# Internet-based Wide Area Measurement Applications in Deregulated Power Systems

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## Abstract

Since the deregulation of power systems was started in 1989 in the UK, many countries have been motivated to undergo deregulation. The United State started deregulation in the energy sector in California back in 1996. Since that time many other states have also started the deregulation procedures in different utilities. Most of the deregulation market in the United States now is in the wholesale market area, however, the retail market is still undergoing changes.

Deregulation has many impacts on power system network operation and control. The number of power transactions among the utilities has increased and many Independent Power Producers (IPPs) now have a rich market for competition especially in the green power market. The Federal Energy Regulatory Commission (FERC) called upon utilities to develop the Regional Transmission Organization (RTO). The RTO is a step toward the national transmission grid. RTO is an independent entity that will operate the transmission system in a large region. The main goal of forming RTOs is to increase the operation efficiency of the power network under the impact of the deregulated market.

The objective of this work is to study Internet based Wide Area Information Sharing (WAIS) applications in the deregulated power system. The study is the first step toward building a national transmission grid picture using information sharing among utilities. Two main topics are covered as applications for the WAIS in the deregulated power system, state estimation and Total Transfer Capability (TTC) calculations. As a first step for building this national transmission grid picture, WAIS and the level of information sharing of the state estimation calculations have been discussed. WAIS impacts to the TTC calculations are also covered. A new technique to update the TTC using on line measurements based on WAIS created by sharing state estimation is presented.

# Dedication

*To the Soul of my father*

*The man to whom I owe every thing*

*To my mother*

*The giver of endless love*

*To my wife and my children*

*You are too patient with me*

*I know that 14hours a day; six days a week is tooooo much*

*But finally I have reached my goal*

*Every thing I have accomplished is for you*

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# Chapter 1 Introduction

## 1.1 General

Since the deregulation of power systems was started in 1989 in the UK, many countries have been motivated to undergo deregulation. The United State started deregulation in the energy sector in California back in 1996. Since that time many other states have also started the deregulation procedures in different utilities. Most of the deregulation market in the United States now is in the wholesale market area, however, the retail market is still undergoing changes.

Unlike the different deregulated sectors such as the communication sector and the transportation sector, the electricity sector has its own characteristics that make it unique. First, electricity is hard to store, as a result the energy market should always try to match generation supply and load demand. Second, electricity transportation over the transmission lines should follow physical laws that must be obeyed by the power system network.

Power system deregulation opened the border among the utilities. The old picture of vertically integrated utilities has changed to an unbundled picture in the deregulated environment. Generation can be exported from any place in the power system network to any load. The utility control centers that preserved reliability and security inside the utility region should be updated to maintain a secure system under this new challenge. Long distance bulk power transfer can happen more frequently in the deregulated power system. The power can be transferred from any lower price utility to any area that is willing to pay for the cost of the electricity and its transportation. Due to the market regulations, parallel flow has started to increase inside the interconnected power network. The old control centers are facing new challenges from these unexpected flows, since most of these parallel flows are created due to other utilities' transactions.

The first step to accommodate these changes is sharing information among the utilities in the power system network. This information will help these utilities have a wide area picture for the entire network. However, information sharing becomes more complicated in the deregulated environment because information to be shared is owned by different utilities and may be considered confidential property in the power market. Information sharing can be used for the benefit of the power system network or it can be abused by the power market and used for the benefit of a specific player in the market [1]. Sharing information is very useful, however, in many cases this information is confidential and is not available to be shared. In the mean time, some information should be shared to maintain secure operation of the power system. To compromise between the confidential issues and the importance of sharing information among the utilities, the minimum amount of information used for the benefit of the power system operation should be shared.

On December 15, 1999 Federal Energy Regulatory Commission (FERC) called upon utilities to develop Regional Transmission Organization (RTO) [2] through FERC's Order 2000. The RTO is a step toward the national transmission grid. RTO is an independent entity that will operate the transmission system in a large region. The goals of the RTO are: outage planning coordination, congestion management, parallel-path flows management, and controlling planning and expanding facilities. The main goal of forming RTOs is to increase the operation efficiency of the power network.

## 1.2 Thesis Objective

The objective of this work is to study Internet based wide area information sharing applications in the deregulated power system. The study is the first step toward building a national transmission grid picture using information sharing among utilities. This primary objective can be broken down into sub tasks:

1. Studying the data volume and latency for present and future power system applications. The thesis will focus on different types of protection schemes.

2. Drawing a blueprint of future Internet based power system information network (PSIN) architecture.

3. Answering some of the ambiguous questions about information sharing such as:
   - What kind of information may be shared?
   - Which information for which applications needs to be shared?
   - What media of communication can be used for sharing this information?

4. Evaluating the minimum information that can be shared to obtain a realistic wide area picture in the deregulated power system network? This wide area picture is the first step in identifying the national transmission grid. Another important issue which will be addressed is the impact of sharing different information levels to the accuracy of wide area state estimation.

5. Studying the impact of the national transmission grid picture to the Total Transfer Capability (TTC) calculations as one of the important deregulation topics.

6. What are the other alternatives for calculating the TTC? A Tracing Load Flow (TLF) program is developed to study the impact of the wide area information sharing the accuracy of TTC calculations. TLF is one of the alternatives of the TTC calculations. The Linear Sensitivity Analysis (LSA) approach is another alternative for TTC calculations.

## 1.3 Thesis Outlines

The thesis is organized in seven chapters as follows:

Chapter 2 highlights the importance of the information sharing role in deregulated power systems. The chapter summarizes the existing technology for telecommunication in the electric power system. The chapter also calculates the present/future data volume and latency for different types of protection, such as primary and backup protection, remedial action schemes and system protection¸ and adaptive relays.

Chapter 3 focuses on Internet applications in the power system. The Internet is selected as the communication media for building the PSIN. The Internet can play an important role in wide area information sharing especially in non-time-critical applications. Brief reviews are given on the current Internet applications in power systems in different areas such as remote information access, Geographic Information Systems (GIS), Supervisory Control and Data Acquisition (SCADA)/ Energy Management System (EMS), condition monitoring, predictive maintenance, customer service, power market, power quality, and distance education / training. The chapter also attempts to draw a blueprint for the future PSIN infrastructure. It was found that though the application of the Internet has been developed in many areas, scattered and individual applications hampered the large-scale integration of the power system information source. To solve this problem, some of our preliminary thoughts on a future Internet based power system information network (PSIN) architecture are discussed. The basic configuration of the PSIN infrastructure is also highlighted.

Chapter 4 discusses the applications of Internet-based wide area information sharing (WAIS) in the power system area. State Estimation has been chosen as one of the most important power system applications. Moving from Independent System Operators (ISOs) to Regional Transmission Organizations (RTOs) or its equivalents is one example of the need for WAIS. A WAIS system can form the basis for the future RTO communication model or as a national level security coordinator communication model, if such a need should arise in the near future. This chapter presents some results of WAIS and the information level sharing on the state estimation calculations. The calculations for power system operations are primarily based on an accurate determination of the power system state viz. the voltage and the angle at each bus. A detailed comparison study between the Integrated State Estimation (ISE), which is based on sharing real time measurements, and the Split State Estimation (SSE), which is based on sharing SE outputs, illustrates the benefit of WAIS.

Chapter 5 develops a tracing load flow (TLF) program that is designed to calculate the Total Transfer Capability (TTC) in addition to many other power system applications. The program is developed to validate the importance of WAIS in TTC calculations. This chapter presents the proposed TLF algorithm and its application examples. TLF is basically a load flow program that has the flexibility to change any input parameters in a systematic way and trace the state variable changes. TTC is a key factor for calculating Available Transfer Capability (ATC). TTC calculations are based on running different load flow cases from the base case until hitting thermal, voltage, or transient stability limits. TLF is able to calculate area-to-area TTC or point-to-point TTC with any generation/load dispatch. TLF can be used in many different applications besides the calculation of TTC such as voltage collapse studies, contingency analysis, power systems studies under different dispatch conditions, and also for analysis of the impact of series compensators / shunt compensators on power systems. TLF is developed using MATLAB and has been tested for many power system models.

Chapter 6 presents a new technique to update the Total Transfer Capability (TTC) using on line measurements based on WAIS created by sharing state estimation as explained in Chapter 4. The traditional technique for calculating TTC is using computer simulations with the forecasted data while all the calculations are performed off-line in the planning stage as explained in chapter five. This chapter proposes look-up tables prepared off-line for correction of TTC. Theses tables can be used to update the TTC values based on real time measurements. This chapter also presents TTC based on the LSA technique as another method of calculating the TTC. A comparison study between the LSA method and the tabulated method is presented.

Chapter 7 summarizes the main contribution points presented in the thesis, conclusions, and directions for a future research.

The thesis also includes five appendices. Appendix A and Appendix B present an overview of simplified WSCC 179-bus system and IEEE 39-bus system. These systems are the main test systems used for testing the new concept and validate the results throughout the thesis. Each appendix includes the bus data, load data, generation data, and branch data for each system. Appendix C, Appendix D, and Appendix E list the program codes for the different algorithms proposed in the thesis. Appendix C documents the program code for the state estimation programs that include the ISE and SSE program codes. Appendix D documents the program code for TLF program. Appendix E highlights the LSA program.

# Chapter 2 Data Volume and Latency in Power System

## 2.1 General

This chapter highlights the important role of information sharing in a deregulated power system. It summarizes the existing technology for telecommunication in the electric power systems. This chapter also calculates the data volume and the latency for different types of protection, such as primary and backup protection, remedial action schemes and system protections¸ and adaptive relays.

## 2.2 Information Sharing in Deregulated Power System

Information Technology plays an increasingly important role in creating a competitive edge in the power industry. In the deregulated environment, information becomes the key to profitability, customer retention, market advantage, and growth. The operational and commercial needs of the power industry require information systems not only to perform many traditional operational functions but also to support many new functions aimed specifically to meet the needs of competition in the deregulated market.

Traditionally, information exchanged in a power system is mostly among individual sections of the same utility. Exchange among different utilities is difficult, complex, and costly. Deregulation is pushing for extensive inter- and intra-utility information exchange, integration, consolidation, dissemination, and open access.

The traditional communication system for power networks was established mainly for intra-company information exchange. Low bandwidth and communication isolation hinders large information exchanges and inter-operability. Deregulation results in horizontal merger and consolidation of many existing utilities. Inter-company communication and integration of data [3] from various control centers, power plants, and substations, are required. The necessity to perform this integration process will drive all utilities toward the standardization of data models and communication protocols.

Existing communication tools must be modified or replaced to accommodate extensive information exchange. The Internet based communication network enables information sharing and various network applications and provides an ideal infrastructure for the next generation of the power communication network. Various Internet/Intranet applications are replacing, upgrading, and extending the existing power communication establishment. The Open Access Same-time Information System (OASIS) [4] is a good example.

## 2.3 Brief Review of the Existing Information Transmission Media

The power system currently uses several media for its protection[5], control, and information-sharing functions. Communications essentially need a connection between the source and the destination [6]. Besides the communication media, signal conversion techniques should be used to covert the signal to either electric or optical signals. Current communication media [7]can be classified into:

1. Copper based circuits which include:
   - Pilot wire channels operated by the power utility
   - Pilot wire channels rented from communication utilities
   - Power Line Carrier (PLC) [8]
2. Satellite communications and microwave
3. Optical fiber communication

### 2.3.1 Copper Based Circuit

The copper based circuit is the first pilot wire technique for communication and still the most commonly used technique in electric power systems. The pilot wire is normally a telephone wire either owned by utility companies or leased from telephone companies. This technique started back in 1918 with the innovation of the long distance telephone lines. Each pair is carrying one communication channel. After that the Frequency Division Multiplexing (FDM) technique was established, it allowed more than one voice communication channel to be broadcast over each pair. The carrier frequencies that could be used were in the 10 to 490 kHz band. The Power Line Carrier (PLC) is the most popular communication technique used for communication among electric power utilities. In this technique, the power lines used to carry electric power will also carry communications signals. The frequency range includes all frequencies up to and including 490 kHz [5]. Efforts have been made to minimize bandwidth duplication among other groups dealing with specific segments of this band. PLC with power output on the order of 100 W can be used up to 150 miles [5]. Normally, PLC carries only one channel of bandwidth that equals 4 kHz. The frequency range is limited by government regulations. The PLC is the most common communication medium used in the US in the protection area. However, PLC has some disadvantages such as the bandwidth limit, propagation delay and induced electrometric interference. It is subject to lightening, switching surges, and network reconfiguration. Overhead pilot wires may also experience interference from power lines while the underground is subject to damages for many obvious reasons.

### 2.3.2 Satellite Communications and Microwave

Telstar-I the first telecommunication satellite was lunched on July 10, 1962 [9]. This satellite started the first satellite communication channels between the United States and Europe. The satellite's orbital speed differed from the rotational speed of the Earth's surfaces. Therefore, its location in relation to the Earth station was continually varying. The contact time with the Earth station was less than half an hour. This problem of varying position was solved on April 6, 1965 by lunching another satellite [10], "Early Bird," that was located in an orbit 22,300 miles above the equator. This satellite has a constant position with respect to the Earth. This type of satellite is known as a geosynchronous satellite. Communication satellites launched recently can communicate with a data rate up to 50 Mbps and hold 60,000 mixed voice and television channels [11].

The major advantage of satellite and microwave communication over the copper based technique is that there is no physical connection between the source and the destination. Satellites are microwave radio repeater stations within Earth's orbit. A satellite receives microwave signals from ground stations on the Earth's surface and retransmits them at a different frequency (to avoid interfering with the signals being received) to other ground stations thousands of miles away. Satellites offer broadcasting transmission that can be received by several receivers. However, the microwave systems use point-to-point communications.

Microwave communication operates in the 150 MHz to 20 GHz frequency range [5]. This bandwidth can carry many communication channels with a variety of information. The disadvantage of the microwave is that the transmission length is limited to a line of sight path between antennas. Microwave is subject to atmospheric attenuation and distortion. The combined latency using modem plus analog microwave is around 100 milliseconds between two adjacent antennas.

### 2.3.3 Optical fiber communication

The first fiber optic transatlantic telephone cable (TAT-8) was laid in 1988 [12]. The cable was designed, with a capacity of 40,000 simultaneous telephone calls, to carry the telephone channels between the United States, the United Kingdom and France. Three years later, the second generation of fiber cable was in service (TAT-9), with a capacity of 80,000 [12] simultaneous telephone calls. During the last decade, a huge increase in the marine fiber optic cables connecting different parts of the world made fiber the dominant inter-continental method of communication in the world.

A huge increase in fiber optics technologies was started in the mid-1990s. High-speed semiconductor circuit switches were developed at gigabit rates. A new technology called dense wavelength division multiplexing (DWDM) allows multiple light wavelengths at controlled bandwidth and spacing, each modulated with a different signal at rates up to 10 Gbps, to be coupled to one fiber cable. Transmission rates up to 30 Gbps over distances of more than 16,000 km have been accomplished by testing existing marine fiber optic cables in the Atlantic (TAT-12) [13] and Pacific (TCP-5) oceans [11].

Fiber now can be considered the most reliable medium for wide area communication. In addition to the capacity advantage, the fiber has no interference with other electric systems. The only disadvantage is the cost of the cable system and cost of construction. Fiber optic communication has the smallest latency among all media of communication.

## 2.4 Data Volume & Latency for Different Protection Types

It is very important to know the data volume and the latency of different types of protection because this information will play an essential role in choosing the media of communication used for control and / or protection. Protection can be classified into the following categories:

- Primary protection
- Backup protection
- Remedial action schemes and system protections
- Adaptive relays

In the following sections some details about the data volume and the latency of these categories will be calculated. However, before we go into the details of these calculations, let’s take a quick review of the sampling process and conversion from analog to digital signals.

### 2.4.1 Conversion of Analog to Digital Signals

Sampling and digitizing can convert the analog signal to a digital signal. The Nyquist rate is the minimum rate for sampling any analog signal. The Nyquist frequency equals twice the highest frequency present in the analog signal. After this the Analog to Digital converter (ADC) convert the samples to digital words. Two factors will affect the data volume in ADC processing

- Sampling rate
- Word length

The sampling rate will depend on the low pass filter used for filtering the analog signal which is dependent on the type of protection. The sampling rate increase will enhance the accuracy of information retrieved from the digital signal. However, this will lead to more computational time problems which can be solved using parallel processing techniques.

An increase in word length will lead to a decrease in ADC quantization errors. The word length can be 8, 12, 16, 32, 64-bit length. Not all of these bits will be used as data bits but some of them will be used for security, synchronization, and address. As an example, the transmission information from the RTU and the master station use the time division multiplexing technique. Suppose the word length is 32 bits, 20 bits or more are used as data bits, and the rest used security and quality purpose [15].

The following numbers will be used throughout the calculations [16],[17] as typical numbers for the sampling rate, word length, and communication protocol overhead factor:

Present sampling rate = 16 sample/cycle
Present word length = 16 bit
Future sampling rate = 96 sample/cycle
Future word length = 32 bit
Present communication protocol overhead =1.5
Future communication protocol overhead =2.0

### 2.4.2 Primary protection & back up protection

Almost all the data needed for primary protection is the same as that needed for back up protection (this is true if we consider that these relays are traditional relays and not adaptive relays), the only difference will be the latency. While for other types of protection (differential protection as an example) the data volume can change if this type of protection is used for transmission lines or transformers.

The latency of the primary protection can tolerate no intentional delay. The fastest primary relay can operate in a ¼ cycle (4 ms); however, typical delay for primary protection is 2 cycles (33 ms), which means that the primary protection latency is 4-33 ms [5]. While the latency of the backup protection is about 18 cycles for the second zone [18], and 60 cycles for the third zone, this equals the backup protection latency that is from [5] 0.3:1 seconds. We can classify the primary protection [5] into:

- Over current protection
- Differential protection
- Distance protection

#### 2.4.2.1 Over current protection

The information needed for over current protection is only the current at one end of the equipment protected by this relay. This information is sent from Data Acquisition Unit (DAU) to the protective relay processor in the substation [19]. The data volume needed in the single bus configuration is

Data volume = number of channels • sampling rate • frequency • overhead factor • word length

Data volume = 3 • 16 • 60 • 1.5 • 16= 69120 bps= 67.5 kbps

Future data volume = 3 • 96 • 60 • 2 • 32= 1105920 bps = 1080 kbps

If the protection scheme is changed to the breaker and half scheme and the zero sequence current is measured. Then the calculations will be as follows:

Data volume = (6+1) • 16 • 60 • 1.5 • 16= 161280 bps.

Future data volume = (6+1) • 96 • 60 • 2 • 32= 2580480 bps= 2520 kbps

### 2.4.2.2 Differential protection

The information needed for the differential protection may vary according to the apparatus protected. As an example, in most cases the current is the variable used for the differential protection. In other cases, such as long transmission lines differential protection both current and voltage signals are needed from both sides because of the effect of charging current in the line capacitors. The sampling rate may vary according to the apparatus protected. As an example, the sampling rate for the differential protection of the transformer [20] should be higher than the sampling rate for the protection of the transmission lines or bus bars because the protection design might detect the inrush current by checking the second harmonics presented in the wave, i.e. this will deal with a frequency 120 Hz that may affect the Nyquist frequency and the sampling rate.

The distances needed for this type of protection also vary according to the protection apparatus protected. For all apparatus protection the distance will be within the substation (from DAU to the protective relay processor). However, in case of transmission line protection the distance will depend on the length of the line because the signal should transmit from one end of the transmission line to the other.

The data volume in this case is twice the data volume of the over current protection single bus bar arrangement under the assumption of measuring the current at both sides of the protected element.

Data volume = number of channels $\bullet$ sampling rate $\bullet$ frequency $\bullet$ overhead factor $\bullet$ word length

Data volume = $(2 \bullet 3) \bullet 16 \bullet 60 \bullet 1.5 \bullet 16$= 138240 bps = 135 kbps

Future data volume =$(2 \bullet 3) \bullet 96 \bullet 60 \bullet 2 \bullet 32$=2211840 bps = 2160 kbps

If we consider that both current and voltage are needed, as in the case of a long transmission line, the previous number will be doubled.

#### 2.4.2.3 Distance protection

The information needed for the distance protection [21] is the voltage and the current at the protected point. The data volume for distance protection will be equal to the data volume for differential protection. The distance in this case will be within the substation from the DAU to the protective relay processor.

Data volume = number of channels • sampling rate • frequency • overhead factor • word length

Data volume = (2 • 3) • 16 • 60 • 1.5 • 16= 138240 bps = 135 kbps

Future data volume =(2 • 3) • 96 • 60 • 2 • 32=2211840 bps = 2160 kbps

### 2.4.3 Remedial Action Scheme and System Protection

The remedial action schemes and system protections [22] have many issues which can be considered. In this instance, only two points will be considered in more detail:

- Load shedding relay
- Out of step relay

#### 2.4.3.1 Load shedding relay

Sudden changes in generation capacity [5] either through the loss of generation or tie lines can make a severe load generation unbalance, resulting in a rapid frequency decline. If the generator and the boilers cannot respond quickly enough, the system may collapse. Rapid selective and temporary dropping of loads can make system recovery possible.

Load shedding relays are used to preserve the power system integrity after it suffers a loss of generation. If the power system forms a relativity small island, the frequency itself is an indicator of the amount of load that must be shed. In this case, under frequency relays are used at the distribution substation to drop the loads in a predefined number of steps, at predefined frequency settings. On the other hand, if the system maintains its interconnections to its neighbors, the frequency doesn't decay significantly even after the loss of generation, and the load shedding must be achieved through supervisory control.

Area control error (ACE) [23] is an accurate measurement of the generation deficiency. The ACE technique needs information about the local frequency. These measurements can be achieved accurately using the technique of phasor measurement [24]. Accurate measurement of phasor voltage in real time at the important nodes in the system is the key for calculating the frequency and the rate of change of frequency at these nodes.

From the previous discussion, the data volume needed in case of loss of generation in an interconnected system will depend on how many real generation units or equivalent generation points are in this interconnected system. From these generation units the three-phase voltage is measured and the result sent to the control center so that the frequency can be calculated and the ACE determined.

The communication distance is equal to the distance from the equivalent points to the local control center. The final decision will go from the local control center to the distribution substations to trip the under frequency relays for load shedding. Assuming that there will be a local control center in each important part of the interconnected network, the latency of the load shedding depends on the type of frequency relay. Typical operating times in different types of under frequency relays [22] are in the order of 4-6 cycle i.e. 0.06-0.1 sec.

If we consider that the number of monitored points are N, then the data volume needed for the load shedding protection in the interconnected system could be calculated as follows:

Data volume = number of channels • sampling rate • frequency • overhead factor • word length

Data volume = (N • 3) • 16 • 60 • 1.5 • 16= 69120 N bps = 67.5N kbps

Future data volume =(N • 3) • 96 • 60 • 2 • 32=1105920 N bps = 1080N kbps

#### 2.4.3.2 Out of step relay

The objective of the out of step relay [22] is to reduce possible generator damage as a result of the out of step condition. The present relaying practice is to pre-define certain separation points, and carry out the separation by permitting local out of step relays to trip if the system swing goes through their trip zone, or use transfer trip commands from relays which can detect the out of step condition. These actions taken by the pre-set relays may not be appropriate for the existing system conditions.

Adaptive out of step relaying solves system condition matching problems. From the data volume point of view, two important points can be considered as adaptive features. The first is changing the status of important transmission lines. The relay receives the status of the circuit breakers on the critical transmission lines. Measuring the current in these lines provides confirmation of the new status. The second adaptive feature is the ability to record phasor data from angle swings and the line faulted in the monitored substations.

The data volume needed in the case of the adaptive out of step relays will depend on the equivalent circuit of the interconnected system. To be specific, the data volume will depend on how many critical transmission lines are in the equivalent circuit and how many important points can be used to measure the swing. The distance of communication is the distance from the equivalent points to the adaptive out of step relays. Assuming that the number of critical locations is N, voltage and current will be sent to the relay from these critical points. The data volume needed in this case can be calculated as follows:

$$\text{Data volume} = \text{number of channels} \bullet \text{sampling rate} \bullet \text{frequency} \bullet \text{overhead factor} \bullet \text{word length}$$

$$\text{Data volume} = (N \bullet 6) \bullet 16 \bullet 60 \bullet 1.5 \bullet 16 = 138240 \text{ N bps} = 135 \text{ N kbps}$$

$$\text{Future data volume} = (N \bullet 6) \bullet 96 \bullet 60 \bullet 2 \bullet 32 = 2211840 \text{ N bps} = 2160\text{N kbps}$$

### 2.4.4 Adaptive relays

Adaptive relays have been defined [14] as follows: "*Adaptive protection is protection philosophy which permits and seeks to make adjustments to various protection functions automatically in order to make them more attuned to prevailing power system conditions* ". The adaptive relaying concept may be used for different kinds of protection and control [25] schemes, for example:

- Adaptive relay for distribution system [26]
- Mutual compensation on parallel lines [27]
- Protection of multi terminals line [16]

#### 2.4.4.1 <u>Adaptive multi terminal lines</u>

As the use of adaptive relays [14] increases in the protection field, the distinction between protection and control becomes fuzzier. For example, out of step relaying, load shedding, and load restoration can be considered as control tasks. Consider the three-terminal line shown in Figure 2-1

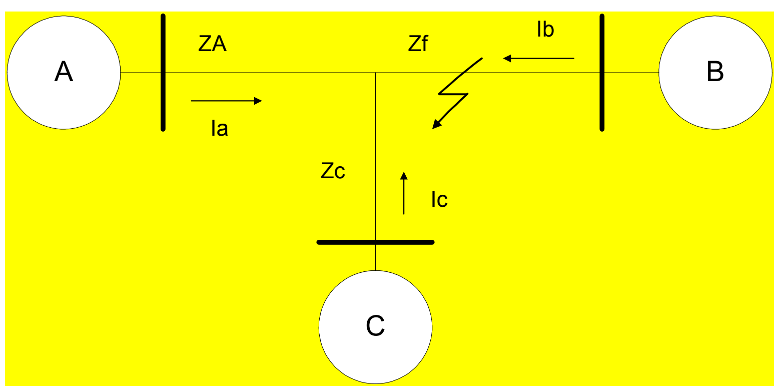


Figure 2-1: Three terminals lines example

The distance relay at bus A sees a fault impedance of

$$Z = Z_A + Z_f \left( \frac{I_a + I_c}{I_a} \right) \qquad (2.1)$$

According to the available communication channel capacity adaptive relaying can be classified into:

- On-line measurement of the voltage and the current at each terminal
- Off-line measurement which can be divided into two categories:
  - Updating the status of breakers A, B, C
  - Updating the voltage and current at each terminal in addition to the status of circuit breakers

On-line communication is more accurate; however, it needs high speed communication channels among the three terminals. The latency of this scheme of adaptive relaying will depend on the zone of protection protected by this scheme, and the latency will be the same as the requirements of the primary and back up protection systems. The data volume in this case can be calculated as follows:

Data volume = number of channels • sampling rate • frequency • overhead factor • word length

Data volume = (3 • 3) • 16 • 60 • 1.5 • 16= 207360 bps = 202.5 kbps

Future data volume =(3 • 3) • 96 • 60 • 2 • 32=3317760 bps = 3240 kbps

Table 2-1 summarizes the previous results

Table 2-1: Data volume and latency for different types of protection

| Type of relay | Data Volume (kbps) | | Latency (sec.) | |
|---|---|---|---|---|
| | Present | Future | Primary | Secondary |
| Over current protection* | 157.5 | 2520 | 4-33 ms | 0.3-1 |
| Differential protection | 135 | 2160 | 4-33 ms | 0.3-1 |
| Distance protection | 135 | 2160 | 4-33 ms | 0.3-1 |
| Load shedding** | 67.5 N | 1080 N | 0.06-0.1 | |
| Adaptive multi terminal** | 202.5 | 3240 | 4-33 ms | 0.3-1 |
| Adaptive out of step** | 135 N | 2160 N | | |

Note

* The Data volume based on one and half breaker scheme

** The Data volume depends on the system configuration

# Chapter 3 Power System Information Network (PSIN) Architecture

## 3.1 General

This chapter summarizes Internet applications in power systems and draws a blueprint for the PSIN architecture. Literature reviews are given on current Internet applications in power systems in areas such as remote information access, Geographic Information Systems (GIS), Automated Mapping/Facilities Management Systems (AM/FM), Supervisory Control and Data Acquisition (SCADA)/ Energy Management System (EMS), condition monitoring, predictive maintenance, customer service, power market, power quality, and distance education / training. Many applications in the power industry focus on specific tasks and no universal standard has been developed. A new Internet based Power System Information Network Architecture (PSIN) is proposed as a solution to that problem.

## 3.2 Information Technology Role in Power System Area

The rapid development of information technology (IT) is pushing the power system information network to a remarkably innovative state. Internet/Intranet can play an important role in the power system information network. While many IT and Internet applications in power systems have been developed in recent years, most efforts focus on specific tasks, and no universal standard is available. Isolation among applications hinders the development of the power system information infrastructure. For example, OASIS [4] is only used for power transmission transactions, AM/FM/GIS [28] are mostly used for single utility information management [29], and Internet applications in SCADA [30] and EMS [31] are limited to remote display and local control.

Lack of standardization is resulting in a waste of many resources. The power industry of the future will require an overall information architecture; integrated data model and standard communication networks that support the different data requirements, rates, and quantities of data flow among the various systems. Existing information management systems can not satisfy the new challenges as the demand for more and faster information increases as demanded by many players as shown in Figure 3-1

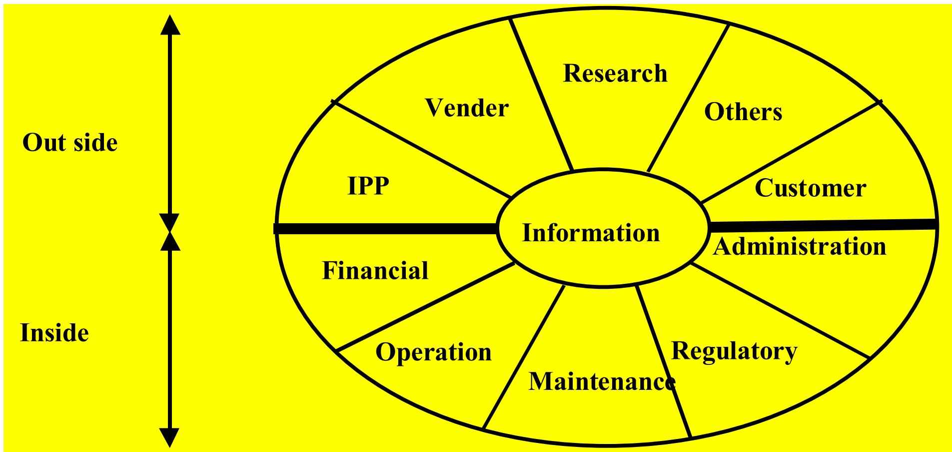


Figure 3-1: Information needs in the deregulated environment

On the financial side, deregulation introduces the need for data sharing among different utilities, independent system operators (ISO), metering firms, billing firms, independent power producers (IPP) [32], and Regional Transmission Organizations (RTO) [2]. As an example, the IPPs, ISOs and RTOs are now required to share the SCADA [33] data to a different degree. Rapid development of information technology (IT) enables information integration and easy access, and provides more effective information management modes for the power industry. Information in the form of data warehouse, distributed database, AM/FM/GIS, OASIS, etc., are being used to replace the traditional information management system from device level to enterprise level. Open information architecture is the norm of the future.

## 3.3 Internet / Information Technology Applications in Power

Internet and IT have been involved in many aspects of the power industry as shown in Table 3-1. In the following sections, some of these areas will be discussed in greater detail.

Table 3-1: Internet applications in power systems

| Areas | Internet/IT Applications |
|---|---|
| Utility information management | AM/FM/GIS |
| | Data warehouse/database |
| Operation | Remote information access and processing (SCADA, APT) |
| | EMS/MIS |
| | Substation automation |
| | Distribution automation |
| | Fault location and disturbance analysis |
| Maintenance | Power quality |
| | Remote monitoring and diagnosis |
| Power market | Open Access Same-time Information System (OASIS) |
| Education and training | Distance learning courses, laboratories, and operator training /Inter-university, inter-utility education program sharing |
| Protection and control | Distribution system reconfiguration / differential relay |

It is clear from Table 3-1 that the Internet is a wonderful framework for many power system applications. The advantage of the Internet can be summarized in the following points:

- Multi-point access
- No need for client software installation
- Hardware / platform independent
- Familiar web interface (Netscape / Explorer)
- Multimedia graphics display capable

There are limitations in today's Internet that may be summarized as follows:

- Security and reliability problems
- Delays due to:
    - Buffer delays during packet assembly
    - Conflicts on the asynchronous network
    - Re-transmission due to errors
    - Network traffic and routing path
    - 7-200 ms as typical delay in TCP/IP in Ethernet [34]

### 3.3.1 Utility Information Management

In 1960, Geographic Information System (GIS) technology started to integrate graphical features with tabulated data in order to evaluate real problems. As GIS systems develop [35] and get better, new solutions offer greater functionality that can no longer be described as automated mapping/facilities management (AM/FM) only [36]. For large utilities, the means to bond their project applications from many different Relational Database Management Systems (RDBMS) and data formats [37] have employed Internet and Intranet networks. AM/FM data is much more valuable when it is accessible to more people within an organization. Internet/ Intranet can be used to automate hot links to/ from the field [38] that will have significant benefits for field personnel and end users.

Geographic information system with automated mapping and facilities management (AM/FM/GIS)[39] and data warehousing [40] are good examples of managing power system information. AM/FM/GIS techniques also can be used for intra-utility business management covering finance, human resources, network analysis, outage and distribution management.

### 3.3.2 Power Systems Operation

Deregulation has increased the need for the Internet in many areas of power system engineering. The interface to the SCADA database [41],[42] is an example. Due to deregulation, SCADA data is requested by many different segments of the industry such as independent power producers (IPP), transmission and distribution companies, and power trading and exchange companies. An ideal result of deregulation is that the structure of the power system is changing from the hierarchical structure to a more distributed and open system structure. As a result, many users such as control room dispatchers, operating and planning staff, control center managers, training staff, and engineering users will need access to SCADA data. Since the Internet can provide remote and open access data possibilities, Web based SCADA display-systems, and flexible EMS architectures were designed. Real time operational data could be distributed utilizing the existing public communication infrastructure. For localized functions, Intranet enables substation[43], plant[44], and distribution automation[45]. Many functions, such as tele-control, integration, automatic and intelligent decisions from device level to enterprise level can be realized through Intranet[46],[47]. Web based network analysis, such as power flow computation, is also being developed[48].

Substation automation [49] is *the ability of the substation to take automated intelligent decisions with minimal user intervention*. To satisfy this goal, Intelligent Electronic Devices (IEDs) were developed [19]. The Internet can play a more important role in accessing the IEDs and connecting the islands of data after the advent of IEDs.

Another important application is fault location and disturbance analysis[50]. The main idea for this application is the analysis of synchronized data. Power system data captured by the protection relay can be synchronized using GPS signals in the substation and then sent to the utility center through utility Intranet. The post manipulation of these data can lead to fault location calculations and fault analysis. Using this technique, the number of fault locators and fault recorders can be reduced.

### 3.3.3 Maintenance of Power System

On-line condition monitoring [51] of HV transmission system equipment [52]such as circuit breakers and other important equipment are becoming necessary. Remote vision [53] is important in some special situations such as when the substation is located in an island. It will save time and cost by permitting service organizations to work independent of equipment operators. Internet based diagnostic tools enhance the automation of periodical maintenance activities and optimize monitoring information analysis. Substation diagnostic programs are being developed[51], which collect and analyze critical substation equipment information such as transformers and circuit breakers.

Power quality (PQ) monitoring [50] becomes more important in the deregulated environment. On-line PQ monitoring systems have been in operation at utility companies such as Electricite De France (EDF) [54]and Dranetz-BMI [55] via Internet. Anyone can view timely monitored results via a web browser. On-line PQ monitoring benefits both the provider and the customer as it enables problems to be identified from both sides and corrective action to be taken. It also improves coordination and communication between the utility and its customers in policing power quality problems.

### 3.3.4 Power Market

On the energy trading side, development of e-business enables execution of the electric power transactions, maintenance of offers, bids, and transaction histories, and access of real time pricing information via Internet [56]. The Open access Same-time Information System OASIS [57] is one such example.

On April 24, 1996 FERC introduced wholesale competition through open access non-discriminatory transmission service by public utilities. All the utilities have modified the way they operate to provide an open access to the interconnected transmission grid to all buyers and sellers of electricity. The FERC order also requested transmission owners not to support any entity's efforts to market power, even if the marketing was being done by the same company.

The main target of this separation is to prevent information abuse to gain market privileges over any other entity in the power market even if this entity is the same company that owned the transmission lines. All market players have the same information at the same time through Internet-based information system websites. OASIS is used to post the availability of transmission services and any other information required by FERC.

### 3.3.5 Education and Training

Distance education[58], learning[59],[60] and training [61],[62] are important applications of the Internet as a cost-effective alternative. It facilitates self-paced learning with the ability for individualized instruction through immediate reinforcement and feedback.

Internet-based distance learning has some limitations [62] in the present Internet technology especially for home computer users. The first limitation is slowness in audio/video information presentations. The second limitation is the discontinuance of support for the old version of online distant learning materials. This is not a real problem if the old versions are really old, but fast developments of this kind of software make some one or two months old versions obsolete. However, there are many other ways to overcome these audio/video problems by using other Internet features such as graphics, sound power point presentations, email, bulletin boards, and interactive tests using the HyperText Mark up Language (HTML) or java script.

### 3.3.6 Protection and Control

Although Internet latency is a problem in using the Internet for protection and control applications, recent publications have mentioned the possibility of using the Intranet for some of the protection [63] and control action[64]. The dedicated utility Internet network can be used as communication media with an acceptable traffic delay. The simulation results show that the delay for light traffic is around 1.5 cycles (24 ms), medium traffic is around 2.5 cycles (44 ms), and the heavy traffic is around 11 cycles (179 ms). The practical time delay may be more, but with the improvement technique for quality of service for the routing technology, a specific priority can be assigned to the protection information packets to reduce the traffic delay.

Another application running at Virginia Tech [64] is using Ethernet for fast reconfiguration of distribution system. The objective of the project is to reduce the reclosing time for the distribution-sectionalized system using Ethernet communication among these sections.

## 3.4 General Outline of the PSIN Architecture

This framework of the architecture will basically consist of

- Physical attributes
- Logical attributes
- Tools that deal with these attributes

GIS is our guide to the PSIN. Power information can be organized in layers so that each layer belongs to a specific topological type and relates to a specific type of data. Simply, one can navigate through these layers moving from the global picture to the more detailed picture.

*Physical attribute* is about the information location, such as spatial information, connection information, etc, while *logical attributes* which depend on the former physical attribute, consist of information functionality, security, timeliness, and objective. In the following sections specific details regarding these layers will be presented.

### 3.4.1 Physical Attributes

In the basic PSIN architecture shown in Figure 3-2, data and information that may be scattered throughout the organization, in different divisions and categories, is integrated in a generic manner. Physical layers relate the physical information location. It can be divided into many sub-layers according to the physical attributes. Areas controlled by one ISO can be one physical sub-layer, which also consists of different voltage-level transmission line layers, power plant layers, substation layers, and control center layers.

All the physical layers will contain information at different levels of detail. As an example, the regional layer will contain some information about the power plants but if one needs a complete picture, he will need to go downstream to the power plant information levels. As a general navigating rule in the physical layer, when going downstream, you will get information in greater detail. On the other hand, when going upstream, a general picture of the power system will be given. These physical layers will be used as a search guide in PSIN.

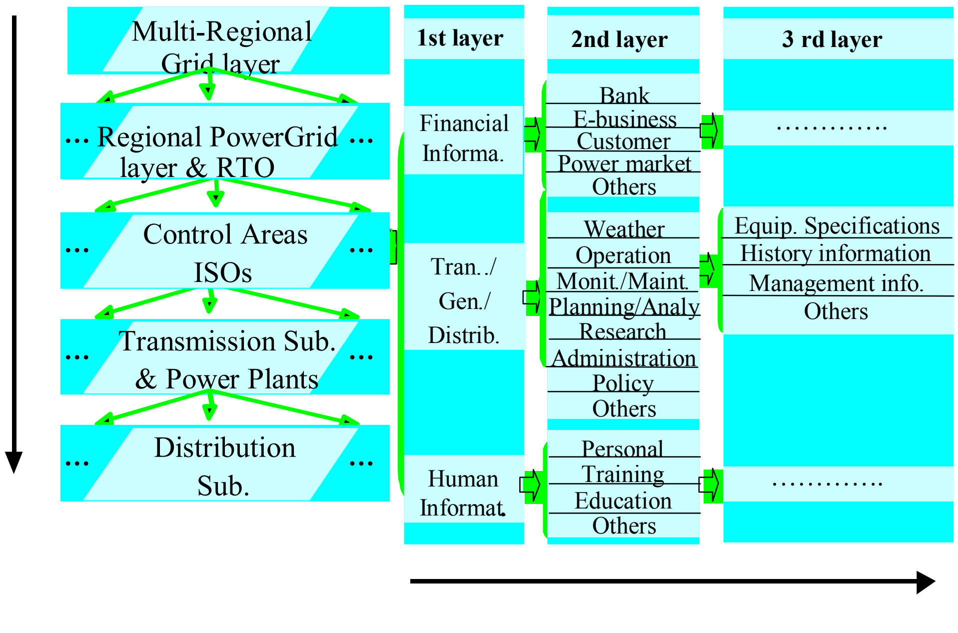


Figure 3-2: Basic architecture of the power system information network

### 3.4.2 Logical Attributes

Logical layers are divided according to information functionality. With the detailed information functions, logical layers will extend to more sub-layers in either horizontal or vertical directions. Logical layers depend on physical layers. Different physical layers may have different logical layers but, generally, all these logical layers have a similar structure. On the multi-regional HV power grid map, power market layers for inter-ISO transactions are shown, but information about the distribution and customer layers are not needed. For the same logical layer, information contents are different for different physical layers or same physical layers in different areas. Flexibility, inheritance (a parent-child relationship between one layer and its sub-layers), and encapsulation between layers are used for the PSIN architecture.

### 3.4.3 Data Manipulation Tools

Another important part of this infrastructure deals with tools required for data manipulation. Data manipulation can be realized between layers and within the same layer. As shown in Figure 3-3, data manipulation depends on information functionality and its layer location in the PSIN architecture, and can be divided into different classes. SCADA/EMS/DSS and DMS are considered as certain types of information manipulation. Load flow analysis is another example of data manipulation.

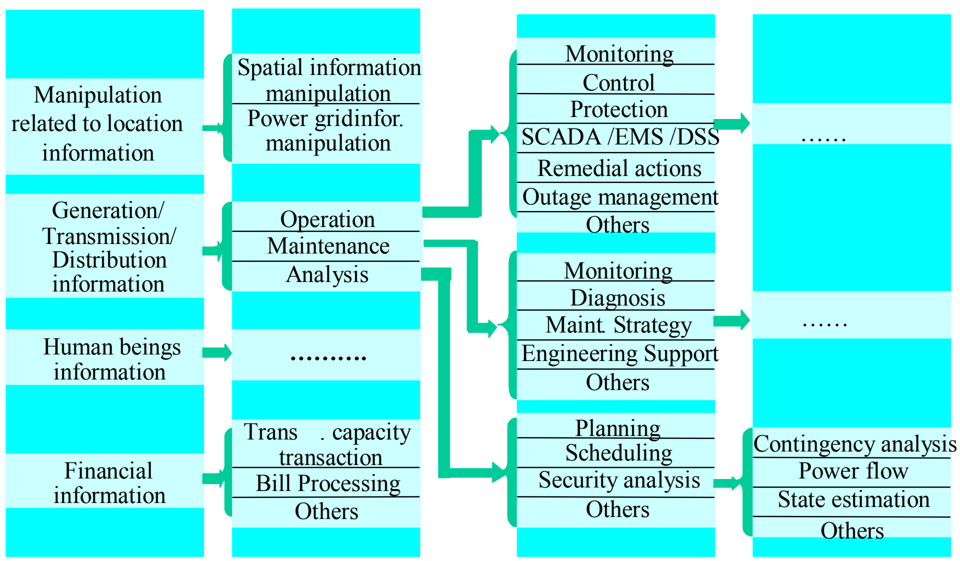


Figure 3-3: Categories of information manipulation / Tools

As stated earlier, based on object-oriented techniques, information manipulation should have the following features: encapsulation, inheritance, and polymorphism. Encapsulation means that most data manipulation should be combined with related data into a single entity. For example, SCADA and its related database should be encapsulated together into one object. Inheritance is cloning one module after another. It defines the manipulations in upper layers as having the same behaviors as its sub-layers and additional functions. For example, SCADA operation in utility physical layers can manipulate the plant data in addition to the substation data in substation layers, but SCADA in substation layers can only manipulate the substation data. Polymorphism means the same operation may have different functions for different layers or different data. Monitoring at system operation level may mean the detection of variables such as power frequency, voltage, current, active and reactive power, and a different set of variables in equipment maintenance, such as temperature, pressure, transients, etc.

Many components or methods will be integrated using object-oriented techniques. By combining the information manipulation and the information management parts together, the entire PSIN architecture is basically formed. This new infrastructure will offer many functions. To list a few, it should include:

- Geographic queries and analysis
- Complete picture of the power network
- Improved information management and integration among ISOs or RTOs
- Reduced data redundancy
- Standard way of communication among different entities
- Improved power flow, system security, and congestion management

It is important to point out that PSIN is only a framework and it attempts to provide a standard architecture in many aspects. However, access authorities for different types of information will remain under the power of the information owners.

# Chapter 4 Internet-based Wide Area Information Sharing and Its Role in Power System State Estimation

## 4.1 General

This chapter presents a mathematical background for State Estimation (SE) and proposes a new combination method for State Estimation (SE) using Wide Area Information Sharing (WAIS). This chapter also presents a comparison study between Integrated State Estimation (ISE), which is based on sharing real time measurements, and the proposed Split State Estimation (SSE), which is based on sharing SE outputs. The factors affecting the accuracy of SSE will also be presented. This chapter discusses the advantages and disadvantages of SSE over ISE. The results of the proposed method for combing the state estimation and data volume analysis between SSE and ISE will also be presented.

## 4.2 Mathematical Background of State Estimation

SE is an existing technique used for many applications in modern Energy Management Systems that can be used for building more realistic real-time models of the power network. SE can be defined [65]*as a method to assign logical values to the system state variables basically from measurements gathered from this system according to some criteria*.

The previous definition of SE is a general definition; however, we will take a close look at the SE in the power system context[66],[67]. Power system state variables are chosen to be the voltage magnitudes and the relative phase angles at the system nodes for a SE. Circuit breaker and switch status as well as the transformer tap settings are also needed for network configuration before state estimation can be performed. The measurements that can be used to estimate the system state variables are the available measurements from the network, such as voltage magnitudes (V), active power flows (P), reactive power flows (Q), or the current magnitudes (I). SE programs estimate the state vector of the system from these available measurements which may have many sources of error. All the measurements use transducers (current/voltage transformer) and these transducers contribute some error to the measurements. Another source of error is occasional failure of the communication links leading to missing measurements. The SE obtains a weighted least squares solution when the number of measurements is greater than the number of unknowns. The mathematical basis of the SE can be summarized as follows.

