AN INTEGRATIVE APPROACH TO RELIABILITY ANALYSIS OF AN IEC 61850 DIGITAL SUBSTATION

A Thesis

by

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ABSTRACT

In recent years, reliability evaluation of substation automation systems has received a significant attention from the research community. With the advent of the concept of smart grid, there is a growing trend to integrate more computation and communication technology into power systems.

This thesis focuses on the reliability evaluation of modern substation automation systems. Such systems include both physical devices (current carrying) such as lines, circuit breakers, and transformers, as well as cyber devices (Ethernet switches, intelligent electronic devices, and cables) and belong to a broader class of cyber-physical systems. We assume that the substation utilizes IEC 61850 standard, which is a dominant standard for substation automation.

Focusing on IEC 61850 standard, we discuss the failure modes and analyze their effects on the system. We utilize reliability block diagrams for analyzing the reliability of substation components (bay units) and then use the state space approach to study the effects at the substation level. Case study is based on an actual IEC 61850 substation automation system, with different network topologies consideration concluded.

Our analysis provides a starting point for evaluating the reliability of the substation and the effects of substation failures to the rest of the power system. By using the state space methods, the steady state probability of each failure effects were calculated in different bay units. These probabilities can be further used in the modeling of the composite power system to analyze the loss of load probabilities.

DEDICATION

I dedicate my thesis work to my great family, teachers and friends.

ACKNOWLEDGEMENTS

Firstly, I would like to express my sincere gratitude to my academic advisors, Dr. Chanan Singh and Dr. Alex Sprintson, for their great support and guidance during my studies and research in Texas A&M University. Dr. Chanan Singh provided me with lots of support regarding to the power system reliability, as well as my daily study in this field. I would thank him for being patient and spending much time on my research. I would also thank Dr. Alex Sprintson for his great help on my network communication study. His knowledge inspired me many ideas to this thesis.

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NOMENCLATURE

SAS	Substation Automation Systems
GOOSE	Generic Object Oriented Substation Event
RBD	Reliability Block Diagram
MU	Merging Unit
ES	Ethernet Switch
CB	Circuit Breaker
IED	Intelligent Electronic Device
BrkrIED	Breaker IED
CtrlIED	Control IED
ProtIED	Protection IED
TS	Timing Source
MTTF	Meant Time to Failure
FR	Failure Rate
MRT	Mean Repair Time
RpR	Repair Rate
R	Transit Matrix
Pi	Stead State Probability in State i
f	Frequency
Pf	Probability of failure
HMI	Human Machine Interface

SCADA	Supervisory Control and Data Acquisition

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1. INTRODUCTION

Cyber physical systems have been rapidly gaining attention in the past few years. The modern power systems with more and more integration of computation and communication technology are becoming complex cyber physical systems. Traditional electric substation systems are facing a challenge on integrating the physical parts like the conventional Circuit Breakers (CB) with the new digital relays and Ethernet Switch (ES) networks. Utilities and manufacturers have been using different protocols and devices in the electric substation design and operation, which often create some unnecessary technical difficulties and extra cost on coordination [1].

In recent years, IEC 61850, as a newly approved international substation communication standards has made significant impacts on the above cited problems by providing detailed specification of layered substation communication architecture. Considering the protection system on this new protocol, IEC 61850-9-2 digital process bus accelerates the development of all-digital protection system. With the applications of Merging Unit (MU), Ethernet Switch (ES) network and GOOSE (Generic Object Oriented Substation Event, a higher-speed peer to peer communication methods), the IEC 61850 substation is expected to have higher reliability than the conventional substation which has been used for many decades. Furthermore, many features mentioned in the IEC 61850, such as Fiber Optics, redundancy settings and self-testing and monitoring system, are contributing to improve the reliability of the IEC 61850 Substation Automation System (SAS) [2].

With high emphasis on smart grid, there is a growing trend to integrate more computation and communication technology into power systems. Intelligent Electronic Devices (IEDs) and digital relays streamline the flow of information within the substation. The emerging new digital substation is, in fact, a complex cyber-physical system in which diverse physical devices (such as transformers and circuit breakers) seamlessly operate with cyber devices (such as digital protection relays, routers, and switches).

While these novel communication and computational capabilities are expected to improve the performance of the power systems, they might also be an unintended source of failures and also be vulnerable to cyber-attacks. The complex interaction and interdependency between these components pose a significant challenge in evaluating the reliability of such systems.

1.1 Motivation for This Research

In recent years, reliability evaluation of substation automation systems has received a significant attention from the research community. However, to the best of our knowledge, all the previous work has either focused on the reliability of physical components of the substation or the reliability of the protection schemes (separately). The goal of this work is to develop a holistic approach that integrates physical and cyber components in the reliability study of the substation and provide its interface with the rest of the power system. In particular, in this thesis we integrate both reliability block diagrams and state space methods to develop a comprehensive approach for evaluating the reliability of digital substation systems.

1.2 Related Work

The related work for this thesis can be considered as four parts:

A. Works related to the analysis of IEC 61850 SAS models and functions.
B. Works related to the building RBD and fault analysis.
C. Works related to the building state space and reliability analysis.
D. Works related to exploring different topologies applied to IEC 61850 SAS

The Reference [3] used Reliability Block Diagrams to evaluate the availability of different components of substation automation systems that utilize IEC 61850 protocol. The same technique was used in [4] and [5] to analyze different architectures of all-digital substations as well as the availability characteristics of different redundancy schemes. In [6], was analyzed the reliability of the entire system.

1.3 Organization of the Dissertation

This thesis is organized as follows. A brief background of Cyber-physical power system technologies with IEC 61850 and its benefits to power systems is presented in Section 1. The main research objectives and related works are also included in this section.

In Section 2, we introduce and describe the architecture of the IEC 61850 based substation automation system. In Section 3, we present a specific substation layout as well as failure modes and their effects.

In Section 4, we present the methodology for comprehensive reliability analysis of the substation network. And in Section 5, we explore the different topologies applied in IEC 61850 substation automation systems.

Finally in Section 6, we summarize the impact on the whole system and conclude. We also mention the future possible research in this part. References are added at the end.

2. IEC 61850 BASED SUBSTATION AUTOMATION SYSTEMS

2.1 Substation Automation Systems

Typical electric substations are supposed to receive, transform the electricity either by stepping up or down the voltage and then send it forward. Substations designed in the past made use of protection and control schemes implemented with a single-function, electromechanical or static devices and hard-wired relay logic. With the advent of microprocessor based multi-function Intelligent Electronic Devices (IEDs), we get the opportunity to move more functionality into fewer devices; as well as resulting in simpler designs with reduced wiring. Beginning in early 1990s, industry developed a communications architecture that would facilitate the design of systems for protection, control, monitoring and diagnostics in the substation, which was the Substation Automation Systems (SAS).

2.2 IEC 61850 Based SAS

The IEC 61850 protocols provide the utilities and manufacturing entities with a new standard and design for the modern electric substation. Modern communication network technology and the use of merging units accelerate the development of substation automation system and push the traditional substation to the cyber-physical systems stage. Since the approval of IEC 61850 by UCA (Utility Communication Architecture) International Users Group in 2004, many European and Chinese utilities have implemented IEC 61850 standards on the newly installed smart high voltage substations, i.e. 110/10kV air insulated substation [7]. Figure 1 depicts the IEC 61850 based substation architecture; the different components are described below.

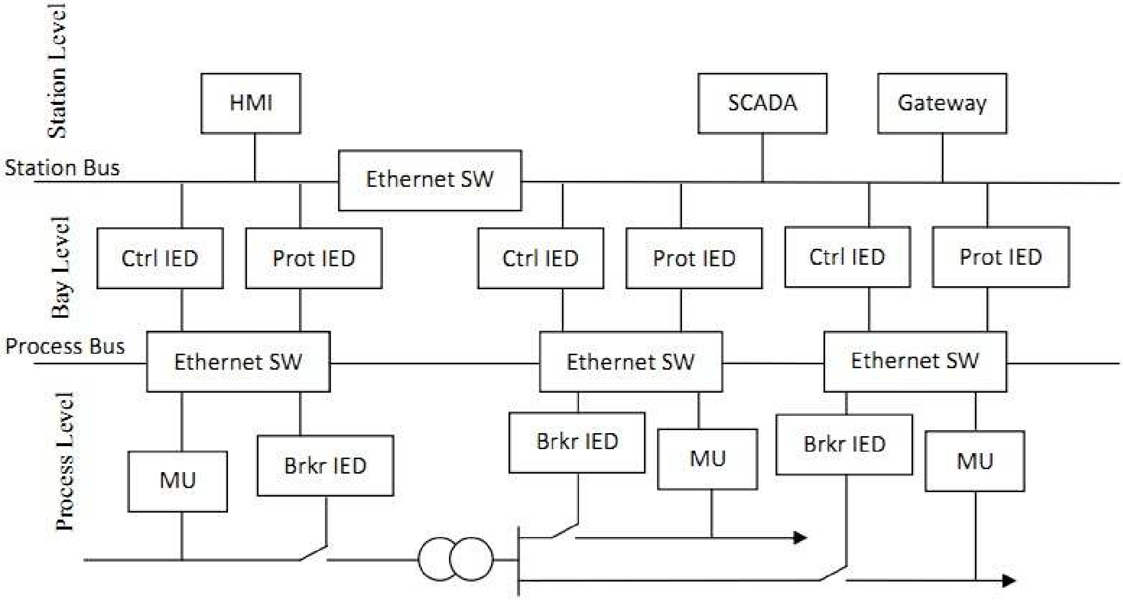


Figure 1 IEC 61850 Based Substation Architecture.

Regarding to the substation protection, IEC 61850 protocols standardized the data exchange rules over the Process and Station bus in high-speed peer-to-peer communications. Generic Object Oriented Substation Event (GOOSE) message is introduced through the entire system to make sure the high priority of the signals from Circuit Breaker IEDs. Some critical devices and structures are described in the following parts.

2.2.1 IEC 61850 Critical Devices

1) Merging Unit (MU)

A merging unit combined with the instrument transformer (CT/PT) monitors the working status of lines and devices. Unlike the conventional analog signal, MU can digitize the original current and voltage signals and send them over the Ethernet network in the form of sampled values.

Existing Merging Units have the following functionality:[8]

- Signal Processing of all sensors – conventional or non-conventional
- Synchronization of all measurements – 3 currents and 3 voltages
- Analogue interface – high and low level signals
- Digital interface – IEC 60044-8 or IEC 61850-9-2

The Merging Units (MU) multicast sets of measured sampled values to multiple other IEDs in the substation over the substation local area network, which shows as the process bus level. Status and all the information for circuit breakers and circuit switches are available through the input/output unit. Merging unit and these input/output units are usually combined into single devices and recognized as Merging Unit.

2) Intelligent Electronic Devices (IEDs)

Intelligent Electronic Devices (IEDs) are devices that perform electric protection or control functions in power systems, with advanced local control intelligence and have the ability to monitor processes. IEDs receive data from sensors and power equipment, and can issue control commands, such as tripping circuit breakers if they sense voltage, current, or frequency anomalies, or raise/lower voltage levels in order to maintain the desired level. Common types of IEDs include protective relaying devices, load tap changer controllers, circuit breaker controllers, capacitor bank switches, reclose controllers, voltage regulators, etc.

