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QUANTITATIVE MODELING OF RELIABILITY AND SURVIVABILITY FOR CYBER-PHYSICAL POWER SYSTEMS

by

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A THESIS

Presented to the Faculty of the Graduate School of the

MISSOURI UNIVERSITY OF SCIENCE AND TECHNOLOGY

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN COMPUTER ENGINEERING

2014

Approved by

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ABSTRACT

Critical infrastructure systems are increasingly reliant on cyber infrastructure that enables intelligent real-time control of physical components. This cyber infrastructure utilizes environmental and operational data to provide decision support intended to increase the efficacy and reliability of the system and facilitate mitigation of failure. Realistic imperfections, such as corrupt sensor data, software errors, or failed communication links can cause failure in a functional physical infrastructure, defying the purpose of intelligent control. As such, justifiable reliance on cyber-physical critical infrastructure is contingent on rigorous investigation of the effect of intelligent control, including modeling and simulation of failure propagation within the cyber-physical infrastructure.

To this end, this thesis investigates the reliability and survivability of a simulated cyber-physical power grid based on the IEEE 9-bus test system. The research contributions include quantitative modeling of both non-functional attributes, based on data from N-1 contingency analysis that considers failures in physical and cyber components of the system. The resulting survivability model is utilized in determining the “importance” of each transmission line. The final research contribution is identification of optimal recovery strategies for the system, where the objective is to maintain the highest possible survivability in the course of recovery.

ACKNOWLEDGMENTS

I would like to express my greatest gratitude to my advisor Dr. Sahra Sedigh Sarvestani. She has been a great advisor and a great support for me during the time I spent to do my research. I learned a lot from her. Her guidance and encouragement helped me in finishing my thesis.

I would also like to thank my committee members Dr. Ali R. Hurson and Dr. Minsu Choi for serving on my committee.

I am grateful to all of my colleagues in the research group - a special thanks to Andrea, Koosha, Nathan, and Mark for helping me while I was writing my thesis. I would like to thank all of the new friends I met in Rolla for their support and for filling my life with happiness.

At the end, I want to thank my father for supporting me with my decision to pursue graduate education in the U.S. Also, I would like to thank my two sisters. And to the most important person in my life, my mother, you are the reason for the person I have now become. Thank you.

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1 INTRODUCTION

Recent blackouts attest to the need for measures to predict and assess the reliability of power grids. The August 2003 Northeast blackout affected nearly 50 million customers in seven US states and Ontario. Rigorous investigation of the cause determined that aging infrastructure, lack of real-time information and diagnostic support, local decision-making without regard to interconnectivity, and human error allowed localized failure of a generating plant to force the shutdown of over 100 power plants [1]. The source of the cascade was contact of stressed power lines with overgrown trees - a failure whose effects could have been mitigated given intelligent and real-time diagnostic support that would reconfigure adjacent power grids to prevent propagation of the failure.

Eight years later, in August 2011, a blackout affected nearly three million customers near San Diego. The causes were judged to be strikingly similar to those of the 2003 blackout, despite significant activity by regulatory bodies in an attempt to prevent outages similar to what occurred in 2003 [2]. Recent large-scale and high-consequence outages in several other countries, including India and Brazil, attest to the importance of predicting, preventing, and mitigating the effects of cascading failures. Complete replacement of aging infrastructure is infeasible; however, use of cyber infrastructure can equip power grids with the information required for prompt detection and diagnosis, and the ability to limit failure propagation. Monitoring capabilities and intelligent control are among the essential attributes of smart grids, which are intended to increase the dependability and sustainability of power distribution. The communication, computing, and control elements required to embed the power grid with the required intelligence make smart grids more complex than their purely physical counterparts. Each added component is a potential source of failure, and the increased connectivity of the grid makes failure propagation more likely. Assessment, modeling, and prediction of the reliability and survivability of smart grids is critical to justifiable reliance on these systems. Failures are inevitable, and as such, techniques are required to guide recovery.

In this thesis, we propose solutions to both challenges and illustrate the application of our techniques on a simulated small smart grid based on the IEEE 9-bus test system. Utilizing the Power System Analysis Toolbox (PSAT) for N-1 contingency analysis, we derive information about potential cascading failures and use this information to populate a stochastic reliability model proposed in our earlier work [3]. Our prior work considered a larger grid, but was constrained in application. *The first contribution of this thesis is extension of the previous model to allow for consideration of a richer set of intelligent devices in determining reliability of the smart grid.* The simulation framework through which our case study was conducted facilitates analysis of survivability by allowing for degraded levels of functionality. Instead of the hardware-in-the-loop simulator that bound us to a specific topology and specific cyber infrastructure, the current simulation framework allows for analysis of arbitrary physical and cyber-physical topologies, and facilitates fine-grained fault injection. In determining reliability, our focus is on the consequences of a specific failure, not its cause. As such, the technique can be utilized in security analysis.

Reliability quantifies the likelihood of a system to function as specified, under given conditions, over a given duration [4]. It takes a binary view of a system, where the only states possible are “functional” and “failed.” As such, this metric is of limited use in evaluating the system after a failure occurs. A quantitative metric useful to this end is “survivability,” defined as the capability of a system to fulfill its mission in a timely manner - quantifying the remaining functionality of a system after a failure occurs [4]. *The second contribution of this thesis is identification of an index appropriate for analysis of survivability, and using the resulting metric in* *decision support for recovery from line failures in the IEEE 9-bus system.* Our earlier work utilized resilience - the ability of a system to bounce back from failure - to the same end [5].

The remainder of this thesis is organized as follows. Section 2 positions our work in the context of related literature. Our models for reliability and survivability are presented in Section 3. As a case study, application of these metrics to the IEEE 9-bus is illustrated in Section 4. Section 5 concludes the thesis and describes future extensions planned for this research.

2 BACKGROUND AND RELATED WORK

Cascading failures, defined as “the usual mechanism by which failures propagate to cause large blackouts of electric power transmission systems,” are a major cause of widespread outages in the power grid [6]. A significant historical blackout in 1996 affected seven million customers in the United States and Canada, and caused financial losses of \$1.5B [7]. This was considered the largest blackout in history, until the 2003 blackout described earlier, which left up to 60 million customers in the US and Canada without power, at a cost of approximately \$12.4B [1]. Such incidents have motivated considerable study of failure propagation in power systems, including our earlier work [3, 8–12].

Relevant studies include [13], where the authors propose a model for cascading failure and utilize the model to determine the effect of hidden failures. This study considers the lack of awareness of human operators of potential failures of transmission lines. Ref. [14] also considers the effect of hidden failures and suggests mitigation techniques for them. In [15], the authors develop a DC power flow model to study the effect of the topology of the power grid on failure propagation. The intuitive conclusion reached was that increased connectivity can delay cascading, but reduced connectivity can lead to improved performance during contingencies. The effect of using local power sources was investigated in [16], where simulation was used to demonstrate that local power sources can reduce the probability of cascading failure. The role of the depth of cascading failures on robustness of the network was investigated in [17]. They showed that system robustness increases when the grid can tolerate deeper cascading failures and decreases when the system fails quickly.

Contingency, defined as the failure of a device, e.g., a line or transformer, is one cause of failures in power grids. Studies such as [18] investigate the effect of line contingencies on cascading failure and determine "importance" values for each line. This study, as the vast majority of related studies, considers a purely physical infrastructure. The addition of power electronics devices that can control the flow of power on a given line and prevent or mitigate the effect of contingencies creates a cyber-physical power infrastructure. One type of intelligent device used to this end is a Thyristor-Controlled Series Capacitor (TCSC). The success of such devices in preventing and mitigating cascading failures has been demonstrated in several studies, including [19–21]. These studies illustrate the impact of prudent location of the TCSC on load management and distribution during a contingency. The broader category of FACTS, which can be considered to comprise TCSCs, has been investigated in studies such as [22, 23]. Both studies propose techniques for optimal placement of FACTS and algorithms for determination of the best settings for the devices.

The work most closely related to the research presented in this thesis considers quantitative modeling of the reliability of physical (vs. cyber-physical) power systems. Examples include [24], which mainly focuses on reliability of power transmission systems, and [25] which describes an analytical approach and a Monte Carlo simulation technique for evaluating the reliability indices of distribution systems. A graph-theoretical model for reliability, and subsequent importance analysis of a power grid is presented in [26]. Our model for reliability considers the effect of failures in the cyber infrastructure in the overall likelihood of a cascading failure.

When a failure occurs in one of the components of a system, it is possible that the system will survive this failure. The extent of functionality retained after failure - survivability - has been qualitatively defined. These qualitative descriptions are of limited use, as they lack the means to measure the survivability. In contrast, the quantitative model proposed in [27], is based on a quantitative definition by the Working Group on Network Survivability Performance. The group defines survivability based on a "measure of interest," M. Assuming that this measure has the value

m_0 immediately prior to the failure, and m_a immediately afterward, survivability can be assessed in terms of the difference between m_a and the value of M at any given time after the failure. In the approach proposed in [27], survivability is assessed based on two underlying models. The first model describes the performance of the system under study during any type of failure. The second model is an availability model for the same system, which describes how much of the system is available during failures. These two models are combined to identify states where the system can survive certain failures.

In a related study [28], authors propose an analytical model for survivability of power grid. The underlying survivability metrics are computed through state space factorization, state aggregation and initial state conditioning. Markov chain models are applied to reduce the state space of the analytical model. Compared to the proposed survivability index in this thesis, their metrics depend on the available power for each customer, but in our work, the survivability index depends on the available power in the system. In addition, the failed state of the system is the initial state, where in our work, the initial state is when the system is fully functional.

In [29–31], the authors utilize graph theory to analyze a smart grid. They subsequently test for its vulnerability, and then increase the survivability by eliminating these vulnerabilities of the system. Although the stated objective is increasing the survivability of the grid, the authors do not explicitly quantify survivability.

The fundamental differences between the work presented in this thesis and the aforementioned studies is our consideration of cyber-physical interdependencies. In modeling reliability, we consider failures in both transmission lines (physical components) and FACTS devices (cyber components). The resulting analysis reveals and quantifies the effect of cyber-physical interdependencies on reliability and survivability of the system. It also allows us to identify the transmission lines most critical to survivability of the system. We subsequently utilize this information in guiding recovery efforts for the system - the more critical lines will be repaired first.

3 APPROACH

In this section, we present a detailed description of our proposed approach to modeling the reliability and survivability of a cyber-physical power grid. The models developed were populated with data from PSAT, an open source MATLAB-based simulator that utilizes the Simulink library [32]. PSAT is capable of performing several types of power analysis, including power flow (PF), continuous power flow (CPF), optimal power flow (OPF), small-signal stability analysis (SSA), time-domain simulation (TD), and N-1 contingency analysis. It is possible to run functions of PSAT from the command line in MATLAB, or from the PSAT graphical user interface. The GUI makes it easy to build models, run different types of power flow analysis, and edit and display simulation results.

In this research, reliability and survivability are the two dependability metrics of interest. Reliability can capture the phase where the power grid is operating normally without any disruptive event and is capable of supplying the power demanded. After any failure or disruptive event, the power grid will transfer to the second phase of operation, where survivability captures the partial functionality that remains. In this phase, it is possible that the power grid will continue supply part of the demanded power. The survivability level of a power grid after failure depends on the failure. Some failures might collapse the system. However, the power grid might sustain operation after other failures. For example, a failure of a generator is different from a failure of a transmission line. Both will affect the power grid, but the failure of a generator will decrease the amount of the supplied power, while the failure of a transmission line might cause overload of other transmission lines.

3.1 RELIABILITY MODELING

Reliability is defined as "the probability that a system will perform satisfactorily for at least a given period of time when used under stated conditions" [33]. Modeling the reliability of a system must consider the state of the components of the system and the operational conditions. Power grids are highly connected, redundant, and complex systems. To find the reliability of such systems, special techniques must be used. Therefore, we used one of these special techniques - the Markov Chain Imbeddable Structure (MIS) - for the purpose of modeling. Also, we used the Power Systems Analysis Toolbox (PSAT) to find the necessary information required for the MIS technique to derive the appropriate reliability model.

We will explain the MIS technique using an example. Assume that we have a system that has three transmission lines. We will create a $3 * 2^3$ binary matrix, as shown in Table 3.1. The state of each transmission line will be represented by binary value, 0 or 1. When the transmission line is working, it will be represented by 1. Otherwise, it will be represented by 0.