The basic idea of the SE is minimizing the cost function [65] *J (x)*. The cost function can be defined as follows:

$$\min \quad J(x) = \sum_{i=1}^{N_m} \frac{[Zm_i - h_i(x)]^2}{\sigma_i^2} \qquad (4.1)$$

Where

| | |
|---|---|
| x ………… | System state variable |
| $h_i$ ……… | i'th measurement as a function of the state variables |
| $\sigma_i^2$ ……… | Variance of the i'th measurement |
| *J (x)* ……… | A cost function |
| $N_m$ ……….. | Number of independent measurements |
| $Zm_i$ ……... | i'th measurement |

This equation can be expressed in per unit or in physical units. The AC measured quantities (for example the real and reactive powers P and Q) have a non-linear relationship to the state variables (Voltage magnitude and phase angles), therefore the minimization of the residual resorts to an iterative technique. Common technique to solve this minimization problem is to calculate the gradient of the residual ($\nabla_x\, j(x)$) and then force it to zero using Newton's method.

$$\nabla_x J(x) = \begin{bmatrix} \frac{\partial J(x)}{\partial x_1} \\ \frac{\partial J(x)}{\partial x_2} \\ . \\ . \end{bmatrix} \tag{4.2}$$

$$= -2 \begin{bmatrix} \frac{\partial \ h_1(x)}{\partial \ x_1} & \frac{\partial \ h_2(x)}{\partial \ x_1} & \frac{\partial \ h_3(x)}{\partial \ x_1} & ....... \\ \frac{\partial \ h_1(x)}{\partial \ x_2} & \frac{\partial \ h_2(x)}{\partial \ x_2} & \frac{\partial \ h_3(x)}{\partial \ x_2} & ......... \\ . & . & . & \\ . & . & . & \end{bmatrix} \begin{bmatrix} \frac{1}{\sigma_1^2} & & \\ & \frac{1}{\sigma_2^2} & \\ & & \end{bmatrix} \begin{bmatrix} [Zm_1 - h_1(x)] \\ [Zm_2 - h_2(x)] \\ . \\ . \\ . \\ . \end{bmatrix} \tag{4.3}$$

$$\nabla_x \quad j(x) = -2\left[H\right]^T \left[R\right]^{-1} \begin{bmatrix} [Zm_1 - h_1(x)] \\ [Zm_2 - h_2(x)] \\ . \end{bmatrix} \tag{4.4}$$

Where

[H] ………. is $N_m$ by $N_s$ matrix $= \begin{bmatrix} \frac{\partial \ h_1(x)}{\partial \ x_1} & \frac{\partial \ h_2(x)}{\partial \ x_1} & \frac{\partial \ h_3(x)}{\partial \ x_1} & ....... \\ \frac{\partial \ h_1(x)}{\partial \ x_2} & \frac{\partial \ h_2(x)}{\partial \ x_2} & \frac{\partial \ h_3(x)}{\partial \ x_2} & ......... \\ . & . & . & \\ . & . & . & \end{bmatrix}$

Nm ……… is the number of measurements

Ns ……….. is the number of state variables being estimated

[R] ……….. is covariance matrix of measurement errors $\begin{bmatrix} \sigma_1^2 & & \\ & \sigma_2^2 & \\ & & . \end{bmatrix}$

Using Newton's method to make $\nabla_x \ j(x)$ equal to zero

$$\Delta x = \left[\frac{\partial \nabla_x J(x)}{\partial x}\right]^{-1} \left[-\nabla_x J(x)\right] \tag{4.5}$$

The Jacobian of $\nabla_x J(x)$ is calculated assuming that [H] is a constant matrix

$$\left[\frac{\partial \nabla_x J(x)}{\partial x}\right] = -2[H]^T [R]^{-1} [-H] \tag{4.6}$$

Substituting in equation ( 4.5 )

**4.2.1.1**

$$\Delta \ x = 0.5\left[[H]^T [R]^{-1} [H]\right]^{-1} \left\{ 2 \ [H]^T [R]^{-1} \begin{bmatrix} Zm_1 - h_1(x) \\ Zm_2 - h_2(x) \\ . \end{bmatrix} \right\} \tag{4.7}$$

$$\Delta \ x = \left[[H]^T [R]^{-1} [H]\right]^{-1} \ [H]^T [R]^{-1} \begin{bmatrix} Zm_1 - h_1(x) \\ Zm_2 - h_2(x) \\ . \end{bmatrix} \tag{4.8}$$

To solve equation ( 4.8 ) an iterative technique is used until $\Delta x$ is very small and tends to zero and the solution in this case equals

$$X^{new} = X^{old} + \Delta X \tag{4.9}$$

## 4.3 Split State Estimation Motivations

Deregulation has brought significant changes to many aspects of power system engineering. The Federal Energy Regulatory Commission (FERC) recognized these changes in system operations, and requested formation of the Regional Transmission Operators (RTO) [2], which simply will merge ISOs into large RTOs. The old boundaries among utilities/ISOs will disappear and in the near future power transactions can take place anywhere in the deregulated network. From this point of view the old structure for controlling the power network should be modified [68] to accommodate the large changes in the deregulated power markets. WAIS becomes increasingly important for these deregulated power systems.

WAIS is one of the ways to enhance the SE calculations under the new RTOs structure. SE enhancement can be achieved through a new EMS, which would cover a wide area, bringing all the real time measurements to this EMS and develop the state estimator for the entire area [69]. However, this option faces many roadblocks. One of the main problems is that the new EMS must obtain real time information from different control areas at different utilities that may be unacceptable for various reasons. The alternative solution is to let each area perform its own State Estimation, and then combine the SE outputs of each area to form the large area SE.

This basic idea of sharing SE outputs from different areas was proposed in different literature as hierarchical SE[70]. A hierarchical model using Artificial Neural Network (ANN) [71] was proposed to solve the dynamics of the power system. Two levels of power system state estimators[72],[73] were proposed as a hierarchical computing scheme for power system state estimation. However, all these methods are based on the fact that the information can be shared among the hierarchies. The concept of this work is different in the sense that SE outputs are the only information that can be shared among the utilities. The major problem will be the lack of common reference among these systems. This common reference problem can be solved based on local measurements.

The basic idea for solving the common reference problem is based on monitoring the tie lines flows among the integrated areas and using the equivalent transmission line models to calculate the difference in angle between these areas. The details and the factors affecting the common reference calculations will be presented in the next section.

### 4.3.1 Common Reference Considerations

The available information, which should be shared to obtain a global common reference, is

- SE outputs for all the subsystems
- The individual local reference of each area

For a two-area system, knowing at least one bus angle with respect to the reference buses of the two areas will solve the problem. For more than two areas the same rule is applicable. One of the references is selected to be the global reference and the relationship of all other references to the global reference is determined. A two-area example shown in Figure 4-1 will illustrate the concept.

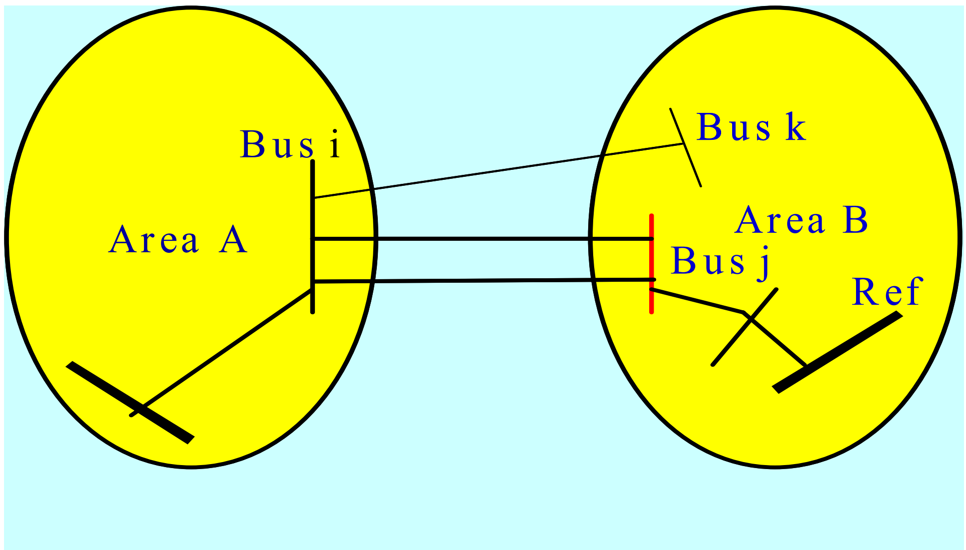


Figure 4-1: Common reference estimation for a two-area System.

Bus ‘i’ in area A has an angle $\theta_i$ with respect to area A reference. Bus ‘j’ in area B has an angle $\theta_j$ with rrespect to area B reference. Consider the calculation of the common reference from the point of view of area A. The $\pi$-equivelent of the tie line is known to area A, along with the power flow of the tie line and the voltage and angle of bus ‘i’ with respect to area A refenence. Similarly, from the SE output of area B the voltage and angle of bus ‘j’ with respect to area B reference is also known. Using simple $\pi$-equivalent calculation the voltage and the angle of bus ‘j’ can be recalculated with respect to the reference in area A as shown in Figure 4-2.

Bus ‘j’ now has two angles with respect to the two references of the two areas: the first reference in area A ($\delta_j$), and the second reference in area B ($\theta_j$). The difference between the two angles is

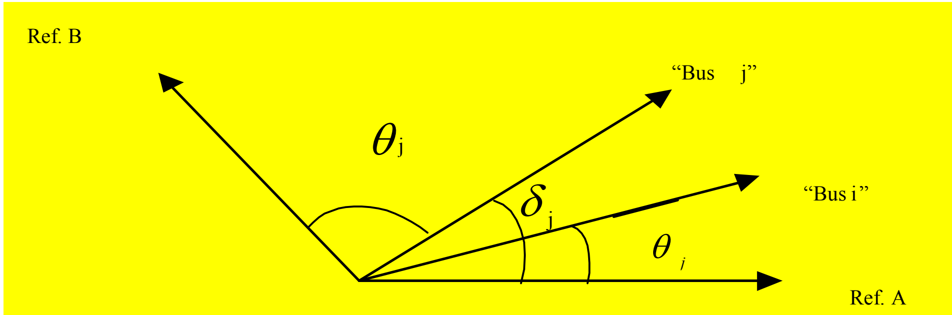


Figure 4-2: Phasor diagram with a common reference.

$$\phi_{ref} = \theta_j - \delta_j \qquad (4.10)$$

Where $\phi_{ref}$ is the common reference shift angle. Using this angle to shift all the voltages and currents in system B with respect to system A produces a coherent state for the combined system. In general, if there are 'm' tie lines between the two areas then $\phi_{ref}$ may be calculated as an average:

$$\phi_{ref} = \sum_{i=1}^{m} (\theta_j - \delta_j) / m \qquad (4.11)$$

Many factors can affect the accuracy of the calculation of a common reference

- The accuracy of the tie lines flow measurements
- The accuracy of the model of the tie line
- The number of the tie lines between two consecutive areas
- Connections among all the areas

The better the accuracy of the tie line equivalent circuit and flow measurements, the better will be the accuracy of the common reference calculation. Calculating the common reference angle based on averaging more than one tie line is more accurate than calculating it based on just one tie line.

## 4.4 Data Volume for SSE and ISE

As mentioned before, sharing real time measurements among different control areas may not be an available option for various reasons. However it is instructive to compare the data volume for SSE and ISE. To make an accurate comparison, the details of the systems under consideration should be known. For simplicity, the following assumptions are made:

- All the active and reactive power are monitored at both ends of all the transmission lines.
- Active power, reactive power, and voltage magnitude are monitored at each bus in the network.
- The ratio between the number of branches and the number of buses in a network will be assumed to be two.

Variations on these assumptions will be considered later.

Assume that we have three areas under consideration as shown in Figure 4-3. Each area has its control center/ISO that is responsible for estimating the state for its own area. To combine these three ISOs to form one RTO capable of doing ISE for the whole system, the real time measurements for the other two areas should be exported to this RTO.

Assuming that the number of buses in each area is equal to N and the number of branches will be equal to 2N. The number of measurements will be exported from one area to the other two areas under the previous assumptions and can be calculated as follows:

Data exported /area = TL measurements + bus measurements

$= 2N \bullet 4 + N \bullet 3$

$= 11N$

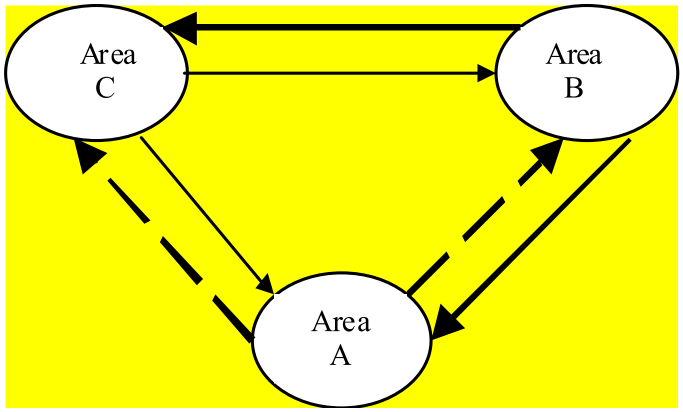


Figure 4-3: Three-area example.

The data is exported for the 3 areas so that each area will have the other two areas' measurements:

Total Data volume = 3 • 11N
= 33N

This result corresponds to the maximum data transfer requirements. Under a different set of assumptions:

- All the active and reactive power are monitored at one end of the transmission lines.
- One voltage magnitude is monitored at one bus in the network.
- The ratio between the number of branches and the number of buses is assumed to be 1.5.

In this case, the above calculation yields:

Data exported /area = 1.5N • 2+1 • 1 = 3N+1
Total Data exported = 9N+3

The previous calculation is based on sharing real time measurements. Now consider the SSE scenario, in which the SE outputs of each area are shared.

Data exported /area = 2N

Total Data exported = 6N

Comparing the data volume between sharing the real time measurements (ISE) and sharing the SE outputs (SSE), the ratio is between 1.5 and 5.5 (Figure 4-4), depending upon the number of real time measurements shared.

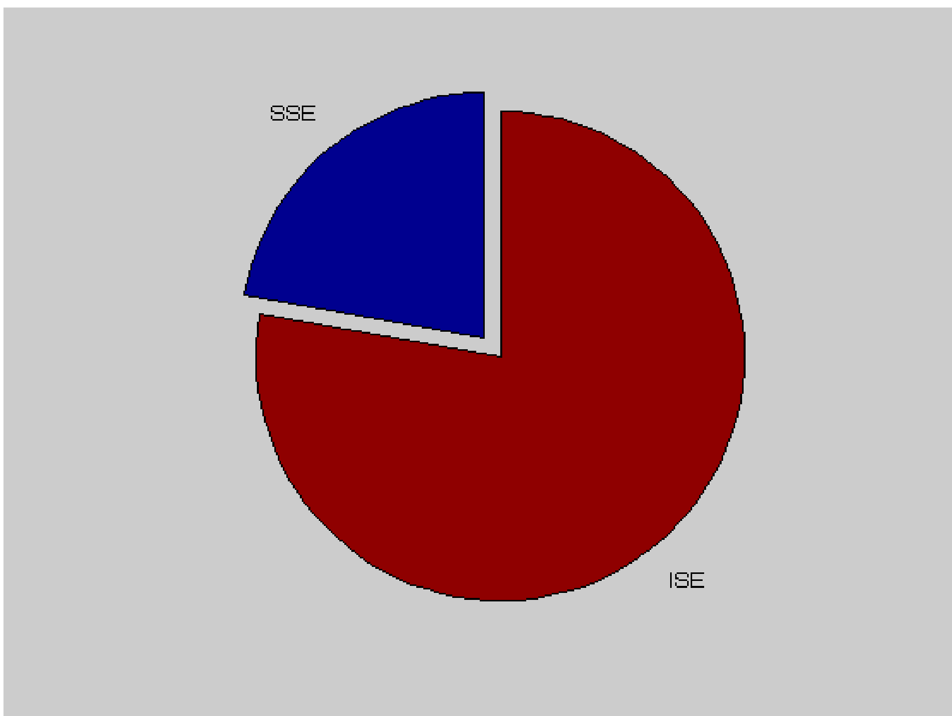


Figure 4-4: Average data volume comparison between ISE and SSE

In addition to the saving of data volume (average saving equal to 3), there are other important factors in favor of sharing the SE outputs. The average scan time to get SE outputs may be in the order of 4 minutes, and therefore the Internet is well suited as a communication medium. The SSE based on the Internet has the following features:

- No changes in the old structure of the power system control center.
- Reuse the old EMS because the new integration does not need new SE programs capable of dealing with larger numbers of buses.
- No new hardware is required.
- No special communication facilities are required.
- The average latency of the Internet is much less than the scanning time for SE.
- Multi-point access so that each area is required to transmit data only once.
- No special communication software installation is needed.

As shown in the following, the accuracy of the SSE is equivalent to that of the ISE. In the following sections, a comparison of SSE and ISE will be presented.

## 4.5 SSE Program Algorithm

The algorithm used for the comparison study between SSE and ISE is shown in Figure 4-5. The basic idea for this algorithm is running the ISE and SSE out of the same measurements pool. As a result, the output results for ISE and SSE rely only on the methodology used in each case. The main algorithm steps can be summarized as follows:

1. Prepare the measurement pool for both SSE and ISE. This can be achieved as follows:

   - Run the load flow for the whole system. The load flow output can not be considered measurement input to the SE program because real measurements should have some kind of noise unlike the load flow output.
   - Calculate the standard deviation of measurement device ‘i’ as follows [74]:

$$\sigma_i = \frac{1}{3}\left(0.02 \bullet M_i + 0.0052 \bullet F_{si}\right) \qquad (4.12)$$

Where

$M_i$ ……….. is the complex power measurement, or voltage magnitude measurement for the i'th measurement.

$F_{si}$ ………… is the full-scale value of the measuring instruments i.

- Add noise to the load flow outputs. In this study, the errors are assumed to be aero-mean Normal distribution dependent on the measurement devices. This noise level will change each time the program is running based on the Normal distribution generation. For that reason, the Monte-Carlo simulation technique is the best available method.

2. Calculate the ISE outputs by feeding the SE program all the measurements available in the system.

3. Preparing the measurement data to run SSE.

   - Split the measurement pool to sub-pools depending on the number of sub systems in the whole area. In our case there are only two sub- areas.
   - Run the SE program for each individual area separately.
   - Calculate the common reference angle among these areas as explained in the previous section in Equation (4.13).

4. SSE output is the combination of SE outputs of each individual area using the common reference angle to have a common reference for the whole system as explained in section 4.3.1.

5. The Monte-Carlo technique will be used to repeat this algorithm for different error levels.

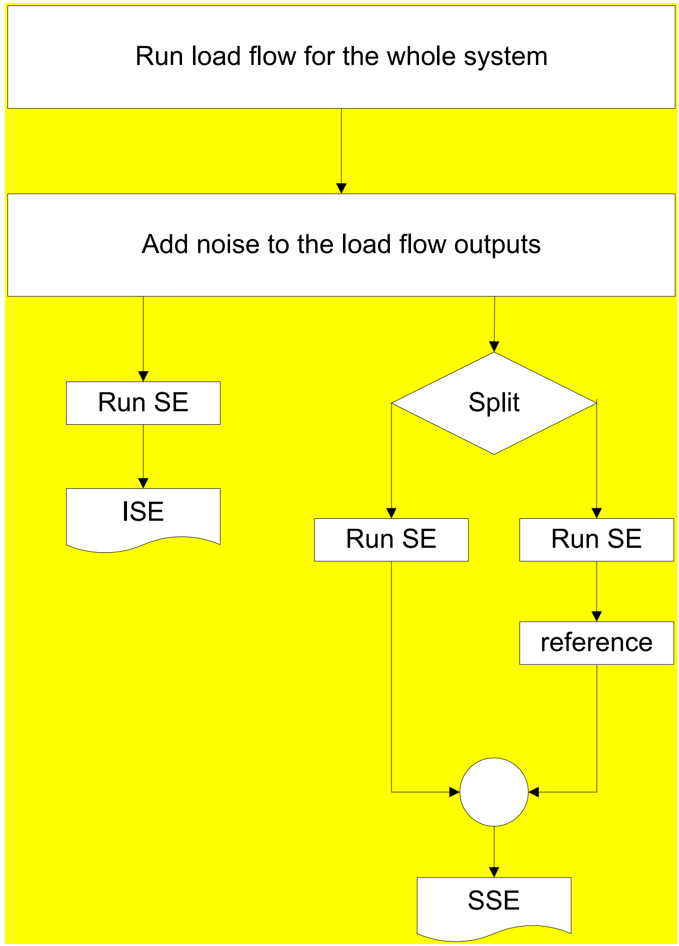


Figure 4-5: Flow chart of the simulation program.

The following points are the assumptions made for the analysis of different cases:

- The true values of the tie line flows are assumed to be equal to the load flow value.
- The simulations performed are based on the Monte-Carlo Technique (500 runs are used).
- The percentage change for both ISE and SSE are calculated from load flow solution as a true value.
- IPFLOW is the program used to run load flow solution and MATLAB is used to read the output of the IPFLOW using the algorithm shown in Figure 4-5.
- ISE and SSE comparisons will focus on the tie-line data.

- It is assumed that both ends of all the transmission lines are metered. No bus injection measurements are used, and voltage magnitude is measured at all the buses.

## 4.6 Simulation Results

The simplified WSCC 179-bus system Appendix A is the base case for the simulations presented here. However, the algorithm has also been tested on IEEE 14-bus, 30-bus, and 39-bus systems. The simplified WSCC system consists of 11 control areas, 5 of which are system equivalents and the rest have different levels of detail as shown in Figure 4-6. For the sake of the present simulations, all the areas are grouped into two main areas:

- North area that includes Canada, North West, and Montana and consists of 42 buses.
- South area contains the rest of the areas with a total of 137 buses. Four 500 kV lines connect the two areas. These lines will be considered as tie lines between North and South.

Two cases are presented in this section:

- Noisy measurements are assumed for the tie line flows.
- Accurate measurements are assumed for the tie line flows.

The first case studied was the noisy tie line measurements. In this case the same standard deviation has been used to calculate the measurements from the load flow output data, as the one used for calculating the tie line flow measurements. Therefore, this case is named noisy tie line flows. Practically speaking, this case is a typical case if the measurement devices at the tie lines have the same accuracy as the rest of the measurement devices throughout the system.

The second case studied was the noise free tie lines measurements. In this case the measurements at the tie lines are assumed to be equal to the tie line load flow outputs. No noise has been added to the tie lines flows. Therefore, this case is named accurate tie line measurements. This case is assuming that there are accurate measurement devices at the tie lines. The rest of the measurements have normal noise level assumed in case one.

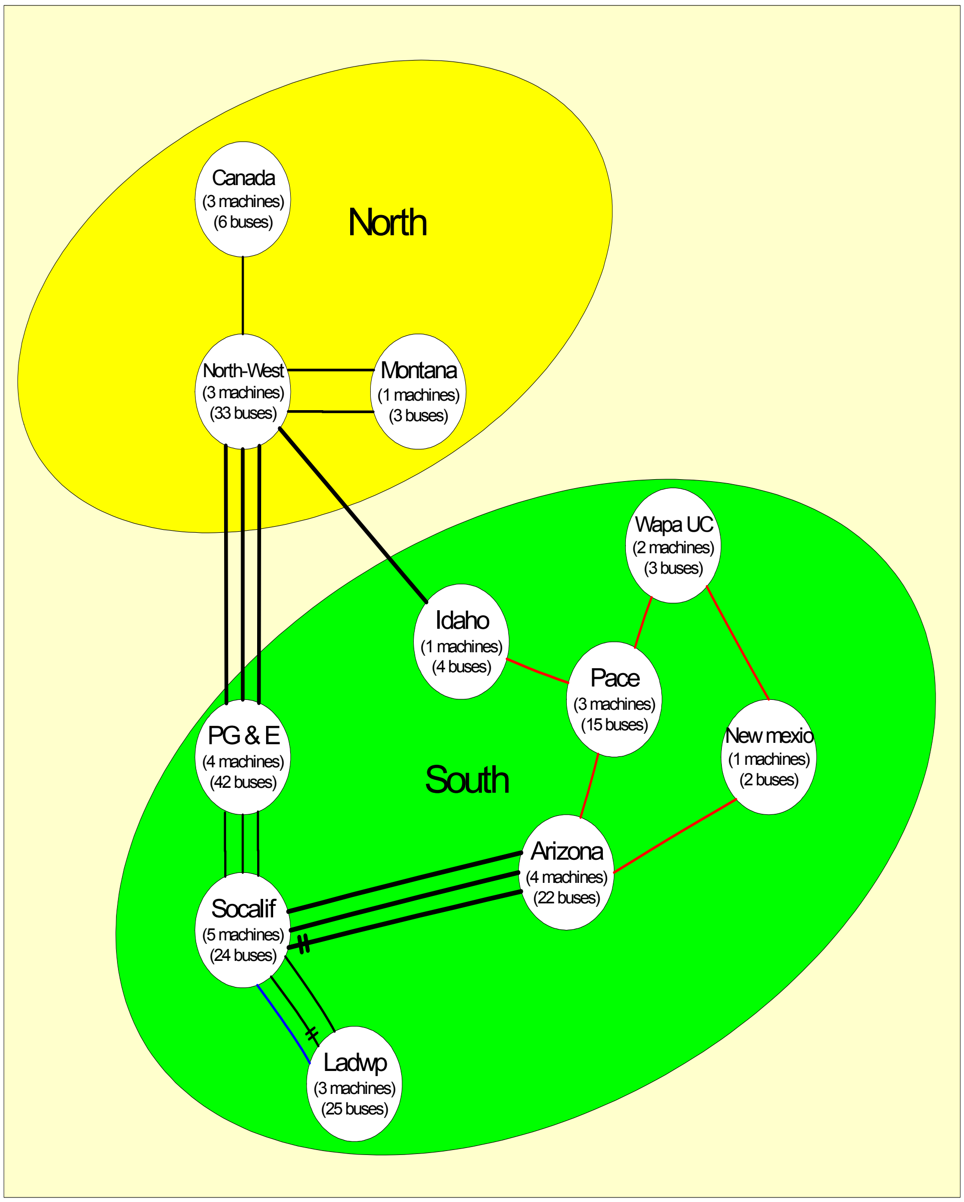

Figure 4-6: Two regions for simplified WSCC 179 bus system.

Both cases use the SSE algorithm explained in Figure 4-5 to obtain SSE and ISE results. The previous algorithm has been run using the Monte-Carlo Technique for 500 times. In each run, three measurements sets are recorded:

- The first measurement set is the transmission line measurements which are equal to the load flow result plus the Normal distribution noise.
- The second measurement set is the ISE transmission lines flow outputs. The output in this case is created with the assumption of sharing all the measurements between the North and South areas shown in Figure 4-6.
- The third measurement set is the SSE transmission line flow outputs. The output in this case created with the assumptions of sharing the output of the state estimations between the North and the South areas and calculating the common reference angle between the two systems.

These three sets of measurements are repeated 500 times each time with different measurement noise levels. All noise levels are pulled out from the Gaussian distribution. The following standard deviation (STD) comparison has been calculated based on this 500 measurements record. The common reference angle is also calculated 500 times based on equation (4.14). The SSE and ISE tie lines flows are calculated and the percentage change from the load flow tie lines flows are calculated as another comparison indicator between SSE and ISE.

### 4.6.1 Noisy Tie lines Measurements

Figure 4-7 shows a comparison study for the STD results of some of the transmission line flows calculated using the Monte-Carlo Technique. These transmission lines are picked far from the tie lines. For that reason, this study will be named internal transmission lines. As is clear from Figure 4-7 the ISE and SSE STD are almost identical and both of them are less than the STD of the applied error. We can conclude that both methods for calculating SE are perfect; however, the proposed method (SSE) has succeeded in reducing the data volume as shown in Figure 4-4.

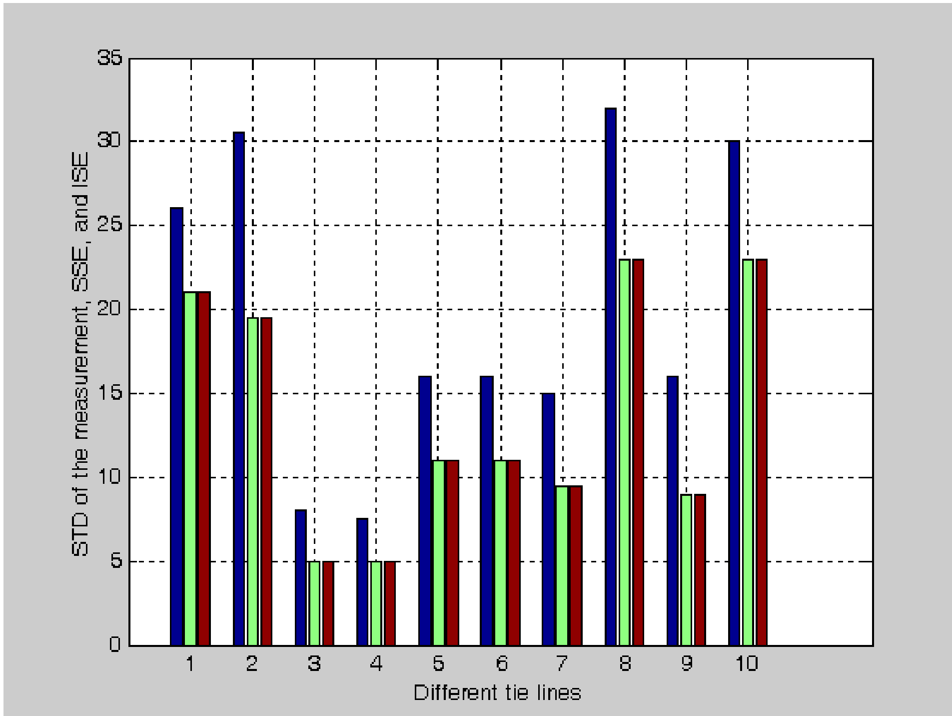


Figure 4-7: STD comparison at internal transmission lines for noisy tie lines flow

Figure 4-8 shows a comparison study for the STD results at the tie lines flows calculated using the Monte-Carlo Technique. ISE and SSE STD in this case are not exactly equals as in Figure 4-7. However, SSE STD results are better than STD results of the applied error. The SSE STD results are higher than the ISE STD results at the tie lines; however, for the whole system the proposed SSE results are acceptable. An improvement in these results can be achieved by providing accurate measurements at the tie lines as will be shown in the second case.

Table 4-1 shows the average percentage change for the SSE and ISE tie line flows with respect to the load flow results. The mean of the ISE tie lines flows average is 0.6402 % from the actual load flow results; however, in the case of the SSE it is 1.501 %. The average in the ISE case is lower than the SSE case but both values are significantly good. The SSE results can also be improved by providing accurate measurements at the tie lines as in the following case.

Table 4-1: Average percentage changes at tie lines for noisy tie lines flow

| Tie-line | SSE | ISE |
|---|---|---|
| 1 | 1.2957 | 0.7214 |
| 2 | 1.4022 | 0.6389 |
| 3 | 1.6145 | 0.5987 |
| 4 | 1.6917 | 0.6019 |
| Average | 1.5010 | 0.6402 |

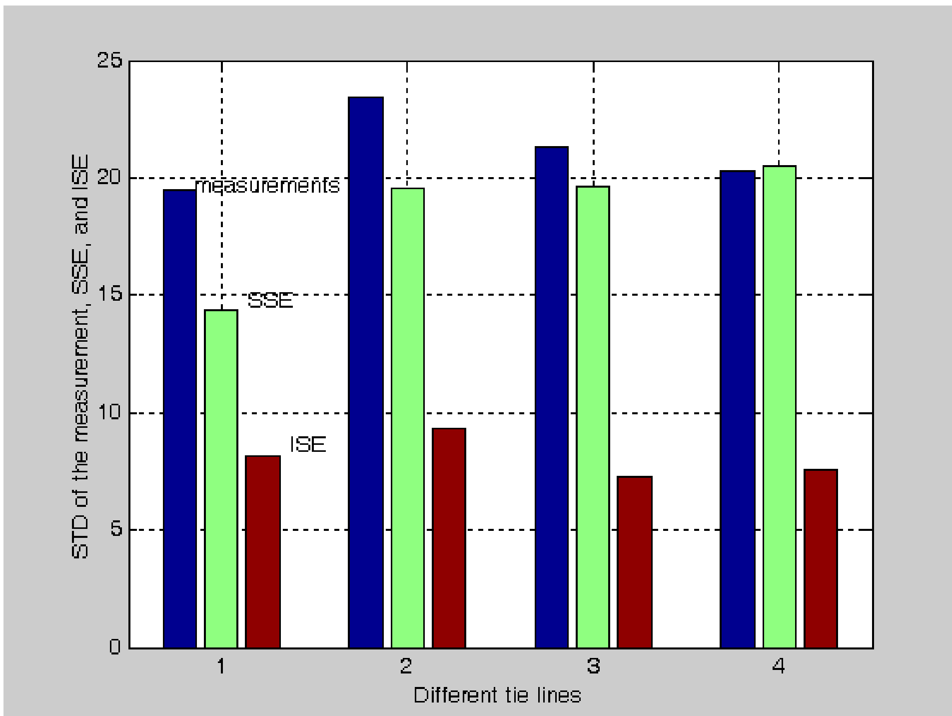


Figure 4-8: STD comparison at the tie lines flows for noisy tie lines

Figure 4-9 shows the histogram of the common reference angle ($\phi_{ref}$) calculated using equation (4.15). The STD in the errors of $\phi_{ref}$ in this case is 0.6514. The histogram is based on the 500 $\phi_{ref}$ values calculated using the transmission line flows of the Monte Carlo simulations.

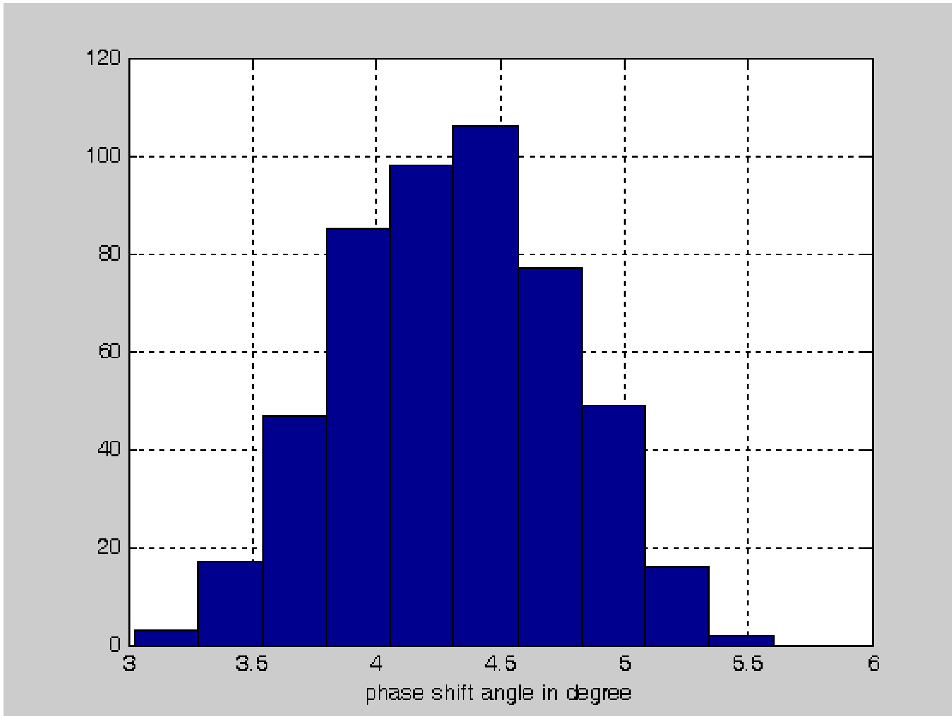


Figure 4-9: Histogram for the phase shift angle for noisy tie lines flow

### 4.6.2 Accurate Tie lines Measurement

In this case the tie line flows are assumed to be perfect measurements. The tie line flows in this case are assumed to be equal to the load flow outputs. The accurate tie line flow measurements (Figure 4-10) have no effect on the STD of the internal transmission line results demonstrated in the previous case (Figure 4-7). However, the effect is clear for STD at the tie lines shown in Figure 4-11. The STD of SSE at the tie lines is improved because the $\phi_{ref}$ calculations are improved and the STD of the error of the $\phi_{ref}$ in this case is dropped from 0.6514 to 0.5161. The STD of ISE tie line flow improvement is not significant because the accurate tie line measurements are only a small set out of a large set that includes all the system measurements which still have the same measurement error. The STD of the measurements is kept the same for both cases. Table 4-2 tabulates the STD at the tie lines measurements for the three records we have (ISE, SSE, and measurements).

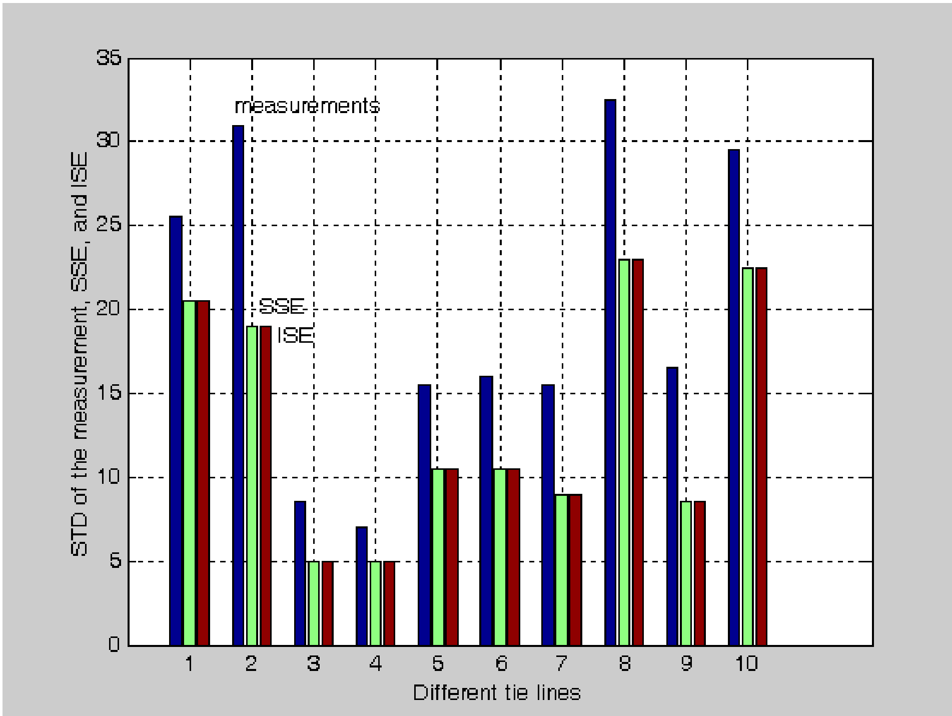


Figure 4-10: STD at internal transmission lines for accurate tie lines flow

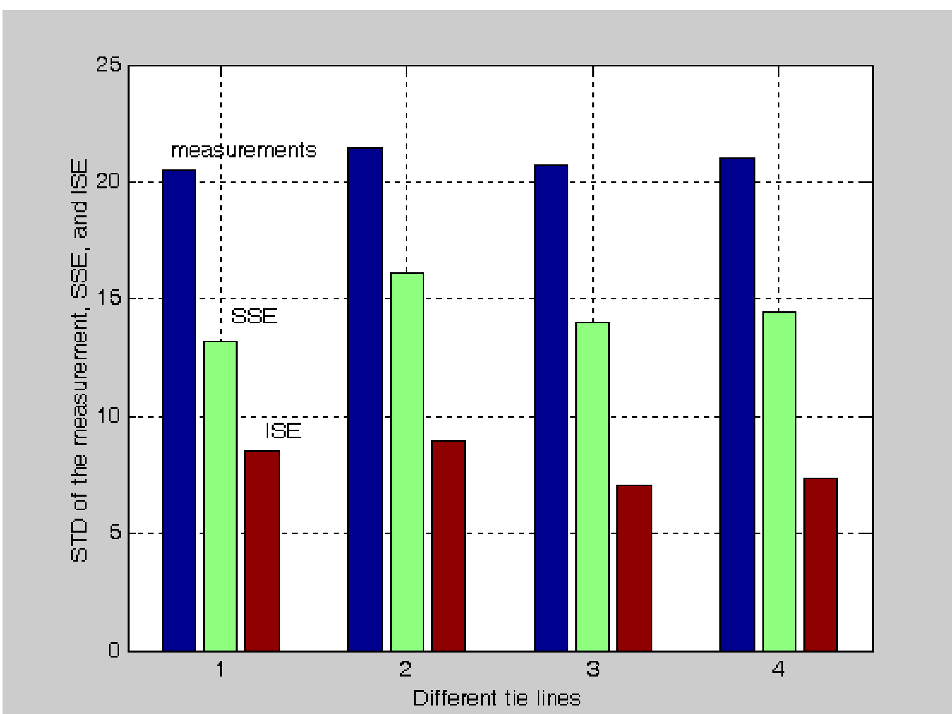


Figure 4-11: STD comparison at the tie lines flows for accurate tie lines flows

Table 4-2: STD comparison at the tie lines for accurate tie lines flow

| Tie-line | SSE | ISE | Err |
|---|---|---|---|
| 1 | 13.1967 | 8.5112 | 20.5117 |
| 2 | 16.1356 | 8.9757 | 21.4312 |
| 3 | 13.9647 | 7.0396 | 20.7211 |
| 4 | 14.4672 | 7.3550 | 21.0184 |

Table 4-3 shows the average percentage of changes for the tie SSE and ISE line flows with respect to the load flow results. The ISE result is almost the same as the previous case 0.6391 %. However, improvement of the SSE result is achieved, the average is dropped from 1.501% as shown in Table 4-1 to 1.1806% as shown in Table 4-3. This improvement can be attributed to the improvement of the $\phi_{ref}$ calculations.

Table 4-3: Average percentage changes at tie lines flow for accurate tie lines flows

| Tie-line | SSE | ISE |
|---|---|---|
| 1 | 1.2090 | 0.7586 |
| 2 | 1.1438 | 0.6198 |
| 3 | 1.1619 | 0.5797 |
| 4 | 1.2076 | 0.5985 |
| Average | 1.1806 | 0.6391 |

## 4.7 Result Analysis

The proposed SSE has acceptable results compared to the ISE. The data volume reduction between sharing the real time measurements (ISE) and sharing the state estimation outputs (SSE) is large enough to use the SSE technique. Besides the SSE technique can be used as an interim solution for the transition situation between ISO and RTO until the infrastructure for RTO is in place. The following points summarize the comparison between the ISE and SSE techniques used in this chapter:

- The STD of ISE and SSE are almost identical at the internal transmission lines (far from the border areas) as shown in Figure 4-7and Figure 4-10.
- At the border area, the STD of the ISE is lower than that of the STD of SSE and both of them are lower than STD measurements.
- The STD of SSE can be improved by increasing the measurements accuracy of the tie lines flows as shown in Figure 4-8 and Figure 4-11.

- The prediction of the common reference shift angle $\phi_{ref}$ can also be improved by increasing the measurements accuracy of the tie line flows.
- The average percentage change in the tie line flows can also be improved by increasing the measurement accuracy of the tie line flows as shown Table 4-1 and Table 4-3.

# Chapter 5 A Tracing Load Flow Program for Total Transfer Capability Calculations

## 5.1 General

This chapter presents a tracing load flow (TLF) program that is designed to calculate the Total Transfer Capability (TTC) in addition to many other applications. TLF is basically a load flow program that has the flexibility to change any input parameters in a systematic way and trace the state variable changes. TTC is a key factor for calculating Available Transfer Capability (ATC). TTC calculations are based on running different load flow cases from the base case until hitting thermal, voltage, or transit stability limits. TLF is able to calculate area-to-area TTC or point-to-point TTC with any generation/load dispatch. TLF can be used in many different applications besides the calculations of TTC such as voltage collapse studies, contingency analysis, power systems studies under different dispatch conditions, and can also be used for analysis of impact of series and shunt compensators on power systems. TLF is developed using MATLAB and has been tested for many power system models of different sizes.

## 5.2 Transfer Capability Definition

The deregulation of the power system imposes many new challenges in the power system area. This new competitive market environment will increase the demand for transmission services. Transmission services become an important issue in this competitive market and all the players in this market should understand the electrical limitations for the transmission services. One of these limitations is the transmission transfer capability of the system. However, transmission line transfer capability is an old term that became more important after power system deregulation. Transfer capability is important in power system security, transmission expansion planning, generation expansion planning, long term market forecasting, contingency analysis, and TTC calculations.

The North American Reliability Council (NERC) established a standard reference document [75] for the Total Transfer Capability (TTC). The engineering committee approved this document in November 1994. The value of TTC comes from its importance for calculating ATC [76] in the market transactions. ATC is frequently updated in the OASIS [4] site and all bidding and trading of electricity is controlled by these values.

ATC is an important term that has recently been used in the deregulated interconnected transmission networks in the electricity market. The ATC calculation is directly related to physical capabilities of the interconnected network. The ATC can be defined [76] as "*A measure of transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses*".
This definition can be formulated as equation (5.1)

$$ATC = TTC - TRM - CBM \quad (5.2)$$

Where

TTC ……... Total Transfer Capability
TRM …….. Transmission Reliability Margin
CBM …….. Capacity Benefit Margin

**TRM** "*The amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.*"

**CBM** "*The amount of transfer capability reserved by load serving entities to ensure access to generation from interconnected systems to meet generation reliability requirements.*"

**TTC** "*The amount of electric power that can be transferred over the interconnected transmission network in a reliable manner while meeting all of a specific set of defined pre- and post- contingency system conditions.*"

For a better understanding of TTC definition some important terms related to TTC definition will be highlighted:

**System conditions:** TTC calculations are based on base-case load flow that is identified for the period to be analyzed. For any change in the system conditions, the calculation of TTC should be modified to accommodate these changes.

**System limits:** TTC are determined by the physical and electrical limitations of the power system. Therefore, TTC is determined by the first violation of thermal limit, voltage limit, or stability limit.

**Critical contingencies:** TTC calculation should consider at least n-1 contingencies in the system. The contingency set can be initially determined by linear sensitivity analysis (LSA) [77],[78]. LSA is an incremental solution over an exact pre-solved case. LSA bypasses the complexity of AC simulation under the same assumptions of DC load flow (Q is neglected, loss is neglected, and all bus voltage magnitudes are equal to 1.0 per unit). LSA factors simply show the change of the active power in line flows due to generation changes in the network and due to transmission line outages. More details of the LSA technique will be explained in Chapter 6.

## 5.3 Transfer Capability Applications

Transfer capability determines many applications in power system engineering:

- Power system security
- Transmission expansion planning
- Generation expansion planning
- Long term market forecasting
- Contingency analysis
- ATC calculations

The first application of the transfer capability is studying the security of the interconnected power system. The reliability of the interconnected power system [79] can be measured by the ability of the system to stay stable and within safe operating limits after one or more contingencies. To keep the generation load balance this system should export a certain amount of generation from the neighborhood to balance the load. Transfer capability of the tie lines connecting this system to the interconnected system is a measure of the capacity available for additional power transfer with adequate security. The main goal of transfer capability calculation from a security point of view is calculating the amount of generation in one area that can be exported to other areas.

Transfer capability is also a very useful tool in the planning studies of the power system. For example, transmission lines that increase the transfer capability among different areas is the best choice for the transmission expansion especially if this expansion will help to reduce electricity prices. From the same prospective the generation expansion is also influenced by the transfer capability calculation. The locations and the sizes of the new generations' expansion, especially the independent power producers (IPPs) should consider the transmission line capability through which their power will be transfered to the rest of the inter-connected system.

In the deregulation environment, long-term studies of the behavior of the electricity markets do not need the details of the power system. A simplified model for the power system is usually sufficient. The transfer capabilities of the tie lines among different areas play an essential role in these simplified models.

ATC is an important term that has recently been used in deregulated interconnected transmission networks in the electricity market. The ATC calculation is directly related to transfer capabilities of the interconnected network. In addition to ATC, the contingency analysis becomes more important and more difficult in the deregulated environment because frequently most of the inter-connected systems are pushed to the limit of the security.

## 5.4 Total Transfer Capability Calculations

The calculation of the TTC is based on computer simulations for specific operating conditions. TTC calculations are commonly performed using two main methods:

- Linear calculations [80]
- Non-linear calculations [81],[82]

TTC linear calculation is based on the DC load flow technique. The linear approach has many limitations because all the calculations are based on linear models while the actual power system is non-linear. Examples of these limitations include: neglecting reactive power [83], neglecting the voltage limit, and disregarding the system voltage collapse.

TTC non-linear calculation is based on the AC load flow technique .The importance of using the AC method[84] in the deregulated power system has increased for many reasons such as:

- Increasing the influence of the reactive power due to the unusually heavy transactions in the deregulated environment.
- Some of the interconnected power systems are suffering from unusual voltage drops close to the collapse margin from unscheduled flows that increased as a result of bilateral contracts.
- The new challenges of the deregulated inter-connected power network security.
- Market requirements which hope to reduce the uncertainty of the TTC calculations for more profit.

As a result of these issues, ATC [85],[86] contains these uncertainties by including a TRM. Increasing TRM will help to accommodate effects of many uncertainties in the network. However, the power market needs to cut down these uncertainties in order to increase the transactions. One way to do that is to calculate accurate TTC based on the non-linear method instead of the linear method. The AC method does suffer from disadvantages such as long execution time because of repeating of the load flow calculations till hitting certain system violations.

For the TTC calculations, one area is considered the "source" area (for example area A) and the other considered the "sink" area (area B). TTC is a directional quantity from the source to the sink i.e. TTC from area A to area B ( $A \rightarrow B$ ) is not equal to the TTC $B \rightarrow A$. The term "area" used in this context can be used to refer to a generating station, power pool, control area, or a substation.

TTC calculations are based on computer simulations of different operating conditions in the two areas. Each simulation is a snapshot of the operation. Two scenarios can be used for TTC calculation:

- **Load / Generation method (LG):** Loads in the sink area are increased and the source area will compensate for this increase by increasing its generation.
- **Generation / Generation method (GG):** Generations are dropped in the sink area and the source area will increase its generation to balance these generation drops.

Different dispatching assumptions may be considered for TTC calculations such as: single generation/load dispatch, uniform generation/load dispatch, proportional generation/load dispatch, and arbitrary generation/load dispatch. Some other important points to be considered in TTC calculations:

- The system limit is the minimum among thermal, voltage, or stability limits.
- Multiple contingencies could be considered in the calculation if necessary.
- To calculate TTC $A \rightarrow B$, both LG and GG scenarios are used. TTC $A \rightarrow B$ is the lower value between these two scenarios.
- The normal thermal rating of the transmission lines is used in case of normal operation, while emergency rating is used in case of contingencies.

- The system limit isn't necessarily reached on the tie lines between area A and area B, the system limit could be reached on any line or equipment in area A, area B, or outside A and B. Due to this fact, wide area calculation is very important for TTC calculation.

## 5.5 Tracing Load Flow Program Features

TLF is an excellent tool that can run load flow programs in a consecutive manner to calculate TTC. TLF can be used in many different applications besides TTC calculations such as:

- Voltage collapse studies
- Contingency analysis
- Power system behavior under different dispatch conditions
- Impacts of series / shunt compensators on power system

TLF uses the AC load flow technique as the core of its algorithm. TLF attempts to cut down the execution time by systemically (instead of manually) repeating the load flow until hitting system violation. TLF is designed so that its systematic repeating steps reduce execution time by using the previous step's initial conditions rather than starting from the base case initial conditions. Continuation power flow [87],[88] is capable of doing the same, however, it is more suited for voltage collapse studies and not for TTC calculations. The main characteristics of this program (TLF) are:

1. Able to change any generation or load dispatch and calculate TTC based on this new dispatch.
2. TTC can be determined using thermal limits of transmission lines and bus voltage limits.
3. Calculate the load flow solutions under different transmission and generator contingencies.
4. Calculate load flow dependency on the transmission line impedance variations.