The IEDs applied to IEC 61850 have the following categories:

- Protection IEDs (Prot IED):

These include the bus, transmission line, and transformer relays which perform protection functions. For example:

SEL-487B Bus Differential and Breaker Failure Relay

SEL-487E Transformer Protection Relay

SEL-421 transmission line Protection system

- Control IEDs (Ctrl IED):

These include transformer tap changers with monitoring and metering functions. For example:

GE Multilin DTR Transformer Tap changer Controller

- Breaker IEDs (Brkr IED):

These are the circuit breaker monitors and controllers which operate and trip the breakers. Breaker IEDs belong to process bus level as well as merging units. GOOSE messages are sent from these IEDs to the entire system, mostly the upper level IEDs, informing the state change and status that occurs in the local power electric substation network.

2.2.2 Communication Bus Level Structures

There are two classes:

- The Process Bus:

The process bus enables the sending and receiving of digitized signals and messages between the process level and bay level, which builds a communication bridge for the control IEDs and protection IEDs to trip the breakers. Typically, the process bus applications cover interface units (like MUs) for voltages and currents, smart controllers (like Brkr IEDs) for disconnect and reclose switches and circuit breakers, which capable of energizing the trip coil of a circuit breaker for fault isolation. These interface units are usually located closely with each other, to communicate with the IEDs in the control level to perform protection, control, monitoring and metering functionalities.

- The Station Bus:

The station bus enables the communication between the station level and bay level, which make the higher control center (HMI, SCADA) in the station level monitor and observe the working status in bay level and process level. Typically station bus provides SCADA control, monitoring, alarm functions as well as engineering access in the substation. It also supports the Human Machine Interface (HMI) for lines diagram display, station-wide controls and data exchanges and communications with the help of Ethernet networks.

The architecture of station bus is oriented to specific requirements of the substation. Ring and star topologies are the most usual architectures used by IEC 61850 based SAS.

2.2.3 An IEC 61850 SAS Test Case Layout and Configuration

One specific IEC 61850 based SAS has been designed to test the requirement specifications for simulation of communication network based on OPNET. The SAS layout has been fully tested and verified in [9]. In this thesis we consider that the physical components follow the layout depicted in Fig. 2. This is a typical substation layout that is used in many reliability studies (see e.g., [9])

In the following we provide a description of the various subsystems of the SAS. These include the description of substation, transmission and transformer bay configurations.

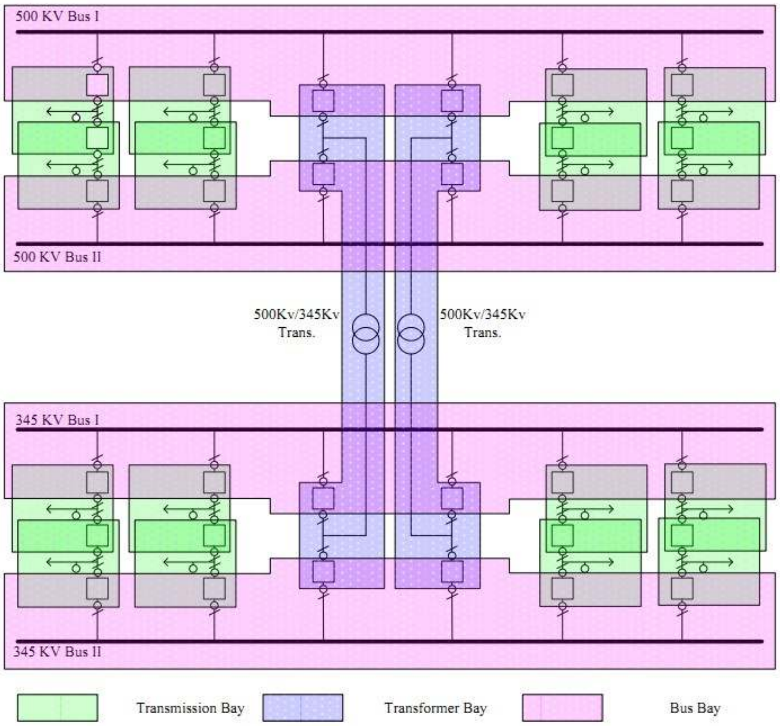


Figure 2 One Practical IEC 61850 Based SAS Layout

A. Substation Description

Table 1 shows the details of this substation layout with the number of lines, buses, transformers and other components used.

B. Transmission line bay configuration

Table 2 shows the components constituting each transmission line bay configuration. With this configuration, the network topology of this bay can be built as shown in Figure 3. To communicate with each other, all the devices are connected to a central Ethernet switch. It is important to note that in order to improve the reliability, two protection IEDs are used to provide redundancy. Breaker IED2 shown in Fig 3 is also connected to the Ethernet switch within the next bay.

For circuit breaker protection design, we consider to use one-and-a-half breaker arrangement in this specific IEC 61850 SAS. One-and-a-half breaker arrangement means a double busbar substation where, for two circuits, three circuit-breakers are connected in series between the two busbars, the circuits being connected on each side of the central circuit-breaker [10].

C. Transformer bay Configuration

For each transformer bay, Table 3 and Figure 4 show the configurations and basic component topology respectively. Compared to the transmission line bay, a control IED is included in this topology, to control and monitor the transformer tap changing status.

Similarly to the transmission line bay, two protection IEDs are used to be redundancy with each other's. Figure 4 shows the transformer bay network topology.

Table 1 Substation Details Description

Components Name	Numbers in Use	Locations
Bus	4	Bus Bays
Transformer Bay	2	Transformer Bays
Transmission Line Bay	16	Transmission Line Bays
Breaker IEDs	32	Within each bay
Protection IEDs	20	Within each bay
Control IEDs	2	Transformer Bays
Merging Units (MU)	20	Transmission Line and Transformer Bays
Ethernet Switches (ES)	19	Within each bay

Table 2 Per Transmission Line Bay Configuration

Components Name	Numbers in use
Merging Units (MU)	1
Breaker IEDs	3/2
Circuit Breakers	3/2
Protection IEDs	2
Ethernet Switches (ES)	1

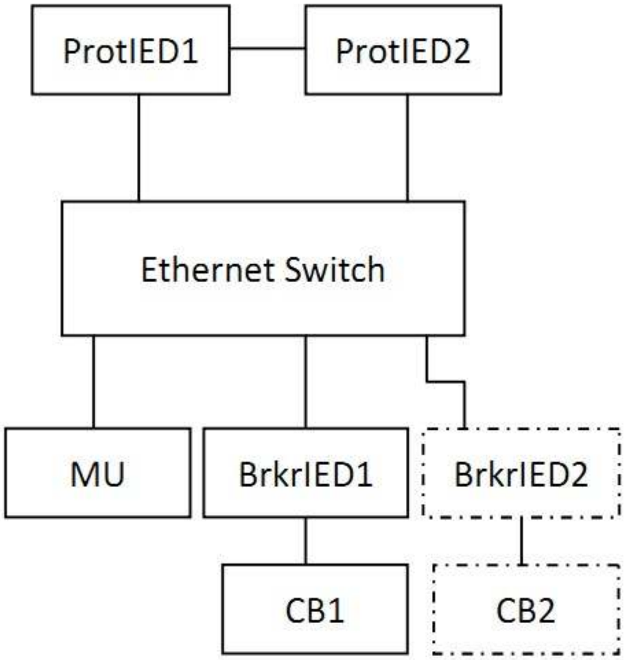


Figure 3 Transmission Line Bay Network Topology

Table 3 Per Transformer Bay Configuration

Components Name	Numbers in use
Merging Units (MU)	2
Breaker IEDs	4
Circuit Breakers	4
Protection IEDs	2
Control IEDs	1
Ethernet Switches (ES)	1

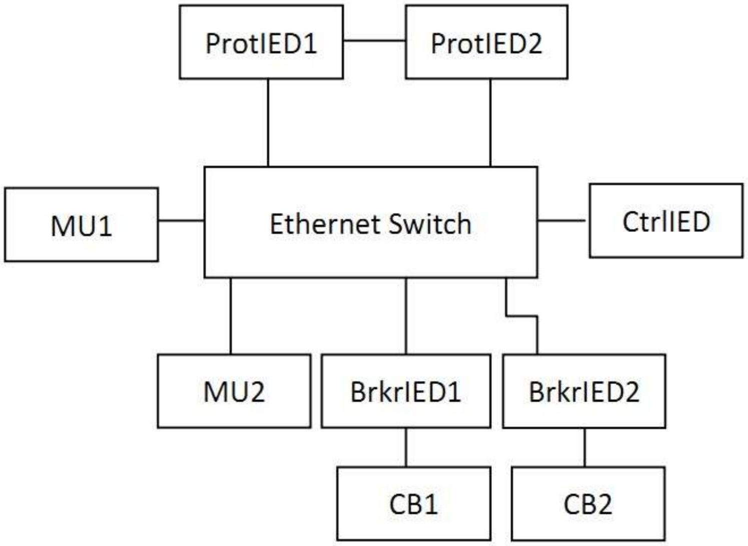


Figure 4 Transformer Bay Network Topology

D. Bus bay Configuration

Bus bays share the components with the transmission line bays and transformer bays and no control IEDs are used within bus bays. In reliability analysis, bus bays could only be considered with their failure effects.

3. RELIABILITY ANALYSIS AT THE BAY LEVEL

At the bay level of IEC 61850 SAS, we have used the reliability block diagram approach [11]. Reliability Block Diagram (RBD) is usually used to show and illustrate the network relationships in the reliability analysis of the complex systems. The structure of RBD can define the logical interaction of component failures required to support the system operation. Reliability block diagram approach works well when the intent is to find probability of a given condition. The RBDs of transmission line and transformer bays are described below.

3.1 Transmission Line Bay RBD

According to the transmission line network topology shown in Fig 3, it is possible to find the Reliability Block Diagram for each transmission line bay as shown in Figure 5. In this figure, since all the devices are critical to the system, basically they are connected in series. For Breaker IED2 and CB2, they will be discussed in details in next parts when considering a fault occurs in the system.

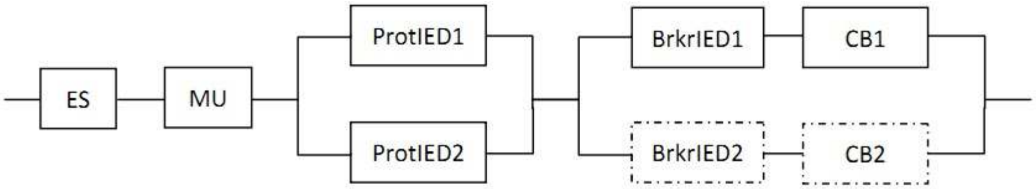


Figure 5 Transmission Line Bay RBD

3.2 Transformer Bay RBD

According to the transmission line network topology shown in Fig 4, it is possible to find the Reliability Block Diagram for each transmission line bay as shown in Figure 6. In this figure, since all the devices are critical to the system, basically they are connected in series.

