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Comparative Reliability Analysis of Substation Automation Architecture Based on IEC 61850 Standard

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ABSTRACT

Using IEC 61850 standard would increase the reliability and availability of electricity network and put a huge impact on network automation. Even though much research works have been done in substation system reliability, there are few works in automated substation control system reliability. This paper evaluates the reliability of IEC 61850-based substation automation system comparatively considering vender's different intelligent electrical devices. The technique is based on fault tree analysis approach and the tie sets methodology is used to evaluate quantitatively. In this paper, the proposed method is implemented on Mianeh Aydoghmush substation automation system in 5 different scenarios. Comparative studies are used to establish the most reliable architecture compared with the others. Using IEC 61850 standard in substation automation system provides us to use different manufacturers' products with identical protocols. Furthermore, producers of different intelligent electrical devices, in 3 different ranges of mean time between failures, are tested in various scenarios and reliability of system is evaluated quantitatively. The proposed method provides rate of change of system mean time to failure index. Using this index can be a useful tool to choose the best range of intelligent electrical devices.

1. Introduction

Substation automation designers are faced with many choices about system topology, primary and back up devices, and redundant paths. Substation Automation System (SAS) includes Intelligent Electrical Devices (IEDs) which have the ability to process and implement software [1]. IEDs are protection and control devices which do the process on information sent by I/O devices or intelligent sensors and actuators. In addition to monitoring, control and protection functions, SAS provides interfaces to be used in Control and Data Acquisition (SCADA) and Human Machine Interfaces (HMI) which brings both local and remote access. The basic problem faced by substation automation designers is to provide interoperability between monitoring, control and protection devices from different manufacturers. Previously, all manufacturers have been using their own exclusive communication protocols. Huge investments are needed to improve protocol converters. On the other hand, protocol converters decline system reliability. Highlighted issues with several communication networks of SAS are discussed in [2-4]. This directed in 2003 to establish a standard as IEC 61850 by an IED working group called TC57. IEC61850 standard provides cooperation between different parts by defining communication protocol, data format and language configuration. This standard specifies OSI-7 layer based on Ethernet communication protocol. According to IEEE dictionary, reliability is system ability to perform functional needs under special condition in specific time. As mentioned, reliability can consider the system or its components.

According to the definition contained in [5], the system is a set of components for specific function or set of functions. Most of the well-known methods for reliability analysis, such as Fault Tree Analysis (FTA), Reliability Block Diagrams (RBDs), Markov chains and Bayesian Net-works (BNs) provide a visual modeling language to increase the understanding and ease the analysis.

The reliability analysis of SAS based on IEC 61850 using the RBD methodology is shown in [6] and [7]. Methods to calculate reliability of the SAS based on IEC 61850 process buses for different architectures are presented in references [8]-[11].

An approach for reliability assessments of various substation automation systems is presented in [12]. The results show that both the ring and hybrid topologies are the most reliable architectures in comparison with the others. Reference [12] suggests the component importance analysis for identifying the bottleneck of the automation system reliability.

Reference [13] presents an approach to quantitatively assess the reliability of six conventional automated substation configurations. Also, the literature [13] introduces an appropriate reliability model which is based on the event trees and the Reliability Block Diagram (RBD) for a typical SAS known as a simple star architecture. Taking into account the effects of substation automation systems, a particular distribution automation scheme, automated substations, automated primary distribution systems, and the interaction between them are presented in [14]. In reference [15], a typical protection system based on the IEC 61850 concepts, incorporating both physical and cyber components, is presented. The cyber-physical interface matrix decouples the analysis of the cyber part from the physical part and provides the means of performing the overall analysis of a composite system in a more controllable manner.

In this paper, a new reliability evaluation for practical substation architecture, Mianeh Aydoghmush automation system is implemented using fault tree quantitative methodology. Different scenarios are considered to quantitatively assess reliability indices and compare results to find the best case. Three ranges of different venders IEDs are used to model the impact of different range of IEDs Mean Time between Failures (MTBF) in SASs reliability evaluation based on IEC 61850.

The proposed method presents the Rate of Change (ROC) of system Mean Time to Failure (MTTF) index which can provide the best solution to improve system reliability cost, effectively.

2. Substation Automation System Based on IEC61850

Communications inside a SAS mainly fall into three categories: Data gathering, data monitoring and event logging. In the IEC 61850 standard all inquiries and control activities toward physical devices are modeled as getting or setting the values of the corresponding data attributes, while data monitoring provides an efficient way to track the system status.

According to [16], there are three levels in the functional hierarchy of IEC 61850 depicted as in Figure 1.

Process level: This level includes switchyard equipment's such as CTs / PTs, Remote I/O, actuators, etc.

Bay level: Bay level includes protection and control IEDs of different bays.

Station level: The functions requiring data from more than one bay are implemented at this level.

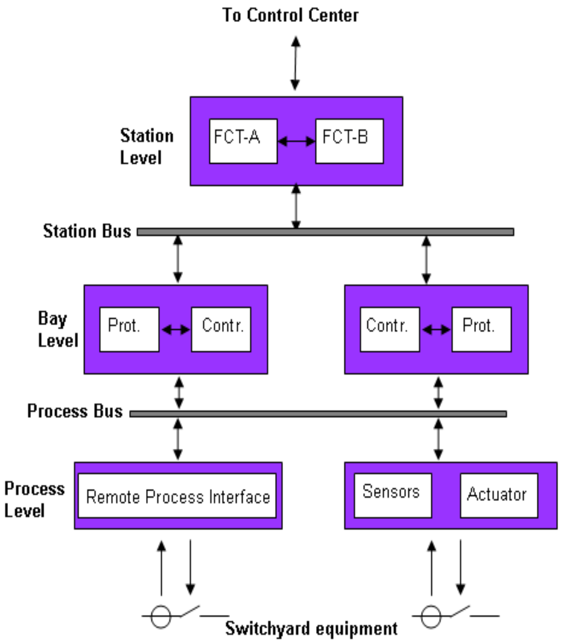


Figure 1: Architecture of IEC 61850 [16].

