A COMPREHENSIVE DYNAMIC SECURITY ASSESSMENT OF BANGLADESH POWER SYSTEM

By

Md. Farhad Hossain

A Thesis Submitted to the Department of Electrical and Electronic Engineering of Bangladesh University of Engineering and Technology in Partial Fulfillment of the Requirement for the Degree of

Master of Science in Electrical and Electronic Engineering

Department of Electrical and Electronic Engineering

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

Dhaka-1000, Bangladesh

March, 2019

The thesis titled **"A Comprehensive Dynamic Security Assessment of Bangladesh Power System,"** submitted by **Md. Farhad Hossain,** Roll No.: 0409062128, Session: April 2009, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of Master of Science in Engineering on March 24, 2019.

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Md. Farhad Hossain

Acknowledgements

The author expresses heartiest gratitude to his supervisor Professor Dr. Abdul Hasib Chowdhury, not only for his guidance in this work, but also for his astute role as a mentor to the author and for his support in various aspect of life, apart from usual campus- activities.

The author is very thankful to Mr. Sahbun Nur, Executive Engineer (System Planning) of Power Grid Company of Bangladesh for his encouraging discussions and valuable support in collecting information and data on transmission system protection in the Bangladesh.

The author is equally grateful to several persons from the utilities in Bangladesh for their friendly support in proving operating information and data on the systems, namely, Mr. Md. Kausar Ameer Ali, General Manager (Chief Engineer), Commercial Operation , BPDB; Mr. Md. Sakhawat Hossain from Power Grid Company of Bangladesh. Amongst these persons, the author expresses utmost gratitude to Md. Kausar Ameer Ali for his warm encouragement and appreciation for this work.

The author is indebted to his father for all kinds of financial and moral support in the course of his whole academic life.

Lastly, but most significantly, the author bids his heartiest and innermost gratitude to his mother, who helped him to come up to this point of life with her love, affection and support in the course of graduate studies.

Abstract

Power system security analysis is a key to reliable operation at maximum efficiency. Security analysis in this context refers to the ability of a power system to withstand pre-specified disturbances called contingencies. A power system must be able to survive dynamic events, and hence dynamic security assessment is more computationally intensive as it requires the electro-mechanical transient stability analysis of the system which concerns the transient behavior of the power system when moving from the pre- to post- contingency operating point. Dynamic security assessment is an evaluation of the ability of a certain power system to withstand a defined set of contingencies and to survive the transition to an acceptable steady-state condition. This is dependent on the transient stability evaluation which provides information in relation to the ability of a power system to retain stable operation during major disturbances resulting from either the loss of generation or transmission facilities, sudden or sustained load changes, or momentary faults. In the event of disturbances, the electro-mechanical oscillation of synchronous generator will be used to measure the transient stability. It is determined by observing the variation of the rotor angle as a function of time throughout the duration of the fault. The transient stability depends on the magnitude of the fault, duration of the fault and the speed of the protective devices. If the system is transiently stable, the oscillation of the rotor angle will damp down to a safe operating limit. Dynamic security assessment identifies those disturbances that cause instability and the results of the transient stability analysis are used to determine the system's security level.

This thesis demonstrates a methodical approach to dynamic security assessment. The method is based on a combination of voltage and angular criterion, N-1 and N-2 contingency analysis, transient voltage dip, transient stability analysis, and use of a performance index. A combined contingency ranking based on bus phase voltage and phase angle, and stability margin for all machines in a power system is used. The method is very effective for secured planning and operation of a power system, and for protection scheme design.

The method is applied to the Bangladesh power system network (BPSN) for dynamic security assessment of the system. Critical buses and the paths connecting them are identified. These forms the backbone of BPSN and the system is most vulnerable at these locations as any serious contingency involving these nodes may lead the system to partial or complete

blackout. Additional protective measures should be taken for the most critical buses of the system to prevent sudden system collapse or blackout.

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LIST OF ABBREVIATION

BPDB	Bangladesh Power Development Board
BPSN	Bangladesh Power System Network
CCT	Critical Clearing Time
DSA	Dynamic Security Analysis
FACTS	Flexible AC Transmission System
FCT	Fault Clearing Time
HVDC	High Voltage Direct Current
kV	Kilo Volt
PF	Power Flow
PGCB	Power Grid Company of Bangladesh
PI	Performance Index
PSAF	Power System Analysis Framework
RES	Renewable Energy Sources
SEP	Stable Equilibrium Point
SSA	Steady State Security Analysis
SMIB	Single-Machine Infinite-Bus
TSA	Transient Stability Assessment
TVD	Transient voltage dip
UEP	Unstable Equilibrium Point
SLI	Voltage Stability Load Index

CHAPTER 1

INTRODUCTION

1.1 Overview

Power systems are designed to provide continuous power supply that maintains voltage stability. However, due to undesired events, such as lightning, accidents or any other unpredictable events, short circuits between the phase wires of the transmission lines or between a phase wire and the ground which may occur. Due to a fault, one or more generators may be severely disturbed causing an imbalance between generation and demand. If the fault persists and is not cleared in a pre-specified time frame, it may cause severe damages to the equipment which in turn may lead to a power loss and power outage. Therefore, protective equipment are installed to detect faults and clear/isolate faulted parts of the power system as quickly as possible before the fault energy is propagated to the rest of the system. Therefore, a fast and accurate assessment of pre-fault and post-fault stability of the network is necessary.

Security assessment has always been an important topic in power system operation. It refers to the analysis and quantification of the degree and risk in a power system's ability to survive imminent disturbances (contingencies) without interruption to customer service [1]. Corresponding actions are designed and applied, if necessary, to reduce the risk.

Security analysis relates to the ability of the electric power systems to survive sudden disturbances such as electric short circuits or unanticipated loss of system elements. It consists of both steady state and dynamic security analyses, which are not two separate issues but should be considered together. In steady state security analysis including voltage security analysis, the analysis checks that the system is operated within security limits by PF (power flow) after the transition to a new operating point. Until now, many utilities have difficulty in including dynamic aspects due to computational capabilities. On the other hand, dynamic security analysis is needed to ensure that the transition may lead to an acceptable operating condition. Transient stability, which is the ability of power systems to maintain synchronism when subjected to a large disturbance, is a principal component in dynamic security analysis.

Usually any loss of synchronism may cause additional outages and make the steady state analysis of the post-contingency condition inadequate for unstable cases.

The security assessment of power systems includes steady-state security assessment (SSA) and dynamic security assessment (DSA). SSA studies the system steady state operating points between dynamic transitions, whereas DSA focuses on the security of system dynamics in various timescales, from transients of several seconds to slow dynamics of several minutes or even hours.

A rapid increase of the energy demand, utilization of renewable energy sources leads growth of the power grids and their complexity. Nowadays the electrical networks utilize more energy than they were originally designed to handle [2].Consequently, the power grids are nearing not only their thermal limits, but more often their dynamic stability limits, which lead to unexpected critical situations in the power grids e.g. blackouts. Therefore, the dynamic security assessment of power systems has recently become a very important topic in the area of the electrical network monitoring.

In DSA, many security aspects of power systems are assessed, including transmission line thermal loading, voltage, rotor angles and frequency deviation. This is very computationally burdensome and requires many efforts. Historically, DSA is performed only off-line. The system dynamic security is assessed under forecasted operating scenarios, which should be exhaustive to cover the uncertainties. On the other hand, online DSA relies only on current operating scenario and assesses the ongoing real-time (or near real-time) dynamic security status, thus is able to give timely control actions to maintain system stability.

1.2 Literature Review

Power system security is the ability of system to withstand sudden disturbances with minimum disruption to its quality of service. It means that after the disturbance occur the power system will have to meet two requirements: (1) surviving the ensuing transient and move into an acceptable steady-state condition, and (2) in this new steady-state condition all components are operating within established limits[3].

The analysis used for the first requirement is the transient analysis or dynamic security assessment (DSA) while that for the second condition is known as static security assessment

(SSA). Typically, the SSA is performed first and then the dynamic security assessment. The static security analysis evaluates the post contingent steady state of the system neglecting the transient behavior and any other time-dependent variations. On the other hand, the dynamic security analysis evaluates the time-dependent transition from the pre-contingent to the post-contingent state, specifically, the stability of the system both from small and large disturbances.

The requirements for improvement in the stability of electric power systems and reduction in the effect of abnormal system conditions on sensitive customers can be met only by better understanding of the behavior of the system and optimized configuration of the different protection and control systems. The changes in the electric power systems caused by deregulation, energy markets and independent power producers result in an increase in the number of power transactions and new supply patterns that push transmission systems to the limit. Increased line loading leads to reduced margins that affect the system stability and reliability. At the same time the need for improved performance of all protection and control systems in order to reduce the effects of short circuit faults or other abnormal system conditions on sensitive customers require the application of optimized and adaptive solutions. All these factors lead to the need of improved quality of simulation of normal or abnormal system conditions, which is possible only when using advanced simulation tools based on accurate system models using the state-of-the-art programs which are designed to provide comprehensive and accurate simulation of different system conditions as power flow, dynamic stability, short circuit analysis and protective relays coordination [4].

Power system steady state stability and its margin is one of the basic problems ensuring the security of power system operation. Steady state stability analysis always calculates a large number of cases with different flow and network configuration, the estimated stability limit is usually too conservative to normal states, and at some abnormal state it may lead to incorrect result. Hence it is necessary to carry out DSA which analyzes system stability during disturbance condition. With advancement of commercially available of computer and simulation software for power system security and stability to meet ever increasing need for distant and bulk transmission of electrical energy, analyses had been carried out in the power sector to realize DSA of entire network for enhancement of stable power system network in consideration with practical implementation factors.

Deregulation of the electricity market around the world compels transmission systems to be loaded up to highest possible limit, which is mostly governed by network stability problems, especially the voltage and angle stability. A joint taskforce of IEEE/CIGRE [5] defines this as the ability of a power system to maintain steady voltage upon encountering a disturbance from an initial operating condition; physical appearance of the severity of the disturbances and faults, the power system may lose its security, which can result in catastrophic consequences, such as wide-spread a phenomenon of "blackout" or abnormally less security in network resulting from a collection of events accompanying voltage and angle instability. Since several major blackouts around the world have been directly associated with this incident [6], it is of high importance in the industry. Secure/insecure property of the power system operating points when meeting the transient disturbance associated with pattern discovery result and according contingency ranking is prepared.

Over the last decade or so, a number of approaches have been proposed for dynamic security assessment in power system operations. Sobajic and Pao have proposed a technique using a multi-layered network to predict the critical clearing time (CCT) for a given system disturbance [7].In this paper, the authors have shown that the neural networks can generalize to previously un-encountered system topologies and load levels, and correctly estimate CCTs. In a follow up, they also presented a combined unsupervised and supervised learning algorithm to solve the same problem [8]. The input data was pre-processed using an unsupervised learning system in order to enhance the accuracy of the supervised learning algorithm.

El-Sharkawi et al. exploited a multi-layer perception to predict the dynamic stability status of power system [9].A layered perception was trained to learn the mapping between varying system operating state, active and reactive power injections in some system buses the corresponding dynamic security status. Kumar et al. [10] discussed implementing the NN for the dynamic security assessment in a large system, and proposed a hybrid expert system/neural network approach, which utilize the knowledge of system operators while training neural works. In Mansour et al. [11], a neuron network approach to provide contingency screening and ranking in dynamic security was proposed. The B. C. Hydro and Hydro Quebec systems were used to test the neuron network. The static and dynamic features were applied as inputs, and the selected outputs were energy margin and maximum swing angle.

Emanuele et. al. discussed a risk-based dynamic security assessment method which can account for uncertainties affecting a power system state, initiating events (contingencies), and system response to contingencies themselves[12]. In quasi real time operation, the tool can rank the selected contingencies on the basis of the threats currently affecting the system state, thus evaluating the risk of instability to which the power system is exposed, due to the contingencies. This can help operators focus on the riskiest events, including multiple dependent contingencies on substation bus bars and power plants. In operational planning, the tool can quantify the effect of uncertainties due to renewable energy source and load forecast errors on the risk of losing angle, voltage, and frequency stability, while looking at the complementary cumulative distribution functions of the risk indicators, and highlighting which disturbances show the highest impact sensitivity to these uncertainties.

Power systems are operated close to their stability limit due to shortage of transmission corridor and massive increase in loads and demands. The various components of a power system often respond to contingencies and system try to acquire a new acceptable equilibrium condition to maintain stability. Dynamic security is assessed considering the limits on voltage, frequency, angular stability, transient stability, etc [13]. In [14], Chaudhuri et. al. discussed DSA through voltage stability load index (VSLI) through load shedding and capacitor bank switching. But only load shedding and capacitor bank switching cannot assure system security because renewable energy sources (RES) and high-power transfer capability limit also present in power system. Varying operating condition, increased the maximum power transfer capacity and accurate setting of protection relay assure DSA more reliable and stable even if more RES penetration and major disturbance occurred [15].

In [16], Ren et. al. discussed intelligent learning techniques for online DSA which can make fast assessment decision based on the real-time power system operating status. In doing so, the uncertainties in power system operation can be timely captured and reflected in DSA results.

In [17], Chychykina et.al. analyze the online DSA through accurate power system model, appropriate power system protection, contingency analysis, contingency screen and Plausibility check of the power system model and its states. Hence it is able to forecast the electrical network dynamic behavior when the power system moves towards the critical state and alarm the network operator about it early enough. Finally, this online DSA system can recommend different remedial measures to avoid critical situations in the power grid.

The growth of synchronously interconnected grids, the higher exploitation of transmission corridors and the higher unpredictability of the power flows make security problems (such as grid congestions) more frequent and increase the risk of energy supply problems for customers, as large blackouts and recent warnings have been pointed out [18]. In order to assess different security aspects, various methods and tools are deployed. Typical analyses take into account static and dynamic phenomena (steady-state violations, angle stability, voltage stability, frequency stability). Methods are based on different modeling approaches (e.g. power flow static models, quasi-steady state dynamic models, detailed electromechanical models) and provide different types of output such as stability indices, security margins, transfer capacities, preventive or corrective control measures. In [19], Ciapessoni et. al. analyzes DSA application function through integrated security assessment platform (ISAP). Two kinds of studies are carried out: (1) loadability limit (due to voltage stability issues) of an initial power system scenario (with no contingencies applied) in case of specific load/generation stresses to calculates voltage instability indexes (referring to nodes and lines) to assess the components which are more prone to voltage instability;(2)transient stability assessment (TSA) for power system scenarios in case of contingencies through a) the ranking of the contingency severity by means of kinetic energy-based TSA indexes, b) the calculation of the critical clearing times (CCT) over sets of contingencies (typically N-1-line contingencies).

An electric power system is rarely found to stay in any equilibrium state for a long time; it is rather continuously changing due to natural load behaviors, faults, outage of network elements and so on. A DSA system has to be able to cover these constraints and to show the operators the “distance” to the dangerous system stages by reporting the system margins. The individual characters of electrical networks require of a DSA system to be flexible in simulation of all-important components representing the passive equipment (lines, cables, transformers, etc.) and the active switching or control elements (capacitor banks, FACTS devices etc.) together with their control schemes. To check the limitations of the protection system in respect to e.g. overload or power swings, the protection devices must be available in the simulation tool. This is essential and indispensable for the simulation of cascading faults [20]. In [20], Krebs discussed the requirements for a DSA system to prove whether the system fulfils the constraints after outages or severe system faults under different system states. Main constraints of a system are margins to thermal and stability limits. The constraints can be expressed by concrete criteria like critical under/over voltages, critical loading of lines, critical under/over frequencies or critical angle differences between generators or system areas. The SIGUARD®-DSA provides graphical user interface analysis of dozens of contingencies per minute, based on the actual state of the system, and potential system failures. With the help of graphical representation as voltage-current- or power flow-profiles it is easier possible to recognize in a short period of time the weakest points in a system, which allows to establish preventive measures to avoid undesirable situations.

In [21], authors reviewed the typical dynamic behaviors of a power system upon occurrence of a disturbance. The first few cycles upon the disturbance occurred is referred to as sub transient period where rapid decay of AC and DC components of fault current takes place. If the disturbance occurred is severe and rotor angle excursion is large, then the duration of first half-cycle of rotor angle oscillation is called the "First Swing Period", which usually lasts for 0.5-1 sec. This period is highly significant as this is the span of time where transient stability may be loss. The contingency events referred to in this section are three-phase faults on lines followed by removal of the faulted lines from service by appropriate protection devices. Faults are large disturbances on the system and have significant impact on transient stability. DSA for n-1-1 contingencies is done in two steps. The first step is to simulate the initial contingency and check whether it is stable. If the system is stable and reaches an acceptable equilibrium after all automatic controls have acted, the second contingency is simulated. If the second contingency is stable and an acceptable steady state is reached, the n-1-1 contingency is labeled as secure. Otherwise, the n-1-1 contingency is labeled as insecure. To alleviate the computational burden associated with the n-1-1 contingency analysis, a two-stage approach is used. In stage I, a subset of n-1-1 contingencies is screened for further classification. The screening process is based on the power flow results of the n-1 analysis. In stage II, the screened contingencies are classified based on kinetic energy gained due to a fault and the change in Thévenin's impedance (Z_{th}) at the point of interconnection (POI) of the affected generators in the post-fault network. Once the contingencies are screened and classified accordingly, detailed TDSs are conducted to check whether the contingencies may lead to dynamic security issues.

Datta and Vittal [22], discussed risk-based security assessment (RBSA) methodology for ranking critical contingencies that can affect the system reliability due to transient instability events. It can also be used in defining new standards for transient stability to relax the security limits imposed by deterministic methods. Standards should be formulated such that the overall system risk is maintained at a defined risk threshold value. Zonal risk assessment can help system planners in identifying key areas within the system that can significantly affect system reliability.

In [23], Oyekanmi et. al. discuss the contingency analysis approaches model of a large power system under contingencies and presents a score based on the post-fault dynamics of the algebraic state variables that are related to the machine to rank the severity of the disturbance and consequently the critical components of the transmission network are determined based on the ranks. The post-fault trajectories of the machine rotor angles are compared with the scores.

Discussions presented above provide a literature-based idea on the limitations imposed by DSA on power system by operating within its limits, possible enhancement by applying contingency analysis and also motivates to study the effect of DSA techniques for power system security enhancement of Bangladesh Power System.

1.3 Problem Identification

Bangladesh Power System (BPS) is a small system with a peak demand of about 10,500 MW at the time of year 2013. The transmission system of BPS has formed an integral grid of two voltage levels of 132 and 230 kV. The BPS grid network is inherently radial in nature and divided into six regions. The status of different regions in terms of generation capacity and loads are different [24].

No study or analysis has been found from Bangladesh Power Development Board(BPDB) or Power Grid Company of Bangladesh(PGCB) during this work, in support of power system security analysis limitation; verbal discussion with System Planning Directorate of BPDB and PGCB uncovered that instability nature have been found beyond security analysis.

This work investigates the possibility of applying contingency analysis to recognize the stability nature and weak part of system components while considering system security. A comprehensive conceptual framework for dynamic security assessment is presented in this thesis.

1.4 Organization of the Thesis

This dissertation has been organized into five chapters and two Appendices. Chapter 1 contains brief literature review on security and stability with focus on the specific goals of this work, i.e., transmission capability enhancement. Chapter 2 deals with the basic concept of security and stability and describes the dynamic models in brief. Chapter 3 discusses briefly the analytical techniques and simulation tools used in this work. Chapter 4 Simulation and results of analyses have been presented and discussed. Chapter 5 provides the DSA projects conclusions and scope for future research work. Appendices are provided to supplement the study and analysis presented herein.

CHAPTER 2

POWER SYSTEM STABILITY AND SECURITY

2.1 Basic Concepts and Definitions

Power system stability may be defined as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [25].

Instability of power system can occur in many different situations depending on the system configuration and operating mode. Traditionally, the stability problem has been to maintain synchronous operation or synchronism especially since power systems generation relies on operation of synchronous machines. Necessary condition for satisfactory system operation is that all synchronous machines operate in synchronism. This aspect is influenced by the dynamics of the generator rotor angles and power-angle relationship.

Power system security refers to the ability of the power system to remain in synchronism or stable in the event of disturbances. The process of determining whether the system is able to go into stable state or being secured is known as power system security assessment.

In a power system network, there are equipment's that provide online measurement of the power system's parameters that are required for the security (stability) assessment of the network. The monitoring mechanism measures the real time values of components such as line power, line current power injections, bus voltage magnitudes and even the status of the breakers and switches. These values obtained formed the basis for the computation of power system security assessment.

In the security assessment, the concern is the behavior of the power system when subjected to transient disturbance. The disturbance may be small in the form of load changing conditions, or large in the form of short-circuit on a transmission line or other large disturbances such as, loss of large load or generator, or loss of tie-line between two subsystems. The system response to a disturbance involves much of the equipment. For example, a short-circuit on a critical element followed by its isolation by protective relays will cause variations in power transfers, machine rotor speeds, and bus voltages, the voltage variations will actuate both generation and transmission system voltage regulators, the speed variation will actuate prime mover governors; the change in tie line loading may actuate generation controls; the changes in voltage and frequency will affect loads on the system in varying degrees depending on their individual characteristics [25]. Many assumptions are usually made to simplify the problem and to focus on factors influencing the specific type of security problem.

To provide a framework for our proposed method, we briefly describe different form of power system instability and associated concepts. Analysis of small idealized system will be used to show each type of instability.

2.1.1 Rotor Angle Stability

Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism. The stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is how the outputs of synchronous machines vary with respect to their rotors oscillations. A brief discussion of synchronous machines characteristics is helpful to develop the basic concepts of stability.

A synchronous machine has two essential circuits: the field, which is on the rotor, and the armature, which is on the stator. The field winding is supplied by direct current power while the terminals of the armature provide the load power. The rotating magnetic field of the field winding induces alternating voltages when the rotor is driven by a prime mover (turbine). The frequency of the induced voltages depends on the speed of the rotor and the number of poles of the machine.Thefrequencyoftheelectricalvoltageandtherotormechanicalspeedare synchronized (or in synchronism), at50 Hz in Bangladesh and most other countries and60 Hz in USA, Canada and South America.

When two or more synchronous machines are interconnected, the stator voltages and currents must have the same frequency and the rotor mechanical speed of each machine is synchronized to this frequency. To change the electrical torque (or power) output of the generator, the mechanical torque input is changed to advance the rotor to a new position relative to the revolving magnetic field of the stator.

Consider the system shown in Figure 2.1.It consists of two synchronous machines connected by a transmission line having an inductive reactance X_L but negligible resistance and capacitance. Assume that machine 1 represents a generator feeding power to a synchronous motor represented by machine 2.

The power transfer from the generator to the motor is a function of the angular separation δ between the rotors of the two machines. This angular separation is due to three components: generator internal angle δ_G, angular difference between the terminal voltages of the generator and motor, and the internal angle of the motor.

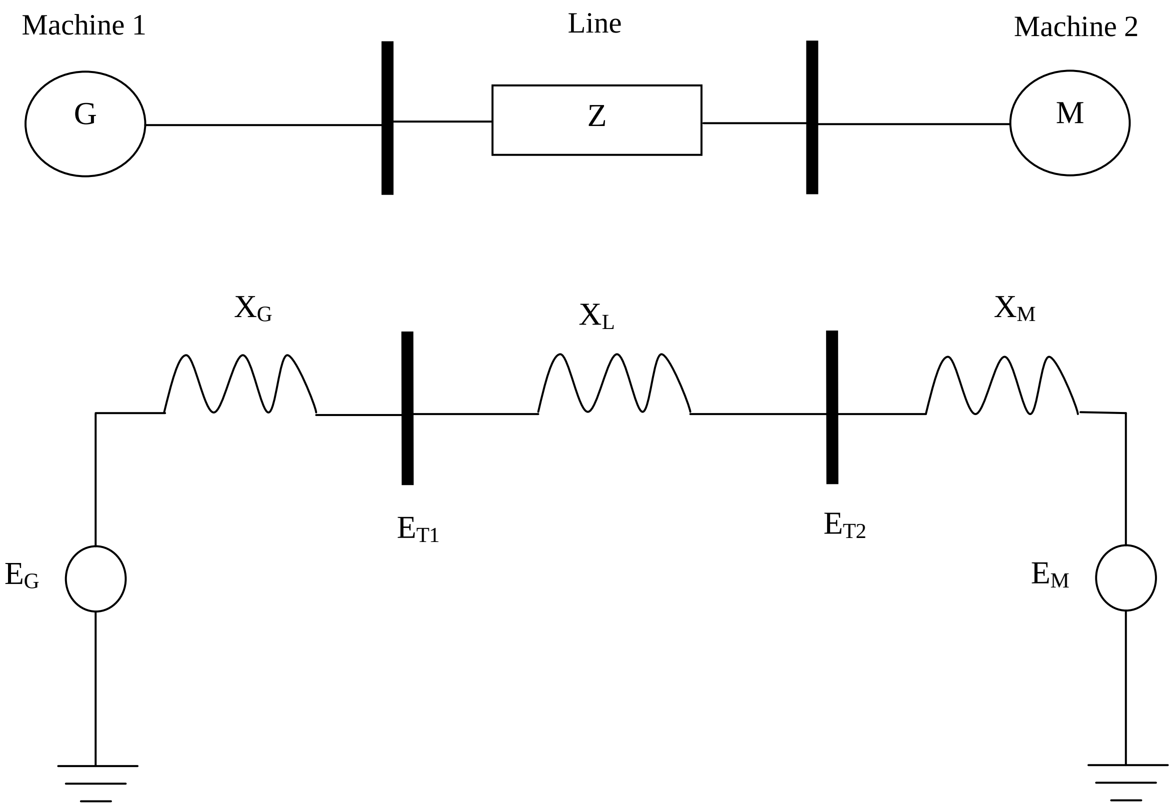

Figure 2.1: Single line diagram and equivalent circuit of a two machine system

A phasor diagram identifying the relationships between generator and motor voltages is shown in Figure 2.2. The power transferred from the generator with reactance of X_G to the motor with reactance of X_M through a transmission line with reactance of X_L is given by Equation 2.1.

$$P = \frac{E_G E_M}{X_T} \sin \delta \tag{2.1}$$

Where, $X_T = X_G + X_L + X_M$

The corresponding power versus angle relationship is plotted in Figure 2.3. In the equivalent model, an idealized model is used which makes the power varies as a sine of the angle. However, with a more accurate machine models including the effects of automatic voltage regulators, the variation in power with angle would deviate significantly from the sinusoidal relationship, but the general form would be similar. As the angle is increased, the power transfer increases up to a maximum. After a certain angle, normally 90˚, a further increase in angle results in a decrease in power. When the angle is zero, no power is transferred.

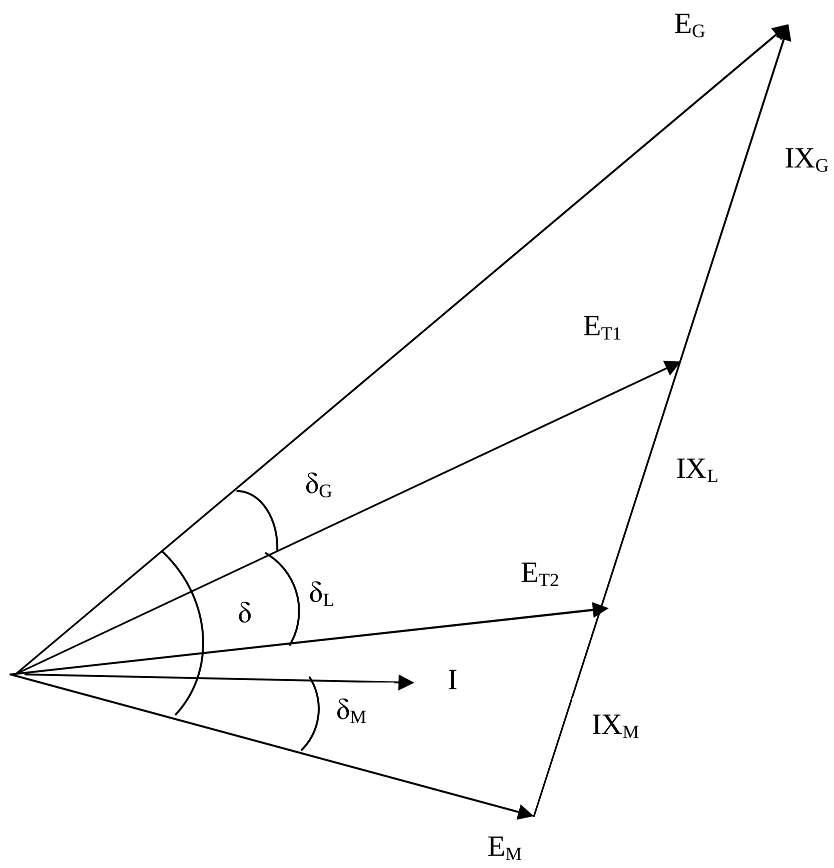

Figure 2.2: Phasor diagram or power transfer characteristic of a two-machine system [25]

In the Figure 2.3, there are two points of interest: stable equilibrium point (SEP) δ^0, and the unstable equilibrium point (UEP) δ^u. In the steady-state status, the system rests on the SEP where the mechanical power is equal to the electrical power. However, if the system swings to the UEP, where the mechanical power is equal to the electrical power graphically, the synchronous machine loses synchronism (unstable). Note that the system is assumed to be lossless.

When there are more than two machines, their relative angular displacements affect the interchange of power in a similar manner. However, limiting values of power transfers and angular separation are a complex function of generation and load distribution.