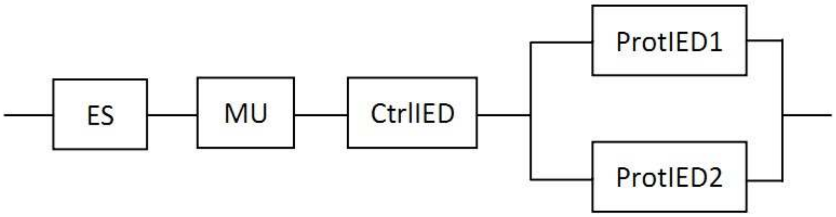


Figure 6 Transformer Bay RBD

3.3 Reliability and Mean Time to Failure (MTTF) by Using RBD

According to power systems reliability concept, for exponential distribution, reliability R(*t*) should be,

$$R_i(t) = e^{-\lambda_i t} \tag{3.1}$$

Mean value for exponential distribution is designated as Mean Time To Failure (MTTF), shown as,

$$MTTF_i = \int_0^\infty R_i(t)dt = \frac{1}{\lambda_i} \tag{3.2}$$

Since the each bay of IEC 61850 based SAS can be considered as a complex of parallel and series structures, it is necessary to consider the theoretical analysis of basic system only consisting of two basic components, series and parallel individually. Additionally, since all the devices can be recognized as repairable, the whole system will be considered as a repairable system.

A. Series Systems:

The series system structure and the Markov model for a repairable system are shown as in Figure 7(a) and Figure 7(b):

'U' represents Up, which means the component is working properly

'D' represents Down, which means the component is not working

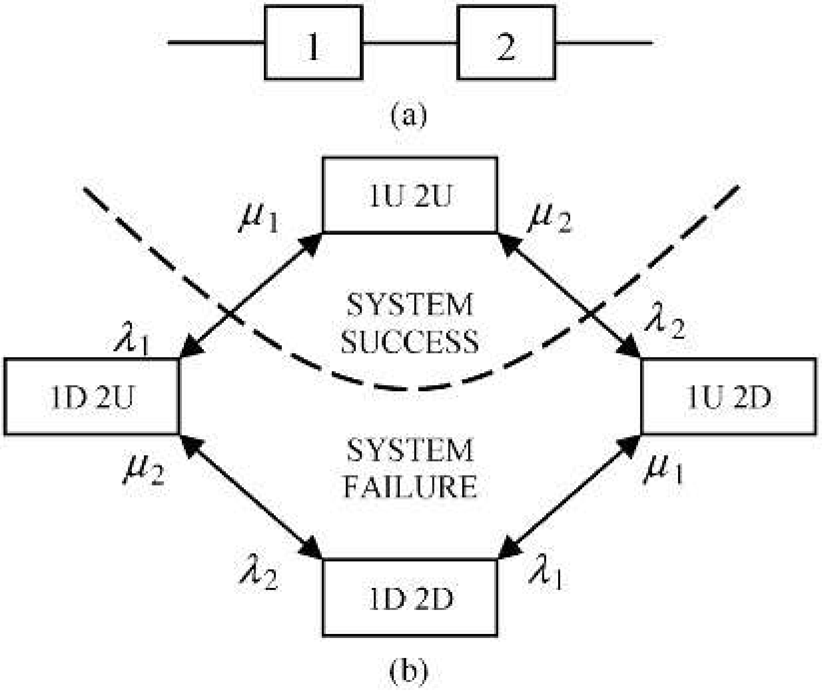


Figure 7 Repairable Series System(a) with Marcov Model(b)

Reliability of the series system shown as,

$$R_s(t) = R_1(t)R_2(t) = e^{-\lambda_1 t}e^{-\lambda_2 t} = e^{-(\lambda_1+\lambda_2)t} \tag{3.3}$$

Failure rate and MTTF are then obtained as,

$$MTTF_s = \int_0^\infty R_s(t)dt = \frac{1}{\lambda_1+\lambda_2} \tag{3.4}$$

$$\lambda_{series} = \lambda_1 + \lambda_2 \tag{3.5}$$

B. Parallel System:

The parallel system structure and the Markov model for a repairable system are shown as in Figure 8(a) and Figure 8(b):

'U' represents Up, which means the component is working properly

'D' represents Down, which means the component is not working

Reliability of the parallel system shown as,

$$R_p(t) = R_1(t) + R_2(t) - R_1(t)R_2(t) = e^{-\lambda_1 t} + e^{-\lambda_2 t} - e^{-(\lambda_1+\lambda_2)t} \tag{3.6}$$

Failure rate and MTTF are then obtained as,

$$MTTF_p = \int_0^\infty R_p(t)dt = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} - \frac{1}{\lambda_1+\lambda_2} \tag{3.7}$$

$$\lambda_{parallel} = \frac{\lambda_1\lambda_2(\mu_1+\mu_2)}{\lambda_1\mu_2 + \mu_1\lambda_2 + \mu_1\mu_2} \tag{3.8}$$

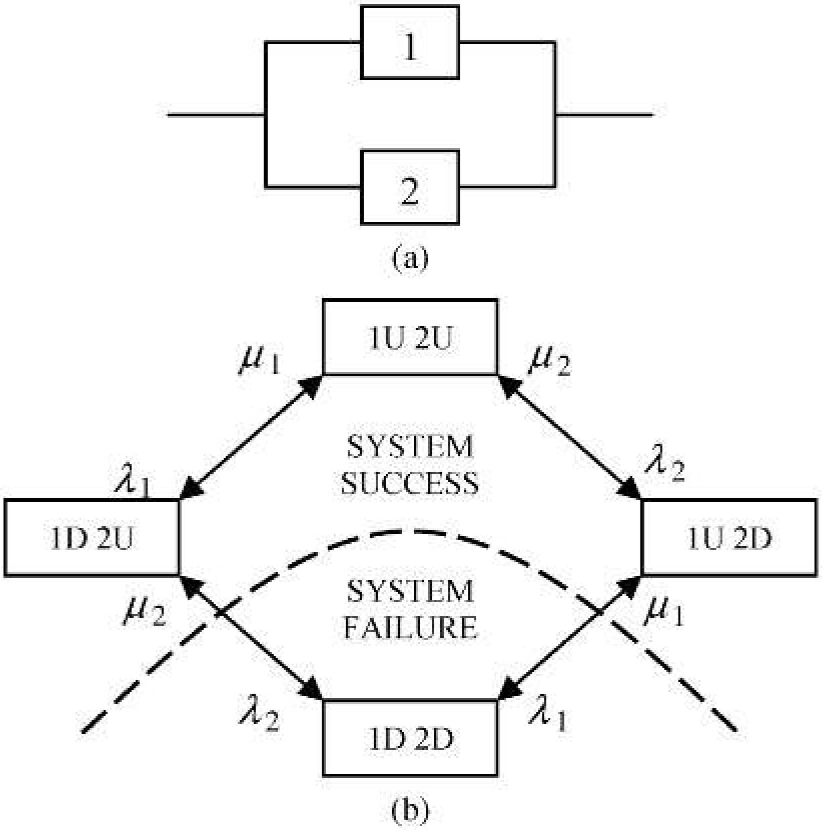


Figure 8 Repairable Parallel System(a) with Marcov Model(b)

4. RELIABILITY ANALYSIS AT SUBSTATION LEVEL

To understand how the failures at the bay level translate to the substation level, first we describe the Failure Mode and Effect Analysis (FMEA). Subsequently we will describe the reliability model at the substation level using the results of this FMEA.

4.1 Signal Flow within IEC 61850 Based SAS

IEC 61850 protocols provided powerful data exchanging channel and capacity. There are three kinds of major high priority signals: Sample Values, sent by merging units; Trip message sent by protection IEDs and GOOSE message sent by breaker IEDs.

When detecting faults on the transmission lines or transformers, merging units will generate and send the digitized sample values to protection IEDs through Ethernet switches. After receiving these signals, protection IEDs send trip messages to breaker IEDs to control the circuit breakers to open the circuit. Breaker IEDs will generate the highest priority GOOSE message to protect the circuits and send signals back to higher control level through the Ethernet network.

Any parts broken or any excessive delays on these messages will make the line/transformer protection fail to work and so the consequences are severe, not only on the fault lines but also on other lines or even one entire bus.

4.2 Failure Modes & Effects Analysis Based on Substation Protection

4.2.1 Transmission Line Bay Failure Modes & Effects

Since two transmission lines share three circuit breakers, the two transmission line bays would be considered and analyzed together to obtain their failure modes and effects. As Line 1 and Line 2 are symmetrical with each other, only one fault on either Line 1 or Line 2 would be considered for illustration. The other one has the similar results. In this part, ESi, MUi, IEDi stand for the devices in within the ith bay. Figure 9 shows the two transmission line bays with a fault on Line 1.

According to Figure 5, the Transmission Line Bay RBD (depicted in Fig 5), since ES, MU, ProtIEDs, and BrkrIED1 are connected in series mode,

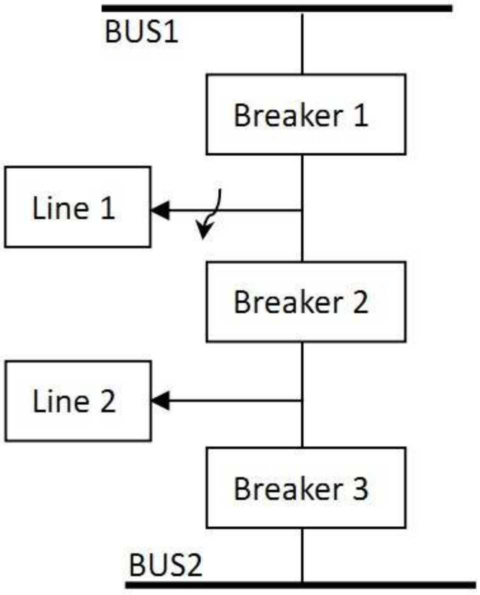


Figure 9 Two Transmission Line Bays with a Fault on Line 1

these components can be combined as a block for determining the failure effects. The following are the possible failure modes and their effects.

A. All components operate as intended:

When there is a fault on Line1, the MU will detect the fault on Line 1 and send the digitized messages to ProtIEDs through the ES. Then the ProtIEDs will send a GOOSE message over the network to trip BrkrIED1 and BrkrIED2 to open the CB. In this case, Line1 is correctly tripped by the fault and Line2, Bus1 and Bus 2 will not be affected.

B. One or more components of ES1, MU1, ProtIED1, BrkrIED1 fail to operate:

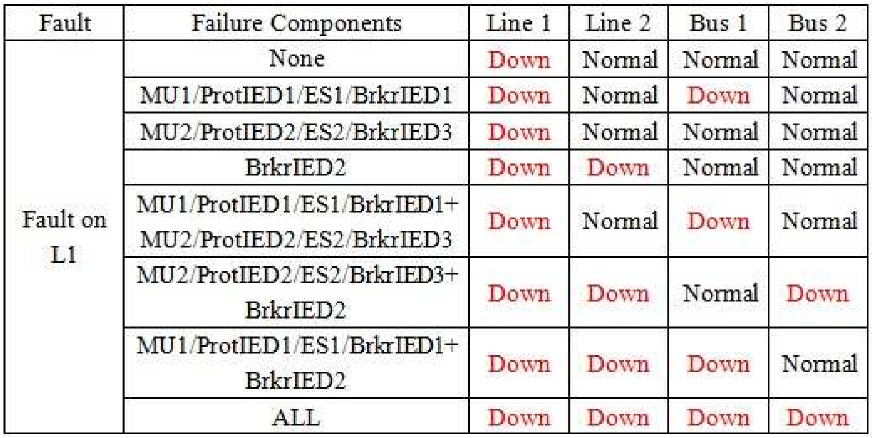
When the fault occurs, CB1 and CB2 will not open at first since the network in Bay1 fails to work. When this fault comes to affect the Line 2 across CB2, the network in Bay2 will be able to clear this fault by tripping the CB2 to open. In this case, Line 1 and Bus 1 will be isolated as bus 1 is connected to Line 1 because of the failure of CB1 to operate.

