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Research Article

A Review Reliability and Availability Analysis of IEC 61850 Based Substation Communication Architectures

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Abstract

Modern Ethernet technology's high-speed capabilities enable efficient data transfer, and its leadership in the LAN space further distinguishes Ethernet as an intriguing communication method. For important substation automation applications to operate successfully, communications must meet cost, performance, and reliability requirements technology for substation automation management. The IEC 61850 standard was published by the International Electro-Technical Commission (IEC) to provide interoperability among enterprise substation automation systems for communication networks within power substations. This standard specifies Ethernet-based communication systems for substation automation systems (SAS). With the aid of Ethernet switches, Ethernet offers versatility in terms of configuring different designs. On the other hand, before using appropriate Ethernet architectures for critical applications in substations, they must be assessed for availability and reliability. This study uses the reliability block diagram (RBD) approach to analyse the availability and reliability evaluation of practical Ethernet Cisco device topologies. With a typical transmission substation in mind, dependability block diagrams for intra-bay and inter-bay communications have been created. Additionally, the dependability and accessibility of the actual Ethernet topologies have been compared, and some recommendations have been derived from the findings. These recommendations include the following Index Terms: substation automation systems (SAS), availability, IEC 61850, smart electronic device (IED), and dependability.

Keywords

Automation System (SAS), Substation, Communication, Ethernet, Smart Electronic Devices

1. Introduction

The main obstacle a design engineer faces in ensuring interoperability amongst different manufacturers' equipment for monitoring, control, and protection is substation automation design. All of the manufacturers were utilizing their fundamental, proprietary communication methods as of late. Developing expensive and complicated protocol converters requires a significant financial investment [1, 2]. IEC working group TC57 was able to produce IEC 61850, "Communication Networks and Systems in Substation," in 2003 as a solution to this problem [3, 4]. By addressing the communication protocol, data format, and configuration language, IEC 61850 standards enable compatibility [5, 6]. Additionally, based on OSI-7 layer specifications, this standard Ethernet is proposed at the station level and at the process level, respectively, in IEC 61850 parts 8 and 9. High adoptability of Ethernet is offered in terms of communication architectures as well as integration of fast growing communication technology [7].

Modern Ethernet technology's high-speed capabilities en-

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able efficient data transfer, and its leadership in the LAN space further distinguishes Ethernet as an intriguing communication method. For important substation automation applications to operate successfully, communications must meet cost, performance, and reliability requirements technology for substation automation management [8, 9]. On the other hand, IEC 61850 recommended Etherne [10, 9]. The point of failure has been compromised in accordance with IEC 61850 reliability regulations, ensuring that there would be no reason for the substation to become inoperable. IEC 61850 does not, however, mandate redundancy, even for critical applications; substation design engineers are responsible for this. Improvements in SAS availability and reliability would therefore rank among the most difficult problems for the substation systems design engineer based on IEC 61850. This topic has reportedly been covered in a wide range of literatures. Leaving aside communication network performance constraints, this study presents the availability and reliability analysis of real-world Ethernet communication topologies for IEC 61850 based SAS using the reliability block diagram technique.

2. Literature Review

The International Standard for Communications inside Substations (IEC 61850) is based on Ethernet and was previously conventional between 2003 and 2005. It has since gained popularity and its applicability has grown significantly [11]. Time synchronisation and interoperability, two of the IEC 61850 standard's most crucial features, are described by the substation automation system. The three tiers of substation automation functions are process, bay, and station level functions [12]. The switchgear equipment, along with the sensors and actuators needed to monitor and operate the switchgear, are arranged at the lowest level, called the process level. Devices including current transformers, circuit breakers, and isolators are found at the process level [13].

The middle level, known as the bay level, is where the dispersed control equipment for protection is located. The transmitted data mostly comprises of binary and analogue input or output information, such as voltage and current transformer outputs and trip controls from the protective relay. These devices are typically hardwired to bay level.

The station level is the uppermost level that houses the Human Machine Interface (HMI), centralised system computers, and gateways that connect to the Network Control Centre (NCC) [14]. Intelligent Electronic Devices (IEDs), such as intelligent sensors and actuators, may also be present at the process level.

Process bus connections to IEDs are often made using Local Area Network (LAN) technology. In the future, all process-level devices are expected to be connected to the process bus, negating the need for hardwiring. The next section examines IEC 61850 as a protocol for communication between the process and bay levels [15].

According to research, in order to have a feel for the cutting-edge technology, some of the early installations of this new technology relied on vendor-specific communication solutions. Although a typical substation will have two redundant protections from different vendors due to the multi-vendor connection between sensors and protection equipment at the bay level, in the mid-1990s, there was a strong customer drive for standardised solutions for the Ethernet standardisation activities throughout the United States and Europe [16]. While UCA 2.0 Utility Communication Architecture efforts in the United States focused mostly on standardisation between the station and bay levels, the European approach (led by IEC TC57, WG 10, 11, and 12) integrated communication from the start down to the time-critical process level. In 1998, the two initiatives came together to create IEC 61850, the single globally applicable standard [17]. Rather than argue over multiple competing field buses, an agreement was made to use Ethernet as the station bus's communication backbone.

Proper device selection, appropriate communication media, and appropriate communication protocol are essential for the power system to operate profitably. Plans for protection and control must be considered, as well as communication with control centres. The control system, on the other hand, is responsible for the overall stability, security, and strength of the power system. Among other things, it must have access to the vital data communication from the distribution side in order to accomplish this goal. thorough examination of fundamental communication developments for system engineering responsive demand and communication protocols that continuously address power demand equal to power generation [18]. The ability to use substation automation with Ethernet communication technology was made possible by its high-speed characteristics and strong market share in the local area network (LAN) space. While there was little rivalry when using traditional 10-Mbit/s Ethernet While IEEE 802.5 token ring and other classical 10-Mbit/s Ethernet competitors existed, fast (100 Mbit/s and higher) switched Ethernet was unrestricted. Other standards for communication, such as automated teller machines (ATMs) [19] and fiber distributed data interface (FDDI) [20] have encountered little to no difficulty in the LAN field. In the future, gigabit Ethernet may face some competition from a new communication technology called the InfiniBand Architecture, which was recently established by a consortium of the seven biggest computer corporations in the world.

High-performance interconnect technology known as InfiniBand, with link speeds ranging from 2.5 to 30 Gbit/s, will replace today's non-scalable PCI bus in this regard. It can also be used for computer networking, where switches and routers are essential building blocks. It can also be used for computer networking, where switches and routers are essential building blocks [21]. The industry would prefer to move away from the different (and typically incompatible) communication networks at the traditional Substation Automation (SA) levels and towards a single, comprehensive network model for a variety of standardisation and economic reasons. As a result, it was customary to take Ethernet technology into account for communication between the process and bay levels. Modern switched Ethernet's potential in such a widespread network architecture supporting several concurrent traffic kinds. To comprehend the substation automation performance for the Ethernet switches [22] also studied LAN congestion scenarios in Ethernet-based substations.

Bandyopadhyay et al. [23] provides a method for calculating the availability and reliability of a process bus based on IEC 61850 for various architectures.

Han and Crossley [24], Kanabar and Sidhu [9], Scheer and Dolezilek [25] in their study have demonstrated the dependability of various communication setups; their study emphasises the significance of availability and reliability studies for Ethernet communication networks.