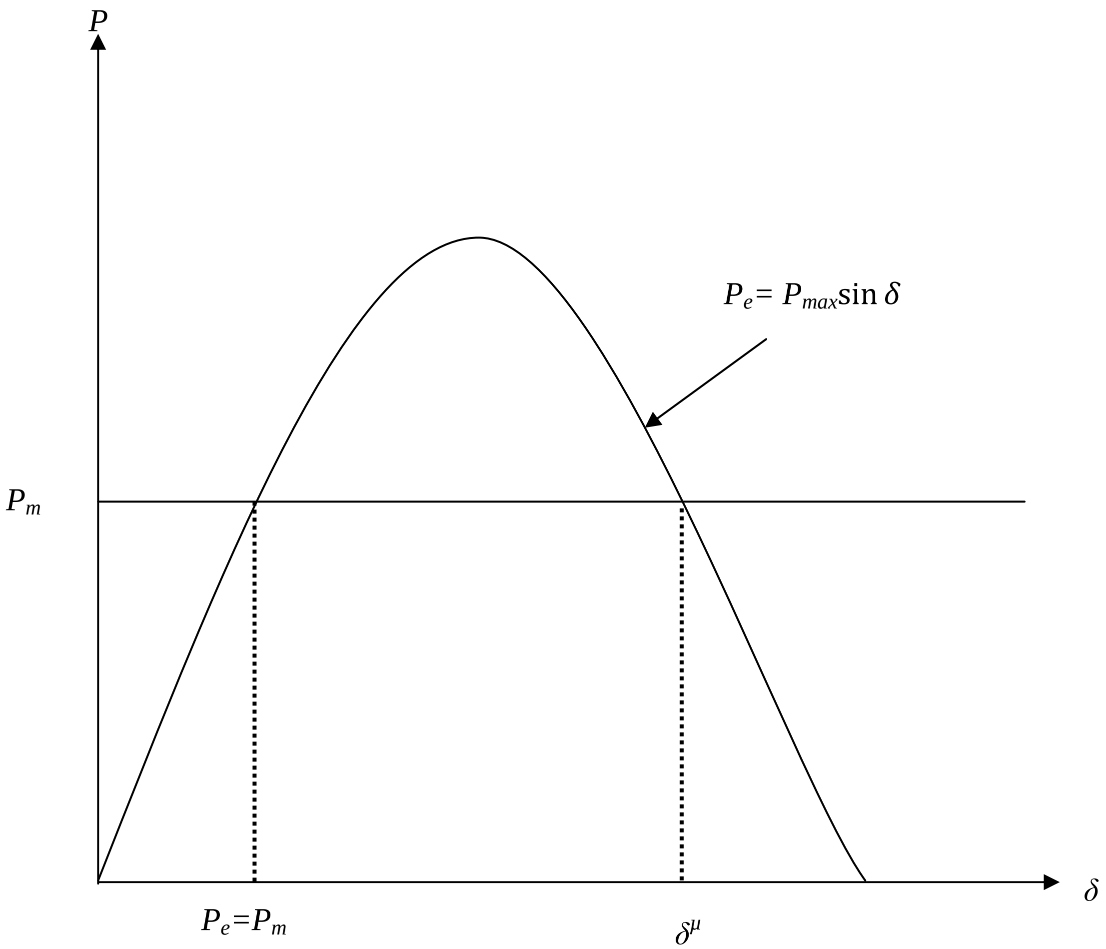

Figure 2.3: Power-angle characteristic of a two-machine system [1]

Stability is a condition of equilibrium between opposing forces. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act whenever there are forces tending to accelerate or decelerate one or more machine with respect to other machines. In steady-state, there is equilibrium between the input mechanical torque and the output electrical power of each machine, and the speed remains constant. However, if the system is perturbed, this equilibrium is disturbed resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body [25]. If one generator runs faster than the other, the rotor angle of the faster machine relative to the rotor angles of the slower machines will change and that particular machine may lose synchronism causing disturbance to the other machines. As previously discussed, beyond a certain limit, an increase in angular separation is accompanied by a decrease in power transfer, this increases the separation further which leads to instability. For any given situation, the stability of the system depends on whether or not the deviations in angular positions of the rotors result in sufficient restoring torque.

Loss of synchronism can occur between one machine and the rest of the system or between groups of machines. In this case, synchronism may be maintained within each group after its separation from the others.

The change in electrical torque of a synchronous machine following a perturbation can be resolved into two components:

$$\Delta T = T_S \, \Delta\delta + T_D \, \Delta\omega \qquad (2.2)$$

Where in Equation 2.2,

$T_S \, \Delta\delta$ is the component of torque change in phase with the rotor angle perturbation $\Delta\delta$ and is referred to as synchronizing torque component, Ts is the synchronizing torque coefficient,

$T_D \, \Delta\omega$ is the component of torque change in phase with the speed deviation $\Delta\omega$ and is referred to as the damping torque component;

T_D is the damping torque coefficient.

Lack of sufficient synchronizing torque may result in instability through an aperiodic drift in rotor angle. On the contrary, lack of sufficient damping torque results in oscillatory instability.

Rotor angle stability phenomenon is categorized into two main categories: small-signal stability, and transient stability.

2.1.2 Small-Signal Stability

It is the ability of the power system to maintain synchronism under small disturbances. These types of disturbances occur on the system because of small variation in load sand generation. Instability that may result can be of two forms: (i) steady increase in rotor angle due to lack of sufficient synchronizing torque, or (ii) rotor oscillations of increasing amplitude due to lack of sufficient damping torque. The system response to small disturbance depends on: initial operation, the transmission system strength, and the type of generator excitation controls used. For a generator connected radially to a large power system, in the absence of automatic voltage regulators (i.e. with constant field voltage) the instability is due to lack of sufficient synchronizing torque. This result is shown in Figure 2.4. With continuously acting voltage regulators, the small-signal stability is one of ensuring enough damping of system oscillations. Figure 2.5 shows this type of instability.

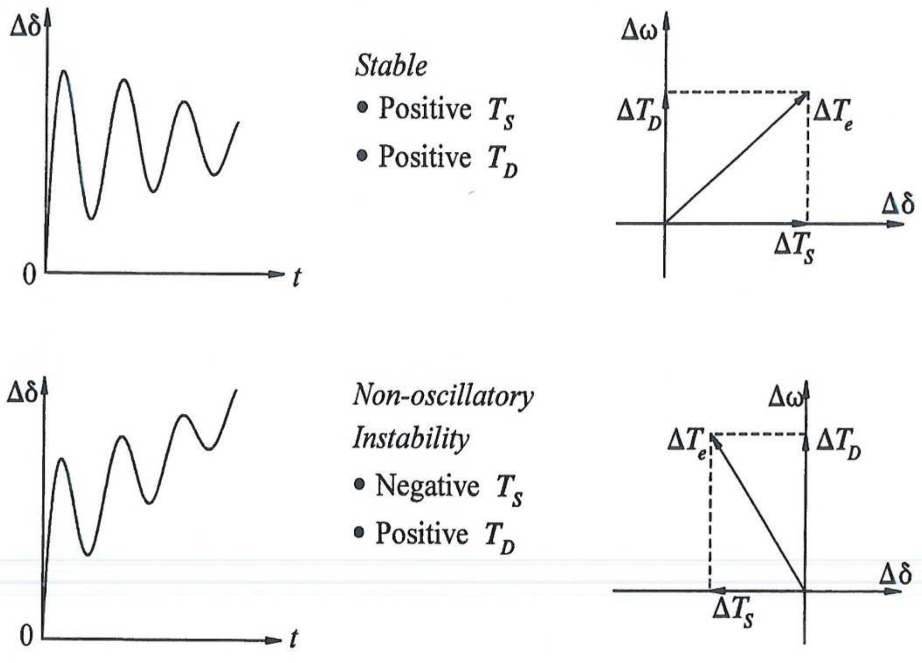

Figure 2.4: Nature of small-disturbance response with constant field voltage. Redrawn from [25].

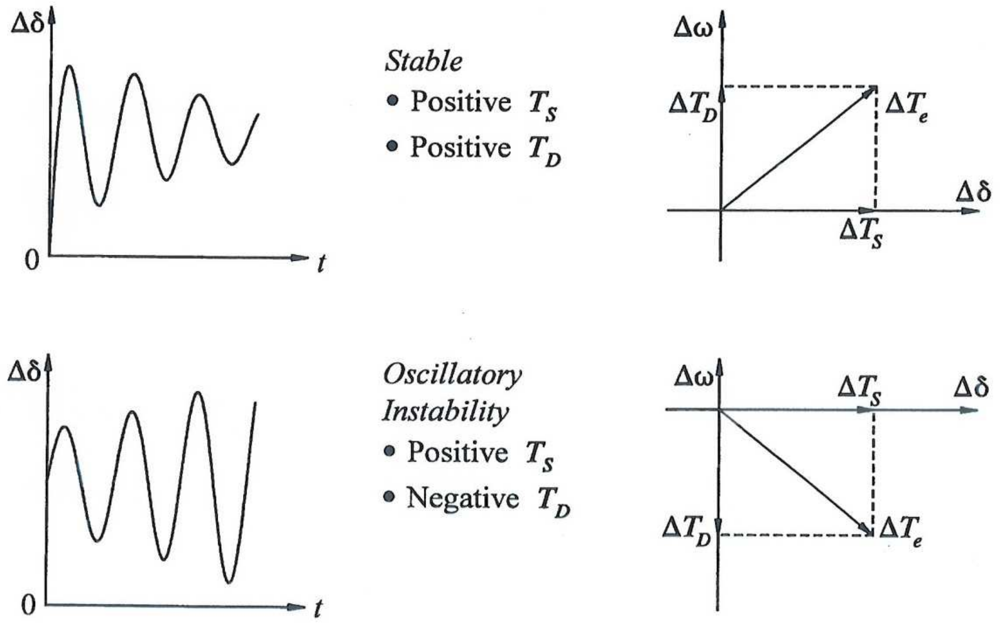

Figure 2.5: Nature of small-disturbance response with excitation control. Redrawn from [25]

Practical power system may experience small-signal instability due to insufficient damping of oscillations. The stability of the following types of oscillations is of concern:

- Local modes or machine-system modes: these are associated with the swinging of units at a generating station with respect to the rest of the power system.
- Interareamodes: these are associated with the swinging of many machines in one part of the system against machines in other parts.
- Control modes: these are associated with generating units and other controls.
- Torsional modes: these are associated with the turbine-governor shaft system rotational components.

2.1.3 Transient Stability

Transient stability is the ability of the power system to maintain synchronism when subjected to sever transient disturbance. The response to this type of disturbance involves large excursions of rotor angles and is influenced by nonlinear power-angle relationship. Stability depends on the initial operating state of the system and these verities of the disturbance. The system usually altered after the disturbance which may cause the system to operate in a different steady-state status from that prior the disturbance.

Power systems are designed to be stable for a selected set of contingencies. The contingencies usually considered are short-circuits of different types: phase-to-ground, phase-to-phase-to-ground, or three-phase. They are usually assumed to occur on the transmission lines, but occasionally bus or transformer faults are also considered.

Figure2.6 illustrates the behavior of asynchronous machine for stable and unstable situations. In Case 1, the rotor angle increases to a maximum, then decreases and oscillates with decreasing amplitude until it reaches a steady state. This case is considered transient stable. In Case 2, the rotor angle continues to increase steadily until synchronism is lost. This type on transient instability is referred to as first-swing instability. In Case 3, the system is stable in the firstswingbutbecomesunstableasaresultofgrowingoscillationsastheendstateisapproached. This form of instability occurs when the post fault steady-state condition is itself is small-signal unstable.

In transient stability studies, the study period of interest is usually limited to3to5 seconds following the disturbance, although it may extend to about ten seconds for very large systems with dominant inter-area modes of oscillation.

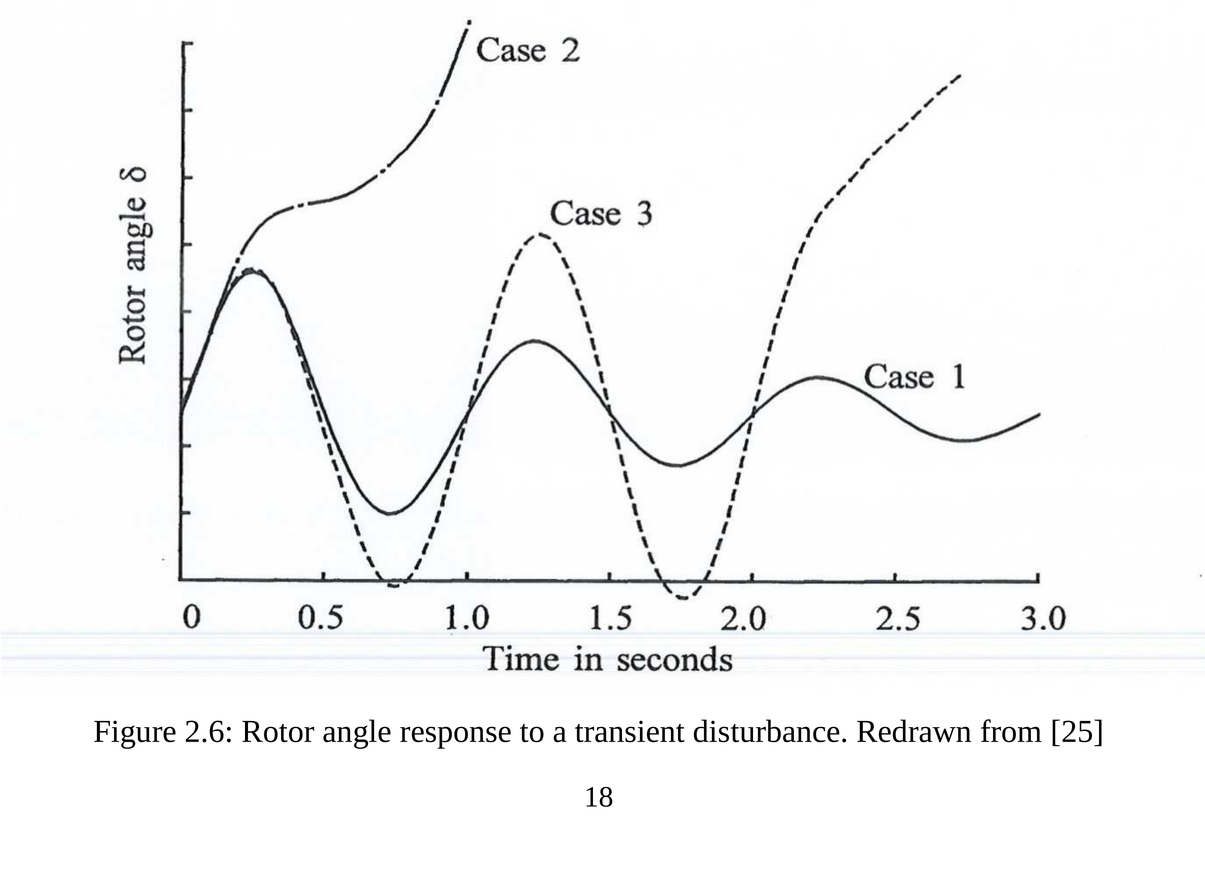

Figure 2.6: Rotor angle response to a transient disturbance. Redrawn from [25]

2.2 Power System Security Assessment

Power system security assessment is performed to determine whether and to what extent a power system is able to operate in secure mode after a fault occurs during its operation. It involves the evaluation of available data collected and estimate the security level of the system in its present state and estimation of the near future state.

Due to the nature of the disturbance and the setup of the power system network, there are two main elements to power system security assessment, static security assessment and dynamic security assessment [26]. Static security assessment is usually performed prior to dynamic security assessment.

Static security assessment evaluates the post contingent steady state of the system. It neglects the transient behavior and any other time dependent variations caused by changes in load conditions. Static security assessment also applies the assumption that the transition to new operating conditions has taken place. Its main objective is to ensure that the operating conditions are met in the new operation conditions. This assessment basically ignores the dynamics of the system and synchronization of the power system network during the process of transiting into post fault condition state remains unknown.

This level of assessment will only be able to give a rough estimation of the post contingency stability. It also made a dangerous assumption that the system remains stable in the event of fault. This assumption is not always true as most disturbances will cause oscillation to a certain extent which in turn causes the system to fall into unstable category. In any case, the actual mode of stability is still required to be determined for any preventive remedial action if required.

The transition into post condition state is the area of interest for dynamic security assessment. The assessment will ensure that the transition will lead to an acceptable operating condition. Dynamic security assessment is required due to the constant variation of loads and change in the behavior of the power system. Gradual changes such as load variations over the day are normal and can be anticipated to some extent.

In the event of unexpected loss of a generating plant due to equipment failure, there will be a large impact on both the user and the supplier. These disruptive changes will cause the system variables such as frequency and voltage to oscillate regardless of how small the disturbance is. If the system is secured, these oscillations will decay and be damped out eventually. Otherwise, the oscillation of the frequency and voltage will grow to the extent of shutting down the generator.

If the disturbance is small, which means that the voltage only oscillates close to the equilibrium point, it is then appropriate to examine the eigen values of a linear version of the system model. If the system experiences a major disturbance, the oscillation will keep growing to a significant magnitude. The stability is then measured based on the trajectories of the disturbed systems motion related to the region of attraction of the final equilibrium state. For such situations, the use of non-linear system model and the analysis theory for non-linear system are required.

In the event of disturbances, the electromechanical oscillation of synchronous generator will be used to measure the transient stability. It is determined by observing the variation of the rotor angle as a function of time throughout the duration of the fault. The transient stability depends on the magnitude of the fault, duration of the fault and the speed of the protective devices. If the system is transiently stable, the oscillation of the rotor angle will damp down to a safe operating limit.

2.2.1 Static Security Assessment

To maintain security of the power system at all times is the main responsibility of the operator. The long term planning provides adequate reliability. The short term operations planning ensure that there is enough generation and transmission capacity in the system to meet the projected conditions for the next day or week. In real time the control center computers automatically sends out signals to the generators to follow load and also monitors for adequate reserves in case a generating unit is suddenly lost. The static security assessment program ensures that the loss of any equipment a generating unit, a transformer, a transmission line, etc. does not result in voltages beyond their operating limits and transmission lines beyond their loading limits.

The calculations needed for the static security assessment is exactly the same as described in the transmission planning section where all possible single contingencies are studied by solving the power flow equations for each contingency on the base case. In real time the same contingency cases have to be studied but for the real time conditions. To do this a power flow solution that accurately portrays the real time conditions must be obtained. This is done by using the real time data measurements from the power system to obtain the best estimate of the system state variables, which are the bus voltages. To do this state estimation of bus voltage with reasonable accuracy requires the acquisition of real time measurements with adequate redundancy. Many control centers are set up to do this state estimation every few minutes. Thus a power flow solution, updated every few minutes, of the real time conditions of the power system is then available in the control center to the operator.

The real time conditions very seldom mirror any of the base cases that were actually studied off-line. The off-line studies usually construct worst-case scenarios to develop operational guidelines, and by their very nature tend to be conservative. Thus the operational limits obtained from off-line studies are often too restrictive or, in the case when the real time conditions stray into totally unstudied areas, irrelevant. Thus the availability of a power flow solution of the real-time conditions makes it possible for the operator to obtain more realistic operational guidance. This can be done manually by the operator studying the effects of equipment outages one at a time, a procedure very useful if the operator is contemplating some switching operations and could check the aftereffects on the computer before actually doing it.

The main use, however, of the real time power flow solution is the automatic assessment of the static security of the system. The computer automatically studies hundreds of possible contingencies that could happen on the power system and determines how well the system can withstand them. This is tantamount to running hundreds of power flow solutions and then checking for line loading or voltage violations to alert the operator, and it has to be done within a few minutes for the information to be useful. This is quite a computational burden in terms of both the number of power flow solutions and the data shifting needed for checking violations. Thus much of the development of static security assessment tools in the last two decades has concentrated on making this computation more efficient.

Instead of finding full power flow solutions for all hundreds of contingencies, more approximate but fast solutions are obtained to determine which contingencies pose the biggest hazards. This calculation is known as contingency screening. Most of the time, for well-planned systems, single contingencies should not cause any limit violations, and the main purpose of the contingency screening is to isolate the very few problem cases from the hundreds of non-threatening contingencies. In addition to running fast approximate solutions, the screening must evaluate these solutions by a severity index to determine which contingencies are the worst. These severity indices must reflect line overloads and voltage violations such that the contingencies can be ranked according to their severity. Once this is done, only the worst contingencies are further studied with accurate power flow solutions and the resulting overloads and under voltages are reported to the operator as alerting messages.

The static security assessment program is thus designed to alert the operator if a particular contingency would cause the system to violate operational limits. The operator, if so alerted, must then decide whether to take preventive action right away so that this contingency does not pose a problem or to take no action at the present time but be ready to take corrective action if the contingency does occur. In most cases of overloading or under voltages, the operator usually has several minutes to take corrective action and so the latter course is most often taken. This approach saves the operator from making expensive changes in the operating condition and the contingency may never occur. However, in some regions the operator must ensure no violations for single contingencies and in that case the more expensive but secure preventive action must be taken whenever any contingency study detects limit violations.

2.2.2 Dynamic Security Assessment

The static security assessment checks for limit violations after outages but it assumes that the system reaches steady state after these outages occur. Since outages are usually the results of an accidental short-circuit which causes the protective systems to isolate the short-circuited elements, the power system may experience significant excursions in the voltages and power flows during this disturbance. If the disturbance is severe enough, these swings may actually cause generators to become unstable (lose synchronism) in which case there would be widespread outages instead of the single outage expected.

The dynamic security assessment identifies those short-circuits or contingencies that causes instabilities. Again, for a properly planned system no contingencies should make the system unstable if operated within its limits. However, as noted before, in real time operation the power system does end up in conditions that were not anticipated when the planning was done. Thus it is important to check whether contingencies can make the system unstable. The problem is that the stability calculations (described in the transmission planning section) are even more time consuming than the power flow calculations and the on-line checking of stability for hundreds of possible contingencies is a daunting task.

With the price-performance ratio of computers falling continually, dynamic security assessment has become a reality. Techniques learnt from running static security assessment as well as new algorithms have been very useful in developing the dynamic security assessment tools. The concept of contingency screening to quickly isolate the worst contingencies also holds for dynamic security: most of the contingencies will be stable and the task is to isolate the few that are not.

Contingency screening requires a quick approximate method to determine the stability of the system. The traditional, and accurate, method is the time domain solution integrated over a long enough time periods that allows the trajectories to portray stable or unstable behavior. The approximate methods developed so far calculates the time domain solution

for only a short time, usually just beyond fault clearing, and then projects the stable or unstable behavior from these trajectories by other calculations. The various techniques use transient energy and their margins, the equal area criterion, different coherency measures, and signal energy. These measures also provide the stability indices that can be used to rank the contingencies to determine the worst cases. Once the worst cases are determined the traditional time domain solution can be used to accurately determine stability of the system.

These techniques mentioned here work quite well for systems that are vulnerable to instabilities caused by the lack of synchronizing power. These instabilities occur quickly, within a second or so, and can be detected by a smaller amount of calculations. Several experimental programs are now operating in various parts of the world and commercial packages for control centers are now available. Instabilities occurring after several oscillations because of negative damping are difficult to detect without detailed and longer simulation or by modal analysis. For these kinds of systems, on-line dynamic security assessment is still not available and conservative operating limits calculated off-line are the only answer.

In those rare cases where the dynamic security assessment detects instabilities, the operator, once alerted, needs to take preventive action. This is because once the contingency occurs, the onset of instability is very rapid and there is no possibility of the operator taking manual corrective action after the fact. In some cases, the operator may be able to arm special protection devices to shed load or generation that ensures stability. More commonly, the preventive action available to the operator is modification of the generating pattern. Since this invariably increases the cost of operation, researchers are trying to find methods to quickly calculate the minimum changes required to maintain stability for a particular contingency. Often, the simplest way to do this is by recalculating the power flow limits on a particular transmission corridor.

2.3 Preventive Measures to Avoid System Instability

In power system design and preparation stage, a wide number of disturbances have to be assessed by system operators. If the system is found to be unstable (or marginally stable) following any contingency, variety of actions can be taken to improve the system stability. These preventive actions can be classified mainly into Offline and online preventive actions. Offline preventive measures: Improvement of system stability can be achieved by many actions including:

- Organizing the system configuration and maintenances in such that being suitable for the particular operating conditions without overloading during abnormal conditions.

- Reduction of transmission system reactance which can be achieved by adding additional parallel transmission circuits, providing series compensation on existing circuits and by using transformers with lower leakage reactance.

- Activating new generation facilities for reactive power support and voltage control service such as power system stabilizers, FACTs, distributed generation technologies, and rapid thermal units with fast-valving capability and fast acting automatic excitation systems.

- Connecting dynamic breaking resistors at the generator and substation terminals in order to break the acceleration of the rotor of generators during faults. Shunt resistors can be switched in to create an artificial load following a fault, in order to improve the damping of accelerated generators.

- Installing efficient protective devices and coordinating between the interconnected system operators for faster fault clearing and initiating proper corrective actions during abnormal conditions.

- Online remedial and preventive measures: The operation of interconnected power system is economically oriented based competitive manner in the most cases. This complicates the ability of Offline preventive measures to keep the power system away from the stability limits. This produces the importance of system operators to use online DSA and operating the power system within these limits. There are many online preventive measures can be used to safeguard and enhance system stability such as:

- Changing the system topology such as tripping of critical generator to ensure that the other generators maintain in synchronism. In addition, generation rescheduling/re-dispatching can be used to reallocate power generation in order to avoid system overloads and relieve constraints.

- Using of high-speed protective schemes such as transmission line protection with single-pole tripping and adaptive reclosing capabilities to minimizes system disturbance. High-speed automatic reclosing system is effective methodology to restore power continuity.

- Effectively use of online transformer tap-changers and phase shifting transformers to control the power flow across transmission system by continuous control of voltage regulator set points and changing the phase using taps.

- Automatic load shedding of interruptible consumers is an effective corrective counter-measure to maintain the frequency at nominal value during abnormal conditions. In the simple implementation, under frequency relays installed at fixed points and with fixed settings can be made adaptive by adjusting the location and level of shedding in accordance with power flow and voltage conditions on the transmission network [8].

- Assuring reactive-power generation or absorption control and using special control of HVDC links to control the DC power and maintain generation/load balance in AC networks during disturbances.

- Implementation of high-speed excitation systems to rapidly boosts field voltage in response to disturbances. Increasing of the internal voltage of a generator has the effect of proving transient stability.

2.4 Power System Models

In order to analyze any power system, a mathematical model is used to represent the system. It is very important to understand the various power system models before applying them in this thesis. Therefore, power system models are presented in this section. The models that are presented in this section include: SMIB classical and detailed models, and multi-machine classical model.

2.4.1 Single-Machine Infinite-Bus System

2.4.1.1 Classical model

Consider the single-machine infinite-bus (SMIB) system shown in Figure 2.8

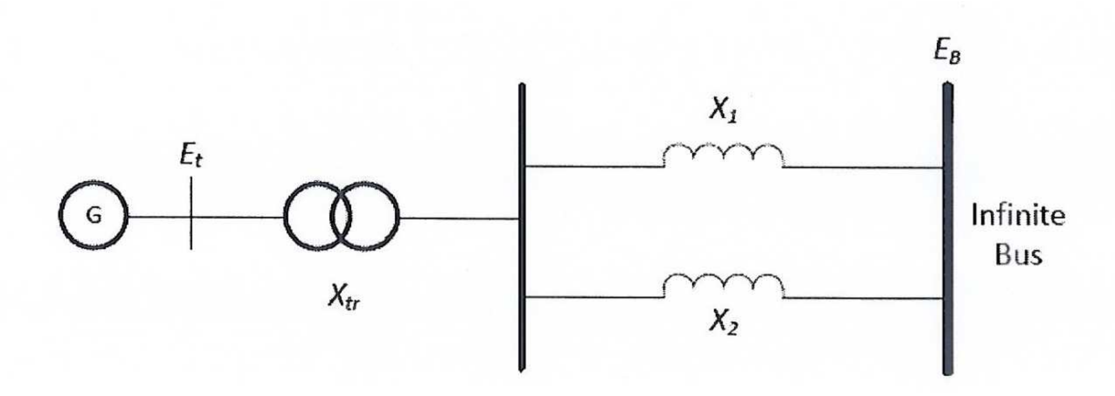

Figure 2.7: Single-machine infinite-bus system [25]

The generator is represented by the classical model, which ignores saliency of round rotor, that is, for the purpose of transient stability, only the transient reactance X_d' is considered with the assumption that the direct and quadrature components are equal. Also, the speed governor effects are neglected. The generator's voltage is denoted by E', and the infinite-bus voltage is denoted by E_B. The rotor angle δ represents the angle by which E' leads E_B. When the system experiences a disturbance, the magnitude of E′ remains constant at its pre-disturbance value and δ changes as the generator rotor speed deviates from synchronous speed ω_0.

The generator's electrical power output is:

$$P_e = \frac{E' E_S}{X_T} \sin\delta = P_{max} \sin\delta \tag{2.3}$$

where, $P_{max} = \frac{E' E_S}{X_T}$ (2.4)

The equation of motion or the swing equation may be written as:

$$\frac{2H}{\omega_0}\frac{d^2\partial}{d^2 t} = P_m - P_{max}\sin\delta \tag{2.5}$$

where

P_m = mechanical power input, in pu

P_{max} = maximum electrical power output, in pu

H = inertia constant, in MW.s/MVA

δ =rotor angle, in elec. rad

t =time, in s

2.4.1.2 Detailed model

In this model of synchronous machine, the field coil on the direct axis(d-axis) and damper coil on the quadrature axis (q-axis) are considered. The machine differential equations are[2]:

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}\left[- E'_q + (X_d - X'_d)i_d + E_{fd}\right] \tag{2.6}$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{qo}}\left[- E'_q + \left(X_q - X'_q\right)i_q\right] \tag{2.7}$$

$$\frac{d\delta}{dt} = \omega_B(S_m - S_{mo}) \tag{2.8}$$

$$\frac{d\delta_m}{dt} = \frac{1}{2H}[T_m - DS_m - T_e] \tag{2.9}$$

$$T_e = E'_q i_q + E'_d i_d + (X_q - X'_q) i_d i_q \tag{2.10}$$

$$E'_q + X'_d i_d - R_a i_q = V_q \tag{2.11}$$

$$E'_d + X'_q i_q - R_a i_d = V_d \tag{2.12}$$

From Equations 2.11 and 2.12, i_d and i_q can be solved as:

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \frac{1}{R_a^2 + X'_d X'_q} \begin{bmatrix} R_a & X'_d \\ -X'_q & R_a \end{bmatrix} \begin{bmatrix} E'_q - v_q \\ E'_d - v_d \end{bmatrix} \tag{2.13}$$

Where,

T_m the mechanical torque in the direction of rotation

T_e the electrical torque opposing the mechanical torque

T'_{do} d-axis open circuit transient time constant

T'_{qo} q-axis open circuit transient time constant

S_m machine slip

S_{m0} initial machine slip (= 0in steady-state)

ω_B the electrical angular frequency

X_d d-axis reactance

Xq q-axis reactance

X'_d, X'_q d-axis and q-axis transient reactance, respectively

R_a armature resistance

E'_d , E'_q d- and q-axis generator's voltage

i_d , i_q d- and q-axis current

E_{fd} control voltage.