Table 3.1. Binary Matrix

	Components		
States	l_1	l_2	l_3
S_0	1	1	1
S_1	1	1	0
S_2	1	0	1
S_3	1	0	0
S_4	0	1	1
S_5	0	1	0
S_6	0	0	1
S_7	0	0	0

Next, we will create a vector of probabilities, $\mathbf{\Pi_0}$. This vector represents the probability of the system being in initial state, S_i.

$$\mathbf{\Pi_0} = [Pr(Y_0 = S_0), Pr(Y_0 = S_1), ..., Pr(Y_0 = S_N)]^T \tag{3.1}$$

Now, we create a transition probability matrix, Λ_l. Each element in the matrix, $p_{ij}(l)$, is the probability of the system changing its state from state S_i to state S_j due to the failure of transmission line l. For example, in Table 3.1, when transmission line l_1 fails, the system will change from state S_0 to state S_4. The probability will be 1 because during the failure of l_1 will transition the system to one specific state.

Finally, we will create a vector, $\mathbf{u}$, of length 2^3. Element $\mathbf{u[i]}$ in the vector will depend on state S_i in the binary matrix. If state S_i is a functional state, then $\mathbf{u[i]}$ will be 1. However, if state S_i is a failed state, then $\mathbf{u[i]}$ will be 0.

The reliability model for an n-component system is defined as:

$$R_n = (\mathbf{\Pi_0})^T (\prod_{l=\mathbf{1}}^{n} \mathbf{\Lambda}_l)\mathbf{u} \tag{3.2}$$

In this research, modeling the reliability of a power grid has two parts. The first part is analyzing and modeling reliability for a pure physical power grid without any control device. The second part is enhancing the power grid by adding control devices that can help in mitigating failures in the system, and then introducing the a reliability model for this cyber-physical grid. Following is a detailed discussion of the two parts.

3.1.1 Analysis of a Purely Physical Power Grid. To determine a reliability model for a purely physical power grid, it is necessary to find the critical failures of transmission lines that might lead to a failure of another transmission line, and then the entire system. One method for finding all these critical failures is to perform N-1 contingency analysis, where the transmission lines are disconnected one-by-one, and power flow analysis is carried out for the resulting grid, where all but one of the transmission lines is functional. If the power flow analysis carried out after outage of a particular line does not complete, it means that the disconnected transmission line is important and has great impact on the power flow in the system. However, if the power flow analysis completes, then the failure of this line has less importance than the transmission lines that cause the simulation to stop.

The final result of N-1 contingency analysis will be a list of the transmission lines and their impact on the system during failure. PSAT has a built in function that can perform the N-1 contingency analysis and generate a file that contains a list of the transmission lines with their failure importance.

The results of the contingency analysis will be used to populate the **u** vector, which identifies all failed and functional states for the system. Earlier, we defined an $n * 2^n$ matrix, and assumed that each element in the **u** vector depends on whether the equivalent combination in the combinations matrix is failed or functional. Therefore, only the equivalent of the combinations, in the $n * 2^n$ matrix, that has one of the safe transmission line failures will be "functional". In addition, for this part of analysis, we assumed that concurrent outage of more than a single transmission line will lead to a failed state for the system - a typical assumption in power system analysis.

For a power grid with n transmission lines, the **u** vector will contain 2^n elements. The number of functional states in the **u** vector will be the same as the number of transmission lines whose outage will not lead to system failure.

The resulting MIS reliability model for a purely physical power grid will be:

$$R_{sys} = p_L^n + X * p_L^{n-1} q_L \tag{3.3}$$

where:

p_L is the reliability of a transmission line. We assume that all the transmission lines are equally reliable.

q_L is the unreliability of a transmission line.

n is the number of transmission lines.

X is the number of functional states in the $\mathbf{u}$ vector, excluding the state where all components are functional.

3.1.2 Analysis of a Cyber-Physical Power Grid. In the previous section, we described modeling of the reliability of a purely physical power grid. However, it is possible to enhance the reliability of the power grid by using control devices. In this research, we use the Static Synchronous Series Compensator (SSSC) control device, which is a type of FACTS devices.

An SSSC control device usually consists of a coupling transformer, an inverter, and a capacitor. The device is connected in series with a transmission line, and it generates and injects a series voltage that can be used to change the effective reactance of the line [34].

In PSAT, it is possible to place control devices on any transmission line and modify their parameters. The SSSC device, in PSAT, has many parameters; however, there is only one parameter that can affect the power flow in the model. This parameter is known as the Percentage Amount of Series Compensation (PASC). This parameter ranges from 0 to 99. The value 0 means that the SSSC device is on the transmission line, but it acts like a closed circuit breaker.

In order to model the reliability for a cyber-physical power grid with an SSSC control device, it is necessary to find the best location for the device, and to determine the optimal settings for it. However, for a power grid network with n transmission lines, and 100 potential values for PASC, the simulation will have to be performed $n * 100$ times. We wrote a script for exhaustive search of these combinations, where the objective was to determine the transmission line where placement of an SSSC device will reduce the number of failed states for the system.

The decrease in the number of transmission line failures will be reflected in the component matrix and the **u** vector, as an increase in the number of functional combinations and states. Therefore, the reliability model for cyber-physical power grid will be:

$$R_{sys} = (p_L^n + A * p_L^{n-1} * q_L) * p_{SSSC} + \sum_{\forall states \in S} p_L^{n-1} * q_L * p_{SSSC} \tag{3.4}$$

where:

A is the total number of functional states when a single failure occurs, regardless of the existence of the SSSC device.

S is the set of the new safe states added to the system by adding an SSSC with the optimal setting.

p_{SSSC} is the reliability of the SSSC device.

In our case study, simulation results will be used to populate the reliability model of Equation 3.4, in order to find the reliability of the IEEE 9-bus system with a SSSC control device.

3.2 SURVIVABILITY MODELING

In the previous section, the method for modeling reliability of pure physical and cyber-physical power grid was discussed. In this section, we will present a method to calculate the survivability of the system and suggest a recovery process based on a proposed survivability index.

A survivable system is a system that can continue operating, albeit with lower performance, after failure of one (or more) of its components. However, this describes survivability from a qualitative rather than quantitative perspective, because it does not define any criteria or method to measure the survivability [27].

Survivability has no specific metric [27]. The metrics used in previous studies depend on the parameter of interest. In our work, we will define an index that is based on the state of the system after the failure compared to the status of the system before failure. For example, assume that we have a power grid with four generators and a total power of 250 MW. Assume outage of a transmission line that connects a 75 MW to the power grid. Then the power grid will be working at 70% of its nominal power. Our work will focus on measuring if the system will survive a specific failure. Also, based on the survivability level during the failure of each component, we will assign an importance value to each component.

The aforementioned index depends on the available power and load in the system after failure, and the available power and load in the system before failure. Mathematically, we can calculate a value that represents the survivability of the system. Equation 3.5 represents the mathematical equation for the survivability index.

$$V = \frac{\frac{P_n}{L_n}}{\frac{P_o}{L_o}} = \frac{P_n}{L_n} * \frac{L_o}{P_o} \tag{3.5}$$

where:

V is the survivability metric.

P_n is the amount of available power after failure.

P_o is the amount of available power before failure.

L_n is the amount of power consumption by loads after failure.

L_o is the amount of power consumption by loads before failure.

There are three explanations for the value of V. If there is no failure in a specific time interval, then the value for V will be 1. This means the system is stable. If a transmission line fails and causes a load to be disconnected from the system, then the value of V will be greater than 1. In this case, the system can continue operating and there is no need to continue analyzing the survivability of the system. If a transmission line fails and causes a generator to be disconnected, then the value of V will be less than 1. This is the interesting case in our study, because we will need to analyze the failure, and then identify the level of survivability of the system.

Also, we will make an assumption about Equation 3.5. If a failure in the system causes the generated power to be zero, then the index value will be zero.

For the purpose of analysis, we define four levels for system survivability when the value of the index V is less than 1. These levels are:

1. First level of degradation

   In this level, one of the components with low importance has failed. The failure may reduce the performance of the system, but the survivability index, V, is greater than 0.8.

2. Second level of degradation

   In this level, failure of a component leads to a survivability index, V, in the range of 0.6-0.79.

3. Third level of degradation

   In this level, failure of a component leads to a survivability index, V, in the range 0.4-0.59.

4. Fourth level of degradation

   This level results from failures that cause the survivability index, V, to fall below 0.4. The impact of this type of failure on the system is considered catastrophic - recovery is assumed infeasible.

These levels are define based on transmission line outages that will cause failure of a generator or load. However, there exist other failures that will not cause any change in the generation power or load, but will cause overloading of other transmission lines. Therefore, we will use the number of overloaded transmission lines to determine the importance of the failed transmission line. For example, a transmission line leads whose outage leads to overload of only one other transmission line is considered less important than another transmission line that will cause overload of three transmission lines when it fails. For this case, we will use PSAT to perform power flow analysis during the failure of each transmission line, then test for the change in the power flow in each transmission line in the system.

3.3 DECISION SUPPORT FOR SYSTEM RESTORATION

Earlier, we defined different levels of survivability. There are two reasons for defining different survivability levels. The first reason is it is possible that the different transmission lines of a complex system such as the power grid will not be of equal importance. As such, a failure in one transmission line may have an impact different from that of the failure of another transmission line. The second reason is there is a possibility that there are more than one failure might happen at the same time. These failures might impact the system at different levels. Therefore, we will be testing for different scenarios that will cause the system to degrade through these levels, and then arrange the transmission lines based on their importance in order to determine the best procedure to restore the system. For example, if we have a power grid system where two transmission lines failed. One of these transmission lines caused disconnection of a generator bus, and the other transmission line failure caused disconnection of a load bus. Clearly, it is necessary to restore the transmission line that disconnected the generator bus before restoring the transmission line that connects the load. Therefore, there will be more power available in the system in the case of restoring the generator bus before the load bus, and then a better value for the survivability index V.

In our work, we will be focusing on single and double failures of transmission lines. From single failures, we will determine a recovery sequence based on the value of the survivability index, V, where the transmission line whose failure yields the lowest value for V will be considered the most important transmission line. The transmission line whose failure yields the second-lowest value for V will be considered the second most important transmission line, and so on. Also, from double transmission line failures, we will validate the importance assigned to the transmission lines.

4 SIMULATION RESULTS AND ANALYSIS

In this section, we will present a case study, specifically on the IEEE 9-bus test system, and apply the techniques presented earlier in Section 3 to modeling reliability and survivability. In addition, we will present an example to clarify the decision support process and its effectiveness in recovering the system from failure.

The IEEE 9-bus system, depicted in 4.1, includes nine buses, three of which (buses 1,2, and 3) are generator buses. For simulation purposes, we will assume bus number 1 is the Reference Bus. The system has three load buses (5, 6, and 8). The system also contains nine transmission lines. The generator capacity on bus 1 is 72 MW, the generator capacity on bus 2 is 163 MW, and the generator capacity on bus 3 is 85 MW. The load on bus 5 is 125 MW, the load on bus 6 is 90 MW, and the load on bus 8 is 100 MW [35].

For reliability modeling, we use simulation results from PSAT to populate the Markov chain Imbeddable Structure (MIS) model [33].

4.1 RELIABILITY MODELING FOR THE IEEE 9-BUS SYSTEM

The reliability modeling technique discussed in 3.1 was applied to the IEEE 9-bus system, both in its conventional (purely physical) form and in the modified cyber-physical form described in the previous section.

4.1.1 Reliability Analysis for Purely Physical IEEE 9-Bus System. In carrying out N-1 contingency analysis, we determined that of the nine transmission lines in the IEEE 9-bus test system, only three can lead to failures of other lines and eventually system failure. These transmission lines are highlighted in Figure 4.2.

