP1 is connected to a MU1 and a CBC1via the Ethernet switch. These four devices are modelled using OPNET model library. The periodic SVs are generated by MU1 while GOOSE messages are sent each other between MP1 and CBC1. Rapid Spanning Tree Protocol (RSTP) was considered in Ethernet switch. Process Bus 1 acts as the main protection in the substation. Therefore, should any Ethernet link be disconnected inprocess Bus 1, a short period of time is needed for backup protection (process Bus 2) to operate. As a result, the recovery time of RSTP may not meet the IEC 61850 SAS communication network performance requirements.

3.2.2 Modelling of A Ring Process Bus with HSR Protocol

In the process bus utilizing a ring network with HSR protocol (Figure 3-5), each device model is configured as a DANH, performing functions such as generating and duplicating message frames (HSR Frame A and HSR Frame B). These frames circulatesimultaneously in separate directions within the HSR ring, reaching intermediate IEDs within 5 µs [67]. After circulating theentire ring, the frame returns to the source IED and is discarded. The destination IED receives duplicated frames successively, ensuring continued operation in case of frame loss. HSR proves efficient in handling single point failures on the Ethernet link, providing zero recovery time.

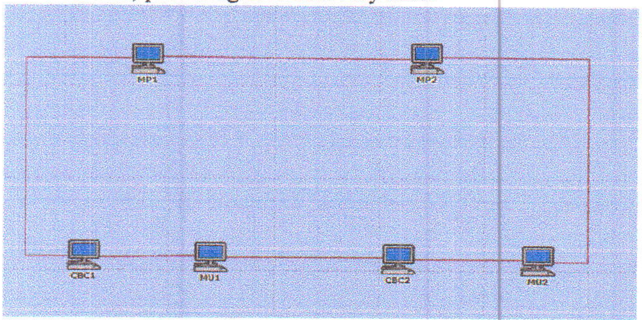


Figure 3-5 HSR Network Modelling

3.2.3 Modelling of A Parallel Star Network Process Bus withPRP protocol

Figure 3-6 presents the simulation scenario for process buses using a parallel star network with PRP protocol. DANP has been configured in this network. DANP has two individual communication ports in each device. Two independent ports onlytransmit two copies of frames without receiving and forwarding. However, all frames will be duplicated and transmitted into two separate networks as LAN A and LAN B simultaneously. It should be noted that the topologies of LAN A and LAN B are not required to be identical. The frame arriving first at the destinationnode is received whilst the later one will be discarded. All traffic will never return to the source. In addition, normal Ethernet switches can be utilized in this network.

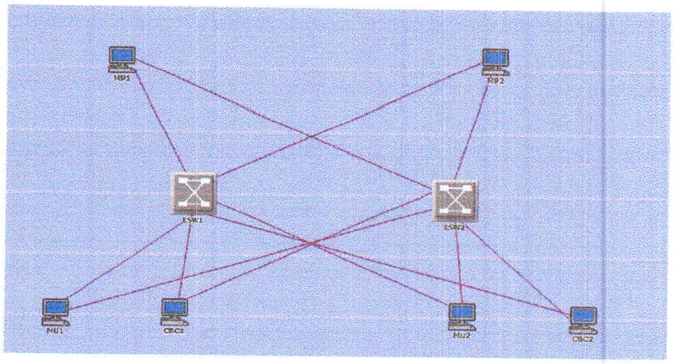


Figure 3-6 PRP Network Modelling

3.3 Results and Analysis

The simulations have been conducted several times with a different number of MUs to assess and evaluate the performance of three kinds of process bus network. During the simulation, eachscenario has been run for 30 seconds. The results of network time delay and communication network bandwidth utilization under different situations are presented.

3.3.1 System Time Delay study

3.3.1.1 System time delay with 2 MUs

Figure 3-7 shows the system time delay for three redundancynetworks with basic protection scheme as 2 MUs connected.

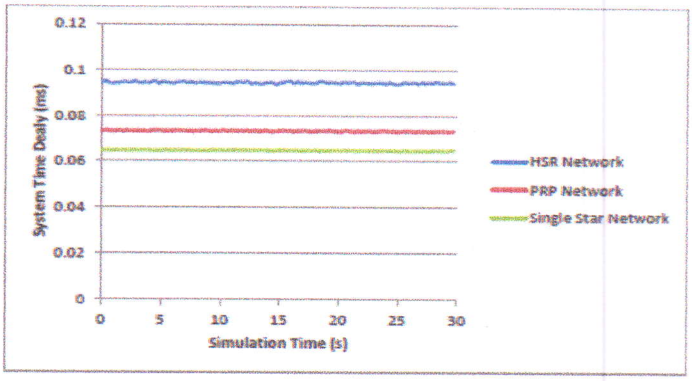


Figure 3-7 Time Delay Performance of three RedundancyNetworks with 2 MUs Connected

It can be inferred that the time delay for HSR network is 0.095ms which is longer than PRP (0.075ms) and two independent parallel star networks (0.065ms). This is because message packets need a long distance to arrive at the destination in ring topology, while message packets are propagated through a central Ethernet switch to be received by IEDs in star topology. PRP is also more complexthan the star network. In this scenario, all three networks performed well.

3.3.1.2 System Time Delay from 2 MUs to maximum MUs

Figure 3-8 shows the simulation results of system time delay for three studied networks where an increasing number of devices areconsidered.