Since the advent of sophisticated microprocessing and digital communication in substations, automation of power system substation and control has experienced significant modifications. Traditional panels were replaced with specialised standalone relays, metres, control switches, mechanical status indicators, and smart, multifunctional, communicative relays. These devices, also known as IEDs (Intelligent Electronic Devices), are becoming increasingly important in power system automation because of their strategic location and dependability. Complete elimination of hardwired systems appears to be possible through growing efforts to increase the reliability of the other components of the control and automation system, like message lines and switches, also to the level of the IEDs [26]. Even so, The majority of these IEDs are primarily designed to prevent damage to power system equipment during failures; moreover, because of their placement within the power system, they are perfect for implementing automation and control systems.

The advent of microprocessor-based communicable IEDs for defence has made it simpler to network many relays and use logical procedures. This is determined to be a more economical option than duplicating the resources in a substation by supplying specialised devices for automation and control. For more than 20 years, communication in substations has been widely used. We've come a long way from the days when communication was limited to offline data collection, and now we can see that much more important real-time functions are being realised through communication. The lack of a standard communication protocol created specifically for this purpose has been a significant barrier to the use of communication in substation automation and control [27]. Substations are frequently controlled, safeguarded, and monitored through the use of substation automation (SA) [28].

Private serial communication technologies have been employed up to this point in SA communication, in addition to traditional parallel copper cable, particularly from the process to the switchgear. A complete worldwide standard for all communication requirements in the substation is being introduced with the introduction of IEC 61850. dependability of the employed SA communication architectures is of major significance, since the dependability of substation automation strongly influences the reliability of the power supply from the power transmission and distribution grid. Since the new communication standard uses widely used communication channels like Ethernet, it offers a great degree of flexibility not found in the private or specialised channels that have been utilised up to this point, this desire is relevant for any communication system. First thoughts regarding crucial elements that the authors published in a study [2, 29] has been expanded to give a thorough, general understanding of SA architectures based on IEC 61850. To meet the performance requirements, the facilities that support communication techniques give several outstanding options. The standard-selected common communication channels, such as MMS, TCP/IP, and Ethernet, are accessible to a wide range of communication designs in addition to communication technological advancements [30].

There are no guidelines provided by the standard for the SA communication structure. IEC 60870-4 defines reliability, however it is defined as the ability of a piece of machinery or a system to carry out its intended task for a predetermined amount of time under predetermined conditions. To increase the new system's availability, there are a few options. Replacing copper wires with fibre optics, as directed by IEC 61850, is one recognised way to significantly lower the overall part count. Redundancy is another option because the all-digital protection system enables genuine redundancy in everything from communication links to protection relays to redundant instrument transformers and merging units [31], Since the new approach will nearly eliminate the amount of unsupervised functions and components, the third option involves self-testing and monitoring [32]. The dependability models for the all-digital protection system have been built to provide an approach that utilises every feature specified in any protection system completely created in accordance with the IEC 61850 protocol. Numerous studies have been conducted to investigate various aspects of traditional protection systems' reliability. Using a Markov model is one crucial method. Certain reliability indices have been defined, including protection unavailability and probability [33], abnormal unavailability [34-37]. Additionally, Fault Tree Analysis (FTA) [38, 39] is a useful method that may be used to analyse the relative unavailability of different protection methods. [40-42]. All-digital protection systems can benefit from the same reliability analysis methodologies that are used in conventional protection systems.

The success of a Substation Automation System (SAS) depends on connecting the many protection, control, and monitoring components in a substation via an efficient communication system. The primary obstacle encountered by substation automation design engineers is ensuring compatibility between the many manufacturers' control, monitoring, and protection systems. Developing expensive and complex protocol converters requires a significant financial investment [43, 44].

IEC working group TC57 released IEC 61850, titled

Communication Networks and Systems in Substation, in 2003 to address these SAS concerns [45]. The IEC 61850 standard addresses both how and what should be communicated. The capabilities of IEC 61850 surpass those of DNP3, IEC 60870-5-103, and the majority of proprietary protocols [46]. By specifying the communication protocol, data structure, and configuration language, IEC 61850 ensures interoperability. However, before IEC 61850 based SAS is implemented, a few outstanding concerns must be rectified. Sidhu et al., [47] and Valdes et al., [48] assessed the effectiveness of the Jain and Verma substation communication topologies, which are based on IEC 61850. [49]. Talk about particular problems pertaining to SAS's communication network. Adrah and associates, [50].

Have looked into SAS based on IEC 61850 functionality concerns. A few of the difficulties in putting IEC 61850-based SAS into practice. A thorough analysis is conducted on the communication system's problems at both the process and station levels. Additionally, planning-related and SAS-functional difficulties are covered. There are various potential strategies to tackle the implementation concerns and overcome these challenges. An overview of the Ethernet communication networks' availability and dependability is given in this study. For a typical small transmission substation, comprehensive reliability block diagrams for both intra-bay and inter-bay communication are produced. The dependability and availability data are used to compare every real-world communication architecture.

3. Methodology

The 138/69 kV substation with 29 circuit breakers is the basis for the assessments that follow. The substation refurbishment comprised 84 protective relays total—complete primary and backup protective relays. Every relay has an Ethernet interface for these situations. In order to facilitate connection between 23 equipment-monitoring devices that lack Ethernet capabilities, EIA-232 serial-to-Ethernet gateways are added as communications processors [51].

To provide the human-machine interface (HMI) and other data clients based on servers, an industrial computer was added. The substation local area network (LAN) and the system-wide area network (WAN) are connected via the router. Another advancement uses an FPGA-embedded controller to conduct system functions and acquire data at a fast and dependable rate. A single time source is used to monitor the power systems' steady-state and transient states because of the system's high sampling rate [52].

The LAN is used by the IoT platform to transmit and store data. System administrators can obtain data from the networked network attached storage (NAS) and view it remotely using a remote terminal (RT). This internet of things (IoT) based monitoring system was designed with communication methods and protocols, cybersecurity measures, and system protection against external unauthorised accessibility in mind. This finally allows the system operator to visualise the substation's overall operations in real time. [53] High-speed sampling data that has been recorded in the NAS offers comprehensive information for system analysis to prevent similar problem events in the future [54, 55].

Substation solutions take into consideration the space constraints found in substations and the industry's shift to wireless communication technologies for interconnection with various switches, mostly for remote distributions. Low-Power Wide-Area Networks (LPWANs) facilitate connecting to the substation's back-end systems for remote installations, while Wireless Personal-Area Networks (WPANs) enable device interconnection within substations [56]. The Internet of Things (IoT) technology retrofitting of SGs is dependent on substation solutions that meet the same standards as the (i.e., comply with IEC 61850), are intelligent enough to function in controlled environments with limited Quality of Service (QoS), and interoperable at the application layer (e.g., compatible with RE presentational State Transfer, or REST). Based on these specifications, the IEC 61850 standard supports many communication protocols [57] and has been reviewed [58] for its mapping to the Constrained Application Protocol (CoAP).