The failure of each one of the other six transmission lines, one at a time, will not lead to the failure of the entire system. Table 4.1 contains simulation results

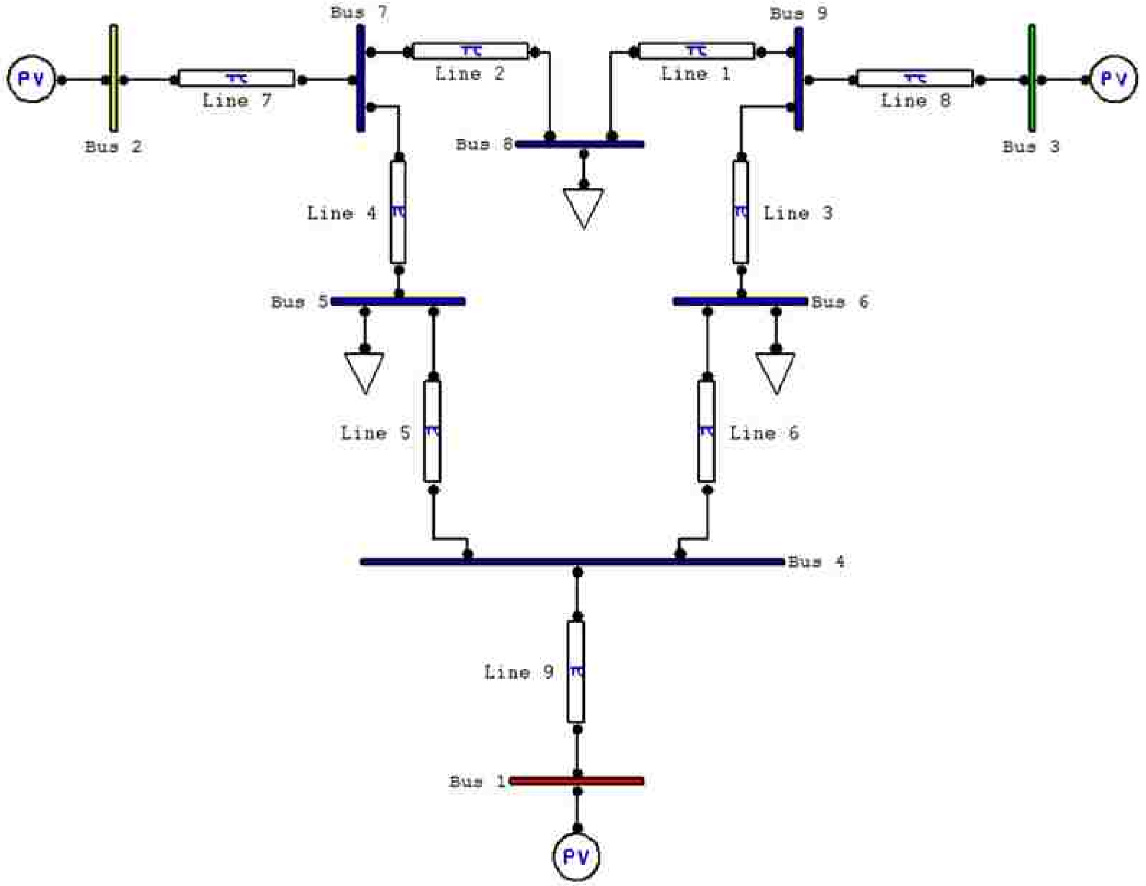

Figure 4.1. IEEE 9-Bus System

from PSAT for the power flow contingency analysis. By applying simulation results to equation 3.3, and using n=9, and X=6, we will get the following reliability model:

$$R_{sys} = p_L^9 + 6p_L^8 q_L \tag{4.1}$$

The reliability model in 4.1 describes the operational condition for the system. Where the term p_L^9 means the system is operational when all the transmission lines are operating properly. However, the term $6p_L^8 q_L$ means that there are six possible failures, and the system is operational during the occurrence of any of these failures once at a time.

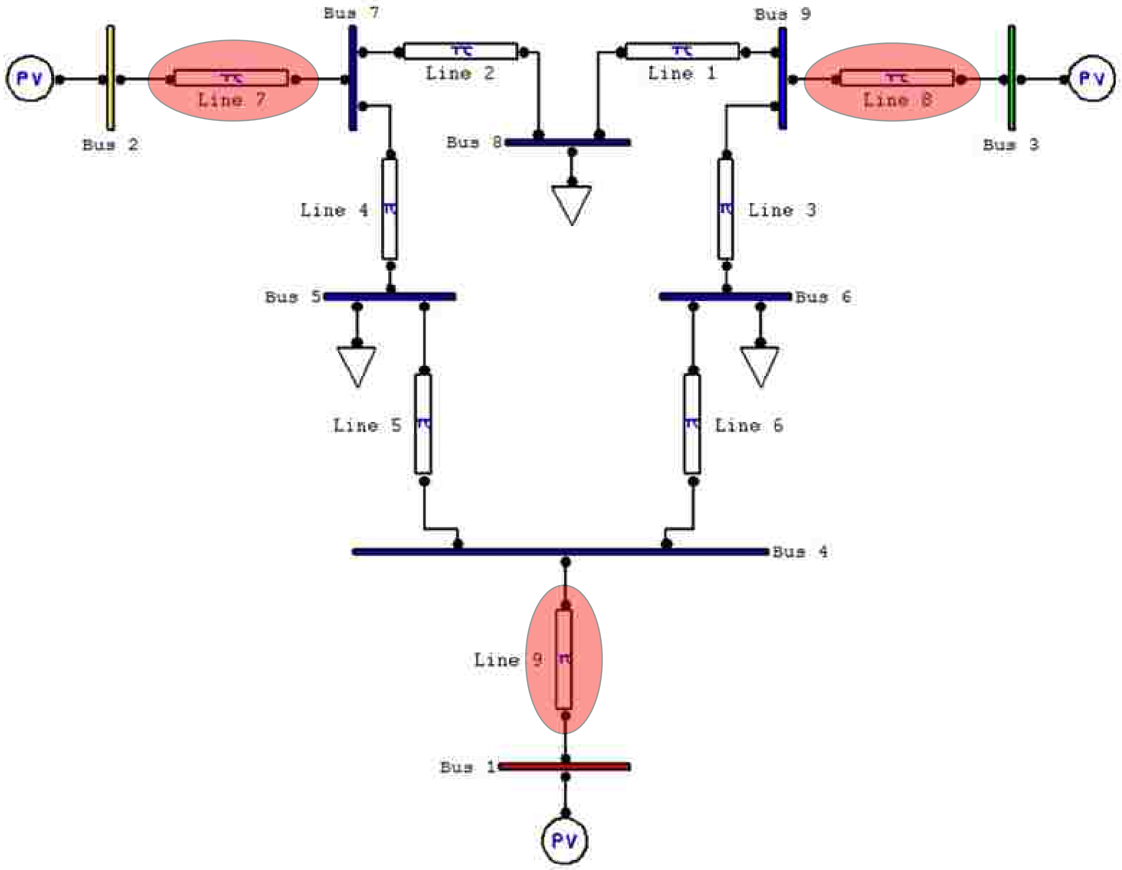

Figure 4.2. The Transmission Lines with the Most Effect on the System During Failures

4.1.2 Reliability Modeling for Cyber-Physical IEEE 9-Bus System. In order to increase the reliability of the IEEE 9-bus system, we used a SSSC control device in the system. In PSAT, the SSSC control device has multiple parameters. From simulation results, we concluded that only one of these parameters can affect the performance of the power grid. This parameter is known as Percentage Amount of Series Compensation (PASC). The PASC value ranges from 0 to 99. The value 0 means the SSSC is on the transmission line but it does not act like a SSSC. However, it acts like a closed circuit breaker.

In [19–21,36,37], it was proven that by placing the control devices in different locations in the power grid, the entire performance of the grid will change. Therefore,

Table 4.1. PSAT Simulation Results for N-1 Contingency Analysis

Transmission Line	From Bus	To Bus	Failure Impact
1	9	8	Functional
2	7	8	Functional
3	9	6	Functional
4	7	5	Functional
5	5	4	Functional
6	6	4	Functional
7	2	7	Failed
8	3	9	Failed
9	1	4	Failed

we tested for the best location to place the SSSC control device with the best value for PASC.

In our work, we tested for placing only one SSSC control device in the IEEE 9-bus system. Simulation results has shown that there are two location to place the SSSC control device to increase the reliability of the IEEE 9-bus system. Also, the value of the PASC parameter is not the same at these two locations. For the first location, placing the SSSC on transmission line 1 with PASC value ranges from 49 to 61 will increase the reliability of the system by decreasing the number of cases that can lead to system failure from 3 to 2. Table 4.2 shows the simulation results for placing the SSSC device on transmission line 1 as in Figure 4.3.

The second location for the SSSC device is on transmission line 4 with PASC value ranges from 15 to 34. Table 4.3 shows the simulation results for placing the SSSC device on transmission line 4 as in Figure 4.4.

From the previous cases, if we assume that the reliability of the SSSC device is 1. Then the reliability model for the IEEE 9-bus system will be as following:

Table 4.2. PSAT Simulation Results for N-1 Contingency Analysis When Using One SSSC Device on Transmission Line 1

Transmission Line	From Bus	To Bus	Failure Impact
1	9	8	Functional
2	7	8	Functional
3	9	6	Functional
4	7	5	Functional
5	5	4	Functional
6	6	4	Functional
7	2	7	Failed
8	3	9	Functional
9	1	4	Failed

Table 4.3. PSAT Simulation Results for N-1 Contingency Analysis When Using One SSSC Device on Transmission Line 4

Transmission Line	From Bus	To Bus	Failure Impact
1	9	8	Functional
2	7	8	Functional
3	9	6	Functional
4	7	5	Functional
5	5	4	Functional
6	6	4	Functional
7	2	7	Functional
8	3	9	Failed
9	1	4	Failed

$$R_{sys} = p_L^9 + 7p_L^8 q_L \tag{4.2}$$

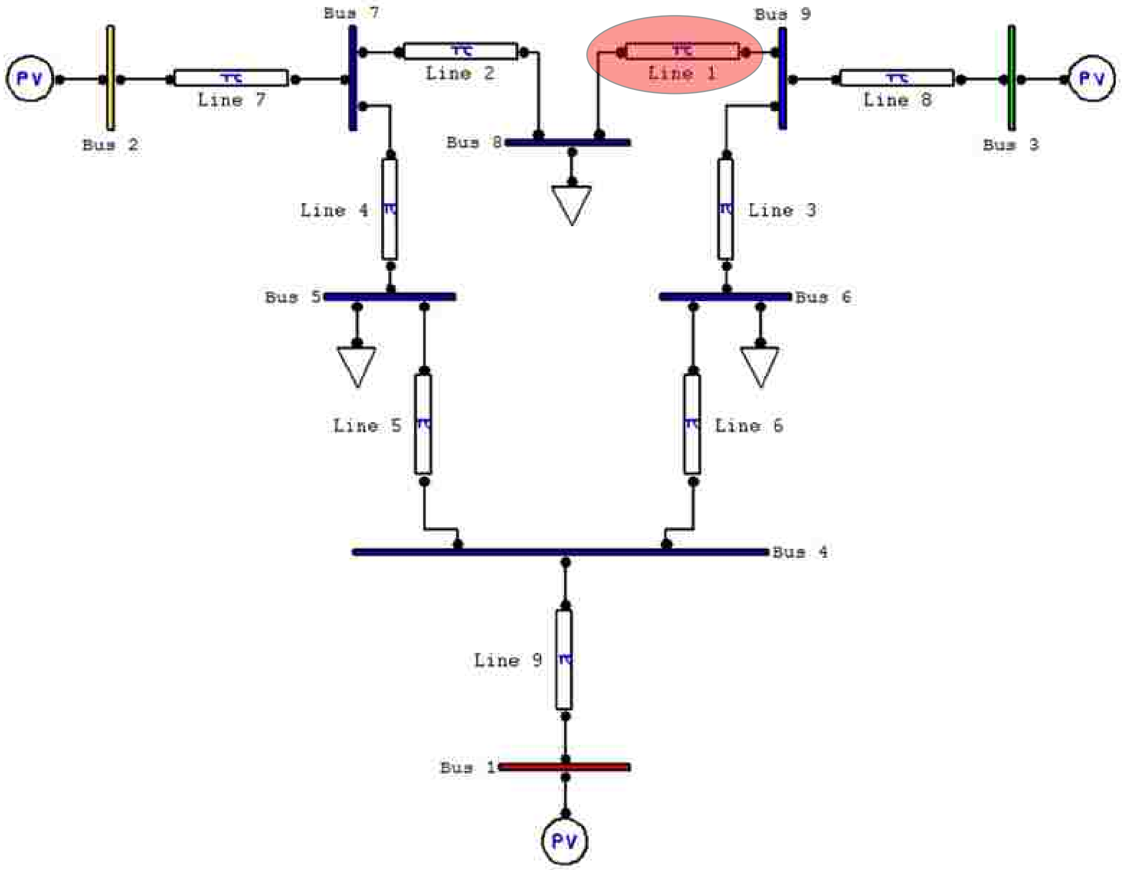

Figure 4.3. The First Optimal Location for the SSSC Control Device

However, if we consider the real reliability of the SSSC device, then the reliability model for the IEEE 9-bus system will be as following:

$$R_{sys} = (p_L^9 + A * p_L^9 q_L) * p_{SSSC} + \sum_{\forall states \in S} p_L^8 q_L * p_{SSSC} \tag{4.3}$$