5. Completely coded using MATLAB so it is easy to modify to fit any application.
6. Different input data file formats can be used such as IEEE / PTI.
7. Is fast and reliable. TLF uses fast screening to calculate coarse TTC and then can use fine screening to calculate precise TTC.
8. Can be used to calculate TTC area-to-area. The area could have one-bus or multiple buses.
9. Trace the state variables of the power system at different loading conditions.
10. Voltage collapse and steady state stability violation can be tracked and identified.
11. Power loss calculations at different loading conditions.

## 5.6 Tracing Load Flow Algorithm

As shown in Figure 5-1 the TLF algorithm can be summarized as follows:

- Load input data file. TLF can read from PTI / IEEE format.
- Specify the TTC calculation method. Either GG or LG method can be used.
- Determine the source area and the sink area.
- Specify load /generation dispatching scenario.
- Specify the initial contingency set (transmission lines and generations).
- Determine a precision level for which the fast TTC calculations will stop and the precise calculations will start. This number is a percentage from the transmission line thermal limits or bus voltage limits.
- Determine the step size for increasing / decreasing the generation / loads in the sink area. Small steps will lead to increase in the number of iterations for the precise screening calculations. However, if the system is stressed, a small step size is recommended.
- Run the base case load-flow under one of the selected contingencies out of the initial contingency set.
- Start TTC fast screening loop. In each loop step, record the power system state variables (active power, reactive power, bus-voltage, and bus-angle). These variables can be used for further analysis.

- After finishing the fast TTC calculations, switch to the precise calculations. The precise calculations start from the last unconstrained step in the fast screening. The precise screening margin is set equal to the thermal limit or the minimum acceptable voltage.
- Repeat the fast and the precise screening loop for every contingency.
- The TLF report contains a TTC values for each contingency. TLF can also report state variable profiles. For example, the most critical voltage bus profiles, the critical phase angle profiles across the transmission lines.

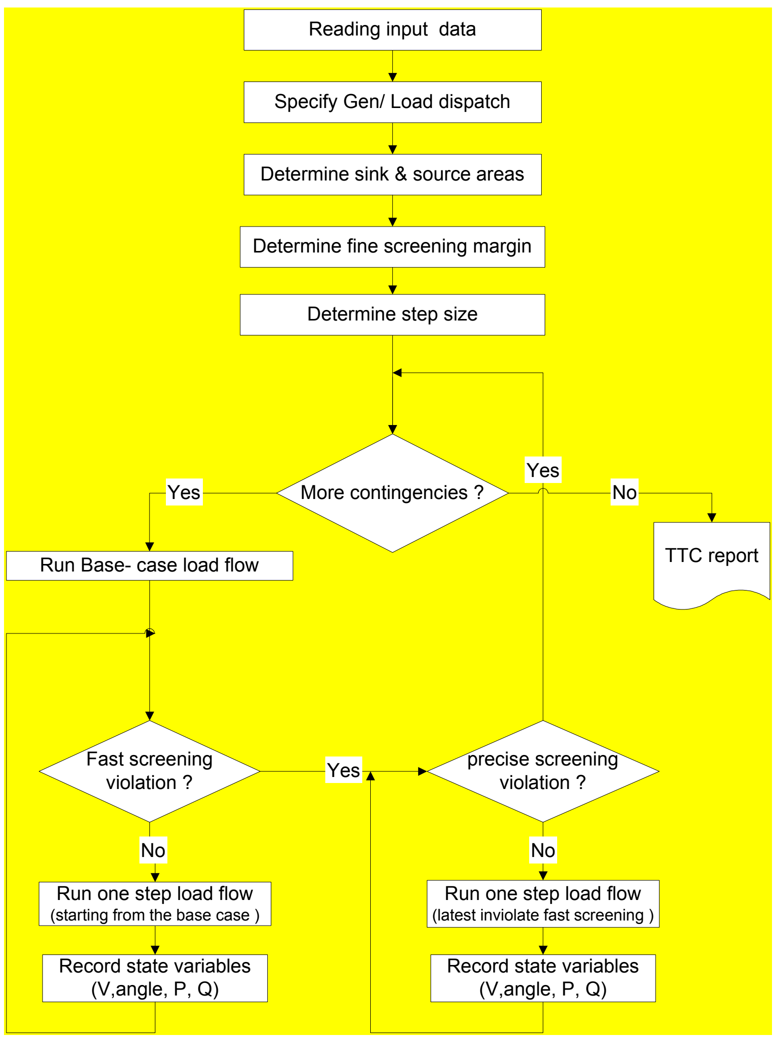


Figure 5-1: TLF program algorithm

## 5.7 System under Study

TLF has been tested for the IEEE 39-bus system (Appendix B) and for the simplified WSCC 179-bus system (Appendix A). The results presented in the next section are for the simplified WSCC 179-bus system. The simplified WSCC system consists of 11 control areas as shown in Figure 5-2. For the sake of simplicity, these control areas are grouped into three main areas, namely North, West, and Central.

North area consists of three control areas:

- Canada equivalent area consists of two machines (G1and G5).
- North-West control area consists of three machines (G8, G13 and G19).
- Montana equivalent area consists of one machine (G42).
- Base case total generation equals to 30308 MW.
- Base case total loads are equal to 27881 MW.
- Number of buses is 42 buses.

West area consists of three control areas:

- PG & E control area consists of four machines (G123, G128, G148, and G154).
- SOCALIF control area consists of five machines (G92, G94, G99, G103 and G111).
- LADWP control area consists of three machines (G165, G171, and G178).
- Base case total loads are equal to 27747 MW.
- Number of buses is 91 buses.

Central area consists of five control areas:

- Idaho equivalent area consists of one machine (G45).
- WAPA UC equivalent area consists of two machines (G63, and G64).
- New-Mexico control area consists of one machine (G66).

- Pace control area consists of three machines (G50, G55, and G61).
- Arizona control area consists of four machines (G70, G73, G81, and G85).
- Base case total generations are equal to 16942 MW.
- Base case total loads are equal to 12330 MW.
- Number of buses is 46 buses.

Both the Central and North areas are exporting power to the West area. Therefore, the most valuable TTC calculations are TTC from $North \rightarrow West$ and from $Centeral \rightarrow West$. The next section will show the results for these calculations under different contingency cases.

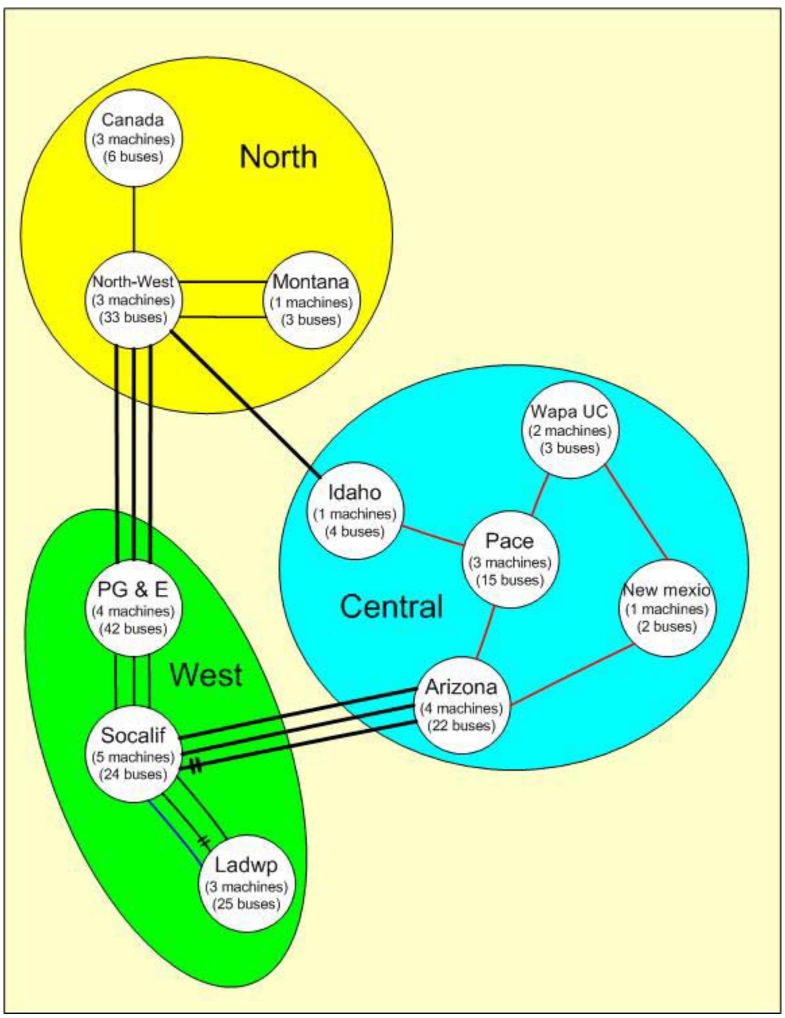


Figure 5-2: Three regions for simplified WSCC 179-bus system

## 5.8 TTC Calculation Results Using TLF

TTC calculation is based on computer simulations for specific operating conditions. This section will show the results of TTC calculations from $Centeral \rightarrow West$ and from $North \rightarrow West$. TTC under different line and generation outages will also be calculated. State variable profiles such as voltage profiles in stable and unstable cases will be used for improved security assessment. Before performing to the TTC calculations, TLF was initialized as follows:

- Load the interconnected system base case.
- GG scenario is the scenario that has been chosen to calculate TTC.
- Proportional generation dispatch for sink/source areas.
- Sink/source combinations have been chosen to be West/Central area and West/North area.
- The precision level has been chosen as 1 MW from the thermal limit. No voltage limit is considered. However, TLF always considers voltage collapse.
- Step size has been chosen to be 5 % from the ratio of the generator capacity to the total generation capacities in this area.

### 5.8.1 TTC Calculation Result from Central to West

Table 5-1 shows TTC under different generator outage conditions in the West area. Refer to Appendix A for details about these generator locations. TTC is calculated based on both normal and emergency thermal ratings. TTC at the normal thermal rating in the case of generator-92 outage is equal to 1595 MW while based on emergency rating equals 1938 MW. This is a typical case that has thermal limit violation controlling the TTC value. Figure 5-3 shows the most critical voltage buses in this case. TTC for the whole system based on a normal rating is equal to the minimum value of TTC in the normal rating column. TTC in this case is equal to 1163 MW. The emergency thermal rating is equal to 1163 MW as well. The result shows that TTC in this case is not due to thermal violation and there should be another violation. Tracing the output state variables will help to show the detailed analysis of this case. Figure 5-4 shows the voltage profile of this case. It is easy to conclude that the violation in this case was voltage collapse. The most critical voltage buses are located in the West area as a direct consequence of the generator outage in that area.

Table 5-1: TTC from $Centeral \rightarrow West$ (generator outage)

| West Generator Outage | TTC Central to West | |
|---|---|---|
| | Normal Thermal Rating (MW) | Emergency Thermal Rating (MW) |
| None | 1545 | |
| 92 | 1595 | 1938 |
| 94 | 1600 | 1939 |
| 99 | 1370 | 1538 |
| 111 | 1163 | 1163 |
| 123 | 1179 | 1404 |
| 148 | 1433 | 1700 |
| 154 | 1324 | 1575 |
| 165 | 1433 | 1522 |
| 171 | 1506 | 1900 |
| 178 | 1458 | 1643 |

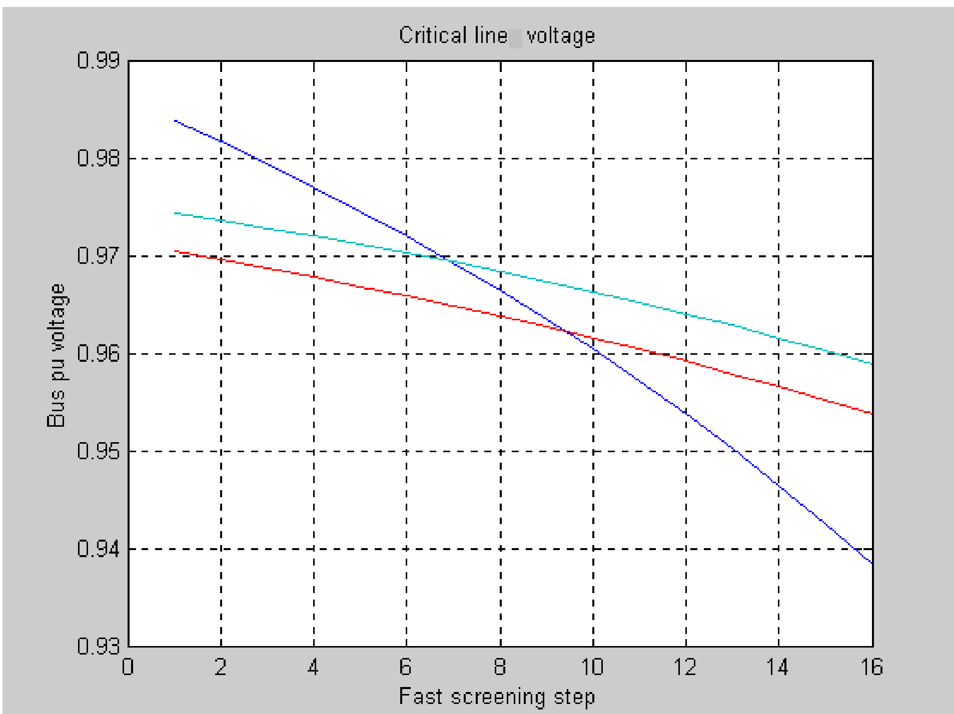


Figure 5-3: Outage of generator 92, no voltage collapse

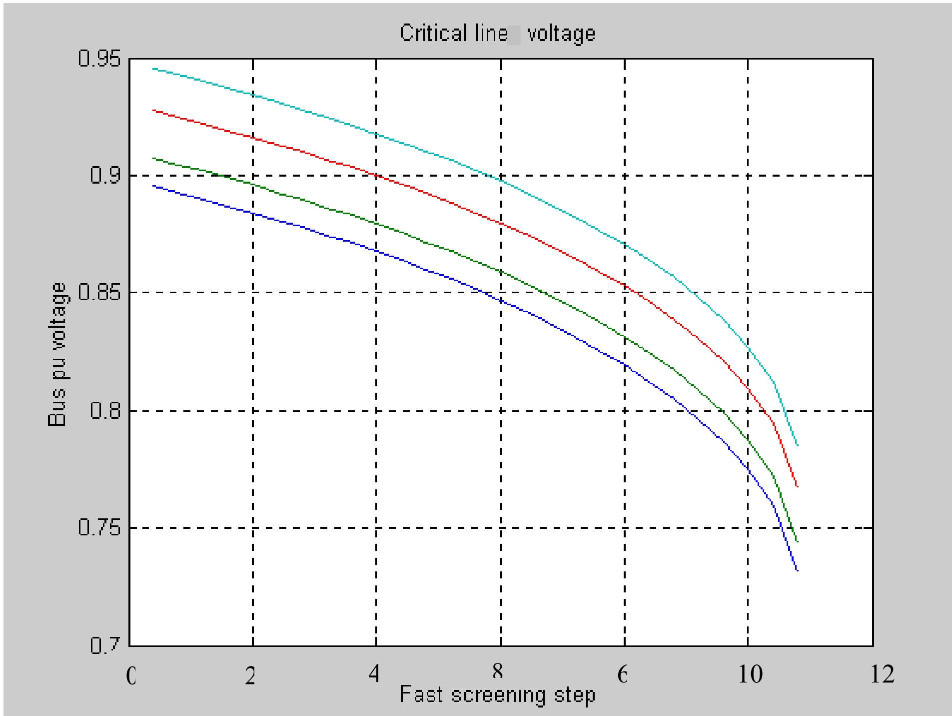


Figure 5-4: Outage of generator 111 leads to voltage collapse

Table 5-2 shows the TTC from $Centeral \rightarrow West$ for different line outages. These transmission lines have been chosen to be distributed in the whole system.

Table 5-2: TTC $Centeral \rightarrow West$ (Line outage)

| Line outage | TTC Central to West | |
|---|---|---|
| | Normal thermal rating (MW) | Emergency thermal rating (MW) |
| None | 1545 | 1945 |
| 47-46 | 1095 | 1290 |
| 87-76 | 1505 | 1795 |
| 62-59 | 1370 | 1477 |
| 82-79 | 1550 | 1855 |
| 30-33 | 1400 | 1695 |
| 30-39 | 230 | 1085 |
| 30-34 | 265 | 1125 |
| 80-91 | 1535 | 1845 |
| 84-90 | 195 | 530 |

From Table 5-2 we can get some details about TTC from $Centeral \rightarrow West$ :

- TTC based on normal thermal rating assuming that the table includes all the possible contingencies is equal to 195 MW. TTC based on emergency rating is 530 MW.
- Line outage in the North area may affect the value of TTC like the case of lines 30-33, 30-39, and 30-34. Some of these lines are key factors for determining the correct value TTC. The status of these lines should be known even if these lines aren't in the two areas involved in these calculations.
- If the North area is represented as an equivalent system. These transmission lines will disappear and the TTC calculations will not be correct. This fact proves that the details of the neighboring system are very important to calculate the correct first contingency TTC.
- An outage in one of the four tie lines between Central and West (80-91) is not so critical because the parallel line will compensate for its absence.

### 5.8.2 TTC Calculation Result from North to West

TTC from the North to the West area is one of the most important calculations because most of the power is coming from Canada to feed the Western system which is characterized by a heavy load profile. As shown in Figure 5-2, the West area is connected to the North area through 3 tie lines and to the Central area through 4 tie lines. These tie lines will be studied as contingency lines in addition to the internal tie lines connecting the three-control areas inside the West area (PG & E, SOCALIF, and LADWP). The typical limit between North and West areas are stability limits. Stability limit in this case is expressed as new thermal limit and replaces the typical thermal limit of the tie lines between North and West.

Normal TTC $North \rightarrow West$ without any contingency is 975 MW while the emergency TTC is 1070 MW as shown in Table 5-3. The first three line outages (89-88, 90-84, and 91-80) in Table 5.3 are the tie lines from West to Central. Any single line contingency within these lines isn't affecting the TTC value very much. The minimum normal TTC in this case is 830 MW and the emergency TTC is 1035 MW. All the emergency TTC values calculated in this case are limited by the voltage collapse as shown in Figure 5-5.

Table 5-3: TTC $North \rightarrow West$ (Line outage)

| Line outage | TTC North to West | |
|---|---|---|
| | Normal thermal Rating (MW) | Emergency thermal Rating (MW) |
| None | 975 | 1070 |
| 89-88 | 830 | 1035 |
| 90-84 | 885 | 1045 |
| 91-80 | 900 | 1045 |
| 136-39 | 60 | 355 |
| 135-34 | 75 | 375 |
| 134-33 | 370 | 685 |
| 113-104 | 980 | 1065 |
| 114-105 | 980 | 1065 |
| 115-106 | 980 | 1065 |
| 156-95 | 900 | 1055 |
| 156-90 | 935 | 1060 |
| 155-112 | 0 | 1025 |
| 95-96 | 975 | 1070 |
| 97-91 | 830 | 1030 |
| 101-109 | 970 | 1065 |

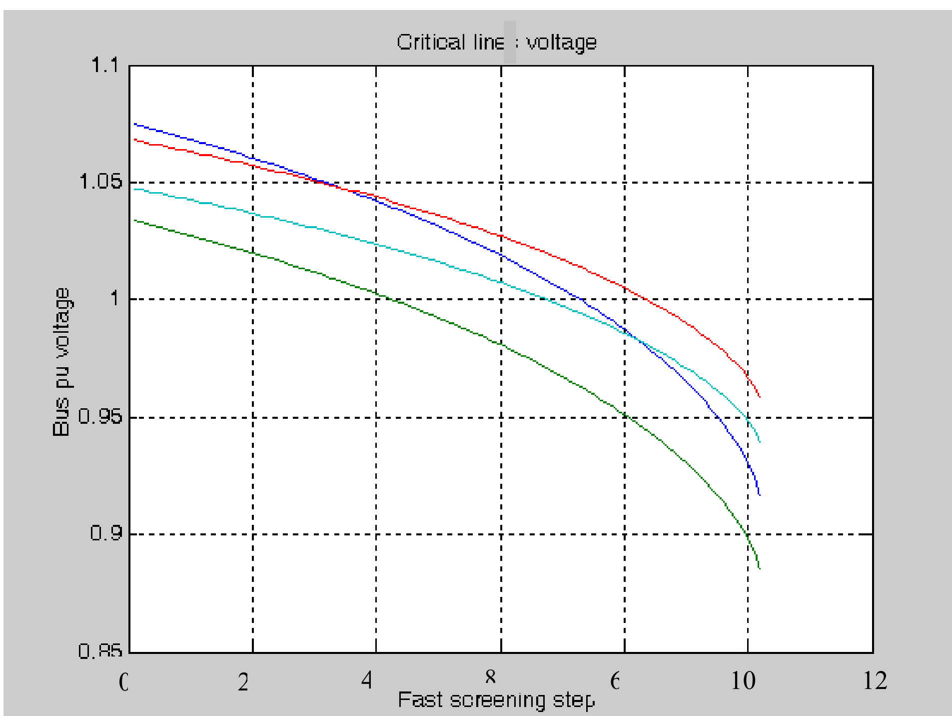


Figure 5-5: Voltage profile for emergency TTC (89-88 line outage)

The three lines (136-39,135-34,and 134-33) in Table 5-3 are tie lines from the North area to the West area. As mentioned before, these tie lines are limited by the stability limit, which is represented as a new thermal limit in the load flow data. The Normal TTC in case of outage of one of these lines is a relatively small number. The minimum TTC in this case is 60 MW with stability limit constraint. In case of Emergency TTC in the same case the min value is 335 MW and in this three-outage contingency case the limit is the stability limit rather than the voltage collapse as in the previous case. TLF helps us to understand this case by providing the voltage profile of the critical bus voltage as shown in Figure 5-6. As is clear in Figure 5.6 this case isn’t a voltage collapse and the limit in this case is the stability limit that is represented as the thermal limit in the load flow file.

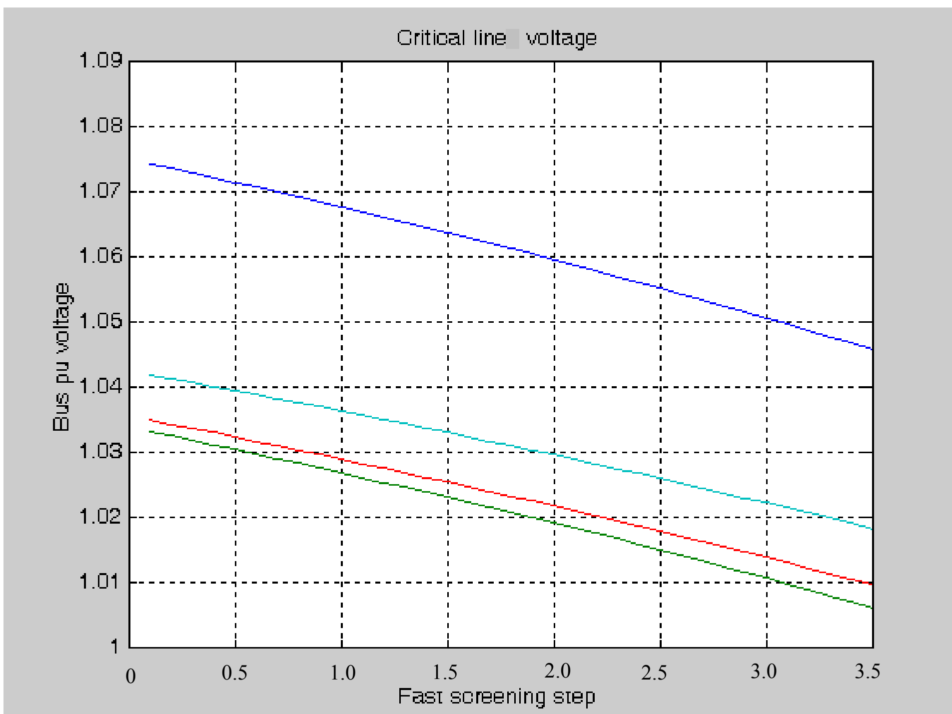


Figure 5-6: Voltage profile for emergency TTC (136-39 line outage)

The next six lines are the internal transmission lines connecting different control areas inside the West area. The outage of one of these lines (155-112) tends to reduce the TTC at normal thermal rating to zero. The emergency TTC in this case is not zero but it is equal to 1025 MW. The last three outages in Table 5-3 are different lines inside the West area; they don’t have too much effect on the TTC calculation.

From Table 5-3, the most critical line considering normal thermal rating is one of the lines inside the West area and not one of the tie lines. Another observation is that the stability limit in some cases is very important and it is the factor limiting the TTC. TLF handles this issue by considering it as a new thermal limit; however, this new thermal limit should be calculated from transit stability studies.

To study the effect of the generator outage on the TTC calculations from North to West, Table 5-4summarizes the result of some generator outages. The generator near the outaged generator will compensate for that generator loss; the slack bus will not contribute to this outage. From Table 5-4, the entire TTC emergency rating is limited by the voltage collapse (Figure 5-7); however, all other TTC are limited by the stability limit (Figure 5-8) mentioned previously. Another important fact to note is that not all generation losses affect the TTC calculations as the last 4 generators in Table 5-4.

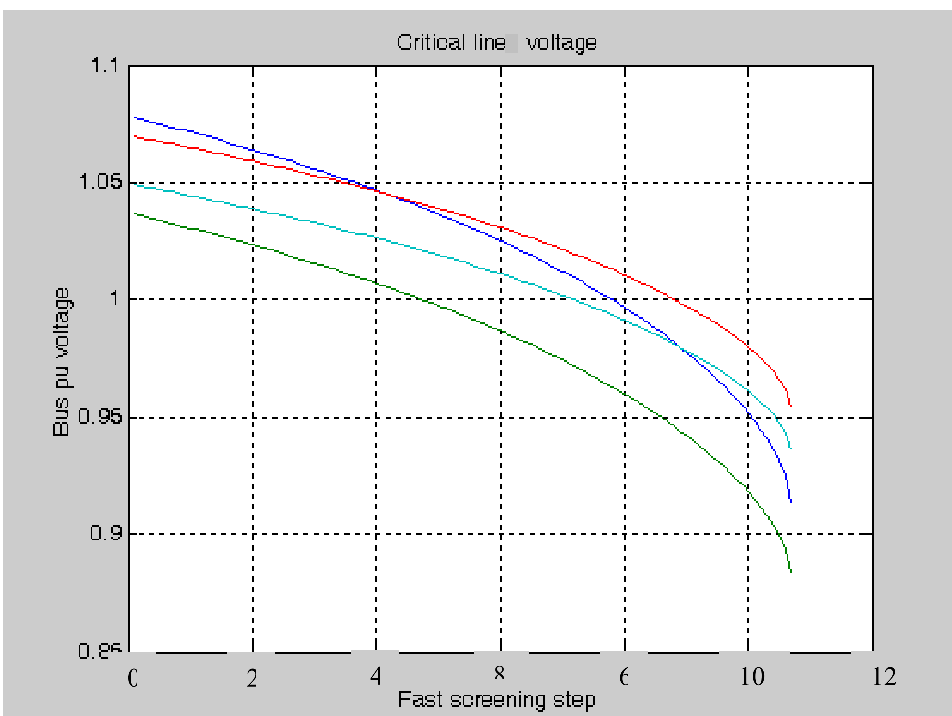


Figure 5-7: Voltage profile for emergency TTC (111 generator outage)

Table 5-4: TTC from $North \rightarrow West$ (generator outage)

| West Generator Outage | TTC North to West | |
|---|---|---|
| | Normal thermal Rating (MW) | Emergency thermal Rating (MW) |
| None | 975 | 1070 |
| 92 | 1004 | 1074 |
| 94 | 1006 | 1077 |
| 99 | 961 | 1064 |
| 111 | 941 | 1069 |
| 123 | 1028 | 1033 |
| 148 | 956 | 1091 |
| 154 | 975 | 1033 |
| 165 | 975 | 1070 |
| 171 | 975 | 1070 |
| 178 | 975 | 1070 |

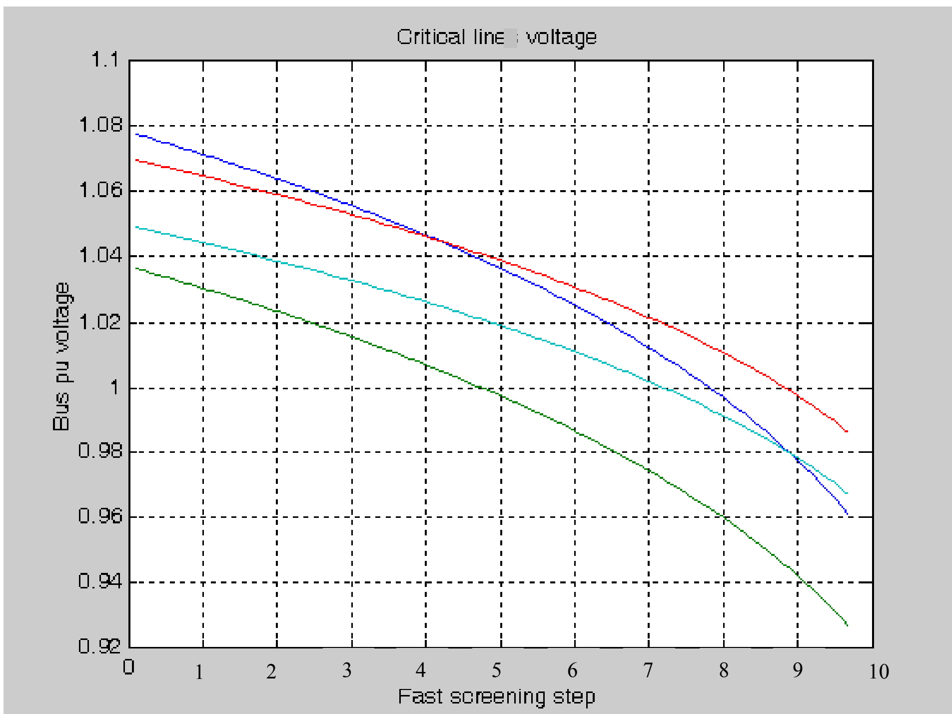


Figure 5-8: Voltage profile for normal TTC (111 generator outage)

### 5.8.3 Power Loss Calculations

TLF can help to calculate the transaction loss inside and outside the sink area. From the definition of TTC "*The amount of electric power that can be transferred over the interconnected transmission*", this amount can be calculated from the view point of the load change (TTC-load), tie line flow change (TTC-tie-line), or generation change (TTC-gen). The difference among these values is due to system loss. If the loss is neglected the three values should be identical. TLF can calculate TTC $_{North \rightarrow West}$ from all points of view as shown in Table 5-5.

Figure 5-9 shows a graphical representation of the previous TTC calculations. The loss inside and outside the West area can be calculated from Figure 5-9. The loss inside the West area is the difference between the TTC-tie lines and the TTC- load; the average loss in this case is 130 MW. The loss outside the West area is the difference between the TT-Gen and the TTC- tie line; the average in this case is 165 MW. The losses in both cases increase linearly until hitting voltage collapse and then linearly decrease after that as shown in Figure 5-10.

Table 5-5: TTC from generation, tie lines, and load point of view

| **TTC-Gen** | **TTC-load** | **TTC-Tie-line** |
|---|---|---|
| 1077.33 | 839 | 952.99 |
| 1111.49 | 866 | 982.84 |
| 1146.43 | 893.5 | 1013.26 |
| 1181.47 | 921 | 1043.67 |
| 1215.9 | 948 | 1073.45 |
| 1251.9 | 976 | 1104.39 |
| 1287.4 | 1003.5 | 1134.73 |
| 1322.57 | 1030.5 | 1164.53 |
| 1358.99 | 1058 | 1194.97 |
| 1396.4 | 1085.5 | 1225.48 |
| 1436.02 | 1111.5 | 1254.79 |
| 1442.23 | 1119.5 | 1261.39 |
| 1449.04 | 1127.5 | 1268.09 |
| 1453.59 | 1135 | 1273.98 |
| 1458.66 | 1142.5 | 1279.98 |
| 1464.11 | 1150 | 1286.04 |
| 1469.8 | 1157.5 | 1292.14 |
| 1473.83 | 1165 | 1297.55 |
| 1479.98 | 1172 | 1303.75 |
| 1484.54 | 1179 | 1309.27 |
| 1489.42 | 1186 | 1314.84 |
| 1494.55 | 1193 | 1320.46 |
| 1500.06 | 1200 | 1326.14 |
| 1503.74 | 1207 | 1331.13 |
| 1509.46 | 1213.5 | 1336.86 |
| 1513.99 | 1220 | 1341.96 |
| 1518.34 | 1226.5 | 1347.05 |
| 1523.12 | 1233 | 1352.2 |

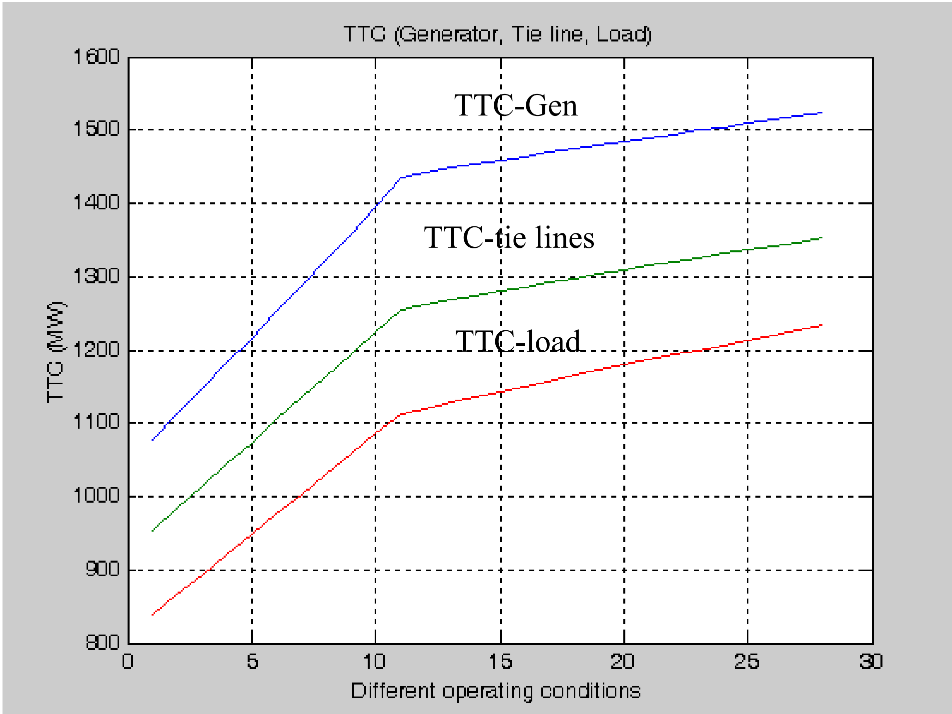


Figure 5-9: TTC from generation, tie lines, and load point of view

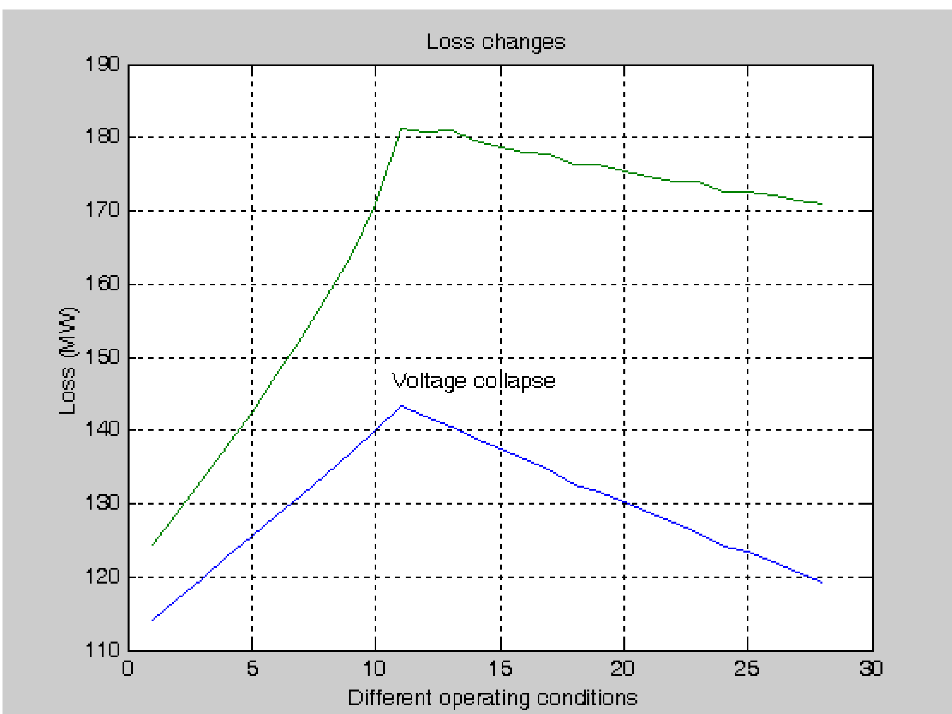


Figure 5-10: Loss in West and outside West area at different operating conditions

# Chapter 6  Real Time Updating for Total Transfer Capability

## 6.1 General

This chapter presents a new technique to update the Total Transfer Capability (TTC) using real-time system measurements. The traditional technique for calculating TTC is using computer simulations with the forecasted data while all the calculations are performed off-line in the planning stage as explained in Chapter 5. This chapter proposes correction look-up tables prepared off-line. These tables can be used to update the TTC values based on real time measurements. This chapter also presents the TTC calculation method based on linear sensitivity analysis technique.

## 6.2 Table Updating Technique

TTC calculations are based on computer simulations for specific operating conditions. Each simulation is assumed to be a snapshot of the interconnected network state under a set of scenarios. These simulations are performed "OFF LINE" based on these scenarios. These scenarios include:

- Realistic generator dispatch
- Forecasted load demands
- Maintenance schedules
- Scheduled power transfer
- Realistic contingencies

All these factors are forecasted values and could vary in real time. As a result, the TTC in real time will be different from the calculated one. The proposed method will address the uncertainty of the calculation of the TTC coming from the off-line simulations of the forecasted projection factors. This method proposes a new technique to update the TTC values based on real time measurements using off-line lookup tables. The key point in the lookup tables is to measure the power flow in a critical line in the system and use this value as a primary search key in the lookup tables to know the new TTC. The critical line in the system is the first line in the system that will hit its limit and which will control the TTC value. The advantage of this method is the accuracy of the calculation because the tables were based on AC analysis which permits fast and accurate updating of the TTC values.

The lookup table should be created using the detailed overall state of the system in order to have good results. A wide area representation of the power system should be available to the system operator. This wide area picture can be created using state-estimation outputs shared among different utilities as proposed in Chapter 4[89]. In general, sharing information among utilities will help to establish a robust deregulated power system network.

## 6.3 Linear Sensitivity Analysis Technique

The AC computer simulation used for calculating the TTC is an accurate method. However, it is time consuming because hundreds of scenarios should be considered, particularly if contingency cases are considered. Linear Sensitivity Analysis (LSA) is an incremental solution over an exact pre-solved case. LSA bypasses the complexity of AC simulation under the same assumptions of DC load flow (Q is neglected, loss is neglected, and all bus voltage magnitudes are unity). An iterative linear estimator [90],[91] is proposed to overcome its limitation and to improve the sensitivity analysis calculation.

LSA factors simply show the change of the active power in line flows due to the generation change in the network. These factors are constant as long as the network topology is fixed. The sensitivity factors used throughout this chapter are the Generator Shift Sensitivity Factors (gssf) [78]. The basic definition of gssf is as follow:

$$gssf_{li} = \frac{\Delta Pf_l}{\Delta P_i} \qquad (6.1)$$

Where

$l$ ………….. Line number

$i$ ………….. Bus number

$\Delta Pf_l$ ……… Change in the active power flow in the transmission line $l$ when the generation at bus $i$ is changed by $\Delta P_i$. This change is compensated by the generation at the slack bus.

$\Delta P_i$ ……….. Change of the generation at bus $i$.

Equation ( 6.1 ) shows the basic definition for gssf. Because gssf is a linear estimator; superposition principle can handle the effect of simultaneous changes on multiple generators and the simultaneous compensation from multi-slacks. Based on this fact, equation (3) defines a general form of gssf (Ggssf):

$$Ggssf_{lb,S} = \frac{\Delta Pf_l}{\Delta P_b} \qquad (6.2)$$

Where

$Ggssf_{lb,S}$ …... General gssf of line $l$ when the generation/load at buses $b$ are changed by $\Delta P_b$ and are compensated by the generation at buses $s$.

$l$ ………….. Line number

$b$ ………….. Set of the buses at which the generation or the load is changed.

$s$ ………….. Set of generators bus will compensate for the change $\Delta P_b$.

$\Delta Pf_l$ ……… Change in the active power flow in the transmission line $l$ when the generation/load at buses $b$ are changed by $\Delta P_b$ and are compensated by the generation at buses $s$.

$\Delta P_b$ .......... Change of the generation/load at buses $b$ .

This generalized form of gssf is helpful in calculating TTC between two areas. Let us take the example of TTC $A \rightarrow B$, the generators in area A make up the set of buses $s$, while the generators/load in area B are in the set $b$. It is clear that Ggssf is the function of generator dispatch in area A and B. Based on this Ggssf, equation (6.3) is used to calculate the TTC $A \rightarrow B$.

$$TTC\,(A \rightarrow B) = \min\{TTC\ of\ each\ line\}$$
$$= \min\left\{\frac{thermal\ capacity\ of\ each\ line - power\ flow\ of\ this\ line}{Ggssf\,(A \rightarrow B)}\right\} \qquad (6.4)$$

It is clear from equation (6.5) that LSA calculation of TTC ( $A \rightarrow B$ ) depends on three parameters:

- Thermal Capacity of each line
- Ggssf ( $A \rightarrow B$ )
- Power flow in the lines

The first two factors are not functions of the operating point as long as the generation dispatch for calculating Ggssf is known. The third factor "power flow in the lines" is a function of the operating point. However, any scenario that can produce the same flow in the critical line will have the same TTC under this dispatch. This fact is very important in the proposed new method.

Based on LSA, knowing the thermal capacity of each line, the generalized gssf $A \rightarrow B$ (Ggssf ( $A \rightarrow B$ )), and the power flow in each line (for pre-solved case), TTC $A \rightarrow B$ can be calculated very easily. The advantages of this method are:

- Fast method to calculate TTC, no iteration is needed.

- Fast screening to know the critical lines for a certain operating point.
- TTC can be calculated for any generator dispatch in area A.
- TTC can be used for any generation drop/load increase dispatch in area B.
- This method can be used to calculate the optimal dispatch in area A for maximizing the TTC $A \to B$.

However, there are some disadvantages of using this method:

- It neglects the effect of reactive power in the network, which in some cases may be a dominant factor and should not be neglected.
- It neglects the power loss in the network.

Despite these disadvantages, the LSA method is very fast, and it can give a global picture for multi-scenarios of transactions quickly and with acceptable accuracy. It can also serve as a fast screening methodology to apply AC analysis if more accurate results are needed. The LSA method can also help to determine the generation dispatch for maximizing the TTC for a certain area as will be explained in the next section.

## 6.4 Maximum TTC Dispatch

Dispatching the generators in the interconnected network is accomplished with two techniques:

- Economic dispatch [92],[93]
- Optimal Power flow dispatch (OPF) [94],[95]

The economic dispatch technique is simply an optimization problem, which holds the total generation to be equal to the total load plus the loss under certain constraint. The constraint is minimizing the generation cost. OPF is a more general optimization problem. The objective function may include minimizing the generation cost, minimizing the electrical loss in the transmission system, or some other objective. The OPF may include in addition to the generation load matching constraint some other constraints such as: reactive power, voltage, and security constraint. Using the same principle $Ggssf(A \rightarrow B)$ for fast screening, it is possible to determine the optimal dispatch for generators in area A to maximize the TTC $A \rightarrow B$ without hitting any constraints.

Maximum TTC dispatch is an OPF problem with the objective function being only the safe operation of the power system (such as voltage, stability, and thermal limits) and maximizing the flow from one area to another. Flexible AC Transmission Systems (FACTS) can be used to increase the TTC [96] as well. Maximum TTC dispatch is a very important concept in the deregulated market and it can be considered as a third optimization approach in addition to the economic dispatch and the OPF. The importance of the maximum TTC dispatch relies on two main points:

- Commercial importance
- Power system stability importance

Let's take the example of TTC $A \rightarrow B$, the generators of area A are dispatched according to economic constraints. Let us assume the following scenario, an energy deficiency in area B and more power needed from area A which is higher than the TTC calculated based on economic dispatch. Under this scenario the economic dispatch is not useful because the two areas can be separated. The best choice is the Maximum TTC dispatch from a power system stability point of view. Let's assume another scenario, the price of the energy in area B jumped to a high level. In such cases maximizing the power from area A to B will make a lot of sense, from a financial point of view, and again Maximum TTC dispatch is the best choice in this scenario.

## 6.5 Real-Time Updating Methodology

As we mentioned before, the calculation of the TTC is performed off-line based on forecasted data using AC analysis. This TTC is updated frequently in the OASIS web site; however, the updated values are based on off-line simulation results. The ATC handle this uncertainty in the forecasted data by tuning the TRM and CBM margins. By increasing these margins the system operator will increase security because the system will be far from instability. However, the rest of the power market players( generator owners) will try to push the ATC limit higher in order to sell more energy. The ATC limit is under pressure from two opposite sides, operators need to reduce it to accommodate the system uncertainty, and the market likes to raise it to obtain a higher profit.

One of the solutions to this paradox is trying to minimize the sources of uncertainties. One way to accomplish this is to up-date the TTC values based on real time measurements. The direct way to achieve this goal is to calculate the TTC in real time; however, this goal is very hard to accomplish because it is very time consuming. For this reason the TTC is calculated at the planning stage with forecasted data. The second method that can be used to achieve that goal is the proposed method that can be summarized as follows:

- Create off-line look up tables.
- These tables will be available to the system operator for each forecasted operating point.
- Each table will have a set of operating points created by assuming small perturbation from the forecasted operating point.
- The value of the monitored flow at the critical line will be used as a search key through the table to pick the correct TTC value.

As we mentioned in section 6.3, TTC is a function of three factors. The first two of these factors are thermal limit of the transmission lines and the generalized gssf. These two factors are not functions of the operating condition. The third factor is the transmission line flow that relies on the operating point. Based on LSA *TTC is not a function of the scenario producing this transmission line flow as long as the critical line remains the same.*

To create this table the forecasted operating point should be known. Starting from this point the table begins to be built up. TTC and the flow at the critical transmission line are calculated at the forecasted operating point. The results are tabulated as shown in Table 6-1.

Table 6-1: First step in creating off-line correction table

| Critical line (CL) | Pflow at the CL | TTC |
|---|---|---|
| | | |
| | | |
| Line1 | P_Line1 | TTC_1 |
| | | |
| | | |
| | | |

If the real time operating point matches the forecasted operating point, no correction will be needed. However, if the real time operating point is different from the forecasted point, it will be most likely around the forecasted point with small discrepancy. The rest of the table will be filled with the results of off-line simulations at different operating points in the neighborhood of the forecasted operating point. All TTC and the flow of the critical line of these operating points will be calculated using AC computer simulations. Table 6-2 shows part of these data.

Table 6-2: Off-line correction table

| Critical line (CL) | Pflow at the CL | TTC |
|---|---|---|
| . | . | . |
| . | . | . |
| Line2 | P3_line3 | TTC_3 |
| Line1 | P2_line1 | TTC_2 |
| Line1 | P1_Line1 | TTC_1 |
| Line1 | P4_line1 | TTC_4 |
| Line1 | P5_line1 | TTC_5 |
| . | . | . |
| . | . | |

These tables will be available to the operator for each forecasted operating point. Let us assume that the operator handles 24 forecasted operating points per day (one for each hour). Therefore, he should have 24 tables, each table associated with one of these points. However, in the next 24 hours if the forecasted operating points are not changing too much from the previous day, the same table can be used again. The proposed table can be used for the same hourly forecasted operating point each day as long as the load and the generation dispatch aren't changing dramatically. In other words, the correction table should be updated with a new table when the forecasted load profile or generation dispatch changes completely from the previous day. For the simplified system shown in Figure 6-1 and based on the assumption that the TTC is updated each hour, the number of tables for TTC correction $A \rightarrow B$ is 24 tables. These tables should be updated seasonally with the changing of the load curves. The total number of tables needed for all the combinations among the three areas is 144 tables seasonally.

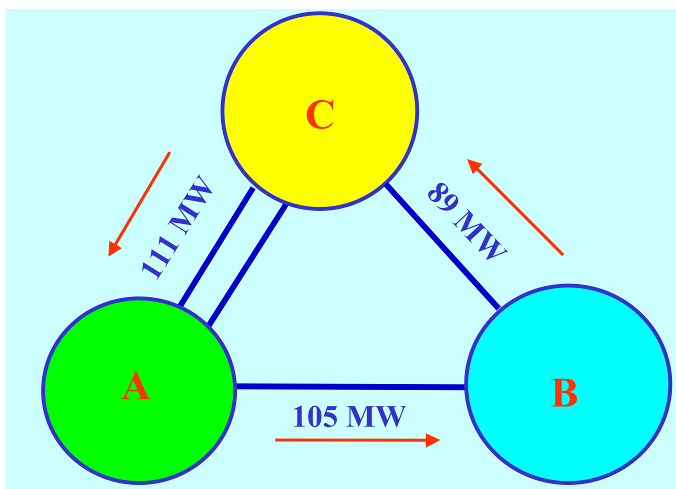

Figure 6-1: Simplified IEEE 39-bus system

Using these tables is an easy job. The operator needs to read the real time flow at the critical line and use it as the primary search key to find the correct TTC value corresponding to this flow from the table. The corrected TTC could be greater/lower than the forecasted one. In case the TTC becomes higher, the market will like this result because it will create the opportunity for more energy trading. However, if it is lower than the forecasted TTC, it is better from the stability point of view because the forecasted TTC could lead the system to instability if the difference is too high. A complete numerical example for the off-line correction table for the IEEE 39-bus system and simplified WSCC 179-bus system will be shown in section 6.7.