The process level consists of current transformers (CTs), potential transformers (PTs), actuators, and merging units (MUs). Received signals from CTs/PTs are digitized by MUs and will be sent to the bay level by the Ethernet network.

In addition, bay level consists of IEDs. IEDs calculate the data from process level and send them through the Ethernet network. Finally, components statuses are available to operators by the station level consisting of the HMI and SCADA systems.

3. Methods for Reliability Analysis

There are many techniques for the reliability analysis of the system. In available qualitative methods, we can find as an example FMEA (Failure Mode and Effects Analysis) [17]. In FMEA, each system component failure mode and its impact on the rest of the system is documented. This method is particularly suitable for systems with single component failures.

So, this method is not suitable for systems with a fair degree of redundancy [18]. An alternative to this method is State-Based Analysis. These methods have taken a big step in the study and analysis of system reliability by counting all possible errors in the system and not being limited to stochastic independent failure of components. Models using Markov chain in the state-based analysis are exponentially increasing corresponding with the increase in system components [19].

One of the frequent methods used in the system is FTA. This model shows the failure behavior of each physical components of the system as a logical model and visual diagram [18]. FTA allows modeler to visualize the terms of the relational dependency of main components to sub-components. FTA method is very similar to RBD method [18], [20]. In fact, RBD is identifying undirected paths between system components in schematically way. At first, 2 points are determined and then communication paths including system components are identified between these two points. The system is available, if at least one path contains a chain of components between two points exists. [21] and [22] show how FTA network can be translated to Bayesian Networks (BNs) [23]. BNs are also a subset of the Probabilistic Relational Model (PRM). PRM using BNs formulation can describe and quantify probabilistic dependences between elements. The use of PRM for the dependability analysis is explained in [24].

4. Proposed Methodology

One of the most frequently adopted methods to evaluate system reliability is FTA, which translates the failure behavior of a physical system into a visual diagram and a logical model [18]. FTA is based on reliability theory, Boolean algebra and probability theory. FTA can be classified into two separate types of analysis qualitative and quantitative. The qualitative part focuses on a logic diagram that visualizes the interrelationships between a potential critical event and the cause for this event to occur. The fault tree represents how combinations of basic events lead to the occurrence of a particular undesired event called the TOP event. Events concern the failure of components, subsystems or of the whole system, and they are graphically represented by rectangles. For quantitative analysis, each event is a Boolean variable, where its initial state is false and changes to true whenever failure occurs. The FTA can be written in the form of Boolean equations where the Boolean equations need to be obtained based on the logic of the gates. then, an equation for the top event is obtained by the rules of the Boolean algebra which contains the sum of yields of basic events (minimal cut-set method).

Reliability analysis using FTA is much similar to the approach based on RBDs. Using RBDs provides us to find system availability by the equations obtained based on Boolean algebra (minimal tie set methodology). A minimal tie set is one in which all the components within the set must work for the system to function, and if any one element does not function then the system is not guaranteed to work.

In this paper, the proposed FTA model for automated substation is presented. Using FTA model provides us to build RBDs to find the system reliability like below.

Assuming that components are independent, and noticing the probability of tie-set (T_i) shows by $P(T_i)$, the reliability of system when the number of connected sets are equal to N is obtained as (1).

$$\begin{aligned} R_S &= P(T_1 \cup T_2 \cup T_3 \cup \ldots \cup T_N) = \\ &\sum_{i=1}^{N} P(Ti) - \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} P(Ti * Tj) + \\ &\sum_{i=1}^{N-2} \sum_{j=i+1}^{N-1} \sum_{k=j+1}^{N} P(Ti * Tj * Tk) - \\ &\ldots (-1)^{N+1} \sum_{i=1}^{1} \sum_{j=i+1}^{2} \ldots \sum_{z=y+1}^{N} P(Ti * Tj * \ldots * Tz) \end{aligned} \tag{1}$$

We should note that multiplications are based on Boolean algebra, where failure rate of component i is constant and the reliability of this component is illustrated as (2).

$$\begin{aligned} R(T_i) &= P(T_i) = \prod_{j=1}^{m} P_j(t) = \\ &\prod_{j=1}^{m} R_j(t) = \prod_{j=1}^{m} e^{-\lambda jt} \end{aligned} \tag{2}$$

According to (2), $P_j(t)$ and $R_j(t)$ are the probability of occurrence and the reliability of j^{th} component at the time t, respectively. λ_j is the failure rate of j^{th} component.

In the next section, the proposed methodology is used to evaluate system reliability indices in one of the case studies that exists in Iran.

5. Case Study

In this study, the IEC 61850-based Mianeh Aidoghmoush 400/230/63 kV substation is used to evaluate the reliability of the SAS. With the aim of supplying power for industry in the region and correction of voltage drop, this substation has been constructed with capacity of 480 MVA.

A. Mianeh Aidoghmoush Substation basic information

In this substation, double busbar configuration on 400KV and 230KV sides and simple one on 63KV side is used.