Communication Architectures for IEC 61850 Based Substation Automation

The function Hierarchy of IEC 61850 is described in this section. The three tiers of the IEC 61850 functional hierarchy, seen in Figure 1 below, become essential when the strain on electrical utilities mounts every day, leading to issues with power distribution. [59] One of the most intelligent solutions to support and address these difficulties related to electrical power services is to use Supervisory Control & Data Acquisition (SCADA) systems. As a recent innovation at the Control Centre, the automation systems integrations replace the earlier processes that could only be completed via a phone speech communication network in different transmission stations. The substations' data and status were gathered via the voice network mentioned above, and operators worked around-the-clock to manage the substations.

The data communication network's fibre optic cable terminals connecting the base station and related satellite back to the national control centre, as well as the protection devices that synchronise different switching for the incoming and outgoing cable connected subsystems, are among the substation-level network components whose complexity is growing daily [60]. These connect the protection control at the bay level to the communication bus. Process networks to process levels also come before these, enabling the interface for remote communications and the sensors and actuators [61]. Consumer demand for electricity has increased, which has also led to higher productivity. This has resulted in the introduction of substation automation communication systems and a reduction in prices, which has raised the need for information gathering and decision-making. The substation distribution network covers substations with varying voltage levels of 230/110/33kV, 110/33/11kV, 110/11kV, and 33/11kV, respectively, and spans a large geographic area. [62].

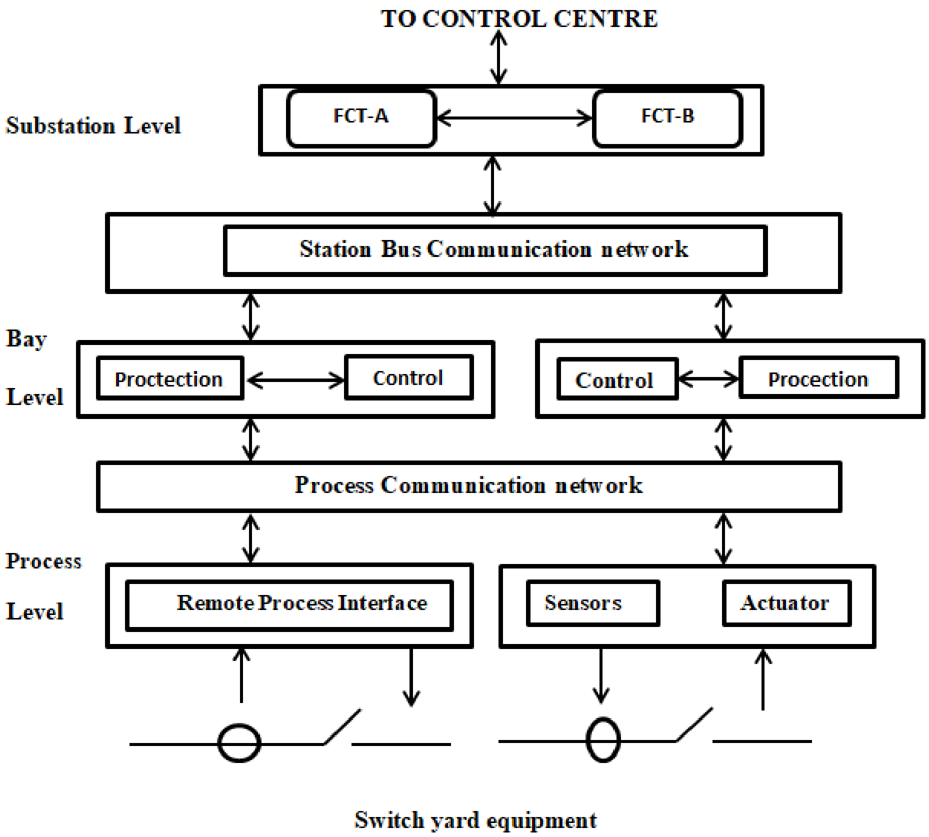


Figure 1. Functional hierarchy of IEC 61850 based SAS [63].

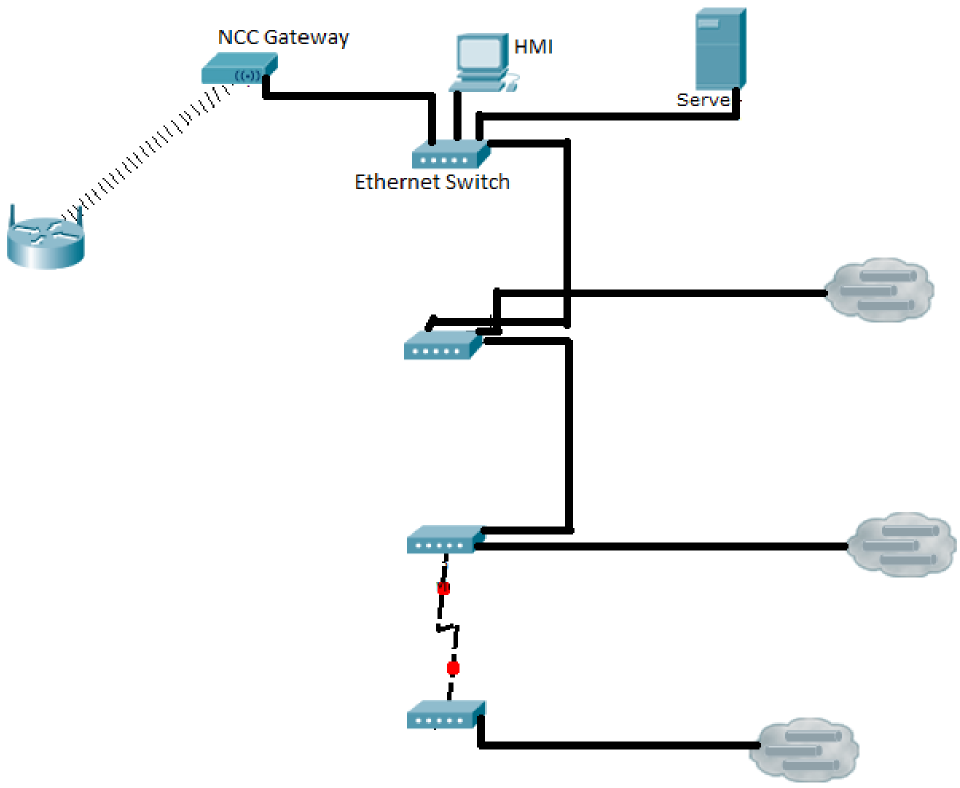


Figure 2. Cascaded architecture [65].