2.4.2 Multi-machine Infinite-Bus System

2.4.2.1 Synchronous reference frame

For this model, the motion of the generators can be represented by the set of differential equations [11]:

$$\left.\begin{aligned} M_i\dot{\omega}_i + M_i\omega_i &= P_i - P_{ei} \\ \dot{\delta}_i - \omega_i, i &= 1, 2, , \dots \dots n \end{aligned}\right\} \quad (2.14)$$

where, for machine *i*,

δ_i- angle of voltage behind transient reactance, indicative of generator rotor position

ω_i- rotor speed

M_i- generator inertia constant

D_i- damping coefficient

The expressions for P_i and P_{ei} are given by:

$$\left.\begin{aligned} P_i &= P_{mi} - E_i^2 G_{ii} \\ P_{ei} &= \sum_{\substack{i=1 \\ j\neq i}}^{n} \left[C_{ij} \sin(\partial_i - \partial_j) + D_{ij} \cos(\partial_i - \partial_j)\right] \end{aligned}\right\} \quad (2.15)$$

Where,

$C_{ij} = E_i E_j B_{ij}$

$D_{ij} = E_i E_j G_{ij}$

P_{mi} mechanical power input

E_i magnitude of voltage behind transient reactance

G_{ii} real part of the *i*th diagonal element of the network's Y-matrix

C_{ij}, B_{ij} real and imaginary components of the *ij* th element of the network's Y-matrix.

CHAPTER 3

DYNAMIC SECURITY ASSESSMENT

3.1 Overview

Sudden changes or disturbances in power systems are associated with a number of phenomena with different timeframe involved. In general, the power system stability can be assessed for the most severe fault possible such as three phase faults. Faults at critical locations may cause circuit tripping due to overloading or loss of synchronism of some generating units. Therefore, DSA is important issue in the modern interconnected power system where the disturbances produce power swings and rotor oscillations. During network disturbances, the power generators have to provide immediate support by changing the currently generated power supplied to the grid. The immediate change is restricted by the power system inertia during the initial few hundred milliseconds. Most turbines are unable to yield the fast torque response required to act in such small level in transient stability. Thus dynamic behavior investment and preparing the proper actions that improve system response during contingencies are important aspects during power system operation and control. The ISO coordinates the available control actions to enhance the system behavior during abnormal conditions. The control variables that can be used to enhance the power system stability are discussed in section 2.3.

Generation rescheduling is considered as a practical preventive or remedial control action to improve the system security during any contingency. The stability enhancement utilizing generation rescheduling is to find a generation configuration with the improved system dynamic behavior while satisfying operational constraints with minimum shift from the economic operation. A fast and robust tool to assess system dynamic behavior is important to prepare the proper online amount of generation rescheduling and necessary actions. The investigation of the dynamic behavior requires extensive mathematical formulation and calculations due to the existence of a large number of different models and the associated nonlinearity. The objective of these calculations is to find the conditions that will exist in the power system just after a sudden change such as opening of a transmission line or occurrence of *N-1* and *N-2*contingencies.

DSA evaluates the time-dependent transition from the pre-contingent to the post-contingent state determining the stability of the system for both small and large disturbances. Two dynamics problems, transient stability and voltage collapse should be considered when performing a dynamic security study. Transient stability assessment is the major concern in DSA for multi-machine power systems analyzing whether a fault on the system, or loss of a large generator, can give rise to large electromechanical oscillations between generating units leading to a loss of synchronism in the system.

3.2 Transient Stability Assessment

Transient stability analysis concerns with the system's ability to reach an acceptable steady state operating conditions following a large disturbance.

Transient stability associated with a large disturbance such as loss of generators, sudden change in loads, network significant changes or three phase short circuit faults. A large disturbance is a disturbance for which the equations describing the system dynamics cannot be linearized for the purpose of analysis. This disturbance causes as imbalance between the mechanical input power to each generator and its electrical output power. Then, the generator rotors start to swing with respected to each other. There are three approaches for transient stability assessment [25]:

Numerical Integration Methods such as Transient stability analysis is routinely performed in utility system planning. The industry standard for transient stability usually requires the ability of the system to withstand severe disturbances, including any "possible but improbable" three-phase fault close to a generator's bus. The method used for analysis is time-domain numerical integration. The time-domain numerical integration is not suitable for on-line security analysis due to the long CPU run times for simulation.

3.2.1 Transient Stability Analysis by Numerical Integration Method

The power system is considered stable if a fault is cleared before the critical clearing time (CCT). The CCT is defined as the maximum value of fault clearing time (FCT). Although a three-phase-fault has a lower probability of occurrence, it has larger impact on a system. Utility companies prepare themselves for the worst case. It is common practice to use three-phase-faults for transient stability studies [29-31].

The most commonly used technique to perform numerical integration is presented:

Newton-Raphson Method [32]:

Consider an error function:

$$f(x) = K \qquad (3.1)$$

With x = x^0at initial value. The error is the difference between K and f(x^0) and calls the error ε as given in equation 3.3

$$f(x^0) + \varepsilon = K \qquad (3.3)$$

To drive the error to zero, we use Taylor expansion of the function about x^0.

$$f(x^0) + \frac{df(x^0)}{dx}\,\Delta x + \varepsilon = K \qquad (3.4)$$

Setting the error to zero, we calculate

$$\Delta x = \left(\frac{df(x^0)}{dx}\right)^{-1}[K - f(x^0)] \qquad (3.5)$$

For solving load flow an equation is written for each bus "i"

$$P + jQ_i = E_i I_i^* \qquad (3.6)$$

Where, $I_i = \sum_{k=1}^{N} Y_{ik}\, E_k$

Then

$$P + jQ_i = E_i\left(\sum_{k=1}^{N} Y_{ik}\, E_k\right)^* = |E_i|^2 Y_{ii}^* + \sum_{\substack{k=1 \\ k \neq i}}^{N} Y_{ik}^*\, E_i E_k^*$$

So, two equations are written for each bus: one for real power and one for reactive power. For each bus,

$$\Delta P_i = \sum_{k=1}^{N} \frac{\partial P_i}{\partial \theta_k} \Delta\theta_k + \sum_{k=1}^{N} \frac{\partial P_i}{\partial |E_k|} \Delta|E_k| \qquad (3.7)$$

$$\Delta Q_i = \sum \frac{\partial Q_i}{\partial \theta_k} \Delta\theta_k + \sum \frac{\partial Q_i}{\partial |E_k|} \Delta|E_k|$$

The Jacobian matrix is as follows:

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial |E_1|} & \cdots \\ \frac{\partial Q_1}{\partial \theta_1} & \frac{\partial Q_1}{\partial |E_1|} & \cdots \\ \vdots & \cdots & \cdots \\ \vdots & \cdots & \cdots \\ \vdots & \cdots & \end{bmatrix} \begin{bmatrix} \Delta\theta_1 \\ \Delta|E_1| \\ \vdots \\ \vdots \\ \vdots \end{bmatrix} \qquad (3.8)$$

The equation, Eq. 3.6 can be expanded as :

$$P + jQ_i = E_i \sum Y_{ik}^* E_k^*$$

This can be expanded as:

$$P + jQ_i = \sum_{k=1}^{N} |E_i||E_k|(G_{ik} - jB_{ik})\varepsilon^{j(\theta_i - \theta_k)}$$

$$= \sum_{k=1}^{N} \{|E_i||E_k|[G_{ik}\cos(\theta_i - \theta_k) + jB_{ik}\sin(\theta_i - \theta_k)$$

$$+j[|E_i||E_k|[G_{ik}\sin(\theta_i - \theta_k) - B_{ik}\cos(\theta_i - \theta_k)]]\} \qquad (3.9)$$

Where,

θ_i, θ_k = the phase angles at buses *i and k*, respectively;

$|E_i|, |E_k|$ = the bus voltage magnitudes, respectively ;

$|G_{ik} + jB_{ik} = Y_{ik}$ is the *ik* term in the *Y* matrix of the power system.

The general practice in solving power flows by Newton's method has been to use $\frac{\Delta|E_i|}{|E_i|}$ instead of simply $\Delta|E_i|$; this simplifies the equations. The derivatives are

$$\frac{\partial P_i}{\partial \theta_k} = |E_i||E_k|[G_{ik}\sin(\theta_i - \theta_k) - B_{ik}\cos(\theta_i - \theta_k)]$$

$$\frac{\partial P_i}{\frac{\partial |E_k|}{|E_k|}} = |E_i||E_k|[G_{ik}\cos(\theta_i - \theta_k) + B_{ik}\sin(\theta_i - \theta_k) \qquad (3.10)$$

$$\frac{\partial Q_i}{\partial \theta_k} = -|E_i||E_k|[G_{ik}\cos(\theta_i - \theta_k) + B_{ik}\sin(\theta_i - \theta_k)$$

$$\frac{\partial Q_i}{\frac{\partial |E_i|}{|E_i|}} = |E_i||E_k|[G_{ik}\sin(\theta_i - \theta_k) - B_{ik}\cos(\theta_i - \theta_k)]$$

For $i = k$:

$$\frac{\partial P_i}{\partial \theta_i} = -Q_i - B_{ii}E_i^2$$

$$\frac{\partial P_i}{\frac{\partial |E_i|}{|E_i|}} = P_i + G_{ii}E_i^2$$

$$\frac{\partial Q_i}{\partial \theta_i} = P_i - G_{ii}E_i^2$$

$$\frac{\partial Q_i}{\frac{\partial |E_i|}{|E_i|}} = Q_i - B_{ii}E_i^2$$

Now, equation 3.8 now becomes,

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \vdots \end{bmatrix} = [J] \begin{bmatrix} \Delta \theta_1 \\ \frac{\Delta |E_1|}{E_1} \\ \Delta \theta_2 \\ \frac{\Delta |E_2|}{E_2} \\ \vdots \end{bmatrix} \qquad (3.11)$$

3.2.2 Critical Clearing Time

The critical fault clearing time is defined as the longest duration of a fault that does not lead to any generator loss of synchronism in the system or any other inadmissible repercussion for the system such that the power system is transiently stable. During large disturbances such as a three-phase short circuit, the protection system senses the presence of fault and the corresponding relays initiate the tripping of the nearest circuit breakers to isolate the fault. The time duration from the instant the disturbance occurs until the circuit breakers isolate the fault is termed by fault clearing time (FCT). Therefore, any generator shall have a CCT higher than FCT of the protection devices installed in the transmission system to avoid a loss of the connected generators. The loss of the connected generators may induce unacceptable consequences for the whole system following contingencies. The total fault clearing time consists of the combination of operating time of the main protection system; signaling time, relay time and breaker interrupting time. Normally, the three phase short circuit faults close to the generator transformer terminals is the worst fault position. Therefore, the corresponding CCT has been used as index to monitor the power system transient stability level during faults in many literatures and is used in this study [33]. As the value of CCT increases, the system has an increased opportunity to isolate and clear the disturbance using the protective relays and circuit breakers. Thus if the CCT value is less than the operating time of the circuit breaker for the corresponding electric component experiencing the fault, then the system is not considered transiently stable. The accepted limit of CCT is different from system to other but the common value is around 350 milliseconds, which is used in this dissertation as the limit for transient stability of the system [61].

The CCT is much more beneficial than the power limits which can be investigated using equal area criteria. TSA using CCT is characterized by the ability to screen and rank a set of contingencies to select the most sever ones beside specifying stability scenarios as stable or unstable state.

3.2.2.1 CCT Evaluation using Equal Area Criteria

Consider a single-machine infinite-bus (SMIB) system of Figure 3.2. For the system model considered in Figure 3.2, it is not necessary to formally solve the swing equation to determine whether the rotor angle increases indefinitely or oscillates about an equilibrium position. Assume that the system is a purely reactive, a constant P_m and constant voltage behind transient reactance for the system in Figure 3.2.

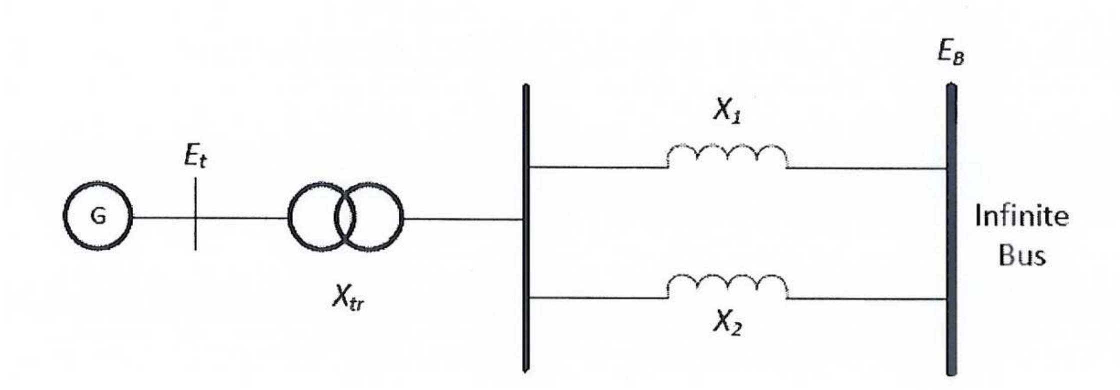

Figure 3.1: Simple SMIB System [34]

Assume that a 3-phase fault appears in the system at t = 0and it is cleared by opening one of the lines. The power angle characteristics of the system are shown in Figure 3.3.

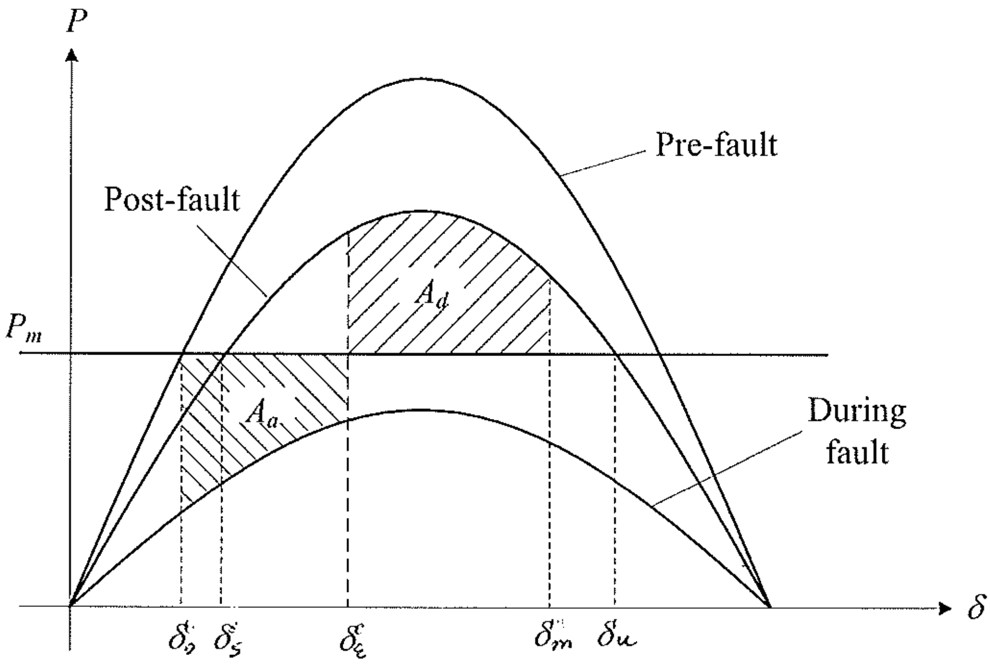

Figure 3.2: Power-Angle Characteristic of the System in Fig. 3.1 [34]

Let δ_0 and δ_s be the pre-fault and post-fault operating or stable-equilibrium points, respectively, of the system. During the fault, the electrical output P_e of the generator reduces drastically (almost to zero) but the mechanical power P_m remains almost constant. Thus the generator accelerates and its angle δ increases. When the fault is cleared by disconnecting the faulted line at time t_c, the output power of the generator becomes greater than the mechanical power and the generator decelerates to bring its speed to normal as shown in Figure 3.3. If the system is stable, the generator will recover to its steady-state speed (or zero speed deviation) at some peak angle δ_m. At δ_m, $P_e > P_m$ and the generator will continue to decelerate. The angle

δ decreases from δ_m and reaches a minimum value below δ_s before it starts to increase again. The generator angle will oscillate around δ_s and eventually it will settle down at δ_s because of the system damping. For a given clearing angle δ_c, the peak angle δ_m can be determined by equating the accelerating area A_a to decelerating area A_d. The expressions for A_a and A_d are

$$A_a = \int_{\delta_0}^{\delta_{cr}} \left(P_m - P_e^f\right) d\delta = P_m(\delta_{cr} - \delta_0) \tag{3.12}$$

$$A_d = \int_{\delta_c}^{\delta_{max}} \left(P_e^p - P_m\right) d\delta \;=\; (P_{max} \sin \partial - P_m)$$

$$= P_{max}(\cos \delta_{cr} - \cos \delta_{max}) - \; P_m(\delta_{max} - \delta_{cr}) \tag{3.13}$$

Where

P_e^f is the during-fault electrical power

P_e^p is the post-fault electrical power

For a system to be transient stable, the maximum decelerating area is greater than the accelerating area. That is, $A_d > A_a$. For a clearing time t_c when $A_d = A_a$, we reach the maximum clearing time referred to as the critical clearing time t_{cr}. At the instant of fault clearing, the increase in rotor speed and the angle separation between the generator and infinite bus are given, respectively, by the following equation

$$\frac{d\delta}{dt} \;=\; \frac{\omega_s\, P_m}{2H} t_c \tag{3.14}$$

And,

$$\delta(t) = \frac{\omega_s\, P_m}{4H} t_c^2 \; + \delta_0|_{t_c} \tag{3.15}$$

Equating the expressions for A_a and A_d and transposing terms, yield

$$\cos \delta_{cr} = \left(\frac{P_m}{P_{max}}\right)(\delta_{max} - \delta_0) + \; \cos \delta_{max} \tag{3.16}$$

We see from the sinusoidal power–angle curve that

$$\delta_{max} = \pi - \delta_0 \quad elec\; rad \tag{3.17}$$

And,

$$P_m = P_{max} \sin \delta_0 \tag{3.18}$$

Solving for critical clearing angle δ_{cr}

$$\delta_{cr} = \cos^{-1}[(\pi - 2\delta_0) \sin \delta_0 - \cos \delta_0] \tag{3.19}$$

Substituting this value of δ_{cr} in the equation (3.15) yields

$$\delta_{cr} = \frac{\omega_s P_m}{4H} t_{cr}^2 + \delta_0 \tag{3.20}$$

And we find the critical clearing time

$$t_{cr} = \sqrt{\frac{4H(\delta_{cr} - \delta_0)}{\omega_s \ P_m}} \tag{3.21}$$

From verbal discussions with PGCB and BPDB engineers it has been found that no study has been done on CCT. Only the grid code declares target clearance time 80 ms for 400 kV and above, 100 ms for 230 kV, 120 ms for 132 kV and 160 ms for 33 kV [60].

Henceforth, we calculated critical clearing time using equation 3.21 considering maximum generation, maximum power flow in each zone, such as CCT for bus Ashuganj and Ghorashal buses in zone 1, Hathazari and Comilla North buses in zone 2, Ishurdi bus in zone 5 and Bheramara bus in zone 6. Table 3.1 presents the calculated CCT for BPS.

Table 3.1: Calculated critical clearing time for different zones in BPS

Sl No	Name of Generator	Name of Bus	Zone	Critical clearing time with respect to generator/area (ms)
1	Ashuganj_150	Ashuganj	Z1	175 ms
2	Ghorasal_210	Ghorasal	Z1	252 ms
3	AES_235	Comilla_N	Z2	236 ms
4	Raozan_210	Hathazari	Z2	267 ms
5	Sirajganj_150	Ishurdi	Z5	205 ms

Sl No	Name of Generator	Name of Bus	Zone	Critical clearing time with respect to generator/area (ms)
6	Bheramara_100	Bheramara	Z6	224 ms

3.3 Transient Voltage Dip Assessment

Transient voltage dip (TVD) refers to the short-term voltage magnitude reduction after faults or other disturbances, such as transformer energizing, large motor starting and heavy load switching [35], that result in extreme increase of currents. TVD is an important aspect of power quality. Severe TVD brings high consequences in various industry areas [36-39]. To avoid TVD, time-domain simulations must be done and preventive actions taken when unacceptable TVD is detected [40].

There is a significant body of literature on assessing TVD. In [41], the IEC and IEEE TVD standards and application areas were reviewed. Reference [42] presented various TVD indices relating voltage dip duration and energy variation. Reference [43] developed a TVD index considering compatibility between equipment and supply. The TVD duration assessment criteria were summarized in [44] from various industry resources. Some other TVD assessment standards include voltage dip window criterion [45] and economic cost [46]. In [47, 48], stochastic methods were presented for TVD assessment.

Inspired by security analysis, a familiar metric to indicate power system rotor angle stability [49, 50], TVD is used to detect vulnerability of the system for dynamic security subject to fault-initiated contingencies. In this work TVD is used to calculate performance Index (PI). The calculated PIs are used to rank the TVD severity of assessed contingencies for BPSN.

Commonly used criteria consider both low voltage and high voltage limits during the oscillations and the time duration when a limit is violated, i.e., violation duration, as shown in Figure 3.4. The criteria are used to evaluate the post fault transient voltage and define the boundary of TVD dynamic security region. System performance subject to various disturbances can then be classified as acceptable or unacceptable in terms of TVD [51, 52]. Unacceptable cases need special attention to enhance the system dynamic security.

The criteria defined by NERC/WECC are used in this work, stated as follows [44]:

- **N-1 contingencies:** Not to exceed 25% at load buses or 30% at non-load buses. Not to exceed 20% for more than 20 cycles at load buses.

- **N-k (k ≥ 2) contingencies:** Not to exceed 30% at any bus. Not to exceed 20% for more than 40 cycles at load buses. Both N-1 contingencies and N-k (k > 2) contingencies are considered in the

Transient voltages exceeding the defined magnitudes are treated as violations, as shown in Figure 3. 4. The violation regions include both voltages overshooting region and voltage dip region. The violation duration is defined as the total time that a trajectory is out of the secure region. NERC/WECC criteria allow a few cycles of short periods exceeding certain voltage levels; this violation allowance is not included in the violation duration.

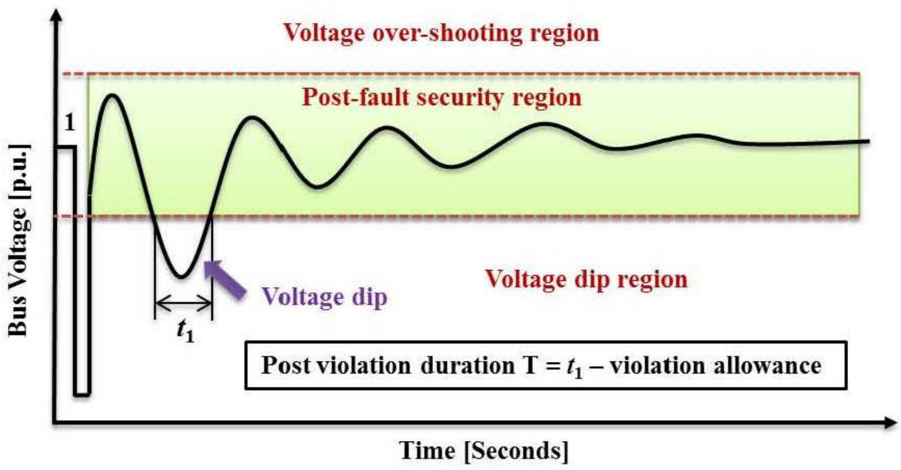

Figure 3.3 Illustration of TVD dynamic performance criteria

3.4 Security Analysis with Contingency Case Selection

Power system dynamic model is composed of linear and nonlinear equations, which involves many discrete and continuous state variables with sophisticated models. Time domain simulation (TDS) provides an accurate calculation of transient stability analysis (TSA) involving repeatedly solving large, sparse, time varying nonlinear state space differential equations of power networks over thousands of time steps. These iterative calculations cannot be applied in the real-time applications. Similarly, contingency based analysis is an efficient method for estimating the damping of oscillations following power system disturbances as performance index but it is time consuming in input data preparation.

A full AC power flow method give full accuracy but takes too long. Because of the way the full power system is designed and operated, very few of the outages will actually cause trouble. Security based analysis reveals the improvement in performance of N-1and N-2 contingency from a transmission security point of view. To demonstrate the improvement with the security in an actual network, AC power flow security analysis with contingency selection is applied. Newton-Raphson based power flow, as available with the simulation tools, has been used for this work. Individual phase voltages and phase currents violation were observed in the load flow results to select severe contingency on the BPS network. A flowchart for a process like this appears in Figure 3.5.

Two types of contingency are considered: N-1contingency and N-2 contingency.

A. N-1 Contingency: For N-1 contingency, four types of components are considered: transformer, generator, bus and line. First, component loss without fault is assessed. System stability margin can refer to result of N-1 contingency. This kind of contingency is simple and prevalent in the network. If system is unstable in this circumstance, there needs some operation adjustment. It has to be done before further analysis [53]. On the contrary, if the system retains stability with this kind of contingency, more severe contingencies can be involved.

B. N-2 Contingency: For N-2 contingency backup protection is considered. One is that when the major protection does not work properly to cut off faulted component, system has to depend on backup protection. We can replace the action time of the major protection with that of backup protection. If the new stability margin is negative, it shows that the system is unable on this kind of N-2 contingency [54].

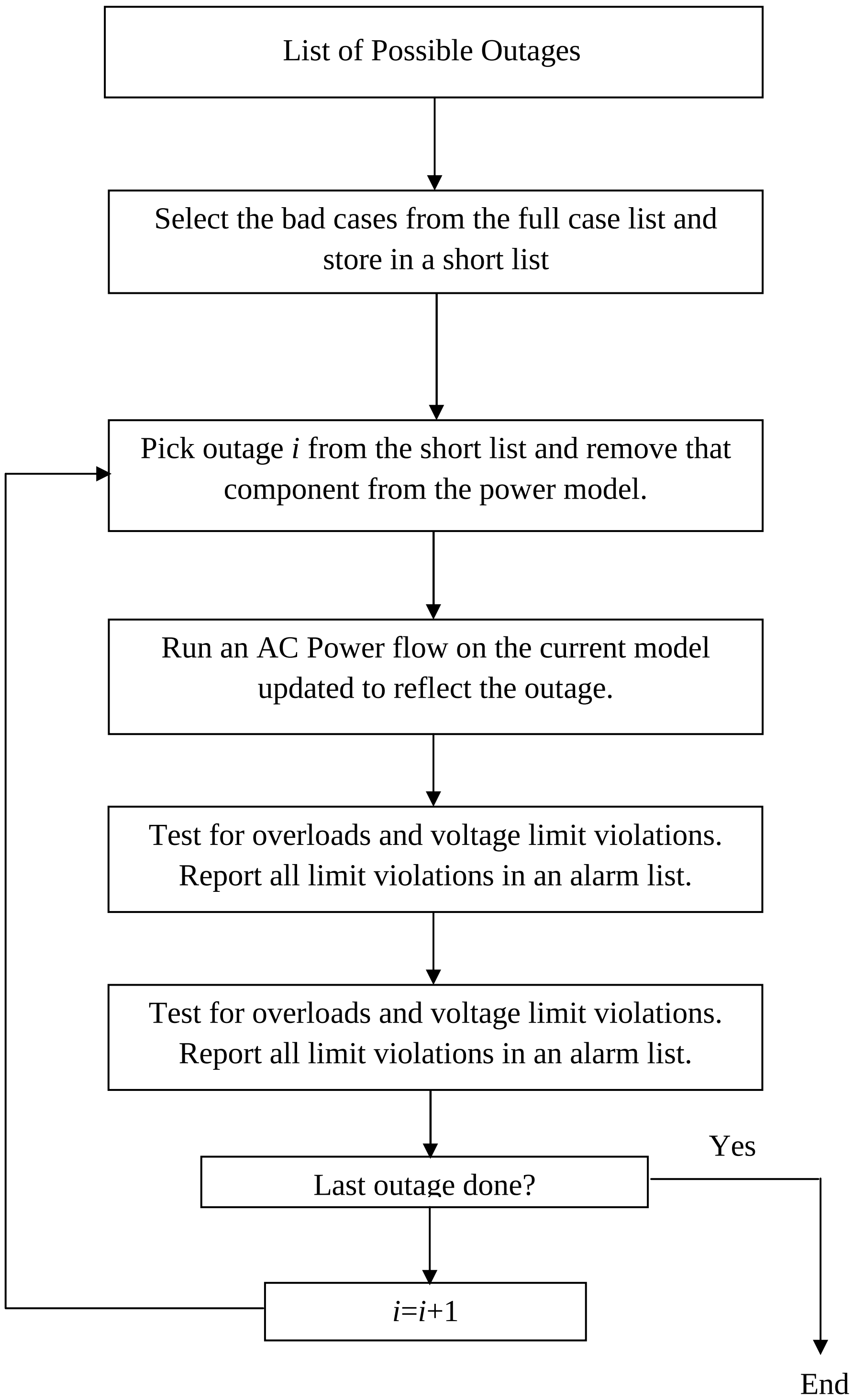

Fig.3.4: AC Power flow security analysis with contingency case selection

3.4.1 Contingency Screening

The objective contingency screening is to shortlist critical contingencies for deeper evaluation of the power system. Since in practice not every contingency will bring instability problem to the power system. Conformation of critical contingencies list is created according to the comparisons of the performance of power system [55-57].

The performance of power system after being subject to each contingency are evaluated with respect to capacities of equipment's (e.g. rated generation of a generator), operating constraints etc. During contingency screening, contingencies with small influence on power system operation are removed. Their exclusion from critical contingencies achieves a significant reduction of information for real-time operation. This gets the DSA faster.

The contingency screening often uses some approximate and fast algorithms to study a huge list of contingencies to judge them to be critical or not. During contingency screening, the instability aspects (voltage, frequency, rotor angle, protection system etc.) of the power system should be specified for the DSA. In this work, critical contingencies are selected by using a performance index (PI) which are then used for the DSA.

3.5 Proposed Method for Contingency Selection

The proposed method is based on N-1 and N-2 contingency according to stability criteria explained in sections 3.2to 3.4.Since the focus of this work is on the combined contingency ranking, the method is explained for the PI and severity on the system.