This substation includes three 400KV line bays to connect Ardebil, Shahid Ghayati and Tabriz power plants via transmission lines and two extension bays and four 230KV line bays to supply the power of pumping stations, industrial state and steel factory.

DCS is used in this substation and has a specific automation architecture system. Protection and control equipment is provided from reputable manufacturers in Europe. It is very likely to use the other manufacturers' equipment with different MTBF in order to expand substation bays. If we want to use the other venders' products, we will be necessarily imposed to compare these products by evaluating their impacts on system reliability and availability.

Mianeh Aidoghmoush SAS comprises a set of components like: Human Machine Interface (HMI), DC Power Supply (DCP), Network Control Center Server (NCCS), Industrial Personal Computers (IPC), Ethernet Switch (ESW), and Ethernet Interface (EI).

B. Reliability modeling

The configuration of the substation automation system of Mianeh Aidoghmoush for the first loop is shown in Figure 2. Here, we have three BCRs that IEDs are placed there.

According to Figure 2 and SAS configuration, we can illustrate the architecture of Mianeh Aidoghmoush SAS in Figure 3.

FTA for this system is presented in Figure 4. Using FTA model, RBD is obtained and proposed in Figure 5.

Simplified RBD for this structure is presented in Figure 6.

According to Figure 4, A_{series} can be obtained as (3):

$$A_{Series} = DCP * IED^{21} * EI^{21} * ESW^{4} \tag{3}$$

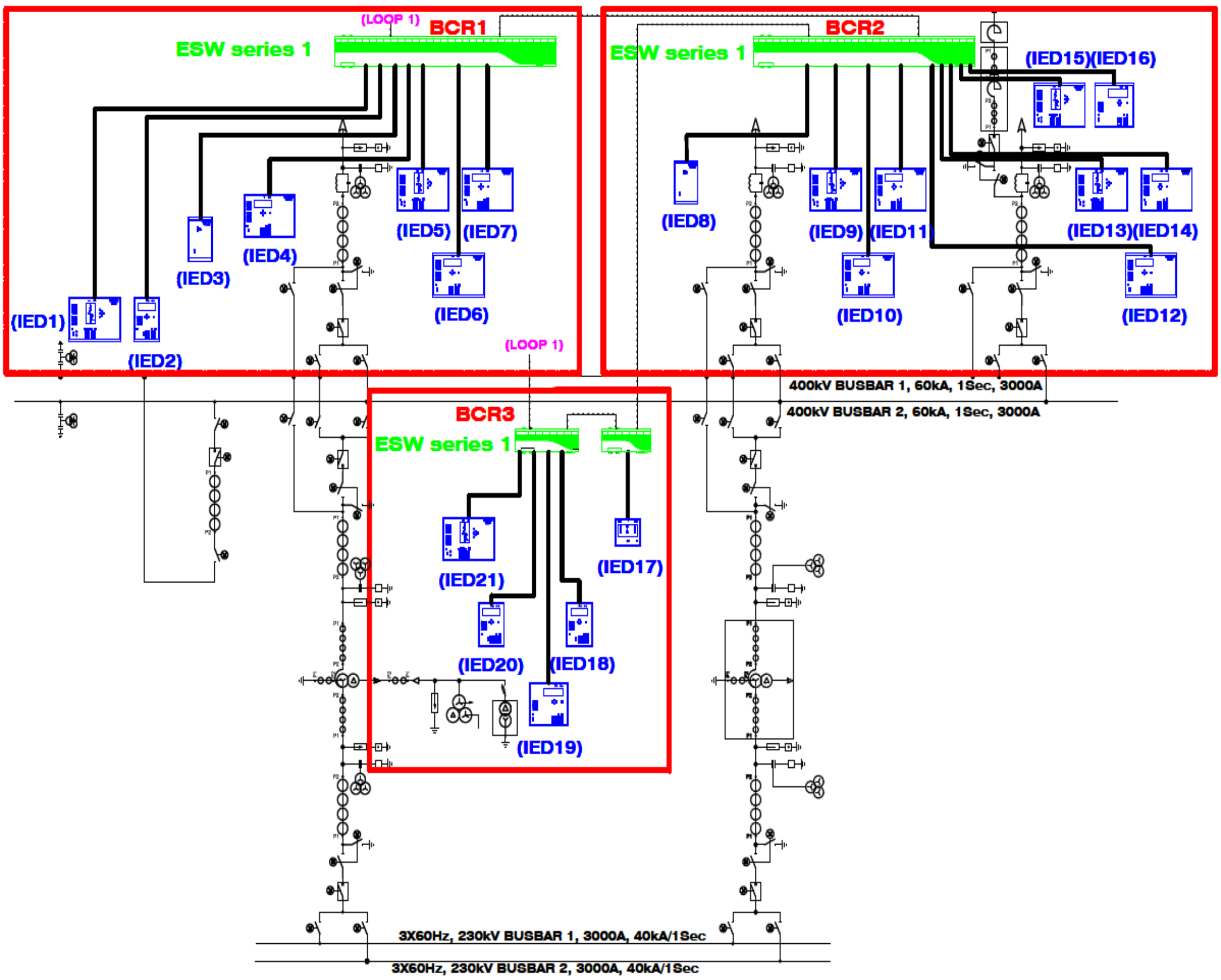


Figure 2: SAS layout in Mianeh Aidoghmoush substation with three BCRs.

