IEC 61850 Substation Communication Network Performance & Reliability Assessment Based on Network Real Time Operating Data

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***Abstract*—The optimal performance of power grid depends on many factors, and one of which is the reliability of the substation communication network. These substation communication networks are required for real time monitoring and control of the power grid. Power grid operators are always eager to know the behavior of the substation communication network to enable the operators perform real time monitoring and control function of the power grid through the communication network. Substation communication network historical data and real time operating data are vital requirements for effective design of a robust and reliable communication network. These communication networks historical data are also required for predicting future performance of the grid network. This paper has demonstrated the successful use of communication network collected data (that is historical data) to determine the reliability and performance of an IEC 61850 substation communication network. The key findings of this study are that increased data rate of an IEC 61850 based communication network, reduces the network latency and the implementation of network redundancy scheme improved the network reliability. Also, increased data rate and implementation of network redundancy scheme improved the derived communication network reliability averagely by 3.8% over fifteen years period. The derived communication network improved reliability was also found to meets the IEC 61850 transfer time requirements required for performing substation protection, monitoring and control functions.**

Keywords*— *Failure Rate (f(t)), IEC 61850, Parallel Redundant Protocol (PRP), Mean Time Between Failure (MTBF) and Reliability.

I. INTRODUCTION

Communication network operational data are required for analyzing and simulating communication network to quantitatively evaluate and predict the reliability and performance of the communication network. Substation communication network technology is evolving and understanding the network components Mean Time To Failure (MTTF) and Average (Mean) Time Between Failure (MTBF) are very critical and key to analyzing the communication network devices reliability.

Typical substation communication network consists of networking devices that are usually designed with semiconductor with failure rate ranging from 10^{-10} to 10^{-7} h^{-1}. Failure of these semiconductors usually occur at the early stage of the network operational life and the chances of failure of these networking devices are relatively very low once normalized [1], thus using these devices historical and operational data to determine the network performance and reliability tends to lead to more consistent results.

Communication networks data are rapidly generated in various ways that could lead to significant large substation data generation per hour. These networks generated data play critical role in performing monitoring and control of power grid network that improve the performance of the power grid network. Monitoring and control of distributed networks helps the network operators understand the real time behavior of the network, thus easing network operator's ability to manage the network [2].

An IEC 61850 based communication network typically demands for higher reliability and availability to ease the protection, monitoring and control functions of the substation. The Parallel Redundancy Protocol (PRP) scheme as defined in IEC 62439-3 standard, provides high-availability in Ethernet networks. Parallel Redundancy Protocol is responsible for replicating/discarding function and does not show any period of unavailability. PRP implements its redundancy functions in the end nodes attached to two similar and identical disjointed LANs that are operated in parallel [3]. Each data frame is replicated on the sending node, transmitted over the redundant network channel and the receiving node is able to discard the duplicated data. The PRP schemes are essentially designed for substation automation application, to allow duplication of communication network data simultaneously over uncorrelated (stochastically independent) channel to achieve communication network redundancy that enhance the reliability of the network [4].

The success of any Substation Automation System (SAS) depends upon successful interoperability of all intelligent devices connected to the substation communication network [5], implementation of network redundancy scheme through PRP and the effective design of communication network [6], [7]. The performance of SAS communication network depends on different network characteristics, including network latency and network bandwidth utilization [8]. Hence, it is very important to ensure that all Ethernet networking devices used in establishing an IEC 61850 based communication network in an SAS is capable of sending/receiving protection, monitoring and control messages (signals) within the allowable IEC 61850 transmitting/receiving period of time [9].

II. Network Setup

The experimental setup for this study consists of a dual station bus connecting Intelligent Electronic Devices (IEDs), data concentrator (or Remote Terminal Unit (RTU)), station controller and a GPS time clock source.