The first step is to carry out fast approximate solutions; the screening process evaluates these solutions using a performance index to determine which contingencies are the worst. These severity indices must reflect line overloads and voltage violations such that the contingencies can be ranked according to their severity. Once this is done, only the worst contingencies are further studied with accurate power flow solutions and the resulting overloads and under voltages are reported to the operator as alerting messages. For this purpose, we used a performance index (PI) that includes both line overload and voltage violation. In order to determine the PI, a tolerance is set as specified in Table 3.2.

Table 3.2: Stability criterion and parameters of searching

Stability Criterion	Angular Criterion	360^0
	Voltage Criterion	0.90 p.u last for 300 ms
Searching Parameter	Range	100 ms – 1500ms
	Accuracy	20ms

The performance index (PI) is defined as:

$$PI = \sum_{all\ branches\ i} \left(\frac{P_{flow\ l}}{P_l^{max}}\right)^{2n} + \sum_{all\ buses\ j} \left(\frac{\Delta|E|_j}{\Delta|E|^{max}}\right)^{2n} \quad (3.21)$$

Where, *n* and *m* is a number used for PI limit.

$P_{flow\ l}$ power flow in a transmission line

P_l^{max} maximum power flow in a transmission line

$\Delta|E|_j$ the difference between the voltage magnitude as solved at the end of the |P|Q procedure and the base case voltage magnitude

$\Delta|E|^{max}$ the value set by system requirement.

The flow chart in figure 3.5 presents the PI calculation steps.

Only voltage violation and angle cannot identify severe weak part of the network. In this work, we also used protection time to find out severe weak part of the system by using the difference between the protection operation time and fault clearing time (FCT) used as a stability margin index. During the analysis procedure, each contingency's stability margin index is calculated through PI. Therefore, we can make security assessment and locate weak part of the network by combined ranking procedure.

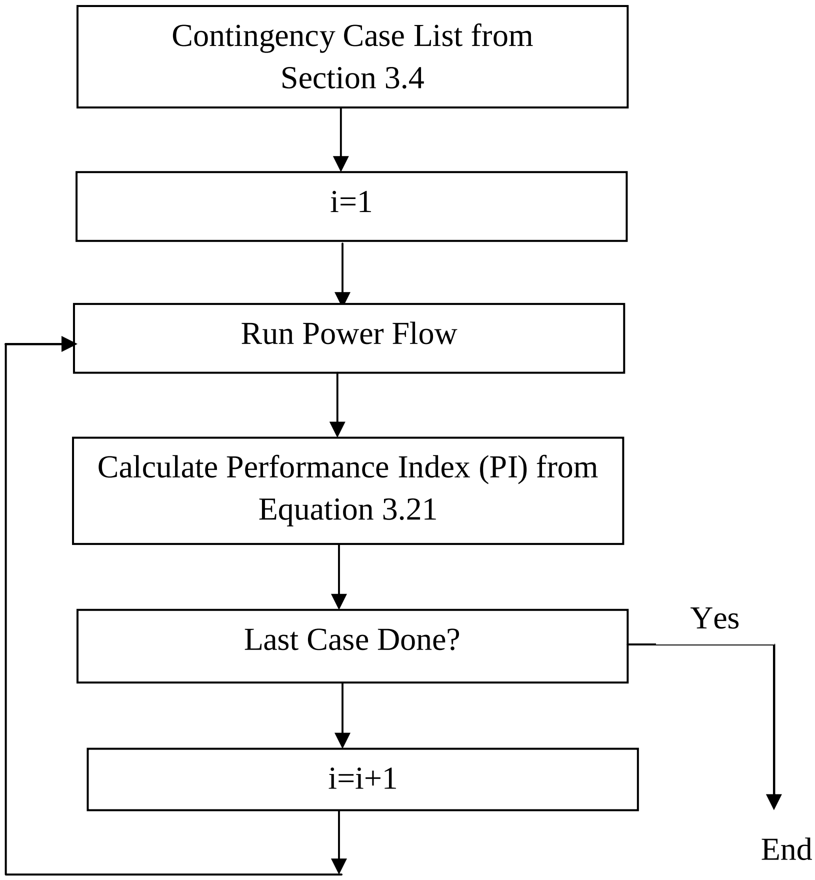

Fig.3.5: Calculation of performance index (PI) from contingency case list

CHAPTER 4

SIMULATION AND RESULTS

4.1 Introduction

The technique presented in Chapter 3 is applied to the actual network of the Bangladesh Power System (BPS). BPS is a small system with an installed capacity of around 10000 MW at the year of 2013 and an annual peak demand around 7000 MW. The transmission system of BPS has formed an integral grid of two voltage levels of 132 kVand 230 kV. It supplies electricity to whole country, graphically divided into six regions. The status of different regions in terms of generation capacity and loads are different. While four of these regions are load rich the rest two are generation rich [24].

4.2 Overview of Bangladesh Power System

The BPS grid network is inherently radial in nature. Fig. 4.1 shows the BPS grid in terms of a number of regions. Topology of this system has been derived from the actual network configuration of BPS network that can be approximated as radial one, divided into 6 operational regions. The figure clearly shows that the regions are like island connected radially to Dhaka region. The status of different islands in terms of generation capacity and loads of a typical day for 2014 is given in Table 4.1. The table shows that most of the lands are load rich. A load rich island is one whose available generation is less than the load and generation rich island has available generation more than its load. The system is shown in Figure 4.2. In this chapter, the test data and parameters used to simulate the method of DSA are introduced. All BPS network data are provided in Appendix A1.

Only Dhaka and Sylhet regions are generation rich. In the Dhaka region only the four generation substation buses are considered, namely, Ghorsal, Ashuganj, Comilla- North, Tongi. In which, Ghorsal, Ashuganj,buses are to tie- lines that supply power to the load rich regions North- Bengal and Khulna-Barishal regions. In the Sylhet region, the Shahjibazar bus acts both as a generator bus and tie-bus that supply power to other regions through the Ashuganj. Though, newly connected Fenchuganj bus supply power to comilla-North for Chittagong regions.The Khulna- Barishal regions act as a net load to the Ishwardi bus in the

North Bengal region. Power from Dhaka region flows through these Ishwardi and Sherajganj bus. Moreover, India to Bangladesh HVDC line is connected to Bheramara bus to supply power both Khula-Barishal and Ishwari bus [58].

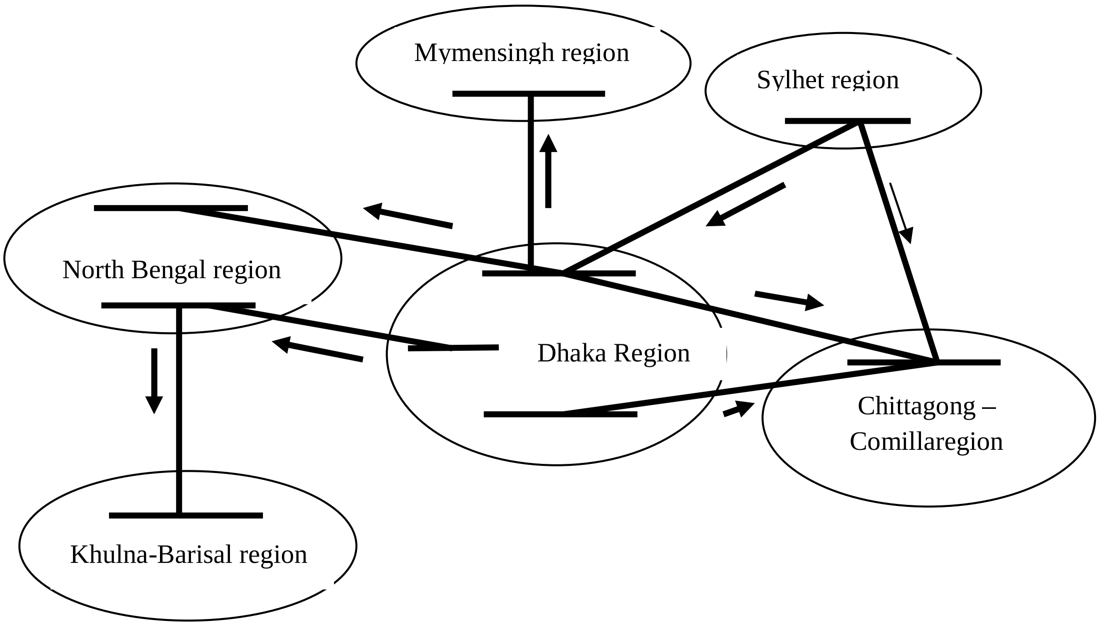

Figure 4.1: Radial Nature of Bangladesh Power System (2013)

Table 4.1: Status nature of different radially connected regions of BPS

Description of Island	**Available generation (MW)**	**Demand (MW)**	**Status of the island**
Dhaka region	3334 MW	2624 MW	Generation rich
Ctg. Comilla, Noakhali region	784 MW	1224 MW	Load rich
Sylhet region	519 MW	352 MW	Generation rich
Mymensingh region	150 MW	333 MW	Load rich
North Bengal region	897 MW	1130 MW	Load rich
Khula- Barisal region	1115 MW	1011 MW	Load rich

4.2.1 Protection System of BPS

No item of electrical equipment shall be allowed to remain connected to the transmission system unless it is covered by appropriate protection aimed at reliability, selectivity, speed and sensitivity. In Bangladesh power system, the maximum fault clearance time, from stability consideration, for faults on any user's system directly connected to the transmission system, or any faults on the transmission system itself, are given Table 4.2 [60].

Table 4.2: Target clearance times at different voltage levels in BPSN

Sl. no.	Voltage level (kV)	Target clearance time (ms)
1	400	100
2	230	160
3	132	160

All generating units and all associated electrical equipment of the generator connected to the transmission system shall be protected by adequate and coordinated protection so that the transmission system does not suffer due to any disturbance originating from the generating unit. In the event of failure of the protection systems provided to meet the fault requirements detailed above, backup protection provided by the generator with a fault clearance time not slower than 400ms for faults on the generating unit's HV connections.

In this study, pole slipping, loss of excitation, power system stabilizer and negative phase sequence tripping protections are not considered

For transmission line, one distance protection plus directional earth-fault protection (in directional comparison scheme) are provided as the main protection. All protection coordination relay setting data are provided in Appendix A2.

Table 4.3: Component list of Bangladesh Power System Network (BPSN)

Sl. No.	No. of transformer		No. of Generator	No. of bus		No. of line	
	Fixed-tap (132/33 kV)	T-cul (230/132 kV)		132 kV	230 kV	132 kV	230 kV
Zone 1	124	16	50	36	09	63	23
Zone 2	71	06	19	23	03	48	08
Zone 3	16	---	03	05	---	09	---
Zone 4	34	01	19	07	01	12	02
Zone 5	77	09	20	22	06	42	10
Zone 6	64	02	19	21	02	32	02
Total	385	34	130	113	21	206	45
Grand Total	419		130	134		251	

4.2.2 Inertia Constant of All Engine-based Private Generation of BPSN

A large percentage of generated power is from private power stations that are engine based. Their inertia constant is very less compared to turbine-based power station. Hence, these power station losses synchronism very quickly if any faults happens on these connected bus. This may render the system unstable. This study considers all the engine based generation along with turbine base generation for contingency analysis. Table 4.4 shows the list of engines based private generation in BPSN and their calculated inertia constants.

Table 4.4: Inertia constant of engine based generation

Sl No.	Name of Generator	Capacity	Calculated inertia constant (MJ/MVA)	Area (Zone)
1	ASH 80 MW (Aggreko)	80 MW	0.40	Dhaka (Zone 1)
2	ASH 53 MW (Aggreko)	53 MW	1.74	
3	ASH 55 MW (Precision)	55 MW	0.58	
4	ASH 53 MW (United)	53 MW	0.43	
5	ASH 51 MW (Midland)	51 MW	0.49	
6	GPS(Aggreco) 100 MW	100 MW	0.51	
7	GPS(Aggreco) 45 MW	45 MW	0.23	
8	GPS(Regent) 45 MW	45 MW	1.01	
9	Madanganj (Summit) 102 MW	102 MW	0.97	
10	Keranig. (Powerpac) 100 MW	100 MW	1.01	
11	Norsingdi (Dorin) 22 MW	22 MW	0.20	
12	Siddirganj (Desh) 96 MW	96 MW	1.08	
13	Siddirganj (DutchB)100 MW	100 MW	1.12	
14	Pagla (DPA) 50 MW	50 MW	0.47	
15	Gangnagor (Orion) 102 MW	102 MW	1.12	
16	Gazipur (RPCL) 102 MW	102 MW	0.56	
17	Summit (Ashulia) 33 MW	33 MW	0.33	
18	Summit (Rupganj) 33 MW	33 MW	0.33	
19	Maona (Gazipur) 33 MW	33 MW	0.33	

Sl No.	Name of Generator	Capacity	Calculated inertia constant (MJ/MVA)	Area (Zone)
20	Daudkandi (PDB) 52 MW	52 MW	0.50	Comilla (Zone 2)
21	Feni (Doreen) 22 MW	22 MW	0.20	
22	Feni (Mohipal) 11 MW	11 MW	0.10	
23	Summit (jangalia) 33 MW	33 MW	0.33	
24	Summit (Comilla) 25 MW	25 MW	0.23	
25	Raozan (RPCL) 25 MW	25 MW	0.27	Chittagong (Zone 2)
26	Potenga 50 MW	50 MW	0.52	
27	Hathazari (PDB) 98 MW	98 MW	1.03	
28	Dohazari (PDB) 102 MW	102 MW	1.07	
29	Julda 100 MW	100 MW	1.08	
30	Barabkundo22 MW	22 MW	0.20	
31	Malancha	53 MW	0.52	
32	B. Baria	70 MW	0.70	Sylhet (Zone 4)
33	S. Bazar 50 MW	50 MW	0.48	
34	S. Bazar (E.Prima)86 MW	86 MW	0.87	
35	Fenchugang (Baraka) 51 MW	51 MW	0.49	
36	Fenchuganj (E.Prima) 44 MW	44 MW	0.48	
37	Sylhet48(E. Prima) 54 MW	54 MW	0.48	
38	Sylhet (Shahjahan) 25MW	25 MW	0.25	
39	Sylhet (Desh) 10 MW	10 MW	0.25	

Sl No.	Name of Generator	Capacity	Calculated inertia constant (MJ/MVA)	Area (Zone)
40	Baghabari 52 MW	52 MW	0.53	North Bengal (Zone 5)
41	Bera 70 (PDB) MW	70 MW	0.84	
42	Baghabari West Mnt 102 MW	102 MW	0.94	
43	Baghabari (PDB) 50 MW	50 MW	0.54	
44	Amnura 50 MW	50 MW	0.55	
45	Katakhali (Northen) 50 MW	50 MW	0.50	
46	Katakhali Peaking 50 MW	50 MW	0.49	
47	Santaher (PDB) 50 MW	50 MW	0.49	
48	Rajlanka 52 MW	52 MW	0.47	
49	Bogra 20 MW	20 MW	0.21	
50	Bogra GBB 20 MW	20 MW	0.23	
51	Khulna (KPCL -1) 110 MW	110 MW	1.16	South Bengal (Zone 6)
52	Khulna (KPCL -2) 115 MW	115 MW	1.18	
53	Faridpur (PDB) 55 MW	55 MW	0.59	
54	Gopalganj (PDB)102 MW	102 MW	1.17	
55	Noapara (Quantum) 101 MW	101 MW	1.25	
56	Khula (Khanjahan) 40 MW	40 MW	0.40	
57	Khulna (Aggreko) 55 MW	55 MW	0.57	
58	Bheramara(Quantu) 105 MW	53 MW	1.31	

4.3 Dynamic Security Assessment Simulation

The proposed method emphasizes the concept of performance index and stability margin so that the aims of DSA establishing whether the power system is able to maintain the secure condition in the case of predefined contingencies. During N-1 contingency the proposed method analyzes the whole power system, considering all the contingencies such as fault, loss of transmission equipment and loss of generation which gives the worst contingency of the network.

Only N-1 contingency cannot identify the weak part of the system henceforth N-2 contingency is applied on the BPS network which provides the status of protection system through the stability margin. Also, protection system performance is compared with the calculated critical clearing time (CCT).

After these analyses, combined contingency ranking identify the vulnerable part of BPS network.

The following steps depicted in flow charts are considered during the dynamic security assessment:

Step 1: Develop the system model of Bangladesh Power System Network (BPSN)

Step 2: Run the load flow of BPSN

Step 3: Run the Transient Stability Analysis (TSA)

Step 4: Performance Index Evaluation during N-1 Contingency analysis

Step 5: Evaluation of Transient Voltage Dip (TVD)

Step 6: N-2 Contingency Analysis for Power System Protection Security Assessment

Step 7: Combined Contingency Ranking and Identification of Weak Part of Bangladesh Power System Network

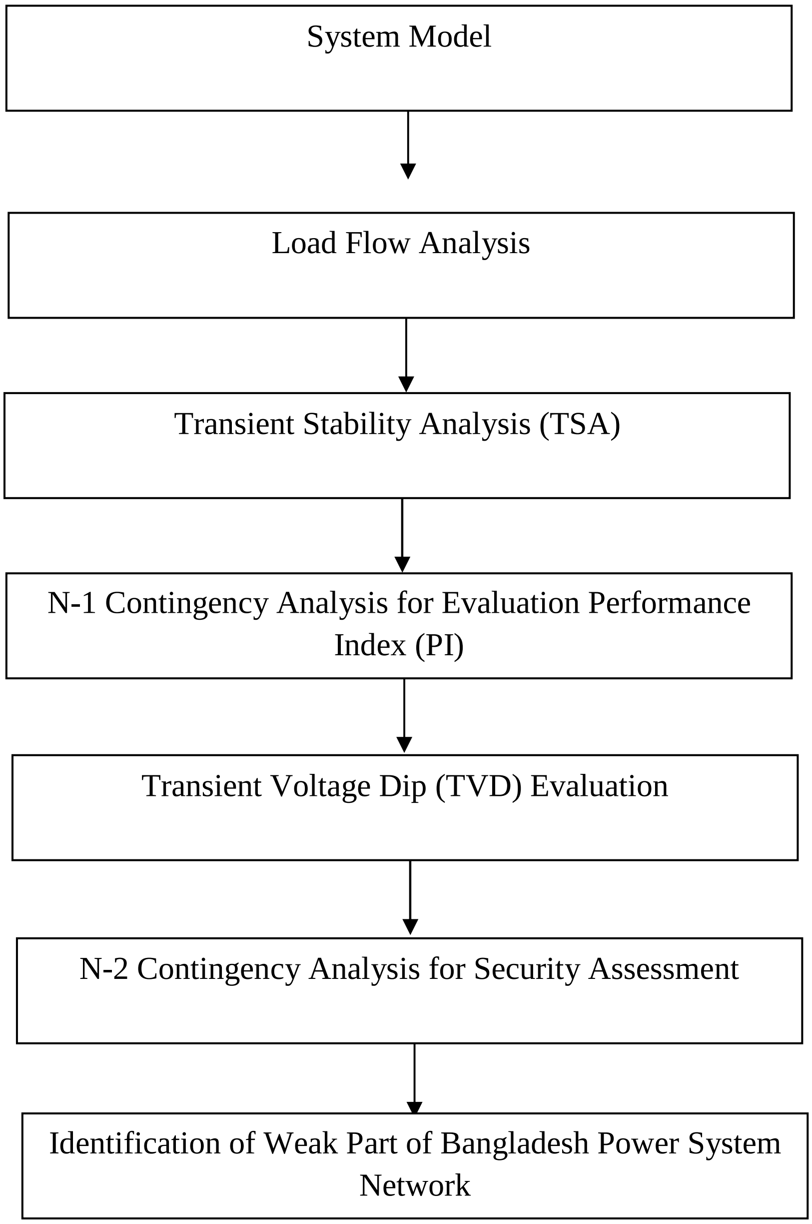

Fig. 4.2: Dynamic security assessment steps.

4.3.1 Performance Index Evaluation for BPS

The method we proposed is based on N-1 and N-2 contingency. In BPS, the performance index is used to assess the weak part of the network during N-1contingency according to voltage and angular stability criteria.

Algorithm:

i. Set up the parameters of the system and the used model of the system.

ii. Run power flow calculations to determine the steady-state values of the system.

iii. Save CSA file for Transient stability Analysis.

iv. Save all generators voltages, rotor angles.

v. Run time domain (TD) numerical simulation from the fault occurrence to the fault clearing instant using the method explained in Chapter 3.

vi. Use the appropriate CSA file to determine the PI for N-1 Contingency.

vii. Use Equation 3.21to find sectors of severely PI using an appropriate tolerance defined in the system.

viii. Sort PI for the descending order according to voltage violation and branch overload.

4.3.2 Determining the Fault Clearing Time

Algorithm

i. Set up the parameters of the system and the used model of the system.

ii. Run power flow calculations to determine the steady-state values of the system.

iii. Use CSA file for Transient stability Analysis.

iv. Save all power flow data

v. Start the process by setting up a fault with 0 seconds clearing time.

vi. Setup CYMTCC accordingly

vii. Choose an acceptable error tolerance. The error is the difference between the stable and unstable time. In this research, 0.01 is used.

viii. Use the CSA file on cymtcc determines FCT for N-2 contingency.

ix. Compare the main protection and Fault clearing time. If the main protection is less than FCT system is stable. Otherwise, the system is unstable.

x. Sort the stability margin in descending order.

After getting the worst PI and stability margin we can define the weak part of the system.

4.4 Simulation Results

To test the suggested method of DSA of the BPS using combined PI and stability margin, the system is built using PSAF and CYMTCC interface.

At first, the power flow is run and the results are checked by BPS network setting parameters. After that, N-1 and N-2 contingencies are applied by setting a fault and clearing afterward according to the setting of BPSN protection.

Power flow is run in CYME PSAF software using Newton-Raphson's method. The results are documented in Appendix A2.

The N-1 and N-2 contingencies are simulated for 1500ms at different fault locations. According to Bangladesh grid code, fault clearing time for 132 kV and 230kVis 160 ms but there is no CCT. At first, a 3-phase fault is applied for N-1 and N-2 contingency for 80 ms. Then step by step fault clearing time increased up to 300 ms to find out unstable system and weak part of the system.

The following sub-sections present the results and plots.

4.4.1 *N*-1 Contingency

Initially, system state with component loss without any fault involved is assessed. In the second stage, component loss with fault is applied for security violation assessment.

Loss of Transformer

Table 4.5 shows the effect of loss of a transformer in BPSN. No security violation or stability problem is observed. Simultaneous loss of two transformers in a bus also does not have any significant effect on the system. Even in the case of loss of three transformers connected in a single bus the system remains stable; voltage and angle are all within the limits as can been seen in Fig 4.1.

Table 4.5: Stability implications of transformer loss in BPSN without any fault involved

Sl. no.	Name of transformer	Remarks (Stable/Unstable)
1	AES360_1 Fixed-tap	Stable
2	GPS 210_1 Fixed-tap	Stable
3	AES 360_1 Fixed-tap	Stable
….	………	…….
419	Noapara40_Fixed tap	Stable

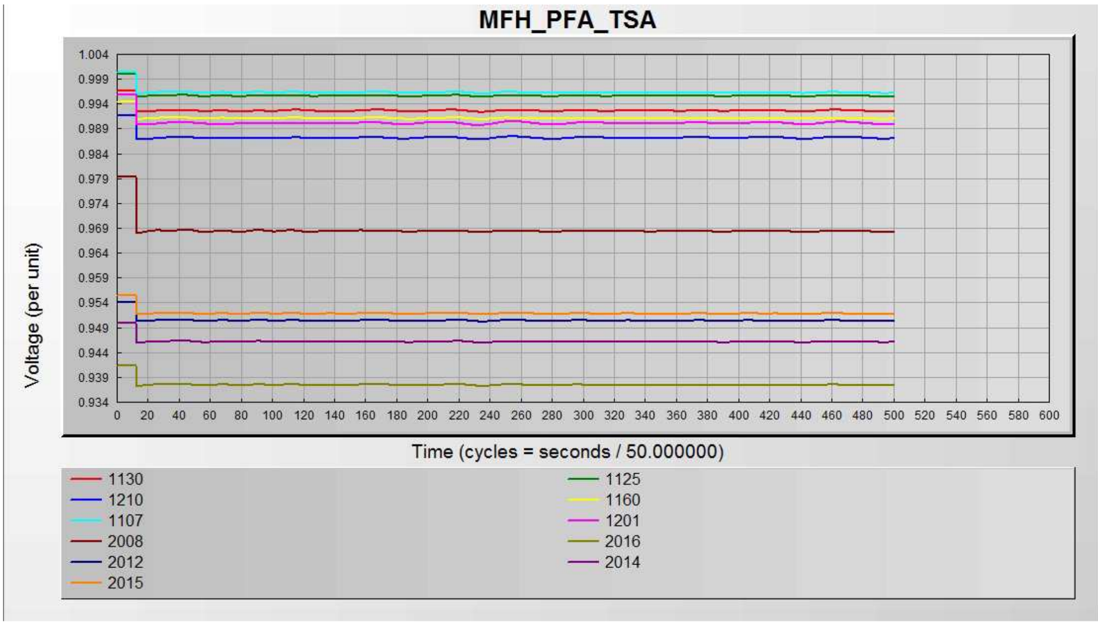

Fig 4.3: Transformer loss without fault.

Table 4.6 presents the result for loss of a transformer with fault in involved. Three-phase dead short-circuit is applied and cleared by isolating the transformer. System stability is based on machine-angle criterion and low-voltage criterion set beforehand. It is observed that the system remains stable for every contingency.

Table 4.6: Stability implications of transformer loss in BPSN with fault involved

Sl. no.	Name of Transformer	Remarks (Stable/Unstable)
1	AES360_1 Fixed-tap	Stable
2	GPS 210_1 Fixed-tap	Stable
3	AES 360_1 Fixed-tap	Stable
….	………	…….
419	Noapara40_Fixed tap	Stable

Loss of Generator

Like with the transformer contingencies, we begin with the loss of generator without any fault involved. From the above assessment results, we observe that losing one of the transformer do not cause system instability. Therefore, losing a generator uniquely connected to a transformer cannot result in system instability. Thus, this kind of contingency analysis can be eliminated.

Loss of Bus

In BPSN, each zone has some buses where large amount of power is transferred from one location to another location. In some cases, power flow from one zone to another zone (e.g Ashuganj (Zone 1) to Sirajganj (Zone 5), Ghorasal (Zone 1) to Ishurdi (Zone 5). The bus fault is more severe than other faults that are observed during the study. Also, engine based private power stations, and HVDC connected to some heavily load bus such as Ghorasal, Ashuganj, Bherama, Comilla(North) may create system unstable. Hence, bus faults are considered only in critical buses in each zone.

A three-phase fault is applied for each zone 230 kV (132 kV) bus and it is cleared after 80ms (240 ms). The following are the plot of the bus voltage and generator rotor angles relative to AC Power flow security analysis with contingency case selection method.

Zone 1:

The following plots are for faults at Ashuganj and Ghorasal 230 kV and 132 kV buses.