In our model, we used one SSSC control device. And for the pure physical system, we have 6 functional states. In addition, the total number of additional safe states after adding SSSC control device is only one state. Then the model in equation 4.3 will be:

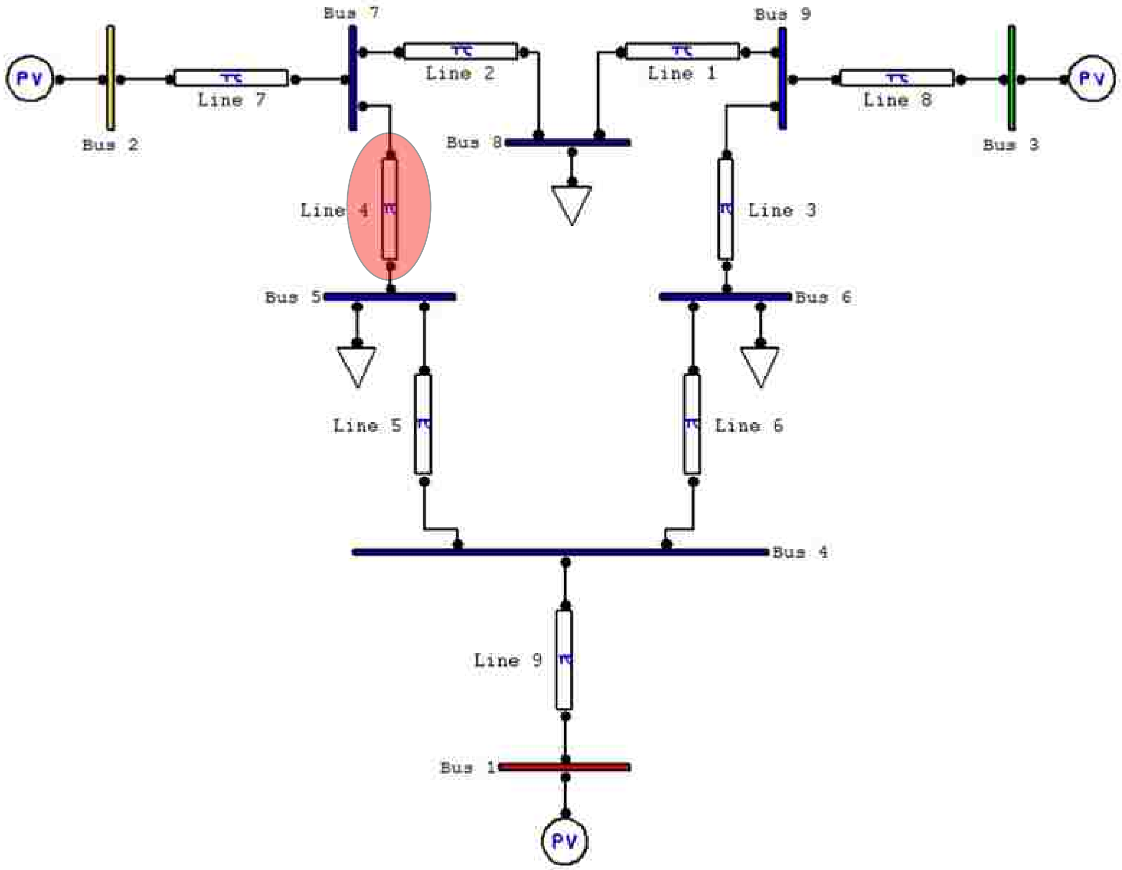

Figure 4.4. The Second Optimal Location for the SSSC Control Device

$$\begin{aligned} R_{sys} &= (p_L^9 + 6 * p_L^8 q_L) * p_{SSSC} + p_L^8 q_L * p_{SSSC} \\ &= p_L^9 * p_{SSSC} + 7 * p_L^8 q_L * p_{SSSC} \end{aligned} \tag{4.4}$$

We plot the reliability models of equations 4.1, 4.2, and 4.4. Figures 4.5, 4.6, and 4.7 show the reliability plots for different values for p_{SSSC}.

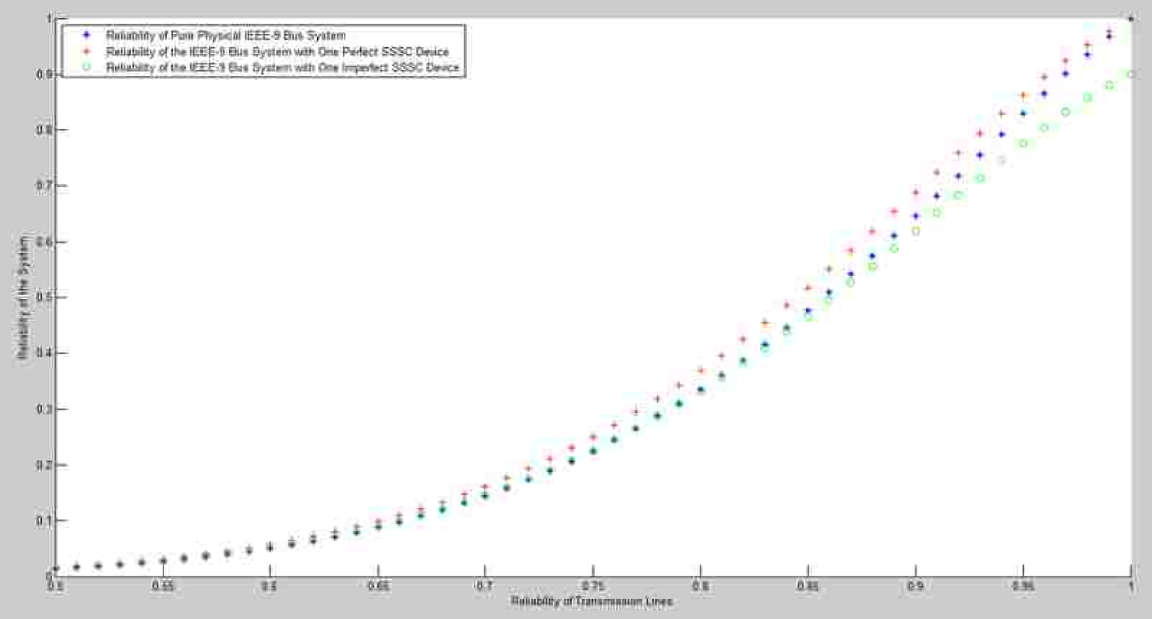

Figure 4.5. Reliability for IEEE 9-Bus System when $p_{SSSC} = 0.9$

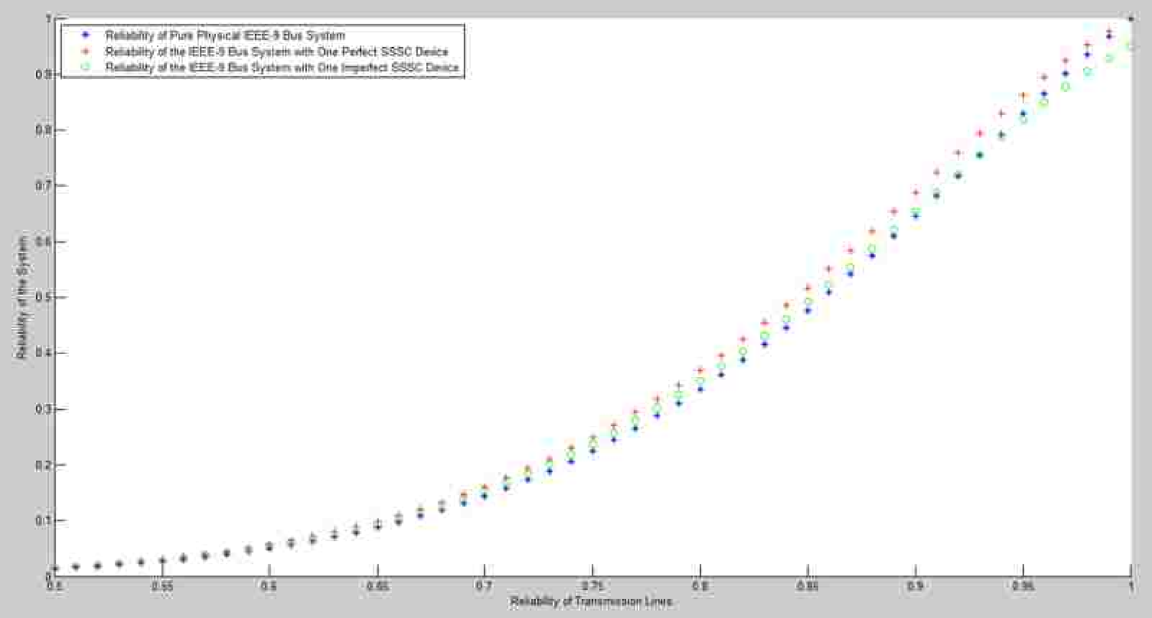

Figure 4.6. Reliability for IEEE 9-Bus System when $p_{SSSC} = 0.95$

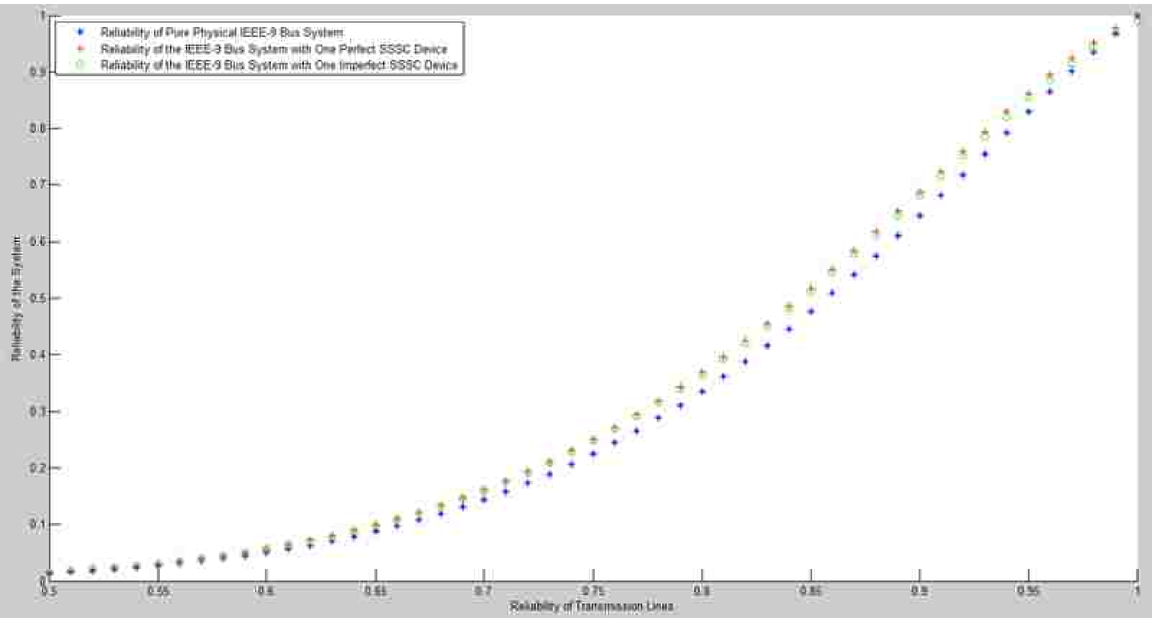

Figure 4.7. Reliability for IEEE 9-Bus System when $p_{SSSC} = 0.99$

4.2 SURVIVABILITY MODELING FOR THE IEEE 9-BUS SYSTEM

The IEEE 9-bus system has three generators that provide 320 MW. The total load in the system is 315 MW. In the simulation, we assumed that each generator can provide a 10% more power in case the consumption increased in the network, or in case of failure of one of the generators.

In 3.2, we mentioned that the metric for measuring survivability is the ratio between the state of the system after failure to the state of the system before failure. By using equation 3.5, we were able to identify different levels for survivability of the system due to different failures. Next, we will discuss simulation results for single and double transmission line failures from the survivability perspective. Also, we will present a restoration procedure for larger system.