C. BrkrIED2 fails to operate

Fault will transfer to Line 2 across the failed CB2, but could be cleared by CB1 and CB3. In this case, Line 1 and Line 2 will be isolated.

Based on this analysis, Table 4 gives the summary of all the failure modes and effects, when considering all the possible component failure.

Table 4 Summary of Failure Effects in Two Transmission Line Bays



Fault	Failure Components	Line 1	Line 2	Bus 1	Bus 2
Fault on L1	None	Down	Normal	Normal	Normal
	MU1/ProtIED1/ES1/BrkrIED1	Down	Normal	Down	Normal
	MU2/ProtIED2/ES2/BrkrIED3	Down	Normal	Normal	Normal
	BrkrIED2	Down	Down	Normal	Normal
	MU1/ProtIED1/ES1/BrkrIED1+ MU2/ProtIED2/ES2/BrkrIED3	Down	Normal	Down	Normal
	MU2/ProtIED2/ES2/BrkrIED3+ BrkrIED2	Down	Down	Normal	Down
	MU1/ProtIED1/ES1/BrkrIED1+ BrkrIED2	Down	Down	Down	Normal
	ALL	Down	Down	Down	Down

4.2.2 Transformer Bay Failure Modes & Effects Analysis

The most serious problems in transformers result from winding faults. Furthermore, only the busses in High-Voltage (HV) side will be illustrated to check the fault effect because they are symmetrical with each other. Figure 10 shows the High-Voltage side transformer bays with winding faults.

According to the Transformer Bay RBD, components ES, MU, CtrlIED and ProtIEDs are in a series mode which means that for purpose of reliability analysis, all these components can be integrated into one block. In this case, only BrkrIED1, BrkrIED2 and the combinations of ES, MU, CtrlIED and ProtIED are left to check the failure modes and effects. Following are the failure modes and effects.

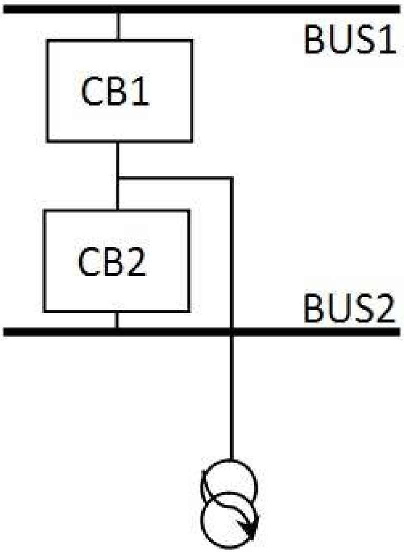


Figure 10 HV Side Transformer Bays with Winding Fault

A. All component are normal

When the winding fault occurs, MU on the HV side can detect the fault and send the message over the Ethernet network to the CrtlIED and ProtIEDs. Then these IEDs will generate the GOOSE message to trip the CB1 and CB2. In this case, the fault will be isolated correctly on the transformer side, and Bus1, Bus2 will not be affected.

B. One or more of ES, MU, CtrlIED and ProtIEDs fail to operate

When one or more of these components fail to work, the network within this bay cannot respond to deal with the winding fault. In other words, no CBs will be tripped to open and all the transformers and buses need be isolated.

C. BrkrIED1 or BrkrIED2 fails to operate

The Ethernet network will transfer the message to trip the CBs. However, since the BrkrIEDs fail to operate, either Bus1 or Bus2 will be affected under this condition.

Based on this analysis, Table 5 gives the summary of all the failure modes and effects, when considering all the possible component failure.

Table 5 Summary of Failure Effects in HV Transformer Bay

Fault	Failure Components	Bus 1	Bus 2
Transformer Winding Fault	None	Normal	Normal
	ES/MU/ProtIED/CtrlIED	Down	Down
	BrkrIED1	Down	Normal
	BrkrIED2	Normal	Down
	ES/MU/ProtIED/CtrlIED + BrkrIED1	Down	Down
	ES/MU/ProtIED/CtrlIED + BrkrIED2	Down	Down
	BrkrIED1,BrkrIED2	Down	Down
	ES/MU/ProtIED/CtrlIED + BrkrIED1+ BrkrIED2	Down	Down

4.3 Integration at the Substation Level

Now we will use the results of the FMEA to analyze the impact at the substation level. Since IEC 61850 based SAS combines the modern communication and traditional physical substation devices, it is hard to consider all the situations and device status. However, some reasonable assumptions can be made to simplify the analysis. First we will outline the assumptions made, and then we will describe the state space approach used to translate the effect of bay level failures to substation level.

4.3.1 Assumptions

Comparing to the simple two-component systems, IEC 61850 SAS includes variety of complex devices, which build a more complex structures. In this case, we need to consider different conditions when dealing with the reliability analysis, instead of direct calculations. Even though, we still can use a similar methodology that we used above applying to the IEC 61850 SAS, with certain assumptions.

IEC 61850 intends to use fiber optics instead of copper wires, which could increase the system reliability. Meanwhile, modern communication itself has variety of protocols and schemes to make the cyber system reliable. Because of this, the Ethernet communication media between devices are very reliable, and are not considered in the following analysis. We will combine the CB with the BrkrIED to act as one part for analysis, which means we can assume that BrkrIEDs acts as the CB and Breaker IED at the same time.

For MU, usually a Timing Source is connected to synchronize the system. This is to make sure the communication over the whole system is in a normal state. This device typically is designed and maintained very well as the whole communication system will suffer as a result of its failure. We can assume the TS are very reliable along with the MU. For simplicity, the MU and Instrument Transformer are regarded as one unit.

For modern substation protection system, the main functional parts of protection system are usually designed to be located in isolated places where the physical distances between them are far enough to avoid mutual interference [12]. In this case, it is reasonable for us to assume all the components of IEC 61850 SAS are independent of each other in most cases. What's more, the component state durations are assumed to be exponentially distributed.

Within this section, transmission line bays and transformer bays will be analyzed respectively, and Ethernet network topologies are not considered. Table 6 shows a reliability data for different components, including the MTTF (Years), FR, MRT (Days) and RpR.

Table 6 General Reliability Data of Each Component

	MTTF	FR λ	MRT	RpR μ
ES	100	0.01	7	52.14
ProtIED	100	0.01	7	52.14
CrtlIED	100	0.01	7	52.14
MU	100	0.01	7	52.14
BrkrIED	100	0.01	7	52.14

For every component, only UP and Down states are considered in this paper as shown in Figure 11.

Figure 11 State Diagram for Each Component

4.3.2 State Space Approach

From tables 4 and 5, it can be seen that the cyber components can be considered in groups and the various groups have different effects on the physical system, ie, the buses and lines. To find the probabilities of the various effects, state space approach [13], can be conveniently used. First the equivalent failure and repair rates of composite groups can be determined and then the state space of the composite components can be created.

4.4 Case Studies

4.4.1 Modeling the Effect of Transmission Line Bay Failures

Based on reliability block diagrams shown in Figures 3 and 7 and according to the failure mode and effects analyses summarized in Table 4, there are three major blocks to be considered in the state space model (see Figure 12). For ProtIED*, two ProtIEDs in parallel provide redundancy for each other.

Figure 12 Three Major Components Blocks in Transmission Lines Bay

For new composite components 1, 2 and 3, we can obtain the equivalent failure rates and repair rates by using network reduction methods. For composite components 1 and 2, we call the equivalent failure and repair rates by λ1 and μ1.

$$\lambda_1 = \lambda_{ES} + \lambda_{\Pr o} + \lambda_{MU} + \lambda_{Brkr} = 0.04$$

$$\mu_1 = f / P_f = \frac{P_{ESu} P_{\Pr ou} P_{MUu} P_{Brkru} (\lambda_{ES} + \lambda_{\Pr o} + \lambda_{MU} + \lambda_{Brkr})}{1 - P_{ESu} P_{\Pr ou} P_{MUu} P_{Brkru}} = 52.11$$

For composite components 3, we denote the equivalent failure and repair rates by λ2 and μ2:

$$\lambda_2 = \lambda_{Brkr} = 0.01$$

$$\mu_2 = \mu_{Brkr} = 52.14$$

Figure 13 shows the State Transition Diagram for this system.

