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Reliability Analysis of IEC 61850 Substation Communication Network Architectures

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Abstract—*The paper investigates the reliability of IEC 61850 Substation Automation Systems (SAS). To study the impact of Substation Communication Networks (SCN) on the reliability indices of a substation protection function, the detailed reliability modeling and analysis is carried out based on Reliability Block Diagram (RBD) approach. The paper presents the reliability analysis of various SCN architectures, considering the IEEE/PSRC (Power System Relaying Committee) suggested traditional Ethernet switched networks, e.g. cascade, star, ring, star-ring, redundant-ring SCN architectures.*

1. INTRODUCTION

The inherent reliability of protection function presents a significant problem in designing Ethernet communication based IEC 61850 protection systems in substations. IEC 61850-3 standard [1] refers IEC 60870-4 standard [2] for the details of reliability requirements, and states that there should be no single point of failure which can cause the substation to be inoperable. Thus, the reliability evaluation of the Substation Communication Network (SCN) architectures is important to evaluate their impact on the protection function reliability indices.

The Reliability Block Diagram (RBD) approach ,as discussed in [3], is one of the most widely used method in SAS reliability assessments among the various available techniques such as Markov model, fault tree, minimal cut set and minimal tie-set methods. Safety related availability of an interlocking function in IEC 61850 based Substation Automation System (SAS) was analyzed using a 3-state Markov model in [4]. References [5-6] presented the reliability assessment of protections systems using fault tree method; whereas, L. Castro Ferreira *et al.* [7] analyzed reliability of protection and control systems using event-tree method. H. Hajian-Hoseinabadi investigated the reliability of SASs in conventional Ethernet network configurations based on 'Tie-Set' approach [8]. The reliability and availability analysis using the RBD method are explained in the literature. References [9-12] presented the impact of process bus Ethernet networks on the reliability and availability of protection system using a preliminary RBD. T.S.sidhu *et al.* [13] also used RBD technique, to evaluate the reliability and availability of SCNs in conventional Ethernet network configurations for T1-1 type substation. Hangtian *et al.* [14] have presented a novel methodology for reliability modeling and analysis of IEC 61850 based substation protection systems. Hoseiabadi [15] presented the quantitative evaluation of reliability for SAS.

Although, the reliability analyses based on these techniques have different formal presentations, they all may give similar results as RBD. The RBD method, which is simpler and easy to implement, can effectively be used to compare the relative reliability of SCNs from simple to complex configurations, and hence it is used in this paper.

The paper presented a reliability analysis of IEC 61850 SCN architectures in standard Ethernet network configurations. In SCN, substation and Ethernet communication devices can be connected in various combinations using Ethernet switched LAN. The comparison of all these SCN architectures is carried out using a sample 220/132 kV electric power substation layout [16]. The quantitative values of reliability and MTTF for these different SAS architectures are obtained using the RBD technique.

The rest of the paper is organized as follows. Section II provides a brief overview of RBD technique for reliability assessment. Section III discusses the RBDs for standard practical Ethernet network architectures. Section IV presented the system reliability equations. Reliability results are presented in Section V. Finally, Section VI concludes this paper.

2. RELIABILITY BLOCK DIAGRAM APPROACH

According to RBD method, the reliability calculation of IEC 61850 SAS application involves the construction and analysis of an RBD, as shown in Fig. 1 that shows the logical relationship among the substation components in terms of a successful SCN. The SAS components are arranged in series and parallel arrangements between the system input and output nodes needed to realize a protection function successfully.

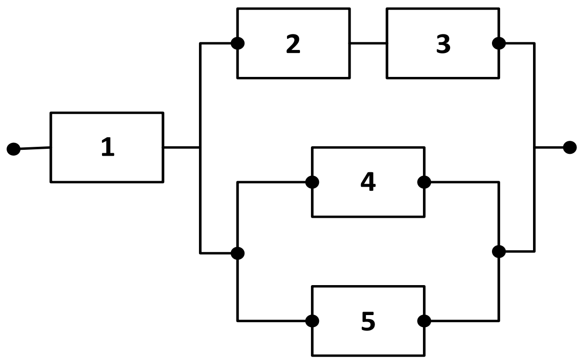

Fig. 1: Relaibility block diagram

The vital components required to perform the protection function effectively are put in series, while the redundant components are put in parallel, where at least one component must function for the protection system to perform. Fig. 2 shows the typical failure rate function of electronic components, which is also referred to as bathtub curve [3]. It can be observed that during normal operation or useful life (region-II), the failure rate function remains constant. Failure rate is the measure of the rate at which failure occurs. This is true for most of the modern SCN architectural devices such as Non-Conventional Instrument Transformer (NCIT), Merging Unit (MU), Protection & Control IED (P&C IED), Circuit Breaker IED (CB_IED), Ethernet Switch (ES), and Time Synchronization source (TS) which are based on electronic components [12-13].

