FAST POWER NETWORK DETECTION OF TOPOLOGY CHANGE LOCATIONS USING PMU MEASUREMENTS

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A Thesis Submitted to the Faculty of the University of
Tennessee at Chattanooga in Partial Fulfillment
of the Requirements of the Degree of
Master of Science: Engineering

The University of Tennessee at Chattanooga
Chattanooga, Tennessee

December 2016

ABSTRACT

System monitoring and contingency analysis are crucial functions in power control centers. These applications need a complete model of the power network to perform the desired analysis. Yet, this model must be continuously updated to account for system dynamics. Several topology processing schemes have been developed to accomplish this task. The majority of these schemes process breaker statuses to detect changes in system topology which results in a complicated analysis method.

In this work, a simple and quick method for on-line detection and identification of system topology changes using PMU measurements is introduced. This method is based on representing line outages with fictitious nodal power injections. The algorithm can be applied on systems that are not entirely covered by PMUs.

The scheme was tested during different outage events in the IEEE39-bus system. The obtained results validated the algorithm's ability to detect and identify line outage events effectively and efficiently.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Power system networks experience several dynamic events during operation. However, network solution programs, such as the state estimator, need a correct and up-to-date configuration of the system in order to perform their function. This necessitates the availability of a mathematical model that incorporates the changing operating conditions of the system [1]. To accomplish this purpose, several topology processing schemes have been developed.

1.2 Problem Statement

Conventional topology processing schemes relies on communicated breaker status information in order to configure the present system topology. However, these schemes generally deploy a sophisticated logic to analyze and process this information and consequently reflect the effect of breaker status changes on system configuration. The complexity of these logics results in a considerable processing time [2]. This implies the need for developing a fast and simple topology processing scheme.

1.3 Objectives

The objective of this work is to develop a fast and reliable scheme for detection of topology change locations in power networks using PMU measurements. This scheme is to be applied on reduced systems where parts of the network are not monitored using PMUs.

1.4 Study Outline

The remaining chapters of this thesis are organized as follows:

- Chapter Two: in this chapter, topology processing schemes presented in the literature are reviewed along with their merits and drawbacks.
- Chapter Three: this chapter introduces the theory behind the proposed scheme. Furthermore, a detailed description of the processes followed to detect and identify topology change locations is provided.
- Chapter Four: this chapter presents simulation results when testing the algorithm performance on the IEEE39-bus system.
- Chapter Five: this chapter discusses the contributions of this work in the area of topology estimation and lists the advantages of the developed scheme.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A power system is said to be secure if it continues to operate despite components failure. Power system security mainly consists of three major functions which are system monitoring, contingency analysis and security-constrained optimal power flow.

System monitoring is achieved through gathering real time measurements from the field. These telemetered measurements reflect the up-to-date condition of the network. Such measurements along with their data transmission system are referred to as energy management system (EMS). The EMS provides the means for monitoring system voltages, power flows, circuit breakers statuses, etc. This tremendous amount of telemetered data implies the use of digital computers in order to process and store them in a database. The data are then used to perform state estimation [1].

State estimation is a process that uses system measurements to assign value to an unknown system state depending on some criteria. The process usually deals with redundant measurements, and estimates the true value of these states using certain statistical criteria. Voltage magnitudes and their relative phase angles are considered to be the state variables in power systems. The best estimate of these states depends on the available measurements. These measurements could be voltage magnitudes, ampere-flow or power-flow quantities [1].

One of the most common approaches to perform state estimation is the weighted least-square method. This method aims to minimize the overall squared difference between the estimated state and the measured one. Equation (2.1) shows the function to be minimized.

$$J = \sum_{j=1}^{M} W_j |X_{m,j} - X_{c,j}|^2 \tag{2.1}$$

Where

$X_{m,j}$ = j-th measurement

$X_{c,j}$ = j-th calculated measurement

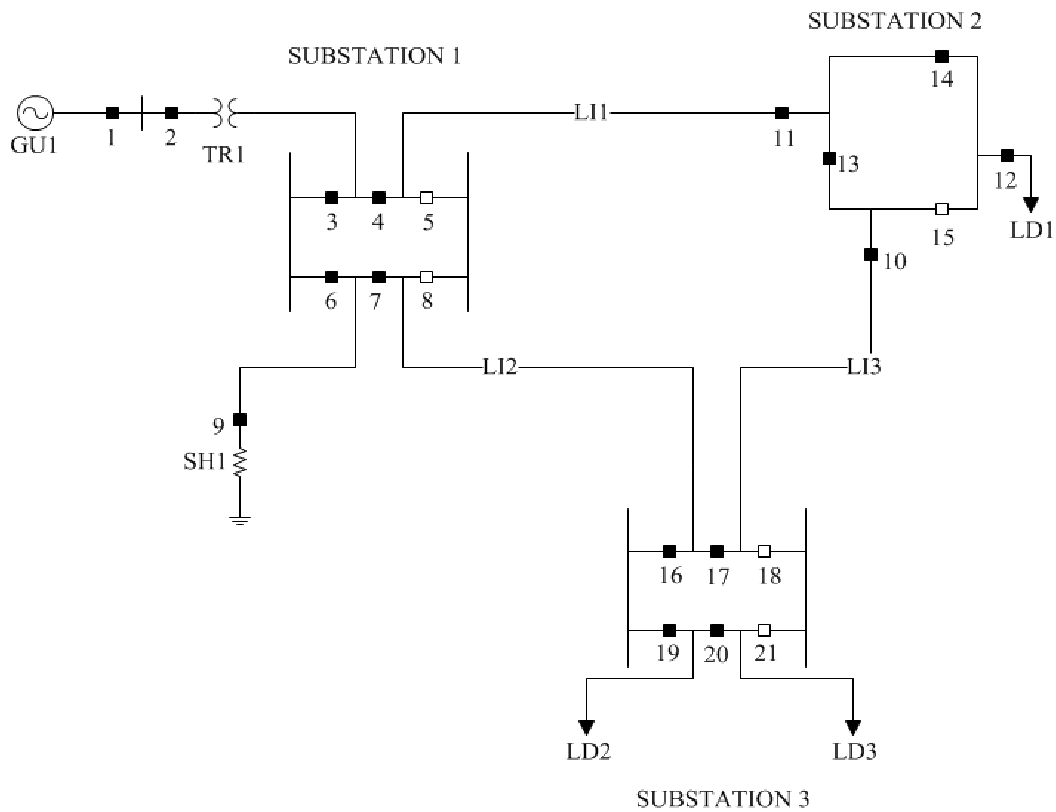
W_j = weighting factor for j-th measurement

M = number of measurements

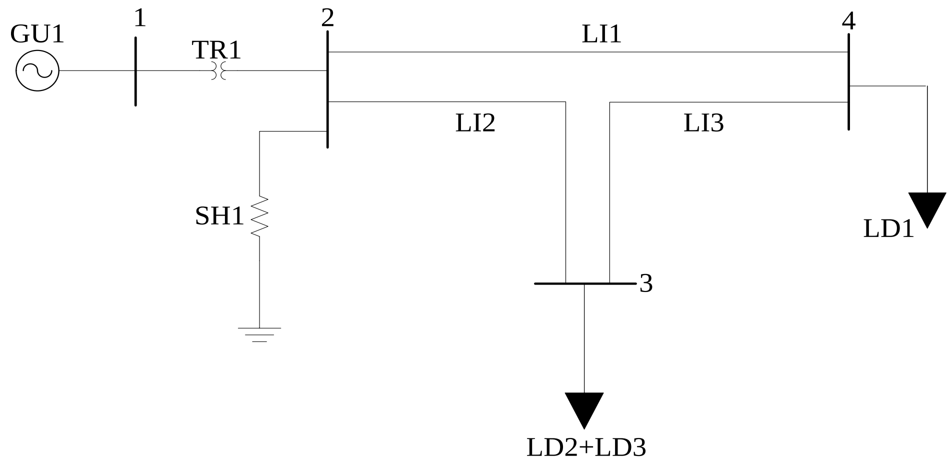
The measurements fed to the state estimator must be combined with the corresponding model of the system to generate an estimate of the present system states. This implies that the system configuration must always be kept up-to-date [2].

Contingency analysis programs simulate potential system failures in order to alarm system operators to any serious trouble which might cause cascading events. A complete model of the power system is needed to perform this analysis. Furthermore, this system model must be continuously updated to reflect current system conditions for the purpose of on-line analysis. Topology processing schemes have been developed to accomplish this task. It is worth mentioning that besides state estimation and on-line contingency analysis, up-to-date system model is also used by many other applications. For example, it can enhance the economic dispatch program by providing updated penalty factors [1].

The power system connectivity data is used to construct a model that can be used by the aforementioned applications. These data are normally stored in terms of bus-sections and circuit breakers. However, in order to perform these analyses, the data need to be expressed in terms of buses and branches. Figure 2.1 shows an example of the transformation from a bus-section/circuit-breaker model to a bus/branch form [3].



(a)



(b)

Figure 2.1 (a) Bus-Section/Circuit Breaker Network Model, (b) Bus/Branch Network Model

2.2 Conventional Topology Processing Schemes

Conventional topology processing schemes use telemetered circuit breaker statuses along with their connectivity data in order to determine the present system topology [3]. Whenever a change in a breaker status occurs, the topology processor is reinitialized to update the existing system model.