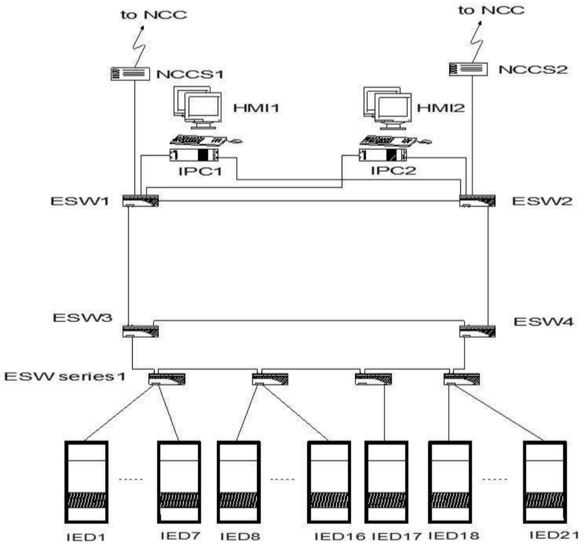


Figure 3: Architecture of SAS in Mianeh Aidoghmoush for the first loop.

C. *Reliability assessment*

According to the obtained RBD presented in Figure 6 and hardware failure rate presented in Table 1, system reliability can be quantitatively evaluated by tie set method. As the number of tie-sets is 12, we should take advantage of computer programming to achieve system reliability. In this paper, we use MATLAB software for solving this issue.

System reliability for SAS of Mianeh Aidoghmoush for 1000 hours (t=1000) is obtained 93.01%.

To analyze the reliability of the system in different topologies, 5 different scenarios have been used as follows: First Scenario: In this case, we do not use auxiliary central server IPC2 and network NCCS2. System network topology is as Figure 7. Second scenario: In this case, we do not use auxiliary central server IPC2 and network NCCS2 but communication path of IPC1 server also passes ESW1 switch, in addition to the switch ESW 2. This scenario network topology is presented in Figure 8.

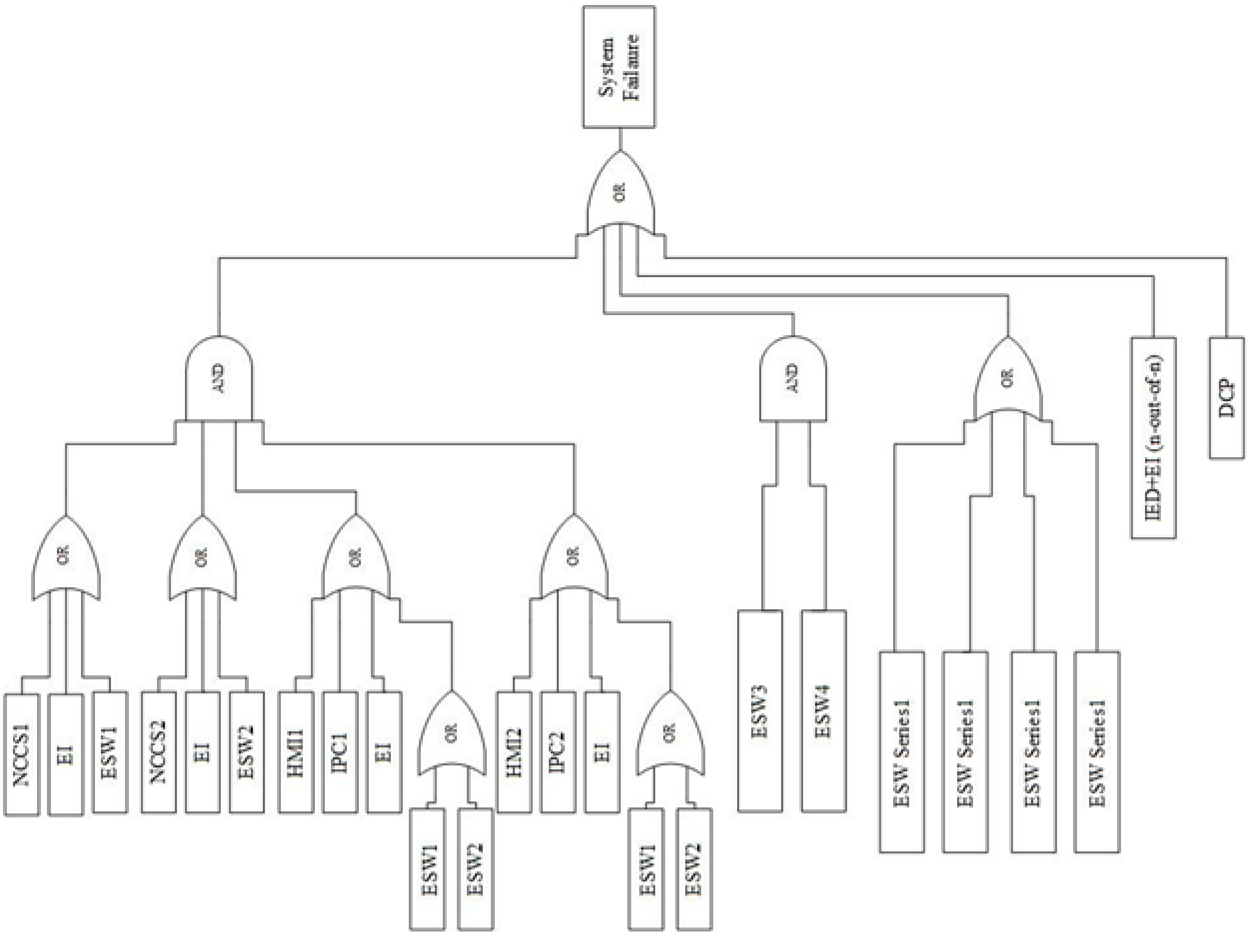


Figure 4: SAS layout in Mianeh Aidoghmoush substation with three BCRs.