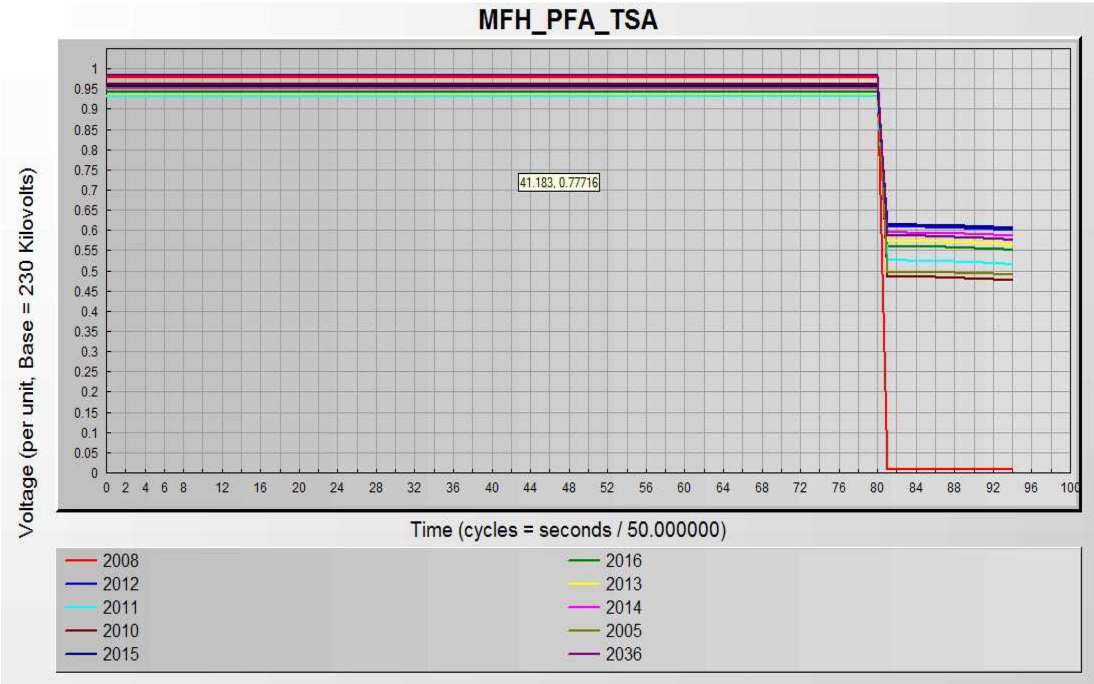

Fig 4.4: Bus voltage after fault at Ashuganj 230 kV bus

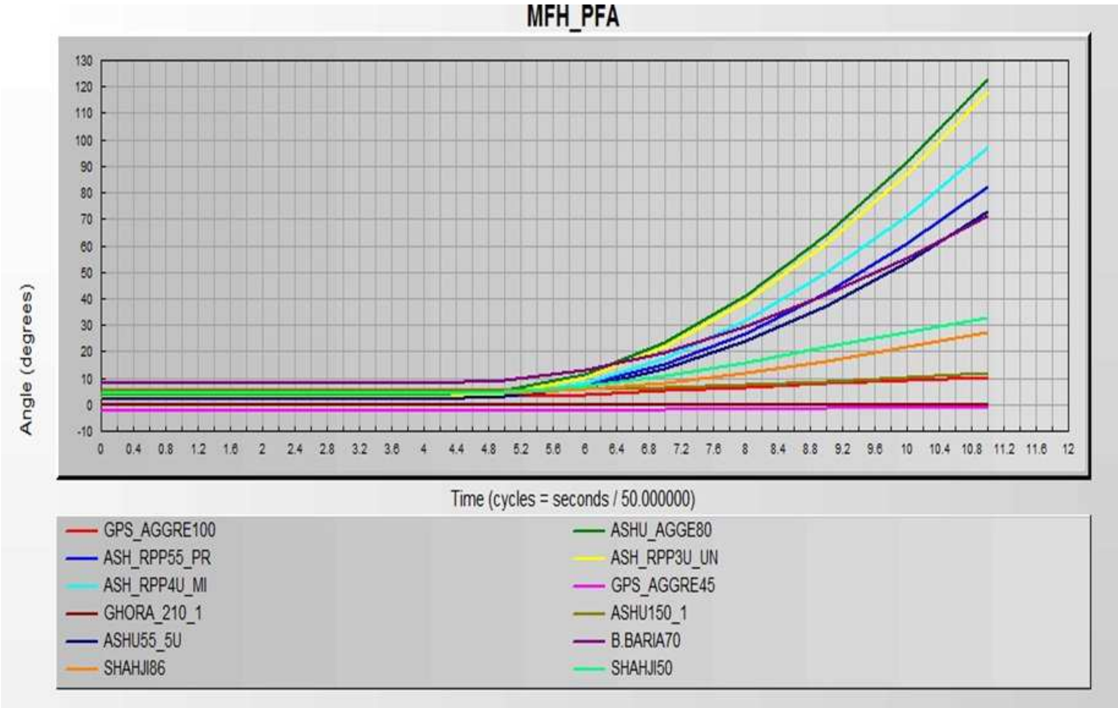

Fig 4.5: Generator rotor angles after fault at Ashuganj 230 kV bus

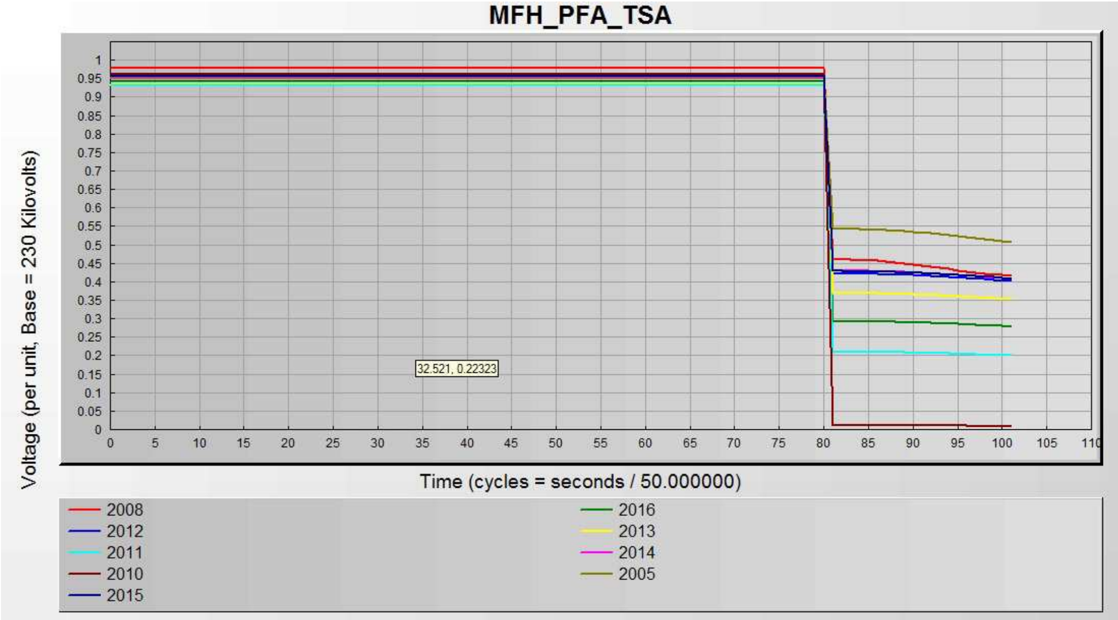

Fig 4.6: Bus voltage after fault at Ghorasal 230 kV bus

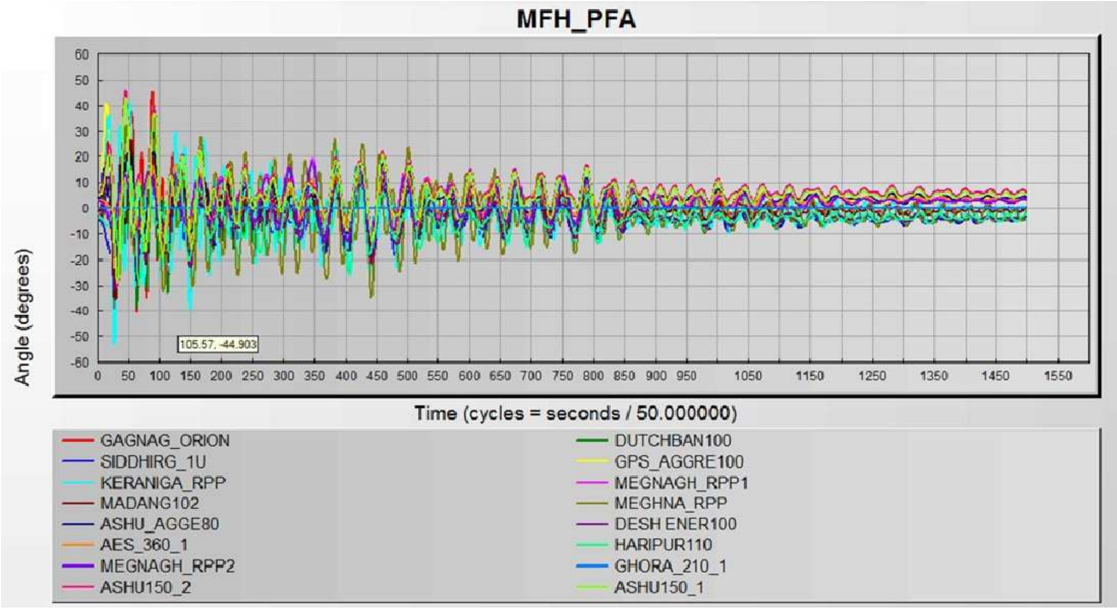

Fig 4.7: Generator rotor angles after fault at Ghorasal 230 kV bus

Zone 2:

The following plots are for Comilla_N and Hathazari 230 kV and 132 kV bus.

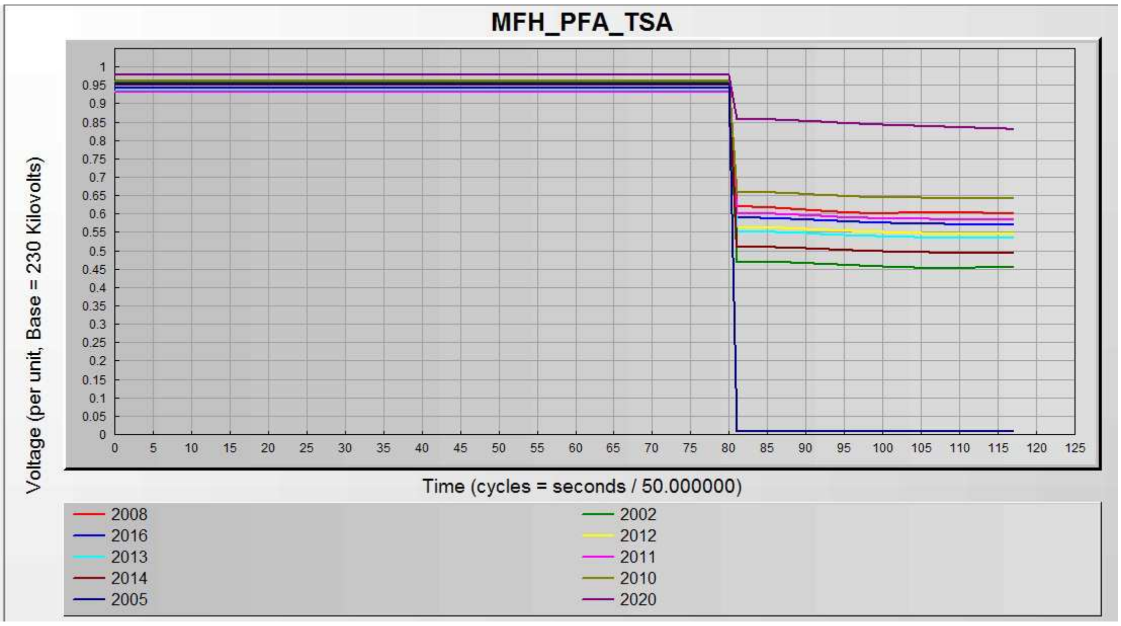

Fig 4.8: Bus voltage after fault at Comilla_N 230 kV bus

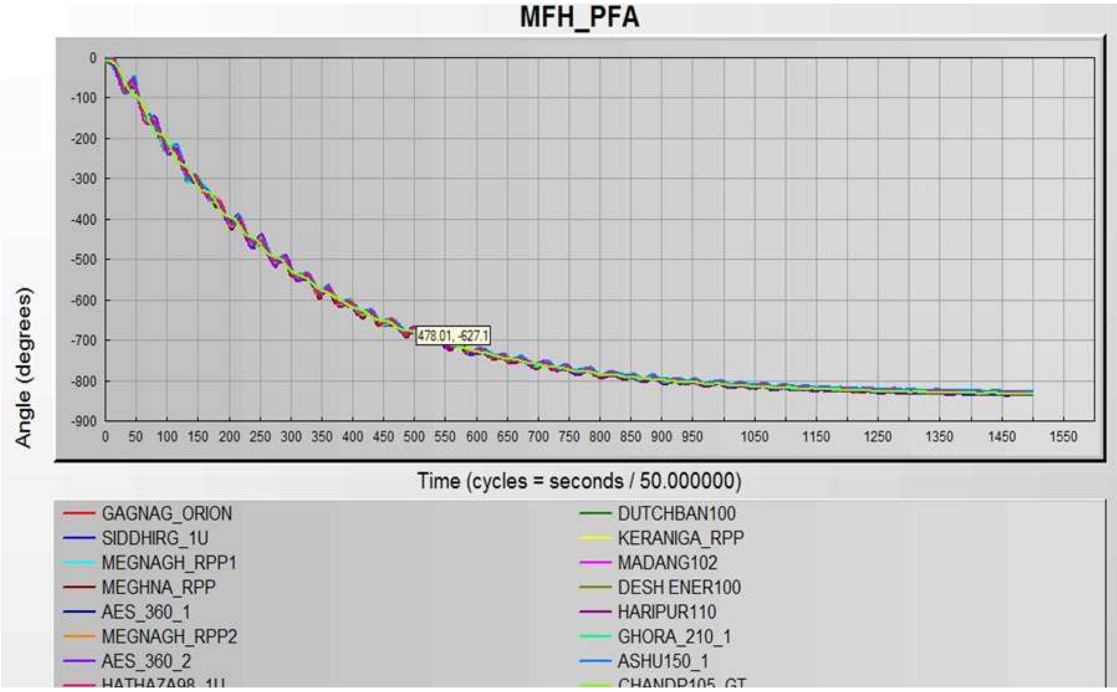

Fig 4.9: Generator rotor angles after fault at Comilla_N 230 kV bus

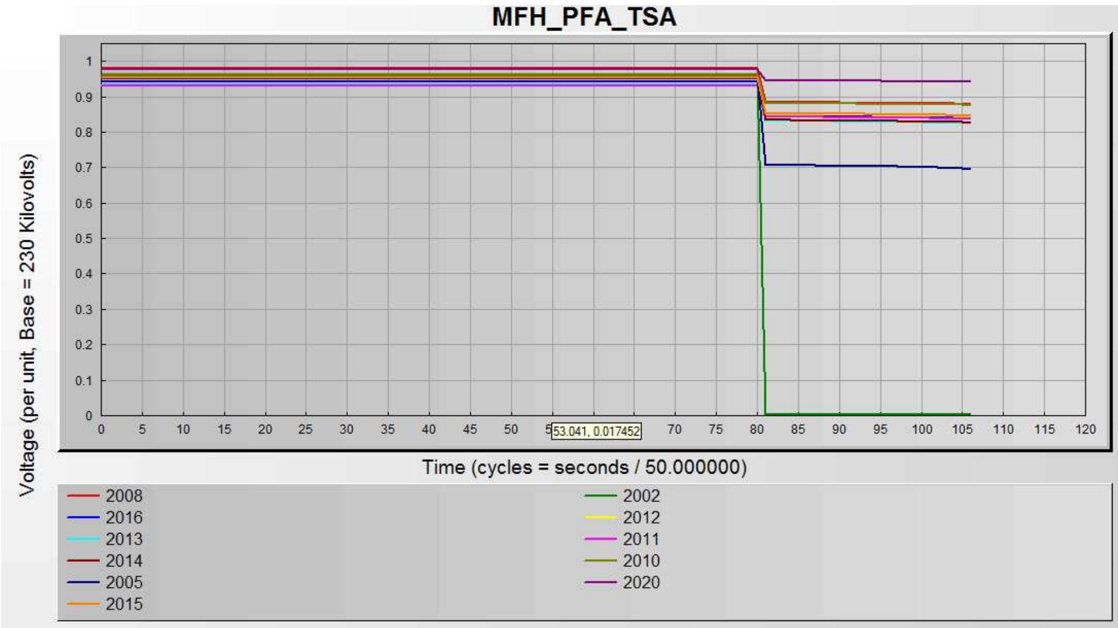

Fig 4.10: Bus voltage after fault at Hathazari 230 kV bus

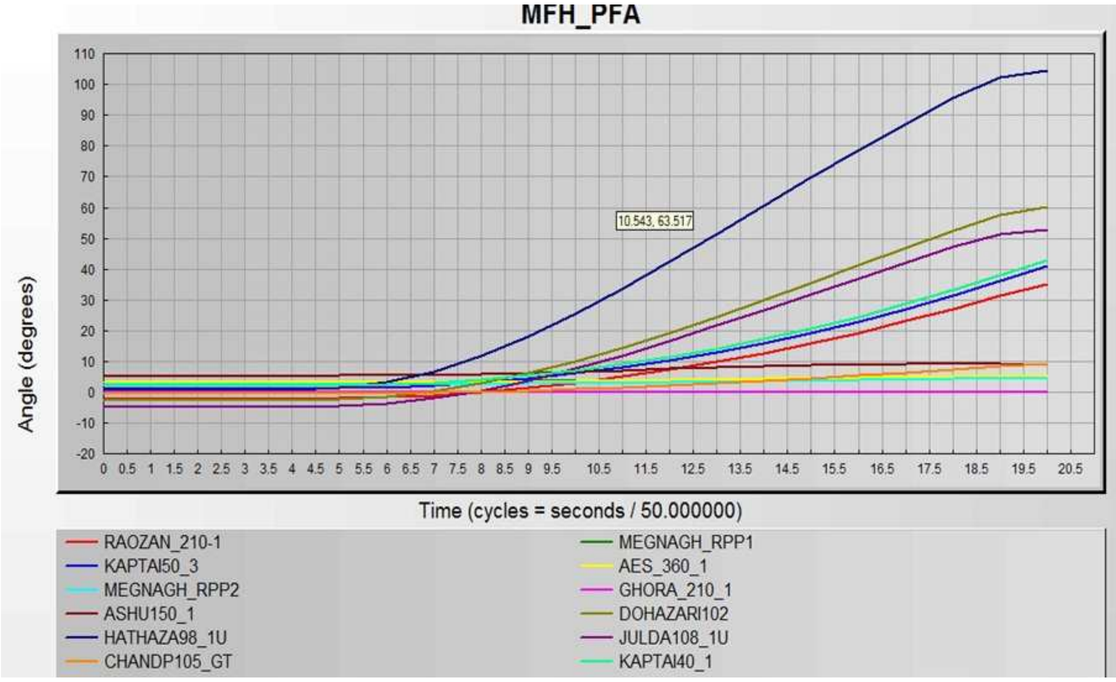

Fig 4.11: Generator rotor angles after fault at Hathazari 230 kV bus

Zone 5:

The following plost are for Ishurdi 230 kV and 132 kV bus.

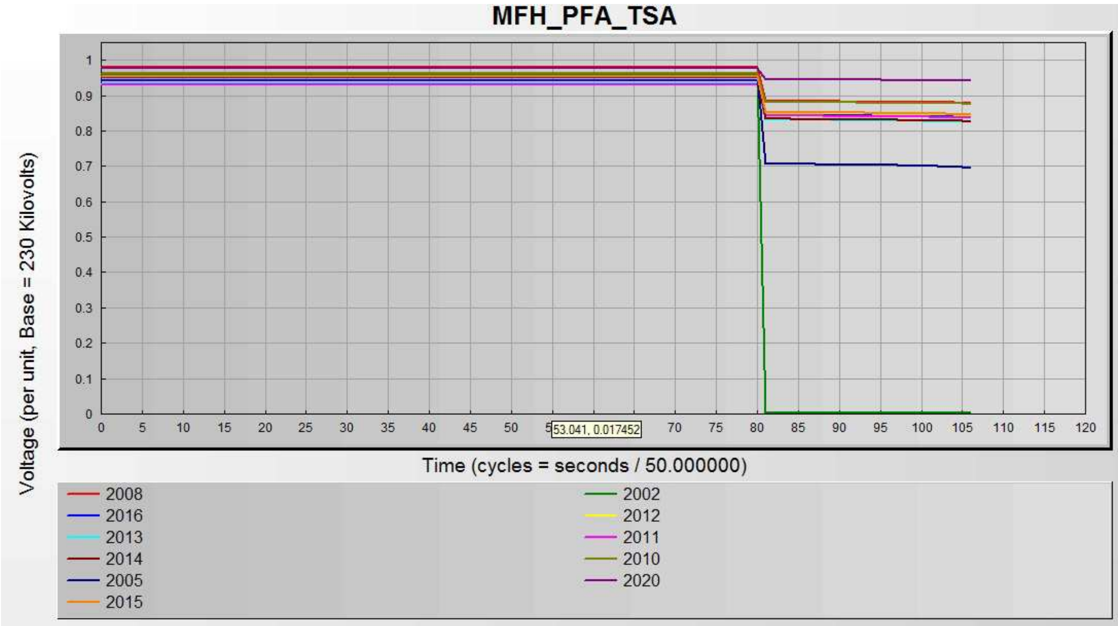

Fig 4.12: Bus voltage after fault at Ishurdi 230 kV bus

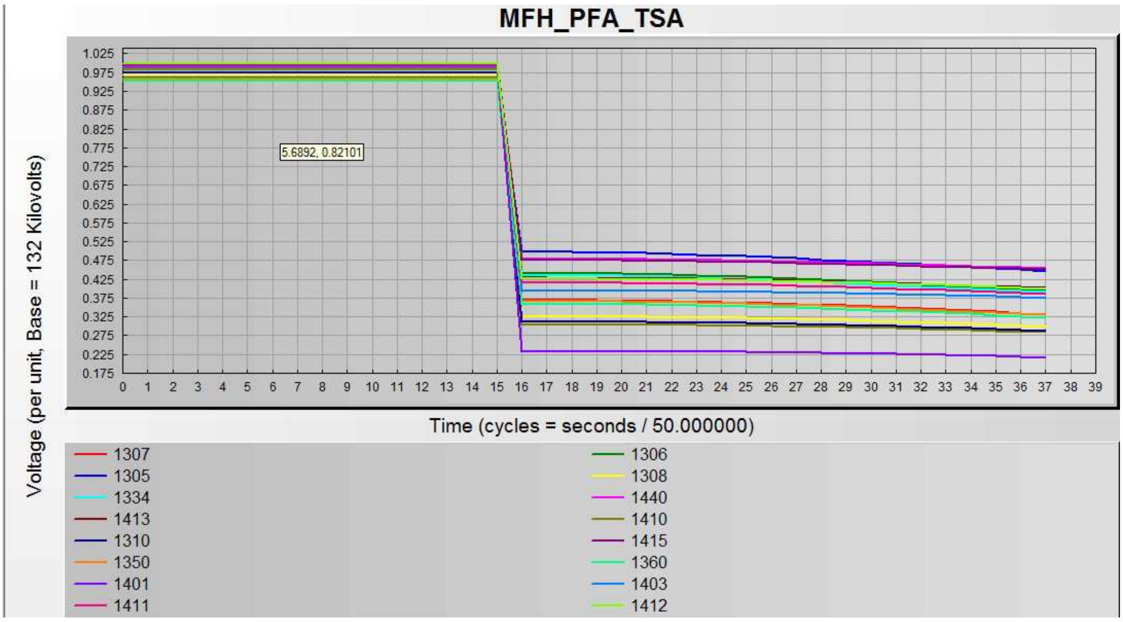

Fig 4.13: Bus voltage at 132 kV buses after fault at Ishurdi 230 kV bus

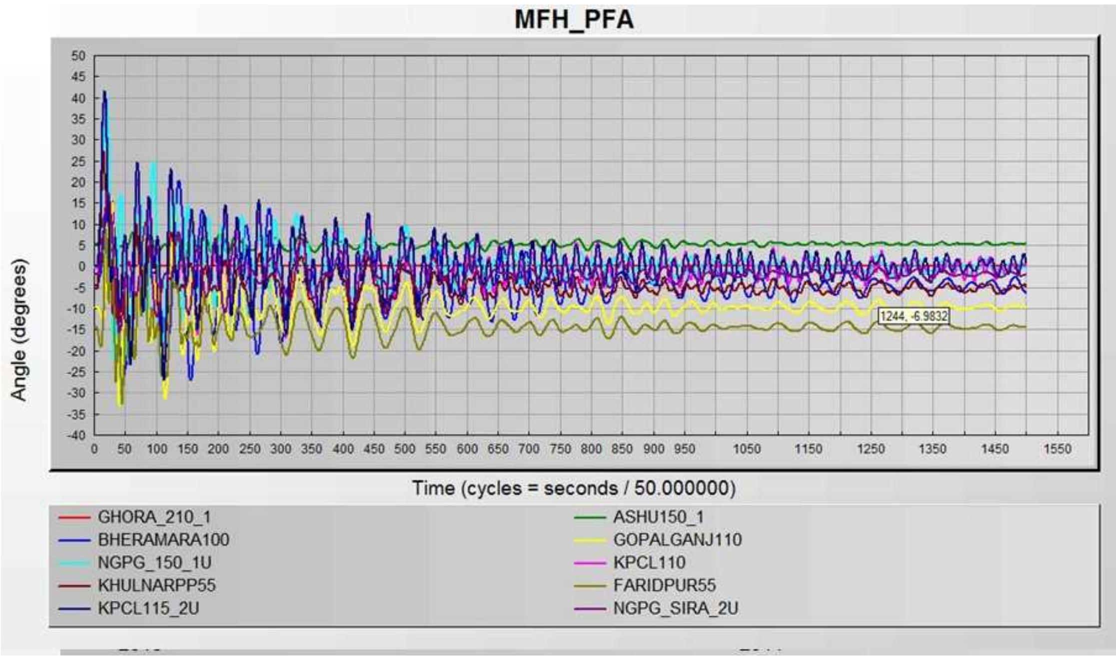

Fig 4.14: Generator rotor angles after fault at Ishurdi 230 kV bus

Zone 6:

The following plots are for fault at Bheramara 230 kV and 132 kV buses.

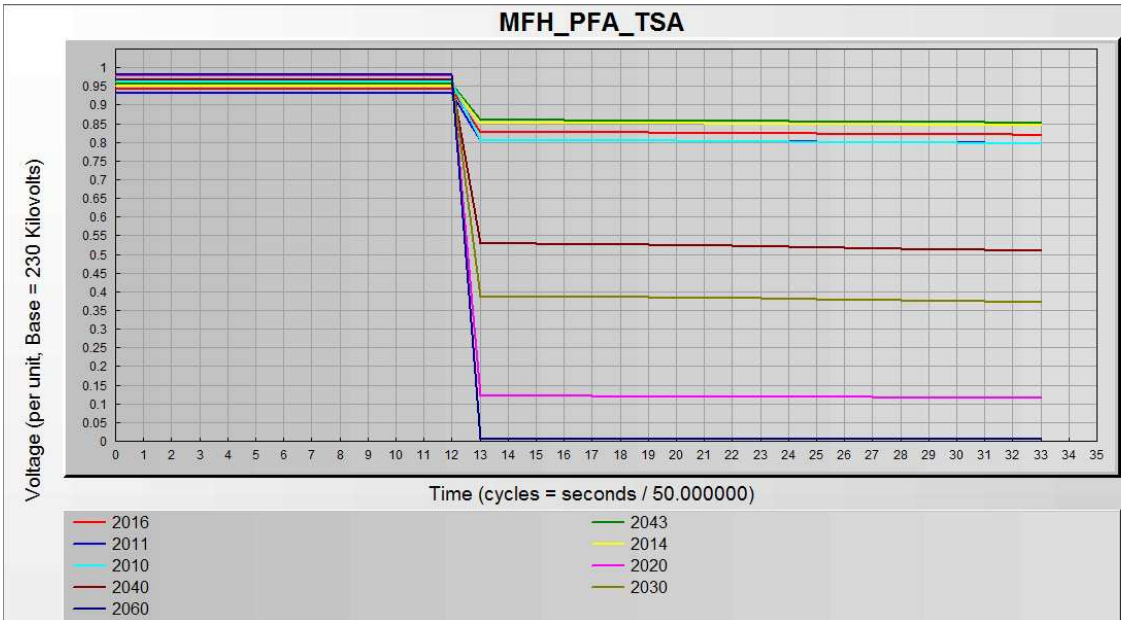

Fig 4.15: Bus voltage after fault at Bheramara 230 kV bus

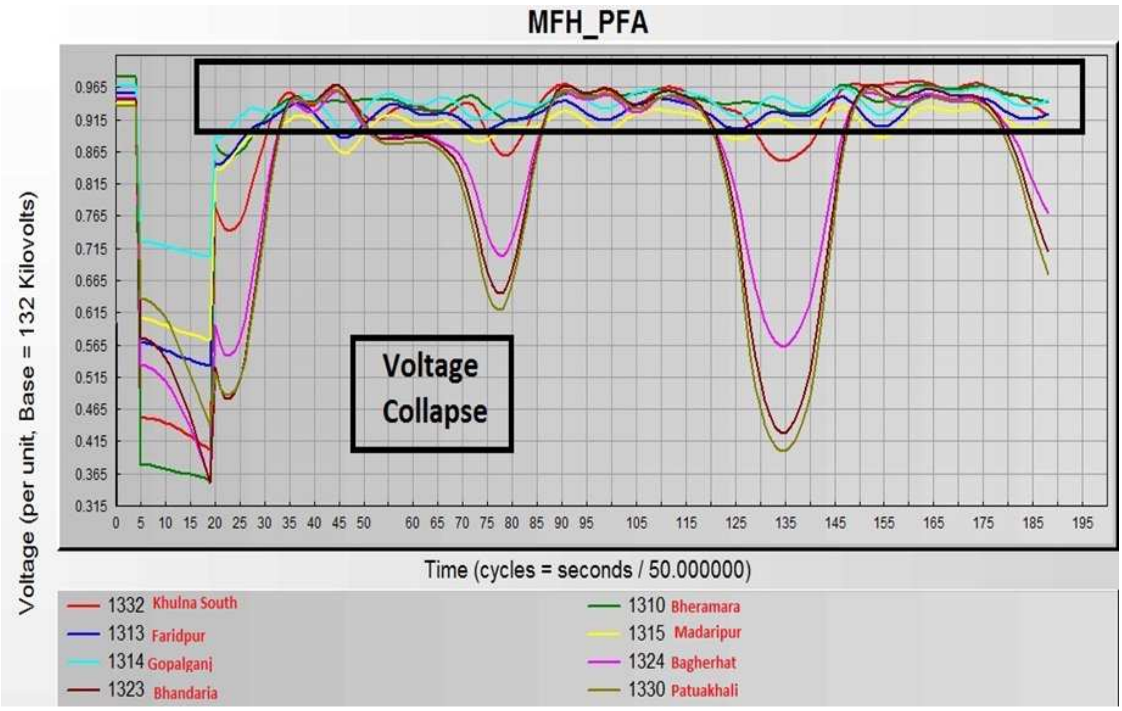

Fig 4.16: Bus voltage of 132 kV buses after fault at Bheramara 230 kV bus

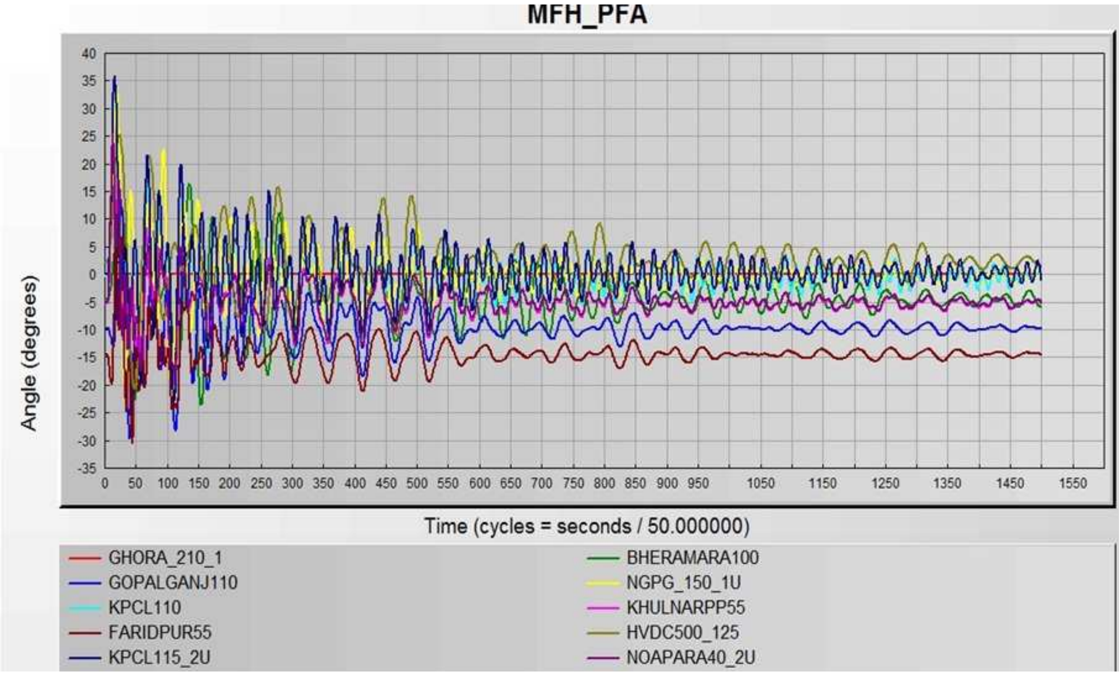

Fig 4.17: Generator rotor angles after fault at Bheramara 230 kV bus

Figs. 4.5 to 4.8 depict that bus fault at Ashuganj and Ghorasal bus (Zone 1) that make voltage dip below the voltage threshold limit. Moreover, number of engine-based power stations are connected on that bus and these generator losses the synchronism quickly so the system losses not only real power, but also reactive power supply. Therefore, the bus loss causes voltage-dip due to the shortage of reactive power.