Several topology processing schemes were proposed in the literature. Reference [2] established one of the schemes which serves as a foundation in this area. The authors proposed a topology processing program that updates the configuration of substations based on breaker status changes. The scheme assigns a number to each substation in the system starting from 1 on. Moreover, transmission lines, transformers and system buses are also numbered in another different sequence. The suggested algorithm starts by creating a table which contains the initial data of circuit breakers. This table stores the two circuits between which a circuit breaker is connected along with the initial status of the breaker. Another table is set up to indicate the availability of transmission line measurements for load flow purposes. Real time data are then collected from the system to detect any loss of measurements or breaker status changes in substations. Such a scenario will trigger the algorithm to update system topology. The scheme examines the substations in which circuit breaker status changes have taken place. The algorithm logic essentially searches for all the closed paths within these substations. Multiple closed paths within a substation indicate that the substation has been disconnected forming new nodes. These nodes are then assigned new numbers with one node keeping the original number of the substation before being split. Subsequently, system data tables are modified to include the new formed nodes. Furthermore, the algorithm detects transmission lines and transformers which are open at one or both ends due to changes in breaker statuses. The measurements of these circuits are then excluded from subsequent load flow analysis. The scheme then proceeds to check whether open lines or transformers have led to the isolation of some parts of the network, creating islands. This process is similar to that followed when searching for closed paths within a substation with lines and transformers being treated as if they were circuit breakers. Transmission lines measurements belonging to areas which don't have a reference voltage bus are also excluded from subsequent analysis.

Although the contribution of this work is considered remarkable in the area of topology processing, the algorithm suffers some major deficiencies [4]. First, it is considered to be time consuming since a change within a substation will cause the algorithm to reassess the topology of the whole system. Furthermore, the algorithm is triggered only by changes within substations i.e. changes in transmission line breakers which are not located in a substation don't cause system topology modifications. The scheme assigns new numbers to nodes resulting from substations splitting. These numbers are hard to trace when multiple events are encountered. Moreover, the algorithm is not designed to deal with breaker closing events [4].

Authors of [5] proposed a topology processing scheme that is based on the work presented in [2]. This latter method repeats topology processing whenever a change is detected without consideration to the model resulting from the previous cycle. However, the method suggested by Prais and Bose [5] makes advantage of the fact that major topology changes in power networks are not frequent. Hence, it is not necessary to rebuild system matrices in each cycle. Instead, the algorithm traces the changes in the bus/branch model and rebuilt system matrices only when major changes have occurred. This would lead to an increase in the execution time of the topology processing, but the overall computation time would be greatly improved. It is to be noted however that this method suffers the same aforementioned deficiencies of [2].

2.3 PMUs in Topology Processing

2.3.1 Phasor Measurement Units

Phasor measurement units (PMUs) are devices used to measure electrical waves namely, voltages, currents and frequencies in a synchronized environment. The deployment of these devices helps achieving better utilization of electrical measurements. PMU measurements are presented in terms of magnitude and angle with a high sampling rate, typically 30 measurements per cycle. Universal standard time is used to synchronize different PMU measurements from various locations. One of the most effective devices to attain this time reference is the Global Positioning System (GPS). Synchronized Measurements obtained from different PMUs are called synchrophasors.

Legacy supervisory control and data acquisition (SCADA) systems provide vital information for power network operators. The asynchronous nature of this information along with the low sampling rate, compared to PMUs, makes it impossible for wide area monitoring and control in real time environment [6]. This can be accomplished however with the employment of PMUs. Table 2.1 presents a brief comparison between SCADA system and PMUs [7].

Table 2.1 SCADA vs PMUs

FEATURE	SCADA	PMU
Sampling rate	1 sample every 2-10 Seconds (steady State Monitoring)	1-60 samples per second (Dynamic Monitoring)
Measurements	Magnitude only	Magnitude and phase angle
Time Synchronization	No	Yes
Employment	Local monitoring and control	Wide area monitoring and control

Synchrophasors obtained from different PMUs enable dynamic monitoring of the system. Such a feature has paved the way for many initiative projects to improve power networks performance. These projects aim to upgrade power systems operation, supervision, protection and control [8].

2.3.2 PMU-Based Topology Processing Schemes

Many researches have been conducted to make use of PMU information to increase situational awareness of power system operators. PMU data are being incorporated in applications such as state estimation, visualization and dynamic security assessment [9]. However, only few researches focused on the use of PMU data for topology processing enhancement. One of the prominent works in this area is presented by Tate and Overbye. The suggested algorithm utilizes PMU phasor angle measurements along with transmission lines and system connectivity data to detect single line outages on the network.

The scheme assumes that a certain number of busses are being observed using PMUs. These buses are referred to as observable buses. Whenever an outage occurs on the system, the phasor angles of the observed buses experience changes. The synchrophasor angle measurements from these buses are low-pass filtered to eliminate transient oscillations. Figure 2.2 shows an example of a PMU angle measurement and its filtered form. An edge detection method is then used to detect changes in these measurements.

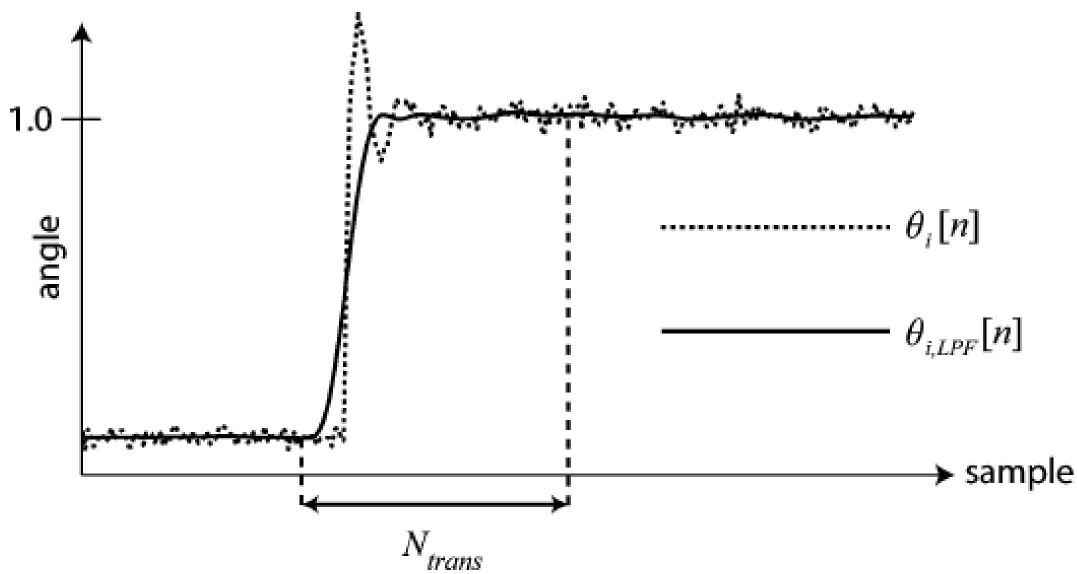


Figure 2.1 Phasor angle measurements

Where θ_i is the actual angle measurements, $\theta_{i,LPF}$ is the filtered one and N_{trans} is the number of samples over which a difference in steady state angles is calculated [9].

The algorithm uses DC power flow equations to express the angle changes in term of the pre-outage flows on the lines as shown in equation (2.2).

$$\Delta\theta = B^{-1}\Delta P \qquad (2.2)$$

Where ΔP is a vector of power injections changes on each bus due to line outage, B is the susceptance matrix. The calculated angle changes together with the observed ones are then used to form an optimization problem. The solution to this problem is the event that drives the difference to be minimum as shown in equation (2.3)

$$\text{Line outage } l^* = \arg min_{l\in(1,2,\ldots L)} |\Delta\theta_{observed} - \Delta\theta_{calculated}| \qquad (2.3)$$

Where l is the number of lines in service before the event [10].

Although this algorithm uses limited number of PMUs to detect line outages, it has some major issues. Firstly, the adoption of DC load flow introduces errors in the calculations of the changes in phasor angles. That is due to the fact that DC load flow conditions do not hold in real systems. Moreover, the changes in phasor angles are not necessarily caused by line outages. Generator outages for instance could also lead to such changes. Another point to consider is that the algorithm will not be able to distinguish between different line outage events that cause similar phasor angle changes. Furthermore, a moving window of samples must be set to include the entire transition region in the case of an event. This will introduce a delay in the detection of phasor angle changes.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, a new topology processing scheme which detects line outage events in real time is presented. Unlike the methods described in chapter two which depends on breaker status data, this method rather uses system state information along with nodal power measurements obtained from PMUs to identify and locate line outages. Furthermore, the scheme can be applied on reduced systems where system state data for unobserved buses is absorbed in the aggregation.

3.2 Background

In [1], a method to simulate line outages without the need to update system topology was developed. This method adds two fictitious injections into the buses between which the line was connected. This can be demonstrated by referring to figure 3.1. Line k is connected to the system through buses n and m. The original flow on the line is P_{nm}. However, when the breakers at the end of the line open, this flow goes to zero. This outage event can be simulated by adding injections ΔP_n and ΔP_m at buses n and m respectively with both breakers closed. The will result in a power $\tilde{P}_{nm}$ flowing in the line. To derive the flow at line breakers to zero, the injected power at bus n should flow through line k and out of bus m. this implies that:

$$\Delta P_n = \tilde{P}_{nm} \quad 3.1$$

$$\Delta P_m = -\tilde{P}_{nm} \quad 3.2$$

The zero flow at both breakers is similar to the breakers open scenario.