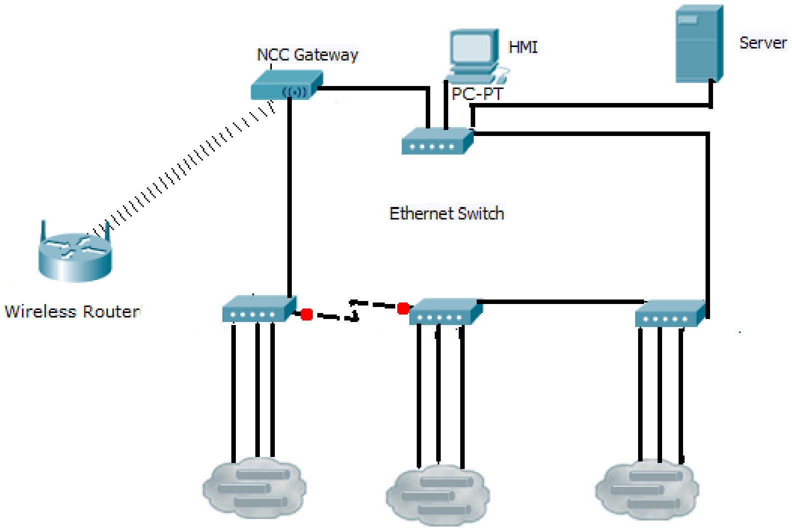


Figure 3. *Ring architecture [66].*

Actuators, remote I/O, CTs, and VTs, among other switchyard equipment, are included in the process level. The protection and control IEDs for various bays are included in the bay level. The operations that need information from many bays are carried out at the station level. Time-sensitive communication, such as sampled values, binary status signals, or binary control signals, between the protection and control IED and the process (the main equipment in the substation) is made possible by the Process bus. Communication between bay level and station level bays is facilitated by the station bus [64]. Whereas Figure 2 depicts a typical cascading arrangement. Every Ethernet switch is cascaded; none of them have loops.

This architecture is inexpensive and straightforward. But in comparison, this design would have a greater time delay (latency).

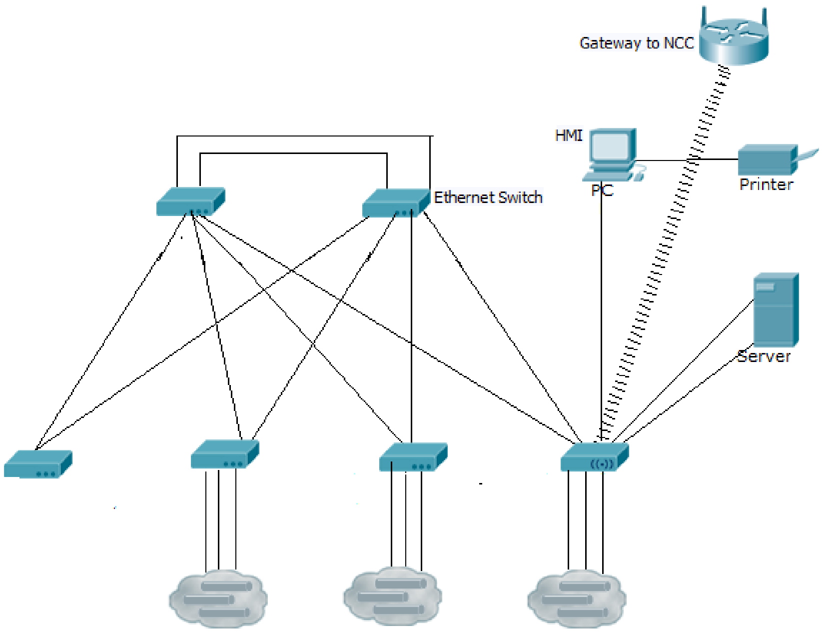


Figure 4. *Star-ring architecture [67].*

With the exception of the loop being closed from the last switch to the first switch, ring architecture and cascaded architecture are quite similar, as seen in Figure 3 [76]. There is no loop support on Ethernet switches. Consequently, managed switches—that is, switches having an internal management processor—that support the rapid spanning tree protocol (RSTP) must be used (IEEE 802.1w). This protocol enables switches to recognise loops, internally prevent messages from cycling within the loop, and reconfigure the network in less than a second in the event of a communication network failure. Because this architecture allows for n-1 redundancy, or the capacity for IEDs to continue communicating even in the event that an ESW or one of the ring connections fails, it may provide improved reliability. Nevertheless, this architecture adds little improvement in network latency and is expensive and complex. Every bay level Ethernet switch in the star-ring LAN design depicted in Figure 4 is directly connected to two redundant main Ethernet switches. These two primary Ethernet switches are linked together in a circle. This offers reduced latency and increased redundancy, but setting up the network in a star-ring arrangement calls for two more switches.

Two fully redundant rings are provided by the redundant-ring architecture, which is shown in Figure 5. In addition, a ring of four main Ethernet switches is formed by connecting both of these rings once more. With reasonable latency, this type of topology offers a fully redundant ring network. However, this architecture necessitates a large number of managed Ethernet switches that support the IEEE 802.1w rapid spanning tree protocol. Additionally, all IEDs must have two Ethernet ports, which will raise the price yet again. Although this network offers the maximum reliability going forward, it is quite expensive and complex.

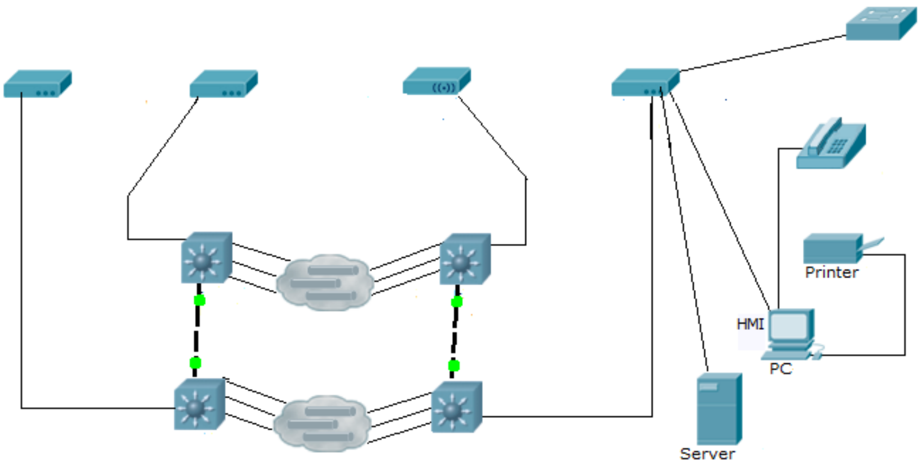


Figure 5. *Redundant-ring architecture [68].*

In this study, we present the reliability and availability analysis of all these realistic architectures by measurement. C. Architecture of Time Synchronisation The proposal in IEC 61850-9 is to digitize the output of the current and voltage transformers (CTs/VTs) at the switchyard (into MUs) and use process bus communication to send the sampled values to the bay level IEDs. In order for the protection function to run several such signal streams from autonomous MUs from different firms, this stream of sampled values needs to be synchronized. IEC 61850 suggests utilizing the simple network time protocol (SNTP) to operate time synchronization on a local area network. The accuracy that SNTP can deliver, however, is only around 1 ms, which is insufficient for raw data sampling values. Using the IEEE-1588 compliant IRIGB synchronization signal is one way to solve the problem [69].

4. Results and Discussion

4.1. Reliability and Availability Analysis of IEC 61850 Communication Architectures

In this paper, a typical transmission substation has been used to calculate the availability and reliability of substation communication topologies. But this is a generic approach that works with any electricity substation. Under Study: A Typical Substation The IEC 61850 categorized T1-1 substation configuration is depicted in Figure 6 [70]. This little substation has a single bus and is 220/132 kV.