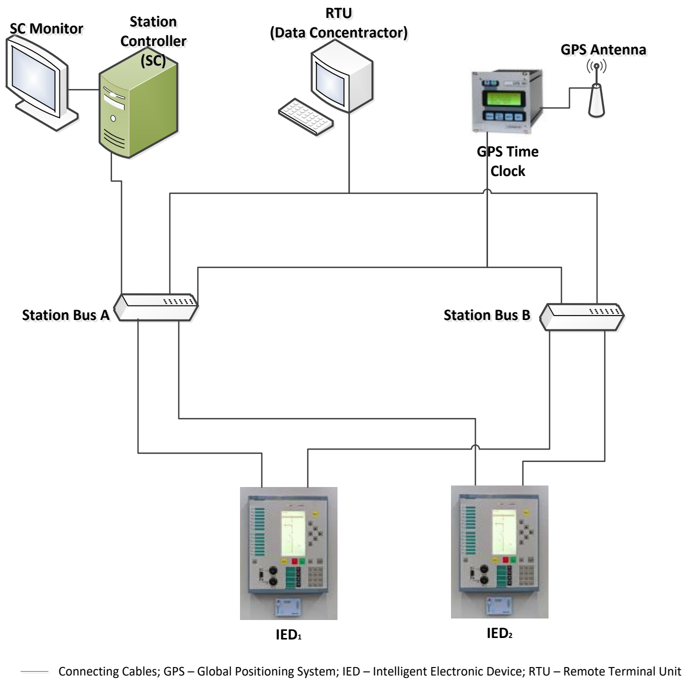

Figure 1: IEC 61850 Based Communication Network – Experimental Setup

The derived network is configured such that the failure domain encompasses section of the network that is negatively affected when a specific device or the entire network service experiences any failure. The connected station bus and IEDs interface are locked down, configured and their respective sharing and control mechanism setup accordingly. A Simple Network Management Protocol (SNMP) installed on the station controller was used to continually monitor and interrogate the network performance periodically, collecting and reporting all network data based on the network defined fault conditions. The GPS time clock source with an accuracy of approximately 500µsec was used to provide a means to precisely synchronize all connected devices within the station bus [10]. The use of Ethernet switched technology with quality of service features allows efficient use of the network available bandwidth and minimizing any potential delays through segregating and prioritizing the network traffic [11].

The network time-stamped failure events log data were classified as either 'Major Failure' (MF^A) or 'Minor Failure' (MF^I). All MF^A were considered to be due to a 'Single Point of Failure (SPOF))' of the derived network, and its occurrence will cause the entire network to completely fail, and totally compromise the entire network reliability. All MF^I are failures that could possibly occur within the network, but their occurrence does not compromise the entire network reliability due to the implemented redundancy scheme at each level of the derived network. In this study, three sources of MF^I were considered and they are;

1 Minor Failure (MF^I_B) due to Poor Data Quality.
2 Minor Failure (MF^I_C) due to Interface Malfunction.
3 Minor Failure (MF^I_D) due to Latency and Device Reboot mainly.

III. Network Testing

Communication network testing are activities undertaken to characterize the operation of the networks and the network associated elements in order to obtained relevant information about the network quality and capability. The network configuration test dataset was based on the IEC 61850-5 and the IEC 61850-90-4 application guides.

The aim of the network testing is to provide quantitative indications that confirmed IEDs ability to publish GOOSE messages, when a change in event takes place in the substation, and also subscribe to them [12], [13] as shown in Figure 2. The setup network was tested to:

1 Proper publishing and subscription of GOOSE messages.
2 Validate network transmit, transfer and transmission time.
3 Verify that all published GOOSE messages are getting to the desired destination.
4 Verify the impact of failure, latency and network reconfiguration on the network.

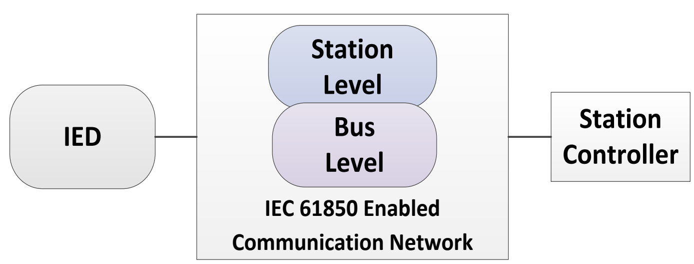

Figure 2: Network Configuration Verification

The station controller and the network configuration monitor' directly connected to station bus Ethernet port were configured to allow passage of all received traffic. The network GPS time clock provides the precise time synchronization to the all network connected devices and the intelligent device publishes set of unique and verifiable GOOSE signal messages into the network. The test shows that the network configuration tester successfully published verifiable GOOSE message to the network, the subscribers successfully received the published GOOSE message in a very timely manner and all information successfully displayed on the station controller. Table I presents a summary of the network verification result that shows that the network is active at the ports switching time.