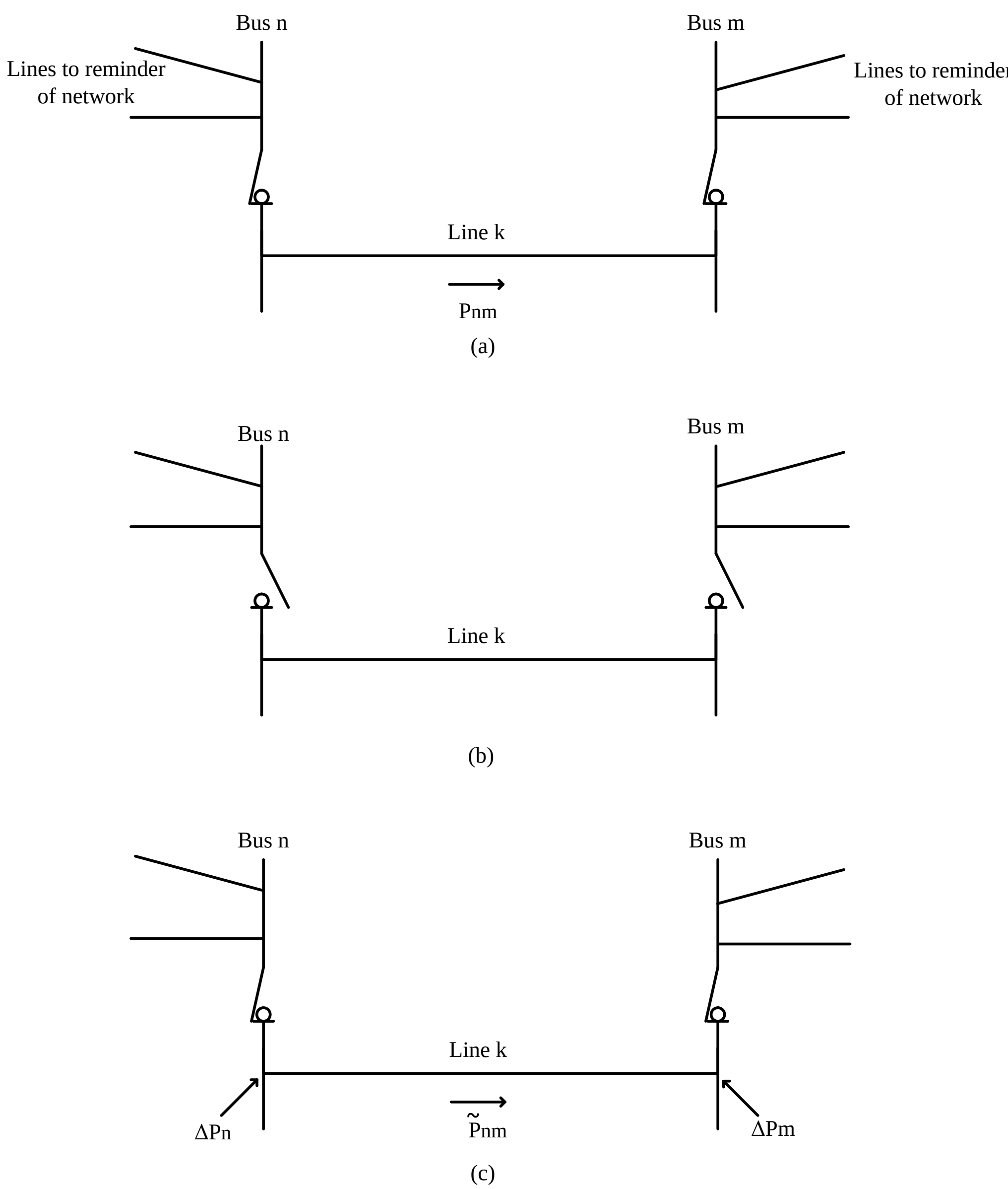


Figure 3.1 (a) Line k before outage, (b) Line k after outage, (c) Simulating line k outage using fictitious injections at buses n and m

3.3 Nodal injections in a Simplified System Model

The theory behind the proposed scheme is introduced in this section using a simple 2-bus system. The system consists of a double-line circuit connecting buses i and j as shown in figure 3.2. It is assumed that the lines are represented using an equivalent π model. The nodal states of the buses, $V_i\angle\delta_i$ and $V_j\angle\delta_j$, as well as the flows of the two lines are monitored using PMUs.

The power flow equations at bus i can be expressed as follows:

$$P_i = \sum_{j=1}^{N-1}\left(\sum_{L=1}^{M}\left[V_i^{\,2} - V_iV_j\cos\left(\delta_i - \delta_j\right)\right].g_L - V_iV_j\sin\left(\delta_i - \delta_j\right).b_L\right) \quad 3.3$$

$$Q_i = \sum_{j=1}^{N}\left(\sum_{L=1}^{M} -V_i^{\,2}.b_{L\_sh} + \left[V_i^{\,2} - V_iV_j\cos(\delta_i - \delta_j)\right].b_L - V_iV_j\sin\left(\delta_i - \delta_j\right).g_L\right) \quad 3.4$$

Where:

P_i ≡ Injected active power at bus i

Q_i ≡ Injected reactive power at bus i

N ≡ Number of buses in the system

M ≡ Number of lines connecting buses i and j

g_L ≡ Series conductance of line L

b_L ≡ Series susceptance of line L

b_{L_sh} ≡ Shunt charging susceptance of line L

In this system, N=2 and M=2. When substituting the nodal states of the system during normal operating conditions i.e. with both lines in service, the resulting P_i and Q_i are equal to the net load and generation at the bus. However, if an outage occurs on one of the circuits, the nodal states will change. Appling these states to the aforementioned power flow equations while keeping the original system model i.e. both lines are included, would result in a total injected power $\mathrm{P_i}$ and $\mathrm{Q_i}$ which differ from the net load and generation at the bus. These injection errors represent the fictitious injections $\mathrm{P_{i-inj}}$ and $\mathrm{Q_{i-inj}}$ that simulate an outage.

$$P_{i-inj} = P_i - \left(P_{i_g} - P_{i_d}\right) \qquad 3.5$$

$$Q_{i-inj} = Q_i - (Q_{i_g} - Q_{i_d}) \qquad 3.6$$

Similarly, when applying the power flow equations to bus j, approximately the same amount of active injected power will appear with a negative sign to drive the flow through the breakers of the outraged line to zero. The difference will be caused by the i^2R losses in the i-j branch.

$$\mathrm{P_{j-inj}} \approx -\mathrm{P_{i-inj}} \qquad 3.7$$

The case is not necessarily the same for reactive power since under light load conditions, the outaged line might generate sufficient vars to mask this power circulation effect, and conversely absorb excessive vars under heavy load conditions.

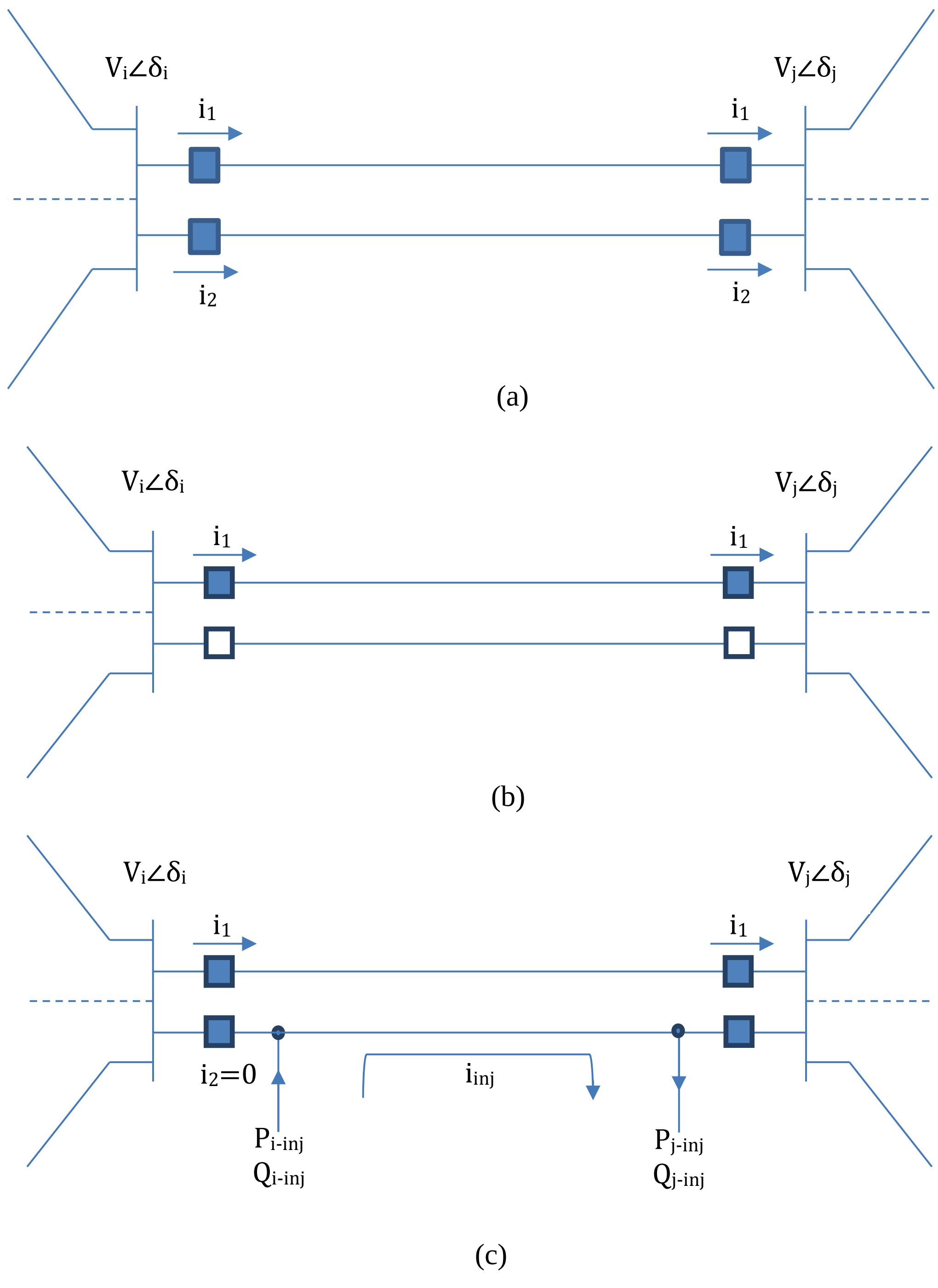


Figure 3.2 (a) Two-Bus system with both lines in service, (b) One of the lines out of service, (c) outaged line in service with power injections