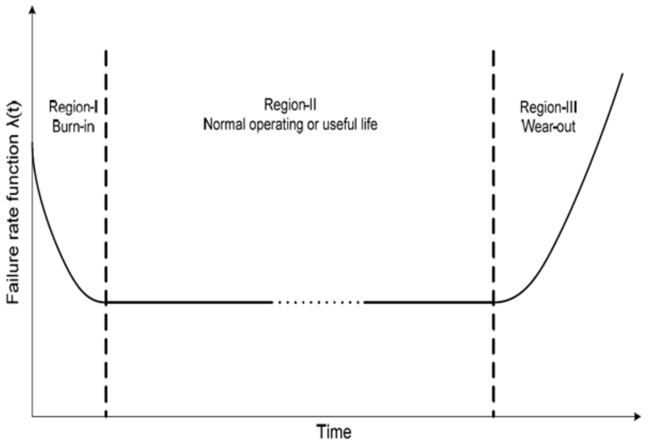

Fig. 2. Failure-rate function of substation components

Hence, Poisson or exponential distribution is valid for the reliability and availability analysis of SAS components, as the failure rate remains constant during normal operating period (region-II). Since the failure rate of components 'i' is constant, the reliability function of SAS components, for exponential distribution, is expressed as in (1)

$$R_i(t)=\exp(-\lambda_i t) \tag{1}$$

Where, 't' is the mission time and 'λ' is the component (i) failure rate.

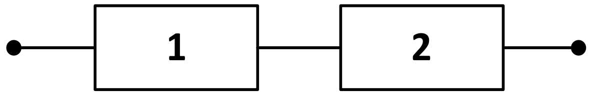

Fig. 3: Series system with two components.

The reliability of a series system, $R_s(t)$, as shown in Fig. 3, is given by (2). Here it is assumed that the reliability of individual components is independent of each other.

$$R_s(t)=\prod_{i=1}^{n} R_i(t)= \exp\left[-\left(\sum_{i=1}^{n}\lambda_i\right)t\right] \tag{2}$$

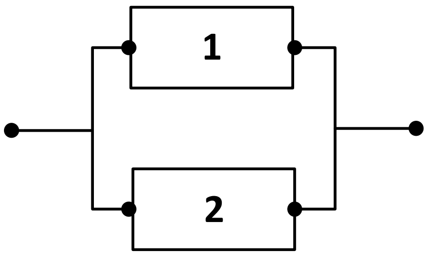

Fig. 4: Parallel system with two components.

$$R_p(t)=1-\prod_{i=1}^{n} Q_i(t) \tag{3}$$

Similarly, the reliability of a parallel system, as shown in Fig. 4, $R_p(t)$ is given by (3).

Where, $Q_i(t)=1-\exp[-\lambda_i(t)]$ and represents the unreliability of ith component. The system unreliability is thus given by (4)

$$Q_{sys}(t)=1-R_{sys}(t) \tag{4}$$

Reliability can be represented as Mean-Time-to-Failure (MTTF) of a system, which is the average time between system breakdowns or loss of service is given by (5).

$$MTTF_{sys}=\int_0^\infty R_{sys}(t)dt \tag{5}$$

The MTTF of the series system is defined in (6)

$$MTTF_s=\int_0^\infty R_s(t)dt=\frac{1}{\lambda_1+\lambda_2}=\frac{MTTF_1 \,.\, MTTF_2}{MTTF_1+MTTF_2} \tag{6}$$

The MTTF of the parallel system is defined in (7)

$$MTTF_p=\int_0^\infty R_p(t)dt=\frac{1}{\lambda_1}+\frac{1}{\lambda_2}-\frac{1}{\lambda_1+\lambda_2}=MTTF_1+MTTF_2-\frac{MTTF_1.MTTF_2}{MTTF_1+MTTF_2} \tag{7}$$

The MTTF and failure rate of various SCN architecture components for reliability calculations are considered from references [13], [17], and are tabulated in Table1.