TABLE I. NETWORK CONFIGURATION VERIFICATION

Test Parameter	Verification Test Result
GOOSE message published	Yes
$GPS_{TIMESERVER}$ setting and the time synchronization on all connected devices ok	Yes
HV apparatus symbols in different condition	Yes
SAS main application start-up ok	Yes
Comments from clicking optional requirements 'Accepted'	Yes

The station controller shows that the derived communication network correctly segregates the traffic and only permits GOOSE signal messages that match the required configuration.

A. Network Fault Modeling

Fault tree and Reliability Block Diagram (RBD) based models are often used to provide reliability and availability estimates for both early and later stages of network design, where the network models are more refined and have more detailed specifications. Markov chain based models are mainly used in the later design phase to perform trade-off analysis among different design alternatives when detailed specification of network design becomes available [14]. Network fault assessment techniques including the top–down modeling technique can be utilized during the design phase of a communication network to aid the analysis of the network performance [15].

This top–down modeling approach, which displays the interrelations between different components that could cause the network to fail, was used in modeling the derived network fault. The fault modeling accounts for four different sources of network failures [16] that are classified into two failure modes (that is contributory events called the MF^A and the MF^I) and modeled through logic gates. The MF^A occurrence will completely compromise the network availability, while the MF^I occurrence will only compromise a specific component or sub-section of the network.

The network associated logic is designed such that, the occurrence of either MF^A event or Intermediate Event (IE) (including Poor Data Quality, Interface Malfunction, Latency and Device Reboot) that would potentially lead to the communication network Terminal Event (TE). The IE is assumed to have occurred whenever all defined minor failure sources has occurred. The logic gates interconnect the contributory events and the defined failure conditions. Figure 3 presents illustration of the network fault tree logic model, where:

TE = Terminal Event

IE = Intermediate Event

A = Major Failure ($MF^A{}_A$): A occurs due to SPOF of the network.

B = Minor Failure ($MF^I{}_B$): B occurs due to Poor Data Quality

C = Minor Failure ($MF^I{}_C$): C occurs due to Interface Malfunction.

D = Minor Failure ($MF^I{}_D$): D occurs due to Latency and Device Reboot.

Also, the implemented network redundant scheme is assumed to be capable of limiting failure of any particular subcomponent of the network, thus the network associated logic is designed such that, the entire network failure occurs only when MF_A has occurred. The probability of the derived network failure is given as:

$$P(TE) = [P(MF^A{}_A) + P(IE)] - [P(MF^A{}_A)P(IE)] \quad (1)$$

$$P(IE) = P(MF^I{}_B)P(MF^I{}_C)P(MF^I{}_D) \quad (2)$$

Therefore,

$$P(TE) = [P(MF^A{}_A) + P(MF^I{}_B)P(MF^I{}_C)P(MF^I{}_D)] - [P(MF^A{}_A)P(MF^I{}_B)P(MF^I{}_C)P(MF^I{}_D)] \quad (3)$$

where;

P(IE) = Probability of failure of the intermediate node.

$P(MF^A{}_A)$; $P(MF^I{}_B)$; $P(MF^I{}_C)$ and $P(MF^I{}_D)$ are the contributory (basic) events probability.

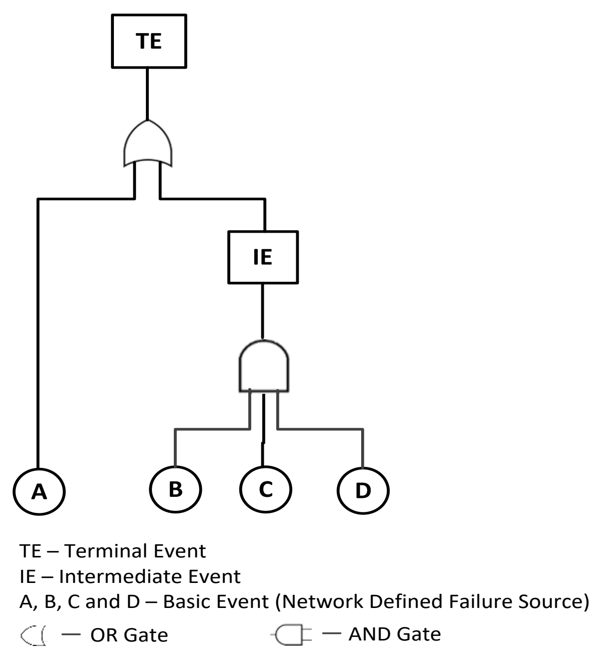

Figure 3: Derived Network Fault Tree Modeling

IV. NETWORK RESULT AND DISCUSSION

The setup network was operated and monitored continuously for 4392 hours (1st April to 30 September, 2019). The network component time stamped events log data that was based on the defined cause of failures within the 4392 hours of continuous operation were collected and used to analyze the derived network reliability and performance.