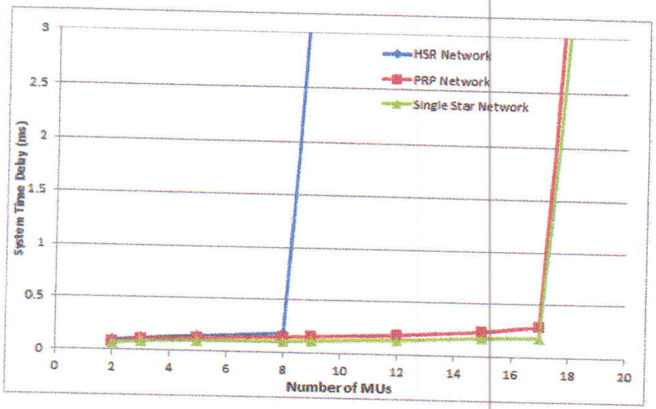


Figure 3-8 Time Delay Performance of three Networks withnumber of MUs connected

The system time delay increases linearly with the addition of devices (MUs) until the network switching capability is exceeded.The relation is nearly linear until reaching the GOOSE time requirement limit of 3ms (Table 2-2). In Figure 3-8, the HSR network's capacity is restricted to 8 MUs, while the PRP network and single star network can accommodate up to 17 MUs. Adding an 18th MU causes the system time delay to exceed 3ms. Notably,the capacity of HSR is halved compared to a single star or PRP network due to message duplication and transmission via twopaths in the ring network.

3.3.2 Network Bandwidth Utilization Study

The network utilization varies with the number of devices connected. Table 3-2 illustrates the network bandwidth utilization in each redundancy network. In the HSR network, with 9 connected MUs, 82.2% of the communication channel is occupied, but the system time delay exceeds performance requirements. This is due to DANH occupying a part of the network bandwidth for message receiving and forwarding, causingmessage packets to queue. Similarly, Ethernet switches in the PRP network and single star network also take up part of the network bandwidth. Simulation results indicate that, with the same numberof connected MUs, the network bandwidth utilization of the HSR network more than doubles compared to the other two networks. This is attributed to message packets being duplicated and propagated into separate paths throughout the entire ring in the HSR network, where packets from the source must return to the source and be discarded, while the packet from the source is recognized at the receiver in the PRP network and single star network.

Table 3-2 Network Bandwidth Utilization in different cases

Number of MUs	Network Bandwidth Utilization (%)		
	HSR Network	PRP Network	Single Star Network
2	21.7	9.3	7.6
3	30.5	13.6	11.9
5	47.5	22.2	20.1
8	73.4	35.4	32.4
9	-	38.9	35.7
12	-	51.7	47.5
15	-	62.4	58.6
17	-	72.8	69.3

3.3.3 Single Ethernet Link Failure on HSR

Unlike two independent process buses and PRP network, a singlepoint failure on HSR could impact the data transmission or receiving time delay. Therefore, the performance of a single Ethernet link failure on the HSR network was investigated and analysed.

As shown in Figure 3-9, during the simulation, the HSR process bus was under normal operation in the first 10s, and then the Ethernet link between the MP1 and MP2 was disconnected. The change of system time delay performance is shown in Figure 3-10.It can be observed that system time delay has become almost double after the link failure, since most packets need a long distance to be transmitted to the destination IEDs. Normally, frames do not propagate clockwise or anticlockwise completely inthe whole ring. The capability of the HSR network will be assessed in this case.

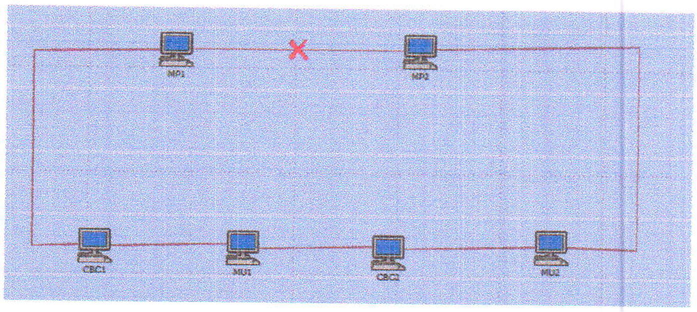


Figure 3-9 Failure of Single Ethernet Link for HSR Network

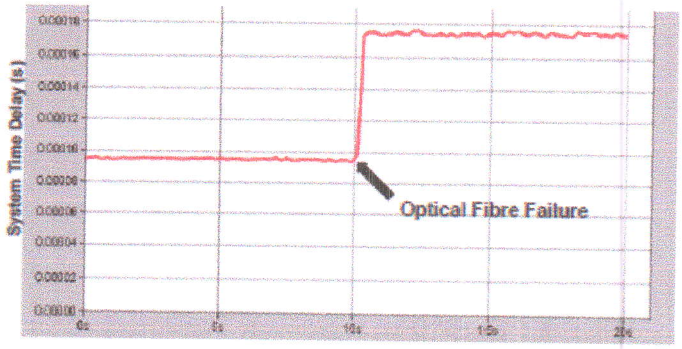


Figure 3-10 System Time Delay Change under Optical FibreFailure

Assume a broadcast message from device A to device B, C, D andF which is shown in