## 6.6 System Under Study

The proposed method is tested using the IEEE 39-bus system (Figure 6-2) and simplified WSCC 179-bus system explained in section 5.7 (Figure 5-2). The Simplified WSCC system introduced in Chapter 5 is the same system used in this chapter with the same areas. For the sake of simplicity the IEEE 39-bus system is divided into three generic areas as the simplified WSCC system:

- Area A has three generators 31,32,and 39.
- Area B has four generators 33,34,35,and 36.
- Area C has three generators 30,37,and 38.

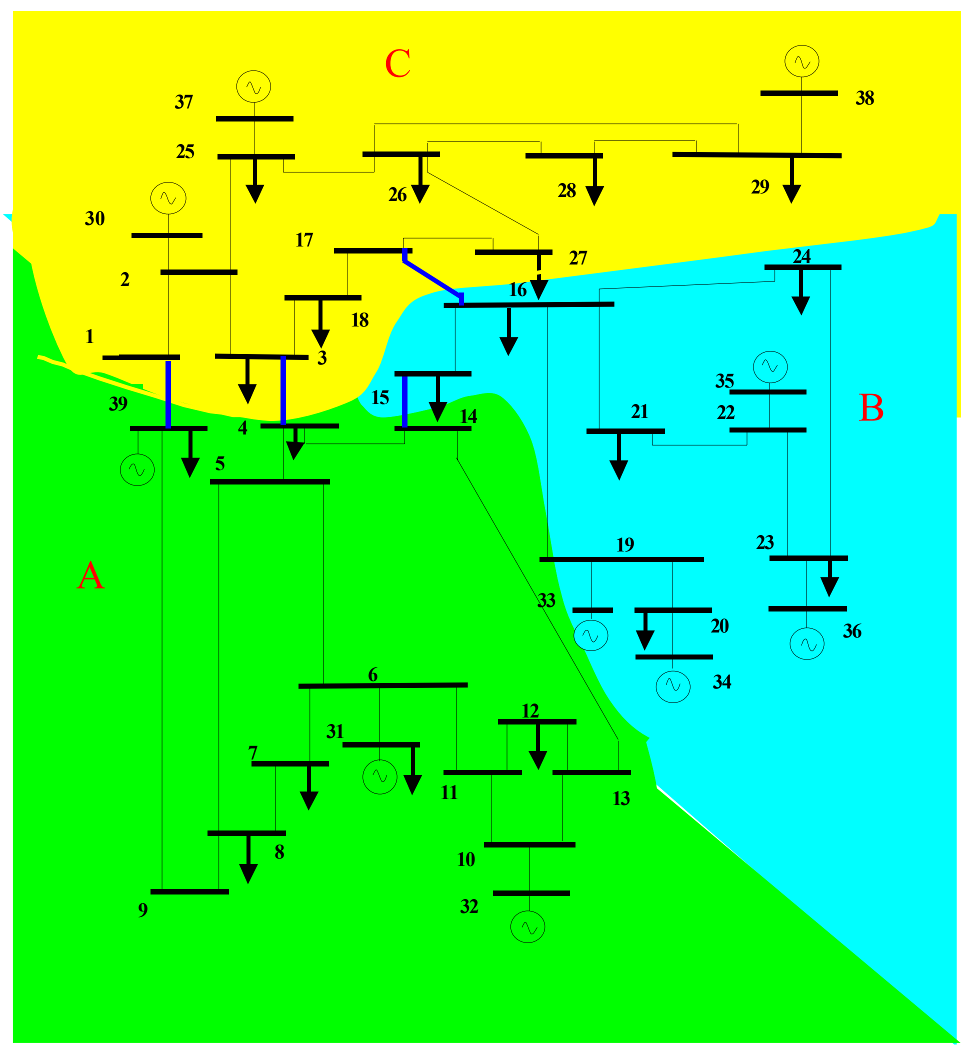


Figure 6-2: IEEE 39-bus system

It is clear from Figure 6-1 that the system has four tie lines connecting these areas. The details of these tie lines follow:

- Two tie lines $A \rightarrow C$, one tie line between bus 1, bus 39, and the other one between bus 3 and bus 4.
- One tie line $A \rightarrow B$, between bus 14 and bus 15.
- One tie line $B \rightarrow C$, between bus 16, and bus 17.

## 6.7 System Simulation Result

The results which will be explained in this section can be grouped into two main areas:

- Results of LSA technique
- Results of the off-line correction table

Despite the limitation of the linear sensitivity analysis technique, the results are very useful in giving a global picture of the whole system and it is also useful as a fast screening technique before using the AC simulations. LSA results are close to the AC simulation results especially when the reactive power is not a dominant factor in the thermal limit and in the voltage stability limit.

### 6.7.1 Result of LSA Technique for 39-bus system

Maximum TTC dispatch results using Ggssf is shown in Table 6-3. In this case TTC $C \rightarrow B$ is calculated using different generation dispatch in area C and uniform generation drop in area B (GG scenario). Thermal limit is the only constraint considered in this case. It is clear from the table that the generator dispatches that produce maximum TTC is 20 % for generator 30, 20% for generator 37, and 60% for generator 38. The maximum TTC in this case is 1340.93 MW. Another observation is that the critical lines are either line number 42 or line number 3 which corresponds to line between bus 26 and bus 27, bus 2 and bus 3 respectively. The critical line in case of maximum TTC is line 42.

Table 6-3: TTC calculated at different generator dispatch in area C (uniform generation drop in area B)

| G30 (%) | G37 (%) | G38 (%) | CL-G | TTC-G (MW) |
|---|---|---|---|---|
| 0 | 0 | 100 | 42 | 1050.78 |
| 0 | 20 | 80 | 42 | 1161.7 |
| 0 | 40 | 60 | 42 | 1298.8 |
| 0 | 60 | 40 | 3 | 1233.83 |
| 0 | 80 | 20 | 3 | 1097.83 |
| 0 | 100 | 0 | 3 | 988.84 |
| 20 | 0 | 80 | 42 | 1195.29 |
| 20 | 20 | 60 | 42 | 1340.93 |
| 20 | 40 | 40 | 3 | 1194.44 |
| 20 | 60 | 20 | 3 | 1066.53 |
| 20 | 80 | 0 | 3 | 963.37 |
| 40 | 0 | 60 | 3 | 1309.68 |
| 40 | 20 | 40 | 3 | 1157.48 |
| 40 | 40 | 20 | 3 | 1036.97 |
| 40 | 60 | 0 | 3 | 939.19 |
| 60 | 0 | 40 | 3 | 1122.74 |
| 60 | 20 | 20 | 3 | 1009 |
| 60 | 40 | 0 | 3 | 916.18 |
| 80 | 0 | 20 | 3 | 982.5 |
| 80 | 20 | 0 | 3 | 894.28 |
| 100 | 0 | 0 | 3 | 873.4 |

Table 6-4 shows the TTC calculations $C \rightarrow B$ using different generation dispatch in area C and uniform load increase in area B (LG scenario). It is clear that the maximum TTC occurs at the same generation dispatch for GG and LG scenario; however, TTC in LG scenario (1564.93 MW) is higher than the GG scenario (1340.93 MW). The critical line in LG scenario is line number 3 while in GG scenario is line number 42. In terms of selecting one TTC out of these two values (1340.93 MW, 1564.93 MW), the smallest value will be used as the system TTC for this dispatch.

After obtaining the overall picture of the system using the LSA technique, if the system operator is still interested in studying TTC for specific dispatch with high accuracy, the AC study can be used to obtain these accurate results using the TLF program explained in Chapter 5. All possible critical lines between two areas are exposed easily using the LSA approach. From the previous tables, the critical line set between area C and area B is (3 and 42). Due to the small size of the critical set the look up tables can simply be used.

Table 6-4: TTC calculated at different generator dispatch in area C (uniform load increase in area B)

| G30 (%) | G37 (%) | G38 (%) | CL-L | TTC-L (MW) |
|---|---|---|---|---|
| 0 | 0 | 100 | 42 | 1277.49 |
| 0 | 20 | 80 | 42 | 1445.25 |
| 0 | 40 | 60 | 4 | 1387.3 |
| 0 | 60 | 40 | 4 | 1250.97 |
| 0 | 80 | 20 | 4 | 1139.04 |
| 0 | 100 | 0 | 4 | 1045.49 |
| 20 | 0 | 80 | 42 | 1497.61 |
| 20 | 20 | 60 | 3 | 1564.93 |
| 20 | 40 | 40 | 3 | 1352.43 |
| 20 | 60 | 20 | 3 | 1190.75 |
| 20 | 80 | 0 | 3 | 1063.59 |
| 40 | 0 | 60 | 3 | 1502.09 |
| 40 | 20 | 40 | 3 | 1305.24 |
| 40 | 40 | 20 | 3 | 1154.01 |
| 40 | 60 | 0 | 3 | 1034.19 |
| 60 | 0 | 40 | 3 | 1261.24 |
| 60 | 20 | 20 | 3 | 1119.48 |
| 60 | 40 | 0 | 3 | 1006.36 |
| 80 | 0 | 20 | 3 | 1086.95 |
| 80 | 20 | 0 | 3 | 980 |
| 100 | 0 | 0 | 3 | 954.98 |

### 6.7.2 Result of LSA Technique for the Simplified WSCC 179-bus system

LSA calculations are also tested for the simplified WSCC 179- bus system introduced in Chapter 5 (Figure 5-2). The calculations will focus on the maximum generation dispatch from the Central area to the West area using the two possible scenarios defined before: GG and LG scenarios. TTC can be calculated using GG scenario (TTC-G) by changing the generation dispatch in the Central area that has 11 generators and proportionally decreasing the generation in the West area. The LG scenario can also be applied to calculate the TTC-L.

Table 6-5 shows the result of different generator dispatches in the Central area. This table only shows the result of a dispatching step of 100% just to reduce the size of the table. However, a small dispatching step (20 %) is also used. From Table 6-5, the maximum TTC of 2866 MW can be obtained if generator 58 is the only generator contributing to compensate for the load increase in the Central area, even with a small dispatching step (20 %), the maximum generation dispatch is still the same. Another important observation is that the TTC-G is nearly equal to/ less than the TTC-L. For this reason, GG scenario is the most appropriate scenario for TTC calculations in this case, because TTC should be equal to the smallest value between TTC-G and TTC-L.

The critical line set is still limited number of lines. In the case of the 100% dispatching step shown in Table 6-5, this set consists of four transmission lines (14,19,82,195). While for the 20% dispatching step, the new set consists of five transmission lines, the old set and transmission line 167. Knowing these critical lines will assist in building the lookup table for simplified WSCC system.

Table 6-5: TTC calculated at different generator dispatch in Central area

| **G45** | **G50** | **G55** | **G61** | **G63** | **G64** | **G66** | **G70** | **G37** | **G81** | **G58** | **CL-G** | **TTC-G** | **CL-L** | **TTC-L** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 82 | 721.25 | 82 | 721.77 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 0 | 19 | 945.67 | 19 | 945.19 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 19 | 945.67 | 19 | 945.19 |
| 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 19 | 953.54 | 19 | 953.04 |
| 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 82 | 995.2 | 82 | 996.15 |
| 0 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 82 | 1138.44 | 82 | 1139.68 |
| 0 | 0 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 19 | 1152.51 | 19 | 1151.76 |
| 0 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 1152.51 | 19 | 1151.76 |
| 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 82 | 1167.76 | 82 | 1169.06 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 195 | 2115.87 | 195 | 2174.63 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 14 | 2718.6 | 14 | 2866.88 |

### 6.7.3 Off- Line Correction Table for 39-bus system

The off-line correction table will handle the limitation of LSA, and it will give the operator a useful tool to correct the TTC based on real time measurements. Table 6-6 shows a numerical example of this table for the IEEE 39-bus system.

Table 6-6: Off-line correction table for a single operating point Using actual load flow

| Critical line (CL) | Pflow at the CL | TTC |
|---|---|---|
| 3 | 545 | 915 |
| 3 | 525 | 955 |
| 3 | 505 | 996 |
| 3 | 485 | 1037 |
| 3 | 465 | 1077 |
| 3 | 445 | 1113 |
| 3 | 425 | 1155 |
| 3 | 405 | 1198 |
| 3 | 385 | 1235 |
| 3 | 365 | 1275 |
| 3 | 345 | 1325 |

By monitoring the flow at critical line 3, the corrected TTC can be picked from the table and can be updated. The TTC calculated from the table is slightly different from the TTC calculated from the LSA because in this case the reactive power has little influence on the transmission line overloading. However, this is not always true. The effect of the reactive power in some other power systems cannot be neglected or predicted in most of the cases. In this case the importance of the lookup table generated by running actual load flow becomes very clear. Table 6-7 shows the LSA for the same loading effect in Table 6-6 under the same dispatch scenario. Figure 6-3 shows graphical representation for both tables.

Table 6-7: Off-line correction table for a single operating point Using LSA

| Critical line (CL) | Pflow at the CL | TTC |
|---|---|---|
| 3 | 545 | 927 |
| 3 | 525 | 967 |
| 3 | 505 | 1008 |
| 3 | 485 | 1048 |
| 3 | 465 | 1090 |
| 3 | 445 | 1130 |
| 3 | 425 | 1171 |
| 3 | 405 | 1212 |
| 3 | 385 | 1252 |
| 3 | 365 | 1293 |
| 3 | 345 | 1334 |

### 6.7.4 Off- Line Correction Table for the Simplified WSCC System

The off-line correction table for the WSCC system is shown in Table 6-8. This table is calculated the same way as for the 39-bus system. By monitoring the flow at the critical line (line 82) TTC can be updated. As we mentioned before, the correction tables try to accommodate for the limitations of the LSA method by running AC analysis. The basic idea behind the correction table is that TTC is limited by the thermal limit of the transmission lines. If the TTC is limited by another system violation like voltage collapse, the correction table cannot be used as shown in the last 8 rows in Table 6-8.

LSA calculation for the same dispatching scenario is shown also in the last column in Table 6-8. As long as the thermal limit is the controlling limit for TTC calculations, LSA results are consistent with the AC results; the only difference between them is the loss and the reactive power effects. The difference will increase dramatically after the system hits the voltage collapse limit because LSA only considered the thermal limit as violation; however, the AC method considers the voltage limit as well. Figure 6-4 shows graphical representation for both AC and LSA method.

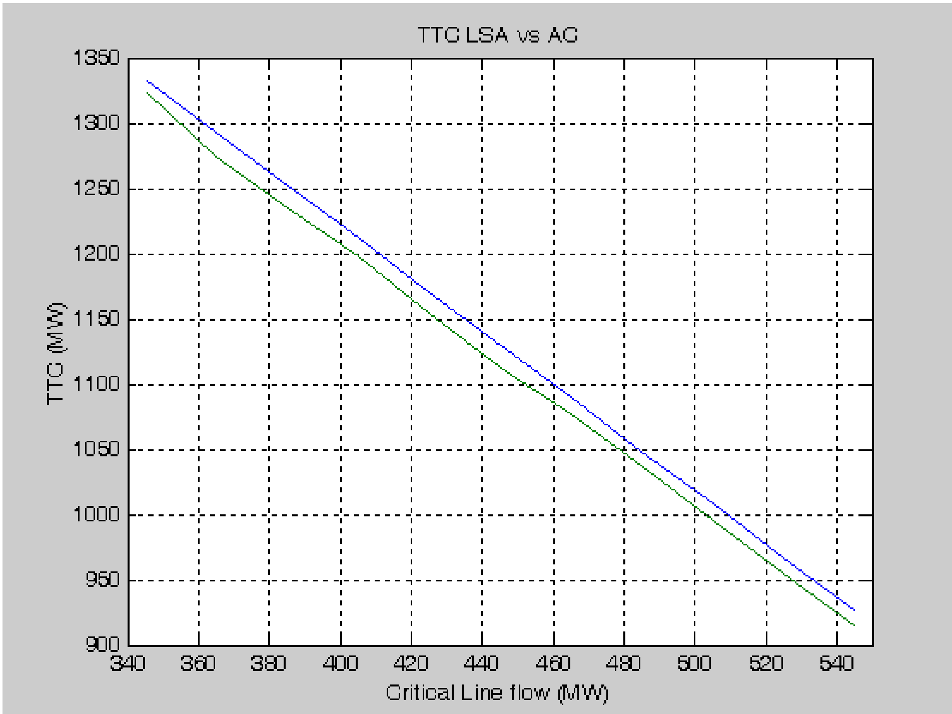


Figure 6-3: LSA & actual load flow solution comparison for 39-bus system

Table 6-8: Off-line correction table for a single operating point using LSA and actual load flow

| Critical line (CL) | Pflow at the CL | TTC(AC) | TTC (LSA) |
|---|---|---|---|
| 82 | 1333 | 839 | 952.15 |
| 82 | 1323 | 866 | 982.18 |
| 82 | 1313 | 893.5 | 1012.21 |
| 82 | 1303 | 921 | 1042.24 |
| 82 | 1293 | 948 | 1072.27 |
| 82 | 1283 | 976 | 1102.3 |
| 82 | 1273 | 1003.5 | 1132.33 |
| 82 | 1263 | 1030.5 | 1162.36 |
| 82 | 1253 | 1058 | 1192.39 |
| 82 | 1243 | 1085.5 | 1222.42 |
| 82 | 1233 | 1111.5 | 1252.45 |
| 82 | 1223 | 1119.5 | 1282.48 |
| 82 | 1213 | 1127.5 | 1312.51 |
| 82 | 1203 | 1135 | 1342.54 |
| 82 | 1193 | 1142.5 | 1372.57 |
| 82 | 1183 | 1150 | 1402.6 |
| 82 | 1173 | 1157.5 | 1432.63 |
| 82 | 1163 | 1165 | 1462.66 |
| 82 | 1153 | 1172 | 1492.69 |

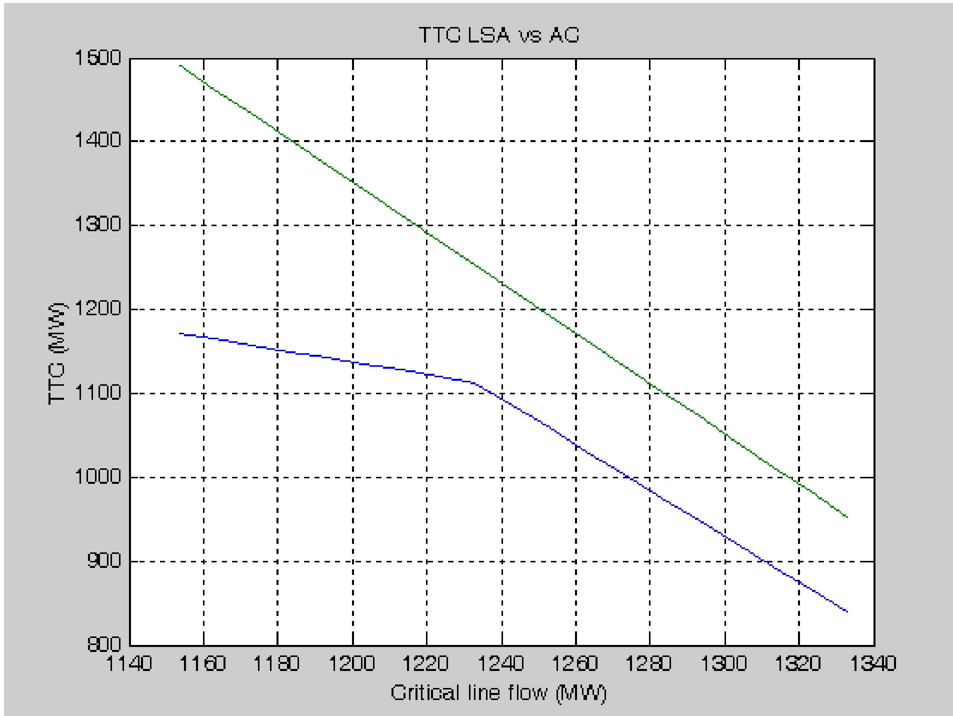


Figure 6-4: LSA & actual load flow solution comparison for the simplified WSCC 179-bus system

# Chapter 7 Conclusions and Future Work

## 7.1 Current Research

The main objective of this thesis is to study the impact of wide area information sharing in the deregulated power system environment. The first problem we encountered was that the power system information did not have a framework to organize the applications and the information in the power system area. The second problem was the amount of information needed to be shared to achieve the minimum requirements of wide area system observability. After proposing adequate solutions for the previous problems, Total Transfer Capability (TTC) calculations were selected as a representative for the deregulated power system applications that can be improved by wide area information sharing. The main contribution of the work done in this thesis can be summarized as follows:

1. A blueprint for the future Internet-based Power System Information Network Architecture (PSIN) [68]has been presented. Internet has many scattered applications in the power system as highlighted in Chapter 3; however, there is no framework for these applications. PSIN has been proposed as a framework for these applications for the future power system network.

2. A new approach for improving the wide area State Estimation (SE) using the Internet as the data communication medium [89] has been proposed in Chapter 4. The proposed method is based on sharing SE outputs instead of sharing the real time measurements. The key benefits of the proposed method are fast solution, small data volume, and no new hardware or software required. The combined state estimate for a multi-area system will be the first step for providing a reliable national transmission grid picture for the whole

system which can be very helpful in the operation and planning of a deregulated power system.

3. A tracing load flow (TLF) program for TTC calculations [97] has been developed in Chapter 5. TLF can be used in many different applications besides the calculations of TTC such as voltage collapse studies, contingency analysis, power systems studies under different dispatch conditions, and analysis of impact of series compensators / shunt compensators on power systems. The basic idea of the TLF program is a load flow program that has the flexibility to change any input parameters in a systematic way and trace the state variable changes. TLF is able to trace all the state variables of the power system under different dispatches and can be a very useful tool for better understanding the power system behavior. TLF is able to calculate TTC for different dispatching scenarios for generation and load.

4. A new method for updating TTC using real time measurements [98] has been proposed in Chapter 6. The basic idea of this method is using off-line correction tables associated with each forecasted operating point. The table contains the simulation results of many operating points located in the neighborhood of the forecasted operating point. The operator will use the real time measurement at the critical line as a primary search key to update TTC.

5. A Linear Sensitivity Analysis (LSA) [98] technique for calculating TTC has been developed in Chapter 6. The LSA method originated from the DC load flow analysis method. LSA calculations for TTC provide a fast method and in some cases the results are close to the AC method. The limitations and the advantages and disadvantages of the proposed method have been listed.

## 7.2 Future Work

The research done in this thesis has highlighted a number of new research topics that need more study. These topics would be a future extension to this work and can be summarized as follows:

1. Enhancing the proposed approach for improving the wide area State Estimation (SE) using Phasor Measurement Units (PMUs). By sharing some of the PMU output states among different areas, the proposed Split State Estimations (SSE) will improve and the future national transmission grid picture will also be more accurate.

2. More work is needed to completely develop the TLF program. This includes a more generalized design to make it able to handle any system with any number of areas. There is also the need to create Graphical User Interface (GUI) to have a friendly user package.

3. The proposed tabulated method for updating TTC can be enhanced by considering contingencies in the TTC calculations. Off-line correction tables can be regenerated based on the new calculations.

4. Expanded study for the LSA technique for TTC calculations can be done. This includes LSA outage effects on TTC calculations. By developing a friendly GUI, a helpful package for LSA TTC calculation can be created.

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# APPENDICES

## Appendix A. Simplified WSCC 179-bus system

### A.1. Introduction

The simplified WSCC 179-bus system has been the test bench study system in this thesis in sections 4.6,and 5.7. The reduced system by EPRI projects [99] EPRI TR-TR-104586s and 2675-04-05. The main objective of the reduced system is to retain an accurate small system representing the simplified WSCC system .The system consists of:

- 179 bus system, 29 machines, and 62-load bus.
- Two-terminal equivalents of the pacific and inter-mountain DC tie lines.
- Total generation in the system is 61411.43 MW.
- Total negative load in the system is 7172.1 MW.
- Total load in the system is 67957.51 MW.
- Total Loss is 626.02 MW, which equivalent to 0.92 %.
- 11 control area (Canada, Montana, Idaho, WAPA UC, New-Mexico, Northwest, Pace, Arizona, PG&E, South California (SOCALIF), and LADWP). The first five-control area is equivalent system.
- 4 voltage levels are represented in the system (2 buses 138 kV, 37 buses 230 kV, 15 buses 345 kV, and 96 buses 500 kV).
- Load model is represented as P, Q constant.

Figure A-1 shows one-line diagram of the simplified WSCC 179-bus system. Table A-1: Table A-4 shows the bus, load, generator, and branch system data.

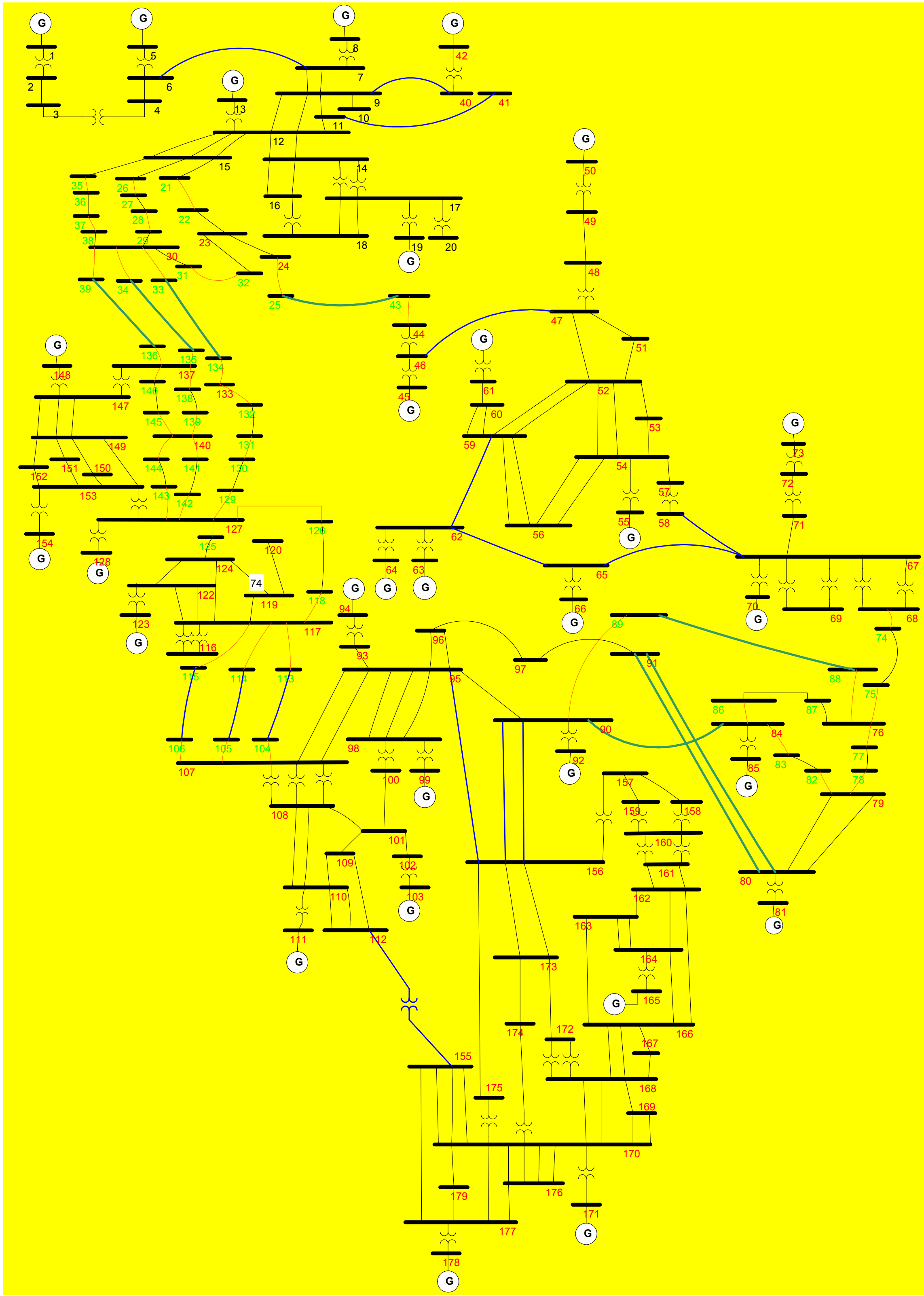

Figure A-1:One-line diagram of the simplified WSCC 179-bus system

## A.2. Simplified WSCC Bus Data

Table A-1 represent the bus data record for the simplified WSCC 179-bus system. Each bus data record has the following format:

Bus #, Bus name, Base kV, Bus type, GL, BL, Area, Zone, Bus voltage, Bus angle

Where

| | |
|---|---|
| Bus # | Bus number (1:179). |
| Bus name | Alphabetic identifier assign to each bus number. |
| Base kV | Bus base voltage; entered in kV. |
| Bus type | Bus type code:<br>(1) Load bus (PQ bus).<br>(2) Generator bus (PV bus).<br>(3) Swing bus. |
| GL | Real component of shunt admittance to ground; entered in MW at one per unit voltage. |
| BL | Reactive component of shunt admittance to ground; entered in Mvar at one per unit voltage. BL is positive for capacitor and negative for inductive. |
| Area | Area number. |
| Zone | Zone number. |
| Bus voltage | Bus voltage magnitude; entered in per unit. |
| Bus angle | Bus voltage phase angle; entered in degree. |

Table A-1: Bus data for the simplified WSCC 179-bus system

| Bus # | Bus name | Base kV | Bus type | GL | BL | Area | Zone | Bus voltage (pu) | Bus angle |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 'CMAIN GM' | 20 | 2 | 0 | 0 | 1 | 1 | 1.02 | 67.7953 |
| 2 | 'CA230 ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.00114 | 62.8741 |
| 3 | 'CA230TO ' | 230 | 1 | 0 | 0 | 1 | 1 | 0.97855 | 53.8252 |
| 4 | 'CANALB ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07861 | 49.2363 |
| 5 | 'CANAD G1' | 20 | 2 | 0 | 0 | 1 | 1 | 1 | 24.7374 |
| 6 | 'CANADA ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.03634 | 20.9468 |
| 7 | 'NORTH ' | 500 | 1 | 0 | 1200 | 1 | 1 | 1.04994 | 12.1081 |
| 8 | 'NORTH G3' | 20 | 2 | 0 | 0 | 1 | 1 | 1 | 26.5867 |
| 9 | 'HANFORD ' | 500 | 1 | 0 | 550 | 1 | 1 | 1.04947 | 0.2256 |
| 10 | 'COULEE ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07 | 0.1644 |
| 11 | 'GARRISON' | 500 | 1 | 0 | 0 | 1 | 1 | 1.03705 | -12.1586 |
| 12 | 'JOHN DAY' | 500 | 1 | 0 | 1019.35 | 1 | 1 | 1.08283 | -11.123 |
| 13 | 'JOHN DAY' | 13.8 | 3 | 0 | 0 | 1 | 1 | 1 | 0 |
| 14 | 'BIG EDDY' | 500 | 1 | 0 | 0 | 1 | 1 | 1.08919 | -13.3097 |
| 15 | 'GRIZZLY ' | 500 | 1 | 0 | -674 | 1 | 1 | 1.0674 | -17.1476 |
| 16 | 'CELILOCA' | 500 | 1 | 0 | 462 | 1 | 1 | 1.08964 | -13.4178 |
| 17 | 'BIG EDDY' | 230 | 1 | 0 | 576.85 | 1 | 1 | 1.06591 | -14.5698 |
| 18 | 'CELILO ' | 230 | 1 | 0 | 792 | 1 | 1 | 1.06158 | -15.0759 |
| 19 | 'DALLES21' | 13.8 | 2 | 0 | 0 | 1 | 1 | 1.055 | -7.9399 |
| 20 | 'BIG EDDY' | 115 | 1 | 0 | 0 | 1 | 1 | 1.06863 | -16.9325 |
| 21 | 'GRIZZLY1' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06533 | -18.7473 |
| 22 | 'GRIZZLY2' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07143 | -16.0155 |
| 23 | 'SUMMER L' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05818 | -18.2346 |
| 24 | 'BURNS2 ' | 500 | 1 | 0 | -220 | 1 | 1 | 0.98437 | -6.6858 |
| 25 | 'BURNS ' | 500 | 1 | 0 | -220 | 1 | 1 | 1.05295 | -19.5512 |
| 26 | 'GRIZZLY3' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07997 | -21.7955 |
| 27 | 'GRIZZLY4' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06943 | -17.2248 |
| 28 | 'GRIZZLY5' | 500 | 1 | 0 | 0 | 1 | 1 | 1.0686 | -22.4487 |
| 29 | 'GRIZZLY6' | 500 | 1 | 0 | 0 | 1 | 1 | 1.0717 | -17.8609 |
| 30 | 'MALIN ' | 500 | 1 | 0 | -110 | 1 | 1 | 1.05433 | -23.3454 |
| 31 | 'MALIN1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05062 | -14.1379 |
| 32 | 'MALIN2 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06088 | -19.8057 |
| 33 | 'MALIN7 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05696 | -17.4395 |
| 34 | 'MALIN5 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06179 | -19.0137 |
| 35 | 'GRIZZLY7' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07926 | -22.0558 |
| 36 | 'GRIZZLY8' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06917 | -17.2246 |
| 37 | 'GRIZZLY9' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06761 | -22.7453 |
| 38 | 'GRIZZLYA' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07104 | -17.8941 |
| 39 | 'MALIN3 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06106 | -19.7688 |
| 40 | 'MONTANA ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04928 | 48.2016 |
| 41 | 'COLSTRP ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07839 | -1.3596 |
| 42 | 'MONTA G1' | 20 | 2 | 0 | 0 | 1 | 1 | 1 | 56.594 |
| 43 | 'BURNS1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 0.97284 | 8.0441 |
| 44 | 'MIDPOINT' | 500 | 1 | 0 | -220 | 1 | 1 | 1.06195 | -5.198 |
| 45 | 'BRIDGER2' | 22 | 2 | 0 | 0 | 1 | 1 | 1.009 | 2.4615 |
| 46 | 'MIDPOINT' | 345 | 1 | 0 | -870 | 1 | 1 | 0.99845 | -1.5707 |
| 47 | 'BENLOMND' | 345 | 1 | 0 | 0 | 1 | 1 | 1.04464 | -3.3928 |
| 48 | 'BENLOMND' | 230 | 1 | 0 | 0 | 1 | 1 | 1.04624 | -3.9584 |
| 49 | 'NAUGHTON' | 230 | 1 | 0 | 0 | 1 | 1 | 1.04453 | 0.6144 |
| 50 | 'NAUGHT ' | 20 | 2 | 0 | 0 | 1 | 1 | 1 | 3.4141 |
| 51 | 'TERMINAL' | 345 | 1 | 0 | 0 | 1 | 1 | 1.03911 | -3.4206 |
| 52 | 'CAMP WIL' | 345 | 1 | 0 | -60 | 1 | 1 | 1.04289 | -2.416 |
| 53 | 'SPAN FRK' | 345 | 1 | 0 | 0 | 1 | 1 | 1.03514 | -1.0919 |
| 54 | 'EMERY ' | 345 | 1 | 0 | -220 | 1 | 1 | 1.03705 | 4.8898 |
| 55 | 'EMERY ' | 20 | 2 | 0 | 0 | 1 | 1 | 1.05 | 9.6053 |
| 56 | 'SIGURD ' | 345 | 1 | 0 | -50 | 1 | 1 | 1.0519 | -0.5454 |
| 57 | 'PINTO ' | 345 | 1 | 0 | -18 | 1 | 1 | 1.04044 | -1.4026 |
| 58 | 'PINTO PS' | 345 | 1 | 0 | 0 | 1 | 1 | 1.03679 | -2.4412 |
| 59 | 'MONA ' | 345 | 1 | 0 | 0 | 1 | 1 | 1.05597 | -2.0072 |
| 60 | 'INTERMT ' | 345 | 1 | 0 | 430 | 1 | 1 | 1.05257 | -4.366 |

Table A-1 continued

| Bus # | Bus name | Base kV | Bus type | GL | BL | Area | Zone | Bus voltage (pu) | Bus angle |
|---|---|---|---|---|---|---|---|---|---|
| 61 | 'INTERM1G' | 26 | 2 | 0 | 0 | 1 | 1 | 1.05 | 0.2812 |
| 62 | 'CRAIG ' | 345 | 1 | 0 | 0 | 1 | 1 | 0.97518 | 16.2756 |
| 63 | 'CRAIG ' | 22 | 2 | 0 | 0 | 1 | 1 | 0.95 | 23.5536 |
| 64 | 'HAYDEN ' | 20 | 2 | 0 | 0 | 1 | 1 | 1 | 33.7299 |
| 65 | 'SAN JUAN' | 345 | 1 | 0 | 390 | 1 | 1 | 1.03559 | -3.8742 |
| 66 | 'SJUAN G4' | 22 | 2 | 0 | 0 | 1 | 1 | 1 | -0.8869 |
| 67 | 'FOURCORN' | 345 | 1 | 0 | -155 | 1 | 1 | 1.00914 | -4.6872 |
| 68 | 'FOURCORN' | 500 | 1 | 0 | -113 | 1 | 1 | 1.06814 | -7.9036 |
| 69 | 'FOURCORN' | 230 | 1 | 0 | 0 | 1 | 1 | 1.00726 | -5.2306 |
| 70 | 'FCNGN4CC' | 22 | 2 | 0 | 0 | 1 | 1 | 1 | 2.2302 |
| 71 | 'CHOLLA ' | 345 | 1 | 0 | 0 | 1 | 1 | 0.97744 | -16.9601 |
| 72 | 'CORONADO' | 500 | 1 | 0 | 0 | 1 | 1 | 0.97947 | -26.1743 |
| 73 | 'CORONADO' | 20 | 2 | 0 | 0 | 1 | 1 | 1.04 | -19.6587 |
| 74 | 'FOURCOR1' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06585 | -5.7791 |
| 75 | 'FOURCOR2' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06933 | -27.9819 |
| 76 | 'MOENKOPI' | 500 | 1 | 0 | -391 | 1 | 1 | 1.06735 | -24.8545 |
| 77 | 'MOENKOP1' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05572 | -23.3904 |
| 78 | 'MOENKOP2' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04116 | -31.0829 |
| 79 | 'WESTWING' | 500 | 1 | 0 | -427 | 1 | 1 | 1.05593 | -29.5908 |
| 80 | 'PALOVRDE' | 500 | 1 | 0 | -146 | 1 | 1 | 1.04856 | -29.6403 |
| 81 | 'PALOVRD2' | 24 | 2 | 0 | 0 | 1 | 1 | 0.96 | -21.7136 |
| 82 | 'NAVAJO4 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.02564 | -31.4583 |
| 83 | 'NAVAJO3 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04693 | -22.1205 |
| 84 | 'NAVAJO ' | 500 | 1 | 0 | -190 | 1 | 1 | 1.07205 | -23.9348 |
| 85 | 'NAVAJO 2' | 26 | 2 | 0 | 0 | 1 | 1 | 1 | -17.8109 |
| 86 | 'NAVAJO1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07025 | -22.8497 |
| 87 | 'NAVAJO2 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06042 | -25.9519 |
| 88 | 'MOENKOP3' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05132 | -15.5497 |
| 89 | 'MOENKOP4' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04671 | -42.3964 |
| 90 | 'ELDORADO' | 500 | 1 | 0 | -319 | 1 | 1 | 1.05122 | -33.0944 |
| 91 | 'DEVERS ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.03539 | -43.5209 |
| 92 | 'ELDORADO' | 20 | 2 | 0 | 0 | 1 | 1 | 1.02 | -25.9729 |
| 93 | 'MOHAVE ' | 500 | 1 | 0 | -196 | 1 | 1 | 1.06999 | -29.36 |
| 94 | 'MOHAV1CC' | 22 | 2 | 0 | 0 | 1 | 1 | 1.05 | -21.0395 |
| 95 | 'LUGO ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05498 | -46.089 |
| 96 | 'SERRANO ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04128 | -50.0771 |
| 97 | 'VALLEY ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.03694 | -47.7604 |
| 98 | 'MIRALOMA' | 500 | 1 | 0 | 400 | 1 | 1 | 1.04087 | -49.6785 |
| 99 | 'MIRALOMA' | 20 | 2 | 0 | 0 | 1 | 1 | 1.05 | -45.4411 |
| 100 | 'MIRALOMA' | 230 | 1 | 0 | 0 | 1 | 1 | 1.03821 | -50.1244 |
| 101 | 'MESA CAL' | 230 | 1 | 0 | 0 | 1 | 1 | 1.00705 | -55.059 |
| 102 | 'LITEHIPE' | 230 | 1 | 0 | 0 | 1 | 1 | 1.01186 | -55.7738 |
| 103 | 'LITEHIPE' | 20 | 2 | 0 | 0 | 1 | 1 | 1.02 | -49.6243 |
| 104 | 'MIDWAY2 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05458 | -49.3075 |
| 105 | 'MIDWAY4 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.0547 | -49.3089 |
| 106 | 'MIDWAY6 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05705 | -49.2851 |
| 107 | 'VINCENT ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06118 | -48.9447 |
| 108 | 'VINCENT ' | 230 | 1 | 0 | -190 | 1 | 1 | 0.99489 | -51.6321 |
| 109 | 'EAGLROCK' | 230 | 1 | 0 | 0 | 1 | 1 | 1.0101 | -52.7595 |
| 110 | 'PARDEE ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.006 | -51.6814 |
| 111 | 'PARDEE ' | 20 | 2 | 0 | 0 | 1 | 1 | 1.01 | -39.5991 |
| 112 | 'SYLMAR S' | 230 | 1 | 0 | 0 | 1 | 1 | 1.02073 | -48.2549 |
| 113 | 'MIDWAY1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04651 | -48.2382 |
| 114 | 'MIDWAY3 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04625 | -48.2331 |
| 115 | 'MIDWAY5 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04598 | -48.2207 |
| 116 | 'MIDWAY ' | 200 | 1 | 0 | -130 | 1 | 1 | 1.16705 | -51.4426 |
| 117 | 'MIDWAY ' | 500 | 1 | 0 | -327 | 1 | 1 | 1.05934 | -48.6048 |
| 118 | 'TEVATR2 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.07046 | -51.7007 |
| 119 | 'LOSBANOS' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04927 | -49.5269 |
| 120 | 'MOSSLAND' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04639 | -49.7917 |

Table A-1 continued

| Bus # | Bus name | Base kV | Bus type | GL | BL | Area | Zone | Bus voltage (pu) | Bus angle |
|---|---|---|---|---|---|---|---|---|---|
| 121 | 'GATES1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.06807 | -49.9919 |
| 122 | 'DIABLO ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05298 | -46.1257 |
| 123 | 'DIABLO1 ' | 25 | 2 | 0 | 0 | 1 | 1 | 0.98 | -42.3235 |
| 124 | 'GATES ' | 500 | 1 | 0 | -91 | 1 | 1 | 1.04707 | -47.6816 |
| 125 | 'TEVATR3 ' | 500 | 1 | 0 | 0 | 1 | 1 | 0.97141 | -35.0588 |
| 126 | 'TEVATR1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 0.97999 | -36.9416 |
| 127 | 'TEVATR ' | 500 | 1 | 0 | 1500 | 1 | 1 | 0.99816 | -38.9935 |
| 128 | 'TEVATR2 ' | 20 | 2 | 0 | 0 | 1 | 1 | 1 | -30.7813 |
| 129 | 'OLINDA4 ' | 500 | 1 | 0 | 0 | 1 | 1 | 0.98098 | -46.5987 |
| 130 | 'OLINDA3 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.02786 | -30.7889 |
| 131 | 'OLINDA2 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.01142 | -38.0292 |
| 132 | 'OLINDA1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05026 | -24.0933 |
| 133 | 'OLINDA ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.03727 | -31.0684 |
| 134 | 'MALIN8 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.03194 | -37.1497 |
| 135 | 'MALIN6 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.02702 | -31.6968 |
| 136 | 'MALIN4 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.02557 | -31.6676 |
| 137 | 'ROUND MT' | 500 | 1 | 0 | -91 | 1 | 1 | 1.03454 | -27.9314 |
| 138 | 'ROUND3 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04054 | -22.0272 |
| 139 | 'ROUND4 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.01079 | -36.1443 |
| 140 | 'TABLE MT' | 500 | 1 | 0 | -91 | 1 | 1 | 1.01342 | -32.0697 |
| 141 | 'TABLE3 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.01755 | -27.3172 |
| 142 | 'TABLE4 ' | 500 | 1 | 0 | 0 | 1 | 1 | 0.99876 | -41.4214 |
| 143 | 'TABLE2 ' | 500 | 1 | 0 | 0 | 1 | 1 | 0.99882 | -45.3402 |
| 144 | 'TABLE1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.01257 | -25.8065 |
| 145 | 'ROUND2 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.01079 | -36.1443 |
| 146 | 'ROUND1 ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04054 | -22.0272 |
| 147 | 'ROUND MT' | 200 | 1 | 0 | -128 | 1 | 1 | 1.12385 | -25.14 |
| 148 | 'ROUND MT' | 20 | 2 | 0 | 0 | 1 | 1 | 1.02 | -15.079 |
| 149 | 'COTWDPGE' | 200 | 1 | 0 | 0 | 1 | 1 | 1.13613 | -30.4881 |
| 150 | 'LOGAN CR' | 200 | 1 | 0 | 0 | 1 | 1 | 1.14016 | -34.5834 |
| 151 | 'GLENN ' | 200 | 1 | 0 | 0 | 1 | 1 | 1.14091 | -34.1984 |
| 152 | 'CORTINA ' | 200 | 1 | 0 | 0 | 1 | 1 | 1.13097 | -34.9739 |
| 153 | 'TEVATR ' | 200 | 1 | 0 | -32 | 1 | 1 | 1.12744 | -39.6329 |
| 154 | 'TEVATR ' | 20 | 2 | 0 | 0 | 1 | 1 | 1.05 | -35.6847 |
| 155 | 'SYLMARLA' | 230 | 1 | 0 | 2146 | 1 | 1 | 1.03831 | -47.1484 |
| 156 | 'VICTORVL' | 500 | 1 | 0 | 0 | 1 | 1 | 1.05866 | -42.4747 |
| 157 | 'VICTORVL' | 287 | 1 | 0 | -108 | 1 | 1 | 1.05209 | -44.4922 |
| 158 | 'STA B2 ' | 287 | 1 | 0 | 0 | 1 | 1 | 1.03663 | -50.7164 |
| 159 | 'STA B1 ' | 287 | 1 | 0 | 0 | 1 | 1 | 1.03663 | -50.7164 |
| 160 | 'STA B ' | 138 | 1 | 0 | 0 | 1 | 1 | 1.03256 | -51.9 |
| 161 | 'STA BLD ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.02727 | -52.1082 |
| 162 | 'STA F ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.02484 | -51.8786 |
| 163 | 'RIVER ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.02361 | -51.8435 |
| 164 | 'HAYNES ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.03129 | -50.6516 |
| 165 | 'HAYNES3G' | 18 | 2 | 0 | 0 | 1 | 1 | 1 | -47.3484 |
| 166 | 'STA G ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.02394 | -51.1737 |
| 167 | 'GLENDAL ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.02337 | -50.922 |
| 168 | 'STA E ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.02516 | -50.0564 |
| 169 | 'VALLEY ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.0293 | -49.03 |
| 170 | 'RINALDI ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.03402 | -47.8383 |
| 171 | 'OWENS G ' | 11.5 | 2 | 0 | 0 | 1 | 1 | 1.02 | -47.2679 |
| 172 | 'STA E ' | 500 | 1 | 0 | 0 | 1 | 1 | 1.04304 | -47.6629 |
| 173 | 'ADELANTO' | 500 | 1 | 0 | 912 | 1 | 1 | 1.06031 | -42.155 |
| 174 | 'ADELAN&1' | 500 | 1 | 0 | 0 | 1 | 1 | 1.0809 | -46.2252 |
| 175 | 'RINALDI ' | 500 | 1 | 0 | -80 | 1 | 1 | 1.07212 | -45.4807 |
| 176 | 'STA J ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.03112 | -48.913 |
| 177 | 'CASTAIC ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.03195 | -47.2897 |
| 178 | 'CASTAI4G' | 18 | 2 | 0 | 0 | 1 | 1 | 1.02 | -45.9799 |
| 179 | 'OLIVE ' | 230 | 1 | 0 | 0 | 1 | 1 | 1.03475 | -47.6286 |

## A.3. Simplified WSCC Load Data

Table A-2 represents the load data record for the simplified WSCC 179-bus system. Each load data record has the following format:

Bus #, PL (MW), QL (MVAR)

Where

| | |
|---|---|
| Bus # | Bus number |
| PL | Real power component of constant MVA load; entered in MW. |
| QL | Reactive power component of constant MVA load; entered in Mvar. |