Table 1: Failure rate and MTTF of SCN components

IEC 61850 SAS Components	MTTF (Yr)	Component Failure rate (λ) (Yr-1)
P&C IED	100	0.01000
Circuit Breaker IED (CB_IED)	150	0.00667
Merging Unit (MU)	150	0.00667
Ethernet Switch (ES)	50	0.02000
Time Synchronization (TS)	150	0.00667
Non-Conventional Instrument Transformer (NCIT)	150	0.00667
Circuit Breaker Trip Coil (CB)	150	0.00667

3. RELIABILITY BLOCK DIAGRAMS

IEC 61850 SAS system consists of electronic devices such as Non-Conventional Instrument Transformers (NCITs), Merging Units (MUs), Protection & Control (P&C_IEDs), Ethernet switches(ES), Time Synchronization Sources(TS), and Circuit Breaker IEDs (CB_IED) etc. MU IEDs act as a source of primary power system data as per IEC 61850-9-2 '*LE*' guidelines. The bay level P&C_IEDs are independently connected to process level equipments such as MUs, NCITs through a process bus network. CB_IEDs controls the status and condition of circuit breaker on the basis of tripping, status and interlocking commands from P&C_IEDs.

The single line diagram of D2-1 type substation, as described in reference [16], consists of six feeder bays (F1-F6 bays), two transformer bays (TI&T2), and one bus section bay (S). Each feeder bay is composed of a bay Ethernet switch, one MU IED, two P&C_IEDs, and one CB_IED. Each transformer bay and bus section bay consists of bay Ethernet switch, two MU IEDs, two P&C_IEDs, and one CB_IED. These bay-components must work together to realize protection function successfully in IEC 61850 SAS. Figures 5-9 show the RBDs drawn for traditional SCN architectures drawn for this substation.

3.1 RBD Analysis of Cascade Architecture

Cascade architecture is formed when all the Ethernet switches are connected in a line without forming any loop. This architecture is simple and less expensive with no redundant paths. However, the worst case latency offered depends upon the total number of switches in cascade and has to be considered while evaluating the performance of time critical operations.

In RBD of cascade architecture, as shown in Fig. 5, all the Ethernet switches must work in sequence for system success and hence all Ethernet switches are connected in series.

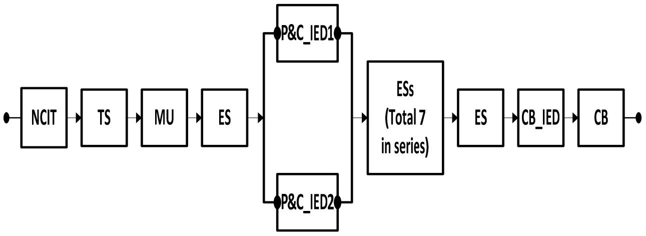

Fig. 5: RBD for cascade architecture

Also, it can be observed from the RBD that this architecture is not fault tolerant; any failure can cause loss of communication.

3.2 RBD Analysis of Star Architecture

Star architecture has the advantage of providing least amount of latency among all other practical Ethernet network architectures. The message transmission time performance may comply with 61850 standards, but it offers least reliability. Hence, star architecture might be practically unsuitable for designing SCN network in substations. The inter-bay communication is possible only through the central Ethernet switch. Hence, in RBD for star network, as shown in Fig. 6, the central switch is connected in series with other critical SAS components.