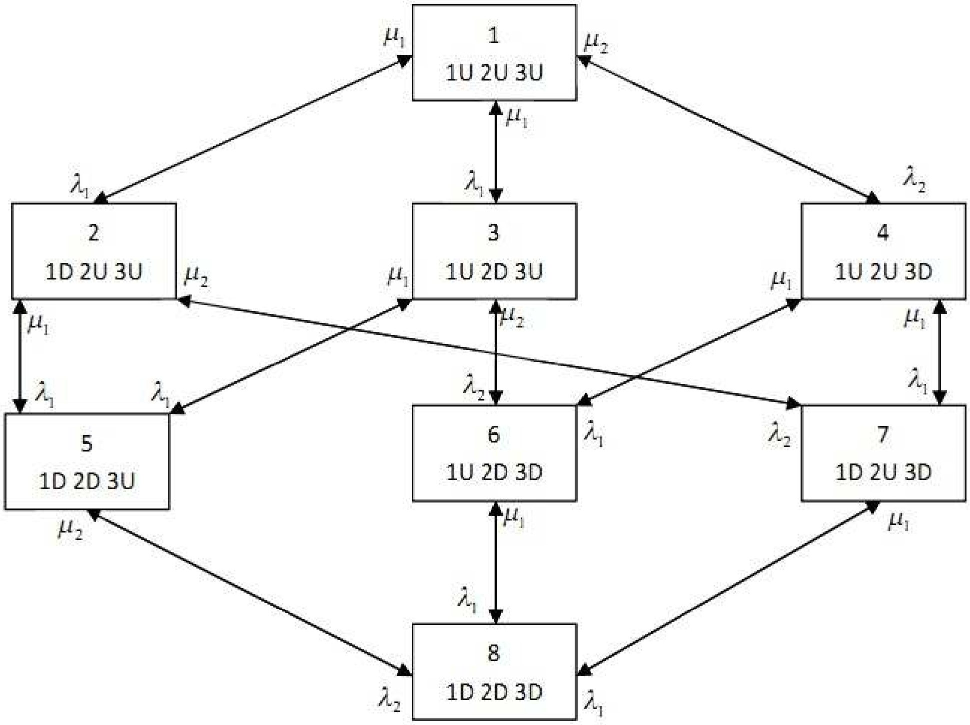


Figure 13 State Transition Diagram for Transmission Line Bay Systems

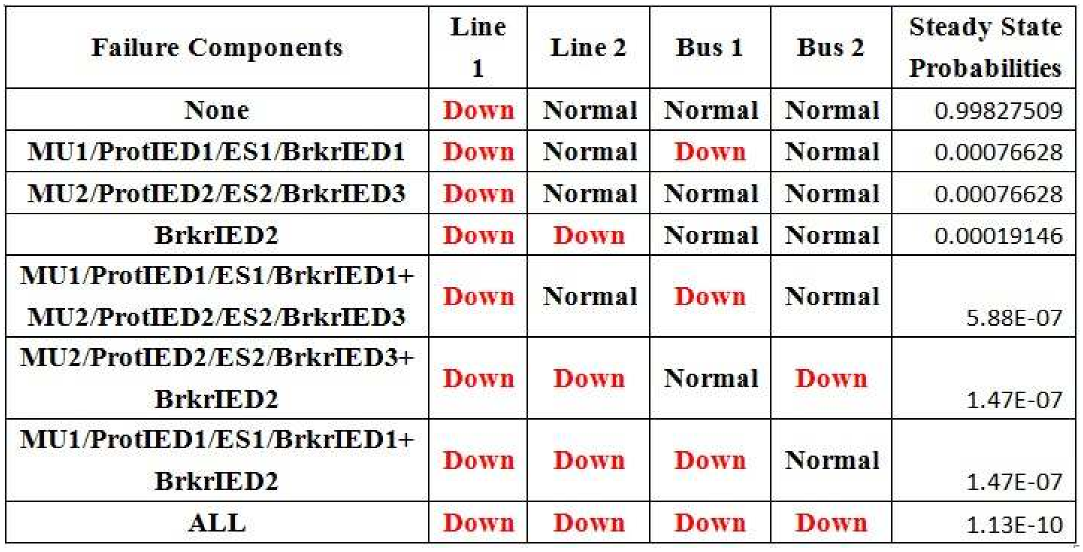
By constructing the Transition Matrix R of the 8-states systems and using:

$$R^T * \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_n \end{bmatrix} = 0 \tag{4.1}$$

$$\sum_{i=1}^{n} P_i = 1 \tag{4.2}$$

, different steady state probabilities can be calculated, shown in Table 7.

Table 7 Steady State Probabilities of Failure Effects (Transmission Lines)



Failure Components	Line 1	Line 2	Bus 1	Bus 2	Steady State Probabilities
None	Down	Normal	Normal	Normal	0.99827509
MU1/ProtIED1/ES1/BrkrIED1	Down	Normal	Down	Normal	0.00076628
MU2/ProtIED2/ES2/BrkrIED3	Down	Normal	Normal	Normal	0.00076628
BrkrIED2	Down	Down	Normal	Normal	0.00019146
MU1/ProtIED1/ES1/BrkrIED1+ MU2/ProtIED2/ES2/BrkrIED3	Down	Normal	Down	Normal	5.88E-07
MU2/ProtIED2/ES2/BrkrIED3+ BrkrIED2	Down	Down	Normal	Down	1.47E-07
MU1/ProtIED1/ES1/BrkrIED1+ BrkrIED2	Down	Down	Down	Normal	1.47E-07
ALL	Down	Down	Down	Down	1.13E-10

4.4.2 Modeling the Effect of Transformer Bay Failures

Similar to the Transmission Line Bay, multiple devices can be combined into composite components. Figure 14 shows the three major blocks to be analyzed. This figure is based on the structure of Figure 10 and Figure 14.

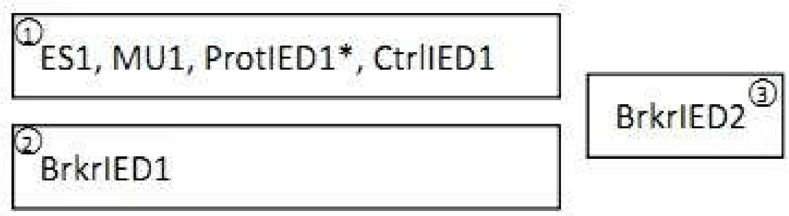


Figure 14 Three Major Components Blocks in Transformer Bay

For new composite components 1, 2 and 3, we can obtain the equivalent failure rates and repair rates by using network reduction methods. For composite components 1, we call the equivalent failure and repair rates by λ1 and μ1. For composite components 2 and 3, we call the equivalent failure and repair rates by λ2 and μ2.

For composite system 1:

$$\lambda_1 = 0.03000383$$

$$\mu_1 = 52.143$$

For composite systems 2 and 3:

$$\lambda_2 = \lambda_{Brkr} = 0.01$$

$$\mu_2 = \mu_{Br\mathrm{k}r} = 52.14$$

For State Space analysis, Figure 15 shows the State Transition Diagram for this system.

By constructing the Transition Matrix R and using (4.1) and (4.2), steady state probabilities of each failure effects are given in Table 8.

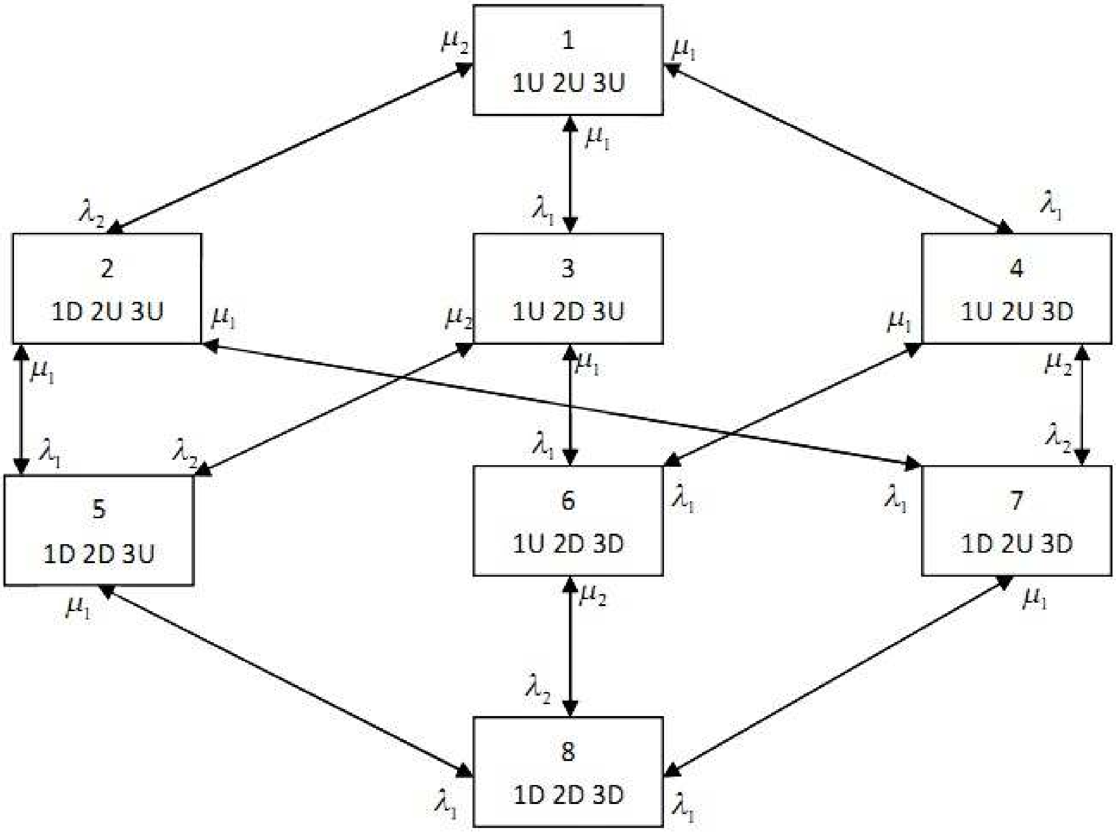


Figure 15 State Transit Diagram for Transformer Bays Systems

4.5 Summary

For a set of two lines, protected by three breakers, Tables 7 and 8 give the probabilities of isolating the various components of the substation as a result of the cyber failures. There are 16 lines arranged in 8 pairs. Although only one pair has been analyzed, the analysis is the same for the remaining pairs. The probabilities calculated

Table 8 Steady State Probabilities of each Failure Effects (Transformer)

Fault	Failure Components	Bus 1	Bus 2	Steady State Probabilities
Transformer Winding Fault	None	Normal	Normal	0.9987
	ES/MU/ProtIED/CtrlIED	Down	Down	1.9153e-4
	BrkrIED1	Down	Normal	5.7464e-4
	BrkrIED2	Normal	Down	5.7464e-4
	ES/MU/ProtIED/CtrlIED + BrkrIED1	Down	Down	1.1021e-7
	ES/MU/ProtIED/CtrlIED + BrkrIED2	Down	Down	3.3066e-7
	BrkrIED1,BrkrIED2	Down	Down	1.1021e-7
	ES/MU/ProtIED/CtrlIED + BrkrIED1+ BrkrIED2	Down	Down	6.3417e-11

in Table 8 are critical for modeling at the system level. These values indicate the probabilities of various components failing to operate as they should if the cyber part did not have any failure and was functioning correctly. This is like the hidden failures in protection system which can lead to wider outages than the intended ones as a result of faults.

For example, it can be seen from Table 7, that if the fault is on L1 and there is no failure of cyber components, then L1 will be isolated and down. But for various cyber failures, more than L1 can be down. For some combinations of cyber failures, L1 and L2 can both be down and for others; the buses can be also down leading to much more serious outages of transmission lines.

So this analysis basically provides the probabilities of various cyber outages and their impact on outage of lines and buses in the substation. This information can then be incorporated into the composite system reliability evaluation methods to study the effect on the whole bulk power system.

5. IEC 61850 SAS REDUNDANCY AND TOPOLOGY ANALYSIS

5.1 Introduction

In an actual power substation system, especially if high reliability of protections is required, redundancy is an important issue. Since IEC 61850 doesn't give specific redundancy settings, most of current IEC 61850 SAS set the redundancy depending on customer requirements. Typical redundancy settings are parallel redundant communication system or ring redundancy system [14].

For network topologies, since IEC 61850is based on Ethernet Switches, there are several topologies for communication. Different network topologies provide different features for the specific substation. Currently, without setting the redundant ES, three major topologies are mostly used in current communication network: Bus, Star and Ring.

5.2 IEC 61850 SAS Redundancy

The fault analysis and reliability calculations in section 4 do not include the redundancy considerations. To avoid single point of failures, there need to be two process bus segments, which connect the sensors (i.e. MU) with the protection and breaker each. Each segment may contain an external or embedded switch [15]. If any component of one segment fails, the protection of only this segment is out, and the other one is still working to support the entire system. All the following calculations and data are based on Table 6.

5.2.1 Alternative Transmission Line Bay Design Reliability

Considering the vulnerability of single set devices system, a design with duplicating the critical components within each transmission line bay and transformer bay is given in Figure 16. Protection 2, Switch 2 and the rest of red color parts are performing redundancy functions. For transformer bay, one Control IED is connected to Switch 2. More details are given below.