Figure 3-11, the time delay for all B, C, D, E and F are listed asshown in Table 3-3,

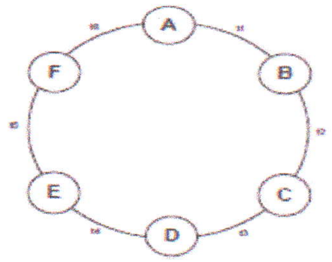


Figure 3-11 Overview of Network

Communication Table 3-3 Message Time Delay for different Routes

Traffic transmission route	Clockwise time delay	Anticlockwise time delay
A to B	t1	t2, t3,t4,5,t6,
A to C	t1,t2	t3,t4,5,t6,
A to D	t1,t3,t3	t4,5,t6,
A to E	t1,t2,t3,t4	t5,t6,
A to F	t1,t2,t3,t4,t5	t6

As in Table 3-3, the short route will be selected for packet transmission. The worst case is A to D which can be described t1+t2+t3 or t4+t5+t6. If the fiber between A and B or A and F is disconnected, the worst case delay is t2, t3, t4, t5, t6 or t1, t2, t3,t4, t5. Since the delay of in the fiber can be ignored as the light speed in the fiber. In the simulation the same switches were usedso the delay in the switches should be the same, hence t1, t2, t3, t4, t5 and t6 are equal.

$$TNormal = (t1 + t2 + t3)\ or\ (t4 + t5 + t6)\ or\ (t1 + t2 + t3 + t4 + t5 + t6) \div 2$$

$$TFault = (t1 + t2 + t3 + t4 + t5)\ or\ (t2 + t3 + t4 + t5 + t6)$$

This can be written as a generalized form for normal and a faultycomponent in the ring in equation (8) and equation (9),

$$TNo\quad mal = (t1{+}t2{+}t3{+}\cdots{+}tN) \quad (8)$$

$$TFault = (t1 + t2 + t3 + \cdots + tN{-}1) \quad (9)$$

According to the results in Figure 3-12, the relationship between the system time delay and the number of connected MUs is almostlinear. It can be found that the maximum number of MUs connected to the HSR network is the same under normal and faulty fiber conditions, i.e. up to 8 MUs. The optical fiber failure will not affect the capacity of the HSR network, while it will result in a system time delay almost double that of a delay under normalconditions.

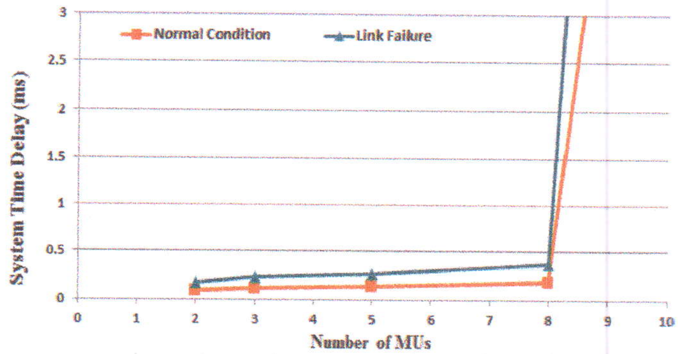


Figure 3-12 System Time Delay under different Scenarios

As Table 3-4 shows, the system time delay can be obtained. The network capability is still 8 MUs. However, compared with HSR capability study under normal conditions, it can be observed that system time delay has doubled under Ethernet link conditions since most packets need more distance to arrive at the destination IEDs. Under this circumstance, a message frame cannot propagate clockwise and anticlockwise completely in the whole ring.

Table 3-4 HSR Network Capability Test in Faulty equipment Case

Number of MUs	System Time Delay (ms)	
	No Point Failure	Single Point Failure
2	0.095	0.174
3	0.121	0.234
5	0.143	0.269
8	0.183	0.371
9	>3	>3

Unlike RSTP protocol which is used in two parallel star networks,zero recovery time is provided by HSR protocol. It is not necessary to find the best route for traffic to be transmitted in the HSR network. The results confirm that a single Ethernet linkfailure has no effect on the capability of the HSR network.

3.3.4 Improvement of HSR Hosting Capability with QRmethod

According to the working principle of the HSR proposal, twocopies of data packets will appear on the Ethernet fibers.

However, there is no duplicated traffic on the same fiber on both PRP networks and single star network. Due to extra traffic generated in the HSR network, the capability performance can bereduced significantly when comparing it with other two.

To remove the duplicated traffic in HSR, a so call Quick Removing (QR) method has been proposed [58]. As shown in Figure 3-13, in the QR method, record and detect functions are added to each port in Double attached Node HSR (DANH) or redbox to clarify the sequence number of flowing message packets. Once packet have been transmitted through DANH mode, the other packet with same sequence number arrived will be eliminated in this model without return to the source IED. Therefore, the all duplicated packets will not circulate the whole HSR ring network.