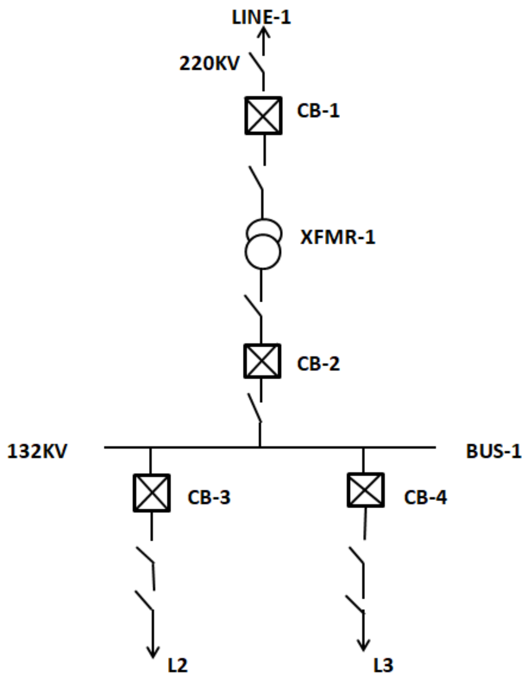


Figure 6. *T1-1 small transmission substation layout [71].*

Table 1 tabulates the IED configuration for the T1-1 substation. Five bays in total—three line bays, a transformer bay and a bus bay. While it is believed that every bay possesses redundant IEDs for protection (main-1 and main-2), the current practice states that the IED for bay control is not redundant. Owing to IEC 61850's planned flexibility in function allocation, control IEDs might be necessary even for bus bay control functions connected to any type of breaker. Based on distant I/O connections and CTs/VTs, the number of MU is calculated. The bus and transformer bays require AC signals from two to three sets of CTs/VTs, hence two MUs are taken into consideration for each bay. On the other hand, feeder bay will just need one MU.

Table 1. *IED Configuration for T1-1 Substation.*

Bay Name	Protection IED	Control. IED	MU
Line-1	2	1	1
XFMR-1	2	1	2
Bus-1	2	1	2
Line-2	2	1	1
Line-3	2	1	1

4.2. Reliability and Availability Calculations

While various methods of reliability analysis, including fault trees, cut sets, path sets, etc., have different formal presentations, they can all produce conclusions that are identical to those of reliability-based design (RBD) [72]. RBD is easier to understand and more preferred for both qualitative and quantitative evaluations; for these reasons, it is employed in this research. In this article, reliability has been expressed simply as MTTF. Table 2 tabulates the MTTF values for reliability calculations, which are taken from sources [73]. The fundamental premise is that the various failure modes operate independently of one another. Since the communication links' MTTF value is often sufficiently high, it is not taken into account in the computation [74]. The MTTF Further, utilising the 8-hour MTTR as a guide [75], The availability of each component has been determined and is displayed in Table 2.

Table 2. *Mttf Considered For Each SAS Components.*

SAS component	MTTF (in years)	Availability
Protection IED	150	0.999993912
Control IED	150	0.999993912
MU	150	0.999993912
Ethernet Switch	50	0.999981735
TS	150	0.999993912

In the subsections that follow, MTTF and availability for intra-bay and inter-bay topologies have been computed using these tabulated individual component values.

4.3. MTTF and Availability for Intra-Bay Communication

All bay IEDs are connected to the matching bay Ethernet switch, which is thought to have a single Ethernet switch per bay. Determining the availability of the communication components for a specific bay communication is the importance of reliability and availability calculations for intra-bay communication. Calculations for Line Bays: Since each line bay has the same number of IEDs, each line bay would be equally reliable and available. Thus, Figure 7 depicts the standard architecture for line bay. It is evident that each IED has a unique communication wire connecting it to an Ethernet switch. We call this type of arrangement "star topology."

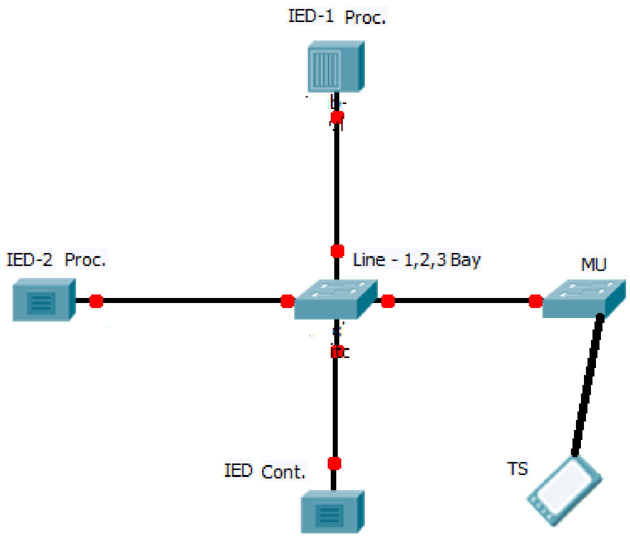


Figure 7. *Star topology for the line bays [76].*

Figure 8 displays the reliability block diagram for the line bays' star topology. Because all of the bays feature duplicate safeguards, as was previously mentioned, the two protective IEDs are displayed in simultaneously. Furthermore, the proper operation of every other bay component, including the Ethernet switch, merging unit, control IED, and time synchronisation, is required in addition to the protective IEDs. As a result, all of these parts are linked in series with IEDs for parallel protection.

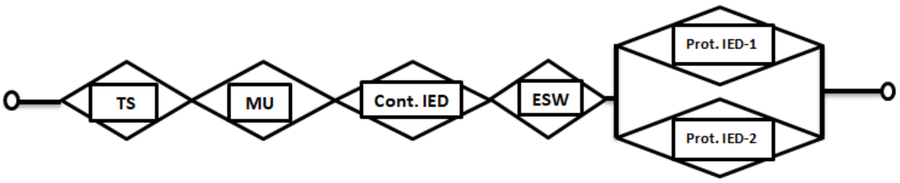


Figure 8. *RBD for the line bays.*

The MTTF and availability values for the RBD in Figure 8 can be calculated using series-parallel combination of the components.

MTTF’ protection = 225

A’ protection = 0.9999999

With these values, MTTF and availability of line bays can be calculated as follows:

$$\text{MTTF lime} = +\frac{1}{MTTF\ ts}+\frac{1}{MTTF\ mu}+\frac{1}{MTTF\ cnt}+\frac{1}{MTTF\ ews}+\frac{1}{MTTF\prime\ proct}$$