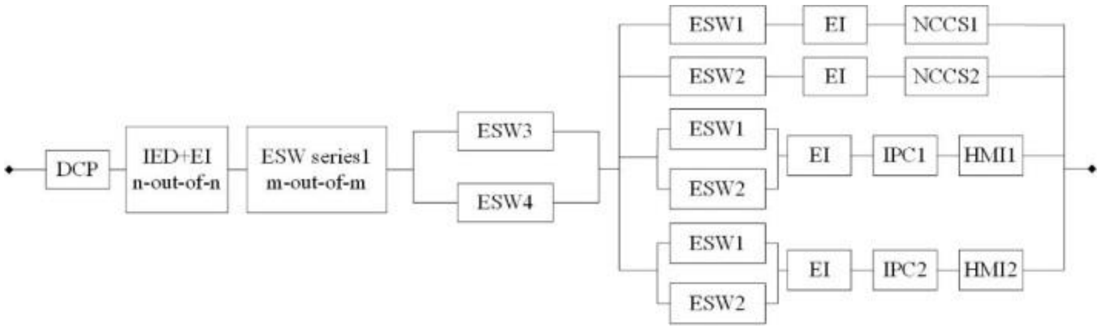


Figure 5: Mianeh Aidoghmoush substation RBD for the first loop.

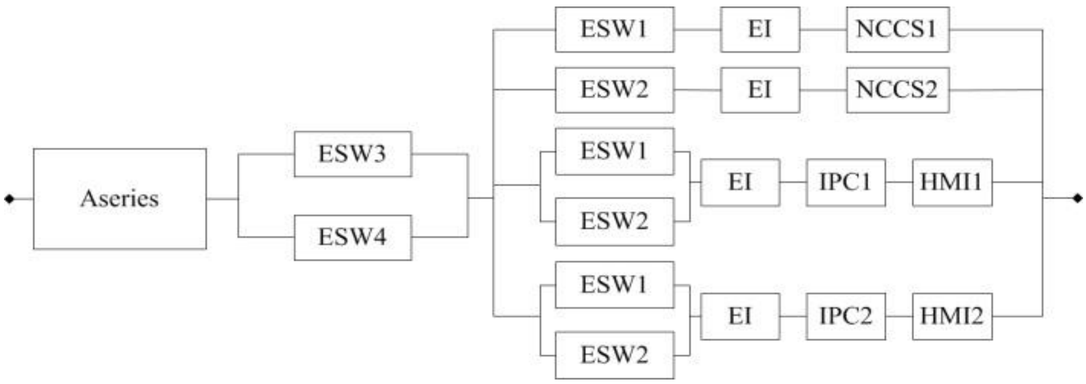


Figure 6: Mianeh Aidoghmoush substation simplified RBD.

TABLE 1
FAILURE RATE OF COMPONENTS IN THE SUBSTATION AUTOMATION SYSTEM [12]

Component	Failure Rate(yr^{-1})	MTTF (yr)	Component	Failure Rate(yr^{-1})	MTTF (yr)
DCP	0.00912	109.6	EI	0.00333	300
IED	0.00966	103.5	NCCS1	0.06993	14.3
ESW	0.08696	11.5	NCCS2	0.06993	14.3
ESW1	0.08696	11.5	HMI1	0.10000	10
ESW2	0.08696	11.5	HMI2	0.10000	10
ESW3	0.08696	11.5	IPC1	0.06993	14.3
ESW4	0.08696	11.5	IPC2	0.06993	14.3

Third scenario: In this case, we do not use auxiliary central server IPC2 and network NCCS2 but communication path of IPC1 server also passes ESW1 switch, in addition to the switch ESW2.

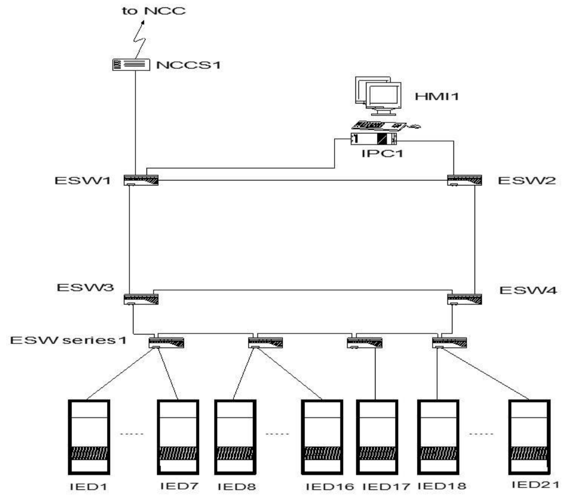
The difference between this and previous scenario is in removals of ESW4 and ESW3 switches. Network topology in forth scenario, is illustrated in Figure 9.

Fourth scenario: In this case, we use auxiliary central server IPC2 and network NCCS2.

The difference between this scenario and the main topology of Mianeh Aidoghmoush substation is in ESW4 switch removal. This network topology is presented in Figure 10.

Fifth scenario: In this case, we use auxiliary central server IPC2 and network NCCS2.