Number of MUs	System Time Delay (ms)	
	Normal HSR Network	HSR with QR
3	0.097	0.08
5	0.135	0.09
8	0.17	0.12
10	>3	0.13
13	>3	0.16
15	>3	0.19
16	>3	>3

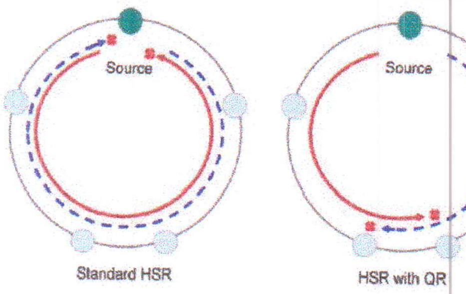


Figure 3-13 Principle of QR Method [58]

Table 3-5 presents the capability test for the HSR network with QR method. The capacity can be increased to 15 MUs. Comparedwith the standard HSR, the capability of the process bus with QR method applied has approximately doubled. This is because in thestandard HSR network, the packets from the source have to returnto the source and be discarded while the packet from the source will be recognised at the receiver. However, with the QR method,intermediate IEDs can discard the packet from the network. The capability of the network can therefore improve significantly.

Table 3-5 Capability Test for HSR Network

3.4 Summary

This chapter assesses the equipment hosting capabilities of two typical PB networks, HSR and PRP redundancies, using OPENT simulation models. A comparison with the single star PB network is made. Results indicate a maximum capacity of 17 MUs for boththe single star and PRP redundancy networks, while the HSR network has a capacity of only 8 MUs.

Other performance metrics, including data exchange time delay, network bandwidth utilization, and the impact of equipment failure in the redundancy network, are also studied. The single starnetwork exhibits the shortest time delay, while the HSR network has the longest. For PB less than 8 MU connections, the HSR network shows better network utilization, but exceeds its hosting capability with more than 8 MUs. PRP network outperforms the single star network in terms of network utilization.

Regarding equipment failure, both RPR and HSR networks show no impact on data exchange delay and hosting capability in case of equipment failure. However, data exchange time delay can doublein the event of HSR network equipment failure. The implementation of QR method in HSR network increases the equipment hosting capability from 8 MUs to 15 MUs.

Chapter 4 Experimental Impact Assessment of Data Network onProtection Scheme Functionality

4.1 Introduction

This chapter focuses on the lab set up and tests for the assessment of the impact of two different redundancy networks HSR and PRPand their faulty components on a protection and control (P&C) scheme functionality and performance. The P&C scheme was based on two main protection and control strategies. The lab set upfor the P&C scheme based on HSR and PRP configurations are the same as in Figure 3-2 and Figure 3-3, respectively. The details of the implementation of a substation real time simulation model using RTDS, test scenarios and the experimental results are analysed and discussed.

4.2.2 Modelling CT saturation

Modeling CT saturation is crucial for evaluating substation redundancy network performance as it reflects a physical phenomenon impacting the proper functioning of protection systems. Despite being well-documented in existing literature [63-65], the underlying principles of CT saturation are reiterated here for clarity. In an ideal scenario, the current in the secondary of a CT is directly proportional to the primary current. However, electromagnetic phenomena within the CT core lead to saturation, where the linear dependence between primary and secondary CT current breaks down. This phenomenon occurs within the CT corematerial, and the ideal B-H curve, depicting magnetic field density (B) against magnetic field intensity (H) without hysteresis andcore losses, is illustrated in Figure 4-9.

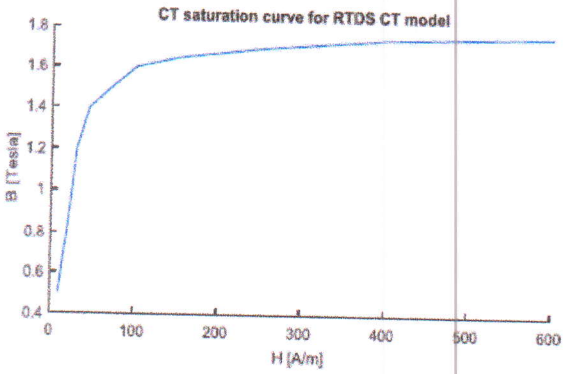
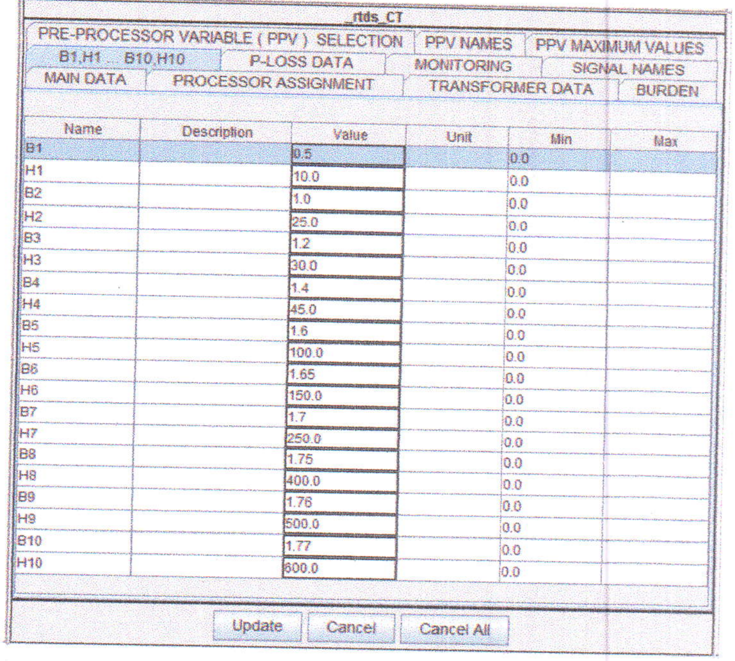


Figure 4-9 CT saturation curve for standard RTDS CT model [66]

For all CTs, the dependence between B and H is closely related to the dependence between the voltage and current respectively. The plot in Figure 4-9 was obtained from the data of the RTDS standard CT model, as given in Figure 4-10.