Table A-2: Load data for the simplified WSCC 179-bus system

| Bus # | PL (MW) | QL (MVAR) |
|---|---|---|
| 1 | 100 | 0 |
| 2 | 3600 | 700 |
| 5 | 100 | 0 |
| 6 | 4400 | 1000 |
| 7 | 5000 | 400 |
| 8 | 100 | 0 |
| 9 | 3500 | 500 |
| 11 | 2584 | 394 |
| 12 | 3200 | 1100 |
| 13 | 100 | 0 |
| 14 | -44.2 | 22 |
| 15 | -66.6 | -97 |
| 17 | -67.5 | 160 |
| 18 | 3137 | 1681 |
| 19 | 100 | 0 |
| 20 | 160 | 31.25 |
| 30 | -339 | -119 |
| 40 | 1700 | 300 |
| 41 | -1525 | -50 |
| 42 | 100 | 0 |
| 45 | 100 | 0 |
| 46 | 610 | -414 |
| 47 | 33.9 | 11.9 |
| 48 | 148 | -7.9 |
| 49 | 255 | 100 |
| 50 | 100 | 0 |
| 51 | 185 | 78.5 |
| 52 | 457.7 | 81.7 |
| 53 | 141.2 | 71.4 |
| 54 | 116.1 | 38.4 |
| 55 | 100 | 0 |
| 56 | 379 | -43 |
| 57 | 31.6 | 11.5 |
| 59 | -62 | 12.8 |
| 60 | 2053 | 907.1 |
| 61 | 100 | 0 |
| 62 | 2350 | -127 |
| 63 | 100 | 0 |
| 64 | 100 | 0 |
| 65 | 840 | 5 |
| 66 | 100 | 0 |
| 67 | 239 | -56 |
| 69 | 139.7 | 23.8 |
| 70 | 100 | 0 |
| 72 | 1750 | -56 |
| 73 | 100 | 0 |
| 79 | 617 | -69 |
| 80 | 793.4 | 207 |
| 81 | 100 | 0 |
| 84 | 90 | 70 |
| 85 | 100 | 0 |
| 90 | 902.3 | -11.4 |
| 91 | 856 | 19.6 |
| 92 | 100 | 0 |
| 94 | 100 | 0 |
| 95 | 204.2 | -28.2 |

Table A-2 continued

| Bus # | PL (MW) | QL (MVAR) |
|---|---|---|
| 96 | 1230 | 72.8 |
| 97 | 406 | 41 |
| 98 | 3098 | 1189 |
| 99 | 100 | 0 |
| 101 | 377.4 | 64.5 |
| 102 | 3191 | 630 |
| 103 | 100 | 0 |
| 108 | 1066 | -10.8 |
| 109 | 175 | 18 |
| 110 | 3118 | 78 |
| 111 | 100 | 0 |
| 112 | 401 | 80.6 |
| 116 | 777.6 | 32.6 |
| 117 | 55.6 | -329 |
| 119 | 265 | 14 |
| 120 | 40 | 21.5 |
| 122 | 50 | 25 |
| 123 | 100 | 0 |
| 124 | 305 | -7.6 |
| 127 | 5661 | 3491 |
| 128 | 100 | 0 |
| 133 | -189 | 61.5 |
| 140 | -0.7 | 118.5 |
| 147 | 148 | 0 |
| 148 | 100 | 0 |
| 149 | 210.4 | -77 |
| 150 | 8.01 | 0 |
| 151 | 27.5 | -0.1 |
| 152 | -43.3 | 20 |
| 153 | 884 | 54.8 |
| 154 | 100 | 0 |
| 155 | -2771 | 1654 |
| 157 | -129 | 32.2 |
| 160 | 237.2 | -63.2 |
| 161 | 138 | 28 |
| 162 | 117 | 24 |
| 163 | 320 | 65 |
| 165 | 100 | 0 |
| 166 | 121 | 25 |
| 167 | 135 | 27 |
| 168 | 807.8 | 132.1 |
| 169 | 205.2 | 17.6 |
| 170 | 121 | 25 |
| 171 | 100 | 0 |
| 173 | -1862 | 971 |
| 176 | 887.7 | -6.2 |
| 178 | 100 | 0 |
| 179 | -72.8 | -17 |

## A.4. Simplified WSCC Generation Data

Table A-3 represents the generation data record for the simplified WSCC 179-bus system. Each load data record has the following format:

Bus #, PG (MW), QG (MVAR), Qmax, Qmin, Vregulated

Where

| | |
|---|---|
| Bus # | Bus number |
| PG | Generator real power output; entered in MW. |
| QG | Generator reactive power output; entered in Mvar. |
| Qmax | Maximum generator reactive power output; entered in Mvar. |
| Qmin | Minimum generator reactive power output; entered in Mvar. |
| Vregulated | Regulated voltage set point; entered in per unit. |

Table A-3: Generators data for the simplified WSCC 179-bus system

| Bus # | PG (MW) | QG (MVAR) | Qmax | Qmin | Vregulated |
|---|---|---|---|---|---|
| 1 | 4480 | 1150.17 | 5320 | -3500 | 1.02 |
| 5 | 4450 | 1011.07 | 4000 | -4000 | 1 |
| 8 | 9950 | 1854.02 | 5780 | -2000 | 1 |
| 13 | 5174.73 | 855.31 | 2649 | -1850 | 1 |
| 19 | 1301 | 431.53 | 692 | -711 | 1.055 |
| 42 | 2910 | 953.29 | 1500 | -1000 | 1 |
| 45 | 1640 | 285.67 | 600 | -525 | 1.009 |
| 50 | 445 | 91.73 | 9999 | -9999 | 1 |
| 55 | 1665 | -31.37 | 9999 | -9999 | 1.05 |
| 61 | 1780 | 534.59 | 850 | -440 | 1.05 |
| 63 | 1048 | -132.91 | 400 | -400 | 0.95 |
| 64 | 2050 | 464.83 | 900 | -900 | 1 |
| 66 | 962 | 148.77 | 300 | -300 | 1 |
| 70 | 2160 | -30.48 | 700 | -500 | 1 |
| 73 | 800 | 123.04 | 300 | -300 | 1.04 |
| 81 | 2640 | 378.08 | 1300 | -900 | 0.96 |
| 85 | 1690 | 195.57 | 700 | -280 | 1 |
| 92 | 982.7 | -128.76 | 300 | -300 | 1.02 |
| 94 | 1680 | 446.63 | 700 | -300 | 1.05 |
| 99 | 1690 | 593.83 | 900 | -400 | 1.05 |
| 103 | 3195 | 1032.5 | 2000 | -900 | 1.02 |
| 111 | 2200 | 393.73 | 600 | -600 | 1.01 |
| 123 | 765 | -206.26 | 330 | -310 | 0.98 |
| 128 | 3467 | 1654.41 | 2500 | -1000 | 1 |
| 148 | 1057 | 25.67 | 400 | -400 | 1.02 |
| 154 | 594 | 192.35 | 300 | -300 | 1.05 |
| 165 | 325 | 68.27 | 300 | -220 | 1 |
| 171 | 110 | 29.08 | 100 | -100 | 1.02 |
| 178 | 200 | -52.15 | 268 | -134 | 1.02 |

## A.5. Simplified WSCC Branch Data

Table A-4 represents the branch data record for the simplified WSCC 179-bus system. Each branch data record has the following format:

Branch #, From bus #, To bus #, ID, R (pu), X (pu), B (pu), Thermal Rate, Tapping, Where

| | |
|---|---|
| Branch # | Branch number. |
| From bus # | Branch starting bus number. |
| To bus # | Branch starting bus number. |
| ID | Circuit identifier. |
| R | Branch resistance; entered in per unit. |
| X | Branch reactance; entered in per unit. |
| B | Total branch-charging susceptance; entered in per unit. |
| Thermal Rate | Thermal transmission rating; entered in MVA. |
| Tapping | Transformer off-normal turns ratio. |

Table A-4: Branch data for the simplified WSCC 179-bus system

| Branch # | From bus # | To bus # | ID | R (pu) | X (pu) | B (pu) | Thermal Rate | Tapping |
|---|---|---|---|---|---|---|---|---|
| 1 | 62 | 59 | 1 | 0.00811 | 0.1369 | 2.4348 | 2000 | 0 |
| 2 | 71 | 67 | 1 | 0.00179 | 0.01988 | 2.576 | 2000 | 0 |
| 3 | 67 | 65 | 1 | 0.0005 | 0.0053 | 0.0882 | 2000 | 0 |
| 4 | 65 | 62 | 1 | 0.00977 | 0.11 | 2 | 2000 | 0 |
| 5 | 84 | 86 | 1 | 0 | -0.00634 | 0 | 1800 | 0 |
| 6 | 86 | 87 | 1 | 0.00077 | 0.01804 | 1.39842 | 3000 | 0 |
| 7 | 87 | 76 | 1 | 0 | -0.00634 | 0 | 1800 | 0 |
| 8 | 84 | 83 | 1 | 0 | -0.01188 | 0 | 1800 | 0 |
| 9 | 83 | 82 | 1 | 0.00241 | 0.05865 | 4.8656 | 3000 | 0 |
| 10 | 82 | 79 | 1 | 0 | -0.01188 | 0 | 1800 | 0 |
| 11 | 76 | 77 | 1 | 0 | -0.00826 | 0 | 1800 | 0 |
| 12 | 77 | 78 | 1 | 0.00179 | 0.04244 | 3.3922 | 3000 | 0 |
| 13 | 78 | 79 | 1 | 0 | -0.00826 | 0 | 1800 | 0 |
| 14 | 76 | 88 | 1 | 0 | -0.01795 | 0 | 1800 | 0 |
| 15 | 88 | 89 | 1 | 0.00207 | 0.04959 | 3.9516 | 3000 | 0 |
| 16 | 89 | 90 | 1 | 0 | -0.01795 | 0 | 1800 | 0 |
| 17 | 80 | 79 | 1 | 0.0004 | 0.0096 | 0.9038 | 3000 | 0 |
| 18 | 80 | 79 | 2 | 0.0004 | 0.0096 | 0.9038 | 3000 | 0 |
| 19 | 68 | 74 | 1 | 0 | -0.00408 | 0 | 1800 | 0 |
| 20 | 74 | 75 | 1 | 0.00177 | 0.04189 | 3.3446 | 3000 | 0 |
| 21 | 75 | 76 | 1 | 0 | -0.00612 | 0 | 1800 | 0 |
| 22 | 6 | 4 | 1 | 0.0035 | 0.07 | 4.606 | 3000 | 0 |
| 23 | 3 | 2 | 1 | 0.002 | 0.02 | 0.8 | 2000 | 0 |
| 24 | 159 | 157 | 1 | 0.0107 | 0.07905 | 0.3667 | 2000 | 0 |
| 25 | 158 | 157 | 1 | 0.0107 | 0.07905 | 0.3667 | 2000 | 0 |
| 26 | 168 | 167 | 1 | 0.00047 | 0.00723 | 0.01624 | 2000 | 0 |
| 27 | 168 | 166 | 1 | 0.00119 | 0.01244 | 0.02798 | 2000 | 0 |
| 28 | 168 | 166 | 2 | 0.00119 | 0.01244 | 0.02798 | 2000 | 0 |
| 29 | 162 | 164 | 1 | 0.00201 | 0.03074 | 0.06886 | 2000 | 0 |
| 30 | 162 | 161 | 1 | 0.00073 | 0.01025 | 0.02558 | 2000 | 0 |
| 31 | 162 | 161 | 2 | 0.00073 | 0.01025 | 0.02558 | 2000 | 0 |
| 32 | 162 | 166 | 1 | 0.0011 | 0.01189 | 0.02514 | 2000 | 0 |
| 33 | 169 | 168 | 1 | 0.00128 | 0.00979 | 0.0212 | 2000 | 0 |
| 34 | 156 | 175 | 1 | 0.00083 | 0.01884 | 1.66668 | 3000 | 0 |
| 35 | 167 | 166 | 1 | 0.00035 | 0.00536 | 0.01204 | 2000 | 0 |
| 36 | 173 | 174 | 1 | 0.00074 | 0.01861 | 1.40264 | 3000 | 0 |
| 37 | 173 | 172 | 1 | 0.00082 | 0.01668 | 1.18802 | 3000 | 0 |
| 38 | 173 | 156 | 1 | 0 | 0.00159 | 0.12002 | 3000 | 0 |
| 39 | 173 | 156 | 2 | 0 | 0.00159 | 0.12002 | 3000 | 0 |
| 40 | 164 | 166 | 1 | 0.00281 | 0.04296 | 0.09648 | 2000 | 0 |
| 41 | 170 | 169 | 1 | 0.00138 | 0.01116 | 0.0247 | 2000 | 0 |
| 42 | 170 | 169 | 2 | 0.00138 | 0.01116 | 0.0247 | 2000 | 0 |
| 43 | 163 | 164 | 1 | 0.0022 | 0.03422 | 0.07716 | 2000 | 0 |
| 44 | 163 | 164 | 2 | 0.00238 | 0.03669 | 0.08284 | 2000 | 0 |
| 45 | 163 | 162 | 1 | 0.00037 | 0.00366 | 0.0083 | 2000 | 0 |
| 46 | 163 | 166 | 1 | 0.00055 | 0.00586 | 0.01246 | 2000 | 0 |
| 47 | 170 | 168 | 1 | 0.00229 | 0.01583 | 0.0306 | 2000 | 0 |
| 48 | 170 | 168 | 2 | 0.00229 | 0.01583 | 0.0306 | 2000 | 0 |
| 49 | 177 | 179 | 1 | 0.00221 | 0.03346 | 0.07338 | 2000 | 0 |
| 50 | 177 | 170 | 1 | 0.0029 | 0.038 | 0.0824 | 2000 | 0 |
| 51 | 177 | 176 | 1 | 0.00309 | 0.04677 | 0.1008 | 2000 | 0 |
| 52 | 177 | 155 | 1 | 0.00226 | 0.03422 | 0.07506 | 2000 | 0 |
| 53 | 170 | 179 | 1 | 0.00029 | 0.00434 | 0.0095 | 2000 | 0 |
| 54 | 170 | 176 | 1 | 0.00141 | 0.00967 | 0.0194 | 2000 | 0 |
| 55 | 170 | 176 | 2 | 0.00141 | 0.00967 | 0.0194 | 2000 | 0 |
| 56 | 170 | 176 | 3 | 0.00161 | 0.00971 | 0.01928 | 2000 | 0 |
| 57 | 170 | 176 | 4 | 0.00161 | 0.00971 | 0.01928 | 2000 | 0 |
| 58 | 170 | 155 | 1 | 0.00027 | 0.00393 | 0.00918 | 2000 | 0 |
| 59 | 170 | 155 | 2 | 0.00027 | 0.00393 | 0.00918 | 2000 | 0 |
| 60 | 170 | 155 | 3 | 0.00027 | 0.00393 | 0.00918 | 2000 | 0 |
| 61 | 11 | 9 | 1 | 0.00142 | 0.02258 | 1.88 | 3000 | 0 |
| 62 | 11 | 12 | 1 | 0.00196 | 0.03304 | 1.88 | 3000 | 0 |

Table A-4 continued

| Branch # | From bus # | To bus # | ID | R (pu) | X (pu) | B (pu) | Thermal Rate | Tapping |
|---|---|---|---|---|---|---|---|---|
| 63 | 11 | 41 | 1 | 0.00179 | 0.01405 | 3.68 | 3000 | 0 |
| 64 | 9 | 10 | 1 | 0.00113 | 0.02069 | 1.85526 | 3000 | 0 |
| 65 | 9 | 12 | 1 | 0.0012 | 0.02316 | 1.7152 | 3000 | 0 |
| 66 | 9 | 12 | 2 | 0.0003 | 0.02 | 3.6 | 3000 | 0 |
| 67 | 7 | 9 | 1 | 0.0002 | 0.0082 | 1.3 | 5000 | 0 |
| 68 | 7 | 9 | 2 | 0.0002 | 0.0082 | 1.3 | 5000 | 0 |
| 69 | 17 | 18 | 1 | 0.00006 | 0.00131 | 0.00378 | 3020 | 0 |
| 70 | 17 | 18 | 2 | 0.00006 | 0.00116 | 0.00332 | 3020 | 0 |
| 71 | 14 | 16 | 1 | 0.00001 | 0.0003 | 0.01434 | 3450 | 0 |
| 72 | 14 | 16 | 2 | 0.00001 | 0.0003 | 0.01844 | 3450 | 0 |
| 73 | 14 | 12 | 1 | 0.00023 | 0.00451 | 0.3332 | 2175 | 0 |
| 74 | 14 | 12 | 2 | 0.0002 | 0.00446 | 0.305 | 2175 | 0 |
| 75 | 15 | 12 | 1 | 0.00063 | 0.01412 | 1.09756 | 3450 | 0 |
| 76 | 15 | 12 | 2 | 0.00109 | 0.02408 | 1.55542 | 3020 | 0 |
| 77 | 15 | 12 | 3 | 0.00108 | 0.02409 | 1.55348 | 3020 | 0 |
| 78 | 15 | 21 | 1 | 0.00041 | 0.00737 | 0.72694 | 3450 | 0 |
| 79 | 21 | 22 | 1 | 0 | -0.01263 | 0 | 2000 | 0 |
| 80 | 22 | 23 | 1 | 0.0006 | 0.01036 | 1.01456 | 3450 | 0 |
| 81 | 30 | 31 | 1 | 0.00072 | 0.01382 | 1.27572 | 3600 | 0 |
| 82 | 31 | 32 | 1 | 0 | -0.00858 | 0 | 1650 | 0 |
| 83 | 32 | 23 | 1 | 0.00012 | 0.00238 | 0.21926 | 3600 | 0 |
| 84 | 15 | 26 | 1 | 0.00066 | 0.01266 | 0.95976 | 3020 | 0 |
| 85 | 26 | 27 | 1 | 0 | -0.01263 | 0 | 2400 | 0 |
| 86 | 27 | 28 | 1 | 0.00074 | 0.01428 | 1.0822 | 3020 | 0 |
| 87 | 28 | 29 | 1 | 0 | -0.01263 | 0 | 2400 | 0 |
| 88 | 29 | 30 | 1 | 0.00078 | 0.01502 | 1.1381 | 3020 | 0 |
| 89 | 15 | 35 | 1 | 0.00066 | 0.01266 | 0.95976 | 3020 | 0 |
| 90 | 35 | 36 | 1 | 0 | -0.01263 | 0 | 2000 | 0 |
| 91 | 36 | 37 | 1 | 0.00074 | 0.01428 | 1.0822 | 3020 | 0 |
| 92 | 37 | 38 | 1 | 0 | -0.01263 | 0 | 2000 | 0 |
| 93 | 38 | 30 | 1 | 0.00074 | 0.01413 | 1.06634 | 3020 | 0 |
| 94 | 25 | 43 | 1 | 0.00264 | 0.05356 | 5.29066 | 3600 | 0 |
| 95 | 43 | 44 | 1 | 0 | -0.02667 | 0 | 1732 | 0 |
| 96 | 133 | 132 | 1 | 0 | -0.01 | 0 | 2667 | 0 |
| 97 | 132 | 131 | 1 | 0.00076 | 0.01952 | 1.8245 | 2894 | 0 |
| 98 | 131 | 130 | 1 | 0 | -0.01 | 0 | 2667 | 0 |
| 99 | 130 | 129 | 1 | 0.00082 | 0.02119 | 1.9842 | 2894 | 0 |
| 100 | 129 | 127 | 1 | 0 | -0.01 | 0 | 2667 | 0 |
| 101 | 119 | 124 | 1 | 0.00083 | 0.01985 | 0 | 2450 | 0 |
| 102 | 119 | 117 | 1 | 0.00153 | 0.0147 | 0 | 1560 | 0 |
| 103 | 120 | 119 | 1 | 0.00053 | 0.01297 | 0 | 2450 | 0 |
| 104 | 137 | 146 | 1 | 0.00002 | -0.00998 | 0 | 1800 | 0 |
| 105 | 146 | 145 | 1 | 0.0014 | 0.02338 | 1.475 | 2396 | 0 |
| 106 | 145 | 140 | 1 | 0.00001 | -0.00666 | 0 | 1800 | 0 |
| 107 | 137 | 138 | 1 | 0.00002 | -0.00998 | 0 | 1800 | 0 |
| 108 | 138 | 139 | 1 | 0.0014 | 0.02338 | 1.475 | 2396 | 0 |
| 109 | 139 | 140 | 1 | 0.00001 | -0.00666 | 0 | 1800 | 0 |
| 110 | 140 | 144 | 1 | 0.00001 | -0.0112 | 0 | 2667 | 0 |
| 111 | 144 | 143 | 1 | 0.00154 | 0.03409 | 2.3114 | 2450 | 0 |
| 112 | 143 | 127 | 1 | 0.00001 | -0.0112 | 0 | 2667 | 0 |
| 113 | 140 | 141 | 1 | 0.00001 | -0.0072 | 0 | 2667 | 0 |
| 114 | 141 | 142 | 1 | 0.00095 | 0.02102 | 1.4252 | 2450 | 0 |
| 115 | 142 | 127 | 1 | 0.00001 | -0.0036 | 0 | 2667 | 0 |
| 116 | 149 | 147 | 1 | 0.01113 | 0.06678 | 0.07286 | 752 | 0 |
| 117 | 149 | 147 | 2 | 0.0105 | 0.0654 | 0.0686 | 602 | 0 |
| 118 | 149 | 147 | 3 | 0.01105 | 0.06642 | 0.0716 | 752 | 0 |
| 119 | 149 | 153 | 1 | 0.03903 | 0.27403 | 0.31072 | 747 | 0 |
| 120 | 149 | 152 | 1 | 0.02482 | 0.16938 | 0.20232 | 838 | 0 |
| 121 | 152 | 153 | 1 | 0.0148 | 0.10101 | 0.12066 | 838 | 0 |
| 122 | 149 | 151 | 1 | 0.01382 | 0.09268 | 0.1106 | 747 | 0 |
| 123 | 151 | 153 | 1 | 0.03058 | 0.2046 | 0.24472 | 747 | 0 |

Table A-4 continued

| Branch # | From bus # | To bus # | ID | R (pu) | X (pu) | B (pu) | Thermal Rate | Tapping |
|---|---|---|---|---|---|---|---|---|
| 124 | 149 | 150 | 1 | 0.01668 | 0.11381 | 0.13608 | 838 | 0 |
| 125 | 150 | 153 | 1 | 0.02235 | 0.16106 | 0.18342 | 838 | 0 |
| 126 | 127 | 126 | 1 | 0.00001 | -0.00755 | 0 | 1800 | 0 |
| 127 | 126 | 118 | 1 | 0.00165 | 0.05719 | 2.4774 | 2450 | 0 |
| 128 | 118 | 117 | 1 | 0.00002 | -0.01331 | 0 | 1800 | 0 |
| 129 | 127 | 125 | 1 | 0.00001 | -0.01098 | 0 | 2450 | 0 |
| 130 | 125 | 124 | 1 | 0.00093 | 0.03644 | 1.3895 | 2450 | 0 |
| 131 | 124 | 121 | 1 | 0.00072 | 0.016 | 1.0879 | 2450 | 0 |
| 132 | 121 | 117 | 1 | 0.00002 | -0.00998 | 0 | 2450 | 0 |
| 133 | 124 | 122 | 1 | 0.00079 | 0.01937 | 1.3285 | 3000 | 0 |
| 134 | 122 | 117 | 1 | 0.00087 | 0.02087 | 1.4571 | 3000 | 0 |
| 135 | 122 | 117 | 2 | 0.00087 | 0.02087 | 1.4571 | 3000 | 0 |
| 136 | 95 | 107 | 1 | 0.00044 | 0.01125 | 0.8292 | 3600 | 0 |
| 137 | 95 | 107 | 2 | 0.00044 | 0.01125 | 0.8292 | 3600 | 0 |
| 138 | 95 | 93 | 1 | 0.0019 | 0.031 | 4.1402 | 3600 | 0 |
| 139 | 90 | 95 | 1 | 0.00193 | 0.02779 | 4.6712 | 3600 | 0 |
| 140 | 93 | 90 | 1 | 0.00056 | 0.01415 | 1.0429 | 3600 | 0 |
| 141 | 91 | 97 | 1 | 0.00042 | 0.00905 | 0.66794 | 3600 | 0 |
| 142 | 95 | 96 | 1 | 0.0006 | 0.0128 | 0.9462 | 3600 | 0 |
| 143 | 98 | 96 | 1 | 0.00021 | 0.00457 | 0.32336 | 3600 | 0 |
| 144 | 96 | 97 | 1 | 0.0004 | 0.0093 | 0.6856 | 3600 | 0 |
| 145 | 95 | 98 | 1 | 0.00028 | 0.00753 | 0.51736 | 3600 | 0 |
| 146 | 95 | 98 | 2 | 0.00035 | 0.0075 | 0.5536 | 3600 | 0 |
| 147 | 110 | 108 | 1 | 0.00285 | 0.03649 | 0.12656 | 2320 | 0 |
| 148 | 110 | 108 | 2 | 0.00138 | 0.03399 | 0.11252 | 2320 | 0 |
| 149 | 109 | 101 | 1 | 0.0019 | 0.0258 | 0.0984 | 2320 | 0 |
| 150 | 109 | 110 | 1 | 0.00845 | 0.07034 | 0.15954 | 1160 | 0 |
| 151 | 102 | 101 | 1 | 0.0011 | 0.0127 | 0.048 | 2320 | 0 |
| 152 | 108 | 101 | 1 | 0.0032 | 0.0395 | 0.144 | 2320 | 0 |
| 153 | 100 | 101 | 1 | 0.00138 | 0.05399 | 0.15252 | 2320 | 0 |
| 154 | 47 | 51 | 1 | 0.0016 | 0.0226 | 0.381 | 2500 | 0 |
| 155 | 52 | 51 | 1 | 0.0008 | 0.0106 | 0.2039 | 2500 | 0 |
| 156 | 47 | 52 | 1 | 0.0024 | 0.0332 | 0.5849 | 2500 | 0 |
| 157 | 52 | 59 | 1 | 0.0017 | 0.0225 | 0.3992 | 2500 | 0 |
| 158 | 52 | 59 | 2 | 0.0021 | 0.0238 | 0.3845 | 2500 | 0 |
| 159 | 54 | 57 | 1 | 0.0096 | 0.0878 | 1.4265 | 2500 | 0 |
| 160 | 52 | 54 | 1 | 0.0052 | 0.0602 | 1.01 | 2500 | 0 |
| 161 | 52 | 54 | 2 | 0.0049 | 0.0537 | 0.8843 | 2500 | 0 |
| 162 | 52 | 53 | 1 | 0.0012 | 0.0172 | 0.2987 | 2500 | 0 |
| 163 | 54 | 56 | 1 | 0.0034 | 0.0374 | 0.6208 | 2500 | 0 |
| 164 | 54 | 56 | 2 | 0.0034 | 0.0372 | 0.6182 | 2500 | 0 |
| 165 | 59 | 56 | 1 | 0.0038 | 0.034 | 0.5824 | 2500 | 0 |
| 166 | 59 | 56 | 2 | 0.0032 | 0.0349 | 0.5722 | 2500 | 0 |
| 167 | 48 | 49 | 1 | 0.0108 | 0.0965 | 0.3296 | 2000 | 0 |
| 168 | 54 | 53 | 1 | 0.0034 | 0.0392 | 0.6524 | 2500 | 0 |
| 169 | 6 | 7 | 1 | 0.00083 | 0.0239 | 3.3 | 3000 | 0 |
| 170 | 9 | 40 | 1 | 0.0007 | 0.074 | 4.87 | 3000 | 0 |
| 171 | 30 | 39 | 1 | 0 | -0.0072 | 0 | 1800 | 0 |
| 172 | 39 | 136 | 1 | 0.00103 | 0.02338 | 1.5804 | 3020 | 0 |
| 173 | 136 | 137 | 1 | 0 | -0.0072 | 0 | 1800 | 0 |
| 174 | 30 | 34 | 1 | 0 | -0.00864 | 0 | 1800 | 0 |
| 175 | 34 | 135 | 1 | 0.00107 | 0.0247 | 1.527 | 3020 | 0 |
| 176 | 135 | 137 | 1 | 0 | -0.0072 | 0 | 1800 | 0 |
| 177 | 30 | 33 | 1 | 0 | -0.01 | 0 | 1800 | 0 |
| 178 | 33 | 134 | 1 | 0.00103 | 0.0323 | 2.796 | 3000 | 0 |
| 179 | 134 | 133 | 1 | 0 | -0.01 | 0 | 1800 | 0 |
| 180 | 117 | 113 | 1 | 0 | -0.00935 | 0 | 2134 | 0 |
| 181 | 113 | 104 | 1 | 0.00123 | 0.02659 | 1.98702 | 3600 | 0 |
| 182 | 104 | 107 | 1 | 0 | -0.00935 | 0 | 2134 | 0 |
| 183 | 117 | 114 | 1 | 0 | -0.00944 | 0 | 2134 | 0 |
| 184 | 114 | 105 | 1 | 0.00123 | 0.02662 | 1.9888 | 3600 | 0 |

Table A-4 continued

| Branch # | From bus # | To bus # | ID | R (pu) | X (pu) | B (pu) | Thermal Rate | Tapping |
|---|---|---|---|---|---|---|---|---|
| 185 | 105 | 107 | 1 | 0 | -0.00935 | 0 | 2134 | 0 |
| 186 | 117 | 115 | 1 | 0 | -0.00935 | 0 | 2134 | 0 |
| 187 | 115 | 106 | 1 | 0.00112 | 0.02517 | 1.83586 | 3600 | 0 |
| 188 | 106 | 107 | 1 | 0 | -0.0084 | 0 | 2100 | 0 |
| 189 | 95 | 156 | 1 | 0.0002 | 0.0041 | 0.2962 | 3000 | 0 |
| 190 | 90 | 156 | 1 | 0.00179 | 0.02524 | 0.53546 | 3000 | 0 |
| 191 | 90 | 156 | 2 | 0.00179 | 0.02524 | 0.53546 | 3000 | 0 |
| 192 | 110 | 112 | 1 | 0.00065 | 0.01187 | 0.04672 | 3070 | 0 |
| 193 | 110 | 112 | 2 | 0.00065 | 0.01187 | 0.04672 | 3070 | 0 |
| 194 | 109 | 112 | 1 | 0.0014 | 0.0264 | 0.102 | 3070 | 0 |
| 195 | 84 | 90 | 1 | 0.0028 | 0.0211 | 1.0194 | 1630 | 0 |
| 196 | 80 | 91 | 1 | 0.00259 | 0.02967 | 2.153 | 1800 | 0 |
| 197 | 80 | 91 | 2 | 0.00259 | 0.02967 | 2.153 | 1800 | 0 |
| 198 | 25 | 24 | 1 | 0 | -0.02667 | 0 | 1732 | 0 |
| 199 | 24 | 23 | 1 | 0.00122 | 0.02373 | 2.2071 | 3600 | 0 |
| 200 | 47 | 46 | 1 | 0.0062 | 0.0673 | 1.1156 | 2500 | 0 |
| 201 | 60 | 59 | 1 | 0.0018 | 0.0245 | 0.4392 | 2500 | 0 |
| 202 | 60 | 59 | 2 | 0.0018 | 0.0245 | 0.4392 | 2500 | 0 |
| 203 | 58 | 67 | 1 | 0.0048 | 0.0436 | 0.7078 | 2500 | 0 |
| 204 | 62 | 64 | 1 | 0 | 0.015 | 0 | 20000 | 1 |
| 205 | 72 | 71 | 1 | 0 | 0.0146 | 0 | 20000 | 1 |
| 206 | 80 | 81 | 1 | 0.00006 | 0.00495 | 0 | 20000 | 1.1061 |
| 207 | 72 | 73 | 1 | 0 | 0.0173 | 0 | 20000 | 0.9545 |
| 208 | 65 | 66 | 1 | 0 | 0.006 | 0 | 20000 | 1.0435 |
| 209 | 68 | 67 | 1 | 0 | 0.011 | 0 | 20000 | 1.063 |
| 210 | 68 | 67 | 2 | 0 | 0.011 | 0 | 20000 | 1.063 |
| 211 | 67 | 70 | 1 | 0 | 0.0059 | 0 | 20000 | 1 |
| 212 | 67 | 69 | 1 | 0.00028 | 0.0138 | 0 | 20000 | 1 |
| 213 | 67 | 69 | 2 | 0.00029 | 0.0139 | 0 | 20000 | 1 |
| 214 | 84 | 85 | 1 | 0 | 0.00666 | 0 | 20000 | 1.08 |
| 215 | 4 | 3 | 1 | 0 | 0.01 | 0 | 20000 | 1.1 |
| 216 | 6 | 5 | 1 | 0 | 0.0015 | 0 | 20000 | 1.05 |
| 217 | 2 | 1 | 1 | 0 | 0.002 | 0 | 20000 | 1 |
| 218 | 156 | 157 | 1 | 0.0002 | 0.02338 | 0 | 20000 | 0.9789 |
| 219 | 60 | 61 | 1 | 0 | 0.0052 | 0 | 20000 | 1.025 |
| 220 | 40 | 42 | 1 | 0 | 0.005 | 0 | 20000 | 1.09 |
| 221 | 44 | 46 | 1 | 0 | 0.0072 | 0 | 20000 | 1.05 |
| 222 | 7 | 8 | 1 | 0 | 0.0025 | 0 | 20000 | 1.066 |
| 223 | 16 | 18 | 1 | 0 | 0.00221 | 0 | 20000 | 1.0234 |
| 224 | 17 | 20 | 1 | 0.00089 | 0.0299 | 0 | 20000 | 0.9873 |
| 225 | 14 | 17 | 1 | 0.0002 | 0.01181 | 0 | 20000 | 1.0238 |
| 226 | 14 | 17 | 2 | 0.00009 | 0.00735 | 0 | 20000 | 1.0238 |
| 227 | 12 | 13 | 1 | 0 | 0.00375 | 0 | 20000 | 1.0977 |
| 228 | 17 | 19 | 1 | 0 | 0.01034 | 0 | 20000 | 1.0455 |
| 229 | 148 | 147 | 1 | 0 | 0.02281 | 0 | 20000 | 0.9174 |
| 230 | 147 | 137 | 1 | 0.0001 | 0.0174 | 0 | 20000 | 1.119 |
| 231 | 128 | 127 | 1 | 0 | 0.00448 | 0 | 20000 | 0.9452 |
| 232 | 154 | 153 | 1 | 0 | 0.01815 | 0 | 20000 | 0.9091 |
| 233 | 153 | 127 | 1 | 0.0002 | 0.0125 | 0 | 20000 | 1.119 |
| 234 | 116 | 117 | 1 | 0.0003 | 0.0174 | 0 | 20000 | 1.119 |
| 235 | 116 | 117 | 2 | 0.0002 | 0.0119 | 0 | 20000 | 1.119 |
| 236 | 122 | 123 | 1 | 0 | 0.0098 | 0 | 20000 | 1.05 |
| 237 | 107 | 108 | 1 | 0 | 0.01149 | 0 | 20000 | 1.0631 |
| 238 | 107 | 108 | 2 | 0 | 0.01149 | 0 | 20000 | 1.0631 |
| 239 | 107 | 108 | 3 | 0 | 0.01149 | 0 | 20000 | 1.0631 |
| 240 | 92 | 90 | 1 | 0 | 0.01512 | 0 | 20000 | 0.996 |
| 241 | 93 | 94 | 1 | 0 | 0.0098 | 0 | 20000 | 1.05 |
| 242 | 103 | 102 | 1 | 0 | 0.00365 | 0 | 20000 | 0.9787 |
| 243 | 99 | 98 | 1 | 0 | 0.00516 | 0 | 20000 | 0.9843 |
| 244 | 98 | 100 | 1 | 0 | 0.005 | 0 | 20000 | 1 |
| 245 | 159 | 160 | 1 | 0.00059 | 0.01491 | 0 | 20000 | 1.0017 |

Table A-4 continued

| Branch # | From bus # | To bus # | ID | R (pu) | X (pu) | B (pu) | Thermal Rate | Tapping |
|---|---|---|---|---|---|---|---|---|
| 246 | 158 | 160 | 1 | 0.00059 | 0.01491 | 0 | 20000 | 1.0017 |
| 247 | 161 | 160 | 1 | 0.0003 | 0.0133 | 0 | 20000 | 1 |
| 248 | 161 | 160 | 2 | 0.0003 | 0.0134 | 0 | 20000 | 1 |
| 249 | 172 | 168 | 1 | 0.00013 | 0.01386 | 0 | 20000 | 1.0106 |
| 250 | 172 | 168 | 2 | 0.00013 | 0.01386 | 0 | 20000 | 1.0106 |
| 251 | 174 | 170 | 1 | 0.00013 | 0.00693 | 0 | 20000 | 1.05 |
| 252 | 164 | 165 | 1 | 0.00058 | 0.02535 | 0 | 20000 | 1.0491 |
| 253 | 175 | 170 | 1 | 0.00026 | 0.01386 | 0 | 20000 | 1.05 |
| 254 | 170 | 171 | 1 | 0.00499 | 0.11473 | 0 | 20000 | 1.0478 |
| 255 | 177 | 178 | 1 | 0.0005 | 0.0238 | 0 | 20000 | 1 |
| 256 | 155 | 112 | 1 | 0 | 0.00115 | 0 | 20000 | 1.0133 |
| 257 | 111 | 110 | 1 | 0 | 0.01026 | 0 | 20000 | 0.9871 |
| 258 | 62 | 63 | 1 | 0 | 0.01238 | 0 | 20000 | 1 |
| 259 | 54 | 55 | 1 | 0.0002 | 0.0058 | 0 | 20000 | 0.9855 |
| 260 | 57 | 58 | 1 | 0 | 0.0195 | 0 | 20000 | 1 |
| 261 | 47 | 48 | 1 | 0.0003 | 0.0181 | 0 | 20000 | 1 |
| 262 | 49 | 50 | 1 | 0.0005 | 0.0141 | 0 | 20000 | 1.0588 |
| 263 | 46 | 45 | 1 | 0 | 0.0046 | 0 | 20000 | 1 |

# Appendix B. IEEE 39-bus system

### D.1. Introduction

The IEEE 39-bus system has been the second test bench study system in this thesis (section 6.6). The IEEE reduced system is the reduced system for New England system. The main objective of this reduced system is to retain an accurate small system representing the New England system. The system consists of:

- 39 bus system, 10 machines, and 20-load bus.
- Total generation in the system is 6192.84 MW.
- Total load in the system is 6150.1MW.
- Total Loss is 42.74 MW, which equivalent to 0.69 %.
- Load model is represented as P, Q constant.

Figure B-1 shows a one-line diagram of the IEEE 39-bus system. Table B-1 -Table B-4 shows the bus, load, generator, and branch system data.

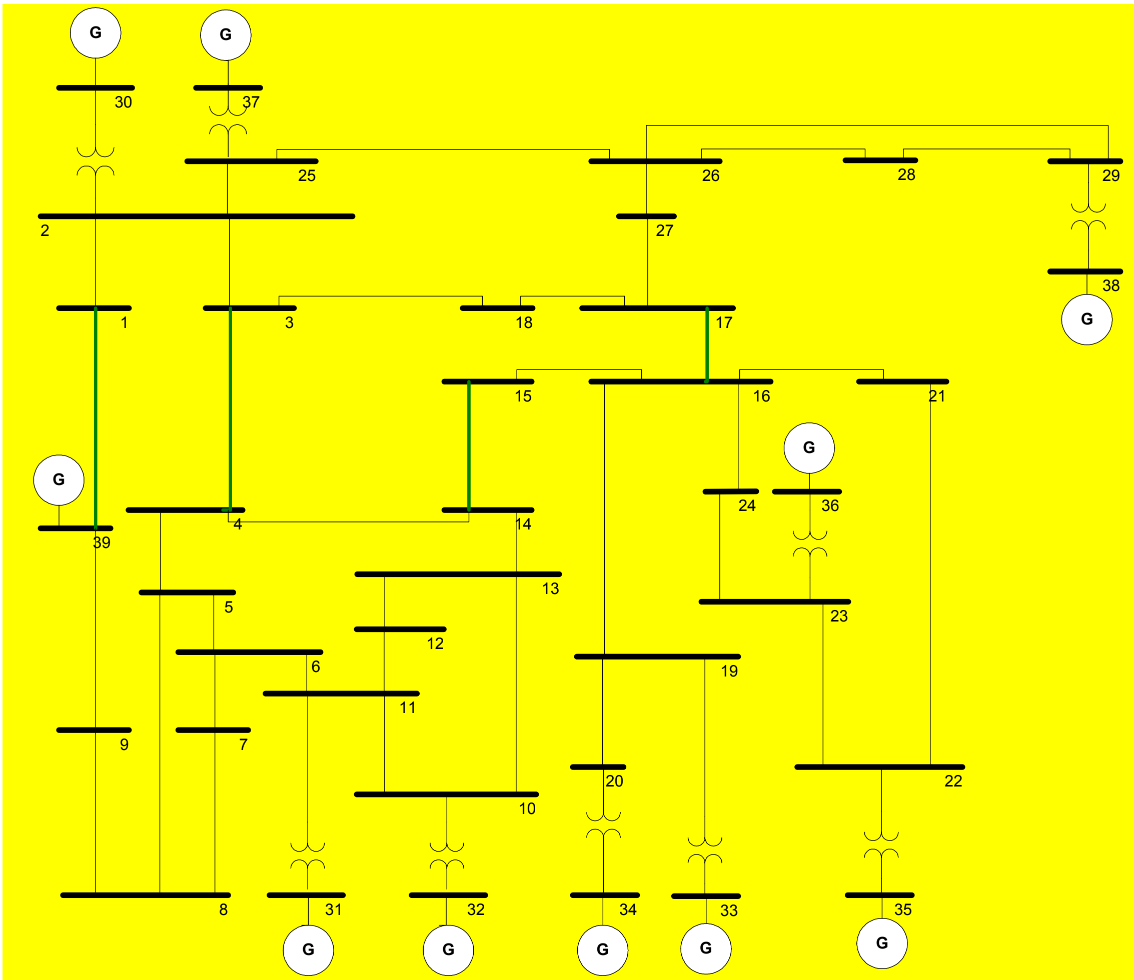


Figure B-1: One-line diagram of 39-bus IEEE system

## D.2. IEEE 39-bus Bus Data

Table B-1: Bus data for IEEE 39-bus system

| Bus # | Bus name | Base kV | Bus type | GL | BL | Area | Zone | Bus voltage (pu) | Bus angle |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 'BUS-1 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.04754 | -9.5707 |
| 2 | 'BUS-2 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.04896 | -7.0111 |
| 3 | 'BUS-3 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.03042 | -9.8581 |
| 4 | 'BUS-4 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.00381 | -10.6546 |
| 5 | 'BUS-5 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.00502 | -9.4687 |
| 6 | 'BUS-6 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.00736 | -8.7668 |
| 7 | 'BUS-7 ' | 100 | 1 | 0 | 0 | 1 | 1 | 0.9967 | -10.9702 |
| 8 | 'BUS-8 ' | 100 | 1 | 0 | 0 | 1 | 1 | 0.99573 | -11.4762 |
| 9 | 'BUS-9 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.02809 | -11.2997 |
| 10 | 'BUS-10 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.01702 | -6.3816 |
| 11 | 'BUS-11 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.01253 | -7.1952 |
| 12 | 'BUS-12 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1 | -7.2106 |
| 13 | 'BUS-13 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.01419 | -7.0959 |
| 14 | 'BUS-14 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.01173 | -8.7648 |
| 15 | 'BUS-15 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.01578 | -9.1807 |
| 16 | 'BUS-16 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.03225 | -7.7766 |
| 17 | 'BUS-17 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.03395 | -8.7748 |
| 18 | 'BUS-18 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.03129 | -9.6156 |
| 19 | 'BUS-19 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.05001 | -3.1525 |
| 20 | 'BUS-20 ' | 100 | 1 | 0 | 0 | 1 | 1 | 0.99096 | -4.5639 |
| 21 | 'BUS-21 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.0321 | -5.371 |
| 22 | 'BUS-22 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.04998 | -0.9239 |
| 23 | 'BUS-23 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.04498 | -1.1221 |
| 24 | 'BUS-24 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.03775 | -7.657 |
| 25 | 'BUS-25 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.05752 | -5.6492 |
| 26 | 'BUS-26 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.05215 | -6.9058 |
| 27 | 'BUS-27 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.03795 | -8.9173 |
| 28 | 'BUS-28 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.05016 | -3.3942 |
| 29 | 'BUS-29 ' | 100 | 1 | 0 | 0 | 1 | 1 | 1.04997 | -0.6351 |
| 30 | 'BUS-30 ' | 100 | 2 | 0 | 0 | 1 | 1 | 1.0475 | -4.5918 |
| 31 | 'BUS-31 ' | 100 | 3 | 0 | 0 | 1 | 1 | 0.982 | 0 |
| 32 | 'BUS-32 ' | 100 | 2 | 0 | 0 | 1 | 1 | 0.9831 | 1.6155 |
| 33 | 'BUS-33 ' | 100 | 2 | 0 | 0 | 1 | 1 | 0.9972 | 2.0647 |
| 34 | 'BUS-34 ' | 100 | 2 | 0 | 0 | 1 | 1 | 1.0123 | 0.6263 |
| 35 | 'BUS-35 ' | 100 | 2 | 0 | 0 | 1 | 1 | 1.0493 | 4.037 |
| 36 | 'BUS-36 ' | 100 | 2 | 0 | 0 | 1 | 1 | 1.0635 | 6.7296 |
| 37 | 'BUS-37 ' | 100 | 2 | 0 | 0 | 1 | 1 | 1.0278 | 1.1355 |
| 38 | 'BUS-38 ' | 100 | 2 | 0 | 0 | 1 | 1 | 1.0265 | 6.4282 |
| 39 | 'BUS-39 ' | 100 | 2 | 0 | 0 | 1 | 1 | 1.03 | -11.1082 |

## D.3. IEEE 39-bus Load Data

Table B-2: Load data for IEEE 39-bus system

| Bus # | PL (MW) | QL (MVAR) |
|---|---|---|
| 3 | 322 | 2.4 |
| 4 | 500 | 184 |
| 7 | 233.8 | 84 |
| 8 | 522 | 176 |
| 12 | 8.5 | 88 |
| 15 | 320 | 153 |
| 16 | 329 | 32.3 |
| 18 | 158 | 30 |
| 20 | 680 | 103 |
| 21 | 274 | 115 |
| 23 | 247.5 | 84.6 |
| 24 | 308.6 | -92.2 |
| 25 | 224 | 47.2 |
| 26 | 139 | 17 |
| 27 | 281 | 75.5 |
| 28 | 206 | 27.6 |
| 29 | 283.5 | 26.9 |
| 31 | 9.2 | 4.6 |
| 39 | 1104 | 250 |

## D.4. IEEE 39-bus Generation Data

Table B-3: Generation data for IEEE 39-bus system

| Bus # | PG (MW) | QG (MVAR) | Qmax | Qmin | Vregulated |
|---|---|---|---|---|---|
| 30 | 250 | 144.92 | 9999 | -999.9 | 1.0475 |
| 31 | 572.84 | 207.04 | 9999 | -999.9 | 0.982 |
| 32 | 650 | 205.73 | 9999 | -999.9 | 0.9831 |
| 33 | 632 | 108.94 | 9999 | -999.9 | 0.9972 |
| 34 | 508 | 166.99 | 9999 | -999.9 | 1.0123 |
| 35 | 650 | 211.11 | 9999 | -999.9 | 1.0493 |
| 36 | 560 | 100.44 | 9999 | -999.9 | 1.0635 |
| 37 | 540 | 0.65 | 9999 | -999.9 | 1.0278 |
| 38 | 830 | 22.66 | 9999 | -999.9 | 1.0265 |
| 39 | 1000 | 87.88 | 9999 | -999.9 | 1.03 |

## D.5. IEEE 39-bus Branch Data

Table B-4: Branch data for IEEE 39-bus system

| Branch # | From bus # | To bus # | ID | R (pu) | X (pu) | B (pu) | Thermal Rate | Tapping |
|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 1 | BL | 0.0035 | 0.0411 | 0.6987 | 1000 | 0 |
| 2 | 39 | 1 | BL | 0.001 | 0.025 | 0.75 | 1000 | 0 |
| 3 | 3 | 2 | BL | 0.0013 | 0.0151 | 0.2572 | 1000 | 0 |
| 4 | 25 | 2 | BL | 0.007 | 0.0086 | 0.146 | 1000 | 0 |
| 5 | 4 | 3 | BL | 0.0013 | 0.0213 | 0.2214 | 1000 | 0 |
| 6 | 18 | 3 | BL | 0.0011 | 0.0133 | 0.2138 | 1000 | 0 |
| 7 | 5 | 4 | BL | 0.0008 | 0.0128 | 0.1342 | 1000 | 0 |
| 8 | 14 | 4 | BL | 0.0008 | 0.0129 | 0.1382 | 1000 | 0 |
| 9 | 6 | 5 | BL | 0.0002 | 0.0026 | 0.0434 | 1000 | 0 |
| 10 | 8 | 5 | BL | 0.0008 | 0.0112 | 0.1476 | 1000 | 0 |
| 11 | 7 | 6 | BL | 0.0006 | 0.0092 | 0.113 | 1000 | 0 |
| 12 | 11 | 6 | BL | 0.0007 | 0.0082 | 0.1389 | 1000 | 0 |
| 13 | 8 | 7 | BL | 0.0004 | 0.0046 | 0.078 | 1000 | 0 |
| 14 | 9 | 8 | BL | 0.0023 | 0.0363 | 0.3804 | 1000 | 0 |
| 15 | 39 | 9 | BL | 0.001 | 0.025 | 1.2 | 1000 | 0 |
| 16 | 11 | 10 | BL | 0.0004 | 0.0043 | 0.0729 | 1000 | 0 |
| 17 | 13 | 10 | BL | 0.0004 | 0.0043 | 0.0729 | 1000 | 0 |
| 18 | 14 | 13 | BL | 0.0009 | 0.0101 | 0.1723 | 1000 | 0 |
| 19 | 15 | 14 | BL | 0.0018 | 0.0217 | 0.366 | 1000 | 0 |
| 20 | 16 | 15 | BL | 0.0009 | 0.0094 | 0.171 | 1000 | 0 |
| 21 | 17 | 16 | BL | 0.0007 | 0.0089 | 0.1342 | 1000 | 0 |
| 22 | 19 | 16 | BL | 0.0016 | 0.0195 | 0.304 | 1000 | 0 |
| 23 | 21 | 16 | BL | 0.0008 | 0.0135 | 0.2548 | 1000 | 0 |
| 24 | 24 | 16 | BL | 0.0003 | 0.0059 | 0.068 | 1000 | 0 |
| 25 | 18 | 17 | BL | 0.0007 | 0.0082 | 0.1319 | 1000 | 0 |
| 26 | 27 | 17 | BL | 0.0013 | 0.0173 | 0.3216 | 1000 | 0 |
| 27 | 22 | 21 | BL | 0.0008 | 0.014 | 0.2565 | 1000 | 0 |
| 28 | 23 | 22 | BL | 0.0006 | 0.0096 | 0.1846 | 1000 | 0 |
| 29 | 24 | 23 | BL | 0.0022 | 0.035 | 0.361 | 1000 | 0 |
| 30 | 26 | 25 | BL | 0.0032 | 0.0323 | 0.513 | 1000 | 0 |
| 31 | 27 | 26 | BL | 0.0014 | 0.0147 | 0.2396 | 1000 | 0 |
| 32 | 28 | 26 | BL | 0.0043 | 0.0474 | 0.7802 | 1000 | 0 |
| 33 | 29 | 26 | BL | 0.0057 | 0.0625 | 1.029 | 1000 | 0 |
| 34 | 29 | 28 | BL | 0.0014 | 0.0151 | 0.249 | 1000 | 0 |
| 35 | 12 | 11 | BL | 0.0016 | 0.0435 | 0 | 1500 | 1.006 |
| 36 | 12 | 13 | BL | 0.0016 | 0.0435 | 0 | 1500 | 1.006 |
| 37 | 6 | 31 | BL | 0 | 0.025 | 0 | 1500 | 1.07 |
| 38 | 10 | 32 | BL | 0 | 0.02 | 0 | 1500 | 1.07 |
| 39 | 19 | 33 | BL | 0.0007 | 0.0142 | 0 | 1500 | 1.07 |
| 40 | 20 | 34 | BL | 0.0009 | 0.018 | 0 | 1500 | 1.009 |
| 41 | 22 | 35 | BL | 0 | 0.0143 | 0 | 1500 | 1.025 |
| 42 | 23 | 36 | BL | 0.0005 | 0.0272 | 0 | 1500 | 1 |
| 43 | 25 | 37 | BL | 0.0006 | 0.0232 | 0 | 2500 | 1.025 |
| 44 | 2 | 30 | BL | 0 | 0.0181 | 0 | 2500 | 1.025 |
| 45 | 29 | 38 | BL | 0.0008 | 0.0156 | 0 | 3500 | 1.025 |
| 46 | 19 | 20 | BL | 0.0007 | 0.0138 | 0 | 1500 | 1.06 |

# Appendix C. State Estimation Program Code

## C.1. General

This appendix contains the input and the output data formats for the ISE and SSE programs explained in Chapter 4. A simplified flow chart for the main program and the main functions will be demonstrated. The appendix also includes a user manual guide with instructions on how to run the program. At the end of this appendix, the MATLAB code for the program is also included.