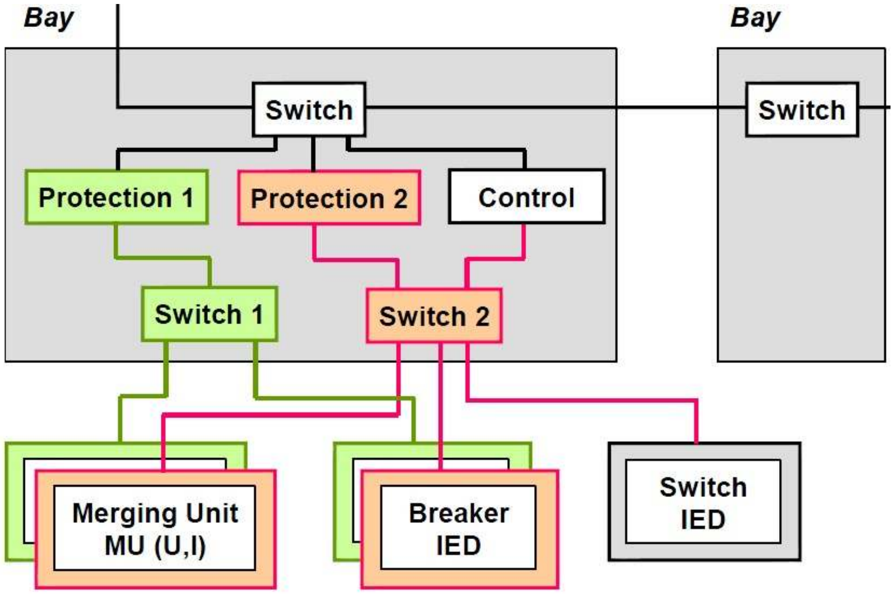


Figure 16 Alternative Process Bus Design with Redundancy Concern

Based on the redundancy concerns above, alternative transmission line bay design is given in Figure 17.

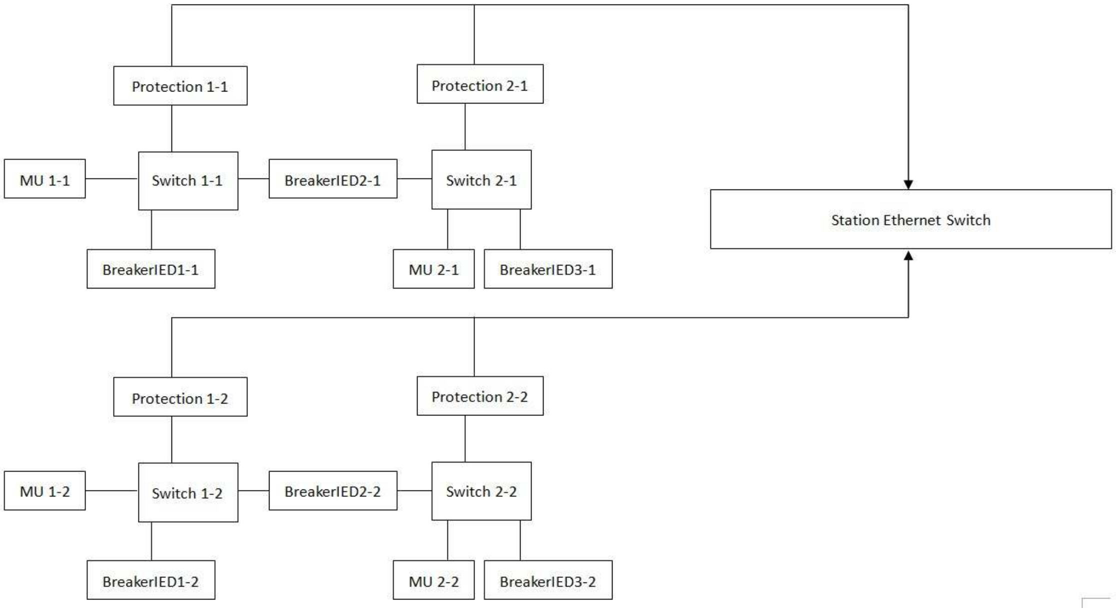


Figure 17 Alternative Transmission Line Bay Network Topology

Compared to Figure 3, two sets of Ethernet Switches and IEDs are considered in each transmission line bay. As with the previous design, we still use one-and-a-half breaker arrangement.

For new composite components 1, 2 and 3, we can obtain the equivalent failure rates and repair rates by using network reduction methods. For composite components 1 and 2, we call the equivalent failure and repair rates by λ1 and μ1. For component 3, we call the equivalent failure and repair rates by λ2 and μ2. Major component blocks are referred to Figure 18.

Figure 18 Alternative Major Components Blocks in Transmission Lines Bay

For the components 1, 2:

Failure Rate: $\lambda_1 = 0.00001534$

Repair Rate: $\mu_1 = 38.35$

For component 3:

Failure Rate: $\lambda_2 = 0.000003834$

Repair Rate: $\mu_2 = 104.28$

For State Space analysis, Figure 19 shows the State Transition Diagram for this system.

Transition rate matrix can be given as follow in Table 9, according to:

$$a_{ij} = \lambda_{ij}, i \neq j \tag{5.1}$$

$$a_{ij} = -\sum_{j} \lambda_{ij} \tag{5.2}$$

By constructing the Transition Matrix R and using (1) and (2), steady state probabilities of each failure effects are given in Table 10

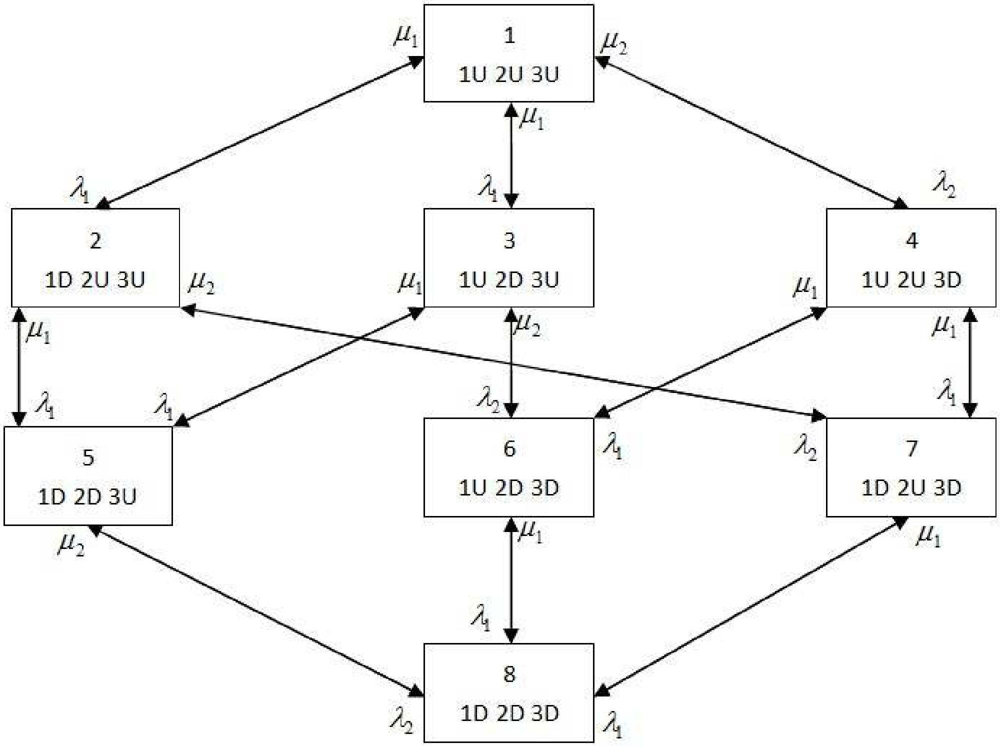
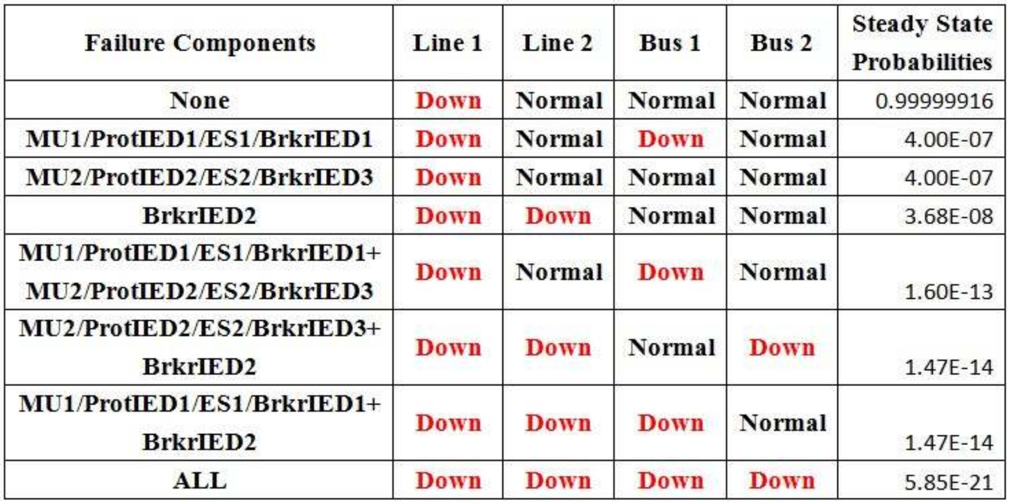


Figure 19 State Transition Diagram for Alternative Transmission Line Bay

Table 9 Transition Rate Matrix for Alternative Transmission Line Bay

	1	2	3	4	5	6	7	8
1	$-2\lambda_1-\lambda_2$	λ_1	λ_1	λ_2				
2	μ_1	$-\lambda_1-\lambda_2-\mu_1$			λ_1		λ_2	
3	μ_1		$-\lambda_1-\lambda_2-\mu_1$		λ_1	λ_2		
4	μ_2			$-2\lambda_1-\mu_2$		λ_1	λ_1	
5		μ_1	μ_1		$-2\mu_1-\lambda_2$			λ_2
6			μ_2	μ_1		$-\mu_1-\mu_2-\lambda_1$		λ_1
7		μ_2		μ_1			$-\mu_1-\mu_2-\lambda_1$	λ_1
8					μ_2	μ_1	μ_1	$-2\mu_1-\mu_2$

Table 10 Steady State Probabilities of Each Failure Effects (Alternative Transmission Line)



Failure Components	Line 1	Line 2	Bus 1	Bus 2	Steady State Probabilities
None	Down	Normal	Normal	Normal	0.99999916
MU1/ProtIED1/ES1/BrkrIED1	Down	Normal	Down	Normal	4.00E-07
MU2/ProtIED2/ES2/BrkrIED3	Down	Normal	Normal	Normal	4.00E-07
BrkrIED2	Down	Down	Normal	Normal	3.68E-08
MU1/ProtIED1/ES1/BrkrIED1+ MU2/ProtIED2/ES2/BrkrIED3	Down	Normal	Down	Normal	1.60E-13
MU2/ProtIED2/ES2/BrkrIED3+ BrkrIED2	Down	Down	Normal	Down	1.47E-14
MU1/ProtIED1/ES1/BrkrIED1+ BrkrIED2	Down	Down	Down	Normal	1.47E-14
ALL	Down	Down	Down	Down	5.85E-21

5.2.2 Alternative Transformer Bay Design Reliability

Based on the redundancy concern above, alternative transmission line bay design is given in Figure 20.