The difference between this scenario and the main topology of Mianeh SAS is in removals of ESW4 and ESW3 switches. This network topology is shown in Figure 11.



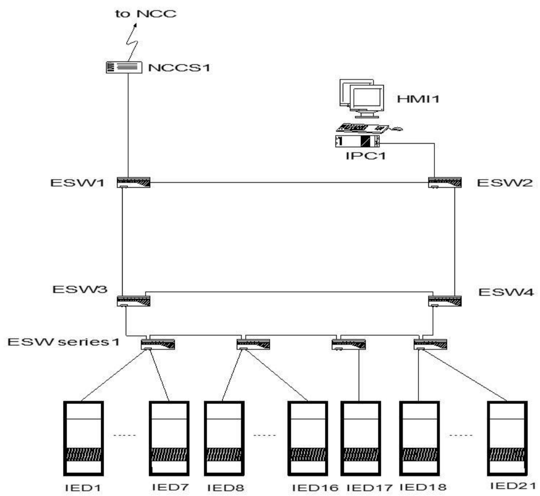


Figure 7: First scenario of Mianeh substation.
Figure 8: Second scenario of Mianeh substation.

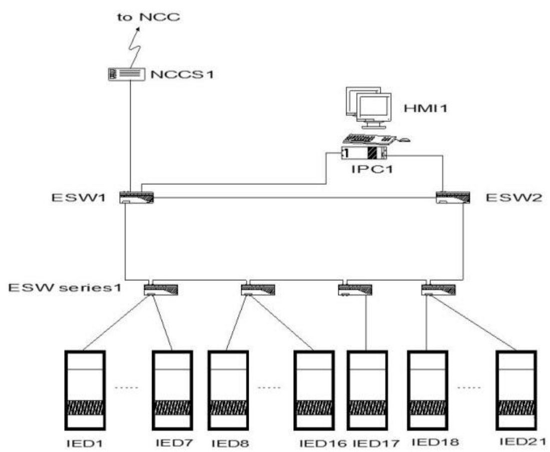


Figure 9: Third scenario of Mianeh substation.

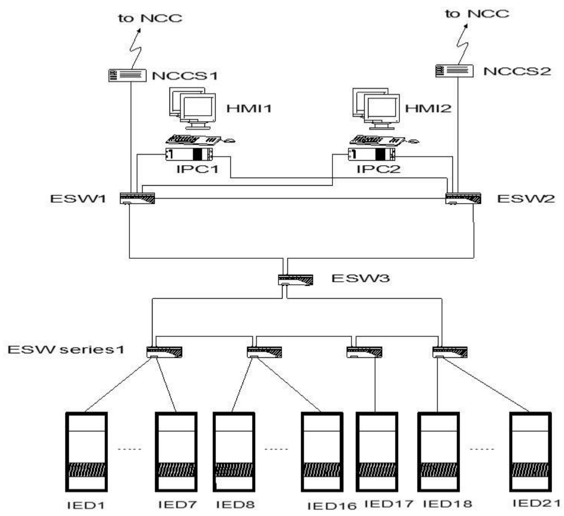


Figure 10: Fourth scenario of Mianeh substation.

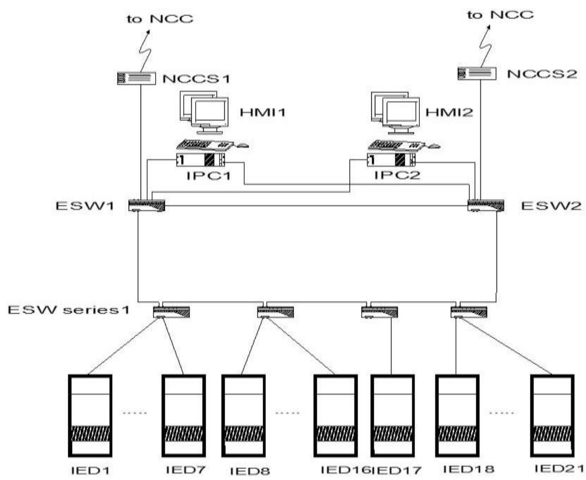


Figure 11: Fifth scenario of Mianeh substation

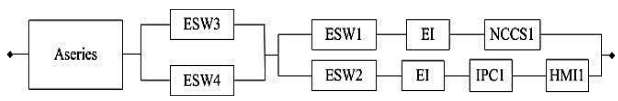


Figure 12: Simplified RBD for Mianeh substation in the first scenario.

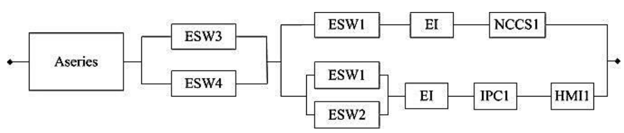


Figure 13: Simplified RBD for Mianeh substation in the second scenario.

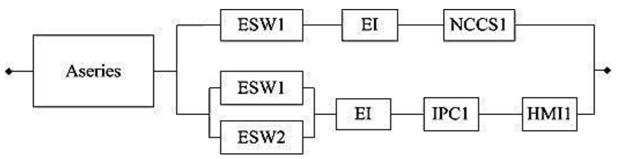


Figure 14: Simplified RBD for Mianeh substation in the third scenario.