## C.2. User Manual for Using the Program

The main input for this program is load flow data in PTI format (*wscc179.pti*) of the system topology which includes detailed descriptions for the system data (bus, load, generator, and branch data). These data are explained in detail in Appendix A. In addition to the PTI format, the program needs the load flow output solution (*wscc179.flw*) for the base case under study. This program is created using the IP-flow program. Some other information should be entered to the program to complete the input data required to run the program such as:

- Set of border buses between the two subsystems.
- The number of buses inside each subsystem.
- The measurement locations.

All the input data required to run the program is highlighted in the next program code. All the output data are explained throughout Chapter 4.

To start the program, the MATLAB complier should be opened first, and then from the MATLAB editor type "*SSE_ISE*". This is the main program for the SSE and ISE algorithm. The input data highlighted inside the MATLAB code in Appendix C.4 should be entered or updated each time a new case is run.

The output of the program is a comparison study between SSE and ISE. One of the outputs is the average of the MVA comparison for each transmission line flow between the SSE and ISE (Table 4-1); the function used in the program is "*perc10*". This MVA compassion is based on the Monte- Carlo simulations outputs. STD comparison is also another output result. Another comparison is STD among the SSE, ISE, and measurement outputs calculated from the Monte-Carlo simulation; the function used in the program is "*std_S_diff*", example of this comparison is shown Figure 4-7. The previous comparison is calculated for all the transmission lines in the system; meanwhile, Borderline comparison is also calculated in the following two functions "*perc10_border_ave*" and "*std_S_diff_border_ave.*". Many examples are shown in Chapter 4 as Figure 4-8.

### C.3. Flow Charts for the SE Main Program and Main Functions

The program is designed in function format to make it easy to modify. Each function can be changed by itself if there is a need. In addition the functions can be reused in any other application, as we will see in the next appendices. Another advantage of using functions is the flexibility of changing any function inside the main program; the only thing that should remain constant the output format of the function. Many functions are created to overcome the lack of information about the real system. For example, the measurement locations should be given input data for each specific system; however, in case of unavailability of this information the program will create it (*M_PQV*). The same thing, for full scale measuring devices is assumed given input data; however, the program will create it unless the data are available. If the full-scale data are available, then the function used in the program to create the full scale (*full_scale*) will be removed and replaced by the real data in the same format that the function output produces. The output format can be checked through the MATLAB code that will be discussed in the following section. The flow chart of the main program (*SSE_ISE*) is shown in Figure C-1.

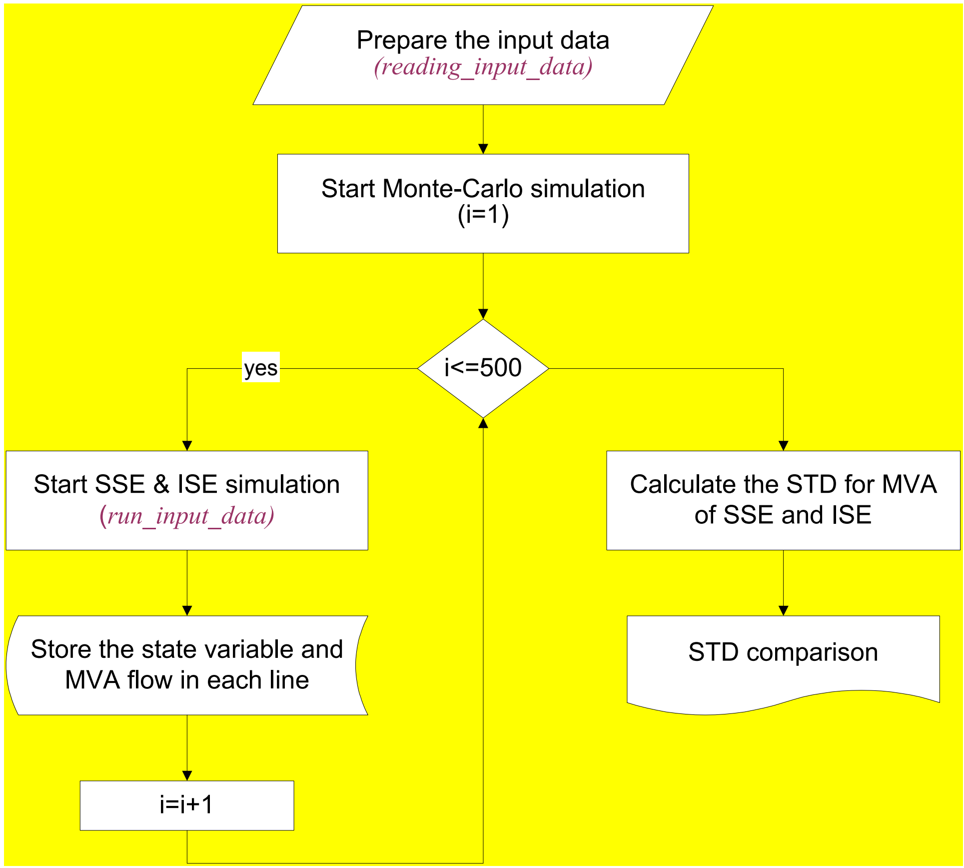


Figure C-1: Flow chart for the main program *(SSE_ISE)*

The main program calls for two main functions. The first function is (*reading_ input_ data*), this function is intended to prepare the input data file for starting the Monte-Carlo simulation. The detailed flow chart of this function is shown in Figure C-2. The main role of this function is preparing the input data required for running the state estimation program. Two functions called by this program can be replaced if we know the real input data (*M_PQV* & *full_scale*) as I mentioned before. The measurement locations (*M_PQV*) output has a square matrix format with the size number of network branches. Matrix elements are either "0" or "1". "1" means that there is a measurement location at that location and "0" means there is no measurement at that location. The diagonal of the matrix is the injection measurement locations which have the same format. The full scale (*full_scale*) out has the vector format which exactly matches the measurement vector format. In the case of the availability of real full-scale data this function can be replaced by the real data that respect the same output format.

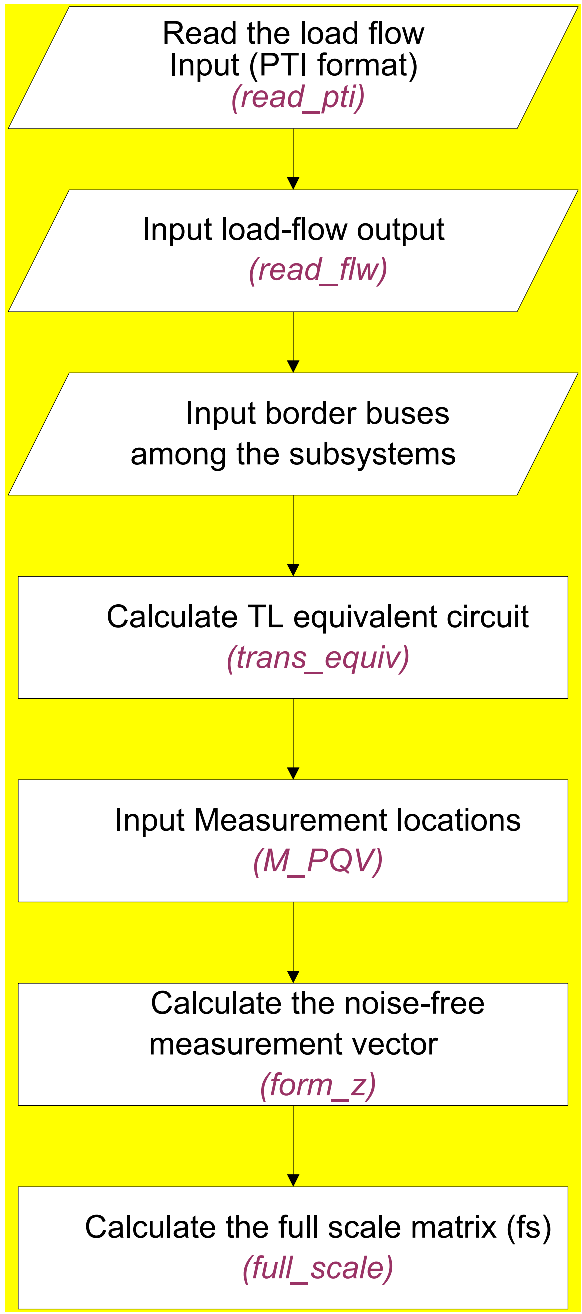


Figure C-2: Flow chart for the input reading function *(reading_input_data)*

The second main function in the main program (*run_input_data*) is the function that will prepare the measurements input data for the SSE program. This function will split the input data into two subsystems (section 4.5) each one has its own slack bus. However, if the real measurements are available, these measurements can replace the *noisy_meas* function with the same output format. The standard deviation is calculated using AEP equation (C.1) The output format of the measurements vector (Zm in equation C.2) has the measurement sorted in the following order:

- Real power flow measurement at each transmission line
- Real power injection measurement at each bus
- Reactive power flow measurement at each transmission line
- Reactive power injection measurement at each bus
- Voltage measurement at each bus

The flow chart of the (*run_input_data*) function is shown in Figure C-3.

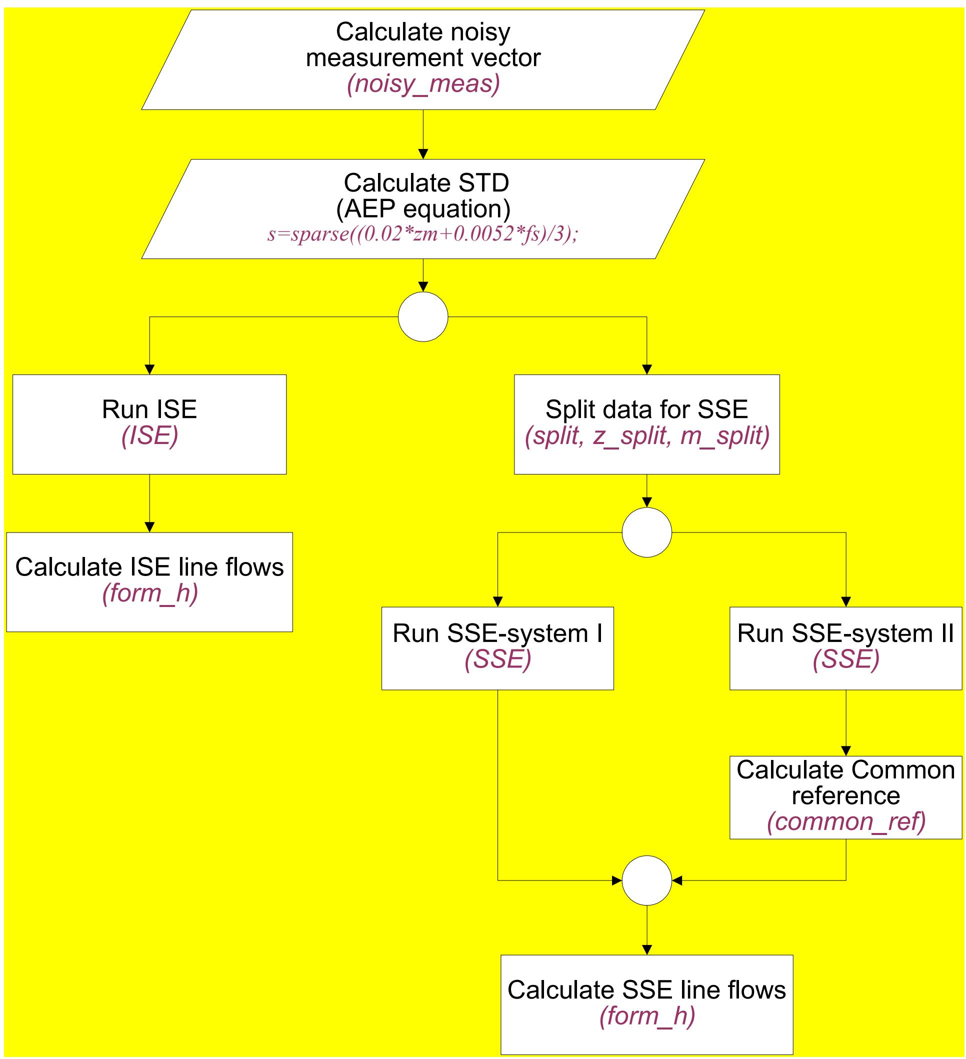


Figure C-3: Flow chart for the function *(run_input_data)*

The previous function (*run_input_data*) is called the main State Estimation function (*SSE* and *ISE*). Both functions have exactly the same algorithm except that the (*SSE*) function has the freedom to change the slack bus of the system to accommodate for the common reference explained in section 4.3.1. The flow chart of the main State Estimation function is shown in Figure C-4. All the mathematical background of this flow chart is explained in section 4.2.

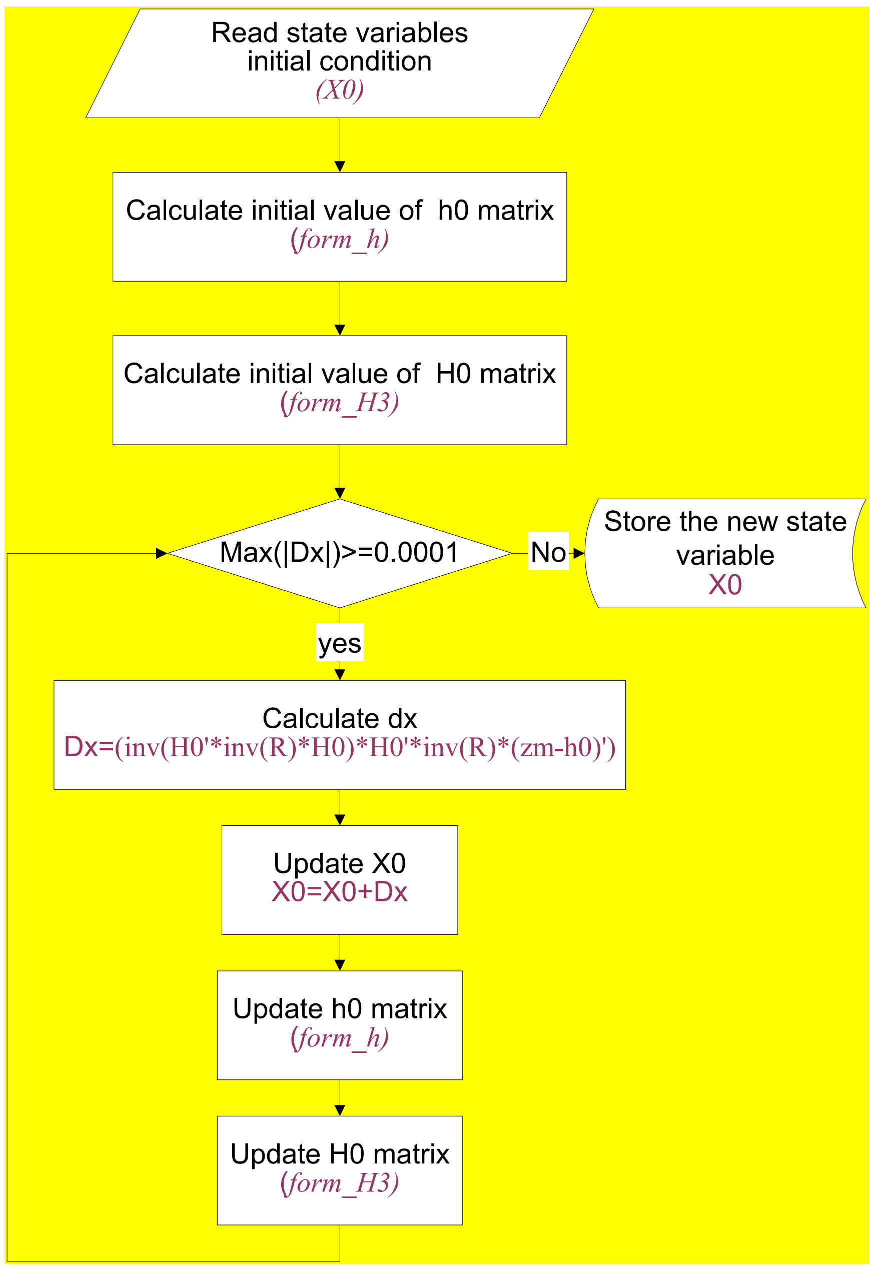


Figure C-4: Flow chart for State Estimation function *(SSE&ISE)*

## C.4. MATLAB Code for SSE and ISE Programs

**SSE_ISE**

```
% This the main program for SSE and ISE Monte-Carlo simulation
% The program reads the input data first and after that go to iteration (try_main179_phase2
% AA_diff ........ the reference angle at each iteration
% AA_hs  ......... the flow at the borderlines in ISE case
% AA_hs_split .... the flow at the border lines in SSE case
% AA_hs_whole  ......... the flow at all the lines in case of ISE.
% AA_hs_split_whole ... the flow at all the lines in case of SSE
% zm … measurement vector
% zm_whole ..... the measurements at each iteration
% std_S_diff ... the standard deviation for all the measurements [STD-SSE, STD-ISE, STD-Zm, Zm]
% std_S_diff_border ... the standard deviation for The border measurements
% MVA_split .... the estimated MVA flow in the SSE case
% MVA_one   .... the estimated MVA flow in the ISE case
% MVA_zm ....... the measurements MVA flow.
% MVA_z ........ the actual MVA came from Load flow study
% z  ……the measurement vector without any noise
% zm ….. measurement vector with noise
% zmp1 … measurement vector with noise for part 1
% zmp2 … measurement vector with noise for part 2
% R … residual matrix
% R … residual matrix for part 1
% R … residual matrix for part 2
% s_lf, s_lf1 ….the standard deviation calculated using AEP equation based on load flow output data.
% cut_set …..set of border buses between subsystems.
% cset … locations of border buses in the z matrix
% mp … locations of active power measurement
% mq … locations of reactive power measurement
% mv  …location of voltage measurement
% PP … locations of active power measurement in the z vector
% QQ … locations of reactive measurement power in the z vector
% VV … locations of voltage measurement in the z vector
% fip …. index of last active measurement in z vector
% fiq …. index of last reactive measurement in z vector
% nr …. index of last voltage measurement in z vector
% nb …. the total number of buses in the system
% nb_p1 …. the number of buses in the subsystem one
% nb_p2 …. the number of buses in the subsystem two
% G …. Transmission line conductance
% Gs …. Shunt conductance
% B …. Transmission line sysabtance
% B …. shunt sysabtance
% trn1 ….fixed transformer tapping  ratio
% trfi …. phase shifter transformer turns ratio
% slack … slack bus
% MVA_base …. MVA base
% Pflow … active power flow matrix
% Qflow … Reactive power flow matrix
% fi_diff … common angle difference
% hs_border …. tie lines calculated measurements vector calculated based on ISE states
% hs_split _border …. SSE tie lines calculated measurements vector calculated based on SSE states
% hs_whole …. the whole calculated measurements vector calculated based on ISE states
% hs_split_whole …. the whole calculated measurements vector calculated based on SSE states
% X2n …..state variable vector calculate based ISE
% X2nn …..state variable vector calculate based SSE
% MVA_split … MVA for SSE calculated measurements
% MVA_one … MVA for ISE calculated measurements
% MVA_z … MVA for the measurements z
% MVA_zm … MVA for the measurements zm
```

```
% MVA_diff_split … MVA difference between the load flow (z) and the SSE calculated measurements
% MVA_diff_one … MVA difference between the load flow (z) and the ISE calculated measurements
% MVA_diff_z … MVA difference between the load flow (z) and the measurements zm
% mean_MVA_diff_split … average MVA difference between the load flow (z) and the SSE calculated
%  measurements (MVA_diff_split)
% mean_MVA_diff_one …. average MVA difference between the load flow (z) and the ISE calculated
% measurements (MVA_diff_one)
% mean_MVA_diff_z … average MVA difference between the load flow (z) and the measurements zm
% delta_S ….. average MVA comparison for ISE, SSE, and zm
% std_S_diff ….. STD of MVA comparison for ISE, SSE, and zm
% perc10 … percentage change in MVA for ISE, SSE, and zm
% perc10_border … percentage change in MVA for ISE, SSE, and zm calculated at the border lines
% delta_S_border ….. MVA comparison for ISE, SSE, and zm at the tie lines
% delta_S_border_ave ….. average MVA comparison for ISE, SSE, and zm at the tie lines
% std_S_diff_border ….. STD of MVA comparison for ISE, SSE, and zm at the tie lines
% std_S_diff_border_ave ….. average STD of MVA comparison for ISE, SSE, and zm at the tie lines
% perc10_border_ave … percentage change in MVA for ISE, SSE, and zm at the tie lines
% fs1 … full scale vector
% T … bus angle vector
% bus … bus information matrix that is read from pti  input file
% colt … column matrix index for elements of the H matrix
% colV … row matrix index for elements of the H matrix
% kk_border …MVA calculated at the border
% Bs … shunt reactance
% PS … shunt active power branch connected to the bus
%QS … shunt reactive power branch connected to the bus
% gen … Generator information that is read from pti data
% branch … branch information that is read from pti data
% X2n … ISE angle and voltage information
% X2nn … SSE angle and voltage information




% Program initialization
clear all
close all

% Starting the reading phase
[z,s_lf,fip,fiq,nr,fs1,s_lf1,cut_set,PP,QQ,VV,mp,mq,mv,nb,nb_p1,nb_p2,G,Gs,B,Bs,trn1,trfi,bus,T,colt,colV,slack,Pflo
w,Qflow,MVA_base]=reading_input_data;

% Start Monte-Carlo simulation 500 iteration
for i=1:500

    i        % display iteration number

    % Starting the main algorithm of SSE & ISE calculations by calculating: reference angle, flow at the
    %borderline,  measurement vector
    [fi_diff,hs_border,hs_split_border,hs_whole,hs_split_whole,X2nn,X2n,zm,cset]=run_input_data(z,s_lf,fip,fiq,nr,fs
    1,s_lf1,cut_set,PP,QQ,VV,mp,mq,mv,nb,nb_p1,nb_p2,G,Gs,B,Bs,trn1,trfi,bus,T,colt,colV,slack,Pflow,Qflow,MV
    A_base);

    % Save all the data for each iteration in Monte-Carlo simulation
    AA_diff(i,:)=fi_diff;    % the reference angle at each iteration.

    AA_hs(i,:)=full(hs_border);                        %  the flow at the borderlines in ISE
    AA_hs_split(i,:)=full(hs_split_border);            %  the flow at the border lines in SSE
    AA_hs_whole(i,:)=full(hs_whole);                   %  the flow at all the lines in case of ISE
    AA_hs_split_whole(i,:)=full(hs_split_whole);  %  the flow at all the lines in case of SSE
    z_whole(i,:)=z;                     % the measurement set created from the load flow output
    zm_whole(i,:)=zm;                   % the measurement set created by adding noise to the load flow output
```

```
    comp=[X2nn(:,1) X2n(:,1)];      % Bus angle comparison between ISE and SSE

end

% MVA Calculation for ISE, SSE, measurements, and load flow outputs for the whole system
MVA_split=abs([AA_hs_split_whole(:,1:fip)+sqrt(-1)*AA_hs_split_whole(:,fip+1:fiq)]);
MVA_one=abs([AA_hs_whole(:,1:fip)+sqrt(-1)*AA_hs_whole(:,fip+1:fiq)]);
MVA_z=abs([z_whole(:,1:fip)+sqrt(-1)*z_whole(:,fip+1:fiq)]);
MVA_zm=abs([zm_whole(:,1:fip)+sqrt(-1)*zm_whole(:,fip+1:fiq)]);

% MVA difference between the load flow (Z) and  ISE, SSE, and Zm
MVA_diff_split=100*[MVA_z-MVA_split];
MVA_diff_one=100*[MVA_z-MVA_one];
MVA_diff_z=100*[MVA_z-MVA_zm];

% Averege calculation of MVA
mean_MVA_diff_split=mean(abs(MVA_diff_split));
mean_MVA_diff_one=mean(abs(MVA_diff_one));
mean_MVA_diff_z=mean(abs(MVA_diff_z));

% STD calculation of MVA
std_MVA_diff_split=std((MVA_diff_split));
std_MVA_diff_one=std((MVA_diff_one));
std_MVA_diff_z=std((MVA_diff_z));

% Percentage change in MVA
mean_MVA_z=mean(MVA_z);
perc10=[mean_MVA_diff_split./mean_MVA_z;mean_MVA_diff_one./mean_MVA_z];

% STD and Average comparison among ISE, SSE, Zm, and Z
delta_S=[mean_MVA_diff_split;mean_MVA_diff_one;mean_MVA_diff_z;100*mean_MVA_z];
std_S_diff=[std_MVA_diff_split;std_MVA_diff_one;std_MVA_diff_z;100*mean_MVA_z];

% Calculating STD at border among ISE, SSE, Zm, and Z
kk=[MVA_z(1,:);MVA_one(1,:);MVA_split(1,:)];
k4=(length(cset)/4);

for i=1:2*k4
      perc10_border(:,i)=perc10(:,cset(i)) ;
      delta_S_border(:,i)=delta_S(:,cset(i)) ;
      std_S_diff_border(:,i)=std_S_diff(:,cset(i));
      kk_border(:,i)=kk(:,cset(i));
end

for i=1:k4
      perc10_border_ave(:,i)=mean([perc10(:,cset(i)) perc10(:,cset(k4+i))]')';
      delta_S_border_ave(:,i)=mean([delta_S(:,cset(i)) delta_S(:,cset(k4+i))]')';
      std_S_diff_border_ave(:,i)=mean([std_S_diff(:,cset(i)) std_S_diff(:,cset(k4+i))]')';
end

% Save the output data
save ak1000_acc
```

---

**reading_input_data**

```
% The program reads the data of the system configuration and the load flow data
```

```
function
[z,s_lf,fip,fiq,nr,fs1,s_lf1,cut_set,PP,QQ,VV,mp,mq,mv,nb,nb_p1,nb_p2,G,Gs,B,Bs,trn1,trfi,bus,T,colt,colV,slack,Pflo
w,Qflow,MVA_base]= reading_input_data

clear all
close all

% Input data files configuration file “wscc179.pti” & load flow output file “wscc179.flw”
file_name='wscc179.pti';
file_name_flow='wscc179.flw';
slack=13; % slack for 179 WSCC system

% Set of border buses between subsystem
cut_set=[25 33 34 39;43 134 135 136];

% Reading all the buses, loads, generators, branches data
[bus,load1,gen,branch,MVA_base,bus_name]=read_pti(file_name);
branchr=rev_branch(branch); % equivalent all the parallel lines

% Reading the Load flow information
[bus1,bname,Pflow,Qflow,PL,QL,V,T,PG,QG,PS,QS,Vm] = read_flw(file_name_flow);
n_bra=size(branchr); % Number of branches after equivalent the parallel lines

% assign the number of buses for the whole system and for the two subsystem
nb=size(bus,1);
nb_p1=42;
nb_p2=nb-nb_p1;


% Calculate transmission line equivalent circuit (including fixed tapping transformer and phase shifter)
% By changing mp, mq, mv you can identify the exact location for the measurements in the network
% in this case we assumed that all the flows are measured at both side of the transmission line and no injections
% are measured
[G,B,Gs,Bs,trn1,trfi]=trans_equiv(branchr);

% Identify the measurements locations for MW, MVAR, and Voltage
    % mp … locations for measurement active power
    % mq … locations for measurement reactive power
    % mv …location for measurement voltage

% By default all the measurements for P, Q, and V flow and injections are measured
[mp,mq,mv] = M_PQV(B);

% Exclude the injection flows. No injection measurement for active or reactive power
mp=mp-speye(length(mp)) ;
mq=mq-speye(length(mq)) ;
% Injections at the border buses are measured
for i=1:size(cut_set,1)
  for j=1:size(cut_set,2)
    mp(cut_set(i,j),cut_set(i,j))=1;
    mq(cut_set(i,j),cut_set(i,j))=1;
  end
end

% Calculate the location of the measurements in the measurements matrix (z)
[PP,fip] = convert_M(mp,0);
[QQ,fiq] = convert_M(mq,fip);
[VV,nr] = convert_M(mv,fiq);


% Calculating the measurements matrix (z)
z = form_z(B,PP,QQ,VV,Pflow,Qflow,PG,QG,PL,QL,PS,QS,V,MVA_base);
```

**% Calculating the full Scale for each Voltage level**
[s_lf1,fs1,m1]=full_scale(bus, Pflow, Qflow,mp,mq,mv,PP,QQ,VV,nb,MVA_base,V,gen,branch,file_name);
s_lf=s_lf1;

**% Calculate the dynamic location of the elements of the H matrix**
[colt, colV] = statevar_indices(nb,slack);

---

**run_input_data**

**% This program is the main program for ISE and SSE**
**% The algorithm is explained in the thesis chapter 4**

function [fi_diff,hs_border,hs_split_border,hs_whole,hs_split_whole,X2nn,X2n,zm,cset]= run_input_data(z,s_lf,fip,fiq,nr,fs1,s_lf1,cut_set,PP,QQ,VV,mp,mq,mv,nb,nb_p1,nb_p2,G,Gs,B,Bs,trn1,trfi,bus,T,colt,colV,slack,Pflow,Qflow,MVA_base)

**% Add noise to the measurement "Z" by STD from load flow**
zm=noisy_meas(z,s_lf);

**% Calculated MVA flow for measurements**
mm=[sqrt(zm(1:fip).^2+zm(fip+1:fiq).^2),sqrt(zm(1:fip).^2+zm(fip+1:fiq).^2) , zm(fiq+1:nr)];
fs=sparse(noisy_meas(fs1,zeros(1,length(fs1)))); **% resize the Full scale matrix**

**% AEP equation for calculating STD**
s=sparse((0.02*mm+0.0052*fs)/3);

**% Constant sigma (comment this line when you don't need it)**
%s=mean(s_lf1)*ones(1,length(z));

**% Calculating "R" matrix**
Rs=sparse(diag(s.^2));
%[R]=zero_flow(zm,Rs); % zero flow
R=Rs;

**% Preparing the data for SSE**

**% Split "Zm", to split the measurements matrix tie-lines flow should be deleted and handled later**
[zmr,cset]=cut_reduction(zm,cut_set,PP,QQ);

**% Split the measurements matrix "Z"**
[zmp1,zmp2]=split(zmr,mp,mq,mv,nb,nb_p1,cut_set);

**% Split R matrix**
[Rr,cset]=cut_reduction(diag(R)',cut_set,PP,QQ);
[Rp1,Rp2]=split(Rr,mp,mq,mv,nb,nb_p1,cut_set);
R_p1=sparse(diag(Rp1));
R_p2=sparse(diag(Rp2));

**% Split "Z" matrix**
[G_p1,B_p1,Bs_p1,Gs_p1,trn1_p1,trfi_p1,G_p2,B_p2,Bs_p2,Gs_p2,trn1_p2,trfi_p2]= z_split(G,B,Bs,Gs,trn1,trfi,nb,nb_p1);

**% Split mp,mv,mq, PP, QQ,VV**
[mp_p1,mq_p1,mv_p1,PP_p1,QQ_p1,VV_p1,mp_p2,mq_p2,mv_p2,PP_p2,QQ_p2,VV_p2]=m_split(mp,mq,mv,nb,nb_p1);

**% intial condtions for the whole system**

```
busm=sortrows(bus,1);
E0=busm(:,8)';
th0=(pi/180)*[busm(1:slack-1,9)' busm(slack+1:length(T),9)'];

% Split initial conditions split E0 th0 T slack colt colV
E0_p1=E0(1:nb_p1);
E0_p2=E0(nb_p1+1:nb);
th0_p1=th0(1:nb_p1-1);
th0_p2=th0([nb_p1:59,61:nb-1])-T(60)*pi/180;
T_p1=busm(1:nb_p1,9);
T_p2=busm(nb_p1+1:nb,9);

% Slack choice for each region
slack_p1=13;
slack_p2=60-nb_p1;
[colt_p1, colV_p1] = statevar_indices(nb_p1,slack_p1);
[colt_p2, colV_p2] = statevar_indices(nb_p2,slack_p2);

% Correct the values of the border injection
[zm_p1,zm_p2]=correct_z(zmp1,zmp2,Pflow,Qflow,cut_set,MVA_base,PP_p1,PP_p2,QQ_p1,QQ_p2,nb_p1);

% Run ISE
disp('whole system')
[X2n,h0]=ISE(G,B,Gs,Bs,E0,th0,mp,mq,mv,PP,QQ,VV,trn1,trfi,colt,colV,slack,T,R,zm,nb);

% Run SSE part -1
disp('part I system')
[X2n_p10,h0_p1] =
SSE(G_p1,B_p1,Gs_p1,Bs_p1,E0_p1,th0_p1,mp_p1,mq_p1,mv_p1,PP_p1,QQ_p1,VV_p1,trn1_p1,trfi_p1,colt_p1,col
V_p1,slack_p1,T_p1,R_p1,zm_p1,nb_p1);

% Run SSE part -2
disp('part II system')
[X2n_p20,h0_p2] =
SSE(G_p2,B_p2,Gs_p2,Bs_p2,E0_p2,th0_p2,mp_p2,mq_p2,mv_p2,PP_p2,QQ_p2,VV_p2,trn1_p2,trfi_p2,colt_p2,col
V_p2,slack_p2,T_p2,R_p2,zm_p2,nb_p2);

% Common reference calculation with noisy measurement
[fi_diff]=common_ref(nb_p1,cut_set,zm,B,G,Bs,X2n_p10,X2n_p20,PP,QQ);

% Common reference calculation with load flow measurement
%[fi_diff]=common_ref(nb_p1,cut_set,z,B,G,Bs,X2n_p10,X2n_p20,PP,QQ);

% Bus phase angles
X2nn=[[X2n_p10;X2n_p20(:,1)-mean(fi_diff) X2n_p20(:,2)]];

% Calculating the flow based on SSE angle calculated
hs_split=form_h(G,B,Gs,Bs,X2nn(:,2),X2nn(:,1)*pi/180,mp,mq,mv,PP,QQ,VV,trn1,trfi);

% Calculating the flow based on ISE
hs=form_h(G,B,Gs,Bs,X2n(:,2),X2n(:,1)*pi/180,mp,mq,mv,PP,QQ,VV,trn1,trfi);

% Flow at tie line for ISE case
hs_border=hs(cset);

% Flow at tie line for SSE case
hs_split_border=hs_split(cset);

% Total line flow for ISE case
hs_whole=hs(1:nr);

% Total line flow for ISE case
```

```
hs_split_whole=hs_split(1:nr);
```

**read_pti**

```
% Reading all the buses, loads, generators, and branches data
% The function is designed to read from the PTI format
% The PTI format can be obtained from IEEE format using IP-flow exporting facility
% The function store these date in matrix format that can easily be handled

function   [bus,load,gen,branch,MVA_base,bus_name]=read_pti(file_name)

% open the PTI file for read
fid=fopen(file_name);
line=fgets(fid);

% Reading the header format of the file that include the MVA base rating
a=sscanf(line,'%*d %f');
MVA_base=a(1);

% Removing the two unused lines

line=fgets(fid);
linea=fgets(fid);

% Counter initialization
section=1;
kb=1;
kL=1;
kg=1;
kbr=1;

while 1

  % Read first four section that include bus, load, generator, and branch data
  line=fgets(fid);
  a1=sscanf(line,'%d');
  if(a1<=0)
         section=section+1;
         line=fgets(fid);
         if (section >4)
            break;
         end
  end

  % Read the first section “bus data”
  if (section==1)
         [a,count,err,wi]=sscanf(line,'%d',1);
         bus(kb,1)=a(1);
         bus_name(a,:)=line(wi:wi+11);
         b=sscanf(line(wi+11:length(line)),'%f %d %f %f %d %d %f %f',8);
         bus(kb,2:9)=[b(1:8)]';
         kb=kb+1;
  end

  % Reading the second section “load data”
  if (section==2)
         [a,count,err,wi]=sscanf(line,'%d',1);
         load(kL,1)=a(1);
```

```
            load_name(a,:)=line(wi:wi+4);
            b=sscanf(line(wi+4:length(line)),'%d %d %d %f %f %f %f %f %f',9);
            load(kL,2:10)=[b(1:9)]';
            kL=kL+1;
  end

  % Reading the third section  "Generator data"
  if (section==3)
            b=sscanf(line,'%d %d %f %f %f %f %f %d %f %f %f %f %f %f %d %f %f %f',18);
            gen(kg,:)=b';
            kg=kg+1;
  end

  % Reading the fourth section "Branch data"

  if(section ==4)
            [a,count,err,wi]=sscanf(line,'%d %d',2);
            branch(kbr,1:2)=a';
            ckt_id(kbr,:)=line(wi:wi+4);
            b=sscanf(line(wi+4:length(line)),'%f %f %f %f %f %f %f %f %f %f %f %f %d',13);
            branch(kbr,3:15)=[b(1:13)]';
            kbr=kbr+1;
  end
end

fclose(fid);
```

**rev_branch**

```
%Equivalent all the parallel lines & remove out of service branch from the branch data
% The SE program is designed to run without any parallel line
%  so the first step in case of parallel line that this to equivalent these lines

function   [LP1]=rev_branch(LP3)

% Detecting the parallel lines
k1 = 1;
for i=1:size(LP3,1)
        if(LP3(i,15)==1)
            LP2(k1,:)=LP3(i,:);
            k1=k1+1;
        end
end

% Modify the branch data for the parallel lines
LP=[LP2;zeros(1,size(LP2,2))];
p = LP(1,1);
q = LP(1,2);
k = 1;

sumlp=LP(1,:);
sumlpp=LP(1,3)+sqrt(-1)*LP(1,4);
LP1(1,:) = LP(1,:);

for i=2:size(LP,1)
      size(LP,1);
      if( LP(i,1)==p & LP(i,2)==q)
            sumlp=sumlp+LP(i,:);
            sumlpp=((1/sumlpp)+1/(LP(i,3)+sqrt(-1)*LP(i,4)))^(-1);
      else
            p = LP(i,1); q = LP(i,2);
```

```
            LP1(k,1) = LP(i-1,1);
            LP1(k,2) = LP(i-1,2);
            LP1(k,3) = real(sumlpp);
            LP1(k,4) = imag(sumlpp);
            LP1(k,5) = sumlp(5);
            LP1(k,6:8)= sumlp(6:8);
            LP1(k,9:10)=LP(i-1,9:10);
            LP1(k,11:14)= sumlp(11:14);
            LP1(k,15) = LP(i-1,15);
            sumlp=LP(i,:);
            sumlpp=LP(i,3)+sqrt(-1)*LP(i,4);
            k = k + 1;
        end
end
```

---

**trans_equiv**

```
% Calculating the equivalent circuit of the transmission line
%(Including the fixed tapping transformer and phase shifter)
% Calculate the parameters of the lines
% Yij= Gij + Bij series reactance of the TL
% Bsij Shunt admittance of the TL

function   [G,B,Gs,Bs,trn1,trfi]=trans_equiv(LP)

for i=1:size(LP,1)
        n1=LP(i,9); % fixed tapping transformer
        nf=LP(i,10); % phase shifter transformer

        % if the branch is just regular transmission line
        if((n1==0 |n1==1)& nf==0)
            Z(LP(i,1),LP(i,2))=sparse(LP(i,3)+j*LP(i,4));
            Z(LP(i,2),LP(i,1))=sparse(LP(i,3)+j*LP(i,4));

            trn1(LP(i,1),LP(i,2))=sparse(1);
            trn1(LP(i,2),LP(i,1))=1;
            trfi(LP(i,1),LP(i,2))=sparse(0);
            trfi(LP(i,2),LP(i,1))=0;

            Bs(LP(i,1),LP(i,2))=sparse(LP(i,5)/2);
            Bs(LP(i,2),LP(i,1))=sparse(LP(i,5)/2);


            Gs(LP(i,1),LP(i,2))=sparse(0);
            Gs(LP(i,2),LP(i,1))=sparse(0);

        % If the branch is just regular tapping transformer
        elseif(n1 ~= 0 & nf == 0 & n1~=1)
            n=p2r(n1,nf);
            Z(LP(i,1),LP(i,2))=sparse(n*(LP(i,3)+j*LP(i,4)));
            Z(LP(i,2),LP(i,1))=sparse(n*(LP(i,3)+j*LP(i,4)));
            trn1(LP(i,1),LP(i,2))=1;
            trn1(LP(i,2),LP(i,1))=1;
            trfi(LP(i,1),LP(i,2))=0;
            trfi(LP(i,2),LP(i,1))=0;

            Bs(LP(i,1),LP(i,2))=sparse(((1/n^2)-(1/n))*(-LP(i,4))/(LP(i,3)^2+LP(i,4)^2));
            Bs(LP(i,2),LP(i,1))=sparse((1-(1/n))*(-LP(i,4))/(LP(i,3)^2+LP(i,4)^2));

            Gs(LP(i,2),LP(i,1))=sparse((1-(1/n))*(LP(i,3))/(LP(i,3)^2+LP(i,4)^2));
```

```
            Gs(LP(i,1),LP(i,2))=sparse(((1/n^2)-(1/n))*(LP(i,3))/(LP(i,3)^2+LP(i,4)^2));


        % If the branch is just phase shifter transformer
        else
            n=p2r(n1,nf);
            Z(LP(i,1),LP(i,2))=sparse((LP(i,3)+j*LP(i,4)));
            Z(LP(i,2),LP(i,1))=sparse((LP(i,3)+j*LP(i,4)));
            if (LP(i,1)< LP(i,2))
                trfi(LP(i,1),LP(i,2))=nf*pi/180;
                trfi(LP(i,2),LP(i,1))=nf*pi/180;
                trn1(LP(i,1),LP(i,2))=n1;
                trn1(LP(i,2),LP(i,1))=n1;
            else
                trfi(LP(i,1),LP(i,2))=-nf*pi/180;
                trfi(LP(i,2),LP(i,1))=-nf*pi/180;
                trn1(LP(i,1),LP(i,2))=1/n1;
                trn1(LP(i,2),LP(i,1))=1/n1;
            end

                Bs(LP(i,1),LP(i,2))=0;
                Bs(LP(i,2),LP(i,1))=0;

                Gs(LP(i,2),LP(i,1))=0;
                Gs(LP(i,1),LP(i,2))=0;
    end
end

% Calculate the series impedance for the branches
[m,n]=size(Z);
for i=1:m
  for j=1:n
    if (Z(i,j)==0)
      Y(i,j)=sparse(0);
    else
      Y(i,j)=1/Z(i,j);
    end
  end
end

G=real(Y);
B=imag(Y);
```

---

**M_PQV**

```
% Form P, Q, and V Measurement Matrices

function [MP,MQ,MV] = M_PQV(B)

N = size(B,1);
MP = sign(B);
MP = MP.^2;
MP = sparse(MP)+speye(N) ;
MQ = MP;
MV = speye(N);
```

---

**convert_M**

```
% Function to convert a binary measurement matrix Mij to
% a measurement matrix with elements corresponding to the
% row indices of the corresponding measurements to h(x)

function [P,final_indx] = convert_M(P,start_indx)

k = start_indx;
for i = 1:size(P,1),
  for j = 1:size(P,2),
    if( i ~= j )
      if( P(i,j) ~= 0 )
        k = k + 1;
        P(i,j) = k;
      end
    end
  end
end

for i = 1:size(P,1),
  if( P(i,i) ~= 0 )
    k = k + 1;
    P(i,i) = k;
  end
end

final_indx = k;
```

---

**read_flw**

```
%  Reading the load flow data
% The function is design to read the load flow out data created by the IP-flow
% The output is flow at each branch in the system

function [bus,bname,Pflow,Qflow,PL,QL,V,T,PG,QG,PS,QS,Vm] = read_flw(f1)

% Open the file to read
fid=fopen(f1,'r');

% Remove the first 11 lines in the flow lines
line1 = fgets(fid);
line2= fgets(fid);
line3 = fgets(fid);
line4 = fgets(fid);
line5 = fgets(fid);
line6 = fgets(fid);
line7 = fgets(fid);
line8 = fgets(fid);
line9 = fgets(fid);
line10 = fgets(fid);
line11 = fgets(fid);

i = 1;
i1=1;
i2=1;

% Read until the end of the file
while 1
  line = fgets(fid);

  if( ~ischar(line) )
```

```
    break;
  end

% start to detect page heading to remove
  if(strcmp(line(1:2),line1(1:2)) ) % Not a Page ID
    line2= fgets(fid);
    line3 = fgets(fid);
    line4 = fgets(fid);
    line5 = fgets(fid);
    line6 = fgets(fid);
    line7 = fgets(fid);
    line8 = fgets(fid);
    line9 = fgets(fid);
    line10 = fgets(fid);
    line11 = fgets(fid);
  else
    if( length(line) > 7 ) %Not a CR
      [a,count,err,ni] = sscanf(line,'%f',1);
      if( length(a) ~= 0 ) % An floating entry

        if (ni == 8) % from bus information P (1 st line)
          A(1,i)=a;
          bus(i) = a;
          bname(bus(i),:) = line(9:24);
          b = sscanf(line(25:length(line)),'%*d %f %f %f %f %f',5);
          V(bus(i)) = b(1);
          T(bus(i)) = b(2);
          PG(bus(i)) =sparse( b(3));
          PL(bus(i)) =sparse( b(4));
          PS(bus(i)) =sparse( b(5));
          i=i+1;

        elseif (ni==36) % from bus information Q (2 nd line)

          [c,count,err,ni1] = sscanf(line,'%f %f',2);
          c1 = sscanf(line(ni1+1:length(line)),'%f %f',2);
          Vm(bus(i1)) =sparse( c(1));
          QG(bus(i1)) =sparse( c(2));
          QL(bus(i1)) =sparse( c1(1));
          QS(bus(i1)) =sparse( c1(2));
          i1=i1+1;

        else % to bus information Pflow, Qflow (3,4,.... line)

          a= sscanf(line,'%f',1);
          to_bus(i-1,i2) = a;
          e = sscanf(line(ni+32:length(line)),'%f %f',2);
          if (i2>=2 & to_bus(i-1,i2-1)==to_bus(i-1,i2))
            Pflow(bus(i-1),to_bus(i-1,i2)) =Pflow(bus(i-1),to_bus(i-1,i2-1))+sparse(e(1));
            Qflow(bus(i-1),to_bus(i-1,i2)) =Qflow(bus(i-1),to_bus(i-1,i2-1))+ sparse(e(2));
          else
            Pflow(bus(i-1),to_bus(i-1,i2)) =sparse(e(1));
            Qflow(bus(i-1),to_bus(i-1,i2)) =sparse(e(2));
          end
          i2=i2+1;

        end
      end
    end
  end
end
```

```
fclose(fid);
```