Once the injection errors $\mathrm{P_{i-inj}}$, $\mathrm{Q_{i-inj}}$, $\mathrm{P_{j-inj}}$ and $\mathrm{Q_{j-inj}}$ are calculated, the outaged line parameters can be directly estimated using equations 3.8 and 3.9.

$$P_i = [V_i^2 - V_iV_j\cos(\delta_i - \delta_j)].g_L - V_iV_j\sin(\delta_i - \delta_j).b_L \quad 3.8$$

$$Q_i = -V_i^2.b_{L\_sh} + [V_i^2 - V_iV_j\cos(\delta_i - \delta_j)].b_L - V_iV_j\sin(\delta_i - \delta_j).g_L \quad 3.9$$

These equations can be rearranged in a compact form as:

$$\begin{bmatrix} P_{i-inj} \\ Q_{i-inj} \\ P_{j-inj} \\ Q_{j-inj} \end{bmatrix} = [H] \cdot \begin{bmatrix} g_L \\ b_L \\ b_{Sh} \end{bmatrix} \quad 3.10$$

The outaged line parameters are then calculated using:

$$\begin{bmatrix} g_L \\ b_L \\ b_{Sh} \end{bmatrix} = \left([H]^T \cdot [H]\right)^{-1} \cdot [H]^T \cdot \begin{bmatrix} P_{i-inj} \\ Q_{i-inj} \\ P_{j-inj} \\ Q_{j-inj} \end{bmatrix} \quad 3.11$$

Consequently, system topology can be updated directly by subtracting the calculated parameters from the corresponding entries within system matrix.

However, if the network is not entirely covered with PMUs, there might be cases where the line outage event occurs inside an area that is not observed. This outage will be reflected by injection errors at the PMU buses at the boundaries of the area. In such a scenario, if more than two boundary circulations are detected, it becomes impossible to estimate the correct topology using the previous set of equations, as more degrees of freedom are needed. Hence, a more generalized scheme is developed in the next section.

3.4 Complete Algorithm

The scheme developed in this thesis assumes only n-1 contingency at any given time. This scheme continuously applies system states obtained from PMUs to the present system topology (equations 3.3, 3.4). In case of a line outage event, a set of injections that is not accounted for appears (equations 3.5, 3.6). However, to account for the stochastic nature of errors in PMU measurements, a threshold value, below which the injection errors are ignored, is defined. This threshold could be a percentage of the total system load for instance.

The identification of the outaged line is relatively easy if all system buses are monitored using PMUs. In such a scenario, a pair of injection errors is detected at the outaged line ends when applying system states to the complete system model. After identifying these two buses, the algorithm constructs the event area model which consists of the two buses along with all lines connected between them, their generation and load as well as the power transferred between each bus and the remainder of the system. These power flows are then treated as load or generation depending on their direction.

Once the event area model is constructed, a trial-and-error method is adopted to detect the outaged line. This is essentially done by first excluding the suspected line from event area model, reducing this model to eliminate unobserved buses and then applying current system states to this updated topology to calculate the new injection errors. If the resulting errors are below the pre-defined threshold, the suspected line is recognized to be out and the present system topology is updated accordingly. Otherwise, the next candidate line is considered.

The algorithm could be further applied to reduced systems where parts of the network are not covered by PMU measurements. In this situation, it would be impossible to estimate the states for unobserved buses unless the exact topology is known. Conversely, these states are needed to determine the exact topology of the system.

At first, a reduced model of the system consisting only of observed buses is constructed. The unobserved nodes are typically tie-buses with no loading. Line outage events in an unobserved portion of the system will cause injection errors at the boundaries of the unobserved area in the reduced network. These boundaries are defined by PMU buses which surrounds the unobserved area. The scheme can make advantage of such behavior to circle the area that contains the event. Strictly speaking, the scheme only considers the cases in which injection errors appear in more than one bus. In addition, these buses must be either directly connected or form boundaries for a specific unobserved area. The detection of injection error in a single bus could represent an unaccounted for load or simply a too high a value of the threshold level. On the other hand, detection of injections in two different areas could represent a previous outage that was not taken into account in the present system topology.

3.4.1 Determining the Event Area

To detect the outaged line in a specific event area, all the buses in this area, which consists of the unobserved buses with their PMU boundaries, must be identified first. The algorithm essentially starts from an observed bus with significant injection error and attempts to find all buses connected to it which also experience notable errors. It is to be noted that two observed buses with injection errors could either be directly connected to each other or a series of unobserved buses might exist between them. The following steps are used to determine the event area buses:

1. Define empty matrices:

AREA, TEMP, PATH.

2. For each bus in the system:

   Check if the injection error is greater than the pre-defined threshold. If yes, add the bus to AREA matrix and go to step 3. Otherwise, check the next bus.

3. For all lines connected to the bus:

   If the remote terminal bus is observed and its injection error is greater than the threshold, add it to AREA and move on to the next line. Else if the remote terminal bus is unobserved, add it to TEMP matrix, add both terminal buses to the first row of PATH and go to step 5. Otherwise, check the next line.

4. Go to the next bus in 2.
5. While TEMP is not empty
   a. Create new empty matrices TEMP1 and PATH1. Set New-Path-Pointer to 1 and set Current-Path-Pointer to 1.
   b. For all unobserved buses in TEMP:
      i. Store the row of the PATH matrix which is pointed to by Current-Path-Pointer in a new matrix called Current-Path.
      ii. For all lines connected to the unobserved bus, if the remote terminal bus is not a part of Current-Path and is observed and its injection error is greater than the threshold, add the remote terminal bus and Current-Path to AREA and move to the next line. Else if the remote terminal bus is unobserved and not included in Current-Path, add this remote bus to TEMP1, enter both Current-Path and the remote bus in

Path1 in the row which is pointed to by New-Path-Pointer, increase New-Path-Pointer by one and move on to the next line. Otherwise, go to the next line.

c. Increase Current-Path-Pointer by 1 and go to the next unobserved bus in 5.b.

d. TEMP=TEMP1

   Path=Path1

6. Go to the next line in 3

The following example is used to demonstrate these steps. Figure 3.3 shows a model of a simple 7-bus system. Buses 1, 4, 5, 6 and 7 are observed using PMUs. It is assumed that line 2-3 experienced an outage which will be reflected as injection errors at buses 1, 4 and 5.

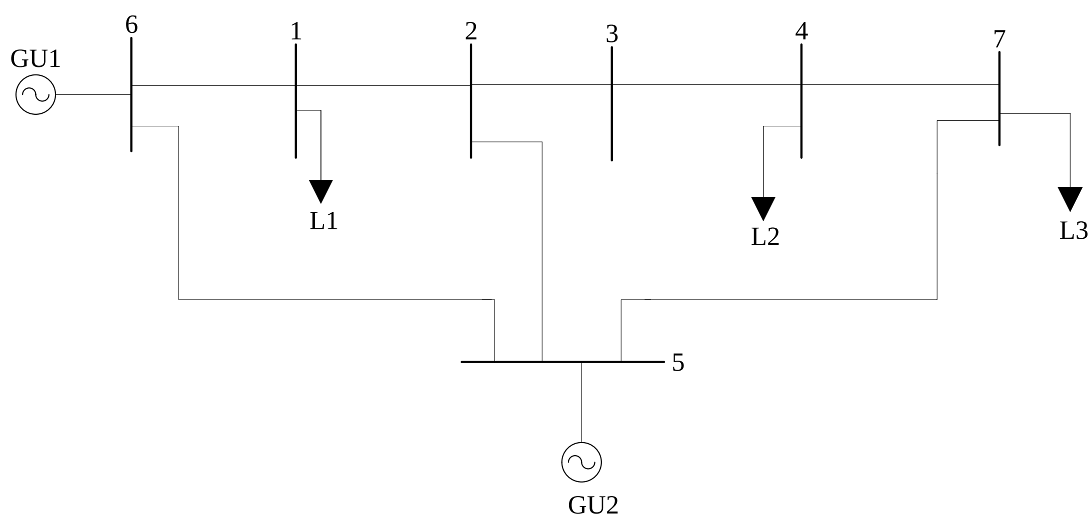


Figure 3.3 7-bus system

Starting from bus 1, the algorithm proceeds as follows:

1. AREA = [ ]; TEMP = [ ]; PATH = [ ];

2. For bus 1:

Since injection error at this bus is greater than threshold value, this bus will be included in the area.