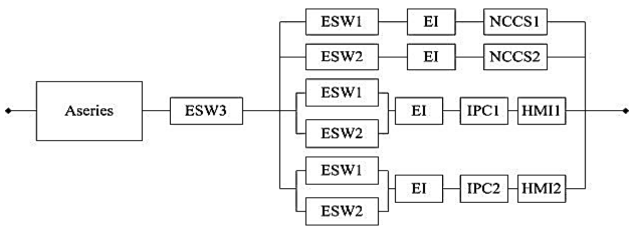


Figure 15: Simplified RBD for Mianeh substation in the fourth scenario.

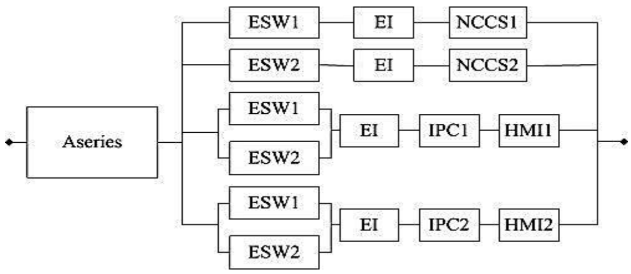


Figure 16: Simplified RBD for Mianeh substation in the fifth scenario.

For each scenario, reliability of the SAS is evaluated and presented in Table 2 (zero scenario represents the current topology of Mianeh Aidoghmoush SAS).

TABLE 2
RELIABILITY OF THE SYSTEM FOR DIFFERENT SCENARIOS

Scenario	0	1	2	3	4	5
System Reliability (%)	93.01	92.97	92.98	92.99	92.10	93.02

RBD for Mianeh substation automation system considering redundancy for one of the IEDs is presented in Figure 17. In this case, system is available even if one of the IEDs fails.

Using Table 1, the reliability of the system for 1000 hours (t = 1000h) equals to 95.91%. For each scenario, reliability of SAS is listed in Table 3.

TABLE 3
RELIABILITY OF THE SYSTEM FOR DIFFERENT SCENARIOS CONSIDERING REDUNDANCY

Scenario	0	1	2	3	4	5
System Reliability(%)	95.91	95.87	95.88	95.89	94.97	95.92

Reliability of the system can be obtained for the IEDs produced by different manufacturers. We consider MTBF of each IED in three different ranges of 103.5, 300 and 600. Considering Mean Time to Repair (MTTR) of IEDs is negligible, the above numbers can be considered as components, MTTF and the above steps can be repeated.

Tables 4 and 5 represent SAS reliability and MTTF for all three types of IEDs produced by different venders without and with considering redundancy. Figures 18 and 19 also represent system MTTF for all different scenarios, respectively.

It can be seen that the values of the SAS MTTF are improved by increasing the MTBF of each IED. According to Figure 20, absolute value of rate of change of systems, MTTF is reduced by increasing the MTBF values intended for IEDs. Using rate of change of system MTTF can be a useful tool to choose the best range of IED's MTBF. Using this index, provides us to evaluate system reliability cost effectively by choosing the best IED. For an instance, using Table 5, it can be seen that if we use the manufacturer 2 instead of manufacturer 1 in scenario 3, ROC of system MTTF will be +9.18%. However, if we want to use manufacturer 3 instead of manufacturer 2, ROC of systems, MTTF will be +1.93%.

This means that the ROC of system MTTF for amount of increased MTBF from 103.5 (yr) to 300 (yr) is more than the one increased from 300 (yr) to 600 (yr) (Fig. 20). So, we can use the second producer instead of the third one.

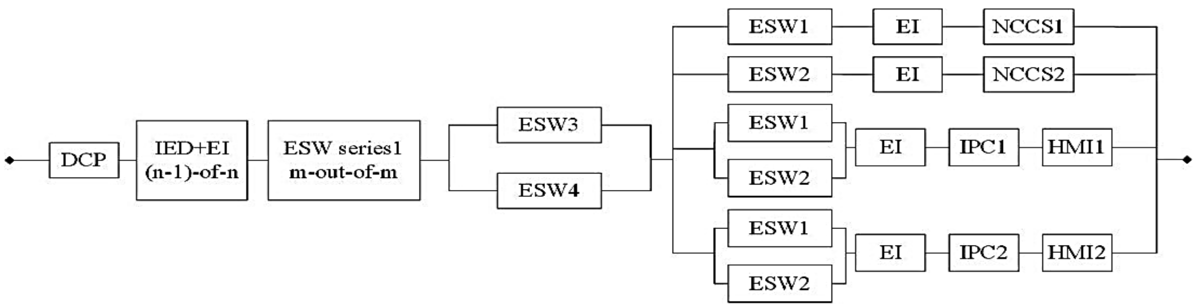


Figure 17: RBD of Mianeh Aidoghmoush SAS considering redundancy.

TABLE 5
SYSTEM RELIABILITY AND MTTF OF THE SYSTEM CONSIDERING REDUNDANCY FOR THREE DIFFERENT TYPES OF IEDS

Producer	1						2						3					
MTBF (yr)	103.5						300						600					
Scenario	0	1	2	3	4	5	0	1	2	3	4	5	0	1	2	3	4	5
System Reliability (%)	95.91	95.87	95.88	95.89	94.97	95.92	95.94	95.90	95.91	95.92	95.00	95.95	95.95	95.91	95.91	95.92	95.01	95.95
$MTTF_{sys}$(yr)	2.0776	1.9193	1.9425	2.0014	1.8437	2.1498	2.2779	2.0780	2.1068	2.1853	1.993	2.3771	2.3240	2.1135	2.1436	2.2275	2.0344	2.4307