4.2.1 Single Transmission Line Failures. For the single failures, we used the results from the N-1 contingency analysis in 4.1.1, where we were able to identify three failures that might cause the failure of the entire system. Each one of these failures will cause disconnection of a generator bus from the system. However, we did not define how fast each failure can cause system failure. Table 4.4 shows these failures and their survivability index values (we assumed that the generators in the system will provide 10% more power in case the consumption became more than the generated power).

By comparing the values for survivability index of each failure, failure of transmission line 7 will results in the lowest survivability index, and hence failure of transmission line 7 will be the most effective on the system. Transmission line 8 is the second most effective transmission line during failure. Finally, transmission line 9 is the least effective one of the three transmission lines. However, all the failures are within the safe degradation levels that we assumed in section 3.2. Therefore, from the survivability point of view, these failures will not cause the failure of the entire system, because the value of the survivability index V is greater than 0.4 in all cases.

So, in case of failure of two transmission lines in the system, where both of the transmission lines are connecting generator buses to the system, we can use the previous results as a reference for the restoration process of the system. Therefore, from the system restoration point of view, it is necessary to restore transmission line

Table 4.4. Survivability Analysis for Effective Failures in IEEE 9-Bus System

Transmission Line	Available Power (MW)	V	Degradation Level
7	172.7	0.54	3
8	258.5	0.81	1
9	272.8	0.85	1

7 before transmission lines 8 or 9, and restore transmission line 8 before transmission line 9.

To find the importance of the remaining transmission lines (1-6), we used the simulation results for power flow of the system. From the power flow simulation results, we looked for the number of overloaded transmission lines caused by each failure. Therefore, transmission line 4 is the most important because it results in overloading four other transmission lines. Transmission line 2 is less important than transmission line 4 because it results in overloading only two transmission lines. Transmission line 3 is less important than transmission line 2 because it results in overloading only one transmission line. Transmission lines 1, 6, and 5 have the lowest importance because they do not result in overloading other transmission lines. Therefore, by arranging the transmission lines according to their importance, we will get this sequence: 7, 8, 9, 4, 2, 3, 1, 6, 5. We will use this sequence for the restoration process.

4.2.2 Double Transmission Line Failures. The analysis of double transmission line failures is not easy because we must find all the combinations for double failures. The IEEE 9-bus system has nine transmission lines. Therefore, the number of different combinations for double transmission line failures is 72 combinations if we assume that the order of failure is important. However, there are some of these combinations not important. For example, in the case of the failure of transmission line 1 and then transmission line 2, bus 8 to which where a 100 MW load is connected, will be disconnected from the system. Therefore, by using Equation 3.5 to determine V , we will find that the survivability index is greater than 1. In this case, survivability analysis will not be useful or meaningful.

On the other hand, by simulating double transmission line failures, we identified six cases of double transmission line failures. These cases are:

1. Case 1: Double Failures Equivalent to Single Load Failure

   In this case, we identified three double transmission line failure combinations (lines 1 and 2, lines 3 and 6, and lines 4 and 5). Figure 4.8 is an example for this case.

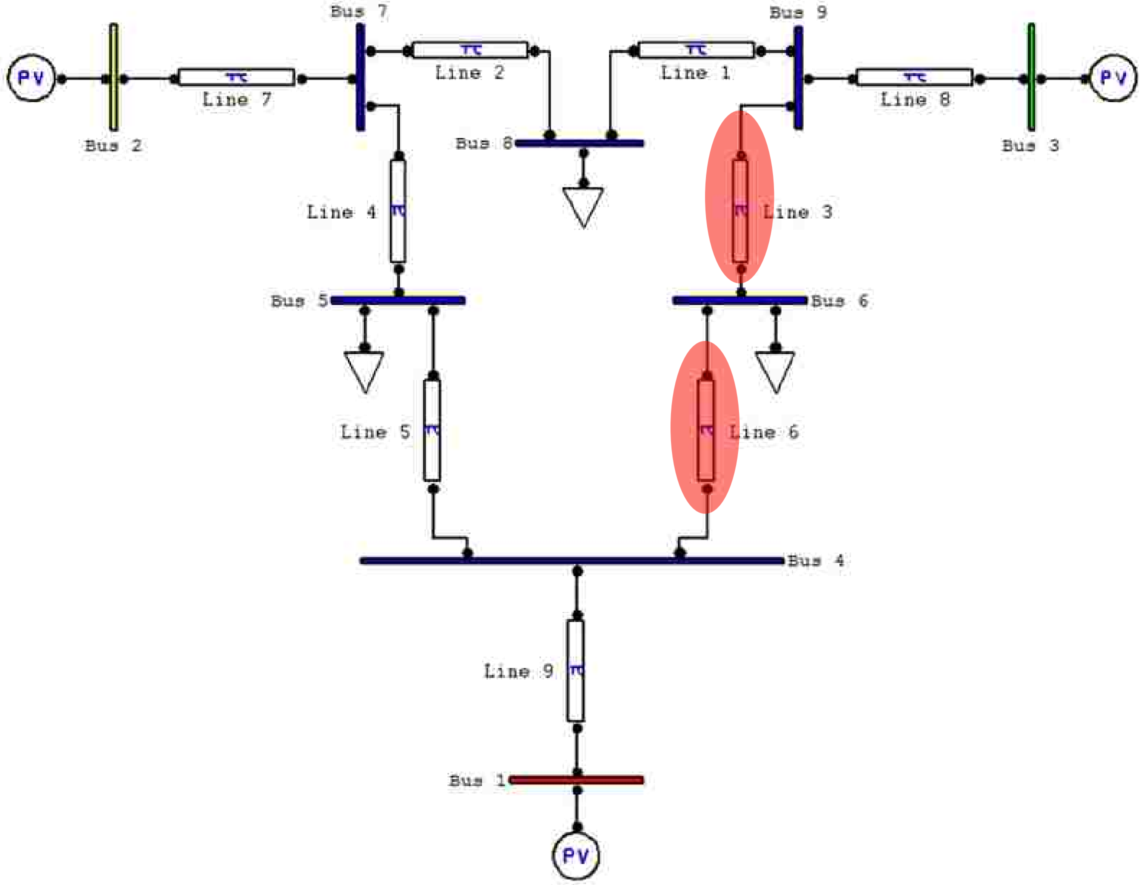

Figure 4.8. An Example of a Double Failure Equivalent to Single Load Failure Case

In this case, if the failures are due to aging in transmission lines, natural causes, or negligence of the power company in maintenance, then the load demand is considered to have not been met. However, if the failures are due to overload by the customer, then the load demand should be considered as having been met, and the survivability factor will be greater than 1, yet indicative of the ability of the system.

2. Case 2: Double Failures Equivalent to Single Generator Failure

   In this case, we identified three different double transmission lines failure combinations. Table 4.5 contain the failures, their single transmission line failure equivalent, and the survivability index. Figure 4.9 is an example for this case.

Table 4.5. Double Failures Equivalent to Single Generator Failures

First TL to Fail	Second TL to Fail	Equivalent Single TL Failure	V
1	3	8	0.81
2	4	7	0.54
5	6	9	0.85

3. Case 3: Disconnection of a Generator Bus and a Failure

   In this case, either transmission line 7 or 8 or 9 will fail, and then one of the rest transmission lines will fail, or vice versa. Figure 4.10 is an example for this case.

4. Case 4: One Generator and One Load

   In this case, a double transmission line failure will split the power grid network into two networks. Table 4.6 lists all the possible combinations with one generator and one load. Table 4.7 is a continuation to Table 4.6. In both tables, when we calculated V, we assumed that the generators increased their generation by 10% in the case the generated power is less than the consumed power. Figure 4.11 is an example for this case.

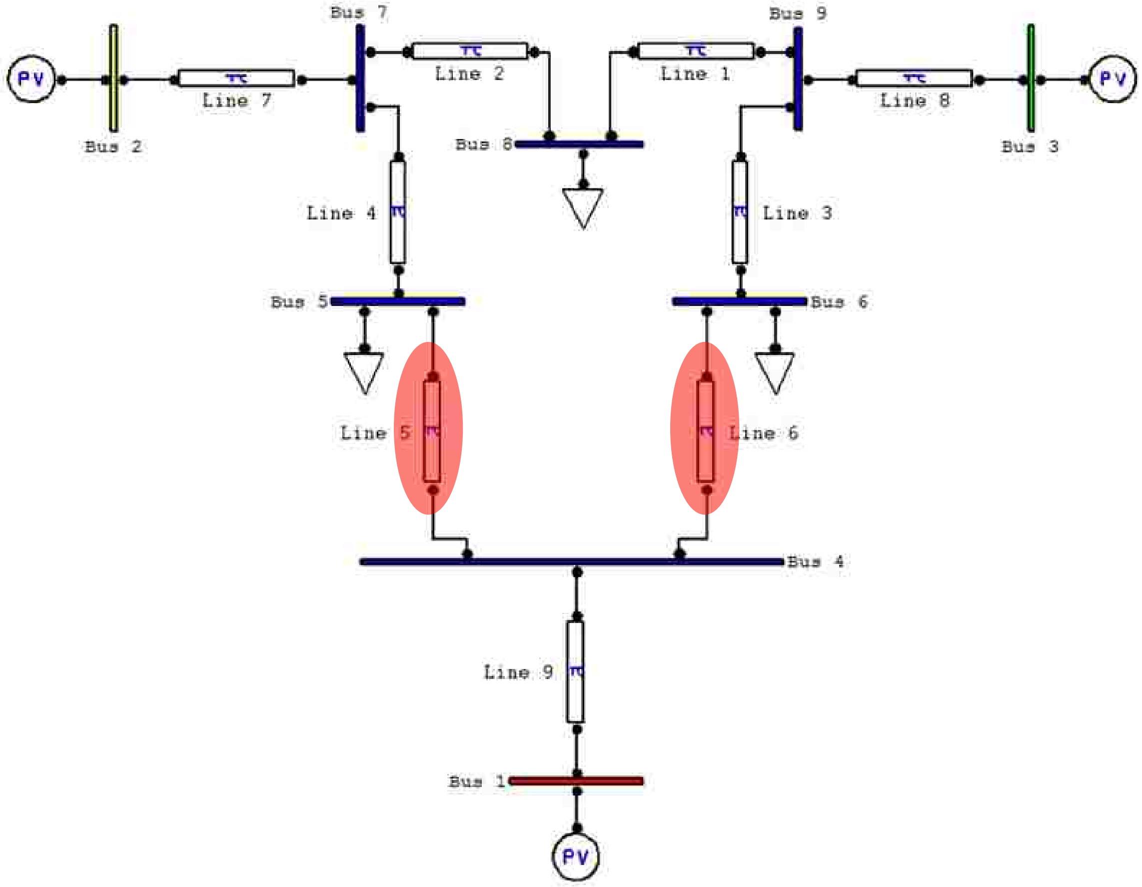

Figure 4.9. An Example of a Double Failure Equivalent to Single Generator Failure Case

5. Case 5: One Generator and Two Loads

   In this case, a double transmission line failure will split the power grid network into two networks. One of the Networks will contain two loads and one generator. The other network will contain one load and two generators. Table 4.8 lists the cases of one generator and two buses. Figure 4.12 is an example for this case.