AREA = [1];

3. For Line 1-2:

Since the remote terminal bus (bus 2) is unobserved, TEMP and PATH will be updated as follows:

TEMP = [2]

PATH = [1 2]

The algorithm then jumps to step 5.

5. While TEMP is not empty:

a. TEMP1 = [ ]; PATH1 = [ ];

New-Path-Pointer = 1; Current-Path-Pointer = 1;

b. For Bus 2 in TEMP

i. Current-Path = [1 2]

ii. For Line 1-2

No action is needed because terminal bus (bus 1) is included in Current-Path

For Line 2-3

Since Bus 3 is unobserved:

TEMP1 = [3]

PATH1 = [1 2 3]

New-Path-Pointer = 2

For Line 2-5

Since Bus 5 is observed with injection error, bus 5 and Current-Path will be included in the area:

AREA = [1 2 5]

c. Current-Path-Pointer = 2

d. TEMP = [3]

PATH = [1 2 3]

Since TEMP is not empty, step 5 is repeated again with the new values for TEMP and PATH:

5. a. TEMP1 = [ ]; PATH1 = [ ];

New-Path-Pointer = 1; Current-Path-Pointer = 1;

b. For Bus 3 in TEMP

i. Current-Path = [1 2 3]

ii. For Line 3-2

No action is needed because terminal bus (bus 2) is included in Current-Path

For Line 3-4

Since Bus 4 is observed with injection error, bus 4 and Current-Path will be included in the area:

AREA = [1 2 5 3 4]

c. Current-Path-Pointer = 2

d. TEMP = [ ]; PATH = [ ]

Since TEMP matrix is empty, the while loop condition is not satisfied anymore. Hence, the algorithm will proceed to the next line (Step 3)

3. For Line 1-6

The terminal bus (bus 6) is observed but it has no injection error. Hence, no action is taken for this line.

The algorithm moves to the next observed bus with injection error and the same steps are repeated until all observed buses are checked.

The AREA resulting from this process consists of buses 1, 2, 3, 4 and 5 which represent the event area.

3.4.2 Identifying the Outaged Element

Once all buses contained within the event area are specified, a model is constructed using these buses along with their connectivity data. The power transferred between each PMU bus and the rest of the system together with the generation and load connected to each bus are also considered in this model. The injection errors at each observed bus are then calculated using equations (3.12, 3.13).

$$P_{i-inj} = P_i - \left(P_{i_g} - P_{i_d} - \sum_{\substack{j=1 \\ j \notin event\ area}}^{N} P_{ij} \right) \qquad 3.12$$

$$Q_{i-inj} = Q_i - \left(Q_{i_g} - Q_{i_d} - \sum_{\substack{j=1 \\ j \notin event\ area}}^{N} Q_{ij} \right) \qquad 3.13$$

Afterwards, the algorithm follows the same trial-and-error method described earlier in order to identify the outaged line. This method starts by eliminating the suspected line from the topology. Matrix partitioning is then applied to determine the equivalent admittances between the observed buses. The updated topology is examined against the current states of these buses to calculate the new injection errors at the boundaries. Once the errors are eliminated, the outage line is recognized and the overall system topology is updated. It is to be stated that an improved search criterion could be implemented to enhance the search time. This criterion assumes that the outaged line is close to buses with higher injection errors. Hence, the search is started with lines connected to these buses.

It must be noted that the injection errors at some boundaries of the area might sometimes be less than the threshold. This situation will introduce difficulties in defining the search area. To mitigate this issue, the algorithm uses the unobserved buses found after applying the previous steps along with the connectivity data to determine the remaining boundaries and unobserved buses of the area. A similar procedure to that described in step 5 is adopted to achieve this purpose.

The overall topology processing scheme developed in this work is summarized in the flowchart shown in figure 3.3.

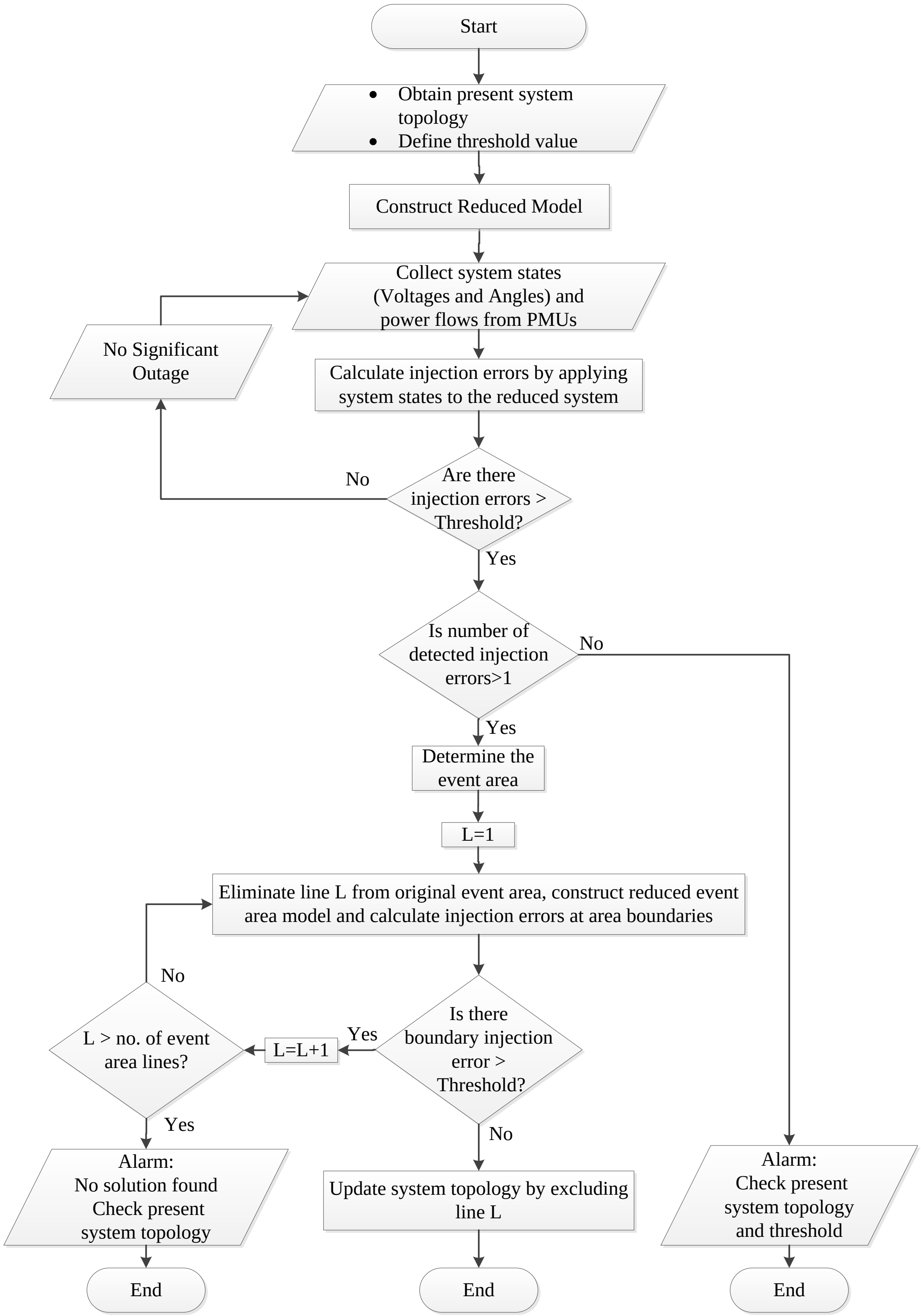


Figure 3.4 Complete topology processing scheme

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Test System Description

The algorithm was tested on the IEEE39-bus system, commonly known as 10-machine New-England power system. This system consists of 10 generators, 18 Loads, 12 transformers and 34 transmission lines as shown in figure 4.1. Complete system data are tabulated in Appendix A. Generator 1 which represents the aggregation of a large number of generators is set to be the swing unit. It is assumed that all generator and load buses are observed using PMUs. The remaining 12 buses are unobserved.