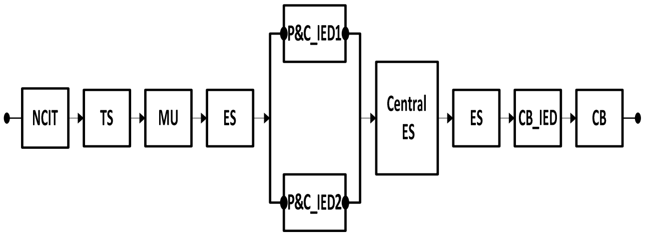

Fig. 6: RBD for star architecture

3.3 RBD Analysis of Ring Architecture

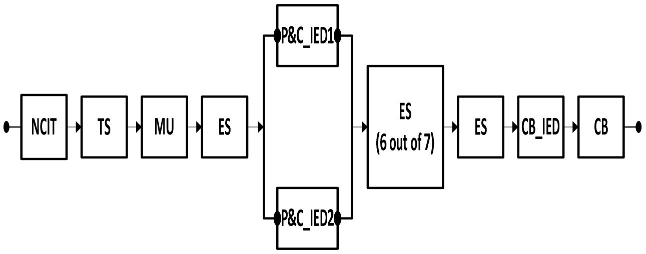

Fig. 7: RBD for ring architecture

Ring architecture is an acceptable and economical solution out of the other practical Ethernet network architectures used for designing IEC 61850 SCN in modern substations. This architecture is very similar to cascade but a loop is formed from the last switch to the first switch. In this way, the architecture offers (n-1) level of redundancy against any physical component or communication network failure. However, the architecture is expensive because of the use of costly managed Ethernet switches that provide IEEE 802.1w RSTP protocol support to manage redundant paths in ring with an allowable reconfiguration time. Also, similar to cascade, the worst case latency calculation is highly significant for designing time critical applications. Hence, in RBD of a ring network, as shown in Fig. 7, only 6 out of 7 managed Ethernet switches, considering the worst-case scenario, are required for inter-bay communication.

3.4 RBD Analysis of Star-ring Architecture

In star-ring architecture, each bay level Ethernet switch is connected directly to two central Ethernet switches; both are connected in ring. This type of architecture, like star, offers lower latency with redundant paths. Thus, it provides a high level of reliability and is immune to faults like link failure, components failure etc. But the architecture is costly due to the use of a number of managed Ethernet switches and might prove non-deterministic under worst load scenarios as it contains limited redundant paths [13].

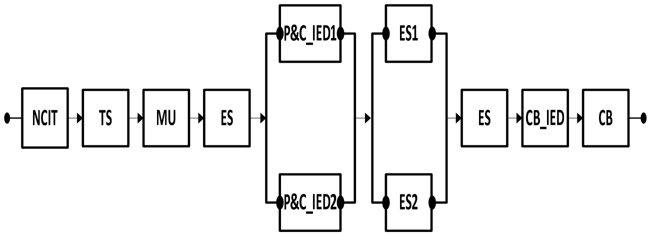

Fig. 8: RBD for star-ring architecture

Hence, in RBD for star-ring network, as shown in Fig. 8, redundant ESs are shown to be connected in parallel with other critically important components within the protection system. Star-ring architecture has not improved reliability and availability with respect to the previous ring architecture. However, as the number of Ethernet switches increases the star-ring architecture reliability and availability will improve as compared to ring architecture.

3.5 RBD Analysis of Redundant-ring Architecture

In redundant-ring, all the SAS IEDs are connected to both redundant ring configurations. Both the networks are independent with each other, and support IEEE 802.1w RSTP protocol. Unlike cascade, ring, star-ring, star; redundant-ring provides redundancy at communication network level. There are improvements in reliability and availability of zones of protection due to the fact that redundant architecture offers complete redundancy in Ethernet switched network at a higher cost and complexity.

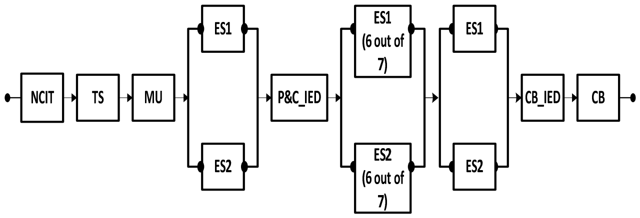

Fig. 9: RBD for redundant-ring architecture

In RBD for redundant-ring architecture, as shown in Fig. 9, all IEDs in each bay are connected to redundant ESs and each IED is connected to redundant-ring configurations and hence, both redundant rings are shown in parallel.

4. SYSTEM RELIABILITY EQUATIONS

The reliability of NCITs, MUs, TSs, ESs, P&C_IEDs, CB_IEDs, and CB trip coils are designated as R_{NCIT}, R_{MU}, R_{TS}, R_{ES}, R_{PRIED}, R_{CBIED}, and R_{CB}, respectively. To consider the worst-case reliability scenario, the idea is to compute the reliability of a protective function that involves inter-bay communication between IEDs placed at extreme ends in the SCN. In such scenario, the IEDs connected to extreme end bay Ethernet switches participate for a successful function execution. The reliability of the protection function using cascade architecture, based on its RBD as shown in Fig. 5, is given by (8).

$$R_{sys}^{Cascade} = R_{NCIT}.R_{TS}.R_{MU}.R'_{PRIED}.R_{ES}^{9}.R_{CBIED}.R_{CB} \tag{8}$$

Similarly, the reliability of the protection function using star and ring architectures are given by (9) and (10), respectively.