Name	Description	Value	Unit	Min	Max
B1		0.5		0.0	
H1		10.0		0.0	
B2		1.0		0.0	
H2		25.0		0.0	
B3		1.2		0.0	
H3		30.0		0.0	
B4		1.4		0.0	
H4		45.0		0.0	
B5		1.6		0.0	
H5		100.0		0.0	
B6		1.65		0.0	
H6		150.0		0.0	
B7		1.7		0.0	
H7		250.0		0.0	
B8		1.75		0.0	
H8		400.0		0.0	
B9		1.76		0.0	
H9		500.0		0.0	
B10		1.77		0.0	
H10		600.0		0.0	

Figure 4-10 RTDS Standard CT model [66]

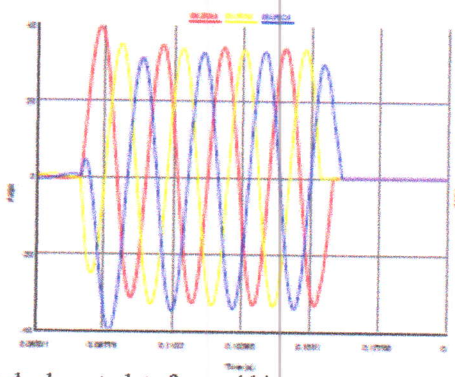
The B-H curve in Figure 4-9 exhibits a linear region on the left and a saturation region on the right, with the knee point between them. During normal loading, the CT's operating point should be within the linear region. However, under high current conditions, such as during a fault, the operating point may enter the saturation region. In this research article, CT saturation tests were conducted by intentionally shifting the initial operating point into the saturation region using a high burden resistance in the RTDS CT model. Three saturation testcases were examined, as outlined in Table 4-1.

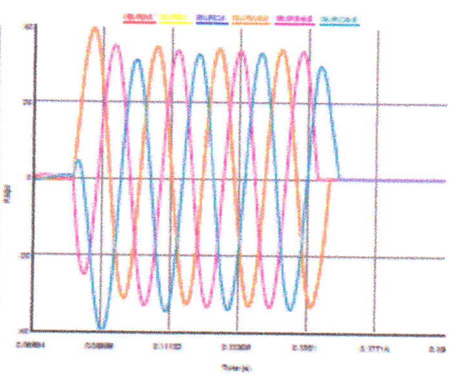
Table 4-1 CT Saturation test cases

Test case	Description	CT model parameters
CTSat0	Ideal CT (No CT Saturation)	R_{burden} = 0.5 ohm; L = 0.035 H
CTSat1	Lightly CT Saturation	R_{burden} = 5 ohm; L = 0.35 H
CTSat2	Deeply CT Saturation	R_{burden} = 50 ohm; L = 3.5 H (initial operating point close to knee point)

To better understand the behavior of the network model RTDS are provided foreach CT saturation test case:

1. CTSat0: Ideal CT





for each test case, several relevant plots from within

Figure 4-11 CT secondary currents with 3-phase-ground fault at the mid-point

Figure 4-12 Comparisons of CT currents with anideal conventional CT

Figure 4-11 shows the symmetric fault currentswith no DC off set at the CT secondary sides when a 3-phase to ground fault occurred at the mid-point of the transmission line. The waveforms are sinusoidal without CT saturation effects. Compared with an ideal CT (see Figure 4-12), the waveforms of each phase overlap each other.

2. CTSat1: Lightly CT saturation

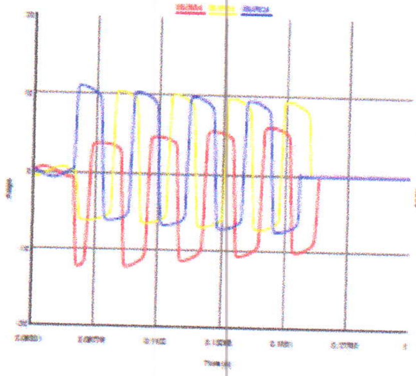


Figure 4-13 CT secondary currents with 3-phase- ground faultat the mid-point

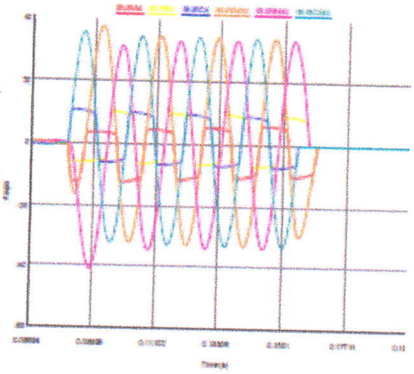


Figure 4-14 Comparisons of CT currents with an idealconventional CT

The secondary fault currents in Figure 4-13 become non-sinusoidal due to the lightly CT saturation effect. From the comparisons shown in Figure 4-14, there is a gap between the saturated CT current and ideal CT current. The calculatedimpedance by distance protection will be higher than the actual value, resulting in delayed protection trips.