A. Network Performance

Network bandwidth utilization was carefully considered during the design and configuration of the communication network to know the data size at any time and optimize the network. The performance analyses of the derived communication network were mainly on the interacting component variables (that is packet delay and packet loss). The derived communication network was configured such that the network data rates, which is an important performance metric used in evaluating networking devices performances, are supported by the IEEE 802.11 standard and all protocols meets the IEC 61850 requirements.

Another concern for any SAS communication network is latency and the requirements for message latency is usually application dependent. The most critical, which is for a teleprotection circuit is typically less than 5 ms or within 5 to 8 ms (IEC 60834-1). The IEC 61850-5 standard as shown in Figure 4, defined the data transfer time and the transit time for a typical substation communication network to includes the time it takes for the message to travel through the communications network.

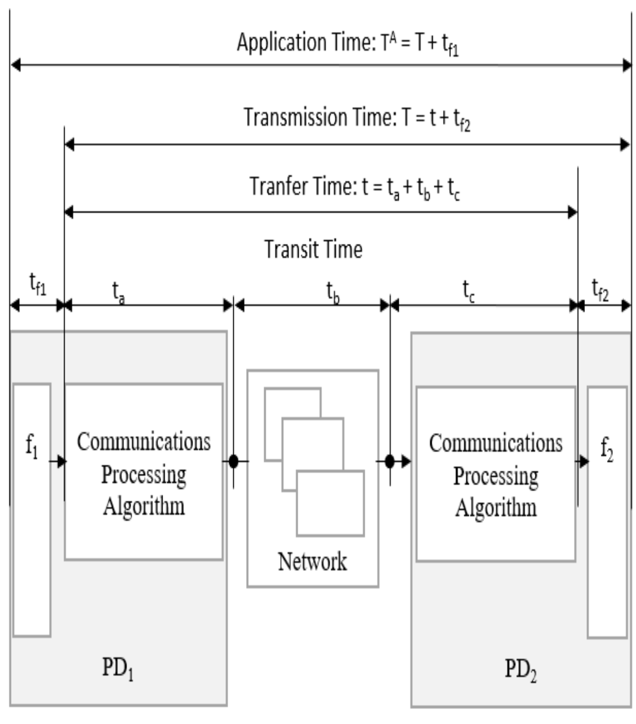

Figure 4: IEC 61850-5 Application, Transmission, Transfer and Transit Time Framework

The maximum allowable Transfer Time and the applicable protocol as per the IEC 61850-5 recommendations as shown in Table II, shows that the trips and blocking (TT_6) application function only permits 3ms latency. The derived network failures were therefore defined by the absence of message at the receiving end and a delay in delivery greater than the defined IEC 61850 acceptable limits [8].

TABLE II. IEC 61850 TRANSFER TIME REQUIREMENT

Transfer Time Class	Transfer Time (ms)	Application Example
TT_0	> 1,000	Files, Events & Log Contents
TT_1	1,000	Events & Alarms
TT_2	500	Operator Commands
TT_3	100	Slow Automation Interactions
TT_4	20	Fast Automation Interactions
TT_5	10	Releases & Status Changes
TT_6	3	Trips & Blockings

The estimated latency of the derived network that was configured as per the IEC 61850-5 traffic recommendations was compared to the IEC-61850-5 recommended ratings for validation purposes. Also, the derived communication network was configured using data usage rates of 10 Mbps and 100 Mbps to ensure that the IEC 61850 fast response time requirements including IED to IED interlocking recovering time of 4ms, IED to IED reserve blocking recovering time of 4ms etc., of a typical SAS are met.

The station bus data rates were analyzed independently to determine the expected performance of the network and the impact of the station bus data rate on latency. The result is summarized in Table III and it is believed that the quality of the networking devices and the network congestion might have contributed to the possible cause of packet losses. It can be observed from Table III that increased data rate reduces the latency, but it is very important to note that both data rates (i.e. 10 Mbps and 100 Mbps) met the IEC transfer time standard requirement. Thus a higher data rate (that is 100 Mbps) was used for the network configuration, to optimize the network latency time and packet loss.