$$R_{sys}^{Star} = R_{NCIT}.R_{TS}.R_{MU}.R'_{PRIED}.R_{ES}^{3}.R_{CBIED}.R_{CB} \tag{9}$$

$$R_{sys}^{Ring} = R_{NCIT}.R_{TS}.R_{MU}.R'_{PRIED}R'_{ES_{6/7}}.R_{ES}^{2}.R_{CBIED}R_{CB} \tag{10}$$

$$\text{Where, } R_{PRIED1} = R_{PRIED2} = R_{PRIED}$$

$$R'_{PRIED} = 1-(1-R_{PRIED1}).(1-R_{PRIED2}) = 2R_{PRIED} - R_{PRIED}^{2} \text{ and,}$$

$$R'_{ES_{6/7}} = 7.R_{ES}^{6}.(1-R_{ES}) + R_{ES}^{7} \tag{11}$$

The reliability in (11) is computed using 'binomial distribution' assuming the condition that minimum '6' or more ESs are required for inter-bay communication under the worst-case scenario. The reliability of the protection function for star-ring architecture, using its RBD as shown in Fig. 8, is given by (12).

$$R_{sys}^{Star-Ring} = R_{NCIT}.R_{TS}.R_{MU}.R'_{PRIED}.R'_{ES}.R_{ES}^{2}.R_{CBIED}.R_{CB} \tag{12}$$

Where, $R_{ES1} = R_{ES2} = R_{ES}$ and,

$$R'_{ES} = 1-(1-R_{ES1})(1-R_{ES2}) = 2R_{ES} - R_{ES}^{2}$$

The reliability of the protection function for redundant-ring SAS architecture, based on its RBD as shown in Fig. 9, is given by (13).

$$R_{sys}^{Redundant-Ring} = R_{NCIT} \cdot R_{TS} \cdot R_{MU} \cdot R'_{ES} R_{PRIED} R''_{ES_{6/7}} \cdot R'_{ES} \cdot R_{CBIED} R_{CB} \quad (13)$$

Where, $R_{MU1} = R_{MU2} = R_{MU}$, $R_{CBIED1} = R_{CBIED2} = R_{CBIED}$,

$$R'_{MU} = 1 - (1 - R_{MU1}) \cdot (1 - R_{MU2}) = 2R_{MU} - R_{MU}^2,$$

and $R'_{CBIED} = 1 - (1 - R_{CBIED1}) \cdot (1 - R_{CBIED2}) = 2R_{CBIED} - R_{CBIED}^2$

Also, $R''_{ES\,6/7} = 1 - \left(1 - R'_{ES_{6/7}}\right)^2 = 2R'_{ES_{6/7}} - {R'_{ES_{6/7}}}^2$

5. RELIABILITY RESULTS

The impact of different SCN architectures on the reliability of substation protection function is discussed here. The MTTF and failure rate of various SAS architecture components for reliability calculations, considered in this study, are tabulated in Table 1.

Table 2: Reliability of SCN architectures

SAS Architecture	Reliability, R sys (%)
Cascade	97.23%
Star	98.56%
Ring	99.15%
Star-Ring	99.18%
Redundant-Ring	99.64%

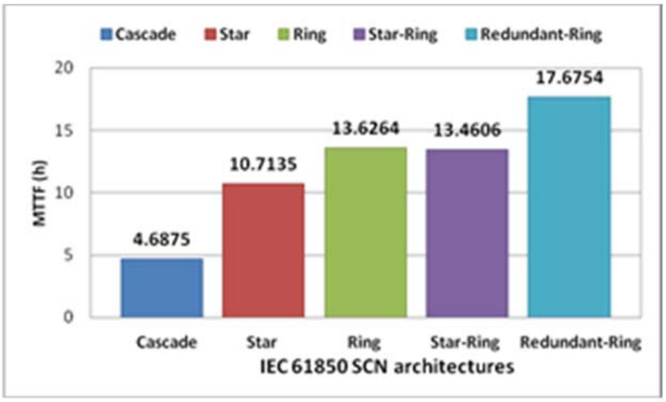

Fig. 10: MTTF comparisons of various SCN architectures

The comparison among these traditional architectures is presented using reliability and MTTF. It is shown in Table 2 that cascade architecture has the lowest reliability, as no-redundant Ethernet switches are used. Star architecture is more reliable than the cascade architecture but the availability of star architecture is considerably less than the other network topologies. Both the ring and star-ring architectures are more reliable than star and cascade architectures but the reliability of these architectures is lower when compared to the redundant-ring architecture. Also, the MTTF of the redundant-ring architecture, as shown in Fig. 10, has significantly higher value of 17.67 years, and concludes that it has the most reliable long operating life in SAS compared to the other existing traditional SAS architectures.