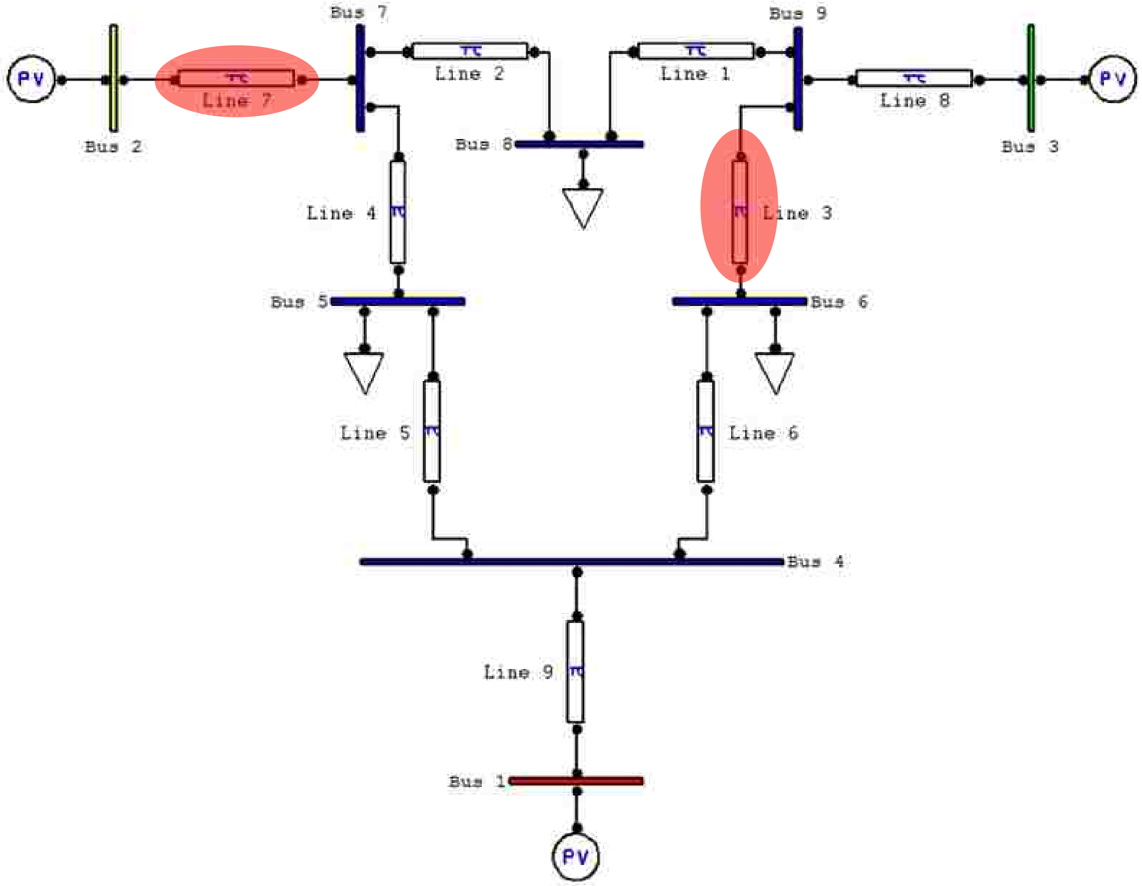

Figure 4.10. An Example of Disconnection of a Generator Bus and a Failure Case

6. Case 6: Disconnection of Two Generator Buses

   This group is considered the group with the most critical cases to the system. Table 4.9 contains a list of these failures. Figure 4.13 is an example for this case.

These cases make the recovery process faster by identifying each failure, then take the right sequence for transmission lines recovery.

4.3 DECISION SUPPORT

The survivability analysis results for double transmission line failures listed in Tables 4.5, 4.6, 4.7, 4.8, and 4.9, can help in creating a recovering strategy for

Table 4.6. One Generator and One Load Cases

First TL to Fail	Second TL to Fail	Generator Bus	Load Bus	V
1	6	3	6	0.98
2	3	3	8	0.92
2	5	2	5	1.28
4	1	2	8	1.6
3	5	1	6	0.86
4	6	1	5	0.62

Table 4.7. Two Generators and Two Loads Cases

First TL to Fail	Second TL to Fail	Generator Buses	Load Buses	V
1	6	1, 2	5, 8	1.02
2	3	1, 2	5, 6	1.07
2	5	1, 3	6, 8	0.89
1	4	1, 3	5, 6	0.79
3	5	2, 3	5, 8	1.08
4	6	2, 3	6, 8	1.13

Table 4.8. One Generator and Two Loads Cases

First TL to Fail	Second TL to Fail	Generator Bus	Load Buses	V
3	4	1	5, 6	0.36
1	5	2	5, 8	0.78
1	6	3	6, 8	0.48

the system based on the importance of each transmission line. By arranging the importance of the cases based on the value of the survivability index, V, we will get the best recovering strategy. In this section, we will discuss a case, where three transmission lines of the IEEE 9-bus system fail. If we assume that we will be able

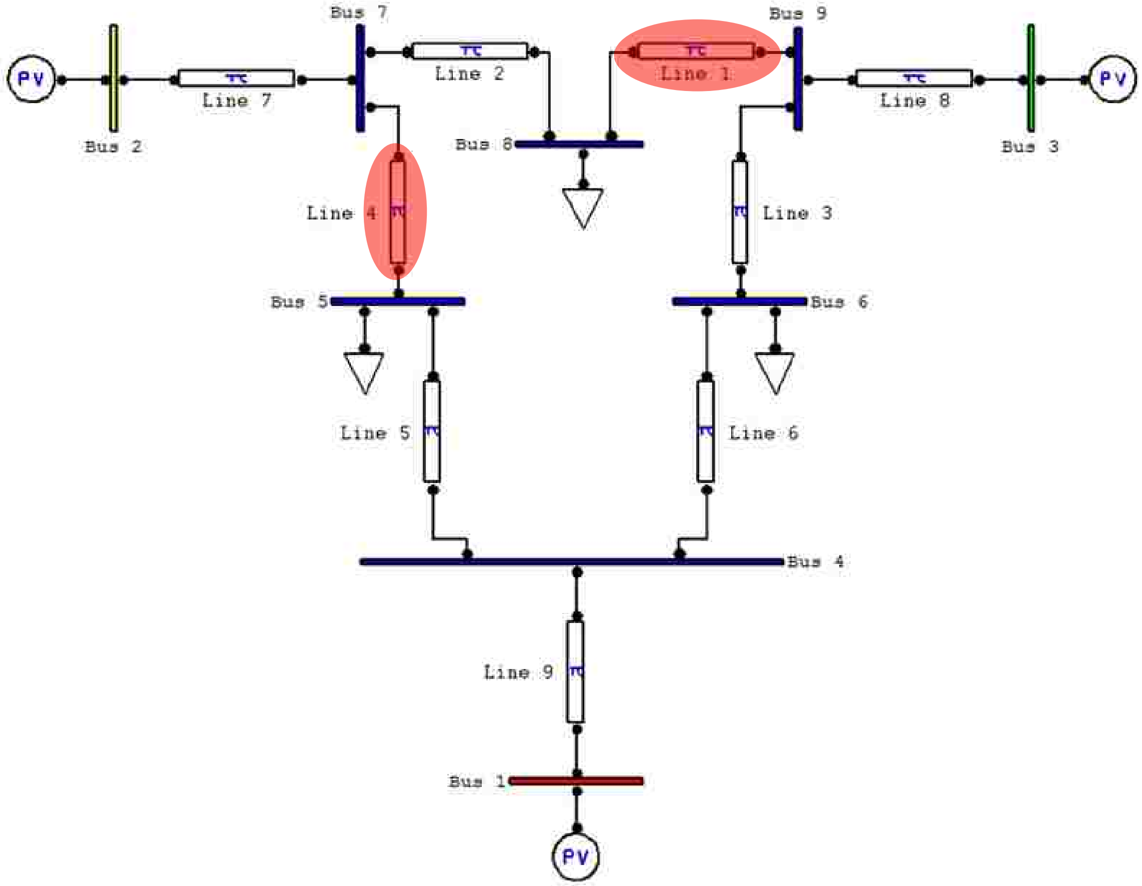

Figure 4.11. An Example for One Generator and One Load Case

Table 4.9. Disconnection of Two Generator Buses

Transmission Lines to Fail	Remaining Generator Bus	V
7, 8	1	0.2475
8, 9	2	0.2922
7, 9	3	0.56

to restore one transmission line at a time. Then the recovery strategy will involve six possible sequences. We will check for the best recovery sequence using the value for the survivability index.

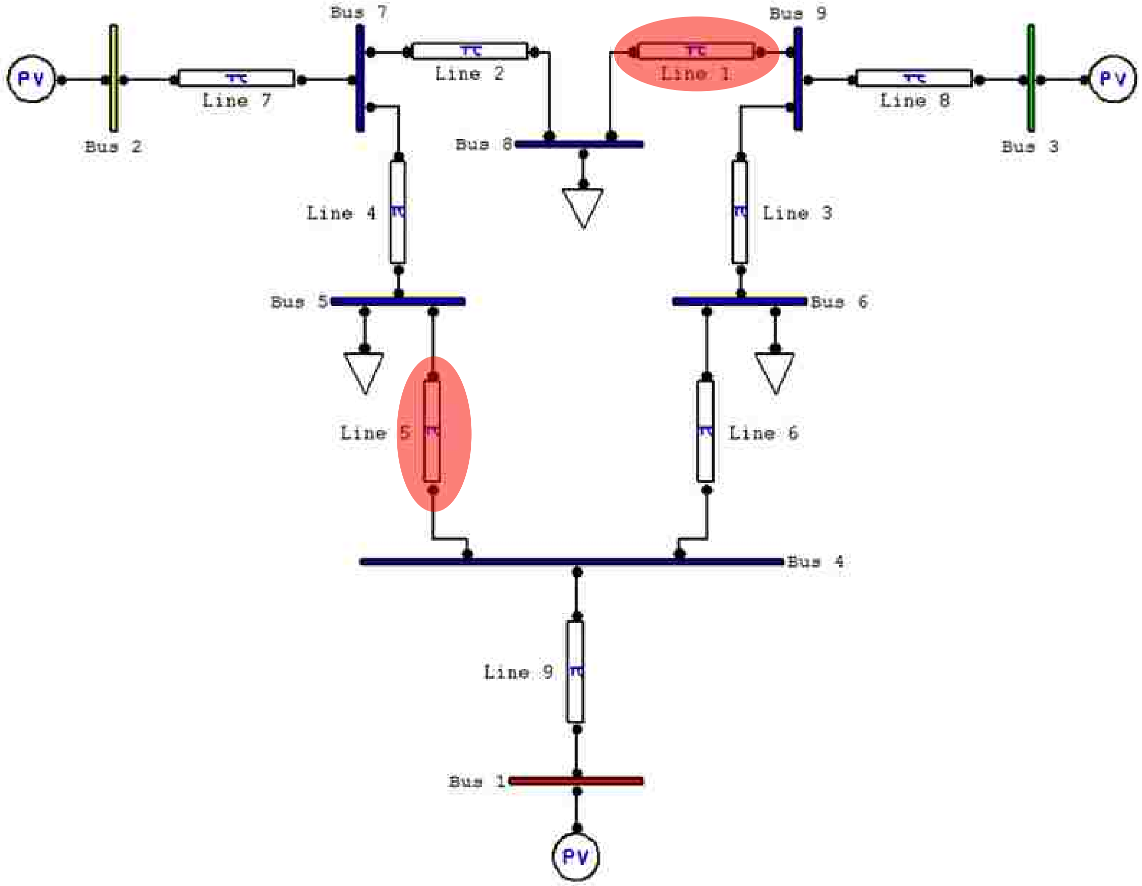

Figure 4.12. An Example for One Generator and Two Loads Case

4.3.1 Problem Setup. If we assume three transmission lines failed in the IEEE 9-bus system. The first transmission line to fail was 8. This transmission line connects an 85 MW generator to the system. The second transmission line to fail was 9. This transmission line connects a 72 MW generator to the system.And finally, the last transmission line to fail was 7. This transmission line connects a 163 MW generator to the system. Figures 4.14, 4.15, and 4.16 illustrates the sequence of failure of the transmission lines.