3. CTSat2: Deeply CT saturation

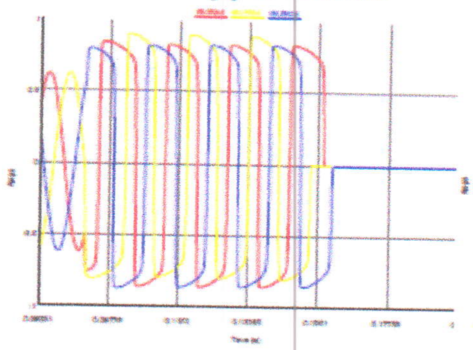


Figure 4-15 CT secondary currents with 3-phase- ground faultat the mid-point

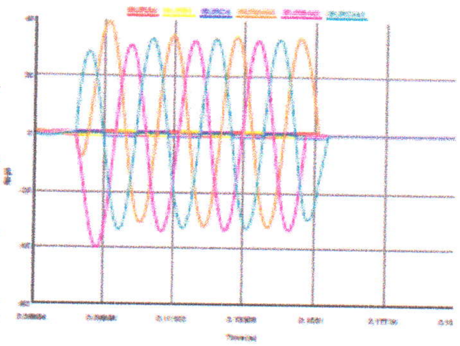


Figure 4-16 Comparisons of CT currents with an idealconventional CT

The initial operating condition in CTSat2 (deeply CT saturation) case is close to the knee point of the B-H curve. However under fault conditions, CT becomes deeply saturated. Figure 6-15 shows the fault currents smaller than 1A, this because all most current from primary flow into magnetized branch, this can cause issues for both distance andovercurrent protection functions.

4.2.3 Testing Cases Setup

4.2.3.1 Case studies under HSR configuration

There are three group scenarios employed to intentionally apply faults within the communication infrastructure which are shown in Table 4-2:

- Scenario A: No communication network component failure. In this scenario, the communication network functionsat its full redundancy capability,

- Scenario B: One optical fiber failure in HSR ring. In this scenario, assume one fiber in HRS ring is broken. As a result, either sample value packets between AMU and MP or GOOGE message between MP and CBC are transmitted andreceived over a longer distance.

- Scenario C: Equipment AMU is failure in the HSR ring. In this scenario, one protection (either MP1 or MP2) in the ring has been incapacitated. In this test case, the SVs fromAMU (GE) to MP1 (ABB diff local) are no longer working. Therefore the loss of connection between AMU (GE) to MP1(ABB diff local) at local has blocked its pair differential protection at the remote.

Table 4-2 Intentional faults applied to communication infrastructure for HSR configuration

Scenario	Description
A	No faulty device or fibre in the HSR configuration.
B	One faulty fibre in the HSR configuration. The redundancy capability of the network is reduced.
C	One equipment AMU is failure in the HSR configuration. MP1 – the differential protection relay blocks their trip function.

4.2.3.2 Case studies under PRP configuration

Similar to HSR configuration, there are also three scenariosemployed to intentionally apply faults within the communication network for PRP configurations and all scenario groups are summarized in Table 4-3.

Table 4-3 Intentional faults applied to communicationinfrastructure for PRP configuration

Scenario	Description
D	No faulty device or fibre in the PRP configuration.
E	One equipment AMU failure and MP1-differential protection relays block their trip function.
F	Equipment AMU failure + one fibre in PRP network is discounted. The redundancy capability of the network is reduced.

Chapter 5 Conclusion and Future Work

5.1 Conclusion

IEC 61850 standards have been published and wildly used fordata exchange communications in a substation automation system (SAS). The standards aim to address the interoperability between different vendor devices, including Merging Units (MUs), Circuit Breaker Controllers (CBCs) and Intelligent Electronic Devices (IEDs). This can bring significant flexibility and benefits to power utilities and industries to confidently deploy new smart equipment, communication and network technology applications.

This research article mainly focuses on assessing and quantifying the communication network performance, in terms of equipmenthosting capability, data exchange time delay and network utilization, for both process bus (PB) and station bus (SB) through simulation studies. The research article report also details the experimental testing bed setup and assessing the impact of different faulty components in both High-availability Seamless Redundancy (HSR) and Parallel Redundancy Protocol (PRP) redundancy data networks on the typical protection scheme (i.e. consisting of MP1 - differential and MP2 – distance) performance though the experimental tests.

For the simulation studies, OPNET Modeller simulation toolhas been used to model (i) both typical PB and SB networks,
(ii) PB networks with different network redundancies, including two independent parallel star networks, a ring network with HSR protocol, and a parallel star network withPRP protocol.