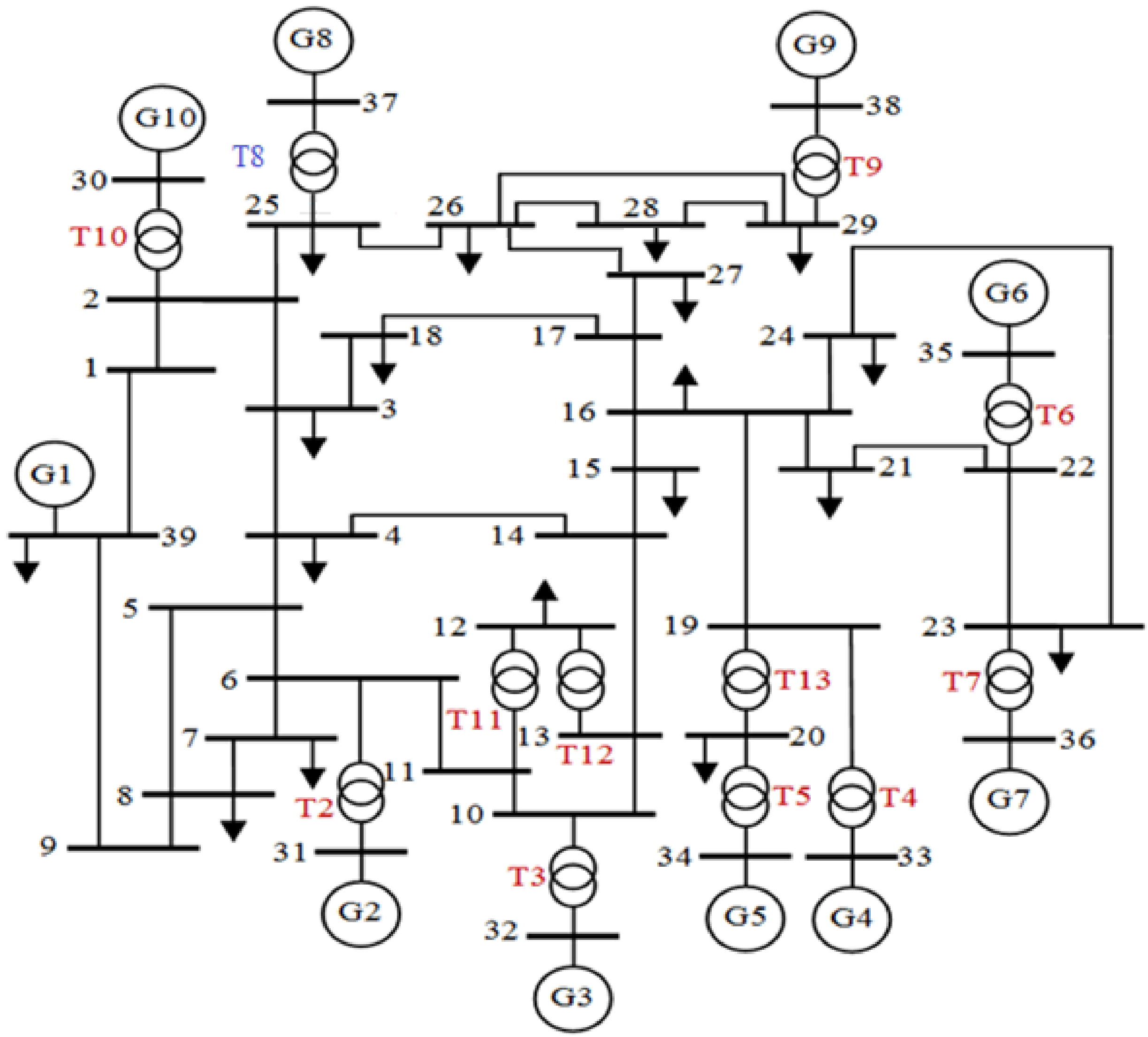


Figure 4.1 IEEE39-bus system

4.2 Simulation Results

4.2.1 Normal Operating Condition

The following tables list the load flow results of the system prior to the application of any outage. Table 4.1 shows system states at each bus whereas table 4.2 lists active and reactive power flow on each line.

Table 4.1 System states during normal operating conditions

Bus	Voltage magnitude (pu)	Angle (degrees)
1	1.038	-0.045
2	1.02	-0.005
3	0.991	-3.879
4	0.956	-6.053
5	0.956	-5.556
6	0.957	-5.082
7	0.949	-6.912
8	0.949	-7.165
9	1.008	-2.839
10	0.963	-1.887
11	0.959	-2.969
12	0.94	-2.805
13	0.961	-2.524
14	0.962	-3.966
15	0.969	-3.551
16	0.988	-1.647
17	0.992	-2.658
18	0.99	-3.588
19	0.99	4.158

20	0.987	3.172
21	0.995	0.926
22	1.021	5.634
23	1.02	5.407
24	0.996	-1.522
25	1.027	1.333
26	1.017	-0.328
27	0.999	-2.634
28	1.019	3.398
29	1.02	6.316
30	1.048	2.423
31	0.982	-2.032
32	0.983	6.007
33	0.997	9.355
34	1.012	8.351
35	1.049	10.609
36	1.063	13.425
37	1.028	8.14
38	1.027	13.396
39	1.03	0

Table 4.2 Active and reactive line power flows

Line		Sending End		Receiving End	
From	To	MW	Mvar	MW	Mvar
1	2	2.025	8.152	-2.023	-81.287
1	39	-2.148	-8.152	2.094	-71.774
2	3	466.53	155.27	-465.159	-145.4
2	25	-214.517	78.182	218.468	-89.05
3	4	176.755	145.233	-179.6	-153.718
3	18	-38.185	-1.922	35.475	-18.684
4	5	-62.929	-0.466	60.496	-11.001
4	14	-262.201	-29.314	260.596	26.502
5	6	-292.461	-23.192	291.916	21.735
5	8	229.104	34.471	-231.568	-40.805
6	7	318.551	63.351	-319.979	-62.65
6	11	-412.852	6.488	412.367	-3.902
7	8	84.125	-21.101	-85.8	14.674
8	9	-211.388	-149.019	206.78	137.555
9	39	-214.718	-137.161	209.177	25.046
10	11	409.205	40.417	-409.042	-39.26
10	13	240.351	12.503	-240.618	-16.532
13	14	227.713	-30.198	-229.009	20.056

14	15	-35.91	-46.258	31.489	12.916
15	16	-354.606	-165.722	354.571	164.434
16	17	189.551	-63.944	-190.257	54.417
16	19	-503.285	43.642	508.779	-22.09
16	21	-329.042	-36.469	329.623	26.429
16	24	-43.41	-139.888	43.103	134.443
17	18	194.454	1.48	-195.592	-11.183
17	27	-6.876	-55.773	3.958	24.317
21	22	-602.805	-141.416	608.904	169.395
22	23	45.592	1.775	-41.897	-20.468
23	24	358.163	49.729	-352.833	-42.213
25	26	97.491	-1.991	-96.236	-48.545
26	27	287.548	88.62	-287.53	-99.699
26	28	-141.244	-26.785	146.404	-44.576
26	29	-190.585	-30.282	203.707	-53.046
28	29	-346.085	17.351	352.091	-25.11

A reduced system model (27-bus system) was derived after eliminating the unobserved nodes (1, 2, 5, 6, 9, 10, 11, 13, 14, 17, 19 and 22). Table 4.3 shows the difference between calculated and observed power injections when applying system states of PMU buses (Table 4.1) to this reduced model (equation 3.5, 3.6). Setting the threshold value to 1% of total system load, the amount of these injection errors is negligible which reflects the present normal operating conditions. The minor values shown are due to calculation rounding.

Table 4.3 Active and reactive power injection errors during normal operating conditions

Observed bus	Active power injection errors (pu)	Reactive power injection errors (pu)
3	0.0509	0.0022
4	-0.0009	0.0000
7	-0.0025	0.0000
8	-0.0059	0.0000
12	0.0012	0.0000
15	-0.0023	0.0000
16	-0.0007	0.0000
18	-0.0005	0.0000
20	0.0004	0.0000
21	-0.0009	0.0000
23	-0.0019	0.0000
24	0.0000	-0.0000
25	-0.1400	0.0141
26	0.0000	-0.0000
27	0.0003	0.0000
28	-0.0000	-0.0000

29	-0.0000	-0.0000
30	0.0670	0.0098
31	0.0024	0.0000
32	0.0047	0.0001
33	0.0005	-0.0000
34	0.0000	-0.0000
35	0.0030	0.0001
36	0.0000	-0.0000
37	0.0000	-0.0000
38	-0.0000	-0.0000
39	0.0274	0.0002

4.2.2 Line Outage between Two Observed Buses

In this section, the algorithm was tested when a line outage event between buses 28 and 29 occurred. System states of PMU buses during this event are shown in table 4.4. Applying these states to the reduced 27-bus system topology with line 28-29 in-service resulted in active and reactive power injection errors shown in table 4.5.

Table 4.4 System states during outage of line 28-29

Bus	Voltage magnitude (pu)	Angle (degrees)
3	0.986	-4.192

4	0.953	-6.348
7	0.947	-7.162
8	0.947	-7.408
12	0.938	-3.073
15	0.965	-3.873
16	0.984	-1.966
18	0.983	-3.921
20	0.986	2.869
21	0.992	0.622
23	1.018	5.12
24	0.992	-1.842
25	1.021	1.129
26	0.993	-0.621
27	0.983	-3.001
28	0.984	-6.38
29	1.006	18.94
30	1.048	2.158
31	0.982	-2.286
32	0.983	5.755
33	0.997	9.06
34	1.012	8.05
35	1.049	10.331

36	1.063	13.15
37	1.028	7.971
38	1.027	26.079
39	1.03	0

Table 4.5 Active and reactive power injection errors during outage of line 28-29

Observed bus	Active power injection errors (pu)	Reactive power injection errors (pu)
3	0.0504	0.0022
4	-0.0009	0.0000
7	-0.0025	0.0000
8	-0.0059	0.0000
12	0.0012	0.0000
15	-0.0023	0.0000
16	-0.0007	0.0000
18	-0.0005	0.0000
20	0.0004	0.0000
21	-0.0009	0.0000
23	-0.0019	0.0000
24	-0.0000	-0.0000
25	-0.1381	0.0139
26	0.0000	-0.0000

27	0.0003	0.0000
28	27.3558	-7.2888
29	-28.5168	-4.9870
30	0.0670	0.0098
31	0.0024	0.0000
32	0.0047	0.0001
33	0.0005	-0.0000
34	0.0000	-0.0000
35	0.0030	0.0000
36	0.0000	-0.0000
37	0.0000	-0.0000
38	0.0000	-0.0001
39	0.0274	0.0002

Taking into account that the threshold value is defined as 0.6 pu for active power injection errors and 0.14 pu for reactive errors, the algorithm detected only the injection errors at buses 28 and 29. Since there is a single line connected between these two buses, this line was recognized to be out. The total processing time for this case was less than 0.03 seconds. After updating system topology, the errors ceased to exist as shown in table 4.6.