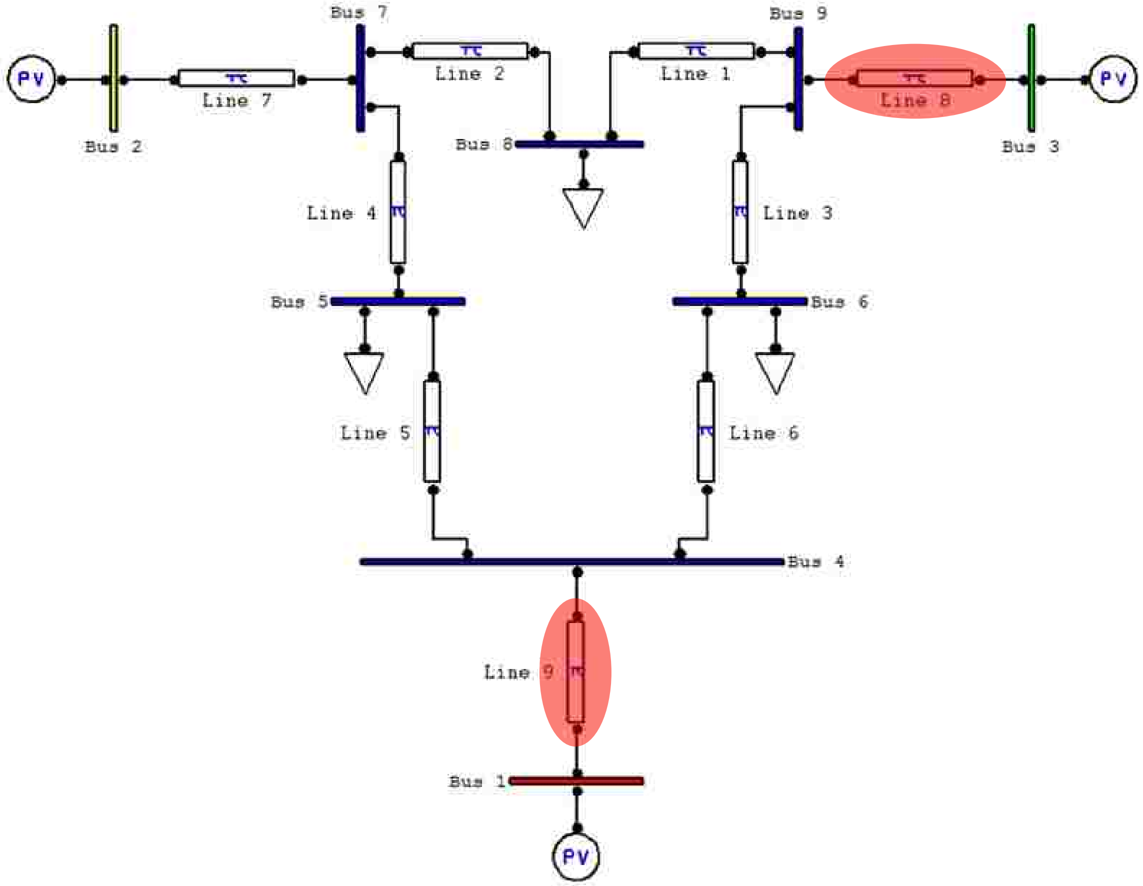

Figure 4.13. An Example for Disconnection of Two Generators Case

4.3.2 Recovery Process. As we mentioned earlier, if we assume that it is possible to recover one transmission line at a time. Therefore, the recovery process for the system can be done in six possible recovery sequences. Each one of these sequences will have a specific impact on the system that can be captured by the survivability index. Since the proposed recovery strategy depends on recovering the transmission lines based on the ranking in Section 4.2.1. Then, the sequence that matches our proposed recovery strategy is (7, 8, 9).

In each one of the possible recovery sequences, we will start by recovering the first transmission line in the sequence. Then, we will check for the highest value for the survivability index. We will continue the recovery process for the sequence that

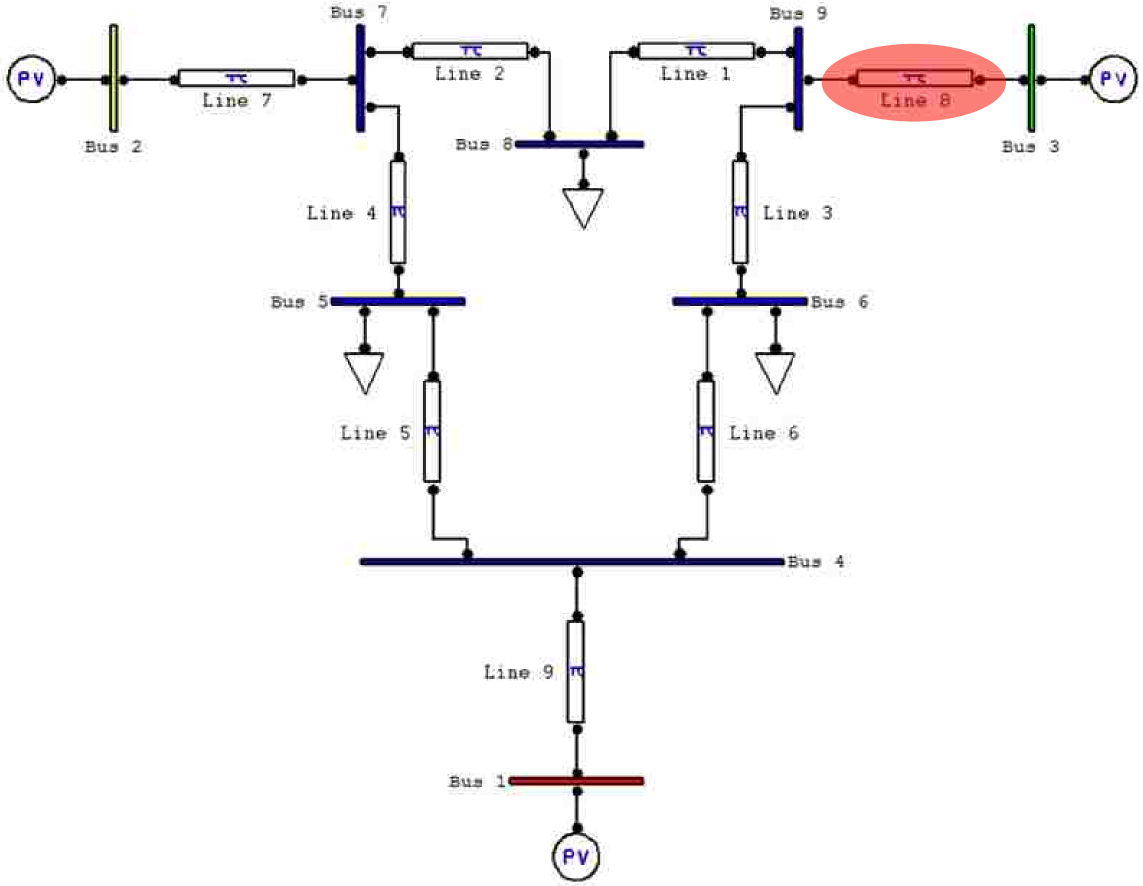

Figure 4.14. Failure of Transmission Line 8

has the highest survivability index. It is possible that two sequences or more will have the highest and the same value for survivability index. In this case, we will continue with both of them. However, it is possible that after restoring the second transmission line, one of these two sequences, will have a higher survivability index. Therefore, we will continue the recovery process using the sequence with the highest survivability index.

It is possible that after restoring the second transmission line, we can have a high value for the survivability index for one of the eliminated recovery sequences. In this case, the value for the survivability index for the eliminated recovery sequence over time will be less than the remaining recovery sequences.

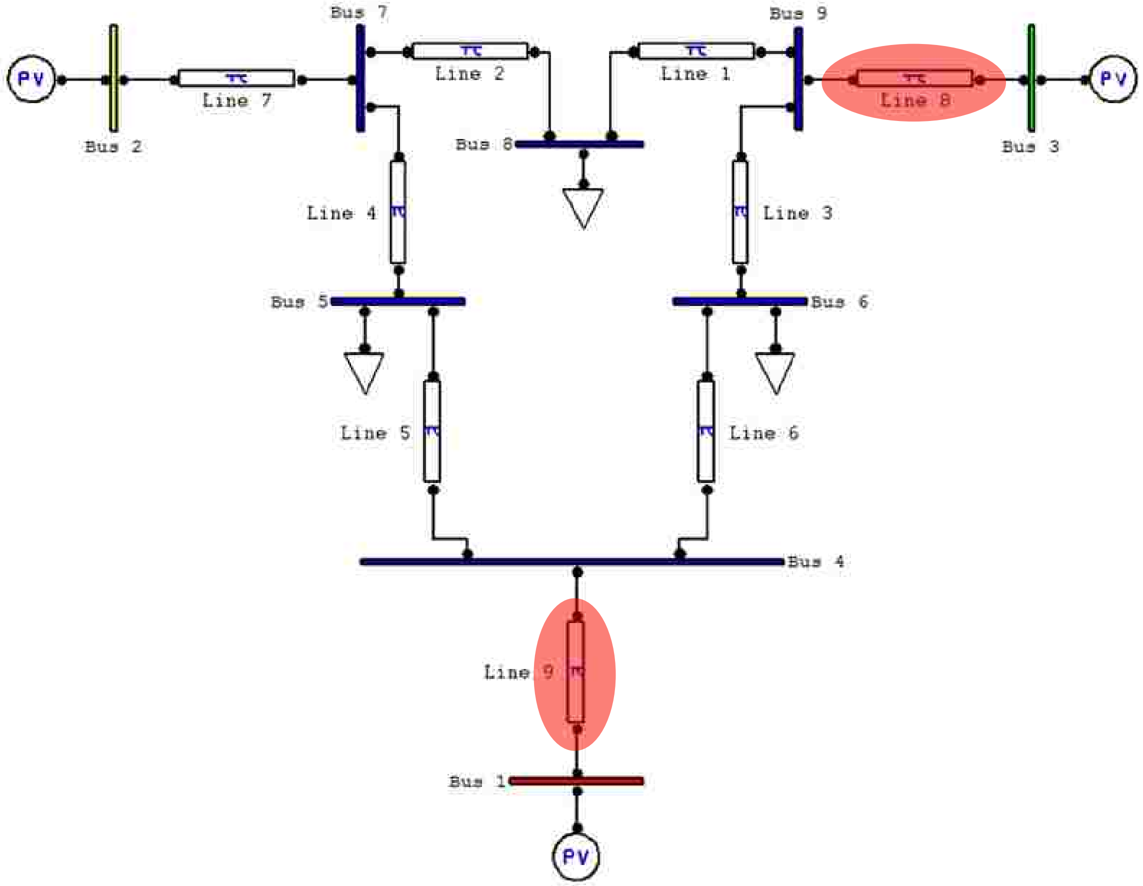

Figure 4.15. Failure of Transmission Line 7

4.3.3 Performance of Recovery Strategies. We assumed earlier that during the failure of one of the generators in the system, the other functional generators can provide 10% more power if the consumed power is more than the available generated power. Therefore, there will be more power consumption than the generated power when restoring the first and second transmission lines.

The first recovery sequence is (7, 8, 9). In this case, we will recover transmission line 7. Since, recovering transmission line 7 will restore 163 MW to the system, and this is lower than the total load, then we will assume that the generation power will increase by 10%. The total generation power will be 179.3 MW. This power is still lower than the total load in the system. Now, the recovery process will continue

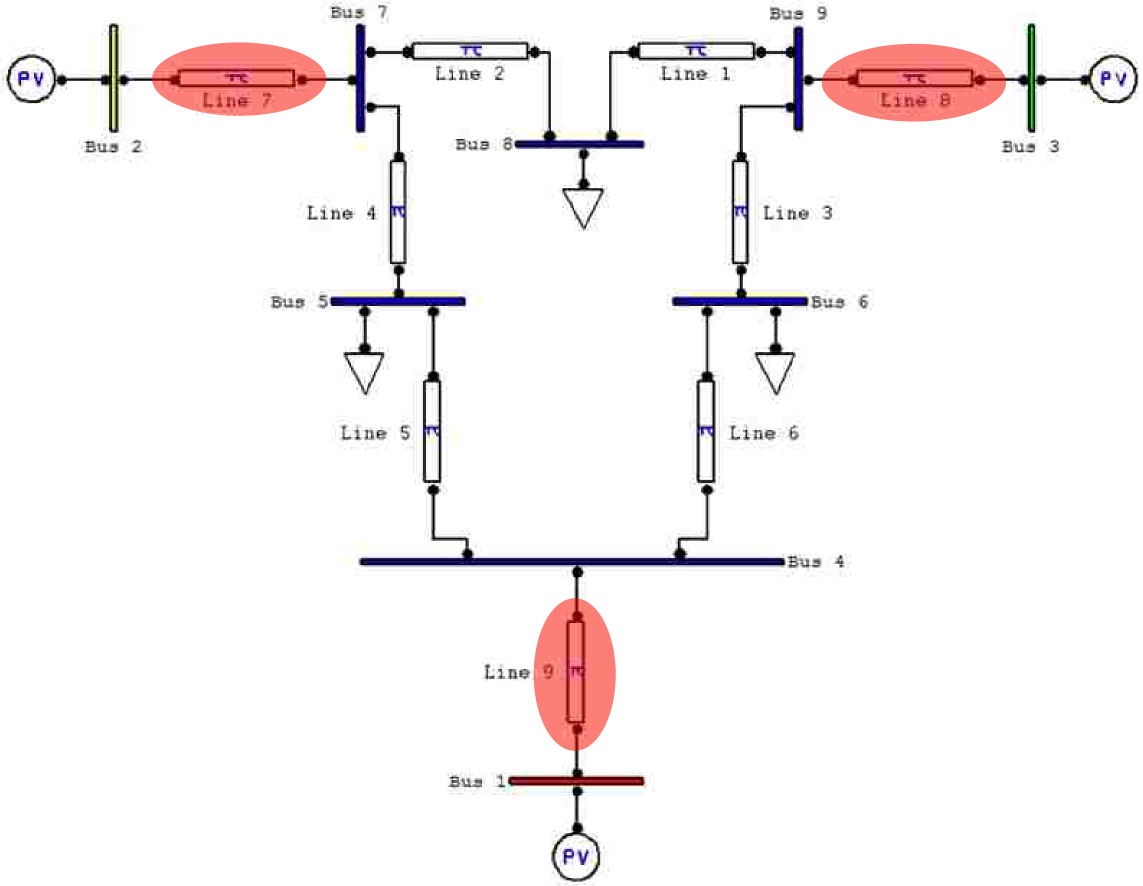

Figure 4.16. Failure of Transmission Line 9

with restoring transmission line 8. Recovering this transmission line will restore 85 MW to the system. Now, the total available power will be 264.3 MW. The total generated power is still less than the load in the system. Therefore, the generator with the 85 MW will increase the generation by 10%, and the total generated power will be 272.8 MW. The total generated power is still less the the load in the system. The recovery process will continue by recovering transmission line 9. After recovering transmission line 9, the other two generators will be back to generating 163 MW and 85 MW.