**form_z**

```
% Calculating the measurements matrix (Z matrix)
% The z matrix has the following format
% z=[P-flow; P-injection; Q-flow; Q injection; V- measurement]

function [z] = form_z(B,MP,MQ,MV,Pflow,Qflow,PG,QG,PL,QL,PS,QS,V,MVA_base)

% Calculate the P-flow
N = size(B,1);
for i = 1:N,
  for j = 1:N,
    irow = MP(i,j);
    if( irow ~= 0 )
      if( i ~= j )
        z(irow) = Pflow(i,j)/MVA_base;
      end
    end
  end
end

% Calculate the P-injection
for i = 1:N,
  irow = MP(i,i);
  if( irow ~= 0 )
    z(irow) = (PG(i) - PL(i) - PS(i))/MVA_base;
  end
end

% Calculate the Q-flow
for i = 1:N,
  for j = 1:N,
    irow = MQ(i,j);
    if( irow ~= 0 )
      if( i ~= j )
        z(irow) = Qflow(i,j)/MVA_base;
      end
    end
  end
end

% Calculate the Q-injection
for i = 1:N,
  irow = MQ(i,i);
  if( irow ~= 0 )
    z(irow) = (QG(i) - QL(i) - QS(i))/MVA_base;
  end
end

% Calculate the V-measurement
for i =1:N,
  irow = MV(i,i);
  if( irow ~= 0 )
    z(irow) = V(i);
  end
end
```

**full_scale**

```
% This program is to create fall scale file. This file is suppose to be given data
% However, in case we don't have this file, this program will create it for you
% Calculate the Full Scale for each voltage level and the STD based on load flow
% The full scale will used to calculate STD using AEP equation explained in chapter 4
% The STD is also calculated from the AEP equation but based on the load flow data

function [s,fsv,m]=full_scale(bus, Pflow, Qflow,mp,mq,mv,PP,QQ,VV,nb,MVA_base,V,gen,branch,file_name)

busn = bus(:,1);
Vbase(busn) = bus(:,2);
kV_base = unique(Vbase);
genn = gen(:,1);

% Identify generator step-up transformers
xfmr = find(branch(:,9)); % Transformer list
step_up = zeros(1,size(branch,1));
for i = 1:length(xfmr)
  if( ismember(branch(xfmr(i),1),genn) |...
      ismember(branch(xfmr(i),2),genn) )
    step_up(xfmr(i)) = 1;
  end
end

filen = strcat(file_name(1:7),'.mat');
fid=fopen(filen,'r');

% Create base flow file for each voltage level
% This file will be created the first time you use different file name

if( fid == -1 )
  disp('Full scale flow FILENAME not found!');
  disp('Will generate automatically...');
  fs = gen_fs(kV_base,Vbase,step_up,Pflow,Qflow,MVA_base,branch);
  fid=fopen(filen,'w');
  fprintf(fid,'%2d %6.2f %7.3f\n',[[1:length(kV_base)]; kV_base; fs]);
else
  table = fscanf(fid,'%d %f %f',[3,inf]);
  kV_base = table(2,:);
  fs = table(3,:);
end
fclose(fid);

% Calculating MVA flow in branches
for l = 1:size(branch,1),
  p = branch(l,1); q = branch(l,2);
  Sflow(p,q) = Pflow(p,q) + sqrt(-1)*Qflow(p,q);
  Sflow(q,p) = Pflow(q,p) + sqrt(-1)*Qflow(q,p);
end

% Normalize the flows, Compute <m>
for l = 1:size(branch,1),
  if( ~step_up(l) )
    p = branch(l,1); q = branch(l,2);
    ip = find(kV_base-Vbase(p)==0);
    iq = find(kV_base-Vbase(q)==0);
    if( PP(p,q) ~= 0 )
      irow = PP(p,q);
      m(irow) = abs( Sflow(p,q)/MVA_base );
```

```
      fsv(irow) = fs(ip);
    end

    if( PP(q,p) ~= 0 )
      irow = PP(q,p);
      m(irow) = abs( Sflow(q,p)/MVA_base );
      fsv(irow) = fs(ip);
    end

    if( QQ(p,q) ~= 0 )
      irow = QQ(p,q);
      m(irow) = abs( Sflow(p,q)/MVA_base );
      fsv(irow) = fs(iq);
    end
    if( QQ(q,p) ~= 0 )
      irow = QQ(q,p);
      m(irow) = abs( Sflow(q,p)/MVA_base );
      fsv(irow) = fs(iq);
    end
  end
end

% Now on Step-Up Transformers
Sgmax = zeros(1,max(busn));
for l = 1:size(branch,1),
  if( step_up(l) )
    p = branch(l,1); q = branch(l,2);
    if( ismember(p,genn) )
      genid = p;
    else
      genid = q;
    end

% How many machines are connected to this bus
    indx = find(gen(:,1)-genid==0);
    nmach = length(indx);

% Take the sum of MVA ratings
    for j = 1:nmach
      if( gen(indx(j),17) == 9.999e03 ) % No can't do
        Sgmax(genid) = Sgmax(genid) + ...
          abs(gen(indx(j),3) + sqrt(-1)*gen(indx(j),4) );
      else
        Sgmax(genid) = Sgmax(genid) + ...
          abs(gen(indx(j),17) + sqrt(-1)*gen(indx(j),5));
      end
    end
  end
end

% Normalize and calculate <m>
for l = 1:size(branch,1),
  if( step_up(l) )
    p = branch(l,1); q = branch(l,2);
    if( ismember(p,genn) )
      genid = p;
    else
      genid = q;
    end
    if( PP(p,q) ~= 0 )
      irow = PP(p,q);
      m(irow) = abs( Sflow(p,q) ) / MVA_base;
```

```
      fsv(irow) = 1.25*Sgmax(genid) / MVA_base;
    end
    if( PP(q,p) ~= 0 )
      irow = PP(q,p);
      m(irow) = abs( Sflow(q,p) ) / MVA_base;
      fsv(irow) = 1.25*Sgmax(genid) / MVA_base;
    end
    if( QQ(p,q) ~= 0 )
      irow = QQ(p,q);
      m(irow) = abs( Sflow(p,q) ) / MVA_base;
      fsv(irow) = 1.25*Sgmax(genid) / MVA_base;
    end
    if( QQ(q,p) ~= 0 )
      irow = QQ(q,p);
      m(irow) = abs( Sflow(q,p) ) / MVA_base;
      fsv(irow) = 1.25*Sgmax(genid) / MVA_base;
    end
  end

end

% Now go over the injections

Sflow1=Pflow+sqrt(-1)*Qflow;
Snet=abs(sum(Sflow1.'))/MVA_base; % Pnet is the Gen - Load
for i = 1:length(Snet)
  if( ~ismember(i,genn) )
    div = fs(find(kV_base-Vbase(i)==0));
    if(PP(i,i) ~= 0 )
      m(PP(i,i)) = Snet(i) / MVA_base;
      fsv(PP(i,i)) = div;
    end
    if(QQ(i,i) ~= 0 )
      m(QQ(i,i)) = Snet(i) / MVA_base;
      fsv(QQ(i,i)) = div;
    end
  end
end

% Finally the voltages
for i=1:nb
  if(mv(i,i)~=0)
    irow=VV(i,i);
    if(irow~=0)
      m(irow)=sparse(V(i));
      fsv(irow) = 1.25;
    end
  end
end

% Obviously, full scale is 1.0 for all meas except voltage
% AEP equation that used to calculate STD "s=(0.02*m+0.0052*fs)/3";
for i = 1:length(m),
  s(i) = (0.02*m(i)+0.0052*fsv(i)) / 3;
end
```

---

**statevar_indices**

```
% Calculate the dynamic location of the elements of the H matrix
% Determines the column indices of state variables
```

```
% colt --> theta;  colV --> E
% For use in the Jacobean matrix H
% N - number of buses
% Slack - slack bus number

function [colt, colV] = statevar_indices(N,slack)

k = 1;
for i = 1:N,
  if( i ~= slack)
    colt(i) = k; % Column index of state theta(i)
    k=k+1;
  else
    colt(i)=0;
  end
end
for i = 1:N,
  colV(i) = k + i-1; %  Column index of state E(i)
end
return
```

---

**noisy_meas**

```
% Add noise to the measurement Z

function [zerr]=noisy_meas(z,var)

% Generate random normal distribution noise using matlab engine
randn('state',sum(100*clock))

for i=1:length(z)
  if (abs(z(i))>0)
    zerr(i)=z(i)+var(i)*randn;
  end
end
```

---

**cut_reduction**

```
% Eliminate the flow of the tie lines from the measurements set

function [zr,cset]=cut_reduction(z,cut_set,PP,QQ)

for i=1:length(cut_set)
  PPset1(i)= PP(cut_set(1,i),cut_set(2,i));
  PPset2(i)= PP(cut_set(2,i),cut_set(1,i));
  QQset1(i)= QQ(cut_set(1,i),cut_set(2,i));
  QQset2(i)= QQ(cut_set(2,i),cut_set(1,i));
end

cset=[PPset1 PPset2 QQset1 QQset2];

for i=1:length(cset)
  if (cset~=0)
    z(cset(i))=10000;
  end
end

k=1;
for i=1:length(z)
  if(z(i)~=10000)
```

```
    zr(k)=z(i);
    k=k+1;
  else
    i=i+1;
  end
end
```

**split**

**% This program splits the whole system data "zr, mp, mq, mv" to two subsystems**

```
function [zp1,zp2]=split(zr,mp,mq,mv,nb,nb_p1,cut_set)

kk=length(cut_set);

% First subsystem
mp_p1=mp(1:nb_p1,1:nb_p1) ;
mq_p1=mq(1:nb_p1,1:nb_p1) ;
mv_p1=mv(1:nb_p1,1:nb_p1) ;

% Second subsystem
mp_p2=mp(nb_p1+1:nb,nb_p1+1:nb) ;
mq_p2=mq(nb_p1+1:nb,nb_p1+1:nb) ;
mv_p2=mv(nb_p1+1:nb,nb_p1+1:nb) ;

[PP,fip,bra_p] = convert_M_bra(mp,0);
[QQ,fiq,bra_q] = convert_M_bra(mq,fip);
[VV,nr,bra_v] = convert_M_bra(mv,fiq);

% First subsystem
[PP_p1,fip_p1,bra_p_p1] = convert_M_bra(mp_p1,0);
[QQ_p1,fiq_p1,bra_q_p1] = convert_M_bra(mq_p1,fip_p1);
[VV_p1,nr_p1,bra_v_p1]  = convert_M_bra(mv_p1,fiq_p1);

% Second subsystem
 [PP_p2,fip_p2,bra_p_p2] = convert_M_bra(mp_p2,0);
[QQ_p2,fiq_p2,bra_q_p2] = convert_M_bra(mq_p2,fip_p2);
[VV_p2,nr_p2,bra_v_p2]  = convert_M_bra(mv_p2,fiq_p2);

zp1=[zr(1:bra_p_p1) zr(bra_p+1-kk*2:bra_p+fip_p1-bra_p_p1-kk*2) zr(fip+1-kk*2:fip+bra_q_p1-fip_p1-kk*2)
zr(fip+bra_p+1-kk*4:fip+bra_p+fip_p1-bra_p_p1-kk*4) zr(fiq+1-kk*4:fiq+nr_p1-fiq_p1-kk*4)];
zp2=[zr(bra_p_p1+1:bra_p-kk*2) zr(bra_p+fip_p1-bra_p_p1-kk*2+1:fip-kk*2) zr(fip+bra_q_p1-fip_p1-kk*2+1:bra_q-
kk*4) zr(fip+bra_p+fip_p1-bra_p_p1-kk*4+1:fiq-kk*4) zr(fiq+nr_p1-fiq_p1-kk*4+1:nr-kk*4)];
```

**z_split**

**% This program splits the whole system data "G, B, Bs, Gs" to two subsystems**

```
function [G_p1,B_p1,Bs_p1,Gs_p1,trn1_p1,trfi_p1,G_p2,B_p2,Bs_p2,Gs_p2,trn1_p2,trfi_p2]=
z_split(G,B,Bs,Gs,trn1,trfi,nb,nb_p1)

% First subsystem
G_p1=G(1:nb_p1,1:nb_p1);
B_p1=B(1:nb_p1,1:nb_p1);
Bs_p1=Bs(1:nb_p1,1:nb_p1);
Gs_p1=Gs(1:nb_p1,1:nb_p1);
trn1_p1=trn1(1:nb_p1,1:nb_p1);
trfi_p1=trfi(1:nb_p1,1:nb_p1);
```

```
% Second subsystem
G_p2=G(nb_p1+1:nb,nb_p1+1:nb);
B_p2=B(nb_p1+1:nb,nb_p1+1:nb);
Bs_p2=Bs(nb_p1+1:nb,nb_p1+1:nb);
Gs_p2=Gs(nb_p1+1:nb,nb_p1+1:nb);
trn1_p2=trn1(nb_p1+1:nb,nb_p1+1:nb);
trfi_p2=trfi(nb_p1+1:nb,nb_p1+1:nb);
```

**m_split**

```
% This program splits the whole system data "mp,mq,mv" to two subsystems

function
[mp_p1,mq_p1,mv_p1,PP_p1,QQ_p1,VV_p1,mp_p2,mq_p2,mv_p2,PP_p2,QQ_p2,VV_p2]=m_split(mp,mq,mv,nb,nb_p1)

% First subsystem
mp_p1=mp(1:nb_p1,1:nb_p1) ;
mq_p1=mq(1:nb_p1,1:nb_p1) ;
mv_p1=mv(1:nb_p1,1:nb_p1) ;

% Second subsystem
mp_p2=mp(nb_p1+1:nb,nb_p1+1:nb) ;
mq_p2=mq(nb_p1+1:nb,nb_p1+1:nb) ;
mv_p2=mv(nb_p1+1:nb,nb_p1+1:nb) ;

[PP,fip,bra_p] = convert_M_bra(mp,0);
[QQ,fiq,bra_q] = convert_M_bra(mq,fip);
[VV,nr,bra_v] = convert_M_bra(mv,fiq);

% First subsystem
[PP_p1,fip_p1,bra_p_p1] = convert_M_bra(mp_p1,0);
[QQ_p1,fiq_p1,bra_q_p1] = convert_M_bra(mq_p1,fip_p1);
[VV_p1,nr_p1,bra_v_p1]  = convert_M_bra(mv_p1,fiq_p1);

% Second subsystem
[PP_p2,fip_p2,bra_p_p2] = convert_M_bra(mp_p2,0);
[QQ_p2,fiq_p2,bra_q_p2] = convert_M_bra(mq_p2,fip_p2);
[VV_p2,nr_p2,bra_v_p2]  = convert_M_bra(mv_p2,fiq_p2);
```

**convert_M_bra**

```
% Function to convert a binary measurement matrix Mij to
% a measurement matrix with elements corresponding to the
% row indices of the corresponding measurements to h(x)

function [P,final_indx,n_obs_bra] = convert_M_bra(P,start_indx)

k = start_indx;
for i = 1:size(P,1),
  for j = 1:size(P,2),
    if( i ~= j )
      if( P(i,j) ~= 0 )
        k = k + 1;
        P(i,j) = k;
      end
    end
  end
```

```
end

n_obs_bra=k;

for i = 1:size(P,1),
  if( P(i,i) ~= 0 )
    k = k + 1;
    P(i,i) = k;
  end
end
final_indx = k;
```

**correct_z**

```
% Correct the values of the border injection
% Convert the flow to the either generation or load depending to the direction
% of the tie line flow

function [z1f,z2f]=correct_z(zmp1,zmp2,Pflow,Qflow,cut_set,MVA_base,PP_p1,PP_p2,QQ_p1,QQ_p2,nb_p1)

for i=1:length(cut_set)

  Pflow1(i)=Pflow(cut_set(1,i),cut_set(2,i))/MVA_base;
  w1=cut_set(1,i);
  w=PP_p1(w1,w1);
  z1(w)=sparse(zmp1(w)-Pflow1(i));
  Pflow2(i)=Pflow(cut_set(2,i),cut_set(1,i))/MVA_base;
  w1=cut_set(2,i)-nb_p1;
  w=PP_p2(w1,w1);
  z2(w)=sparse(zmp2(w)-Pflow2(i));
  Qflow1(i)=Qflow(cut_set(1,i),cut_set(2,i))/MVA_base;
  w1=cut_set(1,i);
  w=QQ_p1(w1,w1);
  z1(w)=sparse(zmp1(w)-Qflow1(i));
  Qflow2(i)=Qflow(cut_set(2,i),cut_set(1,i))/MVA_base;
  w1=cut_set(2,i)-nb_p1;
  w=QQ_p2(w1,w1);
  z2(w)=sparse(zmp2(w)-Qflow2(i));
end

for i=1:length(z1)
  if(z1(i)==0)
    z1f(i)=zmp1(i);
  else
    z1f(i)=z1(i);
  end
end

z1f=[z1f zmp1(length(z1)+1:length(zmp1))];

for i=1:length(z2)
  if(z2(i)==0)
    z2f(i)=zmp2(i);
  else
    z2f(i)=z2(i);
  end
end

z2f=[z2f zmp2(length(z2)+1:length(zmp2))];
```

**ISE**

```
% This is the main program for the State Estimation
% The program uses the slack reference angle equals zero

 function [X2n,h0]=ISE(G,B,Gs,Bs,E0,th0,mp,mq,mv,PP,QQ,VV,trn1,trfi,colt,colV,slack,T,R,zm,nb)

X0=[th0 E0]';
th0n=ins_slack0(th0,slack,T);

% Calculate "h" matrix
h0=form_h(G,B,Gs,Bs,E0,th0n,mp,mq,mv,PP,QQ,VV,trn1,trfi);

% Calculate "H" matrix
H0 = form_H3(PP,QQ,VV,G,B,Gs,Bs,th0n,E0,colt,colV,trn1,trfi);

dx=2;
k=0

% Solve the main iterative technique for State Estimation
while (max(abs(dx))>1e-4)
  Xk1=X0+(inv(H0'*inv(R)*H0)*H0'*inv(R)*(zm-h0)');
  dx=Xk1-X0;
  mdx=max(abs(dx))
  X0=Xk1;
   th0n=ins_slack0(X0(1:nb-1),slack,T);
   E0=X0(nb:2*nb-1);
   h0=form_h(G,B,Gs,Bs,E0,th0n,mp,mq,mv,PP,QQ,VV,trn1,trfi);
   H0 = form_H3(PP,QQ,VV,G,B,Gs,Bs,th0n,E0,colt,colV,trn1,trfi);
   k=k+1
end

X2n=[th0n*180/pi ;E0']';
```

**SSE**

```
% This is the main program for the State Estimation
% The program uses the slack reference angle from load flow data


function [X2n,h0]=SSE(G,B,Gs,Bs,E0,th0,mp,mq,mv,PP,QQ,VV,trn1,trfi,colt,colV,slack,T,R,zm,nb)

X0=[th0 E0]';
th0n=ins_slack(th0,slack,T);

% Calculate "h" matrix
h0=form_h(G,B,Gs,Bs,E0,th0n,mp,mq,mv,PP,QQ,VV,trn1,trfi);

% Calculate "H" matrix
H0 = form_H3(PP,QQ,VV,G,B,Gs,Bs,th0n,E0,colt,colV,trn1,trfi);

dx=2;
k=0

% Solve the main iterative technique for State Estimation
while (max(abs(dx))>1e-6)
```

```
Xk1=X0+(inv(H0'*inv(R)*H0)*H0'*inv(R)*(zm-h0)');
  dx=Xk1-X0;
   mdx=max(abs(dx))
  X0=Xk1;
  th0n=ins_slack(X0(1:nb-1),slack,T);
  E0=X0(nb:2*nb-1);
  h0=form_h(G,B,Gs,Bs,E0,th0n,mp,mq,mv,PP,QQ,VV,trn1,trfi);
  H0 = form_H3(PP,QQ,VV,G,B,Gs,Bs,th0n,E0,colt,colV,trn1,trfi);
    k=k+1
end
X2n=[th0n*180/pi ;E0']';
```

---

**ins_slack**

**% use the slack angle as the load flow angle**

```
function [th_n]=ins_slack(th_n_1,slack,T)

ref=T(slack)*pi/180;
for i=1:length(th_n_1)+1
  if (i < slack)
    th_n(i)=th_n_1(i);
  elseif (i == slack)
    th_n(i)= ref ;
    i=i+1;
  else
    th_n(i)=th_n_1(i-1);
  end
end
```

---

**ins_slack0**

**% use the slack angle equal to zero**

```
function [th_n]=ins_slack0(th_n_1,slack,T)

ref=0;
for i=1:length(th_n_1)+1
  if (i < slack)
    th_n(i)=th_n_1(i);
  elseif (i == slack)
    th_n(i)= ref ;
    i=i+1;
  else
    th_n(i)=th_n_1(i-1);
  end
end
```

---

**form_h**

**% Calculate the h matrix**

**% The matrix h has the following format**

**% h=[Pij-flow; P-injection; Qij-flow; Qij-injection; V-measurement]**

```
function hs=form_h(G,B,Gs,Bs,E,th,mp,mq,mv,PP,QQ,VV,trn1,trfi)

nb=length(B);
```

```
for i=1:nb
  for j=1:nb
    if (j < i)
      if (trn1(i,j)==0)
        trn1(i,j)=1;
      end

% Calculate the transmission line flow "Pij, Pji, Qij, Qji"
P(i,j)=sparse((Gs(i,j)+G(i,j))*E(i)^2-(1/trn1(i,j))*E(i)*E(j)*(G(i,j)*cos(th(i)-th(j)+trfi(i,j))+B(i,j)*sin(th(i)-
th(j)+trfi(i,j))));

P(j,i)=sparse((Gs(j,i)+G(j,i))*E(j)^2*(1/trn1(i,j)^2)-(1/trn1(i,j))*E(i)*E(j)*(G(j,i)*cos(th(j)-th(i)-
trfi(j,i))+B(j,i)*sin(th(j)-th(i)-trfi(j,i))));

Q(i,j)=sparse(-(Bs(i,j)+B(i,j))*E(i)^2 +(1/trn1(i,j))*E(i)*E(j)*(B(i,j)*cos(th(i)-th(j)+trfi(i,j))-G(i,j)*sin(th(i)-
th(j)+trfi(i,j))));

Q(j,i)=sparse(-(Bs(j,i)+B(j,i))*E(j)^2*(1/trn1(i,j)^2) +(1/trn1(i,j))*E(i)*E(j)*(B(j,i)*cos(th(j)-th(i)-trfi(j,i))-
G(j,i)*sin(th(j)-th(i)-trfi(j,i))));
    end
  end
end

% Calculate the bus injection "P,Q"
Pnet=sum(P.');
Qnet=sum(Q.');

% "h" Pij-flow
for i=1:nb
  for j=1:nb
    if(mp(i,j)~=0 & i~=j)
      irow=PP(i,j);
      if(irow~=0)
        hs(1,irow)=sparse(P(i,j));
      end
    end
  end
end

% "h" P-injection
for i=1:nb
  if(mp(i,i)~=0)
    irow=PP(i,i);
    if(irow~=0)
      hs(1,irow)=sparse(Pnet(i));
    end
  end
end

% "h" Qij-flow
for i=1:nb
  for j=1:nb
    if(mq(i,j)~=0 & i~=j)
      irow=QQ(i,j);
      if(irow~=0)
        hs(1,irow)=sparse(Q(i,j));
      end
    end
  end
end
% "h" Q-injection
for i=1:nb
```

```
  if(mq(i,i)~=0)
    irow=QQ(i,i);
    if(irow~=0)
      hs(1,irow)=sparse(Qnet(i));
    end
  end
end

% "h" V-measurement
for i=1:nb
  if(mv(i,i)~=0)
    irow=VV(i,i);
    if(irow~=0)
      hs(1,irow)=sparse(E(i));
    end
  end
end
```

**form_H3**

```
% Assumes that the non-zero elements of P measurement matrix contains the
% indices of each measurement in the h(x) matrix
% Form the Jacobian of h(x)
% Structure of H
%Col.     1  2  3      n-1 n  n+1   2n-1
%State    t1 t2 t3 ... tn-1 E1 E2 ... En-1

function [H]= form_H3(mp,mq,mv,G,B,Gs,Bs,th,E,colt,colV,trn1,trfi)

N = size(B,1); % The number of buses
H(1,1) = sparse(0);

% Derivatives of Pij first
dP_dt = sparse(N,N);
dP_dE = sparse(N,N);

for i = 1:N,
  for j = 1:N,
    if( B(i,j) ~= 0 & j<i )        if (trn1(i,j)==0)
        trn1(i,j)=1;
      end

      % Derivatives Pij WRT to thetas
      dPij_dti=(-E(i)*E(j)*(1/trn1(i,j))*(B(i,j)*cos(th(i)-th(j)+trfi(i,j))-G(i,j)*sin(th(i)-th(j)+trfi(i,j))));
      dPij_dtj=(-dPij_dti);
      dPji_dti=(E(i)*E(j)*(1/trn1(i,j))*(B(i,j)*cos(th(j)-th(i)-trfi(i,j))-G(i,j)*sin(th(j)-th(i)-trfi(i,j))));
      dPji_dtj=(-dPji_dti);

      irow = mp(i,j); % Row index of measurement mp(i,j)
      irow2 = mp(j,i);

      if( irow ~= 0 )
        if( colt(i) ~= 0 ) H(irow,colt(i)) = dPij_dti ; end
        if( colt(j) ~= 0 ) H(irow,colt(j)) = dPij_dtj ; end
      end
      if( irow2 ~= 0 )
        if( colt(i) ~= 0 ) H(irow2,colt(i)) = dPji_dti; end
        if( colt(j) ~= 0 ) H(irow2,colt(j)) = dPji_dtj; end
      end
```

```
            % Derivatives Pij WRT to Es

            dPij_dEi=( 2*(Gs(i,j)+G(i,j))*E(i)-E(j)*(1/trn1(i,j))*(G(i,j)*cos(th(i)-th(j)+trfi(i,j))+B(i,j)*sin(th(i)-
            th(j)+trfi(i,j))));
            dPij_dEj=(-E(i)*(1/trn1(i,j))*(G(i,j)*cos(th(i)-th(j)+trfi(i,j))+B(i,j)*sin(th(i)-th(j)+trfi(i,j))));
            dPji_dEi=(-E(j)*(1/trn1(i,j))*(G(i,j)*cos(th(j)-th(i)-trfi(i,j))+B(i,j)*sin(th(j)-th(i)-trfi(i,j))));
            dPji_dEj=( 2*(Gs(j,i)+G(i,j))*E(j)*(1/trn1(i,j)^2)-E(i)*(1/trn1(i,j))*(G(i,j)*cos(th(j)-th(i)-
            trfi(i,j))+B(i,j)*sin(th(j)-th(i)-trfi(i,j))));

            dP_dE(i,j) = dPij_dEi;
            dP_dE(j,i) =  dPji_dEj;

             if( irow ~= 0 )
               H(irow,colV(i)) = dPij_dEi;
               H(irow,colV(j)) = dPij_dEj;
             end

             if(irow2 ~= 0)
               H(irow2,colV(i)) = dPji_dEi;
               H(irow2,colV(j)) = dPji_dEj;
             end

    end
  end
end


for i = 1:N,
  if( mp(i,i) ~= 0 ) %If measurement is available
    irow = mp(i,i);
    for j = 1:N,
      if( j == i )
        if( colt(j) ~= 0 ) H(irow,colt(j)) = sum (dP_dt(i,:)); end
        H(irow,colV(j)) = sum(dP_dE(i,:));
      else
        if( mp(i,j) ~= 0 )
          prev_row = mp(i,j);
          if( colt(j) ~= 0 ) H(irow,colt(j)) = H(prev_row,colt(j)); end
          H(irow,colV(j)) = H(prev_row,colV(j));
        end
      end
    end
  end
end

dQ_dt = sparse(N,N);
dQ_dE = sparse(N,N);
for i = 1:N,
  for j = 1:N,
    if( B(i,j) ~= 0 & j<i )

      % Derivatives Qij WRT to thetas
      dQij_dti=(-E(i)*E(j)*(1/trn1(i,j))*(G(i,j)*cos(th(i)-th(j)+trfi(i,j))+B(i,j)*sin(th(i)-th(j)+trfi(i,j))));
      dQij_dtj=(-dQij_dti);
      dQji_dti=(E(i)*E(j)*(1/trn1(i,j))*(G(i,j)*cos(th(j)-th(i)-trfi(i,j))+B(i,j)*sin(th(j)-th(i)-trfi(i,j))));
      dQji_dtj=(-dQji_dti);
      dQ_dt(i,j) = -dQij_dtj;
      dQ_dt(j,i) =  dQji_dtj;
      irow = mq(i,j); % Row index of measurement Q(i,j)
      irow2=mq(j,i);

      if( irow ~= 0 )
```

```
      if( colt(i) ~= 0 ) H(irow,colt(i)) = dQij_dti; end
      if( colt(j) ~= 0 ) H(irow,colt(j)) = dQij_dtj; end
    end

    if( irow2 ~= 0 )
      if( colt(i) ~= 0 ) H(irow2,colt(i)) = dQji_dti; end
      if( colt(j) ~= 0 ) H(irow2,colt(j)) = dQji_dtj; end
    end


% Derivatives Qij WRT to Es

    dQij_dEi=( -2*(Bs(i,j)+B(i,j))*E(i)+E(j)*(1/trn1(i,j))*(B(i,j)*cos(th(i)-th(j)+trfi(i,j))-G(i,j)*sin(th(i)-
     th(j)+trfi(i,j))));
    dQij_dEj=(E(i)*(1/trn1(i,j))*(B(i,j)*cos(th(i)-th(j)+trfi(i,j))-G(i,j)*sin(th(i)-th(j)+trfi(i,j))));
    dQji_dEi=(E(j)*(1/trn1(i,j))*(B(i,j)*cos(th(j)-th(i)-trfi(i,j))-G(i,j)*sin(th(j)-th(i)-trfi(i,j))));
     dQji_dEj=(-2*(Bs(j,i)+B(i,j))*E(j)*(1/trn1(i,j)^2)+E(i)*(1/trn1(i,j))*(B(i,j)*cos(th(j)-th(i)-trfi(i,j))-
     G(i,j)*sin(th(j)-th(i)-trfi(i,j))));
    dQ_dE(i,j) = dQij_dEi;
    dQ_dE(j,i) =  dQji_dEj;

    if( irow ~= 0 )
      H(irow,colV(i)) = dQij_dEi;
      H(irow,colV(j)) = dQij_dEj;
    end

    if(irow2 ~= 0)
      H(irow2,colV(i)) = dQji_dEi;
      H(irow2,colV(j)) = dQji_dEj;
    end
   end
  end
end

for i = 1:N,
  if( mq(i,i) ~= 0 )
    irow = mq(i,i);
    for j = 1:N,
      if( j == i )
        if( colt(j) ~= 0 ) H(irow,colt(j)) = sum(dQ_dt(i,:)); end
        H(irow,colV(j)) = sum(dQ_dE(i,:));
      else
        if( mq(i,j) ~= 0 )
          prev_row = mq(i,j);
          if( colt(j) ~= 0 ) H(irow,colt(j)) = H(prev_row,colt(j)); end
          H(irow,colV(j)) = H(prev_row,colV(j));
        end
      end
    end
  end
end

% Finally, simple identity matrix for measured Es
for i = 1:N,
  if( mv(i,i) ~= 0 )
    irow = mv(i,i);
    H(irow,colV(i)) = 1;
  end
end
```

**common_ref**

**% Calculate the angle difference using pi equivalent of the tie lines**

```
function [fi_diff]=common_ref(nb_p1,cut_set,zm,B,G,Bs,X2n_p10,X2n_p20,PP,QQ)

for i=1:length(cut_set)
   k1=PP(cut_set(1,i),cut_set(2,i));
   k2=QQ(cut_set(1,i),cut_set(2,i));
   Ps=zm(k1)
   Qs=zm(k2)
    Z=1/(G(cut_set(1,i),cut_set(2,i))+sqrt(-1)*B(cut_set(1,i),cut_set(2,i)));
   Bt=Bs(cut_set(1,i),cut_set(2,i));
   Vs=X2n_p10(cut_set(1,i),2)
    fis=X2n_p10(cut_set(1,i),1)
    Xc=1/Bt;
   Qc=Vs^2/Xc;
   fi= -(180/pi)*atan((Qc+Qs)/Ps)
   Is=p2r(Ps/(Vs*cos(fi*pi/180)),fi+fis)
   V=p2r(Vs,fis)-Is*(Z);
   fiv(i)=angle(V)*180/pi;
   ff(i)=X2n_p20(cut_set(2,i)-nb_p1,1);
end
    fi_diff=ff-fiv;
```

# Appendix D. Tracing Load Flow Program Code

## D.1. General

This appendix contains the input and output data format for the TLF program explained in Chapter 5. A simplified flow chart for the main function included in this program and explained. A user manual is included to simplify the end user process for running the program. Detailed MATALB codes with helpful comments for all main programs and the functions used in those programs is also documented.

## D.2. User Manual for Using TLF Program

The main input of the TLF program is PTI format of the system topology (*wscc179.pti*). In addition to the PTI input data file, some other information (section 5.5) like contingency data, dispatching strategy due to generator outage, and installed generator capacities are needed to run the program. All input data locations are highlighted in the main program and the related functions.

The TLF is capable of tracing all the power system variables during its path of the basic load flow until hitting any kind of violation. For instance, the program can trace the following variables:

- Thermal limit margin of each transmission line in the system for fast screening (*mmm*) and for precise screening (*mmmp*).
- Generators dispatch for fast screening (*ggg*) and for precise screening (*gggp*)
- Transmission line flows (*Fin_flow_I, Fin_flow_J*)
- Most distributed voltage buses have greater change in voltage from the base case to the system violation (*Critical_Volatge*)
- Most distributed angle lines have the maximum angle between its ends (*critical_angle*)

The TLF program also has graphical representation outputs for the voltage critical buses as many examples show in Chapter 5 (Figure 5-4,Figure 5-8). The program also includes a summary report for the TTC calculations (Figure D-1) as an output:

- Critical line is the first line that has thermal violation.
- The base flow at the critical line.
- TTC from generator point of view.
- TTC from load point of view.
- TTC from tie lines point of view.

```
Critical_line   82     Base flow at this line    =   -1282.9317  MW
TTC at genrator area =   1250.4238 MW
TTC at load area =   -975 MW
TTC at tie lines =   1103.1938 MW
Buses Critical voltage   41  11  10   9
line of Critical angle  170
```

Figure D-1: TLF output report

### D.3. Flow Charts for the TLF Main Program and Main Functions

The main flow chart of the TLF program is explained in Chapter 5. Figure 5-1 shows the detailed algorithm for TLF, this algorithm is encoded using MATLAB as shown in the following section (*TLF_WSCC*). The TLF mainly executes two main loops for TTC calculations, in each loop the program is updating the generator dispatch based on the scenario chosen (GG, LG scenarios). The GG generator updating (*gen_updating_wscc*) scenario is explained in Figure D-2.

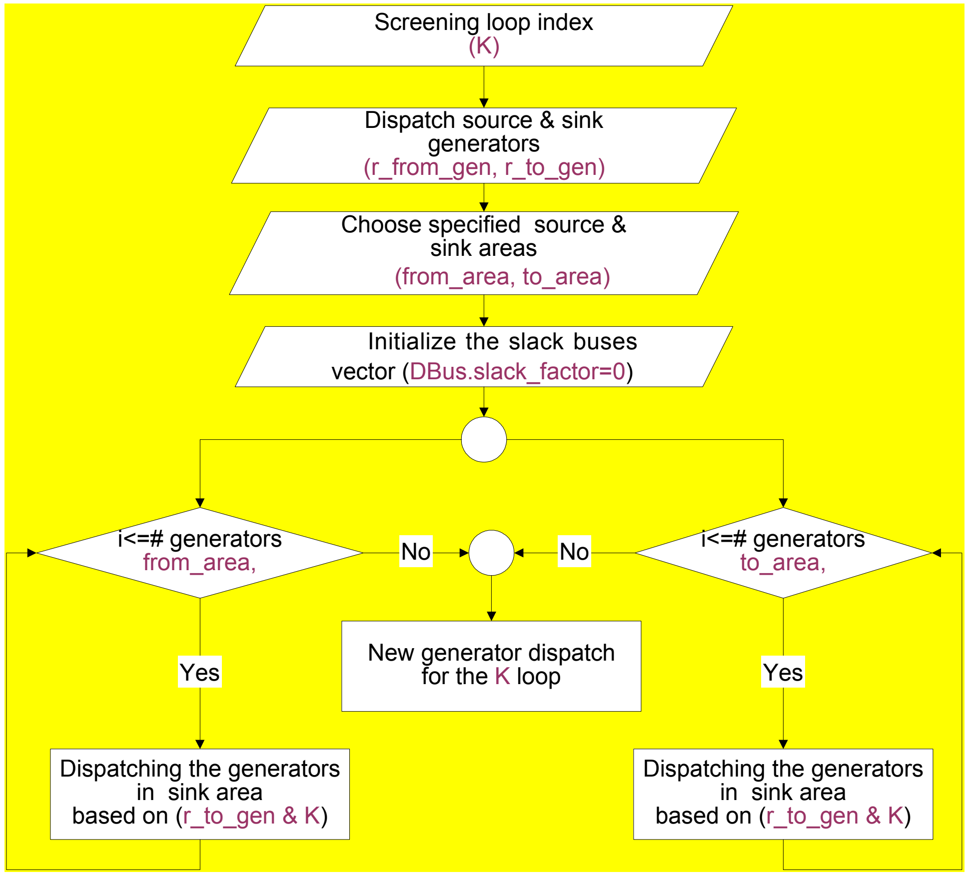


Figure D-2: GG scenario for generator update

## D.4. TLF Main Program Code

**TLF_WSCC**

```
% Main Tracing load flow program
clear all
close all

% Read the input data file in "PTI" format
[bus,load,gen,branch,MVA_base,bus_name]=read_pti('Abdo179_ord.pti'); % area C

% Change the input data to stracture format
[DBus,DBranch,w,R]=fil_bus1(bus,bus_name,load,gen,branch,MVA_base);
clear bus load gen branch MVA_base bus_name;

% If we need to run contingency case uncommnent the following branch status
%DBranch.Status(67)=0;

% If we need use emergency transmission line rating uncommnent the following branch rates
%DBranch.RATES(:,3)=DBranch.RATES(:,3)*1.1;

% If we need use generator outage uncommnent the following threelines
%DBus.Spugen(171)=0;
%DBus.Spuload(171)=0;
%DBus.type(171)=1;

% Generator outage compensation can be assign by identifying the generators will contribute for this outage
% By changing the slack factor as the following example
% DBus.slack_factor([13,45,61,55,73])=[0,2200,2200,2200,1000]/sum([0,2200,2200,2200,1000]);
% In this example generators 45,61,55,73 will contribute propotinally for the outage of generator 50
% The slack bus (13) is set to zero which means that this gen will not contribute for the outage.

% Set the step factor for the precise TTC calculation to 5 %
acu=0.05;

% Run the base load flow
[BBus,BBranch,BInternal] = lf_org(DBus,DBranch,[]);

% Choose the generator contribution scenario
% SS is proportional factor can be changed as the step factor but for the fast screening loop
SS=1;

% Area A has the following generators [92,94,99,103,111,123,128,148,154,165,171,178].
% Generators capacity in area A
adg=([1200,2200,2200,4000,3000,1000,4000,1400,800,400,200,400]);
Adg=SS*adg./sum(adg);

% Area B has the following generators [45,50,55,61,63,64,66,70,73,81,85]
% installed capacity of generators in area B
bdg=([2200,600,2200,2200,1400,2200,1200,2200,1000,3000,2200]);
Bdg=SS*bdg./sum(bdg);

% Area B has the following generators [1,5,8,13,19,42]
% installed capacity of generators in area C
cdg=([5400,5400,12000,6400,1600,3600]); % area C
Cdg = SS*cdg./ sum(cdg);

% Precision level
min_margin=1;
```

```
% Initialization for the fast screening loop
k=1;
PBus=DBus;
PBus.Spugen=BBus.Spugen;

mis_match=0.000001;

% Start the fast screening loop
while (min_margin >=0 & mis_match<=0.001)

% Choose the two areas for TTC calculations and update the generator dispatch based on the previous scenario
   [DBus]=gen_update_wscc(PBus,'C','A',Cdg,Adg,k);    % C-A
   %[DBus]=gen_update_wscc(PBus,'A','B',Adg,Bdg,k); % A-B
   %[DBus]=gen_update_wscc(PBus,'B','A',Bdg,Adg,k); % B-A

 % Run one step load flow based on the new dispatch
   [ABus,ABranch,AInternal] = lf_org(DBus,DBranch,[]);

 % calculate the thermal margin
   mmm(:,k)=BBranch.RATES(:,3)-((abs(ABranch.IMVA) + abs(ABranch.JMVA))./2);

% Calculate the angle across each transmission line
   AAA(:,k)=[angle(ABus.V(ABranch.I))*180/pi-angle(ABus.V(ABranch.J))*180/pi];

% Calculate the new generator dispatches
   ggg(:,k)=real(ABus.Spugen);

% Calculate the voltage change at each bus
   vvv(:,k)=abs(BBus.V) - abs(ABus.V);

% Calculate the voltage at each bus
   vvvA(:,k)=ABus.V;

% Calculate the flow at each branch

   fffI(:,k)=ABranch.IMVA;
   fffJ(:,k)=ABranch.JMVA;

% Update the initial voltage condition for the next iteration
   DBus.V=ABus.V;

% Calculate the min margin for testing violation
   min_margin=min(min(mmm));
   mis_match =  max(abs(ABus.mismatch))
   [V,Rank]=min(mmm)
   k=k+1;
end

'Finish of intial screeing'
k

% Check for confidence interval for fast screening loop if the margin is less than 1 MW stop.
% Otherwise, starts the precise loop iteration

if   min (abs(mmm(:,1:k-2))) >1
   gg=min(mmm);
   acu2=acu;

% intilization for the precise screening loop
   min_marginp=1;
   mis_match=0.000001;
```

```
    kp=1;
    SBus=ABus;
    SBus.Spugen=ggg(:,k-2);
    SBus.V=BBus.V - vvv(:,k-2);

% Start the precise screening loop
    while (min_marginp >=0 & mis_match<=0.001)

 % Choose the two areas for TTC calculations and update the generator dispatch based on the previous scenario
        [DBus]=gen_update_wscc(SBus,'C','A',Cdg,Adg,kp*acu2); % C-A
        %[DBus]=gen_update_wscc(SBus,'A','B',Adg,Bdg,kp*acu2); % A-B
        %[DBus]=gen_update_wscc(SBus,'B','A',Bdg,Adg,kp*acu2); % B-A

% Run one step load flow based on the new dispatch
        [ABus,ABranch,AInternal] = lf_org(DBus,DBranch,[]);

% Calculate the thermal margin
        mmmp(:,kp)=BBranch.RATES(:,3)-((abs(ABranch.IMVA) + abs(ABranch.JMVA))./2);

% Calculate the angle across each transmission line
        AAAp(:,kp)=[angle(ABus.V(ABranch.I))*180/pi-angle(ABus.V(ABranch.J))*180/pi];

% Calculate the new generator dispatches
        gggp(:,kp)=real(ABus.Spugen);

% Calculate the voltage change at each bus
        vvvp(:,kp)=abs(BBus.V) - abs(ABus.V);

% Calculate the voltage at each bus
        vvvpA(:,kp)=ABus.V;

% Calculate the flow at each branch
        fffIp(:,kp)=ABranch.IMVA;
        fffJp(:,kp)=ABranch.JMVA;

% Update the initial voltage condition for the next iteration
        SBus.V=ABus.V;

% Calculate the min margin for testing violation
        mis_match =  max(abs(ABus.mismatch))
        min_marginp=min(min(mmmp))

        kp=kp+1;
    end
    kp
end

% If we only have fast screening because the margin is within the confidence interval

if (min(abs(mmm(:,k-2))) <=1 | kp <= 2)

        % Determine the rank of transmission that has the minimum margin
            [V,Rank]=min(mmm(:,k-2));

        % Determine the original transmission line flow
            orignal_flow=real((BBranch.IMVA - BBranch.JMVA)./2);

        % Determine the transmission line flow just before the contingency
            Fin_flow_I=real(fffI(:,k-2));
            Fin_flow_J=real(fffJ(:,k-2));
```

```
    % Determine the generator dispatch just before the contingency
      Fin_gen=real(ggg(:,k-2));

    % Determine the base flow at the transmission that has the minimum margin
     Critical_line_flow=orignal_flow(Rank);

    % Determine the most distributed voltage buses
     Critical_Voltage=sortrows([[1:length(BBus.V)]' abs(vvv(:,k-2))],2);

    % Determine the most distributed angle between the transmission line ends
     Critical_angle=sortrows([[1:length(BBranch.I)]' abs(AAA(:,k-2))],2);

% If we have precise screening  loop
elseif (min(abs(mmm(:,k-2)))>1 )

    % Determine the rank of transmission that has the minimum margin
      [V,Rank]=min(mmmp(:,kp-2));

    % Determine the original transmission line flow
      orignal_flow=real((BBranch.IMVA - BBranch.JMVA)./2);

    % Determine the transmission line flow just before the contingency
      Fin_flow_I=real(fffIp(:,kp-2));
      Fin_flow_J=real(fffJp(:,kp-2));

    % Determine the generator dispatch just before the contingency
      Fin_gen=real(gggp(:,kp-2));

    % Determine the base flow at the transmission that has the minimum margin
      Critical_line_flow=orignal_flow(Rank);

    % Determine the most distributed voltage buses
      Critical_Voltage=sortrows([[1:length(BBus.V)]' abs(vvvp(:,kp-2))],2);

    % Determine the most distributed angle between the transmission line ends
      Critical_angle=sortrows([[1:length(BBranch.I)]' abs(AAAp(:,kp-2))],2);
end

% TTC outputs calculation report
%[TTC_tie,TTC_load,TTC_gen]=TTC_report('B','A', BBranch, BBus, Fin_flow_I, Fin_flow_J, Fin_gen); % B-A
[TTC_tie,TTC_load,TTC_gen]=TTC_report('C','A', BBranch, BBus, Fin_flow_I, Fin_flow_J, Fin_gen); % C-A
%[TTC_tie,TTC_load,TTC_gen]=TTC_report('A','B', BBranch, BBus, Fin_flow_I, Fin_flow_J, Fin_gen); % A-B

% Output display report
disp(['Critical_line   ' num2str(Rank) '     Base flow at this line    =  ' num2str(Critical_line_flow)   '  MW'])
disp(['TTC at genrator area =   ' num2str(TTC_gen*100)      ' MW'])
disp(['TTC at load area =   ' num2str(TTC_load*100)      ' MW'])
disp(['TTC at tie lines =   ' num2str(TTC_tie)      ' MW'])

figure(1);
disp([' Buses Critical voltage ' num2str(fliplr(Critical_Voltage(size(vvv,1)-3:size(vvv,1),1)'))])
plot(abs(vvvA(Critical_Voltage(fliplr(size(vvv,1)-3:size(vvv,1)),1),1:k-2))');grid
title('Critical lines voltage')
xlabel('Fast screening step')
ylabel('Bus pu voltage')
figure(2)
disp(['line of Critical angle  ' num2str(Critical_angle(length(BBranch.I)))])
plot(AAA(Critical_angle(length(BBranch.I),1),1:k-2));grid
title('Line of Critical Angle ')
xlabel('Fast screening step')
ylabel('Bus-angle degree')
```

**gen_update_wscc**

```
% Changing the operating condition for fast screening and fine screening algorithm using GG scenario

function [DBus]= gen_update_wscc (DBus, from_area, to_area, r_from_gen, r_to_gen, k)

% Initializing the slack factor information
DBus.slack_factor=zeros(179,1);

% Input generator set in each area
Ag=[92,94,99,103,111,123,128,148,154,165,171,178];
Bg=[45,50,55,61,63,64,66,70,73,81,85];
Cg=[1,5,8,13,19,42];

% Start GG scenario between area C and area A
if (from_area == 'C' & to_area == 'A')

   % Generation drop in area A
   for i=1:length(Ag)
      if DBus.type(Ag(i)) >1
         DBus.Spugen(Ag(i),1)=DBus.Spugen(Ag(i),1)-r_to_gen(i)*k;
      end
   end

   % Generation increase in area C
   for i=1:length(Cg)
      if DBus.type(Cg(i)) > 1
         DBus.slack_factor(Cg(i))=r_from_gen(i);
      end
   end

% Start GG scenario between area C and Area B
elseif (from_area == 'C' & to_area == 'B')

   % Generation drop in area B
   for i=1:length(Bg)
      if DBus.type(Bg(i)) >1
         DBus.Spugen(Bg(i),1)=DBus.Spugen(Bg(i),1)-r_to_gen(i)*k;
      end
   end

   % Generation increase in area C
   for i=1:length(Cg)
      if DBus.type(Cg(i)) > 1
         DBus.slack_factor(Cg(i))=r_from_gen(i);
      end
   end

% Start GG scenario between area A and Area B
elseif (from_area == 'A' & to_area == 'B')

   % Generation drop in area B
   for i=1:length(Bg)
      if DBus.type(Bg(i)) >1
         DBus.Spugen(Bg(i),1)=DBus.Spugen(Bg(i),1)-r_to_gen(i)*k;
      end
   end

   % Generation increase in area A
   for i=1:length(Ag)
      if DBus.type(Ag(i)) > 1
         DBus.slack_factor(Ag(i))=r_from_gen(i);
```

```
    end
  end

% Start GG scenario between area A and Area C
elseif (from_area == 'A' & to_area == 'C')

  % Generation drop in area C
  for i=1:length(Cg)
    if DBus.type(Cg(i)) >1
      DBus.Spugen(Cg(i),1)=DBus.Spugen(Cg(i),1)-r_to_gen(i)*k;
    end
  end

  % Generation increase in area A
  for i=1:length(Ag)
    if DBus.type(Ag(i)) > 1
      DBus.slack_factor(Ag(i))=r_from_gen(i);
    end
  end

% Start GG scenario between area B and Area C
elseif (from_area == 'B' & to_area == 'C')

  % Generation drop in area C
  for i=1:length(Cg)
    if DBus.type(Cg(i)) >1
      DBus.Spugen(Cg(i),1)=DBus.Spugen(Cg(i),1)-r_to_gen(i)*k;
    end
  end

  % Generation increase in area B
  for i=1:length(Bg)
    if DBus.type(Bg(i)) > 1
      DBus.slack_factor(Bg(i))=r_from_gen(i);
    end
  end

% Start GG scenario between area B and Area A
elseif (from_area == 'B' & to_area == 'A')

  % Generation drop in area A
  for i=1:length(Ag)
    if DBus.type(Ag(i)) >1
      DBus.Spugen(Ag(i),1)=DBus.Spugen(Ag(i),1)-r_to_gen(i)*k;
    end
  end

  % Generation increase in area B
  for i=1:length(Bg)
    if DBus.type(Bg(i)) > 1
      DBus.slack_factor(Bg(i))=r_from_gen(i);
    end
  end
end
```