Hathazari bus exchanges power through Comilla_N bus and Fig.4.9 to 4.10 shows that fault on this bus create loss of synchronism to zone 2 only; specially, it losses the engine power station quickly. Under this case, load shedding may help the system to recover the voltage level to an acceptable one, otherwise system may incline to voltage instability.

Ishurdi bus is connected to zone 1 (Ghorasal), zone 5 and zone 6 (Bherama HVDC). Figs.4.13 to 4.14 shows fault on that bus voltage below threshold limit at 230 kV bus but in 132 kV bus having more voltage drop due to less generation connected on this bus and load demand is high.

HVDC is connected to Bheramara230 kV bus, and injects about 500 MW at that bus. The protection scheme and restoration process is different and more difficult compared to other generation sites. Load flow analysis shows poor voltage situation in the Southern zone;

especially at Fadirpur, Madaripur, Jessor, Jhenaidah, Kustia, Gopalganj etc. Compensator is required to maintain the voltage. Due to these reasons severe voltage drop occurs in the zone and the nearby zone during the bus fault at Bheramara HVDC. Figs. 4.16and4.17 depict the voltage collapse due to bus fault and if protection scheme does not work properly it may lead to cascading outage of the system and may create system instability.

Loss of Line

Loss of a bus means that cutting off all circuits connected to it. Single circuit outages may overload the other circuit in a double circuit line resulting in tripping of the second circuit too. Hence, only double circuit outages are considered. The following plots are for line outages of different zone.

Figs.4.19 and 4.20 shows that 230 kV line outages at Ashuganj and Ghorasal do not lead to bus voltage violation or create system instability. Numbers of generators are connected to Ashuganj and Ghorasal buses and these generators supplied not only real power but also the required reactive power.

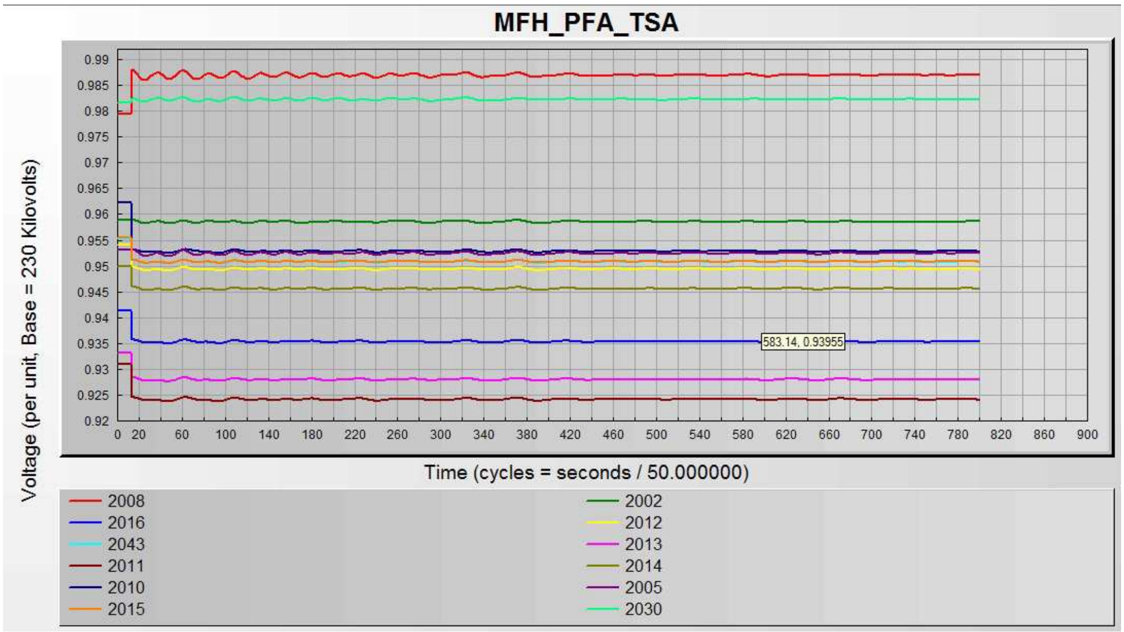

Fig 4.18: Ghorasal_Ashganj 230 kV line outage

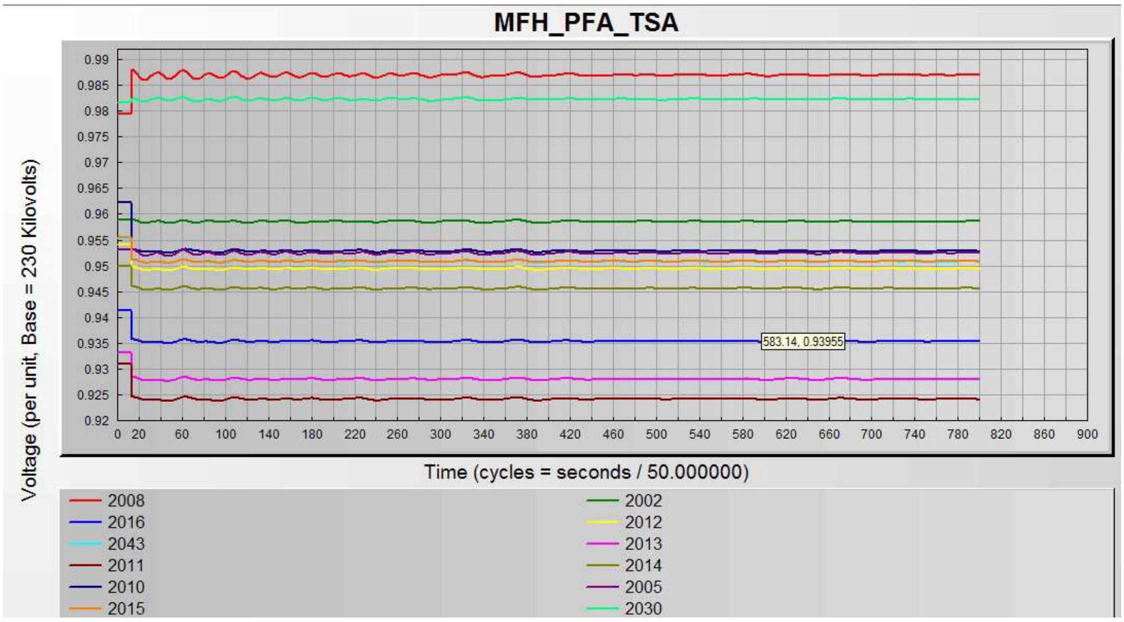

Fig 4.19: Ashuganj_Commilla N 230 kV line outage

Fig 4.21shows that system remains stable with voltages within the limits when line outages between Comilla N to Hathazari 230 kV occurs.

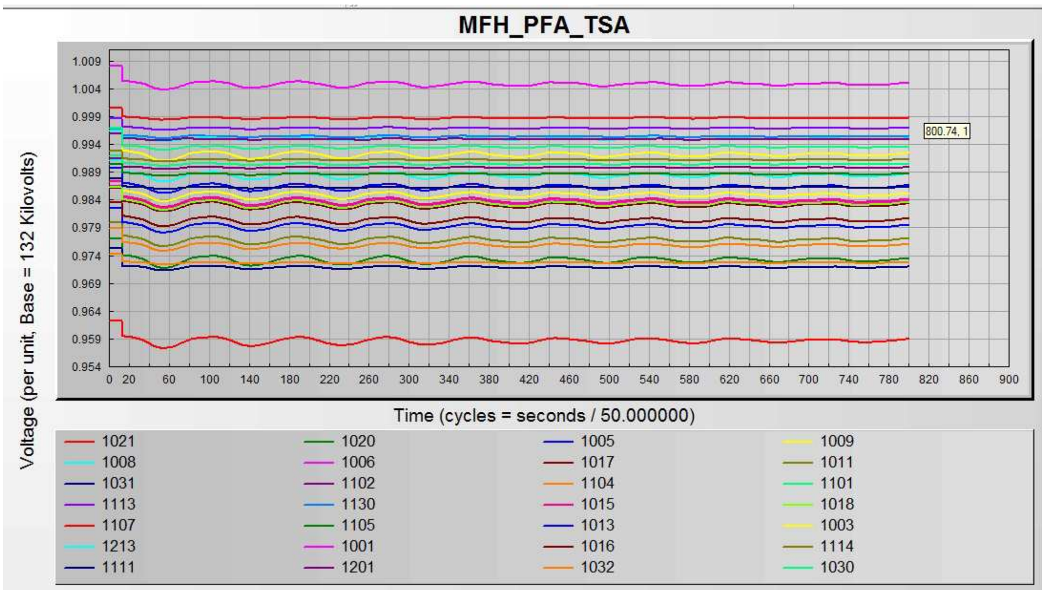

Fig 4.20: Commilla N to Hathazari 230 kV line outage

But in the other hand, line outage between Ishurdi and Bheramara 230 kV double circuit line results in voltage dip to 0.72 p.u. (Fig.4.22), whereas 230 kV bus voltage slightly goes down to 0.90 p.u voltage. Result shows North and South zones require var compensation to maintain the voltage. Moreover, generation requires on the far end also like Jhenida, Madaripur, Natore, Noapara etc.

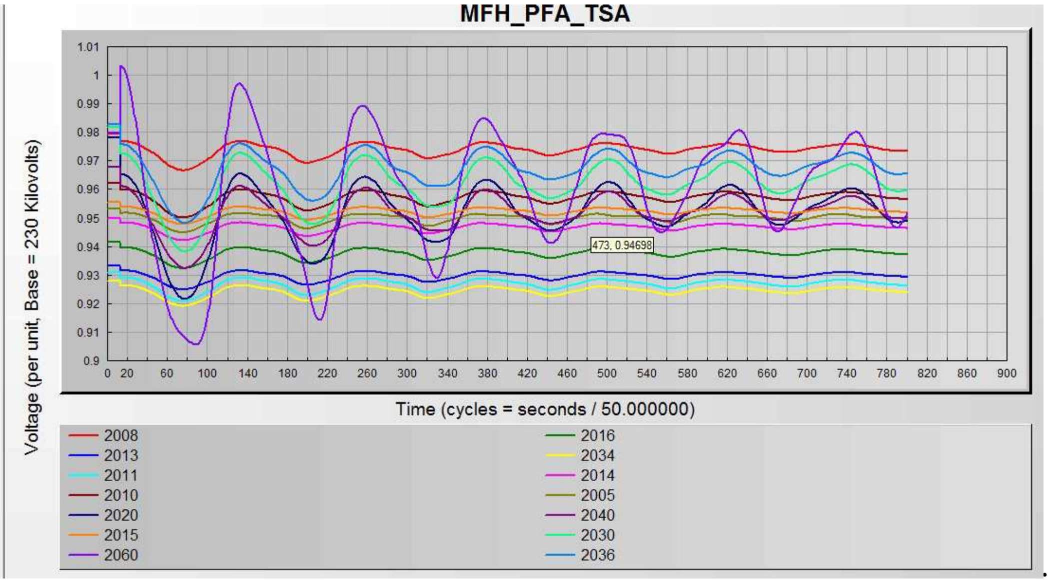

Fig 4.21: Bheramara to Ishurdi 230 kV line outage

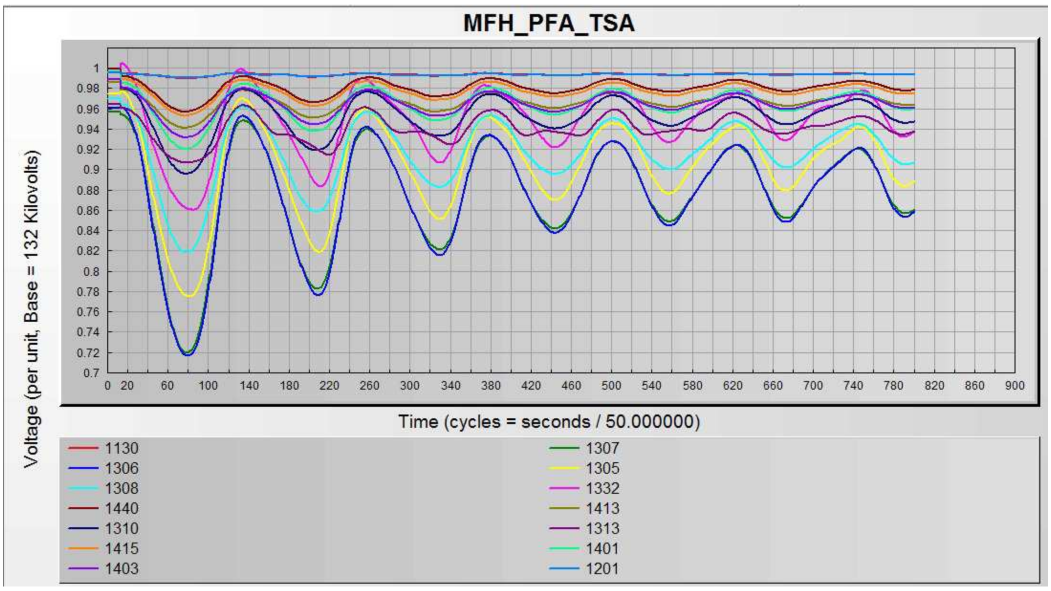

Fig 4.22: Line voltages at 132 kV level after Bheramara-Ishurdi 230kV line outage

Since the bus-loss shows system stability and the line fault is less severe than bus fault, it is unnecessary to analyze the contingency of line-loss without fault.

4.4.2 Determination of Voltage Dip and Generator Rotor Angle from *N*-1 Contingency

During N-1 contingency transformer, generator and line loss are not considered due to their less severe impact on the system. Only loss of bus is considered for the severity and system stability.

Zone 1:

Tables 4.7 to 4.10 shows that Ashuganj and Grorasal 230 kV bus fault creates severe bus voltage collapse. Ashuganj and Ghorasl buses are heavily loaded which supply not only MW but also MVAR to the system. Sudden loss of the MVAR cannot recover the voltage. Around 600 MW and 300 MW from engine based private power station feed power to Ashuganj and Ghrorasal buses, respectively. *H* constant is very low on these engines based power stations, hence, they can easily loss synchronization, and it would be very difficult to hold the voltage within the limit. Also, their rotor angle increases rapidly to a high value.

Table 4.7: Voltage dip, phase angle and frequency during N-1 contingency at Ashuganj 230 kV bus

Sl.no.	Bus name	Voltage (p.u.)	Angle (Degree)	Frequency (Hz)
1	Ashuganj	0.4809	-6.0	50.25
2	B. Baria	0.6616	4.4	50.15
3	Kishorganj	0.5233	-11	50.25
4	Ghorasal	0.6483	-4.2	50.14
5	Bhulta	0.6666	-9.8	50.26
6	Haripur	0.6667	-6.2	50.14

7	Kabirpur	0.5966	2.8	50.25
8	Joydevpur	0.6842	-3.9	50.17
9	Ashganj	0.0092	4.7	50.28
10	Comilla_North	0.5749	-12.2	50.26
11	Ghorasal	0.4821	-7.3	50.26
12	Comilla_North	0.482	-9.3	50.21

Table 4.8: Generator rotor angle during N-1 contingency at Ashuganj 230 kV bus

Bus name	Ash	B. Bari	Ash_1	Ash_2	Ash _3	GPS AG 1	MEG RPP1	MEGRPP2	Keraniganj
Angle (degree)	62.52	47.65	47.8	55.5	53.5	44.23	44.25	39.25	42.37

Table 4.9: Voltage dip, phase angle and frequency during N-1 contingency at Ghorasal 230 kV bus

Sl. no.	Bus name	Voltage (p.u.)	Angle (Degree)	Frequency (Hz)
1	Ghorasal	0.2261	-8.0	50.58
2	Ashuganj	0.4046	2.5	50.52
3	Haripur	0.5211	-10.2	50.71
4	Comilla_N	0.5883	-11	50.4
5	Shyampur	0.508	-12.4	50.68
6	Hasnabad	0.4273	-10.2	50.73
8	Kabirpur	0.3779	-12.7	50.62
9	Bhulta	0.5214	-6.6	50.57
10	Norsingdi	0.4105	45.1	50.65
11	Ashuganj	0.4572	-2.1	50.52
12	Comilla_N	0.5216	-7.7	50.52
13	Ishurdi	0.7009	-6.3	50.24

Table 4.10: Generator rotor angle during N-1 contingency at Ghorasal 230 kV bus

Bus name	Ash	GPS PDB	GPS AG 1	GPS AG 2	Keranig	HARP	Gang. orion	DPA 50	Ash. 80	Ash. 55
Angle (degree)	35	40	45.23	44	42	35	45	47.8	42	43

Zone 2:

Tables 4.11 to 4.14 shows that Comilla_N 230 kV & Hathazari bus fault, Fault at Comilla_N bus may collapse bus voltage which creates generation losses of Chandpur, AES, Daudkandi PS and Meghna private power station. Comilla_N bus is a heavily loaded bus which is connected with the Dhaka, Sylhet and Chittagong regions. This bus is completely disconnected from Chittagong region because power exchanges from Chittagong to Comilla_N is the only one radial network which is connected to BPSN. Moreover, around 850 MW power is transferred from Comilla_N bus so that it is very difficult to hold the voltage within the limit and if protection fails on Ashuganj and Meghnagat it may create cascading outage.

On the other hand, fault at Hathazari bus creates loss of synchronization on Hahazari and Dohazari engine based power plants along with Raozan power station. While fault at Hathazari bus only reduces generation in Chittagong zone, it does not create cascading outage.

Table 4.11: Voltage dip, phase angle and frequency during N-1 contingency at Comilla_ N 230 kV Bus

Sl. no.	Bus name	Voltage (p.u.)	Angle (Degree)	Frequency (Hz)
1	Comilla_N	0.4594	-6.2	50.4
2	Haripur	0.6648	18.8	50.37
3	Chandpur	0.4457	-10.7	50.45
4	Fenchuganj	0.6463	-6.1	50.19
5	Shyampur	0.6809	-11.3	50.36
6	Madanganj	0.6283	-18.6	50.36
8	Hathazari	0.585	-13.7	50.27
9	Comilla_North	0.0072	2.2	50.35

Sl. no.	Bus name	Voltage (p.u.)	Angle (Degree)	Frequency (Hz)
10	Ashuganj	0.6205	23.4	50.34
11	Ghorasal	0.6597	-20.4	50.35
12	Meghnaghat	0.511	-5.8	50.37

Table 4.12: Generator rotor angle during N-1 contingency at Comilla_N 230 kV bus

Bus name	MEG RPP1	MEG RPP2	Gang. Orion	Kerani	Sum. Comi	Sum. jang	DESH ENER	DPA50	DUTCH BAN100
Angle (degree)	35	35	38	42	59.5	60.5	37	36.5	39

Table 4.13: Voltage dip, phase angle and frequency during N-1 contingency at Hathazari 230 kV bus

Sl. no.	Bus name	Voltage (p.u)	Angle (Degree)	Frequency(Hz)
1	Hathazari	0.0026	-1	50.46
2	Raozan	0.0054	-8.6	50.84
3	Sikalbaha	0.4193	-12.7	50.65
4	Dohazari	0.4781	-13.5	50.69
5	Julda	0.4261	-12.8	50.65
6	Comilla_N	0.6987	-4.8	50.11
7	Ashuganj	0.8824	-1.2	50.1
8	Ghorasal	0.8808	-3.5	50.09

Table 4.14: Generator rotor angle during N-1 contingency at Hathazari 230 kV bus

Bus name	Hatha	Dohaz.	Julda	Feni22	Malanc
Angle (degree)	88	50	42	36	41

Zones 5 and 6:

Ishurdi bus is a intersection between northen zone and Bherama bus which is connected with south west side of BPSN. Moreover, 1st east-west interconnection is connected from Ghorasl to Ishurdi. Most important bus is Bheramara bus where HVDC is connected and 500 MW is feeding through HVDC bus. The protection scheme of HVDC bus is very different from normal bus zone protection. Any sudden loss of HVDC can be sustained by special auto load shedding scheme and quick control of HVDC. But in BPSN there is no such scheme. The bus voltage on this region is normally very poor and generation is less. Though capacitive var is installed in the substation of this region it is not sufficient.Tables4.15 to 4.19 shows that Ishurdiand Bheramara230 kV bus fault creates severe voltage drop. Specially, results from Bheramara bus fault in Tables4.17 and 4.18, and Figs.4.16 and 4.17 shows the voltage collapse that creates cascading outage that may lead to complete blackout of BPSN, as the results predicts.

Table 4.15: Voltage dip, phase angle and frequency during N-1 contingency at Ishurdi 230 kV bus

Sl. no.	**Bus name**	**Voltage (p.u.)**	**Angle (Degree)**	**Frequency (Hz)**
1	Pabna	0.2351	-8.2	50.11
2	Shajadpur	0.439	-12.7	50.65
3	Natore	0.2351	-6.2	50.11
4	Rajshahi	0.5267	-10	51.28

Sl. no.	Bus name	Voltage (p.u.)	Angle (Degree)	Frequency (Hz)
5	Sherajganj	0.3928	-11.1	50.32
6	Bogra	0.4202	-9.6	50.12
7	Bheramara	0.3783	-12.8	50.27
8	Kustia	0.4502	-7.2	50.46
9	Chuadanga	0.5129	-19.2	50.43
10	Ishudi	0.5450	-14.2	49.99
11	Bhagabari	0.634	-23	50.31

Table 4.16: Generator rotor angle during N-1 contingency Ishurdi 230 kV bus

Bus name	Siraj 150	Bera 71	Noa Agg	Faridp	Gopalg	Rajlanka	Katakh
Angle (degree)	31.5	58.7	38.3	33	35	39.2	32

Table 4.17: Voltage dip, phase angle and frequency during N-1 contingency at Bheramara 230 kV bus

Sl. no.	Bus name	Voltage (p.u.)	Angle (Degree)	Frequency (Hz)
1	Goalpara	0.4251	-9.2	50.11
2	Khulna Cent.	0.5267	-10	51.28
3	Noapara	0.4965	-11.9	50.11
4	Khulna South	0.4618	-8.8	50.11

Sl. no.	Bus name	Voltage (p.u.)	Angle (Degree)	Frequency (Hz)
5	Jessor	0.4521	-15.1	50.11
6	Jhenaidah	0.4002	-11.6	50
7	Kustia	0.3803	-12.8	50.07
8	Bheramara	0.1502	-9.2	50.5
9	Faridpur	0.5689	-21.6	50.43
10	Goapalganj	0.7141	-18	49.99
11	Madaripur	0.694	-22.6	50.41
12	Satkhira	0.4178	-4.6	50.49
13	Ishurdi	0.3157	-5.9	50.07

Table 4.18: Generator rotor angle during N-1 contingency at Bheramara 230 kV bus

Bus name	Siraj 150	Bera 71	Noa Agg	Bhera 100	Bhera 60	KPCL1	Rajlanka	KPCL2
Angle (degree)	36	47	39	38	35	38	36	39.9

The Transient voltage dips and generator rotor angle shows in Tables 4.7 to 4.18 for providing the vulnerable part of Bangladesh Power System Network (BPSN) according to Performance Index (PI) table 4.19. Based on PI calculation Table 4.20 shows the most vulnerable part of BPSN due to N-1 contingency.

Table 4.19: Performance Index of BPSN during *N*-1 contingency

Sl.no.	Contingency name	Bus Name	Performance Index (PI)
1	*N*-1	Bheramara	1.5126
2	*N-1*	Ghorasal	1.3030
3	*N-1*	Comilla_N	1.1965
4	*N-1*	Ashuganj	1.1793
5	*N-1*	Ishurdi	1.1612

Based on PI calculation, table 4.20 shows the vulnerable part of BPSN after N-1 Contingency analysis.

Table 4.20: Vulnerable buses of BPSN during *N*-1 contingency at the respective buses.

Sl.no.	Bus name	Voltage (p.u.)	Angle (Degree)
1	Bheramara	0.1502	-9.2
2	Ghorasal	0.2261	-8.0
3	Comilla_N	0.4594	-6.2
4	Ashuganj	0.4809	-6.0
5	Ishurdi	0.7450	-14.2

4.4.3 *N*-2 Contingency

The N-2 contingencies are selected based on the severity found on N-1 contingencies, which accounts for bus and line faults together with protection failures. Contingencies are processed using a rough evaluation of their probability, to ensure that the most probable contingencies are processed first. These contingencies, together with N-1 contingencies, are considered the initiating events, and we perform simulation to identify system performance which may lead to further component tripping. Such performance includes circuit overload or under-voltage (relative to emergency ratings), protective relaying operation (e.g., generator over excitation, over-current, over- or under-voltage, over- or under-frequency), and unit loss of synchronism.

For N-2 contingency, the protection system operating time is the Fault Clearing Time (FCT) set by the system stability. Actually, it should be less than critical clearing time (CCT) but since BPSN there is no calculation for CCT, hence calculated CCT is used as a reference to check the protection system and system stability of BPS.

Also there is a consideration for the action of backup relay. When main protection does not work properly back up protection isolates the faulted component. System stability margin can refer to the result of N-1 contingency. If protection action time is greater than backup protection operating time or FCT then the stability margin is negative, it will show that the system is unstable on this kind of N-2 contingency. Table 4.21 shows the consideration of N-2 contingency following N-1 contingency. This N-2 contingency is applied throughout the BPS network. It performed during loss of transformers, generations, lines and buses without and with fault.

Table 4.21: *N*-2 Consideration of BPSN following *N*-1 contingency

SL No.	Consideration of *N*-1 Contingency (for All Six zones)	Effect	Consideration of *N*-2 Contingency (for All Six zones)
1	Loss of Transformer without fault	No effect occurred	Since N-1 Contingency does not creates any severe effect on such kind of event hence N-2 contingency tested for these events but these less effect does not consider for combined contingency ranking
2	Loss of Transformer with fault	System stable with sufficient Margin	
4	Loss of Generation with fault	System stable with sufficient Margin	
6	Loss of Transmission Line with fault	System sustain with its loadability limit but not create a cascading failure	
7	Loss of Bus with fault	Severe voltage collapse happened in each zone may create cascading outages	Details study carried out and effects are considered for combined contingency ranking

After an *N*-1 contingency event a three-phase fault is applied at t = 300 ms the vulnerable buses specified in Table 4.20, i.e. 230 kV buses at Ashuganj, Ghorasal, Comilla_N, Hathazari, Ishurdi and Bheramarain different zones of BPSN with subsequent tripping of bus zone protection at these buses. Tables 4.22 to 4.26 shows the results for N-2 contingency.

For zone 1, Ashuganj bus is stable up to 227 ms and instability start from 228 ms; Ghorasal bus is stable at 359 ms and instability start from 360 ms though calculated critical clearing time (CCT) is less than actual time that may lead to system unstable in this region.

For zone 2, Comilla_N bus is stable up to 254 ms and instability start from 255 ms it may tends to start outages some part of Dhaka region, fenchuganj bus and disconnected Chittagong from the system. Whereas Hathazari bus is stable 269 ms and unstable start from

270 ms and it only start to outage on Chittagong, raozan and engine based powers station. Also calculated critical clearing time (CCT) and FCT is near hence hathazari bus does not leads cascading outages of the system.

For zone 5, Ishurdi bus is stable up to 239 ms and instability start from 240 ms and East-west interconnection line also connected on this bus and CCT is very less compared to FCT that may create tendering cascading outages.

For zone 6, Bheramara bus is very critical in BPSN because 500 MW HVDC is connected on this bus and voltage level near and far from these areas such as madaripur, faridpur, jhenaidah, chuadanga are very vulnerable that found from N-1 contingency. Moreover, same protection concept and setting used in line with PGCB system protection in this study. Special protection scheme that is used in HVDC protection system is not considered. It stable up to 329 ms and unstable from 330 ms which is greater than critical clearing time that may leads subsequent tripping of cascading outages tending to blackout the system.