The recovery process will be repeated for all the other possible sequences. Table 4.10 contains a list of the recovery sequences and their survivability index after recovering each transmission line. We can see that the proposed recovery strategy, represented by the sequence (7, 8, 9), has achieved the best performance after recovering any transmission line. Also, we can see that the sequence (8, 7, 9) has the same value for the survivability index after restoring transmission line 7. However, this is not an optimal recovery sequence, because after recovering transmission 8, the survivability index is lower than the survivability index after restoring transmission line 7 for the sequence (7, 8, 9). Therefore, the recovery sequence (8, 7, 9) will not result in getting the best value for the survivability index over time.

Table 4.10. Survivability Index Comparison

	Survivability Index (V)		
Recovery Sequence	Recovering First TL	Recovering Second TL	Recovering Third TL
7, 8, 9	0.569	0.866	1
7, 9, 8	0.569	0.82	1
8, 7, 9	0.297	0.866	1
8, 9, 7	0.297	0.548	1
9, 7, 8	0.251	0.82	1
9, 8, 7	0.251	0.548	1

5 CONCLUSION AND FUTURE WORK

The goal of the research presented in this thesis was to simulate, analyze, and present models for two operational phases of a power grid system. The first phase occurs when the system is fully functional. For this phase, we presented a quantitative reliability model derived by populating the MIS model with information from N-1 contingency analysis of the grid. This reliability model was presented for both physical and cyber-physical grids. In the latter case, the cyber infrastructure considered was comprised of an SSSC control device whose deployment resulted in an increased number of functional states for the system.

A failure in the system does not mean that the system will be completely unable to perform. The second operational phase investigated in this research begins after occurrence of a failure. To understand and quantify operation of the system in this phase, we defined a survivability index, V, to describe the state of the system after outage of a transmission line. We used this index to determine the importance of each transmission line in the system. We subsequently used this importance analysis to guide recovery of the system - specifically, to determine the order in which components should be restored.

As a case study, we applied the proposed techniques to modeling the reliability and survivability of the IEEE 9-bus system, and to guide its recovery from failure.

Future extensions to this work include application of the proposed techniques to larger cyber-physical grids with a richer cyber infrastructure, as well as extension of the work to other application domains, including intelligent water distribution.

BIBLIOGRAPHY

[1] U.S.-Canada Power System Outage Task Force, “Final report on the August 14, 2003 blackout in the United States and Canada: Causes and recommendations,” tech. rep., Apr. 2012.

[2] Federal Energy Regulatory Commission and North American Electric Reliability Corporation, “Final report on the Arizona-Southern California outages on September 8, 2011,” tech. rep., Apr. 2004.

[3] A. Z. Faza, S. Sedigh, and B. M. McMillin, “Integrated cyber-physical fault injection for reliability analysis of the smart grid,” in *Proc. 29th Int. Conf. Computer Safety, Reliability and Security (SAFECOMP)*, vol. 6351, pp. 277–290, 2010.

[4] A. Avizienis, J.-C. Laprie, B. Randell, and C. Landwehr, “Basic concepts and taxonomy of dependable and secure computing,” *IEEE Trans. on Dependable and Secure Computing*, vol. 1, pp. 11–33, Jan.-Mar. 2004.

[5] M. Albasrawi, N. Jarus, K. Joshi, and S. Sedigh Sarvestani, “Analysis of reliability and resilience for smart grids,” in *Proc. 38th Int. Computers, Software & Applications Conference (COMPSAC)*, (Vasteraas, Sweden), 2014, to appear.

[6] I. Dobson, B. A. Carreras, V. E. Lynch, and D. E. Newman, “Complex systems analysis of series of blackouts: Cascading failure, critical points, and self-organization,” *Chaos: An Interdisciplinary Journal of Nonlinear Science*, vol. 17, no. 2, p. 026103, 2007.

[7] M. Amin, “Toward self-healing infrastructure systems,” *Computer*, vol. 33, no. 8, pp. 44–53, 2000.

[8] A. Z. Faza, S. Sedigh, and B. M. McMillin, “Reliability modeling for the advanced electric power grid,” in *Proc. 26th Int. Conf. Computer Safety, Reliability and Security (SAFECOMP)*, vol. 4680, pp. 370–383, September 2007.

[9] A. Z. Faza, S. Sedigh, and B. M. McMillin, “Reliability analysis for the advanced electric power grid: From cyber control and communication to physical manifestations of failure,” in *Proc. 28th Int. Conf. Computer Safety, Reliability and Security (SAFECOMP)*, vol. 5775, pp. 257–269, September 2009.

[10] A. Z. Faza, S. Sedigh, and B. M. McMillin, “Reliability modeling for the advanced electric power grid: A proposal for doctoral research,” in *Proc. 33rd Annu. Computer Software and Applications Conf. (COMPSAC)*, vol. 1, pp. 672–675, 2009.

[11] A. Z. Faza, S. Sedigh, and B. M. McMillin, “A case study in quantitative analysis of cyber-physical systems: reliability of the electric power grid,” *IEEE Trans. Rel.*, 2013.

[12] A. Z. Faza, S. Sedigh, and B. M. McMillin, "An integrated cyber-physical reliability model for the smart grid," *Reliability Engineering and System Safety*, 2013.

[13] D. L. Pepyne, C. G. Panayiotou, C. G. Cassandras, and Y. C. Ho, "Vulnerability assessment and allocation of protection resources in power systems," in *Proc. American Control Conf.*, vol. 6, pp. 4705–4710 vol.6, 2001.

[14] J. Chen, J. S. Thorp, and I. Dobson, "Cascading dynamics and mitigation assessment in power system disturbances via a hidden failure model," *Int. J. of Electrical Power and Energy Systems*, vol. 27, no. 4, pp. 318–326, 2005.

[15] D. L. Pepyne, "Topology and cascading line outages in power grids," *J. Systems Science and Systems Engineering*, vol. 16, no. 2, pp. 202–221, 2007.

[16] X. Chen, H. Dinh, and B. Wang, "Cascading failures in smart grid - benefits of distributed generation," in *Proc. IEEE Int. Conf. on Smart Grid Communications (SmartGridComm)*, pp. 73–78, 2010.

[17] M. Youssef, C. Scoglio, and S. Pahwa, "Robustness measure for power grids with respect to cascading failures," in *Proc. Int. Workshop on Modeling, Analysis, and Control of Complex Networks (CNET)*, pp. 45–49, ITCP, 2011.

[18] M. Moghavvemi and O. Faruque, "Real-time contingency evaluation and ranking technique," *IEE Proceedings on Generation, Transmission and Distribution*, vol. 145, no. 5, pp. 517–524, 1998.

[19] S. M. R. Slochanal, M. Saravanan, and A. C. Devi, "Application of PSO technique to find optimal settings of TCSC for static security enhancement considering installation cost," in *Proc. 7th Int. Power Engineering Conf. (IPEC)*, pp. 1–394, 2005.

[20] G. I. Rashed, H. I. Shaheen, and S. J. Cheng, "Evolutionary optimization techniques for optimal location and parameter settings of TCSC under single-line contingency," in *Proc. IEEE Power and Energy Society General Meeting*, pp. 1–9, 2008.

[21] A. M. Othman, M. Lehtonen, and M. M. El-Arini, "Enhancing the contingency performance of HELENSÄHKÖVERKKO OY 110 KV network by optimal installation of UPFC based on genetics algorithm," in *Proc. IEEE Power and Energy Society General Meeting*, pp. 1–8, 2010.

[22] A. Lininger, B. McMillin, M. Crow, and B. Chowdhury, "Use of Max-Flow on FACTS devices," in *Proc. 39th North American Power Symposium (NAPS)*, pp. 288–294, Sept 2007.

[23] J. Chaloupek, D. Tauritz, B. McMillin, and M. Crow, “Evolutionary optimization of flexible A/C transmission system device placement for increasing power grid reliability,” in *Proc. 6th Int. Workshop on Frontiers in Evolutionary Algorithms (FEA)*, (Salt Lake City, Utah), pp. 516–519, Nov. 2005.

[24] C. Dichirico and C. Singh, “Reliability analysis of transmission lines with common mode failures when repair times are arbitrarily distributed,” *IEEE Trans. Power Sys.*, vol. 3, pp. 1012–1019, August 1988.

[25] S. Asgarpoor and M. Mathine, “Reliability evaluation of distribution systems with nonexponential down times,” *IEEE Trans. Power Sys.*, vol. 12, pp. 579–584, May 1997.

[26] E. Zio and L. Golea, “Analyzing the topological, electrical and reliability characteristics of a power transmission system for identifying its critical elements,” *Reliability Engineering & System Safety*, vol. 101, pp. 67 – 74, May 2012.

[27] Y. Liu and K. S. Trivedi, “Survivability quantification: The analytical modeling approach,” *International Journal of Performability Engineering*, vol. 2, no. 1, p. 29, 2006.

[28] A. Avritzer, S. Suresh, D. S. Menasché, R. M. M. Leão, E. de Souza e Silva, M. C. Diniz, K. Trivedi, L. Happe, and A. Koziolek, “Survivability models for the assessment of smart grid distribution automation network designs,” in *Proceedings of the 4th ACM/SPEC International Conference on Performance Engineering*, ICPE ’13, pp. 241–252, 2013.

[29] P. Chopade and M. Bikdash, “Critical infrastructure interdependency modeling: Using graph models to assess the vulnerability of smart power grid and scada networks,” in *Emerging Technologies for a Smarter World (CEWIT), 2011 8th International Conference Expo on*, pp. 1–6, Nov 2011.

[30] P. Chopade and M. Bikdash, “Modeling for survivability of smart power grid when subject to severe emergencies and vulnerability,” in *Southeastcon, 2012 Proceedings of IEEE*, pp. 1–6, March 2012.

[31] P. Chopade, M. Bikdash, and I. Kateeb, “Interdependency modeling for survivability of smart grid and scada network under severe emergencies, vulnerability and wmd attacks,” in *Southeastcon, 2013 Proceedings of IEEE*, pp. 1–7, April 2013.

[32] F. Milano, “An open source power system analysis toolbox,” in *Proc. IEEE Power Engineering Society General Meeting*, 2006.

[33] W. Kuo and M. J. Zuo, *Optimal Reliability Modeling, Principles and Applications*, pp. 164–171. John Wiley and Sons, Inc., 2003.

[34] K. K. Sen, “SSSC static synchronous series compensator: theory, modeling, and application,” *Power Delivery, IEEE Transactions on*, vol. 13, pp. 241–246, Jan 1998.

[35] Illinois Center for a Smarter Electric Grid (ICSEG), “Working Toward a Smarter Grid.” `http://publish.illinois.edu/smartergrid/case-1-ieee-9-bus-systems/`, March 10, 2014.

[36] S.-H. Song, J.-U. Lim, S.-W. Jung, and S.-I. Moon, “Preventive and corrective operation of FACTS devices to cope with a single line-faulted contingency,” in *Power Engineering Society General Meeting, 2004. IEEE*, vol. 1, pp. 837–842, June 2004.

[37] R. W. Chang, T. Kuo, and T. Saha, “Mixed-integer method for optimal UPFC placement based on line flow-based equations,” in *Universities Power Engineering Conference (AUPEC), 2010 20th Australasian*, pp. 1–6, Dec 2010.

VITA

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