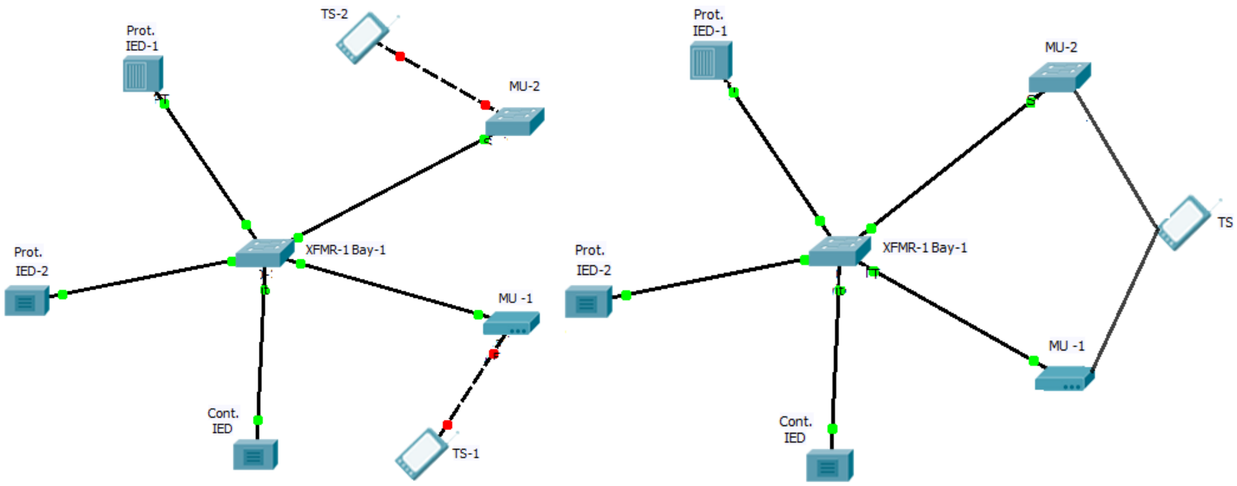
MTTF line = 22.5 years

Aline = Ats.Amu.Acnt.Aesw.A’proct

Aline = 0.9999634

XFMR-1 and Bus-1 bays calculations:

The two integration units in the transformer-1 and bus-1 bays can be connected to a single time synchronisation source (as shown in Figure 9(b)) or to two separate time synchronisation sources (as shown in Figure 9(a)).



(a) (b)

Figure 9. *Star architecture for (a) XFMR-1 and (b) Bus-1 bays.*

The reliability block diagram for MUs in series and two time synchronisation sources, as shown in Figure 10, would be the same for line bays in Figure 9(a). The reliability block diagram for Figure 9(b) would resemble Figure 10 quite a bit, with the exception that there would only be one TS in the first block rather than two in series. Results for the arrangement of Figure 9(b) are directly displayed in summary Table 3.

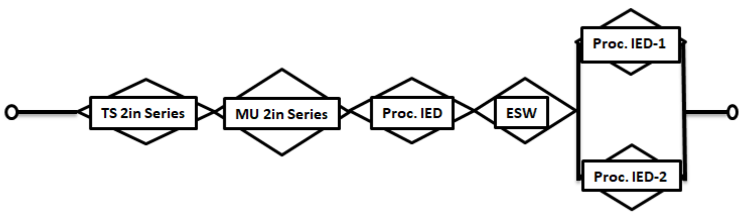


Figure 10. *RBD for XFMR-1 and Bus-1 bays, MTTF and availability for two series time synchronization sources and MUs are calculated using series combination of the components.*

MTTF’ TS = MTTF’ MU = 75 years
A’ TS = A’ MU = 0.9999878

$$\text{MTTF' XFMR} = \frac{1}{MTTF\ ts} + \frac{1}{MTTF\ mu} + \frac{1}{MTTF\ cnt} + \frac{1}{MTTF\ ews} + \frac{1}{MTTF'\ proct}$$

MTTF’ XFMR = 19.57 years
A’ TFMR = A’ ts.A’ mu.Acnt.A esw.A’proct
MTTF’ XFMR = 0.9999513

The MTTF and availability for intra-bay communication are compiled in Table 3. Due to extra MU, transformer-1 and bus-1 bays are noted to have worse MTTF and availability when compared to line bays. However, as shown in Figure 9(b), availability and reliability increase when both MUs in a bay are synchronised via a single TS. Separate TS has been taken into consideration for additional analysis in order to compute the reliability index for the worst case.

Table 3. *Mttf and Availability of Intra-Bay Communication.*

Bay Name	MTTF (years)	Availability
Line-1		
Line-2	22.5	0.9999634
Line-3		
XFMR-1 (separate TS)	17.307	0.9999513
Bus-1 (separate TS)		
XFMR-1 (single TS)	19.57	0.9999573
Bus-1 (single TS)		

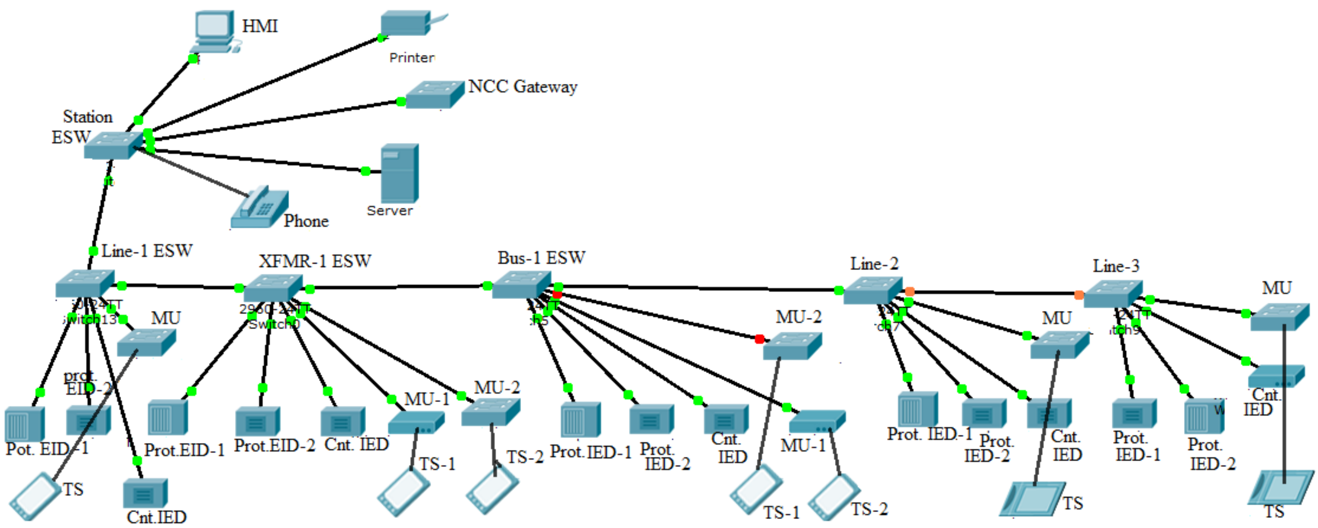


Figure 11. *Cascaded architecture [77].*

D. MTTF and Availability for Inter-Bay Communication: For the inter-bay communication reliability and availability calculations, a total of four realistic SAS communication designs are taken into consideration. It is noteworthy that the availability and dependability of any inter-bay communication link between any two IEDs are computed in this section. Finding the availability and dependability of the communication components for inter-bay communication between any two bays is the significance of this investigation. The entire set of reliability block illustrations was constructed with one control IED in one bay and one protection IED in another. However, the method can also be used to measure any two IEDs from any bay, and the findings would remain the same. The six Ethernet switches in the cascaded architectures are linked in a chain with an open loop topology as demonstrated in Figure 11.

Figure 12 displays the cascaded architecture reliability block diagram. It demonstrates the dependability of the data transmission link between two extreme end IEDs for control and protection (worst case scenario). Due to the requirement for all Ethernet network switches in this architecture to function, the diagram displays all of the components connected in series. Additionally, the two protective IEDs will be connected in series with their matching Ethernet switches.