A. Bus fault at Ashuganj 230 kV Bus

Table 4.22: FCT for a three-phase fault on Ashuganj 230 kV bus

SL No.	Generator name	FCT (ms)	Reason	Calculated CCT w.r.t.Ashg. _150 generator (ms)
1	Ashuganj	227	Voltage	175ms
2	ASH_ Engi, Pre., RPP55,	227	Angular	
3	B. Bari 70	244	Angular	
4	Ash 64-1,2,	259	Voltage	
5	RPCL_1,2,3	294	Voltage	
6	GPS_Agg,Reg,	304	Angular	
7	GPS_210_2	359	Voltage	

B. Bus fault at Ghorasal 230 kV Bus

Table 4.23: FCT for a three-phase fault on Ghorasal 230 kV bus

Sl. no.	Generator name	FCT (ms)	Reason	Calculated CCT w.r.t.Ghorasal _ 210 generator (ms)
1	Ghorasal_1	359	Voltage	252ms
2	Ghorasal_2	361	Voltage	
3	Ash_150_1	390	Voltage	
4	Ash_150_2,3	390	Voltage	
5	Ash_150_2,3	390	Angular	
7	Ash 55	395	Angular	
8	Ash_united	395	Voltage	
9	B. Baria	400	Voltage	
10	Tongi	430	Voltage	
11	Bagrabari	514	Voltage	

C. Bus fault at Comilla_N 230 kV Bus

Table 4.24: FCT for a three-phase fault on Comilla_N230 kV bus

Sl. no.	Generator name	FCT (ms)	Reason	Calculated CCT w.r.t. AES _235 generator (ms)
1	Meghna RPP 1, 2 (Summit)	254	Voltage	236 ms
2	Chandpur 150 MW	269	Voltage	

Sl. no.	Generator name	FCT (ms)	Reason	Calculated CCT w.r.t. AES _235 generator (ms)
3	AES 1,2	289	Voltage	
4	Gangna_orion,	309	Angular	
5	Dutch Bangla,	339	Angular	
6	Haripur,Madang	369	Voltage	
7	Desh Energy	394	Angular	
8	Fenchuganj 32_1, 32_2	429	Voltage	
9	Fench _ Baraka	454	Voltage	

D. Bus fault at Hathazari 230 kV Bus

Table 4.25: FCT for a three-phase fault on Hathazari 230 kV bus

Sl. no.	Generator name	FCT (ms)	Reason	Calculated CCT w. r. t. Raozan_210_1 generator (ms)
1	Hathazari_98	269	Voltage	267 ms
2	Dohazari_102	289	Angular	
3	Julda_100	304	Angular	
4	Raozan_210_1	339	Voltage	
5	Sikalbaha 150	374	Voltage	
6	Kaptai_40_1	394	Angular	

Sl. no.	Generator name	FCT (ms)	Reason	Calculated CCT w. r. t. Raozan_210_1 generator (ms)
7	Kaptai_50_1	409	Angular	

E. Bus fault at Ishurdi 230 kV Bus

Table 4.26: FCT for a three-phase fault on Ishurdi 230 kV bus

Sl.no.	Generator name	FCT (ms)	Reason	Calculated CCT w.r.t.Sirajg. _150 generator (ms)
1	Bera	239	Voltage	205 ms
2	Baghabari 55,71	269	Voltage	
3	Baghabari 100	289	Voltage	
4	Bheramara 100	324	Voltage	
5	Bheramara 71	349	Voltage	
6	Noapara 55, KPCL 110	374	Voltage	
7	Faridpur	394	Angular	
8	Gopalganj	409	Voltage	

F. Bus fault at Bheramara 230 kV Bus

Table 4.27: FCT for a three-phase fault on Bheramara 230 kV bus

Sl. no.	Generator name	FCT (ms)	Reason	Calculated CCT w.r.t. Bherama _100 generator (ms)
1	Bheramara 60	329	Voltage	224 ms
2	Bheramara 100	349	Voltage	
3	Baghabari 100	364	Voltage	
4	Noapara 55	389	Angular	
5	Faridpur 55	404	Voltage	
6	Gopalganj 100	424	Voltage	
7	KPCL 110	439	Angular	

Only transient voltage dip and excessive generator rotor angle during N-1 contingency cannot identify the true vulnerable part of the BPSN, hence we have considered the N-2 contingency to verify with the protection scheme of the network with actual protection settings of BPSN. If any protection action fails with the given protection setting then the backup protection comes into effect. The backup fault clearing time is always less than critical clearing time (CCT). We have used a calculated value of CCT in this study to cross check the protection scheme. Table 4.27 shows the most vulnerable part of BPSN after the study of N-2 contingency. According to the table Ashuganj 230 kV bus is the most vulnerable bus in the whole of BPSN.

Table 4.28: Vulnerable buses of BPSN during N-2 contingency

Sl. no.	Bus name	FCT (ms)	Reason	Calculated CCT (ms)
1	Bheramara	329	Voltage	224 ms
2	Ghorasal	359	Voltage	252 ms
3	Ashuganj	227	Voltage	175 ms
4	Ishurdi	239	Voltage	205 ms
5	Comilla_N	254	Voltage	236 ms

CHAPTER 5
Conclusion

5.1 Conclusion

The electric power system network is a very critical infrastructure. The inter-connectivity of the power grid allows the propagation of disturbances in the network. Bangladesh power system experienced instances of blackout in the past that had cascading effect on other engineered system that depends on electric power grid. Therefore, it is very important to determine the vulnerable nodes in the power system network.

This thesis demonstrates a methodical approach to dynamic security assessment. The method is based on a combination of voltage and angular criterion, N-1 and N-2 contingency analysis, transient voltage dip, transient stability analysis and use of performance index. A combined contingency ranking based on bus phase voltage and phase angle, and stability margin for all machines in a power system is used. The method is very effective for secured planning and operation of a power system, and for protection scheme design.

The method is applied to the Bangladesh power system network (BPSN) for dynamic security assessment of the system. From the outcome of the studies it is understood that Bheramara, Ghorashal, Ashuganj, Ishurdi, Comilla North 230 kV buses are the most critical buses in the system. In the whole network these buses and the paths they connects paths can be called the backbone of BPSN as they connect greater number of nodes in the system and transfer large amount of power and, this also make the system vulnerable at these locations as any serious contingency involving these nodes may lead the system to instability as reported in this work. If any of these buses collapse, the whole network will be affected severely.

It may be concluded that more protective measures should be taken for the most critical buses of the system to prevent sudden system collapse or blackout. And, the method is very effective for secured planning and operation of a power system, and for protection scheme design.

5.2 Future Work

This work has been performed with limitation on the availability of adequate system modeling data and operational records of BPS network. The speed of extended-term time-domain simulation is still a critical constraint in the analysis for large-scale systems. Faster simulation means earlier awareness of system performance violation and thus earlier corrective actions to interrupt the cascading outages. Further research may be conducted so that the method can be improved by using a better performance index. The method may be tested for a different post-fault configuration which may require some optimization techniques. Proper relay coordination of protection system is also required to capture more accurate dynamic behavior of the BPS network to render the analysis more accurate.

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APPENDIX

Power System Data

1. Data Format for PSAF

1.1 Bus Data Format:

Column	Variable	Description	Unit
1	-	Bus number	int
2	-	Zone	int
3	V	Voltage Base	kV
4	V_0	Voltage amplitude initial guess	p.u
5	θ_0	Voltage phase initial guess	degree
6	$Vmin$	Voltage limit min	p.u
7	$Vmax$	Voltage limit max	p.u

1.2 Line Data Format:

Column	Variable	Description	Unit
1	-	From Bus	int
2	-	To Bus	int
3	-	Zone	int
4	V_n	Voltage rating	kV
5	P_n	Real Power Rating	MW
6	Q_n	Reactive Power Rating	MVAR
7	Sn	Power Rating	MVA
8	-	*Line Length*	km
9	r	Resistance	p.u (□/km)
10	x	Reactance	p.u (□/km)
11	b	Susceptance	p.u (F/km)
12	I_{max}	Current Limit	p.u
13	-	Loading	%
14	-	Connection Status	{0,1}

1.3 Transformer Data Format:

Column	Variable	Description	Unit
1	-	From Bus	int
2	-	To Bus	int
3	-	Zone	int
4	Sn	Power Rating	MVA
5	V_n	Voltage rating	kV
6	-	Primary and Secondary Voltage ration	kV/ kV
7	r	Resistance	p.u (□/km)
8	x	Reactance	p.u (□/km)
9	-	Loading Limit	MW
10	-	Connection Status	{0,1}

1.4 Generator Data Format:

Column	Variable	Description	Unit
1	-	Bus number	int
2	-	Zone	int
3	*Sn*	Power Rating	MVA
4	V_n	Voltage Rating	kV
5	V_0	Voltage Magnitude	p.u
6	θ_0	Reference Angle	degree
7	*Qmax*	Maximum Reactive Power	p.u
8	*Qmin*	Maximum Reactive Power	p.u
9	*P*	Active Power	MW
10	*Q*	Reactive Power	MVAR
11	-	Reference Bus	{0,1}
12	-	Connection Status	{0,1}

1.5 PQ Load Data Format:

Column	Variable	Description	Unit
1	-	Bus number	int
2	-	Zone	int
3	*Sn*	Power Rating	MVA
4	*P*	Active Power	MW
5	*Q*	Reactive Power	MVAR
6	-	Reference Bus	{0,1}
7	-	Connection Status	{0,1}

1.6 Fault Data Format

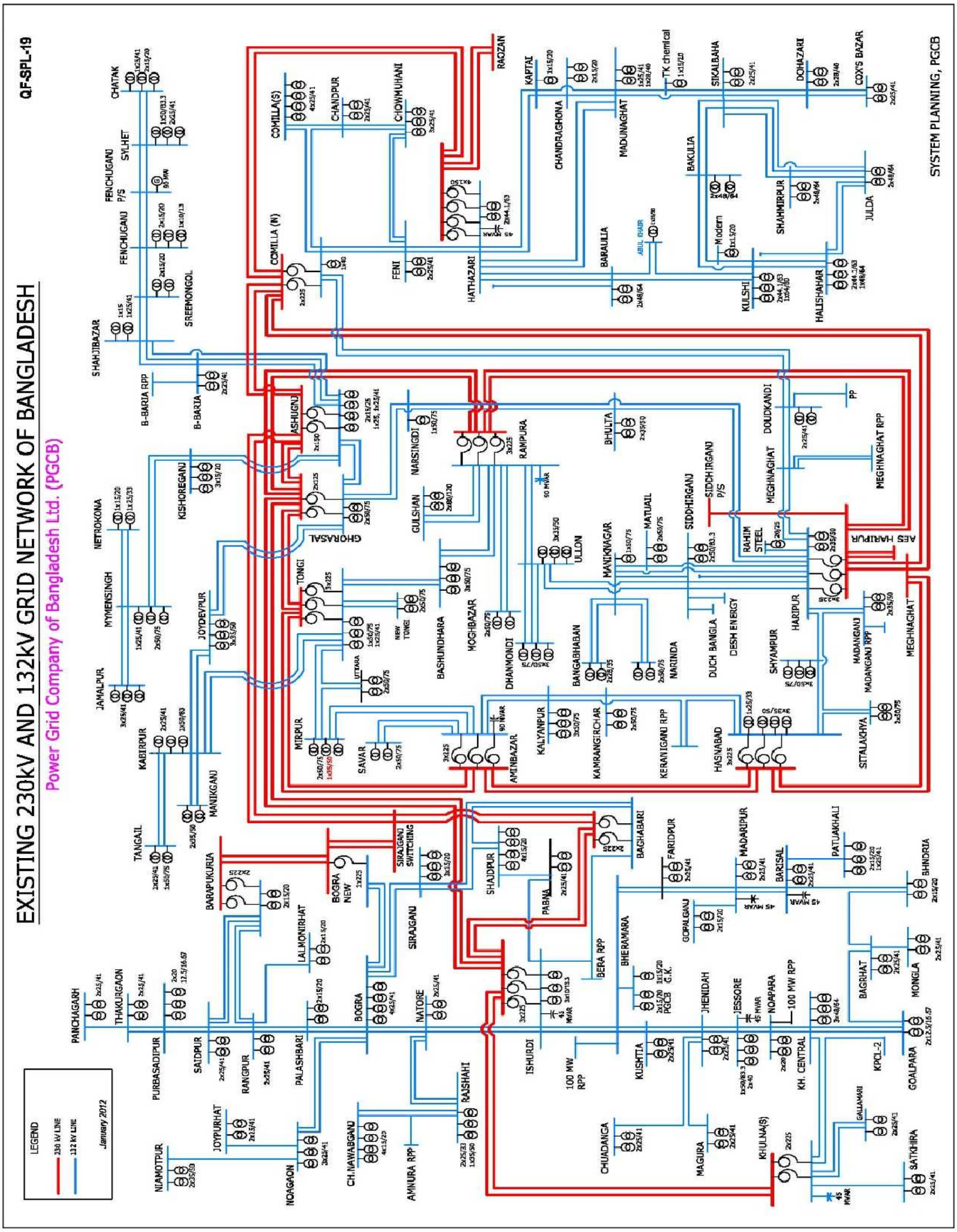
Column	Variable	Description	Unit
1	-	Bus number	int
2	Vn	Voltage Rating	p.u
3	*fn*	frequency	Hz
4	t_f	Fault Time	MW
5	t_c	Clearance Time	MVAR
6	*r*	Fault Resistance	p.u
7	x	Fault Reactance	p.u

1.7 Synchronous Machine Data Format:

Column	Variable	Description	Unit
1	-	Bus Number	int
2	S_n	Power Rating	MVA
3	V_n	Voltage rating	kV
4	f_n	Frequency rating	Hz
5	-	Machine Model	-
6	*xl*	Leakage Reactance	p.u
7	*ra*	Armature Resistance	p.u
8	*xd*	*d-axis Synchronous Reactance*	p.u
9	*x'd*	*d-axis Transient Reactance*	p.u

10	*x''d*	*d-axis Sub transient Reactance*	p.u
11	*T'd0*	*d-axis Open Circuit Transient Time Constant*	s
12	*T''d0*	*d-axis Open Circuit Sub transient Time Constant*	s
13	*xq*	*d-axis Synchronous Reactance*	p.u
14	*x'q*	*d-axis Transient Reactance*	p.u
15	*x''q*	*d-axis Sub transient Reactance*	p.u
16	*T'q0*	*q-axis Open Circuit Transient Time Constant*	s
17	*T''q0*	*q-axis Open Circuit Sub transient Time Constant*	s
18	*D*	Damping Coefficient	-
19	*u*	Connection Status	{0,1}

2. **Bangladesh Power System Network:**



Single line diagram of Bangladesh Power System Network (2013)

3. Power Flow Report:

LOAD FLOW STUDY PARAMETERS	
Study :	MFA_PFA
Time :	Fri Sep 14 19h42m06s 2018
Method :	Newton Raphson
Constraints :	Applied
Flat start :	No
Tcultxfo used as fixed tap :	No
Block Q-flow Txfo Adjustment	n\a
Block P-flow Txfo Adjustment :	n\a
Block Switchable Shunt Adjustment :	n\a
Block DC Link Adjustment :	n\a
Base power :	100.00 [MVA]
Tolerance :	0.100 [MVA]

Generator output

ID	Rated S [MVA]	kV Nominal	Generator Type	P [MW]	Q [MVAR]	S [MVA]	P. Factor [%]	I [pu]	Q max. [MVAR]	Q min. [MVAR]
MEGNAGH_RPP1	150	14.5	PV	105	48.77	115.77	90.7	1.158	90	0
MEGNAGH_RPP2	150	14.5	PV	100	48.12	110.97	90.1	1.11	90	0
BAGHABARI100	134.25	11	PV	98	6.46	98.21	99.8	0.982	80.55	-10
GAGNAG_ORION	127.5	11	PV	102	14.84	103.07	99	1.031	76.5	0
KAPTAI50_3	62.5	11	PV	41	16.06	44.03	93.1	0.44	40	0
TANGA_DO-0	30	11	PV	22	12.83	25.47	86.4	0.255	22	0
KAPTAI40_2	57.5	11	PV	50	14.22	51.98	96.2	0.52	35	0
KAPTAI50_2	62.5	11	PV	42	16.12	44.99	93.4	0.45	35	0
KAPTAI40_1	57.5	11	PV	38	13.2	40.23	94.5	0.402	35	0
GOPALGANJ110	137.5	11	PV	79	34.03	86.02	91.8	0.86	82.5	0
SYL_REN_50	69.25	11	PV	46	4.21	46.19	99.6	0.462	41.75	-10
SANTAHA50_1U	65.25	11	PV	46	16.12	48.74	94.4	0.487	39.5	0
SUMMIT_BULT1	43.74	11	PV	35	12.54	37.18	94.1	0.372	28	0
CHANDP105_GT	138	15.75	PV	105	30.94	109.46	95.9	1.095	82.5	0
BOGRA_20	22.5	11	PV	14	1.44	14.07	99.5	0.141	13.5	0
SIDDHIRG_1U	247	15.75	PV	110	114.06	158.46	69.4	1.585	131	0
ASHU_64_2	80	11	PV	40	4.05	40.2	99.5	0.402	48	0
ASHU150_2	190	15.75	PV	140	42.77	146.39	95.6	1.464	114	-10
ASHU150_3	190	15.75	PV	130	42	136.62	95.2	1.366	114	-10
SIKALBAHA_55	69.25	11	PV	25	12.47	27.94	89.5	0.279	41.75	0
ASHU_AGGE80	112.75	11	PV	83	7.65	83.35	99.6	0.834	67.65	0
SYLHET_REN10	25	11	PV	9	4.48	10.05	89.5	0.101	15	0
KHULNARPP55	69.25	11	PV	44	5.69	44.37	99.2	0.444	41.75	0
SUMMIT_ASH_1	43.74	11	PV	33	2.76	33.12	99.7	0.331	28	-10
ASH_RPP55_PR	68.75	11	PV	47	4.96	47.26	99.4	0.473	41.75	0
KPCL115_2U	143.75	11	PV	116	15.62	117.05	99.1	1.17	86.25	0
ASHU150_1	190	15.75	PV	130	42	136.62	95.2	1.366	114	-10

ID	Rated S [MVA]	kV Nominal	Generator Type	P [MW]	Q [MVAR]	S [MVA]	P. Factor [%]	I [pu]	Q max. [MVAR]	Q min. [MVAR]
BHERA20_3	30.31	11	PV	15	3.26	15.35	97.7	0.154	18	0
GPS_AGGRE100	134.25	11	PV	97	8.05	97.33	99.7	0.973	80.55	0
KERANIGA_RPP	134.25	11	PV	100	4.46	100.1	99.9	1.001	80.55	-30
SYLHET20U	25	11	PV	19	13.01	23.03	82.5	0.23	15	-10
HARIPUR110	137.5	11	PV	96	17.77	97.63	98.3	0.976	82.5	0
SUMMIT_ULLAP	43.74	11	PV	5	12.46	13.43	37.2	0.134	28	0
SIRAJGAN_150	190	15.75	PV	140	43.01	146.46	95.6	1.465	114	-30
HVDC500_235	310	16	PV	230	58.16	237.24	96.9	2.372	210	10
HVDC500_125	156.5	16	PV	110	27.49	113.38	97	1.134	93.75	0
RPCL_GAZIPUR	69.25	11	PV	51	11.77	52.34	97.4	0.523	41.75	0
GHORASAL55_2	69	10.5	PV	43	3.72	43.16	99.6	0.432	41.4	0
GHORASAL55_1	69	10.5	PV	45	3.84	45.16	99.6	0.452	41.4	0
SHAHJI35_2	43.74	11	PV	33	4.85	33.35	98.9	0.334	38	0
SHAHJI35_1	43.74	11	PV	33	4.85	33.35	98.9	0.334	28	0
BARISAL2U	28.13	11	PV	15	12.89	19.78	75.8	0.198	22	0
NOAPARA40_2U	50	11	PV	32	13.53	34.74	92.1	0.347	30	0
KPCL110	137.5	11	PV	108	15.05	109.04	99	1.09	82.5	0
RAJLAN_NATOR	66.9	11	PV	52	11.38	53.23	97.7	0.532	40.14	0
FARIDPUR55	69.25	11	PV	42	33.17	53.52	78.5	0.535	41.75	0
RPCL_1U	87.5	11	PV	50	37.53	62.52	80	0.625	60	0
GHORA_210_3	247	15.75	PV	170	100.29	197.38	86.1	1.974	148.2	0
ASHU64_1	80	11	PV	50	4.7	50.22	99.6	0.502	48	0
RPCL_3U	87.5	11	PV	50	37.53	62.52	80	0.625	60	0
RPCL_2U	87.5	11	PV	50	37.53	62.52	80	0.625	60	0
GHORA_210_2	247	15.75	PV	180	101.02	206.41	87.2	2.064	148.2	0
GHORA_210_1	247	15.75	SW	112	96.89	148.09	75.6	1.481	148.2	0
ASHU56_2	69.25	13.8	PV	40	4.05	40.2	99.5	0.402	41.75	0
BOGRA22_GBB	27.5	11	PV	18	9.11	20.17	89.2	0.202	16.5	0
GPS_REGENT	137.5	11	PV	103	8.8	103.37	99.6	1.034	82.5	0
NORSING_DO_1	27.5	11	PV	19	8.42	20.78	91.4	0.208	16.5	0
BHERAMARA2_1	32	11	PV	15	2.91	15.28	98.2	0.153	25	-15
BHERAMARA100	130	11	PV	100	20.31	102.04	98	1.02	93.75	0
GPS_AGGRE45	56.25	11	PV	43	15.34	45.65	94.2	0.457	33.75	0
SUMITT_COMIL	31.25	11	PV	15	4.93	15.79	95	0.158	18.75	0
SHAHJI50	62.5	11	PV	47	5.48	47.32	99.3	0.473	37.5	0
SHAHJI86	107.5	11	PV	83	9.88	83.59	99.3	0.836	64.5	0
JULDA108_1U	125	11	PV	80	24.39	83.63	95.7	0.836	75	0
SUMIT_JANGAL	43.67	11	PV	34	2.86	34.12	99.6	0.341	26.2	0
NGPG_75_2U	95	15.75	PV	60	22.89	64.22	93.4	0.642	56.25	-20
AES_360_2	156.5	16	PV	108	53.47	120.51	89.6	1.205	93.75	0
ASHU55_5U	69.44	11	PV	42	4.17	42.21	99.5	0.422	41.75	0
AES_360_1	310	16	PV	240	115.1	266.17	90.2	2.662	210	10
SAIDPUR20	25.9	11	PV	17	5.51	17.87	95.1	0.179	15	0
BARAKA_REN50	69.25	11	PV	47	2.7	47.08	99.8	0.471	41.75	-10
CHANDP50_ST	71.25	11	PV	54	22.63	58.55	92.2	0.586	45	-20
MALANC	41.04	11	PV	29	18.15	34.21	84.8	0.342	24	-12
NGPG_150_1U	200	15.75	PV	158	21.6	159.47	99.1	1.595	120	-30
ASH_RPP4U_MI	70.05	11	PV	49	5.07	49.26	99.5	0.493	42.03	0

ID	Rated S [MVA]	kV Nominal	Generator Type	P [MW]	Q [MVAR]	S [MVA]	P. Factor [%]	I [pu]	Q max. [MVAR]	Q min. [MVAR]
ASH_RPP3U_UN	70	11	PV	53	5.3	53.26	99.5	0.533	42	0
MADANG102	127.5	11	PV	95	10.14	95.54	99.4	0.955	76.5	0
BARAPUK1-2	156.56	13.8	PV	91	36.24	97.95	92.9	0.98	93	-54
BARAPUK1_2	156.56	13.8	PV	75	35.23	82.86	90.5	0.829	93	-54
BARISAL20_1	28.13	11	PV	16	12.95	20.58	77.7	0.206	22	0
B.BARIA70	88.47	11	PV	86	11.61	86.78	99.1	0.868	53.08	0
DUTCHBAN100	134.25	11	PV	76	13.79	77.24	98.4	0.772	80.55	0
FENCH32_2	41.04	11.5	PV	25	1.5	25.04	99.8	0.25	24	-12
FENCH35_3	43.74	11	PV	13	1.15	13.05	99.6	0.131	28	0
DPA50	69.25	11	PV	39	11.82	40.75	95.7	0.408	41.75	-20
BERA71_1U	88.47	11	PV	86	4.45	86.11	99.9	0.861	53.08	0
FENCH32_1	41.04	11.5	PV	25	1.5	25.04	99.8	0.25	24	-12
FENCH33_1	41.04	11.5	PV	23	1.42	23.04	99.8	0.23	24	-12
FENCH35_1	43.74	11	PV	30	1.74	30.05	99.8	0.301	28	-10
AMNURA50	69.25	11	PV	41	18.91	45.15	90.8	0.452	41.75	0
BHOLA33	43.74	11	PV	35	23.55	42.18	83	0.422	28	-12
BAGHABARI71	88.47	11	PV	71	4.67	71.15	99.8	0.712	53.08	-10
MEGHNA_RPP	134.25	11	PV	80	9.72	80.59	99.3	0.806	80.55	0
DESH ENER100	125	11	PV	100	14.79	101.09	98.9	1.011	75	0
BAGHABARI50	69.25	11	PV	40	2.75	40.09	99.8	0.401	41.75	-10
SHIKAL_150	200	15.75	PV	100	32.56	105.17	95.1	1.052	112.5	0
KATAKH50_PPP	69.25	11	PV	45	14.24	47.2	95.3	0.472	41.75	0
KATAKH50_NPS	69.25	11	PV	50	14.63	52.1	96	0.521	41.75	0
RAOZAN_210-1	247	15.75	PV	130	88.26	157.13	82.7	1.571	130	-10
DOHAZARI102	138	11	PV	100	15.1	101.13	98.9	1.011	82.5	-15
HATHAZA98_1U	122.5	11	PV	97	9.01	97.42	99.6	0.974	73.5	0
FENI22_SIPP	27.5	11	PV	15	8.86	17.42	86.1	0.174	16.5	0

Line Flows

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
2015	2012	230	2	174	62.01	184.72	1.933	-22.7	0.08	0.29	5.976	32.4
1125	1445	132	3	43.61	15.48	46.28	0.463	-27.6	0.04	-0.02	1.509	30.7
1125	1126	132	21	34.13	16.08	37.72	0.377	-33.3	0.18	-0.45	1.509	25
1216	1215	132	32	-18.5	-10.77	21.44	0.217	147.7	0.08	-1.33	1.509	14.4
1305	1306	132	25	66.91	8.27	67.42	0.691	-15.8	0.69	1.3	1.509	45.8
1425	1430	132	20.9	58.2	-11.26	59.28	0.604	-4.3	0.44	0.55	1.509	40
1415	1417	132	45	49.11	12.85	50.77	0.51	-23.8	0.69	0.22	1.509	33.8
1415	1418	132	50.2	57.09	-3.03	57.17	0.574	-6.1	0.96	0.91	1.509	38
1005	1002	132	30.8	-37.3	-8.44	38.22	0.386	159.6	0.26	-0.63	1.509	25.6
1005	1013	132	12.7	46.96	13.84	48.95	0.495	-24	0.18	0.01	1.509	32.8
1495	1412	132	11	46.01	-5.36	46.32	0.463	4.1	0.14	-0.08	1.509	30.7
1324	1326	132	31.4	19.18	-16.12	25.05	0.256	21.5	0.15	-1.12	1.28	20
1125	1123	132	9	42.67	5.4	43.01	0.43	-15.2	0.1	-0.12	1.509	28.5
1015	1443	132	5	29.22	9.69	30.79	0.312	-26.4	0.03	-0.15	1.509	20.7
1105	1103	132	6	14.05	-17.56	22.49	0.227	43.2	0.02	-0.24	1.509	15.1
1125	1120	132	15	16.45	8.57	18.55	0.185	-35.6	0.03	-0.67	1.509	12.3
1005	1460	132	8	24.46	6.27	25.25	0.255	-22	0.03	-0.3	1.509	16.9
1415	1440	132	2	-104	-51.23	116.23	1.167	144.8	0.16	0.47	1.509	77.3
1165	1030	132	40.2	-3.53	-5.12	6.22	0.063	118.1	0.01	-2.05	1.509	4.2
2015	2012	230	2	174	62.01	184.72	1.933	-22.7	0.08	0.29	5.976	32.4
1125	1445	132	3	43.61	15.48	46.28	0.463	-27.6	0.04	-0.02	1.509	30.7
1005	1013	132	12.7	46.96	13.84	48.95	0.495	-24	0.18	0.01	1.509	32.8
1305	1306	132	25	66.91	8.27	67.42	0.691	-15.8	0.69	1.3	1.509	45.8
1425	1430	132	20.9	58.2	-11.26	59.28	0.604	-4.3	0.44	0.55	1.509	40
1415	1417	132	45	49.11	12.85	50.77	0.51	-23.8	0.69	0.22	1.509	33.8
1415	1440	132	2	-104	-51.23	116.23	1.167	144.8	0.16	0.47	1.509	77.3
1415	1418	132	50.2	57.09	-3.03	57.17	0.574	-6.1	0.96	0.91	1.509	38
1216	1215	132	32	-18.5	-10.77	21.44	0.217	147.7	0.08	-1.33	1.509	14.4
1215	1213	132	33	-40.7	11.27	42.21	0.424	-166.1	0.35	-0.45	1.509	28.1
1104	1446	132	5	22.05	7.87	23.42	0.24	-27.4	0.02	-0.19	1.509	15.9
1134	1120	132	10	40.19	6.05	40.64	0.407	-16.4	0.1	-0.17	1.143	35.6

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
2014	2005	230	70	6.37	-15.57	16.82	0.177	64.1	0.01	-13.32	5.976	3
1124	1125	132	8	-18.2	-22.68	29.05	0.292	120.5	0.04	-0.27	1.509	19.3
1214	1213	132	4	54.34	7.38	54.84	0.549	-7.3	0.07	0.05	1.509	36.4
1444	1203	132	10	50	33.18	60.01	0.625	-43.6	0.23	0.35	1.509	41.4
1475	1406	132	20	41.62	16.82	44.88	0.458	-30	0.25	-0.06	1.509	30.4
1405	1406	132	47	18.93	6.02	19.87	0.203	-25.6	0.12	-1.9	1.509	13.4
1134	1122	132	3	26.84	59.38	65.17	0.652	-73.5	0.07	0.11	1.509	43.2
1125	1126	132	21	34.13	16.08	37.72	0.377	-33.3	0.18	-0.45	1.509	25
1134	1150	132	15.8	58.49	14.16	60.18	0.602	-21.4	0.33	0.39	1.509	39.9
1444	1203	132	10	50	33.18	60.01	0.625	-43.6	0.23	0.35	1.509	41.4
1105	1107	132	4	-115	-87.5	144.59	1.46	134.7	0.49	1.58	1.509	96.8
1315	1314	132	45	-42.8	-6.99	43.35	0.453	155.5	0.53	-0.17	1.509	30
1104	1446	132	5	22.05	7.87	23.42	0.24	-27.4	0.02	-0.19	1.509	15.9
2014	2005	230	70	6.37	-15.57	16.82	0.177	64.1	0.01	-13.32	5.976	3
1124	1125	132	8	-18.2	-22.68	29.05	0.292	120.5	0.04	-0.27	1.509	19.3
1214	1213	132	4	54.34	7.38	54.84	0.549	-7.3	0.07	0.05	1.509	36.4
1444	1203	132	10	50	33.18	60.01	0.625	-43.6	0.23	0.35	1.509	41.4
1405	1475	132	27	0.62	-1.18	1.33	0.014	54.3	0	-1.35	1.509	0.9
1214	1215	132	29	54.32	-11.9	55.61	0.557	12.8	0.52	0.38	1.509	36.9
1134	1120	132	10	40.19	6.05	40.64	0.407	-16.4	0.1	-0.17	1.143	35.6
1134	1150	132	15.8	58.49	14.16	60.18	0.602	-21.4	0.33	0.39	1.509	39.9
1134	1122	132	3	26.84	59.38	65.17	0.652	-73.5	0.07	0.11	1.509	43.2
1107	1124	132	11	40.57	11.11	42.07	0.42	-23	0.11	-0.16	1.509	27.9
1307	1308	132	43.4	-49.2	0.25	49.22	0.514	168.6	0.67	0.31	1.509	34.1
1107	1103	132	5	109.7	50.25	120.64	1.206	-32.3	0.42	1.27	1.509	79.9
1006	1017	132	5	-0.73	4.82	4.88	0.049	-106.6	0	-0.25	1.509	3.3
1126	1127	132	33	27.57	3.03	27.74	0.281	-15.1	0.15	-1.12	1.509	18.6
1307	1350	132	10	26.07	-4.72	26.5	0.277	-1.4	0.04	-0.32	1.509	18.3
1307	1360	132	25	44.39	-2.19	44.45	0.464	-8.9	0.31	-0.06	1.509	30.8
1107	1124	132	11	40.57	11.11	42.07	0.42	-23	0.11	-0.16	1.509	27.9
1017	1011	132	8	59.69	19.68	62.85	0.637	-26.2	0.19	0.28	1.509	42.2
1307	1308	132	43.4	-49.2	0.25	49.22	0.514	168.6	0.67	0.31	1.509	34.1