Table 4.6 Active and reactive power injection errors after updating the topology with line 28-29 out

Observed bus	Active power injection errors (pu)	Reactive power injection errors (pu)
3	0.0504	0.0022
4	-0.0009	0.0000
7	-0.0025	0.0000
8	-0.0059	0.0000
12	0.0012	0.0000
15	-0.0023	0.0000
16	-0.0007	0.0000
18	-0.0005	0.0000
20	0.0004	0.0000
21	-0.0009	0.0000
23	-0.0019	0.0000
24	-0.0000	-0.0000
25	-0.1381	0.0139
26	0.0000	-0.0000
27	0.0003	0.0000
28	-0.0000	-0.0000
29	0.0000	-0.0000
30	0.0670	0.0098

31	0.0024	0.0000
32	0.0047	0.0001
33	0.0005	-0.0000
34	0.0000	-0.0000
35	0.0030	0.0000
36	0.0000	-0.0000
37	0.0000	-0.0000
38	0.0000	-0.0001
39	0.0274	0.0002

4.2.3 Outage Events in Unobserved Area

4.2.3.1 Line Outage - Case Study A

It can be seen from figure 4.1 that the unobserved bus 22 is connected to three PMU buses, 21, 23 and 35. An outage event between buses 21 and 22 will change the states of the system. Applying these states to the original 27-bus system resulted in power injection errors at the boundaries of the area (buses 21, 23 and 35) as shown in table 4.7.

Table 4.7 Active and reactive power injection errors during outage of line 21-22

Observed bus	Active power injection errors (pu)	Reactive power injection errors (pu)
3	0.0493	0.0021
4	-0.0009	0.0000

7	-0.0024	0.0000
8	-0.0058	0.0000
12	0.0011	0.0000
15	-0.0022	0.0000
16	-0.0006	0.0000
18	-0.0005	0.0000
20	0.0004	0.0000
21	22.7320	-2.5520
23	-14.1216	-4.1732
24	-0.0000	-0.0000
25	-0.1382	0.0139
26	0	-0.0000
27	0.0003	0.0000
28	-0.0000	0.0000
29	-0.0000	-0.0000
30	0.0670	0.0098
31	0.0024	0.0001
32	0.0047	0.0001
33	0.0005	0.0000
34	-0.0000	-0.0000
35	-9.1059	-4.9344
36	-0.0000	-0.0000

37	-0.0000	-0.0000
38	-0.0000	-0.0000
39	0.0274	0.0002

Once the event area buses are identified, the algorithm retrieves the data of the lines and transformers belonging to the area. In the subsequent processing, the algorithm deals only with this area while considering the power transferred between its boundaries and the rest of the system as load or generation depending on its direction. These flows are shown in table 4.8. The algorithm then starts the trial-and-error process to identify the line that will cause injection errors to disappear. This condition is satisfied when line 21-22 is removed from the configuration (Table 4.9). It worth mentioning that the algorithm computational time for this case was also less than 0.03 sec.

Table 4.8 Power transferred between event area boundaries and the rest of the system during line 21-22 outage event

Line		Power	
From	To	MW	Mvar
21	16	-275.681	-114.872
23	24	970.11	237.964
23	36	-558.303	-172.91

Table 4.9 Active and reactive power injection errors when updating the topology with line 21-22 out

Observed bus	Active power injection errors (pu)	Reactive power injection errors (pu)
21	0.0168	-0.0000
23	-0.1206	0.0000
35	0.0015	0.0000

4.2.3.2 Line Outage - Case Study B

Referring to figure 4.1, it can be noted that PMU buses 4, 7, 8, 12, 15, 31 and 32 form the boundaries of an unobserved area which contains 11 lines and 3 transformers. The outage of any of these components will be reflected as injection errors at the boundaries of the area. Considering the scenario in which line 10-11 is out, the injection errors experienced when applying system states to the 27-bus system are shown in table 4.10. Although the injection errors at buses 4 and 12 were below the threshold, the algorithm was still able to include these buses in the area boundaries as they are connected to unobserved buses which are already included in the event area.

Table 4.10 Active and reactive power injection errors during outage of line 10-11

Observed bus	Active power injection errors (pu)	Reactive power injection errors (pu)
3	0.0505	0.0022
4	-0.5105	0.0722

7	2.0945	-0.1966
8	1.1934	-0.1264
12	0.3678	0.0689
15	-0.9549	0.0277
16	-0.0007	0.0000
18	-0.0005	0.0000
20	0.0004	0.0000
21	-0.0009	0.0000
23	-0.0019	0.0000
24	-0.0000	-0.0000
25	-0.1398	0.0141
26	0.0000	-0.0000
27	0.0003	0.0000
28	-0.0000	-0.0000
29	-0.0000	-0.0000
30	0.0670	0.0098
31	0.8123	0.0437
32	-3.0233	-0.9321
33	0.0005	-0.0000
34	0.0000	-0.0000
35	0.0030	0.0000
36	0.0000	-0.0000

37	0.0000	-0.0000
38	0.0000	-0.0000
39	0.0274	0.0002

As explained earlier, the algorithm then constructs the event area model and begins the trial-and-error process to find the outaged line. Table 4.11 shows the resulting injection errors at the boundaries of the area during this iterative process. The errors disappeared only when line 10-11 is considered out. The total processing time was again below 0.03 seconds.

Table 4.11 Active power injection errors during trial-and-error process for case B

Candidate line / Boundary	4-5	4-14	5-6	5-8	6-7	6-11	7-8	10-11
4	0.252	-3.653	-1.668	0.944	1.009	-0.650	-0.493	0.017
7	1.849	2.348	3.593	3.297	-2.798	-0.544	2.555	0.001
8	0.938	1.3905	-0.247	-2.318	2.694	-0.262	0.786	0.047
12	0.325	0.911	0.630	0.578	0.807	2.675	0.368	0.001
15	-0.964	0.643	-0.868	-0.885	-0.812	-0.232	-0.951	0.001
31	0.720	0.910	1.384	1.269	1.768	-0.215	0.812	0.002
32	-3.064	-2.492	-2.768	-2.820	-2.602	-0.686	-3.023	0.003

4.2.3.2 Transformer Outage- Case Study C

This study considers the outage event of transformer T12 which is connected between buses 12 and 13. Referring to figure 4.1, it can be seen that T12 belongs to the same area as in Case B. The resulting injection errors during this event are listed in table 4.12. Based on the predefined threshold value, only three reactive power injection errors were detected on buses 4, 12 and 32. Yet, the algorithm was still able to define the area boundaries as illustrated earlier. The scheme then proceeded normally to identify the outaged element in less than 0.03 seconds.

Table 4.12 Active and reactive power injection errors during outage of transformer T12

Observed bus	Active power injection errors (pu)	Reactive power injection errors (pu)
3	0.0509	0.0022
4	-0.0882	-0.2696
7	-0.0383	-0.0957
8	-0.0271	-0.0545
12	0.2017	0.7771
15	-0.0414	-0.1340
16	-0.0007	0.0000
18	-0.0005	0.0000
20	0.0004	0.0000
21	-0.0009	0.0000
23	-0.0019	0.0000

24	0.0000	-0.0000
25	-0.1400	0.0141
26	0.0000	-0.0000
27	0.0003	0.0000
28	-0.0000	-0.0000
29	-0.0000	-0.0000
30	0.0670	0.0098
31	-0.0057	-0.0382
32	-0.0044	-0.2261
33	0.0005	-0.0000
34	0.0000	-0.0000
35	0.0030	0.0001
36	0.0000	-0.0000
37	0.0000	-0.0000
38	0.0000	-0.0000
39	0.0274	0.0002

4.2.4 Other Outage Events

Using the threshold values defined earlier, the algorithm was able to detect and identify all line outage events except one in the IEEE39-bus system in less than 2 cycles. This undetected event was the outage of line 1-39. During this outage, fictitious reactive power injection was detected on bus 39 only whereas active power injection errors were insignificant at all buses. Hence, the algorithm alarmed the user to check the threshold value as well as system topology.

It can be noted that the preoutage power flow on this line was minor compared to other lines in the system (Table 4.2) which justifies the low injection error values. This indicates that the line has insignificant effect on system stability. To verify this conclusion, the effect of the line on voltage stability of the system was measured using the P-index. This index is a voltage stability indicator that is based on normalized voltage and power sensitivities [11].

According to this index, bus-12 of the IEEE39-bus system is the weakest bus. Figure 4.2 shows the P-index for this bus during normal operating conditions and during the outage event of line 1-39. The P-index of bus-12 during the outage of line 21-22, which causes relatively high injections, is also shown in the figure (section 4.2.2).