TABLE III. STATION BUS DATA RATE

Devices	Data Rate (Mbps)	Latency (ms)	
		Average	*Max*
Station Bus (SB_A)	10	0.141	0.205
	100	0.121	0.154
Station Bus (SB_B)	10	0.158	0.220
	100	0.129	0.16

B. Network Reliability

The network components' time between failures, which is the time that a specific network component functions before failing are critical data that can be derived from the network real time data. The network components estimated MTBF were based on the hourly collected data with the pre-defined failure conditions (that is MF^A and MF^I) for 4,392 hours of continuous operations and the result is summarized in Table IV. The derived communication network individual component average time between failure analysis is very critical because it helps in predicting the expected time when each component or subset of the network component spare is required.

TABLE IV. NETWORK COMPONENTS MTBF

Communication Networking Device Mean Time Between Failure (Hrs)		
Station Bus (SB_A)	***Station Bus (SB_B)***	***Data Concentrator (RTU)***
1038	1159	1392

Studies have shown that there is cross correlation between the network components failure rate, network redundancy and network reliability. These parameters can be graphically characterized and used to represent a given population density [17]. Thus, the network historical failure rate and network redundancy correlated values were used to estimate the reliability of the derived network.

After normalizing the network, the observed hourly failure rate data based on the defined cause of failure for the defined consecutive period of continuous operation were used to specify the likelihood function for the derived network.
The communication network reliability was estimated considering the series and parallel connections between all connected devices within the network using Equations (4) and (5), and the assumed underlying failure distribution as given in Equations (8).

$$R_{SS}(\mathrm{t}) = \prod_{i=0}^{n} R_i(t) \tag{4}$$

$$R_{Sp}(\mathrm{t}) = 1 - (\prod_{i=0}^{n}(1 - R_i(t)) \tag{5}$$

where $R_{SS}(\mathrm{t})$and $R_{SP}(\mathrm{t})$ denote the reliability of series connected and parallel connected networks [1], [18].

For the defined population density of the network, all network components were assumed to begin operating continuously at the same time t = 0. The time variable t represents the hours of operation of each individual component. The cumulative failure distribution, is such that the expected number of failures of the network (f(t)) at time t for n components is given as:

$$\mathrm{f(t)} = \left(1 - \left(e^{-(t/\alpha)^{\beta}}\right)\right)n \tag{6}$$

$$In\left(In\left(\frac{1}{1-\left(\frac{f(t)}{n}\right)}\right)\right) = \beta In(t) - \beta In(\alpha) \tag{7}$$

Table V presents the summary of the network estimated β and α data based on 4392 hours of continuous operations for each network device. These data were used in predicting the network reliability at the network assumed end of life.

TABLE V. NETWORK DERIVED β & α DATA

Network Devices	β	∝ (Hrs)
Station Bus (SB_A)	0.736	1113
Station Bus (SB_B)	1.235	1037
Data Concentrator	1.387	1217

The simplified reliability based on Table V derived α and β cumulative failure distribution is given as:

$$\mathrm{R(t)} = e^{-\left(\frac{t}{\alpha}\right)\beta} \tag{8}$$

The expected network reliability at the end of the network designed life as presented in Figure 5, shows that for 24/7 continuous operation, the network estimated reliability is approximately 0.99999 at the first year, an estimated reliability of approximately 0.9998 at the fifth year and an estimated reliability of approximately 0.998 at the end of the network expected designed life (that is fifteen years). The derived network is therefore expected to experience an average partial downtime of approximately 465 minutes per year, but without compromising the network reliability due to the applied network redundancy scheme. The derived network applied redundancy scheme helps the network to recover quickly when the network experiences any minor failure, thus preventing the network from complete failure and mitigating against potential loss of protection, monitoring and control signals (data).