Two sets of Ethernet Switches and IEDs are installed in this system, but Control IED is only connected to ES2. In this case, RBD of this design is given in Figure 21, which showing the basic reliability relationships between all the cyber parts of the IEC 61850 electric substation.

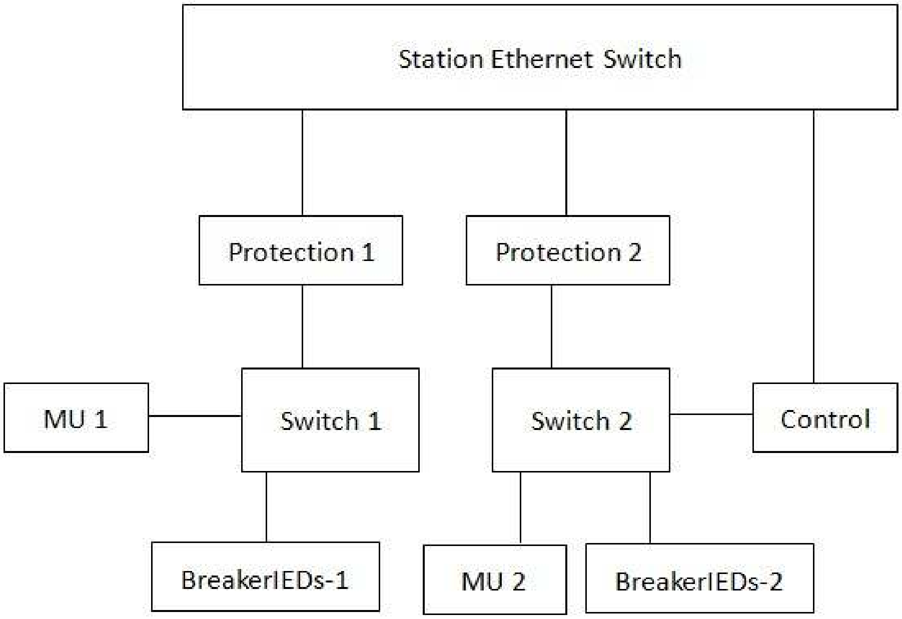


Figure 20 Alternative Transformer Bay Network Topology

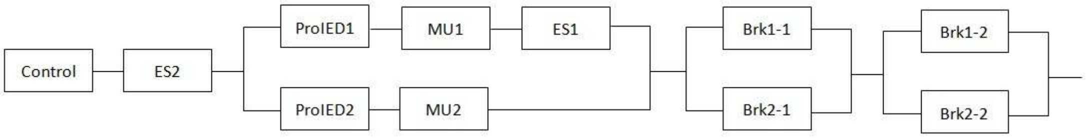


Figure 21 Alternative Transformer Bay RBD

For new composite components 1, 2 and 3, we can obtain the equivalent failure rates and repair rates by using network reduction methods. For composite components 1, we call the equivalent failure and repair rates by λ1 and μ1. For composite components 2 and 3, we call the equivalent failure and repair rates by λ2 and μ2. Major component blocks are referred to Figure 22.

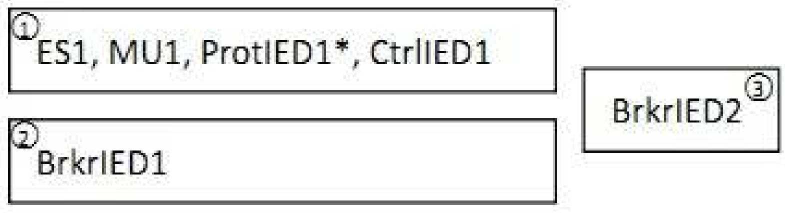


Figure 22 Alternative Major Components Blocks in Transformer Bay

Failure rate and repair rate are given as follows,

For component 1:

Failure Rate: $\lambda_1 = 0.02002300$

Repair Rate: $\mu_1 = 52.177$

For components 2, 3:

Failure Rate: $\lambda_2 = 0.000003836$

Repair Rate: $\mu_2 = 104.17$

For State Space analysis, Figure 23 shows the State Transition Diagram for this system.

Basically the methodology is similar with the original design. The things need to be modified are failure rates and repair rates, and the relationships of them. According to the State Transition Diagram, we could still conclude the Transition Rate Matrix for reliability calculations.

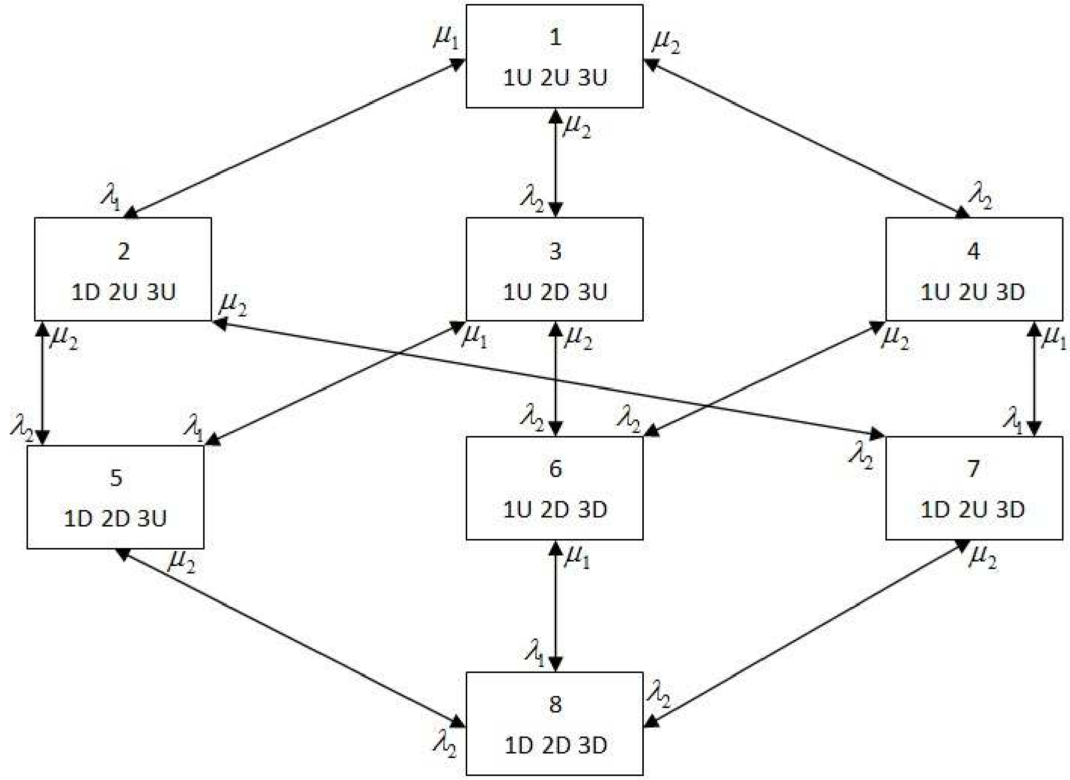


Figure 23 State Transition Diagram for Alternative Transformer Bay

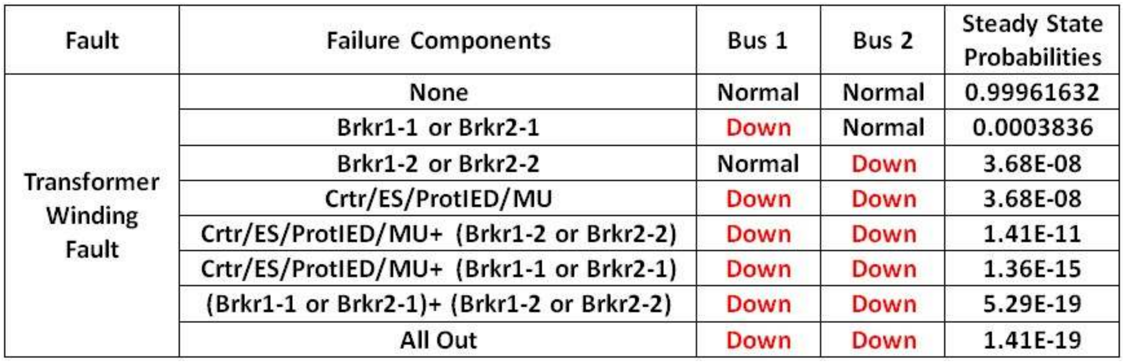
Transition rate matrix can be given as follow in Table 11, according to (11) and (12)

Table 11 Transition Rate Matrix for Alternative Transformer Bay

	1	2	3	4	5	6	7	8
1	$-\lambda_1-2\lambda_2$	λ_1	λ_2	λ_2				
2	μ_1	$-2\lambda_2-\mu_1$			λ_2		λ_2	
3	μ_2		$-\lambda_1-\lambda_2-\mu_2$		λ_1	λ_2		
4	μ_2			$-\lambda_1-\lambda_2-\mu_2$		λ_2	λ_1	
5		μ_2	μ_1		$-\mu_1-\mu_2-\lambda_2$			λ_2
6			μ_2	μ_2		$-2\mu_2-\lambda_1$		λ_1
7		μ_2		μ_1			$-\mu_1-\mu_2-\lambda_2$	λ_2
8					μ_2	μ_1	μ_2	$-2\mu_2-\mu_1$

By constructing the Transition Matrix R and using (1) and (2), steady state probabilities of each failure effects are given in Table 12

Table 12 Steady State Probabilities of Each Failure Effects (Alt Transformer)



Fault	Failure Components	Bus 1	Bus 2	Steady State Probabilities
Transformer Winding Fault	None	Normal	Normal	0.99961632
	Brkr1-1 or Brkr2-1	Down	Normal	0.0003836
	Brkr1-2 or Brkr2-2	Normal	Down	3.68E-08
	Crtr/ES/ProtIED/MU	Down	Down	3.68E-08
	Crtr/ES/ProtIED/MU+ (Brkr1-2 or Brkr2-2)	Down	Down	1.41E-11
	Crtr/ES/ProtIED/MU+ (Brkr1-1 or Brkr2-1)	Down	Down	1.36E-15
	(Brkr1-1 or Brkr2-1)+ (Brkr1-2 or Brkr2-2)	Down	Down	5.29E-19
	All Out	Down	Down	1.41E-19

5.3 IEC 61850 SAS Communication Topology

Based on Ethernet network, there are several topologies for communication. Different network topologies provide different features for the specific substation. Currently, without providing the redundant ES, three major topologies are mostly used in current communication network: Bus, Star and Ring.

5.3.1 Bus Topology

The principle of Bus topology is to use the Bus Ethernet to connect the switchyard and the control center. Figure 24 shows a general bus topology used in the Station Bus of the IEC 61850 SAS [16].

Advantages are Easy-setup, low cost with higher reliability in the long run. Disadvantages are Low security, limited cable length and long delay.