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
1006	1005	132	16.1	-19.6	-4.14	20.02	0.203	160.1	0.04	-0.68	1.509	13.4
1417	1480	132	46	-22.8	-7.49	24.01	0.247	150.2	0.16	-1.71	1.509	16.4
1006	1018	132	6	-0.28	1.57	1.6	0.016	-108.1	0	-0.3	1.509	1.1
1006	1008	132	32.2	6.93	-9.44	11.71	0.119	45.8	0.02	-1.56	1.509	7.9
1006	1016	132	4	58.99	19.74	62.21	0.631	-26.5	0.09	0.13	1.509	41.8
1306	1307	132	45	15.14	-1.22	15.19	0.158	-6.2	0.06	-1.92	1.509	10.5
2036	2040	230	55	162.9	24.2	164.66	1.675	-11.9	1.25	-2.45	5.976	28
1126	1128	132	50	41.58	1.07	41.6	0.421	-10.3	0.51	-0.65	1.509	27.9
1006	1460	132	8	-15	-1.41	15.06	0.153	166.7	0.01	-0.37	1.509	10.1
1417	1485	132	46	39.49	2.54	39.57	0.408	-15.3	0.45	-0.61	1.509	27
1126	1150	132	30	1.73	-2.41	2.97	0.03	45.5	0	-1.52	1.509	2
1104	1109	132	16	-25.6	-12.47	28.45	0.292	146.2	0.08	-0.51	1.509	19.3
1006	1008	132	32.2	6.93	-9.44	11.71	0.119	45.8	0.02	-1.56	1.509	7.9
1306	1307	132	45	15.14	-1.22	15.19	0.158	-6.2	0.06	-1.92	1.509	10.5
1006	1018	132	6	-0.28	1.57	1.6	0.016	-108.1	0	-0.3	1.509	1.1
1006	1016	132	4	58.99	19.74	62.21	0.631	-26.5	0.09	0.13	1.509	41.8
2036	2040	230	55	162.9	24.2	164.66	1.675	-11.9	1.25	-2.45	5.976	28
1126	1128	132	50	41.58	1.07	41.6	0.421	-10.3	0.51	-0.65	1.509	27.9
1101	1160	132	12	-29.5	-1.66	29.58	0.298	170.1	0.06	-0.38	1.509	19.8
1101	1102	132	2	30.27	6.38	30.93	0.312	-18.5	0.01	-0.06	1.509	20.7
1101	1112	132	13	-49.5	1.08	49.5	0.499	174.6	0.19	0.01	1.509	33.1
2001	2002	230	23	65	39.19	75.9	0.786	-35.7	0.15	-3.53	2.988	26.3
2011	2034	230	26	49.26	9.12	50.1	0.538	-15.8	0.06	-4.32	5.976	9
1211	1212	132	36.4	34.22	-3.41	34.39	0.346	8.8	0.25	-0.96	1.509	22.9
1021	1020	132	32	-13	-18.23	22.4	0.233	116.7	0.1	-1.22	1.509	15.4
1450	1016	132	2	-18.6	-13.83	23.17	0.236	135.1	0.01	-0.08	1.509	15.6
1411	1412	132	7	-103	-10.6	103.44	1.044	170	0.59	1.36	1.28	81.6
1401	1403	132	30	43.81	-0.86	43.82	0.44	-4.5	0.34	-0.32	1.509	29.2
1211	1210	132	30	22.55	-1.2	22.58	0.227	6.1	0.09	-1.22	1.509	15
1201	1202	132	51.8	98.26	6.31	98.46	0.989	-2.5	2.94	8.06	1.509	65.5
1001	1003	132	38	32.13	5.89	32.67	0.324	-16.2	0.23	-1.14	1.509	21.5
1210	1201	132	22	33.85	-18.44	38.55	0.389	30.8	0.19	-0.44	1.509	25.8

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
1301	1302	132	1	100.4	1.37	100.4	1.011	-7.5	0.06	0.16	1.509	67
1001	1002	132	8	60.77	21.3	64.4	0.639	-25.1	0.19	0.27	1.509	42.3
1401	1412	132	55	-30.9	8.55	32.07	0.322	-170.2	0.45	-1.51	1.28	25.1
1031	1030	132	15.9	-70.1	-43.73	82.59	0.847	140.5	0.66	1.58	1.509	56.1
1101	1133	132	24	-44.8	17.25	47.96	0.484	-165.6	0.33	-0.04	1.509	32
1411	1413	132	34	33.28	-4.03	33.52	0.338	2.8	0.22	-0.92	1.509	22.4
1310	1447	132	10	32.16	19.08	37.4	0.378	-37.3	0.08	-0.2	1.509	25.1
1113	1118	132	11	80.25	21.9	83.18	0.833	-22	0.44	1.04	1.509	55.2
1401	1410	132	16	0.57	38.74	38.74	0.389	-94.8	0.14	-0.3	1.509	25.8
1410	1495	132	60	-39.4	-2.61	39.52	0.402	170.8	0.56	-1.04	1.509	26.6
1211	1210	132	30	22.55	-1.2	22.58	0.227	6.1	0.09	-1.22	1.509	15
1101	1104	132	12	89.38	45.55	100.32	1.011	-33.7	0.71	1.98	1.509	67
1101	1102	132	2	30.27	6.38	30.93	0.312	-18.5	0.01	-0.06	1.509	20.7
2011	2034	230	26	49.26	9.12	50.1	0.538	-15.8	0.06	-4.32	5.976	9
1101	1111	132	32	18.85	0.22	18.85	0.19	-7.3	0.07	-1.39	1.509	12.6
1211	1212	132	36.4	34.22	-3.41	34.39	0.346	8.8	0.25	-0.96	1.509	22.9
1201	1202	132	51.8	98.26	6.31	98.46	0.989	-2.5	2.94	8.06	1.509	65.5
1001	1003	132	38	32.13	5.89	32.67	0.324	-16.2	0.23	-1.14	1.509	21.5
2001	2002	230	23	65	39.19	75.9	0.786	-35.7	0.15	-3.53	2.988	26.3
1401	1403	132	30	43.81	-0.86	43.82	0.44	-4.5	0.34	-0.32	1.509	29.2
1211	1201	132	52	27.49	-8.97	28.92	0.291	21.2	0.25	-1.79	1.509	19.3
1021	1020	132	32	-13	-18.23	22.4	0.233	116.7	0.1	-1.22	1.509	15.4
1130	1145	132	15	102.3	19.92	104.21	1.046	-13.9	0.95	2.68	1.509	69.3
1101	1160	132	12	-29.5	-1.66	29.58	0.298	170.1	0.06	-0.38	1.509	19.8
1160	1165	132	30	8.49	-0.33	8.49	0.085	-4	0.01	-1.5	1.509	5.7
1210	1201	132	22	33.85	-18.44	38.55	0.389	30.8	0.19	-0.44	1.509	25.8
1301	1302	132	1	100.4	1.37	100.4	1.011	-7.5	0.06	0.16	1.509	67
1130	1201	132	43.4	-70.4	21.84	73.75	0.74	-165.6	1.39	2.79	1.509	49
2010	2011	230	27	221.7	105	245.27	2.549	-28	2.65	9.99	3	85
2010	2016	230	50	98.94	55.07	113.23	1.177	-31.8	0.58	-5.59	5.976	19.7
1130	1132	132	26	109.7	-13.91	110.52	1.109	4.4	1.85	5.37	1.509	73.5

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
2020	2030	230	55	-4.69	-16.74	17.39	0.178	102.2	0.01	-11.09	5.976	3
2010	2020	230	178	7.35	-24.63	25.7	0.267	70.7	0.06	-24.62	3	8.9
2030	2036	230	38	4.65	-10.27	11.28	0.115	62.2	0	-7.72	5.976	1.9
1430	1432	132	43.4	28.2	-11.96	30.63	0.313	6.1	0.12	-1.24	1.509	20.7
1310	1401	132	10	-83.3	-12.09	84.17	0.851	165.1	0.42	1.01	1.509	56.4
1310	1313	132	105	47.37	-5.72	47.71	0.483	0.3	1.86	0.27	1.28	37.7
1420	1442	132	45	-49.9	-7.28	50.38	0.517	157.1	0.69	0.23	1.509	34.2
1020	1030	132	63.5	-27.8	-8.09	28.98	0.297	155.4	0.32	-2.08	1.509	19.7
2040	2042	230	106	57	-30.9	64.83	0.67	22.1	0.33	-18.83	5.976	11.2
2050	2005	230	194	34.45	-9.46	35.73	0.369	13.7	0.21	-36.34	5.976	6.2
2010	2008	230	44.3	-101	-29.7	105.7	1.098	161	0.79	-2.16	2.936	37.4
2060	2020	230	10	120.7	13.45	121.44	1.24	-9.5	0.12	-1.18	5.976	20.7
2032	2060	230	162	-48.9	-39.91	63.1	0.665	135.2	0.43	-28.85	5.976	11.1
1032	1030	132	77	-4.61	-11.61	12.49	0.128	105.1	0.05	-3.72	1.509	8.5
1420	1425	132	41	9.6	-11.35	14.86	0.152	35.1	0.05	-1.87	1.509	10.1
1120	1123	132	13	10.49	-6.8	12.5	0.126	24.7	0.01	-0.63	1.509	8.3
1130	1133	132	20	94.19	-7.74	94.5	0.948	1.9	1.04	2.75	1.509	62.8
1320	1323	132	50	-89.1	22.52	91.92	0.962	163.1	3.59	8.08	1.28	75.1
1122	1118	132	12	0.4	25.39	25.4	0.255	-96.9	0.05	-0.45	1.509	16.9
1160	1170	132	50	12.32	2.51	12.58	0.126	-17.7	0.05	-2.37	1.509	8.4
1170	1030	132	20.2	-25.8	-17.14	30.98	0.314	139.5	0.11	-0.62	1.143	27.5
1320	1330	132	37	53.81	1.14	53.83	0.563	-32.3	0.68	0.73	1.509	37.3
1301	**1324**	**132**	**45**	**198.2**	**8.28**	**198.36**	**1.998**	**-9.1**	**5.03**	**38.35**	**1.509**	**132.4**
1130	1201	132	43.4	-70.4	21.84	73.75	0.74	-165.6	1.39	2.79	1.509	49
2010	2011	230	27	221.7	105	245.27	2.549	-28	2.65	9.99	3	85
2010	2016	230	50	98.94	55.07	113.23	1.177	-31.8	0.58	-5.59	5.976	19.7
2050	2005	230	194	34.45	-9.46	35.73	0.369	13.7	0.21	-36.34	5.976	6.2
1020	1030	132	63.5	-27.8	-8.09	28.98	0.297	155.4	0.32	-2.08	1.509	19.7
1001	1005	132	38.8	42.46	10.56	43.75	0.434	-19.7	0.43	-0.46	1.509	28.8
2020	2030	230	55	-4.69	-16.74	17.39	0.178	102.2	0.01	-11.09	5.976	3
2010	2020	230	178	7.35	-24.63	25.7	0.267	70.7	0.06	-24.62	3	8.9
2030	2036	230	38	4.65	-10.27	11.28	0.115	62.2	0	-7.72	5.976	1.9
2040	2042	230	106	57	-30.9	64.83	0.67	22.1	0.33	-18.83	5.976	11.2

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
1430	1432	132	43.4	28.2	-11.96	30.63	0.313	6.1	0.12	-1.24	1.509	20.7
1410	1411	132	40	-27.4	-1.96	27.44	0.279	170.5	0.18	-1.38	1.509	18.5
1310	1401	132	10	-83.3	-12.09	84.17	0.851	165.1	0.42	1.01	1.509	56.4
1310	1313	132	105	47.37	-5.72	47.71	0.483	0.3	1.86	0.27	1.28	37.7
1420	1442	132	45	-49.9	-7.28	50.38	0.517	157.1	0.69	0.23	1.509	34.2
1420	1425	132	41	9.6	-11.35	14.86	0.152	35.1	0.05	-1.87	1.509	10.1
1420	1421	132	38.2	54.87	11.32	56.03	0.574	-26.3	0.74	0.81	1.509	38.1
1130	1132	132	26	109.7	-13.91	110.52	1.109	4.4	1.85	5.37	1.509	73.5
1101	1145	132	40	-34.8	21.42	40.85	0.412	-155	0.4	-0.57	1.509	27.3
2010	2008	230	44.3	-101	-29.7	105.7	1.098	161	0.79	-2.16	2.936	37.4
2060	2020	230	10	120.7	13.45	121.44	1.24	-9.5	0.12	-1.18	5.976	20.7
2060	2032	230	162	49.3	11.06	50.53	0.516	-15.7	0.43	-28.85	5.976	8.6
1101	1175	132	10	10.02	5.02	11.21	0.113	-33.3	0.01	-0.48	1.509	7.5
1031	1030	132	15.9	-70.1	-43.73	82.59	0.847	140.5	0.66	1.58	1.509	56.1
1150	1127	132	20	42.94	8.3	43.74	0.442	-19.8	0.23	-0.19	1.509	29.3
2013	2014	230	26	-178	-83.96	196.4	2.105	149.5	0.91	1.41	5.976	35.2
2013	2034	230	24	76.58	22.68	79.87	0.856	-21.7	0.14	-3.4	5.976	14.3
1213	1212	132	49.2	-18.8	10.15	21.34	0.214	-151.4	0.14	-2.03	1.509	14.2
1203	1204	132	54.9	53.31	20.23	57.02	0.6	-31.3	1.17	1.76	1.509	39.8
1003	1020	132	89	13.45	4.16	14.08	0.141	-24.3	0.12	-4.09	1.509	9.4
1013	1011	132	13.5	14.33	4.62	15.06	0.153	-26.2	0.02	-0.61	1.509	10.2
1313	1315	132	64	20.37	-1.65	20.44	0.212	-8.9	0.17	-2.48	1.509	14
1413	1415	132	66	39.55	-17.85	43.39	0.44	18.8	0.72	-0.78	1.509	29.1
1403	1405	132	40	15.49	3.87	15.97	0.161	-21.3	0.08	-1.76	1.28	12.6
1403	1415	132	65	20.39	-11.82	23.57	0.238	22.8	0.2	-2.61	1.509	15.8
1203	1205	132	34	23.68	2.11	23.77	0.25	-15.6	0.12	-1.14	1.509	16.6
1003	1005	132	9	47.26	19.19	51.01	0.512	-29.3	0.14	0.04	1.509	33.9
1003	1015	132	12	62.23	16.5	64.38	0.647	-22	0.29	0.44	1.509	42.8
2043	2012	230	2	94.25	96.14	134.63	1.409	-48.7	0.04	-0.15	5.976	23.6
1013	1443	132	8	-16.4	-13.12	20.97	0.213	133	0.02	-0.33	1.509	14.1
1013	1450	132	2	-3.54	-4.16	5.46	0.056	122.1	0	-0.1	1.509	3.7
1332	1334	132	58	51.66	23.62	56.8	0.57	-31.3	0.54	1.49	1.509	37.8

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
1112	1114	132	13	16.3	4.91	17.02	0.171	-22.6	0.02	-0.59	1.509	11.3
1101	1109	132	10	66.01	34.27	74.38	0.75	-34.1	0.33	0.68	1.509	49.7
1113	1111	132	19	31.48	18.17	36.35	0.364	-36.8	0.15	-0.44	1.509	24.1
1113	1180	132	10	-3.29	-1.62	3.66	0.037	147	0	-0.52	1.509	2.4
2013	2034	230	24	76.58	22.68	79.87	0.856	-21.7	0.14	-3.4	5.976	14.3
2013	2014	230	26	-178	-83.96	196.4	2.105	149.5	0.91	1.41	5.976	35.2
1213	1212	132	49.2	-18.8	10.15	21.34	0.214	-151.4	0.14	-2.03	1.509	14.2
1203	1205	132	34	23.68	2.11	23.77	0.25	-15.6	0.12	-1.14	1.509	16.6
1003	1015	132	12	62.23	16.5	64.38	0.647	-22	0.29	0.44	1.509	42.8
1003	1005	132	9	47.26	19.19	51.01	0.512	-29.3	0.14	0.04	1.509	33.9
1013	1011	132	13.5	14.33	4.62	15.06	0.153	-26.2	0.02	-0.61	1.509	10.2
1313	1315	132	64	20.37	-1.65	20.44	0.212	-8.9	0.17	-2.48	1.509	14
1413	1415	132	66	39.55	-17.85	43.39	0.44	18.8	0.72	-0.78	1.509	29.1
1403	1415	132	65	20.39	-11.82	23.57	0.238	22.8	0.2	-2.61	1.509	15.8
1003	1020	132	89	13.45	4.16	14.08	0.141	-24.3	0.12	-4.09	1.509	9.4
1403	1405	132	40	15.49	3.87	15.97	0.161	-21.3	0.08	-1.76	1.28	12.6
1203	1204	132	54.9	53.31	20.23	57.02	0.6	-31.3	1.17	1.76	1.509	39.8
2012	2014	230	12	100.7	44.5	110.12	1.154	-27.1	0.13	-1.41	5.976	19.3
2002	2005	230	130	-19.9	-0.37	19.86	0.207	173.8	0.07	-17.67	3.984	5.2
2012	2016	230	26	120.3	65.36	136.91	1.435	-31.7	0.44	-1.93	5.976	24
1032	1021	132	45	40.06	5.75	40.47	0.413	-14.7	0.45	-0.58	1.509	27.4
1013	1016	132	4	-11.1	-9.04	14.29	0.145	132.5	0	-0.18	1.509	9.6
1302	1332	132	9	-9.45	-19.54	21.7	0.219	109	0.02	-0.37	3.429	6.4
1202	1203	132	58.9	69.25	-6.29	69.53	0.722	0.1	1.77	3.61	1.509	47.8
1102	1105	132	16	66.12	-14.9	67.78	0.684	6	0.43	0.75	1.509	45.3
1332	1333	132	4.8	13.52	7.26	15.35	0.154	-35	0.01	-0.22	1.509	10.2
1302	1305	132	22	75.25	16.84	77.11	0.777	-19.4	0.77	1.69	1.509	51.5
1412	1413	132	38	50.66	0.33	50.66	0.508	-3.6	0.57	0.11	1.509	33.6
1132	1126	132	25	71.74	-17.67	73.88	0.747	7.4	0.81	1.64	1.509	49.5
1442	1425	132	36	74.9	-1.57	74.91	0.752	-10.7	1.18	2.44	1.509	49.9
1113	1114	132	12	-36.9	33.62	49.94	0.5	-144.5	0.18	0.02	1.509	33.1
1323	1324	132	32	-120	34.92	124.79	1.286	171.9	4.09	10.38	1.509	85.2

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
1102	1105	132	16	66.12	-14.9	67.78	0.684	6	0.43	0.75	1.509	45.3
2012	2014	230	12	100.7	44.5	110.12	1.154	-27.1	0.13	-1.41	5.976	19.3
2012	2016	230	26	120.3	65.36	136.91	1.435	-31.7	0.44	-1.93	5.976	24
1122	1180	132	10	-91.2	6.66	91.46	0.919	176.3	0.49	1.26	1.509	60.9
1132	1126	132	25	71.74	-17.67	73.88	0.747	7.4	0.81	1.64	1.509	49.5
1202	1203	132	58.9	69.25	-6.29	69.53	0.722	0.1	1.77	3.61	1.509	47.8
2002	2005	230	130	-19.9	-0.37	19.86	0.207	173.8	0.07	-17.67	3.984	5.2
1302	1305	132	22	75.25	16.84	77.11	0.777	-19.4	0.77	1.69	1.509	51.5
1302	1332	132	9	-9.45	-19.54	21.7	0.219	109	0.02	-0.37	3.429	6.4
1442	1425	132	36	74.9	-1.57	74.91	0.752	-10.7	1.18	2.44	1.509	49.9
1432	1490	132	45	18.11	-7.29	19.53	0.198	3.4	0.1	-1.92	1.509	13.1
1412	1413	132	38	50.66	0.33	50.66	0.508	-3.6	0.57	0.11	1.509	33.6
1032	1021	132	45	40.06	5.75	40.47	0.413	-14.7	0.45	-0.58	1.509	27.4
1013	1015	132	12.9	-21.4	-12.07	24.6	0.25	142.3	0.05	-0.48	1.509	16.6
1332	1333	132	4.8	13.52	7.26	15.35	0.154	-35	0.01	-0.22	1.509	10.2
1032	1031	132	61	12.32	-2.11	12.5	0.128	3.2	0.06	-2.83	1.509	8.5
2008	2005	230	79	89.74	26.28	93.51	0.955	-17	0.82	-5.6	3.984	24
1018	1017	132	7	-0.28	1.88	1.9	0.019	-106.5	0	-0.35	1.509	1.3
1008	1009	132	77.2	24.83	-6.19	25.6	0.258	5.6	0.29	-2.89	1.509	17.1
2008	2036	230	143	58.64	-25.9	64.11	0.655	23.2	0.43	-26.12	5.976	11
1308	1310	132	23	-82.5	-13.89	83.64	0.862	161.5	0.99	2.43	1.509	57.1
1418	1420	132	52	30.07	-2.36	30.17	0.307	-8.2	0.28	-1.57	1.509	20.3
1018	1017	132	7	-0.28	1.88	1.9	0.019	-106.5	0	-0.35	1.509	1.3
1008	1009	132	77.2	24.83	-6.19	25.6	0.258	5.6	0.29	-2.89	1.509	17.1
2008	2036	230	143	58.64	-25.9	64.11	0.655	23.2	0.43	-26.12	5.976	11
1308	1310	132	23	-82.5	-13.89	83.64	0.862	161.5	0.99	2.43	1.509	57.1
1418	1420	132	52	30.07	-2.36	30.17	0.307	-8.2	0.28	-1.57	1.509	20.3
2008	2005	230	79	89.74	26.28	93.51	0.955	-17	0.82	-5.6	3.984	24
1105	1106	132	6	50.44	17.27	53.31	0.538	-27	0	0.1	0.686	78.5
1105	1106	132	6	50.44	17.27	53.31	0.538	-27	0	0.1	0.686	78.5
1105	1106	132	6	50.44	17.27	53.31	0.538	-27	0	0.1	0.686	78.5
1104	1108	132	3	35.06	20.15	40.44	0.415	-37.7	0	0.03	0.686	60.5

Bus From	Bus To	kV Nominal	Length	P [MW]	Q [MVAR]	S [MVA]	I [pu]	I angle [deg]	P losses [MW]	Q losses [MVAR]	Ampacity (Norm.) [pu]	Loading %
1104	1108	132	3	35.06	20.15	40.44	0.415	-37.7	0	0.03	0.686	60.5
1107	1116	132	3	64.62	30.07	71.27	0.712	-32.6	0	0.09	1.509	47.2
1107	1116	132	3	64.62	30.07	71.27	0.712	-32.6	0	0.09	1.509	47.2

BUSES OUTSIDE VOLTAGE LIMITS (100 %)						
Bus ID	**Zone**	**kV Base**	**Vmin - [pu]**	**Vmax - [pu]**	**V sol - [pu]**	**Ang sol - [deg]**
1310	z6	132	0.9	1.1	0.15	-9.2
1307	z6	132	0.9	1.1	0.4	-11.6
1308	z6	132	0.9	1.1	0.38	-12.8
1313	z6	132	0.9	1.1	0.56	50.43
1314	z6	132	0.9	1.1	0.714	-18
1315	z6	132	0.9	1.1	0.694	-22.6
1308	z6	132	0.9	1.1	0.38	-12.8
1305	z6	132	0.9	1.1	0.497	-11.9
1332	z6	132	0.9	1.1	0.527	-9.2
1130	z1	132	0.9	1.1	0.226	-8
1201	z1	132	0.9	1.1	0.705	2.5
1101	z1	132	0.9	1.1	0.521	-10.2
1030	z1	132	0.9	1.1	0.588	-11
1111	z1	132	0.9	1.1	0.508	-12.4
1113	z1	132	0.9	1.1	0.427	-10.2
1126	z1	132	0.9	1.1	0.378	-12.7
1133	z1	132	0.9	1.1	0.521	-6.6
1145	z1	132	0.9	1.1	0.411	45.1
2005	z2	230	0.9	1.1	0.457	-2.1
1401	z5	132	0.9	1.1	0.522	-7.7
1124	z1	132	0.9	1.1	0.701	-6.3
1125	z1	132	0.9	1.1	0.422	-9.2
1126	z1	132	0.9	1.1	0.622	-6.4
1127	z1	132	0.9	1.1	0.692	-5.9
1128	z1	132	0.9	1.1	0.463	-10.2
1132	z1	132	0.9	1.1	0.702	-11.2
1107	z1	132	0.9	1.1	0.822	-8.4
1103	z1	132	0.9	1.1	0.782	-7.3
1201	z1	132	0.9	1.1	0.481	-6
1210	z1	132	0.9	1.1	0.662	4.4
1202	z1	132	0.9	1.1	0.523	-11
1130	z1	132	0.9	1.1	0.648	-4.2
1133	z1	132	0.9	1.1	0.667	-9.8
1101	z1	132	0.9	1.1	0.667	-6.2
1126	z1	132	0.9	1.1	0.597	2.8
1132	z1	132	0.9	1.1	0.684	-3.9
2008	z1	230	0.9	1.1	0.009	4.7

2005	z2	230	0.9	1.1	0.575	-12.2
2010	z2	230	0.9	1.1	0.482	-7.3
1030	z1	132	0.9	1.1	0.482	-9.3
1410	z5	132	0.9	1.1	0.235	-8.2
1411	z5	132	0.9	1.1	0.439	-12.7
1403	z5	132	0.9	1.1	0.235	-6.2
1405	z5	132	0.9	1.1	0.527	-10
1413	z5	132	0.9	1.1	0.393	-11.1
1415	z5	132	0.9	1.1	0.42	-9.6
1310	z6	132	0.9	1.1	0.378	-12.8
1308	z6	132	0.9	1.1	0.45	-7.2
1360	z6	132	0.9	1.1	0.513	-19.2
1401	z6	132	0.9	1.1	0.545	-14.2
1412	z6	132	0.9	1.1	0.634	-23
1030	z2	132	0.9	1.1	0.459	-6.2
1101	z1	132	0.9	1.1	0.665	18.8
1032	z2	132	0.9	1.1	0.446	-10.7
1213	z3	132	0.9	1.1	0.646	-6.1
1111	z1	132	0.9	1.1	0.681	-11.3
1112	z1	132	0.9	1.1	0.628	-18.6
1003	z2	132	0.9	1.1	0.585	-13.7
2005	z2	230	0.9	1.1	0.007	2.2
2008	z1	230	0.9	1.1	0.621	23.4
1130	z1	132	0.9	1.1	0.66	-20.4
2012	z2	230	0.9	1.1	0.511	-5.8

COMPLETE SUMMARY REPORT		
Summary Data	**Active Power**	**Reactive Power**
Total generation	**6795.996**	**2100.249**
Spinning reserve	1307.019	
Static Load	6674.712	3337.526
Shunt loads	0	-2092.269
Motor loads	0	0
Total load	**6674.712**	**1245.257**
Line / cable losses	104.522	-376.74
Transformer losses	16.736	1231.425
Total losses	**121.258**	**854.684**
Mismatches	0.026	0.308
SUMMARY REPORT FOR ZONE: z1		
Summary Data	**Active Power**	**Reactive Power**
Total generation	**3330.996**	**1145.534**
Spinning reserve	661.699	
Static Load	2624.27	1312.216
Shunt loads	0	-792.387
Motor loads	0	0
Total load	**2624.27**	**519.829**
Line / cable losses	31.027	4.701

Transformer losses	6.393	524.196
Total losses	**37.419**	**528.897**
SUMMARY REPORT FOR ZONE: z2		
Summary Data	**Active Power**	**Reactive Power**
Total generation	**784**	**225.438**
Spinning reserve	163.972	
Static Load	1224.19	612.121
Shunt loads	0	-271.969
Motor loads	0	0
Total load	**1224.19**	**340.152**
Line / cable losses	9.879	-194.751
Transformer losses	2.869	189.026
Total losses	**12.748**	**-5.725**
SUMMARY REPORT FOR ZONE: z3		
Summary Data	**Active Power**	**Reactive Power**
Total generation	**150**	**112.576**
Spinning reserve	60	
Static Load	332.996	166.508
Shunt loads	0	-114.396
Motor loads	0	0
Total load	**332.996**	**52.112**
Line / cable losses	12.697	25.641
Transformer losses	0.819	47.445
Total losses	**13.516**	**73.086**
SUMMARY REPORT FOR ZONE: z4		
Summary Data	**Active Power**	**Reactive Power**
Total generation	**519**	**68.37**
Spinning reserve	77.04	
Static Load	351.866	175.94
Shunt loads	0	-98.358
Motor loads	0	0
Total load	**351.866**	**77.582**
Line / cable losses	2.133	-11.064
Transformer losses	0.897	66.626
Total losses	**3.03**	**55.563**
SUMMARY REPORT FOR ZONE: z5		
Summary Data	**Active Power**	**Reactive Power**
Total generation	**1055**	**269.73**
Spinning reserve	201.96	
Static Load	1129.991	565.018
Shunt loads	0	-416.777
Motor loads	0	0

Total load	**1129.991**	**148.241**
Line / cable losses	22.26	-203.08
Transformer losses	3.525	215.927
Total losses	**25.785**	**12.847**
SUMMARY REPORT FOR ZONE: z6		
Summary Data	**Active Power**	**Reactive Power**
Total generation	**957**	**278.602**
Spinning reserve	142.348	
Static Load	1011.399	505.723
Shunt loads	0	-398.382
Motor loads	0	0
Total load	**1011.399**	**107.341**
Line / cable losses	26.531	1.811
Transformer losses	2.236	188.202
Total losses	**28.767**	**190.014**