For the experimental assessment, a testing bed was setup and used for testing the impact of faulty components in either HSRor PRP on the P&C scheme. For considering different type of power system faults, a 400KV substation network model residing in the RTDS facility was implemented and integrated with real commercial IEDs, MUs and CBCs. The devices were:

➢ AMU1 (GE), AMU 2 (ABB), CBC1 (ABB), CBC 2 (ABB), MP1 (ABB diff local) MP2 (GE dis). In addition, MP1(ABB diff remote),

➢ Voltage or current measurements and circuit breakercontrol signals between MUs/CBCs and the RTDS virtualtransmission substation model via amplifiers or electrical signal isolators, respectively,

➢ IEC 61850-9-2 Sampled Values (SV) & 8-1 GOOSE oneither HSR or PRP process bus networks via MUs, CBCs and MPs, Details of the results and discussion are outlined below:

1) Simulation Assessments

In the simulation studies, the data network performance assessments for three types of data networks (i.e. a single star,HSR and PRP, respectively) have been evaluated and investigated under different fault conditions (i.e. feeder fault, fiber failure, storming data). Three

2) Experimental Assessments

In order to analyze the effectiveness of the implemented data network redundancy on the P&C scheme functionality, an experimental testing bed was setup. The assessments of two different redundancy networks HSR and PRP and their faultycomponents impact on the P&C scheme functionality and performance were conducted. The P&C scheme was based ontwo main protection and control strategy.

Both PB with HSR and PRP protocols laboratory setup were based on a configurable Virtual Site Acceptance Testing and Training (VSATT) platform at Manchester where RTDS playsa central role in the laboratory setup because *it represents the real substation and network* model. RTDS represents the source of CT and VT analogue measurements as well as the destination of circuit breakers for trip signals. The RTDS network model can integrate signals from external hardware inreal time, according to Hardware in the Loop (HiL) simulationrequirements. RTDS interfacing with Omicron amplifiers are integrated with AMUs, IEDs and CBCs from different manufacturers. There were no major issues in terms of interoperability, as all devices were compatible with the IEC 61850 standard and their configuration was accomplished according to the guidelines outlined in the IEC 61850 standard.

In PRP tests, various different faulty components and differentCT saturation levels were considered. For the tests on faulty components in PRP with ideal CT, the test results show that the protection scheme under no fault component performs better than these fault component *conditions. Under the faulty component conditions in* PRP, the protection scheme selects the best route to trip. For the tests on faulty components in PRP with lightly CT saturation, the main effect was the faulty AMU that stopped MP1 (differential) to operate and forced MP2 (distance) into backup protection (i.e. zone 2). For the tests on faulty components in PRP with deeply CT saturation, the main effect is the faulty AMU that can stop both MP1 and MP2 in the protection scheme failed to trip.

5.2 Suggestions for future work

5.2.1 Establishing Simulation Model for more ComplexData Network Designs

The data networks for the simulations and experimental testing bed in this have been mainly focused on the simple Ethernet switching configuration. For future digital sudation roll out, data networks would be more complicated.

Hence to would be necessary to establish a more complex data network simulation network made of a number of Ethernet switches. To assess such data network equipment hosting capability and critical time delay performance in responding tothe different probability of stochastic events conditions, a suitable Markov chain model will be needed to deal with multiple data queuing arrival rates $\lambda 1,.., \lambda n$ and multiple switch data services rates $\mu 1,\ldots \mu m$. The aim of the established model should be more generic and can be used for different data network performance studies.

5.2.2 Substation Digital Twins

Adopting digital twins for substations could help large power utilities to improve digital substation design and P&C performance. Electric utilities are leveraging digital twins to manage substations over their lifecycles and are empowering multidiscipline teams to collaborate with other stakeholders. As a result, they are gaining accuracy in their modelling, streamlining design and construction, and increasing safety and reliability.

5.2.3 Cyber Security

The network communication infrastructure of substations provides several benefits to power utilities. However, digital substations can be exploited by an attacker to gain access to the infrastructure of the utility. Recent cyberattack on Ukraine power grid was reported on December 2015 [67] which disrupted the whole electricity network operation.

For this reason, currently cyber security technologies, methods and IEC standards, such as IEC 62351 power system management and associated information exchange – data and communication security, have already developed and published [68].

List of Abbreviations

AMU Analogue Merging Unit

ASCI Abstract Communication Service Interface

AS3 Architecture of Substation Secondary System

BCU Bay Control Unit
BP Backup Protection

CBC Circuit Breaker Controller

CID Configured IED Description

CT Current Transformer
DANH Double Attached Node with HSR
DANP Double Attached Node with PRP
DAR Delay Auto Reclose
DMU Digital Merging Unit

EPRI Electric Power Research Institute

ETE End to End
FITNESS Future Intelligent Transmission Network Substation
FR Fault Recorder

GOOSE Generic Object Oriented Substation Event

HMI Human Machine Interface
HSR High-availability Seamless Redundancy
HV High Voltage
ICD IED Capability Description
IED Intelligent Electronic Device
IEEE Institute of Electrical and Electronic Engineers
KPT Kurdistan Power Transmission
KR Kurdistan Region
KRG Kurdistan Regional Government
LAN Local Area Network
MB Measurement Bus

MMS Manufacturing Message Specification

MP Main Protection
MU Merging Unit

NCIT Non-Conventional Instrument Transformers

NG National Grid

OPI Open Systems Interconnection
PB Process Bus

P&C Protection and Control

PMU Phase Measurement Unit
PRP Parallel Redundancy Protocol
PT Potential Transformer
RB RedBox

RSTP Rapid Spanning Tree Protocol

RTDS Real Time Digital Simulator

RTU Remote Terminal Unit
SAN Single Attached Node

SAS Substation Automation System

SB Station Bus
SCADA Supervisory Control and Data Acquisition
SCD Substation Configuration Description
SCN Substation Communication Network
SCU Switch Control Unit
SV Sampled Value
TVA Tennessee Valley Authority
UCA Utility Communications Architecture
VLAN Virtual Local Area Network
VT Voltage Transformer