**TTC_report**

```
% TTC from tie lines, load, and generator point of view  [TTC_tie,TTC_load,TTC_gen]

function [TTC_tie,TTC_load,TTC_gen]=TTC_report(from_area, to_area, BBranch, BBus, Fin_flow_I, Fin_flow_J,
Fin_gen)

% Input generator set in each area
Ag=[92,94,99,103,111,123,128,148,154,165,171,178];
Bg=[45,50,55,61,63,64,66,70,73,81,85];
Cg=[1,5,8,13,19,42];

% This section for is elaborated for WSCC system.
% Tie lines determination among the subsystems

% Tie lines of area A. [196,197,195,15,178,175,172]; J J J J J J J
A_tie=[find(BBranch.I==80 & BBranch.J==91);find(BBranch.I==84 & BBranch.J==90);find(BBranch.I==88 &
BBranch.J==89);find(BBranch.I==33 & BBranch.J==134);find(BBranch.I==34 &
BBranch.J==135);find(BBranch.I==39 & BBranch.J==136)];

% Tie lines of area B. 196,197,195,15,94]; I I I I J
B_tie=[find(BBranch.I==80 & BBranch.J==91);find(BBranch.I==84 & BBranch.J==90);find(BBranch.I==88 &
BBranch.J==89);find(BBranch.I==25 & BBranch.J==43)];

% Tie lines of area C [175,178,172,94];  I I I I
C_tie=[find(BBranch.I==33 & BBranch.J==134);find(BBranch.I==34 & BBranch.J==135);find(BBranch.I==39 &
BBranch.J==136);find(BBranch.I==25 & BBranch.J==43)];

% TTC from area B to area A
if (from_area == 'B' & to_area == 'A')

  % Original flow at the tie lines
   Org_flow_B=real(BBranch.IMVA(B_tie(1),1))+real(BBranch.IMVA(B_tie(2),1))+real(BBranch.IMVA(B_tie(3),1
   ))+real(BBranch.IMVA(B_tie(4),1))+real(BBranch.JMVA(B_tie(5),1));
    %Org_flow_B=sum(real(BBranch.IMVA(B_tie,1)));

  % Final flow at the tie lines
   Fin_flow_B=real(Fin_flow_I(B_tie(1),1))+real(Fin_flow_I(B_tie(2),1))+real(Fin_flow_I(B_tie(3),1))+real(Fin_flo
   w_I(B_tie(4),1))+real(Fin_flow_J(B_tie(5),1));
  %Fin_flow_B=sum(real(Fin_flow_I(B_tie,1)));

 % TTC from generator point of view
  TTC_B_A_gen_diff=Fin_gen-real(BBus.Spugen);
  TTC_gen=sum(TTC_B_A_gen_diff(Bg));

 % TTC from tie line point of view
  TTC_tie=Fin_flow_B-Org_flow_B;

 % TTC from load point of view
  TTC_load=sum(TTC_B_A_gen_diff(Ag));


% TTC from area B to area C
elseif (from_area == 'B' & to_area == 'C')


   Org_flow_B=real(BBranch.IMVA(B_tie(1),1))+real(BBranch.IMVA(B_tie(2),1))+real(BBranch.IMVA(B_tie(3),1
   ))+real(BBranch.IMVA(B_tie(4),1))+real(BBranch.JMVA(B_tie(5),1));

   Fin_flow_B=real(Fin_flow_I(B_tie(1),1))+real(Fin_flow_I(B_tie(2),1))+real(Fin_flow_I(B_tie(3),1))+real(Fin_flo
   w_I(B_tie(4),1))+real(Fin_flow_J(B_tie(5),1));
  TTC_B_C_gen_diff=Fin_gen-real(BBus.Spugen);
  TTC_gen=sum(TTC_B_C_gen_diff(Bg));
```

```
   TTC_tie=Fin_flow_B-Org_flow_B;
   TTC_load=sum(TTC_B_C_gen_diff(Cg));

% TTC from area C to area A
elseif (from_area == 'C' & to_area == 'A')
   Org_flow_C=sum(real(BBranch.IMVA(C_tie,1)));
   Fin_flow_C=sum(real(Fin_flow_I(C_tie,1)));
   TTC_C_A_gen_diff=Fin_gen-real(BBus.Spugen);
   TTC_tie=Fin_flow_C-Org_flow_C;
   TTC_load=sum(TTC_C_A_gen_diff(Ag));
   TTC_gen=sum(TTC_C_A_gen_diff(Cg));

% TTC from area C to area B
elseif (from_area == 'C' & to_area == 'B')
   Org_flow_C=sum(real(BBranch.IMVA(C_tie,1)));
   Fin_flow_C=sum(real(Fin_flow_I(C_tie,1)));
   TTC_C_B_gen_diff=Fin_gen-real(BBus.Spugen);
   TTC_tie=Fin_flow_C-Org_flow_C;
   TTC_load=sum(TTC_C_B_gen_diff(Bg));
   TTC_gen=sum(TTC_C_B_gen_diff(Cg));

% TTC from area A to area B
elseif (from_area == 'A' & to_area == 'B')
   Org_flow_A=sum(real(BBranch.JMVA(A_tie,1)));
   Fin_flow_A=sum(real(Fin_flow_J(A_tie,1)));
   TTC_A_B_gen_diff=Fin_gen-real(BBus.Spugen);
   TTC_tie=Fin_flow_A-Org_flow_A;
   TTC_load=sum(TTC_A_B_gen_diff(Bg));
   TTC_gen=sum(TTC_A_B_gen_diff(Ag));

% TTC from area A to area C
elseif (from_area == 'A' & to_area == 'C')
   Org_flow_A=sum(real(BBranch.JMVA(A_tie,1)));
   Fin_flow_A=sum(real(Fin_flow_J(A_tie,1)));
   TTC_A_C_gen_diff=Fin_gen-real(BBus.Spugen);
   TTC_tie=Fin_flow_A-Org_flow_A;
   TTC_load=sum(TTC_A_C_gen_diff(Cg));
   TTC_gen=sum(TTC_A_C_gen_diff(Ag));

end
```

---

```
% this version is corrected by Khatib
function [Bus,Branch,Internal] = lf_org(Bus,Branch,Internal)
%usage:  [Bus,Branch,Internal] = lf(Bus,Branch,Internal)
% This routine performs a simple loadflow and removes dead branches from network (but doesn't check for islands)
%Limits are not enforced in this routine
%  THIS IS DISCUSSION CODE
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% DATA STRUCTURE
%Branch =
%       Status: 1 = in 0 = out
%        I: metered bus index
%        J: non-metered bus index
%      NAME:
%        Z: p.u.impedance
%        B: p.u charging
%       YI: shunt admittance at metered bus
%       YJ: shunt admittance at non-metered bus
%      TAP: complex tap
%    RATES: [43x3  sparse] MVA ratings
```

```
%   IpuAmps: [43x1  sparse]
%   JpuAmps: [43x1  sparse]
%     IMVA: [43x1  sparse]
%     JMVA: [43x1  sparse]
%Bus =
%    NAME:
%    NUMBER:
%    Spuload:
%    Spugen:
%             YL:
%    type:
%    slack_factor: the proportion of slack generation provided at each bus
%                    These factors can be set according to a governor dispatch, economic dispatch, or other.
%                    Simple solution is  Bus.slack_factor = sparse(length(Bus.type),1);
%                                         Bus.slack_factor(find(Bus.type == 3)) = 1;
%                    This will let the reference bus pick up all the slack;
%                    Note that you can have a source sink transaction by leaving the Stress.Source empty
%                    and thus the entie transaction plus losses will be assummed by the slacks
%          Vlow: pu minimum voltage magnitude
%   Vmax: pu maxmimum voltage magnitude
%   V: pu complex voltage
%          Qgmax:pu
%          Qgmin:
%          Pgmax:
%          Pgmin:
%  mismatch:

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% remove dead Branches
branchesin = find(Branch.Status == 1);
Branch.Status = Branch.Status(branchesin) ;
Branch.I = Branch.I(branchesin);
Branch.J = Branch.J(branchesin);
Branch.B = Branch.B(branchesin);
Branch.Z = Branch.Z(branchesin);
Branch.YI = Branch.YI(branchesin);
Branch.YJ = Branch.YJ(branchesin);
Branch.TAP = Branch.TAP(branchesin);
Branch.RATES = Branch.RATES(branchesin,:);
Branch.NAME = Branch.NAME(branchesin,:);

% Construct the bus admittance matrix
nbus = length(Bus.NUMBER);
nbranch = length(Branch.I);
Internal.Ybus=diag(sparse(Bus.YL));
Internal.Ybus=Internal.Ybus+sparse(Branch.J,Branch.J,1./Branch.Z+i*Branch.B/2,nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.I,Branch.J,-1./(Branch.TAP.*Branch.Z),nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.J,Branch.I,-1./(conj(Branch.TAP).*Branch.Z),nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.I,Branch.I,1./((abs(Branch.TAP).^2).*Branch.Z)+i*Branch.B/2,nbus,nbus)
;
Internal.Ybus=Internal.Ybus+sparse(Branch.I,Branch.I,Branch.YI,nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.J,Branch.J,Branch.YJ,nbus,nbus);

% Construct the branch admittance matrix
nbrvec=(1:nbranch)';
%YflowI=sparse(nbrvec,Branch.I,1./Branch.Z+i*Branch.B/2+Branch.YI,nbranch,nbus);
%YflowI=YflowI+sparse(nbrvec,Branch.J,-1./(Branch.TAP.*Branch.Z),nbranch,nbus);
%YflowJ=sparse(nbrvec,Branch.I,-1./(conj(Branch.TAP).*Branch.Z),nbranch,nbus);
%YflowJ=YflowJ+sparse(nbrvec,Branch.J,1./((abs(Branch.TAP).^2).*Branch.Z)+i*Branch.B/2+Branch.YJ,nbranch,nb
us);
YflowJ=sparse(nbrvec,Branch.J,1./Branch.Z+i*Branch.B/2+Branch.YJ,nbranch,nbus);
```

```
YflowJ=YflowJ+sparse(nbrvec,Branch.I,-1./(Branch.TAP.*Branch.Z),nbranch,nbus);
YflowI=sparse(nbrvec,Branch.J,-1./(conj(Branch.TAP).*Branch.Z),nbranch,nbus);
YflowI=YflowI+sparse(nbrvec,Branch.I,1./((abs(Branch.TAP).^2).*Branch.Z)+i*Branch.B/2+Branch.YI,nbranch,nbus
);


% Confirm that the initial case is a loadflow solution

ibus=Internal.Ybus*Bus.V;%ibus is the current injected in each node
Bus.mismatch = Bus.V.*conj(ibus) + Bus.Spuload - Bus.Spugen;

%compute the flows
Branch.IpuAmps=YflowI*Bus.V;
Branch.JpuAmps=YflowJ*Bus.V;
Branch.IMVA = 100*Branch.IpuAmps.*conj(Bus.V(Branch.I));
Branch.JMVA = 100*Branch.JpuAmps.*conj(Bus.V(Branch.J));

% if initial case is solved, do the predictor step
% Use DeMarco's method to construct the Jacobian matrix;
%  I learned this from Professor Chris Demarco. Simple and Powerful.
% NOTE : ANYBODY WHO USES THIS METHOD IN SUBSEQUENT SOFTWARE PLEASE GIVE
% CREDIT TO PROFESSOR DEMARCO
% AND THE UNIVERSITY OF WISCONSIN MADISON

dSdd =j*diag(conj(ibus).*Bus.V) ...
  - j*diag(Bus.V)*conj(Internal.Ybus)*diag(conj(Bus.V));
dSdv = diag(conj(ibus).*(Bus.V./abs(Bus.V))) ...
  + diag(Bus.V)*conj(Internal.Ybus)*diag(conj(Bus.V)./abs(Bus.V));

% Now form the expanded Jacobian matrix
dSdq = -j*speye(nbus,nbus);
refbus = find(Bus.type == 3);
Pdir = sparse([1:nbus],1,[Bus.slack_factor],nbus,1);%This is the slack generation

% get PQ and PV lists from type field
Internal.PQlist = find(Bus.type == 1);
Internal.PVlist = setdiff([1:length(Bus.NUMBER)],Internal.PQlist);% PQlist is a list of busindex
nPV = length(Internal.PVlist);
nPQ = length(Internal.PQlist);


temp1jac=[dSdd, dSdv, Pdir, dSdq(:,Internal.PVlist)]';
temp3jac=[real(temp1jac) -imag(temp1jac)]';%A 2*[nbus + nbranch] x [2*nbus + 1 + nPV + 1]real matrix
ref_row = sparse([1:1],refbus,1,1,2*nbus + 1 + nPV );
fix_volts = sparse([1:nPV],nbus+Internal.PVlist,ones(nPV,1),nPV,2*nbus + 1 + nPV );
fulljac=[temp3jac;ref_row;fix_volts];

% fulljac is the full Jacobian matrix including power balance and voltage constraints and reference definition
% and Stress specification and branch real and reactive currents.
% fulljac has ONE MORE COLUMN THAN ROW

rhs = [ real(Bus.mismatch);imag(Bus.mismatch); sparse(1,1);sparse(length(Internal.PVlist),1) ];
dx =  - fulljac\rhs ;   %HERE IS THE UPDATE


itcount =0;
while ((max(abs(Bus.mismatch)) > 0.000000001)|itcount ==0)&(itcount<20)
   if itcount ==19
     disp('no solution for the load flow')
      break
   end
```

```
   itcount = itcount + 1;

   % dx([1:nb]) = angles
   % dx([nb+1:2*nb]) = voltages
   % dx(2*nb+ 1) = slack
   % dx(2*nb+ 2:2*nb + 1 +nPV) = Generator Q out
   % dx(2*nb + 1 +nPV + 1) = Stress step size

   vmag = abs(Bus.V)+ dx([nbus+1:2*nbus]);
   thetas = angle(Bus.V) + dx([1:nbus]);
   Bus.V = vmag.*exp(j*thetas);
   %P gen update
   Bus.Spugen = Bus.Spugen -  Pdir*dx(2*nbus+ 1:2*nbus+ 1);
   %Q gen update
   Bus.Spugen(Internal.PVlist) = Bus.Spugen(Internal.PVlist) + j*dx([2*nbus + 1+ 1:(2*nbus + 1 +nPV)]);
ibus=Internal.Ybus*Bus.V;
   Bus.mismatch = Bus.V.*conj(ibus) + Bus.Spuload - Bus.Spugen;

   dSdd =j*diag(conj(ibus).*Bus.V) ...
     - j*diag(Bus.V)*conj(Internal.Ybus)*diag(conj(Bus.V));
   dSdv = diag(conj(ibus).*(Bus.V./abs(Bus.V))) ...
     + diag(Bus.V)*conj(Internal.Ybus)*diag(conj(Bus.V)./abs(Bus.V));

   temp1jac=[dSdd, dSdv, Pdir, dSdq(:,Internal.PVlist) ]';%A nbus x [2*nbus + 1 + nPV +1]complex matrix
   temp2jac=[real(temp1jac) -imag(temp1jac)]';%A 2*nbus x [2*nbus + 1 + nPV + 1]real matrix
   %A 2*nbus + 1 + nPV  x [2*nbus + 1 + nPV + 1]real matrix
   fulljac=[temp2jac;ref_row(:,[1:2*nbus + 1 + nPV ]);fix_volts(:,[1:2*nbus + 1 + nPV ])];
   rhs = [ real(Bus.mismatch);imag(Bus.mismatch); sparse(1,1);zeros(length(Internal.PVlist),1) ];
            dx =  - fulljac\rhs ;   %HERE IS THE UPDATE
    max_err=max(abs(Bus.mismatch));
end;
% Update branch flows
Internal.dSdd = dSdd;
Internal.dSdv = dSdv;
   %Use Alvarado's method ala DeMarco to det the flow Jacobian matrix
   dIdd =j*sparse(nbrvec,Branch.I,(conj(Branch.IpuAmps).*Bus.V(Branch.I)),nbranch,nbus) ...
     - j*diag(Bus.V(Branch.I))*conj(YflowI)*diag(conj(Bus.V));
   dIdv = sparse(nbrvec,Branch.I,(conj(Branch.IpuAmps).*(Bus.V(Branch.I)./abs(Bus.V(Branch.I)))),nbranch,nbus) ...
     + diag(Bus.V(Branch.I))*conj(YflowI)*diag(conj(Bus.V)./abs(Bus.V));


   Branch.IpuAmps=YflowI*Bus.V;
   Branch.JpuAmps=YflowJ*Bus.V;
   Branch.IMVA = 100*Bus.V(Branch.I).*conj(Branch.IpuAmps);
   Branch.JMVA = 100*Bus.V(Branch.J).*conj(Branch.JpuAmps);

disp([num2str(itcount) ' iterations']);
return
```

# Appendix E. Linear Sensitivity Analysis Program

## E.1. General

This appendix contains the input and output data format for The LSA program explained in section 6.3. The Mathematical background for the generator sensitivity factor is explained. Detailed MATALB codes with helpful comments for all main program functions is also documented.

## E.2. User Manual for Using LSA Program

LSA is the second method for TTC calculations. The method completely depends on the DC load flow calculations. The main program (*LSA_WSCC*) calls many different functions to calculate the TTC. These functions can be listed as follows:

- Read the input data file (*read_pti*)
- Convert PTI format to structure format (*fil_bus1*)
- Run the base case load flow (*lf_org*)
- Calculate the generator shift sensitivity factor (*gssf_fun*)
- Calculate the generalized generator shift sensitivity factor based on the scenario chosen before (*gssf_ttc_gen_wscc*)

All the input data required to run the program is highlighted in the next program code. All the output data are explained throughout Chapter 4.

The input data highlighted inside the MATLAB code in section E.5 should be entered or updated each time a new case is run.

The output of the program is TTC value calculated at a specific dispatch. The program can also report the TTC value calculated based on the second line that would be congested after the critical line.

```
first TTC
 16 ,   16   ,  35 ,  19 ,    5   ,  10 , 82   ,  1102.46

second TTC
 16 ,   16   ,  35 ,  19 ,    5   ,  10 , 177  ,  2111.64
```

Figure E-1: LSA program output

The first six numbers are the generator dispatch for the scenario chosen to calculate the TTC. The number 7 is the critical line. The last number is the TTC value for the first and the second lines. For the output example shown in Figure E-1, the TTC calculated based on the first congested line (line 82) equals 1102.46 MW. The TTC based on the second congested line (line 177) equals 2111.64 MW.

## E.3. Mathematical Background for the Generator Shift Sensitivity Factor

Under the assumptions of DC power flows. The power flow calculations are completely linear and non-iterative algorithm. Equation (E.1) is the basic equation for DC load flow.

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ . \\ . \end{bmatrix} = [B] \begin{bmatrix} \Delta \theta_1 \\ \Delta \theta_2 \\ . \\ . \end{bmatrix} \qquad (E.1)$$

Where

$$B_{ik} = -\frac{1}{x_{ik}} \quad \ldots\ldots\ldots\ldots \quad \text{For off diagonals elements}$$

$$B_{ik} = \sum_{k=1}^{N} \frac{1}{x_{ik}} \quad \ldots\ldots\ldots\ldots \quad \text{For diagonals elements}$$

In other words, B is the imaginary part of the Ybus matrix calculated under the assumption of Dc load flow.

$$\left[B\right] = imag(Y_{bus}) \qquad (E.2)$$

Where

$l$ ……… Transmission line connected between buses n & m

$x_l$ ………. Transmission line reactor of line $l$

The power flows on each transmission line ($P_l$) can be calculated as follows:

$$P_l = P_{nm} = \frac{1}{x_l}\left(\theta_n - \theta_m\right) \qquad (E.3)$$

From equation (E.1) $\Delta\theta$ can be expressed as function of $\Delta P$ as follows:

$$\Delta\theta = \left[X\right]\Delta P \qquad (E.4)$$

The DC model is a linear model and the superposition technique can be used in this model. The generator shift sensitivity factor (gssf) can be calculated by assuming power changes at generator $i$ and this change will be compensated by the slack bus. The gssf can be calculated for each transmission line ($l$) in the system for this generator $i$ by measuring the changes in the transmission line flow ($P_l$) with respect to a change in power injection at bus $i$.

$$gssf_{l\,i} = \frac{dP_l}{dP_i} \qquad (E.5)$$

From equations (E.2) and (E.5) , if we assumed that the transmission line ($l$) is the line connected between bus ($n$) and bus ($m$) then the gssf can be calculated as follows:

$$gssf_{l\,i} = \frac{d}{dP_i}\left(P_l\right) = \frac{d}{dP_i}\left(\frac{1}{x_l}\left(\theta_n - \theta_m\right)\right) \qquad (E.6)$$

$$gssf_{l\,i} = \frac{1}{x_l}\left(\frac{d}{dP_i}\left(\theta_n - \theta_m\right)\right) = \frac{1}{x_l}\left(\left(\frac{d\theta_n}{dP_i} - \frac{d\theta_m}{dP_i}\right)\right) \qquad (E.7)$$

$$gssf_{l\,i} = \frac{1}{x_l}\left(X_{ni} - X_{mi}\right) \tag{E.8}$$

Where

$gssf_{l\,i}$ ……… Generator shift sensitivity factor for transmission line $l$ and due to generator $i$

$X_{ni} = \dfrac{d\theta_n}{dP_i}$ … $ni$ of the matrix X

$X_{mi} = \dfrac{d\theta_m}{dP_i}$ … $mi$ of the matrix X

$x_l$ ………… Transmission line reactance of line $l$

## E.4. Flow Charts for LSA main program

The main flow chart of the LSA program is explained in Figure E-2. This algorithm is encoded using MATLAB as shown in the following section (*LSA_WSCC*). The main program uses many function as shown in Figure E-2; however, the main function which will be explained in detail is used for generator shift sensitivity factor calculations (*gssf_fun*). The flow chart of this function is shown is Figure E-3.

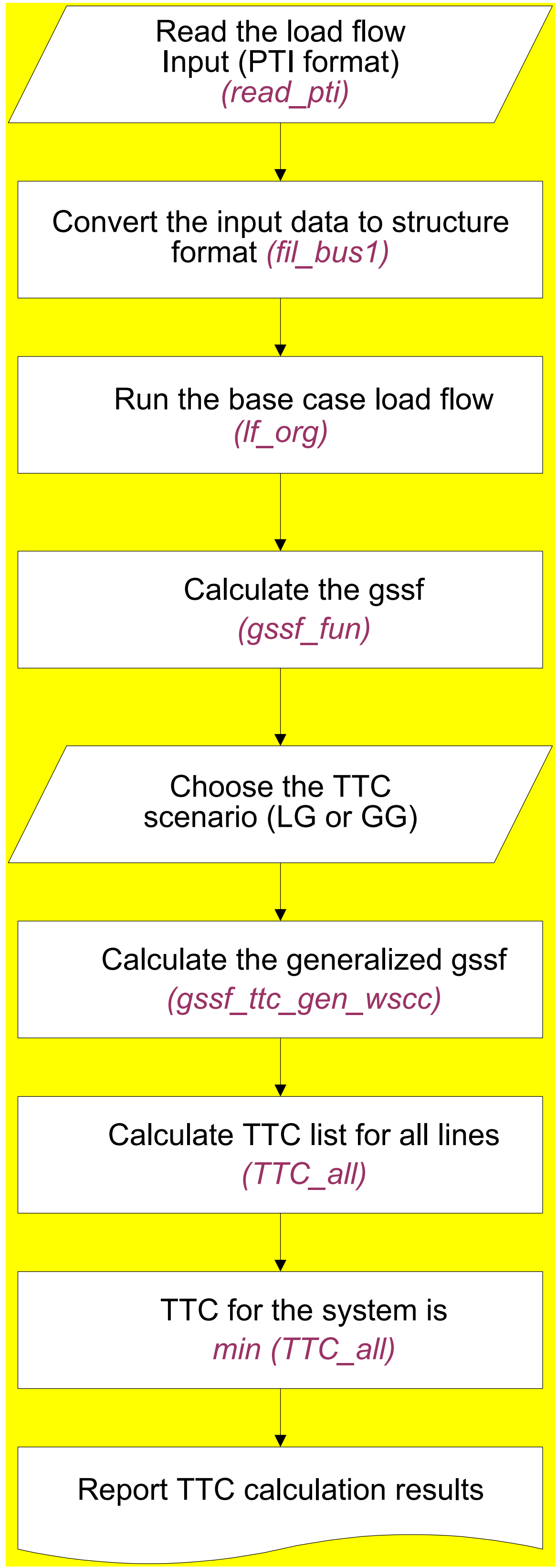


Figure E-2: LSA main program

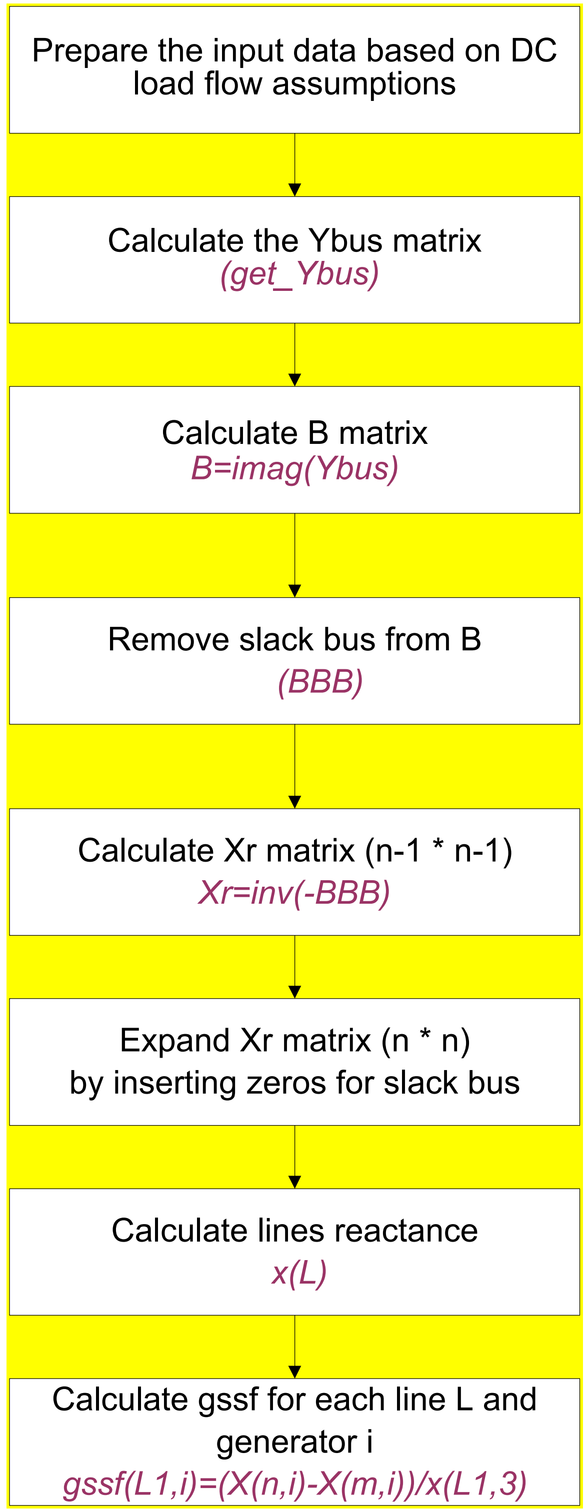


Figure E-3: Generator shift sensitivity factor algorithm

## E.5. LSA program code

**LSA_WSCC**

```
% Linear sensitivity analysis program
clear all
close all
global gssf

tic

% Read the input file in PTI format
[bus,load,gen,branch,MVA_base,bus_name]=read_pti('Abdo179_ord.pti');

% Convert PTI format to structure format
[DBus,DBranch,w,R]=fil_bus1(bus,bus_name,load,gen,branch,MVA_base);

% Run base case load flow
[BBus,BBranch,BInternal] = lf_org(DBus,DBranch,[]);

% Generator proportional distribution factor. These numbers are calculated based on the install capacity and
% the base generation case
Cdg=[0.1570   0.1570   0.3488   0.1860   0.0465   0.1047];
Adg = [0.0577   0.1058   0.1058   0.1923   0.1442   0.0481   0.1923   0.0673   0.0385   0.0192   0.0096   0.0192];
Bdg = [0.1078   0.0294   0.1078   0.1078   0.0686   0.1078   0.0588   0.1078   0.0490   0.1471   0.1078];

% Load proportional distribution factor.
Adl=[0.0320   0.0304   0.0073   0.0437   0.0145   0.1177   0.0136   0.1154   0.0378   0.0062   0.1107   0.0145...
    0.0276   0.0118   0.0094   0.0016   0.0020   0.0108   0.2360   0.0053   0.0079   0.0003   0.0010   0.0314...
    0.0087   0.0050   0.0042   0.0116   0.0044   0.0049   0.0290   0.0073   0.0044   0.0315];

% Calculate generator shift sensitivity factor
gssf=gssf_fun(DBranch,DBus,1);

kk=1;

% Choosing the TTC areas and the scenario
aver_gssf=gssf_ttc_gen_wscc('C','A',Cdg,Adg); % GG scenario C-A
%aver_gssf=gssf_ttc_gen_wscc('B','A',Bdg,Adg); % GG scenario B-A
%aver_gssf=gssf_ttc_load_wscc('B','A',Bdg,Adl); % LG scenario B-A

% Transmission line thermal Limit
TL=BBranch.RATES(:,3);

% Calculate average transmission line flow from the base-case load flow
aver_Pflow=sign(real(BBranch.IMVA)).*(abs(real(BBranch.IMVA))+abs(real(BBranch.JMVA)))/2;

% Calculate TTC for all the Transmission lines
for i=1:size(BBranch.RATES,1)
   if (abs(aver_gssf(i))>0.1)
      % -ive sign in case of Gssf calculated from gen drop , -ive in case gssf calc from load increase
      TTC_all(i)=(-sign(aver_gssf(i))*TL(i)-aver_Pflow(i))/(aver_gssf(i));
   end
end

% Calculate TTC for the system (min of TTC_all)
[GG,II]=sort(abs(TTC_all));
GI=[GG;II];
for i=2:length(GI)
   if (GI(1,i)>0 & GI(1,i-1)==0)
      Cirtical_line = GI(2,i); % first critical line
      second_Cirtical_line = GI(2,i+1); % second critical line
```

```
        Cirtical_TTC = GI(1,i); % TTC for the first critical line
        second_Cirtical_TTC = GI(1,i+1); % TTC for the second critical line
        break
    end
end

% Reporting the first and second contingency for area C
HH=[Cdg*100  Cirtical_line(kk) Cirtical_TTC]; % from area C
S_HH=[Cdg*100  second_Cirtical_line(kk) second_Cirtical_TTC]; % from area C
sprintf('%3.0f ,  %3.0f   , %3.0f , %3.0f ,  %3.0f   , %3.0f , %2.0f  ,  %6.2f\n',HH) % from C
sprintf('%3.0f ,  %3.0f   , %3.0f , %3.0f ,  %3.0f   , %3.0f , %2.0f  ,  %6.2f\n',S_HH) % from C

%HH(kk,:)=[Adg*100  Cirtical_line(kk) Cirtical_TTC(kk)]; % from A
% S_HH(kk,:)=[Adg*100  second_Cirtical_line(kk) second_Cirtical_TTC(kk)]; % from A

%HH(kk,:)=[Bdg*100  Cirtical_line(kk) Cirtical_TTC(kk)]; % from B
% S_HH(kk,:)=[Bdg*100  second_Cirtical_line(kk) second_Cirtical_TTC(kk)]; % from B

toc
```

## fil_bus1

```
%  Convert PTI matrix format to structure format

function    [Bus,Branch,V_load_flow,Renumber]=fil_bus1(bus,bus_name,load,gen,branch,MVA_base)

SB=MVA_base;
V_load_flow=bus(:,8);

% Calculate the bus voltage
w=bus(:,8);
y=(pi*bus(:,9)/180);
v=w.*(exp(j*y));

% The bus number should be renumbered in descending order start from 1
Renumber=[bus(:,1) [1:size(bus,1)]'];

% Bus structure format
Bus=struct('NAME',bus_name,'NUMBER',[Renumber(:,1)],'AREA',bus(:,6),'V',v,'type',bus(:,3),'YL',(bus(:,4)+j*bus(:,
5))/SB);
% Slack bus format
Bus.slack_factor=sparse(length(Bus.type),1);
Bus.slack_factor(find(Bus.type == 3)) = 1;

% load bus format
s2=size(Bus.NUMBER,1);
B=sparse(s2,1);
Bus.Spuload=sparse(B);
s3=size(load,1);
for i=1:s3
    Bus.Spuload(Renumber(find(Renumber(:,1)==load(i,1)),2))=sparse(load(i,5)+j*load(i,6))/SB;
end

% Initializing the generator structure
s4=size(gen,1);
Bus.Spugen=sparse(B);
Bus.Qgmax=sparse(B);
Bus.Qgmin=sparse(B);
Bus.Pgmax=sparse(B);
```

```
Bus.Pgmin=sparse(B);

% Generator structure
for i=1:s4
    Bus.Spugen(Renumber(find(Renumber(:,1)==gen(i,1)),2))=sparse(gen(i,3)+j*gen(i,4))/SB;
    Bus.Qgmax(Renumber(find(Renumber(:,1)==gen(i,1)),2))=sparse(gen(i,5));
    Bus.Qgmin(Renumber(find(Renumber(:,1)==gen(i,1)),2))=sparse(gen(i,6));
    Bus.Pgmax(Renumber(find(Renumber(:,1)==gen(i,1)),2))=sparse(gen(i,17));
    Bus.Pgmin(Renumber(find(Renumber(:,1)==gen(i,1)),2))=sparse(gen(i,18));
end

% Area zone structure
Bus.AREA=bus(:,6);
Bus.ZONE=bus(:,7);


% Changing regular transmission line tapping to 1
for i=1:size(branch,1)
    if branch(i,9)==0
        branch(i,9)=1;
    end
end


for i=1:size(branch,1)
    branch(i,1)= Renumber(find(Renumber(:,1)==branch(i,1)),2);
    branch(i,2)= Renumber(find(Renumber(:,1)==branch(i,2)),2);
end

% Branch data structure
Branch=struct('I',branch(:,1),'J',branch(:,2),'Z',branch(:,3)+j*branch(:,4),'B',branch(:,5),...
    'YI',branch(:,11)+j*branch(:,12),'YJ',branch(:,13)+j*branch(:,14),'TAP',branch(:,9),'RATES',...
    branch(:,6:8),'Status',branch(:,15));

s6=size(Branch.I);
s6=s6(1);

for i=1:s6
    Branch.NAME(i,1:12)= (Bus.NAME(Branch.I(i),:));
    Branch.NAME(i,14:25)=(Bus.NAME(Branch.J(i),:));
end
```

## gssf_fun

```
% Calculate the generator shift sensitivity factor
function gssf=gssf_fun(DBranch,DBus,ref)

n=size(DBus.V,1);
nb=size(DBranch.I,1);

% Prepare the input date to calculate the Ybus for under Dc load flow assumption
DBranch.B=zeros(nb,1); % disregard the branch Shunt capacitor
DBranch.Z=imag(DBranch.Z)*sqrt(-1); % disregard the branch resistor
DBranch.TAP=ones(nb,1); % disregard the transformer taping
DBus.YL=zeros(n,1); %  disregard the bus shunt reactors
DBranch.YI=zeros(nb,1); % disregard the branch shunt reactors
DBranch.YJ=zeros(nb,1); % disregard the branch shunt reactors

% Calculate Ybus  & B matrix
```

```
Ybus = get_Ybus(DBranch,DBus);
B=imag(Ybus);

% Remove the slack bus from the B matrix
if ref==1
   BBB=B(2:n,2:n);
elseif ref==n
   BBB=B(1:n-1,1:n-1);
else
   BBB=B([1:ref-1,ref+1:n],[1:ref-1,ref+1:n]);
end

% Calculate X matrix (n-1 * n-1)
Xr=inv(-BBB);

X1=sparse(1,n);
X2=sparse(n-1,1);

% Expand X matrix to be (n*n) by inserting row and column of zeros
if ref==1
   X=full([X1; [X2 Xr]]);
elseif ref==n
   X=full([[Xr X2];X1]);
else
   X=full([Xr(:,1:ref-1) X2 Xr(:,ref:n-1)]);
   X=full([X(1:ref-1,:);X1;X(ref:n-1,:)]);
end

% Calculate line reactance impedance
x=[DBranch.I DBranch.J imag(DBranch.Z)];

% Calculate the GSSF
for i=1:length(1:n)
   for L1=1:size(x,1)
      n=x(L1,1);
      m=x(L1,2);
      gssf(L1,i)=(X(n,i)-X(m,i))/x(L1,3);
   end
end
```

**get_Ybus**

```
function Ybus = get_Ybus(Branch,Bus)
% Remove dead Branches
branchesin = find(Branch.Status == 1);
Branch.Status = Branch.Status(branchesin) ;
Branch.I = Branch.I(branchesin);
Branch.J = Branch.J(branchesin);
Branch.B = Branch.B(branchesin);
Branch.Z = Branch.Z(branchesin);
Branch.YI = Branch.YI(branchesin);
Branch.YJ = Branch.YJ(branchesin);
Branch.TAP = Branch.TAP(branchesin);
Branch.RATES = Branch.RATES(branchesin,:);
Branch.NAME = Branch.NAME(branchesin,:);

% Construct the bus admittance matrix
nbus = length(Bus.NUMBER);
nbranch = length(Branch.I);
Internal.Ybus=diag(sparse(Bus.YL));
```

```
Internal.Ybus=Internal.Ybus+sparse(Branch.J,Branch.J,1./Branch.Z+i*Branch.B/2,nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.I,Branch.J,-1./(Branch.TAP.*Branch.Z),nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.J,Branch.I,-1./(conj(Branch.TAP).*Branch.Z),nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.I,Branch.I,1./((abs(Branch.TAP).^2).*Branch.Z)+i*Branch.B/2,nbus,nbus)
Internal.Ybus=Internal.Ybus+sparse(Branch.I,Branch.I,Branch.YI,nbus,nbus);
Internal.Ybus=Internal.Ybus+sparse(Branch.J,Branch.J,Branch.YJ,nbus,nbus);
Ybus=Internal.Ybus;
```

---

## gssf_ttc_gen_wscc

```
% gssf between two areas for any generator dispatch and also for any generator  drop dispatch

function [aver_gssf]=gssf_ttc_gen_wscc(from_area,to_area,r_from_gen,r_to_gen)
global gssf

% Input generator set in each area
Ag=[92,94,99,103,111,123,128,148,154,165,171,178];
Bg=[45,50,55,61,63,64,66,70,73,81,85];
Cg=[1,5,8,13,19,42];

% gssf from area A to area B
if (from_area == 'A' & to_area == 'B')

  % Calculate gssf for generators in area B
  for i=1:length(Bg)
    gssff=gssf(:,Bg(i));
    % Assume that all generators in area A will contribute as multi-slack bus with certain ratio (r_from_gen)
    for j=1:length(Ag)
      gssff=gssff-gssf(:,Ag(j))*r_from_gen(j);
    end
     % Consider the generation contribution ratio in area B (r_to_gen)
    gssf_area(:,i)=gssff*r_to_gen(i);
  end

% gssf from area B to area A
elseif (from_area == 'B' & to_area == 'A')
  for i=1:length(Ag)
    gssff=gssf(:,Ag(i));
    for j=1:length(Bg)
      gssff=gssff-gssf(:,Bg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_gen(i);
  end

% gssf from area A to area C
elseif (from_area == 'A' & to_area == 'C')
  for i=1:length(Cg)
    gssff=gssf(:,Cg(i));
    for j=1:length(Ag)
      gssff=gssff-gssf(:,Ag(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_gen(i);
  end

% gssf from area C to area A
elseif (from_area == 'C' & to_area == 'A')
  for i=1:length(Ag)
    gssff=gssf(:,Ag(i));
    for j=1:length(Cg)
```

```
      gssff=gssff-gssf(:,Cg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_gen(i);
  end

% gssf from area B to area C
elseif (from_area == 'B' & to_area == 'C')
  for i=1:length(Cg)
    gssff=gssf(:,Cg(i));
    for j=1:length(Bg)
      gssff=gssff-gssf(:,Bg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_gen(i);
  end

% gssf from area C to area B
elseif (from_area == 'C' & to_area == 'B')
  for i=1:length(Bg)
    gssff=gssf(:,Bg(i));
    for j=1:length(Cg)
      gssff=gssff-gssf(:,Cg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_gen(i);
  end

% Calculate the average of gssf inside the area
aver_gssf=sum(gssf_area');
```

## gssf_ttc_load_wscc

```
% gssf between two areas for any generator dispatch and any dropping load pattern (GL scenario )

function [aver_gssf]=gssf_ttc_load_wscc(from_area,to_area,r_from_gen,r_to_load)
global gssf

% Input generator set in each area
Ag=[92,94,99,103,111,123,128,148,154,165,171,178];
Bg=[45,50,55,61,63,64,66,70,73,81,85];
Cg=[1,5,8,13,19,42];

% Input load set in each area
Cl=[2,6,7,9,11,12,18,20,40];
Al=[90,91,95,96,97,98,101,102,108,109,110,112,116,117,119,120,122,124,127,147,149,150,151,153,160,161,162,163,
166,167,168,169,170,176];
Bl=[46,47,48,49,51,52,53,54,56,57,60,62,65,67,69,72,79,80,84];

% Calculate gssf for GL scenario from area A to area B
if (from_area == 'A' & to_area == 'B')
  for i=1:length(Bl)

    % Calculate gssf for load in area B
    gssff=gssf(:,Bl(i));
    for j=1:length(Ag)

      % Assume that all generators in area A will contribute as multi-slack bus with certain ratio (r_from_gen)
      gssff=gssff-gssf(:,Ag(j))*r_from_gen(j);
    end

     % Consider the load contribution ratio in area B (r_to_load)
    gssf_area(:,i)=gssff*r_to_load(i);
```

```
  end

% Calculate gssf for GL scenario from area B to area A
elseif (from_area == 'B' & to_area == 'A')
  for i=1:length(Al)
    gssff=gssf(:,Al(i));
    for j=1:length(Bg)
      gssff=gssff-gssf(:,Bg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_load(i);
  end

% Calculate gssf for GL scenario from area A to area C
elseif (from_area == 'A' & to_area == 'C')
  for i=1:length(Cl)
    gssff=gssf(:,Cl(i));
    for j=1:length(Ag)
      gssff=gssff-gssf(:,Ag(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_load(i);
  end

% Calculate gssf for GL scenario from area C to area A
elseif (from_area == 'C' & to_area == 'A')
  for i=1:length(Al)
    gssff=gssf(:,Al(i));
    for j=1:length(Cg)
      gssff=gssff-gssf(:,Cg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_load(i);
  end

% Calculate gssf for GL scenario from area B to area C
elseif (from_area == 'B' & to_area == 'C')
  for i=1:length(Cl)
    gssff=gssf(:,Cl(i));
    for j=1:length(Bg)
      gssff=gssff-gssf(:,Bg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_load(i);
  end

% Calculate gssf for GL scenario from area C to area B
elseif (from_area == 'C' & to_area == 'B')
  for i=1:length(Bl)
    gssff=gssf(:,Bl(i));
    for j=1:length(Cg)
      gssff=gssff-gssf(:,Cg(j))*r_from_gen(j);
    end
    gssf_area(:,i)=gssff*r_to_load(i);
  end
end

% Calculate the average of gssf inside the area
aver_gssf=sum(gssf_area');
```

# Vita

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## EDUCATION

**1998- 2002, pursuing Ph.D. in Electrical Engineering**
EE Dept., Virginia Tech, Blacksburg, VA 24061
Dissertation: *Internet-based Wide Area Measurement Applications in Deregulated Power Systems*.
GPA = 3.96 / 4.0

**1993-1996, M.S. in Electrical Engineering**
MTC EE Dept, Cairo, Egypt.
GPA = 3.9 /4.0
Thesis: "*An Expert System for Estimating Faulted Sections in Electrical Power Networks"*

**1992 US Army Diploma**
"*Power Generation Equipment Repair*", US Army Ordinance Center and School

**1986-1991, B.S. in Electrical Engineering**
Graduated with Excellence with Honors
EE Dept., MTC, Cairo, Egypt.
GPA = 4.0 / 4.0
Thesis: *Design distribution networks for a tourist's villages.*

## WORK EXPERIENCE

**2001-2002, Research Associate**
EE Dept., Virginia Tech, Blacksburg, VA 24061. Research concentrated on Phasor Measurements Unite (PMU) placement around Knoxville area in Tennessee Valley Authority (TVA) system. The objective of the project was estimating the voltage collapse condition in real time using phasor measurements.

**1998-2001, Research Associate**
EE Dept., Virginia Tech, Blacksburg, VA 24061. Research concentrated on Internet applications in power systems, state estimation based on wide area measurements, power system protection; wide area measurements and deregulation, this was joint research by EPRI / DOD under the project title

"*Advanced Power Technologies Consortium Innovative Technologies for Defense Against Catastrophic Failures of Complex Interactive Power Networks.*" Some achievements are reached during this period:

- Developed a MATLAB based State Estimation program capable to deals up large numbers of buses (testing up to 300 bus);
- Studying the simplified WSCC 179-bus system from load flow and state estimation point of view.
- Developed a MATLAB based Tracing Load Flow (TLF) program capable to calculated Total Transfer Capability (TTC).

**1996-1998, Assistant Engineer (part time) of EE,**
Worked as a design engineer for distribution system implementation of residential areas, MTC consultation office, Cairo, Egypt.

**1993-1995, Assistant Engineer (part time),**
Design and implementation of distribution system for a hospital (400 beds capacity)

**1992 US Army Diploma**
Diploma of "*Power Generation Equipment Repair*", US Army Ordinance Center and School, Fort Belvoir, Virginia, United State of America.

## TEACHING EXPERIENCE

**2001-2002, Teaching position**
EE Dept., Virginia Tech. Teaching electronic courses

**1999-2001, Graduate Teaching Assistance (GTA)**
EE Dept., Virginia Tech. grading different courses

**1993-1998, Teaching Assistant**
MTC University, Cairo, Egypt. Lectured in most undergraduate courses, in power system analysis, power protection systems, and power system lab.

## COMPUTER SKILL

**Program Language**: *MATLAB, FORTRAN, PROLOG, HTML, EMTP*
**Simulation Packages**: *PSCAD/EMTDC, ETMSP, IP Flow, State Estimation*
**Operation Systems**: *DOS, Win 95/98/NT/2000/XP*

## PUBLICATIONS

- Abdel-Rahman Khatib, Xuzhu Dong, Bin Qiu, Yilu Liu, "Thoughts on Future Internet Based Power System Information Network Architecture", Power Engineering Society Summer Meeting, 2000. IEEE, Vol. 1, 2000, pp. 155 -160.
- Abdel-Rahman Khatib, Mili, L., Phadke, A., De La Ree, J., Liu Y, "Internet based wide area information sharing and its roles in power system state estimation", Power Engineering Society Winter Meeting, 2001 IEEE, Vol. 2, 2001, pp. 470 –475.
- Abdel-Rahman Khatib, Phadke, A., Liu Y, "A Tracing Load Flow Program for Total Transfer Capability Calculations", Power Engineering Society Summer Meeting, 2002 IEEE.

- Abdel-Rahman Khatib, A. Phadke, J. De La Ree, Y. Liu, "Real Time Updating for Total Transfer Capability", proceeding of NAPS 2001, Texas A&M University, October 15-16 2001, pp. 25-31.
- Sebastian P. Rosado, Abdel Rahman Khatib, Nouredine HadjSaid "Tracing The Path Of Electric Power Flow – A Study For Deregulated Power Systems ", Power Engineering Society Winter meeting, 2001. IEEE , Vol. 3 , 2001, pp 1479 –1484.
- Abdel Rahman Khatib, Ibrahem Helal, Mohammed M. Mansour. "A new Expert System for Faulted Section Identification and protection System Analysis". Fifth International Middle East Power System Conference, January 4-6, 1997, Alexandria, Egypt.


## PROFESSIONAL MEMBERSHIP

- IEEE member
- IMAPS (International Microelectronics and Packaging Society and Educational foundation)

## LIST OF RELEVANT GRADUATE COURSES

- Power system analysis
- Power system protection
- Power system protection lab.
- Microprocessor applications in power systems
- Computer applications in power.
- Advanced Topics of Power System Security, Monitor, And Deregulation
- Advanced Topics Of Computer Analysis Power System Transients
- Power Quality And Facts Devices
- Linear System Theory
- Network Synthesis Design
- Basic Semiconductor Devices
- Power system design
- Robust Estimation and Filtering

## REFERENCE

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