Figure 12. *RBD for cascaded architecture.*

The following is how to obtain MTTF and availability: Cascaded MTTF is 8.82 years. A slipped to 0.9999330 Ring architecture: As seen in Figure 13 [9], ring architecture connects all six controlled Ethernet switches in a single loop.

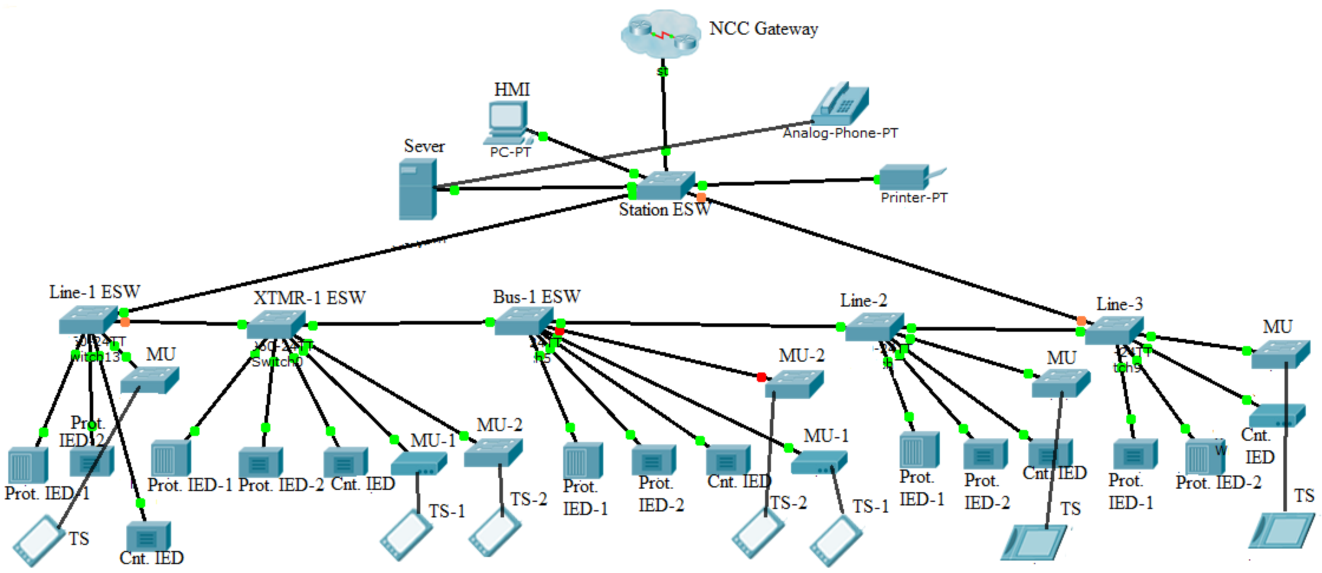


Figure 13. *Ring architecture connecting switches.*

Compared to cascaded design, the RBD of a ring data communication network would be more diversified. As seen in Figure 14, just three of the four Ethernet switches are now needed for inter-bay data transfer, as opposed to the four devices being connected in series. By implementing RSTP into the managed Ethernet switches, this n-1 redundancy is accomplished. In the event that several switches or an Ethernet communication cable connection fails, the data communication network can be reexamined.

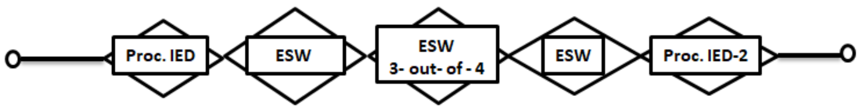


Figure 14. *RBD for ring architecture.*

The following methods can be used to find the ring architecture's availability and MTTF: 12.17 years is the MTTF ring. A ring is equal to 0.9999513. Star-ring architecture: Two more redundant Ethernet switches connected in a ring are needed for star-ring architecture, as seen in Figure 15. The remaining six switches will be connected in a star configuration to both of these Ethernet switches.

The star-ring architectural dependability diagram is displayed in Figure 16. Every bay Ethernet switch is directly connected to both the primary and backup Ethernet switches, as shown in Figure Thus, it is recommended to link the two Ethernet switches in parallel.

The following can be used to calculate MTTF and the availability of star-ring architecture using the series-parallel combinations from the Appendix: Star-ring MTTF = 15 years. Ring – star = 0.9999513. The data above show that, in comparison to ring design, star-ring architecture offers better MTTF but not availability. This is because there are comparable options for three out of four Ethernet switches and two parallel Ethernet switches. Redundant-ring construction:

Every SAS IED is connected to both redundant ring configurations, as seen in Figure 17 [79]. Additionally, four Ethernet switches coupled in a ring architecture connect these redundant rings.