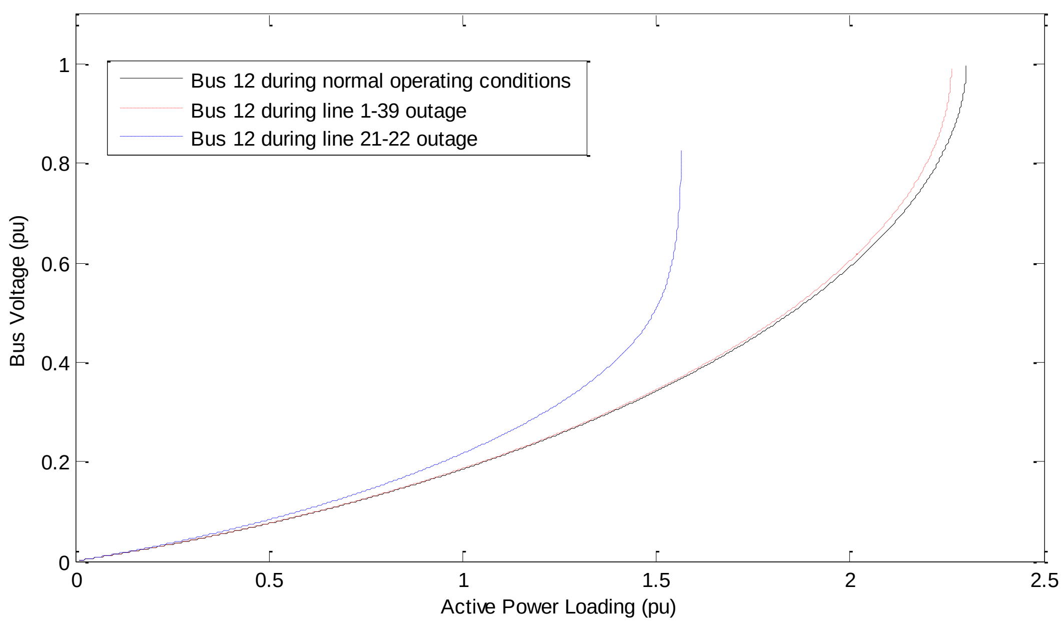


Figure 4.2 Bus-12 P-index during different operating conditions

It can be seen from this figure that the P-index of bus-12 was slightly affected by the outage of line 1-39 whereas the outage event of line 21-22 severely affected it.

CHAPTER 5

CONCLUSION

5.1 Conclusion

In this work, a fast and simple yet reliable topology processing scheme was developed. This scheme is based on PMU measurements. However, it can be applied on reduced systems in which network buses are not entirely covered with PMUs. The introduced algorithm continuously applies system states (voltages and angles) to the present system model in order to calculate injections at the observed buses. In case of an outage, unaccounted for injections appear in the outage location. If the outaged component was connected between two observed buses, injection errors appear only at these buses. However, if the outage event occurred in unobserved area, it will be reflected as injection errors at the boundaries of this area. Once errors are detected, the algorithm determines all the candidate equipment within the event area and follows a trial-and-error method to find the element that eliminates these injection errors.

The performance of the scheme was tested using the IEEE39-bus system where PMUs were deployed only at load and generation buses. The algorithm was successfully able to detect and identify various outage events in less than 2 cycles. This short processing time is due to the simple detection procedure which does not include any processing of breaker status information. In addition, the algorithm limits the area to be searched to a minimal subset of the original network which leads to further improvement in the overall processing time.

5.2 Future Work

As a future work, the algorithm can be improved to account for changes in transformer tap positions. Moreover, an optimization technique can be implemented instead of the trial-and-error method adopted in this work. This might enhance the search time in cases where the event area is relatively large.

REFERENCES

[1] A. J. Wood and B. F. Wollenberg, *Power generation, operation, and control*. John Wiley & Sons, 2012.

[2] A. M. Sasson, S. T. Ehrmann, P. Lynch, and L. S. V. Slyck, "Automatic Power System Network Topology Determination," *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-92, no. 2, pp. 610-618, 1973.

[3] A. Bose and K. A. Clements, "Real-time modeling of power networks," *Proceedings of the IEEE*, vol. 75, no. 12, pp. 1607-1622, 1987.

[4] M. Farrokhabadi, "Automated topology processing for conventional, phasor-assisted and phasor-only state estimators," Master's thesis, Royal Institute of Technology (KTH), 2012.

[5] M. Prais and A. Bose, "A topology processor that tracks network modifications," *IEEE Transactions on Power Systems*, vol. 3, no. 3, pp. 992-998, 1988.

[6] M. V. Mynam, A. Harikrishna, and V. Singh, "Synchrophasors redefining SCADA systems," *Schweitzer Engineering Laboratories, Inc*, 2013.

[7] M. Salah Aldeen Mohamed Zeyada, "Adaptive underfrequency load shedding based on real time simulation," Master's thesis, University of Tennessee at Chattanooga (UTC), 2014.

[8] Z. Dong and P. Zhang, *Emerging techniques in power system analysis*. Springer, 2010.

[9] J. E. Tate and T. J. Overbye, "Line Outage Detection Using Phasor Angle Measurements," *IEEE Transactions on Power Systems*, vol. 23, no. 4, pp. 1644-1652, 2008.

[10] H. Sehwail and I. Dobson, "Locating line outages in a specific area of a power system with synchrophasors," in *North American Power Symposium (NAPS), 2012*, 2012, pp. 1-6.

[11] M. Kamel, "Development and Application of a New Voltage Stability Index for On-Line Monitoring and Shedding," Master's thesis, University of Tennessee at Chattanooga (UTC), 2016.

APPENDIX A

IEEE39-BUS SYSTEM DATA

The following tables provide the data of the IEEE39-bus system on a 100 MVA base.

Table A.1: steady state data for load and generation for load flow purposes

Bus No.	Bus Type	Voltage (PU)	Load (MW)	Load (MVAR)	Generation (MW)
1	P-Q	-	0	0	0
2	P-Q	-	0	0	0
3	P-Q	-	322	2.4	0
4	P-Q	-	500	184	0
5	P-Q	-	0	0	0
6	P-Q	-	0	0	0
7	P-Q	-	233.8	84	0
8	P-Q	-	522	176	0
9	P-Q	-	0	0	0
10	P-Q	-	0	0	0
11	P-Q	-	0	0	0
12	P-Q	-	7.5	88	0
13	P-Q	-	0	0	0
14	P-Q	-	0	0	0
15	P-Q	-	320	153	0
16	P-Q	-	329	32.3	0
17	P-Q	-	0	0	0

18	P-Q	-	158	30	0
19	P-Q	-	0	0	0
20	P-Q	-	628	103	0
21	P-Q	-	274	115	0
22	P-Q	-	0	0	0
23	P-Q	-	247.5	84.6	0
24	P-Q	-	308.6	-92.2	0
25	P-Q	-	224	47.2	0
26	P-Q	-	139	17	0
27	P-Q	-	281	75.5	0
28	P-Q	-	206	27.6	0
29	P-Q	-	283.5	26.9	0
30	P-V	1.0475	0	0	250
31	P-V	0.982	0	0	200
32	P-V	0.9831	0	0	650
33	P-V	0.9972	0	0	632
34	P-V	1.0123	0	0	508
35	P-V	1.0493	0	0	650
36	P-V	1.0635	0	0	560
37	P-V	1.0278	0	0	540
38	P-V	1.0265	0	0	830
39	V-δ	1.03	1104	250	1000

Table A.2: Transmission lines and transformers data

From Bus	To Bus	R (pu)	X (pu)	B(pu)
1	2	0.0035	0.0411	0.6987
1	39	0.001	0.025	0.7500
2	3	0.0013	0.0151	0.2572
2	25	0.007	0.0086	0.1460
3	4	0.0013	0.0213	0.2214
3	18	0.0011	0.0133	0.2138
4	5	0.0008	0.0128	0.1342
4	14	0.0008	0.0129	0.1382
5	6	0.0002	0.0026	0.0434
5	8	0.0008	0.0112	0.1476
6	7	0.0006	0.0092	0.1130
6	11	0.0007	0.0082	0.1389
7	8	0.0004	0.0046	0.0780
8	9	0.0023	0.0363	0.3804
9	39	0.001	0.025	1.2000
10	11	0.0004	0.0043	0.0729
10	13	0.0004	0.0043	0.0729
13	14	0.0009	0.0101	0.1732
14	15	0.0018	0.0217	0.3660

15	16	0.0009	0.0094	0.1710
16	17	0.0007	0.0089	0.1342
16	19	0.0016	0.0195	0.3040
16	21	0.0008	0.0135	0.2548
16	24	0.0003	0.0059	0.0680
17	18	0.0007	0.0082	0.1319
17	27	0.0013	0.0173	0.3216
21	22	0.0008	0.014	0.2565
22	23	0.0006	0.0096	0.1846
23	24	0.0022	0.035	0.3610
25	26	0.0032	0.0323	0.5130
26	27	0.0014	0.0147	0.2396
26	28	0.0043	0.0474	0.7802
26	29	0.0057	0.0625	1.0290
28	29	0.0014	0.0151	0.2490
12	11	0.0016	0.0435	0
12	13	0.0016	0.0435	0
6	31	0	0.025	0
10	32	0	0.02	0
19	33	0.0007	0.0142	0
20	34	0.0009	0.018	0
22	35	0	0.0143	0

23	36	0.0005	0.0272	0
25	37	0.0006	0.0232	0
2	30	0	0.0181	0
29	38	0.0008	0.0156	0
19	20	0.0007	0.0138	0

VITA

Elamin Mohamed was born in Almanaqil, Sudan, to the parents of Ali and Nima. He spent 10 years of his childhood in Saudi Arabia with his family where his father worked there as a doctor. Mr. Mohamed received his Bachelor of Science degree in electrical and electronics engineering –power system concentration- in 2013 from University of Khartoum in Khartoum, Sudan. During this period, Mr. Mohamed was enrolled in many academic and social focused student associations. After graduation, he joined ELECON for Electrical Services LTD as an electrical service engineer. Mr. Mohamed worked there for a year before accepting a graduate research assistantship offer from the University of Tennessee at Chattanooga to purse a Master of Science degree in Electrical Engineering. He was awarded his degree in December 2016. Mr. Mohamed is currently working at Mesa Associates Inc. as an electrical engineer.