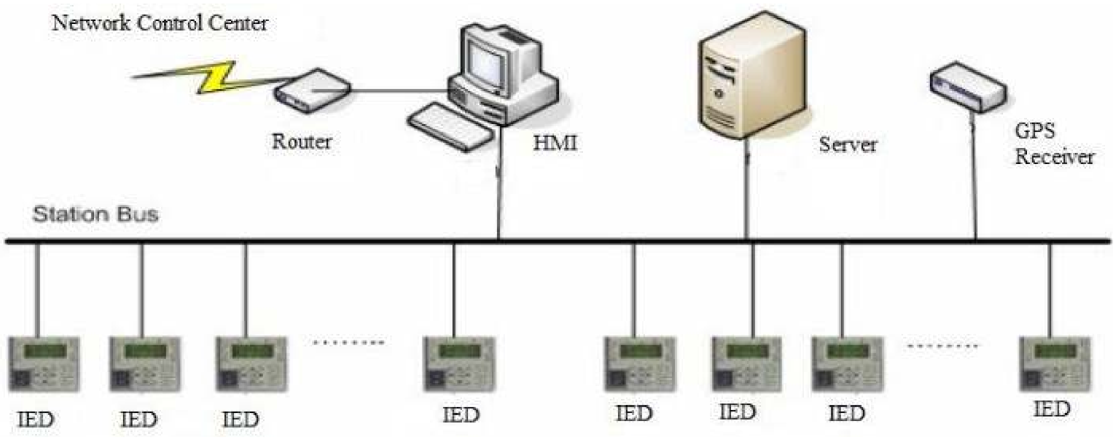


Figure 24 Bus Topology Used in Station Bus of IEC 61850 SAS

5.3.2 Star Topology

As for Star topology shown by Figure 25, one critical Ethernet Switch is used to connect each bay unit.

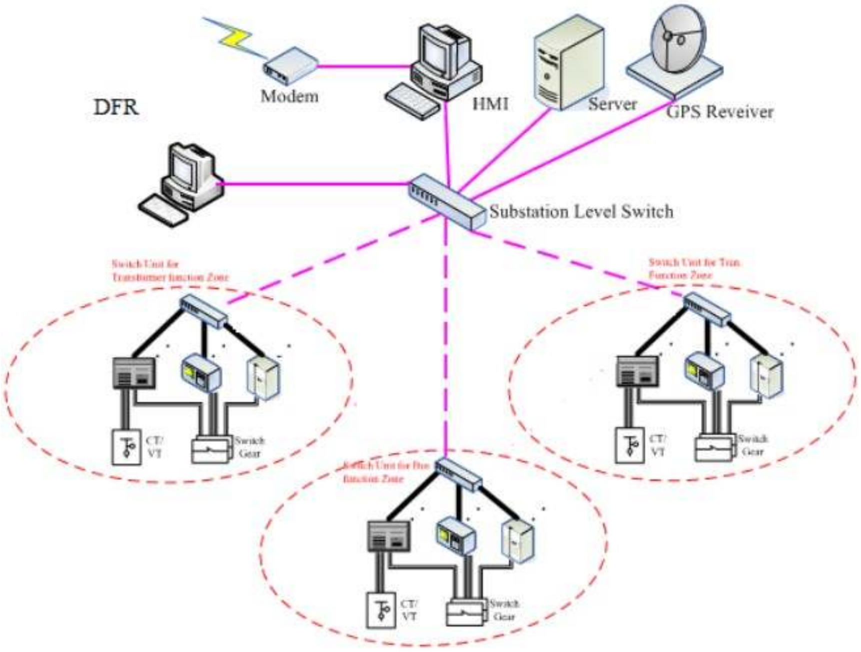


Figure 25 Star Topology Used in Station Bus of IEC 61850 SAS

Advantages: Simplicity of operation, lowest delay, good devices isolation

Disadvantages: Lower reliability, too much dependency on the critical Ethernet Switch

5.3.3 Ring Topology

Similar to the Star topology and also based on Ethernet Switch, Ring topology connects all the devices in a ring and provides the dual-path messages sending and receiving, shown in Figure 26.

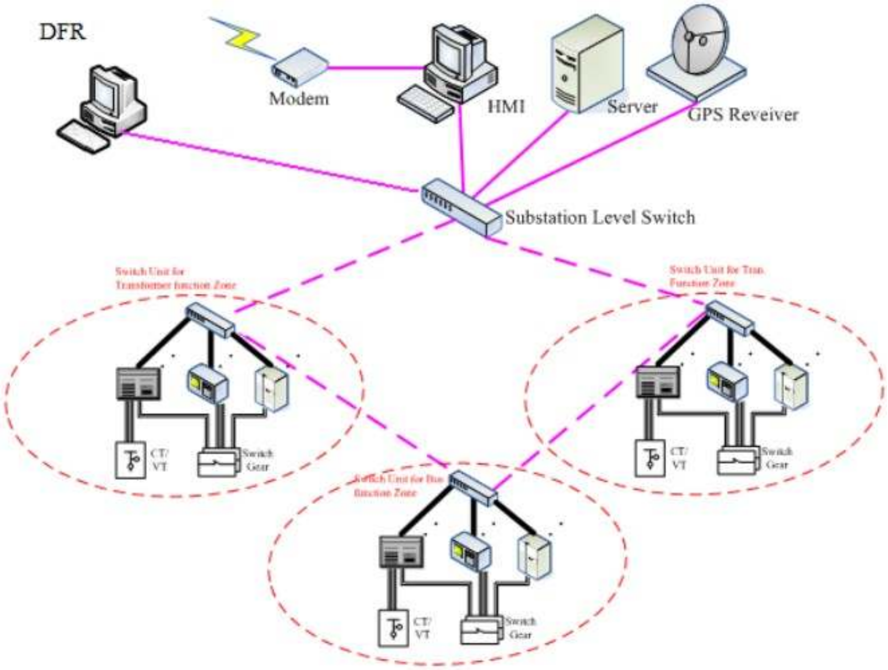


Figure 26 Ring Topology Used in Station Bus of IEC 61850 SAS

Advantages: No critical Ethernet Switch and low chance of collision.

Disadvantages: Slow transit speed and higher network load.

In actual communication network, redundancy is an important factor to increase the system reliability. Based on redundancy considerations, many other topologies are used to build the substation network, such as Cascaded Topology, Star-Ring Topology and Redundant-ring Topology.

5.4 Summary

In this section, IEC 61850 SAS redundancy and several communication topologies are discussed. Since redundancy is very important in power substation protection system, alternative transmission line and transformer structure design are considered in this section. Basic design concept can be found in Figure 16.

Reliability of the alternative transmission line bay and transformer bay are calculated, based on state space methodology as well. From Table 10 and Table 12, we can find when considering redundancy, whether the failure probabilities have been reduced compared to non-redundancy design in section 4. In this case, the reliability of the entire system has been improved.

Different communication topologies with advantages and disadvantages have been introduced in this section. Certain topologies will be used depends on different environmental requirements or customers' requests, such as reliability or communication delay.

6. CONCLUSIONS AND OUTLOOK

IEC 61850 Based Substation Automation System is still a relatively new technology in the power industry. The system combines diverse cyber and physical systems technology.

In this thesis we provide a holistic approach for analyzing the reliability of the major components of the substation. In particular we analyze different failure modes of the various bays. The paper illustrates how the block diagram and state space approaches can be combined to model and analyze the reliability of this system. Using block diagram one can visualize the series and parallel effects and generate composite components. By using the state space methods, the steady state probability of each failure effects were calculated for different bay units. These probabilities can be further used in the modeling of the composite power system to analyze the loss of load probabilities.

Alternative design with redundancy consideration and different communication topologies have been discussed after the non-redundancy reliability calculation. Reliability of the specific IEC 61850 SAS has been significant approved when adding redundancy components to the system. For future work, the reliability of different communication topologies can be developed based on different network message mechanism.

The work reported in this thesis can be used to evaluate the following:,

- For a set of two lines, protected by three breakers, this project gives the probabilities of isolating the various components of the substation as a result of the cyber failures

- Possibilities of wider outages resulting from single line fault or single transformer fault have been explored.
- These results can then be incorporated into the composite system reliability evaluation methods to show the effect on the whole bulk power system.

REFERENCES

[1] C. Singh and A. Sprintson, "Reliability assurance of cyber-physical power systems," in Power and Energy Society General Meeting, 2010 IEEE, pp. 1-6

[2] IEC Standard for Communication network and systems in substations, IEC 61850, 2003

[3] T. S. Sidhu, G. Kanabar and P. P. Parikh, "Implementation Issues with IEC 61850 Based Substation Automation Systems," presented at the 15th National Power Systems Conference (NPSC), IIT Bombay, 2008.

[4] P. Zhang, L. Portillo and M. Kezunovic, "Reliability and Component Importance Analysis of All-Digital Protection Systems," in Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES, pp. 1380-1387

[5] L. Yang, P. A. Crossley, J. Zhao, H. Li and W. An, "Impact evaluation of IEC 61850 process bus architecture on numerical protection systems," in Sustainable Power Generation and Supply, 2009. SUPERGEN '09. International Conference, pp. 1-6

[6] M. G. Kanabar and S. Sidhu, "Reliability and availability analysis of IEC 61850 based substation communication architectures," in Power & Energy Society General Meeting, 2009. PES '09. IEEE, pp. 1-8

[7] J. McGhee and M. Gorja, "Smart High Voltage Substation Based on IEC 61850 Process Bus and IEEE 1588 Time Synchronization," in Smart Grid Communications (SmartGridComm), 2010 First IEEE International Conference, pp. 489-494

[8] R. Moore, R. Midence and M. Goraj, "Practical experience with IEEE 1588 high Precision Time Synchronization in electrical substation based on IEC 61850 Process Bus", Power and Energy Society General Meeting, 2010 , pp. 1-4

[9] E. K. Natarajan, "Design, Simulation, and Analysis of substation automation networks," Master Thesis, Dept. Electric & Computer Eng., Texas A&M Univ. College Station, 2011

[10] D. Nack, "Reliability of Substation Configurations", Iowa State University, 2005, pp. 7-8

[11] C. Singh and R. Billinton, *System Reliability Modeling & Evaluation*, Hutchinson Publishing Group, U.K., 1977

[12] K. Jiang and C. Singh, "Reliability Modeling of All-Digital Protection Systems Including Impact of Repair," Power Delivery, IEEE Trans, 2010, pp. 579-587

[13] R. Billinton and R. N. Allan, Reliabillity Evaluation of Engineering Systems, Concepts and Techniques, Plenum Publishing Corporation, Second Edition, 1992, pp. 221-254

[14] L. Anderson, K. P. Brand, C. Brunner and W. Wimmer, "Reliability investigation for SA communication architectures based on IEC 61850," in 2005 IEEE St. Pertersburg PowerTech, June 27-30, St. Petersburg, Russia, 2005.

[15] K. P. Brand, C. Brunner and W. Wimmer, “Design of IEC 61850 Based Substation Automation Systems According to Customer Requirements”, ABB Switzerland Ltd, Baden and Zürich, Switzerland, 2004

[16] Y. Yin, "Performance evaluation of IEC 61850 based substation automation communication networks," Master's thesis, The University of Western Ontario, London, Ontario, Canada, August 2004