6. CONCLUSION

The paper has investigated the impact of traditional SCN architectures on the reliability of substation protection function. For this, reliability block diagrams have been demonstrated for these traditional Ethernet SCN architectures drawn for a typical substation layout, considering inter-bay communication among IEDs in substation, to quantitatively evaluate the reliability of these protection systems. Reliability results are presented in terms of system failure rate and Mean Time to Failure (MTTF) for Ethernet network configurations such as cascade, star, ring, star-ring and redundant-ring. Redundant-ring is found to be the most reliable and longer operating life in SAS compared to the other existing traditional SAS architectures.

REFERENCES

[1] IEC Standard for communication networks and systems in substation, Part 3: General Requirements, IEC 61850- part 3, 2003.

[2] IEC standard for Telecontrol equipment and systems, IEC 60870-4, 1990.

[3] R. Billinton and R. N. Allan, Reliability evaluation of engineering systems: Concepts and Techniques, Published by Springer, 1992.

[4] K. P. Brand, M. Ostertag and W. Wimmer, “Safety related, distributed functions in substations and the standard IEC 61850,” *in proc. Power Technology Conf.*, vol.2, 2003.

[5] I.E.O.Schweitzer and P. M. Anderson, “Reliability analysis of transmission protection using fault tree methods,” *in Proc. Annual Western Protective Relay Conf.*, Oct. 1997.

[6] Y. Y. Hong, L. H. Lee and H. H. Cheng, “Reliability assessment of protection system for switchyard using fault tree analysis,” *in proc. Power System Technology Conf.*, p.p. 1-8, 2006.

[7] L. R. Castro Ferreira, P. A. Crossley, R. N. Allan and J. Downes, “The impact of functional integration on the reliability of substation protection and control systems,” *IEEE Trans. on Power Delivery*, vol. 16, no. 1, pp. 83-88, Jan. 2001.

[8] H. Hajian-Hoseinabadi, “Reliability and component importance analysis of substation automation systems,” *International Journal of Electrical Power and Energy Systems*, vol. 49, p.p. 455–463, July 2013.

[9] B. Kasztenny, J. Whatley, E.A. Urden, D. Finney and M. Adamiak, “IEC 61850- A practical application primer for protection engineers,” *in proc. Power Systems Conference*, pp. 18-50, Mar. 2006.

[10] V. Skendzic, I. Ender and G. Zweigle, “IEC 61850-9-2 process bus and its impact on power system protection and control reliability,” [Online]. Available: http://www.selinc.com/techpprs

[11] P. Zhang, L. Portillo and M. Kezunovic, “Reliability and component importance analysis of all-digital protection systems,” in *proc. IEEE PES Power Systems Conference and Exposition, PSCE '06, Atlanta,* pp. 1380-1387, 2006.

[12] Ikbal Ali, Mini S. Thomas, Sunil Gupta, and S.M. Suhail Hussain, "IEC 61850 Substation communication network architecture for efficient energy system automation," *Energy Technology and Policy*, Taylor & Francis, Vol. 2 (1), p.p. 82-91, 2015. DOI:10.1080/23317000.2015.1043475.

[13] M. G. Kanabar and T. S. Sidhu, "Reliability and availability analysis of IEC 61850 based substation communication architectures," *presented at the IEEE Power Eng. Soc. General Meeting Calgary*, AB, Canada, July 2009.

[14] H. Lei, C. Singh and A. Sprintson "Reliability modeling and analysis of IEC 61850 based substation protection systems," vol. 5, no. 5, pp. 2194-2202, Sep. 2014.

[15] H. Hajian-Hoseinabadi, "Impacts of automated control systems on substation reliability," *IEEE Transactions on power delivery*, vol. 26, no. 3, pp. 1681-1691, Jul. 2011.

[16] T.S. Sidhu and Yujie Yin, "Modelling and simulation for performance evaluation of IEC61850-based subsation communication systems", *IEEE Transactions on Power Delivery*, vol.22, no. 3, pp. 1482–1489, July 2007.

[17] K. P. Brand, V. Lohmann, and W. Wimmer, Substation Automation Handbook, Utility Automation Consulting, 2003.