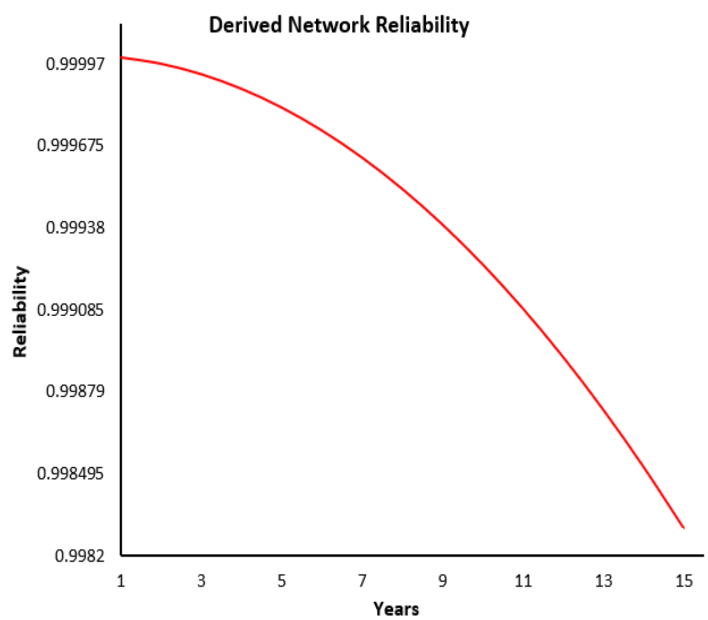

Figure 5: Derived Communication Network Reliability

The derived network improved reliability as shown in Figure 6, shows that the derived network reliability improvement in the first few years is relatively low as expected (that is, it's expected that within the first five years of continuous operations, the network reliability improvement will be approximately 1% averagely, since the network reliability within this time interval is relatively high). Also Figure 6 has shown that between the 6th – 15th year of continuous operation, the derived network reliability will improve significantly by approximately 5%, averagely because of the derived network implemented redundancy scheme, which helps the network to recover from network failures easily.

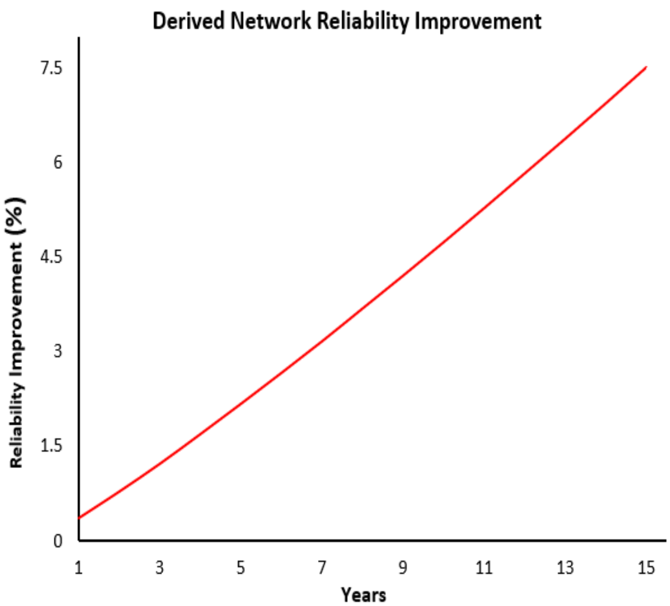

Figure 6: Derived Network Reliability Improvement

V. Conclusion

Substation communication network has become a key aspect of modern power grid due to the increasing demand for reliable power. This increasing demand for reliable power services requires the deployment of robust and reliable IEC 61850 based communication networks that are capable of exchanging real time sensitive data for protection, monitoring and control of the power grid. IEC 61850 based Substation communication network reliability analysis is gradually gaining industrial awareness and it requires both practical experiences and theoretical knowledge to effectively analyze the network performance and reliability.

This paper has presented an IEC 61850 based communication network reliability and performance analysis. The analyzed network is expected to play an important role in providing the desired reliable and robust communication network for power grid monitoring, control and protection functions. Also, this paper has compared the proposed network reliability with a non-redundant network, discussed the network reliability the network improved reliability and the performance of the network.

This paper has also demonstrated how the derived communication network latency conforms to the IEC 61850 transfer time requirements. The paper has also found that the derived network has an estimated average reliability of 0.9995% over the network expected designed life while operating continuously and has an average improved reliability of approximately 3.8% due to the implemented network redundancy scheme.

The analysis presented in this paper has also shown that PRP redundancy scheme helps communication network recover from a potential network failure, mitigate against potential loss of protection, monitoring and control signals (data) and provision for a very high network availability required to perform the necessary protection, monitoring and control function of the substation.

In addition, this paper has demonstrated the successful use of networking devices real time collected operational data to determine the reliability and the performance of an IEC 61850 substation communication network was validated.

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