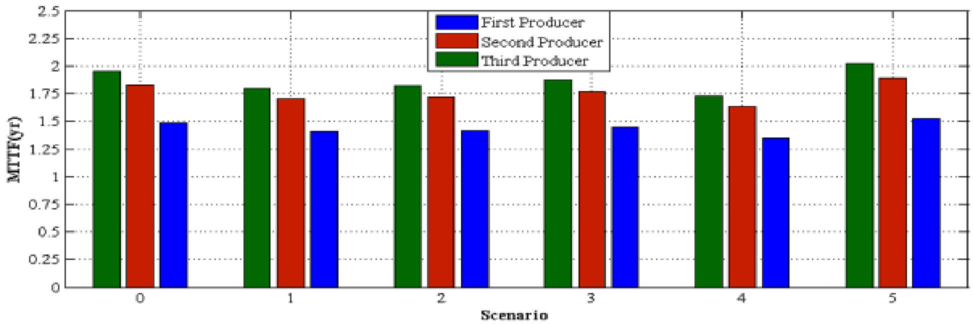


Figure 18: System's MTTF for three different types of IEDs in different scenarios without considering redundancy.

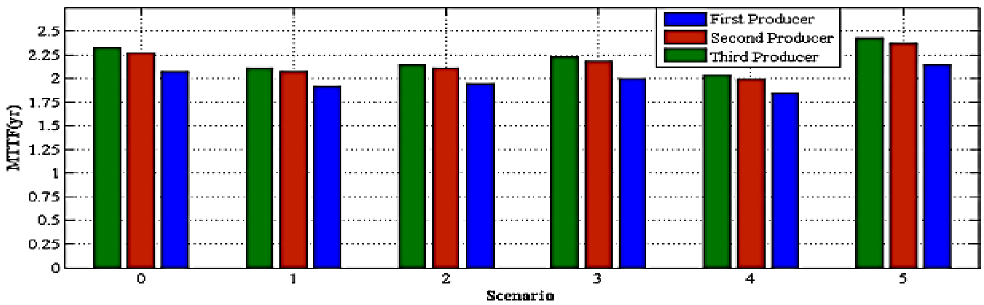


Figure 19: System's MTTF for three different types of IEDs in different scenarios with considering redundancy.

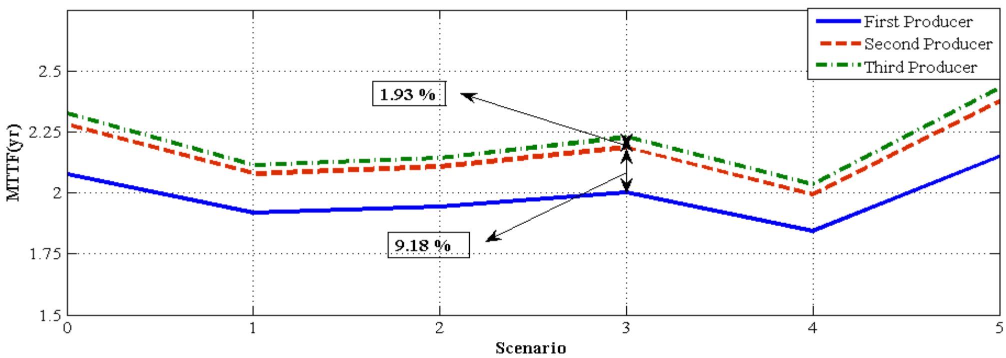


Figure 20: Increasing slope of SAS MTBF using three different ranges of MTBF.

According to the results, it can be seen, while scenario 5 improves system reliability, it reduces the cost of buying additional switches. Also, using a range of IED with average MTBF, it can improve the system reliability, efficiently.

6. Conclusion

General requirements for substation automation system are issues such as reliability, accessibility, serviceability, security, data integrity, performance and the other matters related to the communication system which are used inside substation for monitoring, control structures and processes. These should be considered in accordance with standards IEC 61850, IEC60870-4. The reliability of substation are defined in three classes which can be chosen in agreement with the class system provider and employer. The reliability of hardware and software as well as system configuration and backup communication elements are the major factors determining the reliability of the substation automation system. The fundamental problem facing substation automation design engineers is providing controllers, monitoring, control and protection, made by different manufacturers. In the past, each manufacturer used its own protocols and for coordination with the other systems, protocol exchange was needed that would cause the reduction of security and limitation of systems equipment selection by the designer. Today, using the IEC 61850 standard, communication protocol, format and language configurations, provide equal cooperation between all parts of the system. To assess the reliability of the system, we need to check parameters of reliability. Accordingly, in this paper, after modeling the network, using configuring block diagram and connected set method system reliability is checked. To be able to have a better understanding of the network topology in the system, available surveys have been done for various topologies and under different scenarios. In this project, we have used Mianeh Aidoghmoush substation as a case study in which existing automation system is evaluated. By examining different scenarios, the values obtained for the reliability indices shows that the change in the topology of the system can improve system reliability. At the end, it was observed that scenario 5 not only can reduce the number of switches but also improves system reliability. The results show that for each IED, selected from various manufacturers, levels of system reliability will change. Also, it was observed that system reliability will be improved by higher MTBFs. In this paper, the proposed ROC of system MTTF is presented. Clients can use this index to better choose IED ranges. Considering this point, in order to improve reliability of Mianeh SAS, medium MTBF range of 300 can be used for each IED. In this case, both security and economic dimensions have been taken into account in order to improve system reliability. It seems that presented topology is the best option to improve reliability and to increase availability of Mianeh substation automation, which can be used in the development of the remaining bays.

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