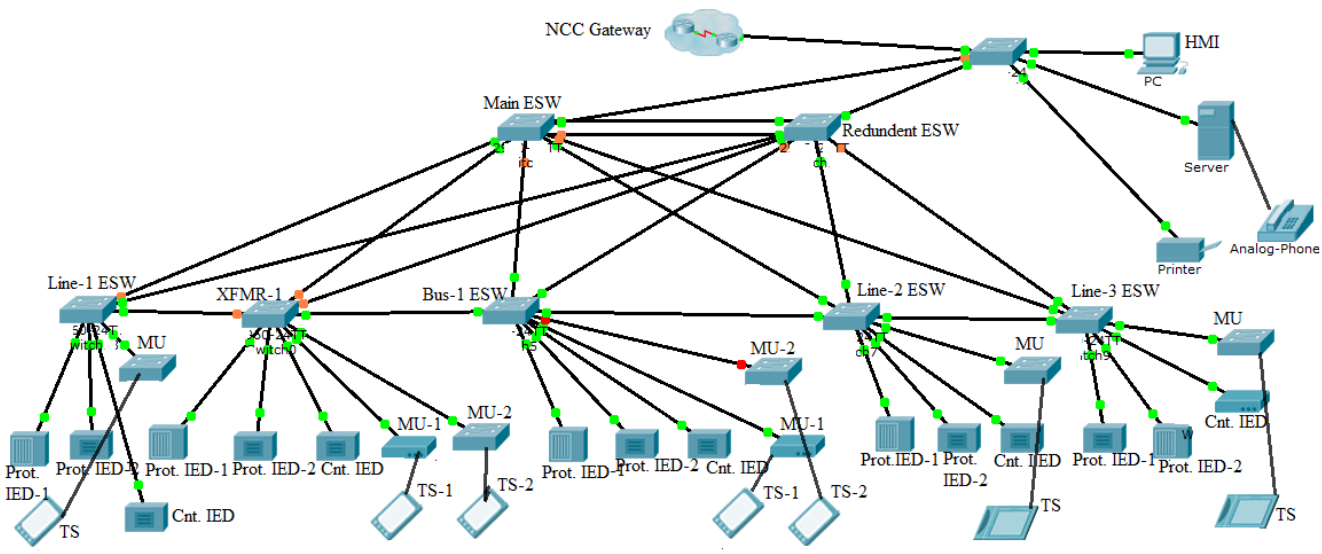


Figure 15. *Star-ring architecture [78].*

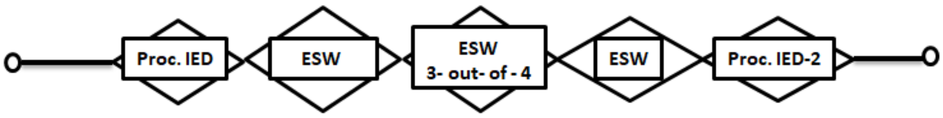


Figure 16. *RBD for star-ring architecture.*

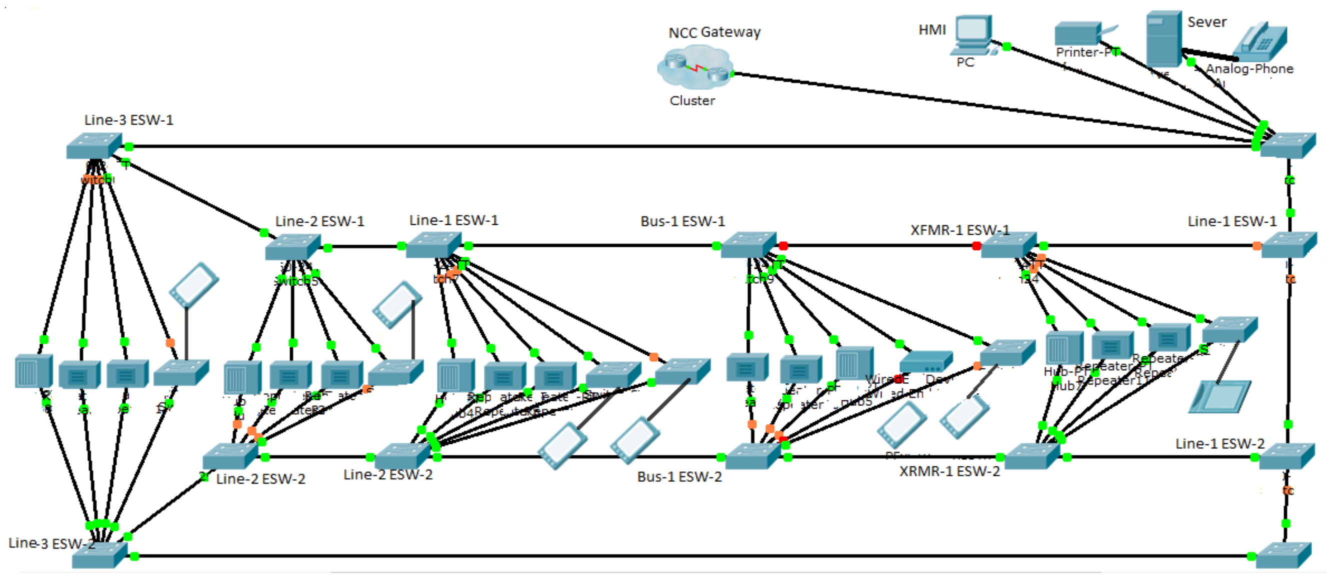


Figure 17. *Redundant-ring construction [79].*

Figure 18 shows the reliability block diagram for the redundant-ring architecture. The image shows that all of the IEDs are connected to two redundant Ethernet switches; as a result, the ESW components for both protective IEDs would be in parallel. Additionally, it is evident that every IED is linked to two redundant ring configurations; therefore, it is necessary to connect both ring configurations in tandem.

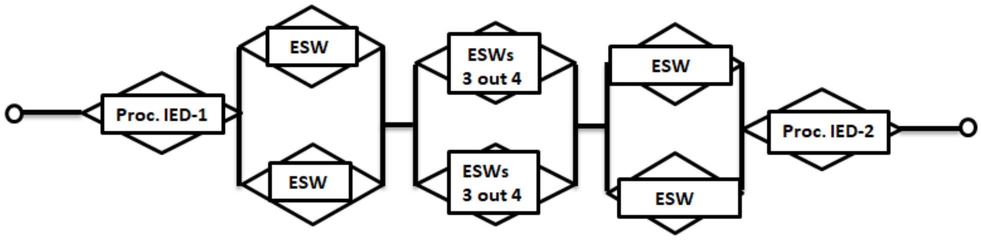


Figure 18. *RBD for redundant-ring architecture.*

The following formula can be used to calculate the series-parallel combinations from the Appendix, MTTF, and availability of redundant ring architecture: Repetitive MTTF ring = 16.89 years A superfluous ring: 0.9999878 The MTTF and availability computed values for each of the four realistic architectures are compiled in Table 4.

Table 4. *Mttf and Availability of Inter-Bay Communication Architectures.*

Communication Architecture	MTTF (years)	Availability
Cascaded	8.82	0.9999330
Ring	12.17	0.9999513
Star-ring	15	0.9999513
Redundant-ring	16.89	0.9999878

Table 4 shows that while cascaded design offers the lowest MTTF (8.82 years) and availability (0.9999330), it is also the least complex and costly configuration. The availability (0.9999513) and MTTF (12.17 years) are enhanced by ring architecture. However, a RSTP-managed Ethernet switch is necessary for ring design. Additionally, star-ring architecture uses two extra Ethernet switches to provide a greater MTTF (15 years). Lastly, redundant-ring architecture has demonstrated gains in availability (0.9999878) and MTTF (16.89 years). However, this architecture necessitates 8 more switches for a T1-1 small transmission substation, and the number of required switches may increase as the substation grows. It is evident that the ring architecture's MTTF in reference [78] is equivalent to the 12.17 years in this paper, at 12.9 years. Nevertheless, the literature lacks availability and reliability studies for the more intricate real-world Ethernet structures, as the redundant ring and star-ring designs suggested in reference [79].

5. Conclusion

From a reliability perspective, several workable Ethernet designs for SAS based on IEC 61850 have been discussed. Reliability block diagram approaches have been used to calculate availability and MTTFs for intra-bay communications in the T1-1 transmission substation. It has been discovered that the MTTF and bay availability are impacted by the inclusion of a merging unit with a time synchronization source. Furthermore, actual Ethernet switch topologies like cascading, ring, star-ring, and redundant ring have been shown to utilize reliability block diagrams. MTTF, availability, and extra component requirements have been used to compare various architectures. Compared to cascaded and ring design, it has been discovered that star-ring and redundant ring architecture offer higher dependability and availability. But these architectures are expensive and complicated because it necessitates more Ethernet switches. When choosing a fit-for-purpose architecture, it is advised to take into account network performance factors including latency, throughput, and cost in addition to availability and dependability. Based on component failure modes, this study discusses communication network availability and dependability. This task can be further expanded by taking into account catastrophic occurrences that have the potential to impact a significant percentage or the entire communication network, as well as by assessing the dependability of protection services.

Abbreviations

IEC	International Electro-Technical Commission
RED	Reliability Block Diagram
SAS	Substation Automation Systems
LAN	Local Area Network
WAN	Wide Area Network
SCADA	Supervisory Control & Data Acquisition
BMI	Body Mass Index
LPWANs	Low-Power Wide-Area Networks
WPANs	Wireless Personal-Area Networks
ATMs	Automated Teller Machines
FDDI	Fiber Distributed Data Interface
IEDs	Intelligent Electronic Devices
SA	Substation Automation
FTA	Fault Tree Analysis

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Conflicts of Interest

The authors declare no conflicts of interest.

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