VSATT Virtual Site Acceptance Testing Training

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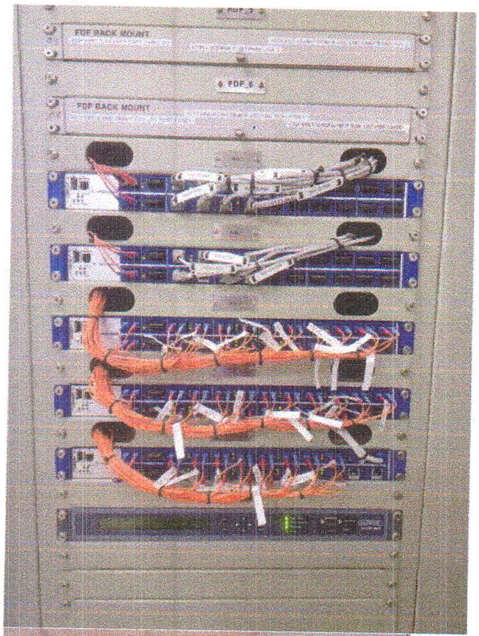
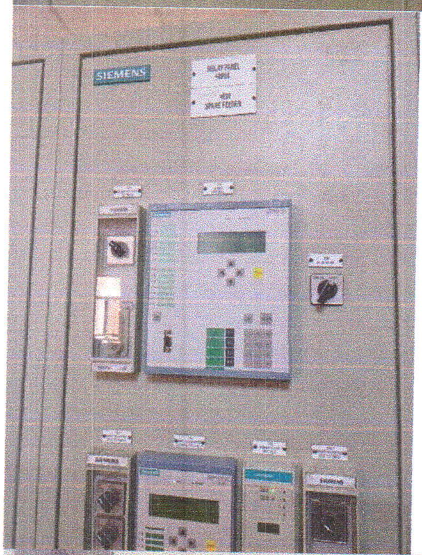
APPENDIX:

"In order to enhance the comprehensiveness of this research and provide readers with additional insights and supporting materials, thefollowing appendices have been included.
Additionally, for a thorough understanding of the entire context and background, readers are encouraged to follow and read all references cited in this paper. These supplementary materials offer a detailed exploration of key aspects of *Communication Networks for Protection and Control in Substations*, aiming to augment thefindings presented in the main text. The appendices serve as a comprehensive resource for those interested in a more in-depth understanding of the research methodology andresults."





SIEMENS

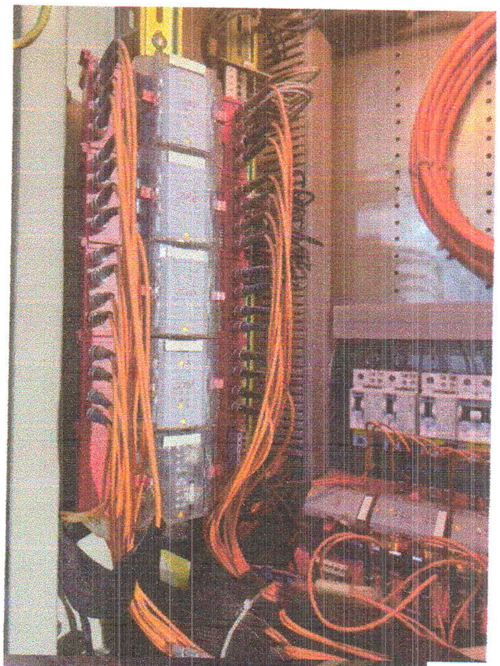
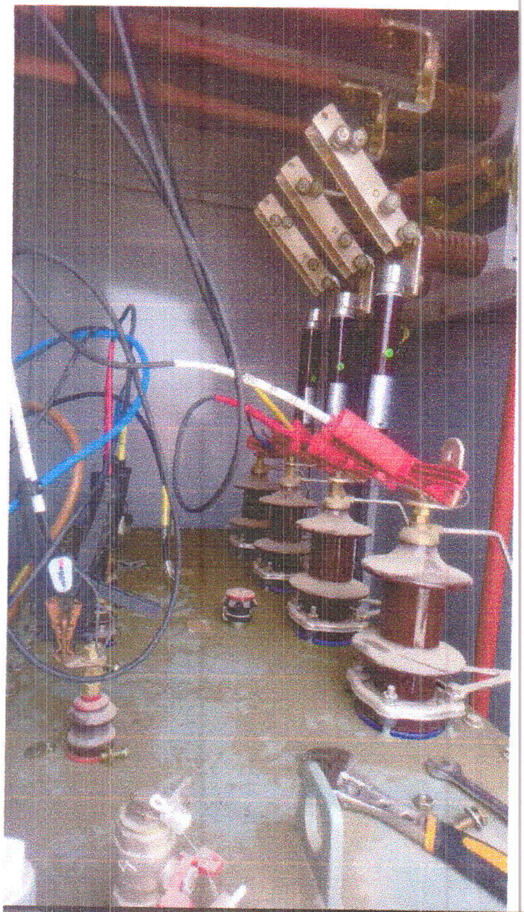


Figure 2 – Gas-insulated switchgear installed in room (photo credit: oconnellelectric.com)



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