A Dynamic-Adaptive Centralized Frequency Arresting Methodology to Prevent Power System Blackout

by

Md. Arifur Kabir

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

June, 2018

The thesis titled "**A Dynamic-Adaptive Centralized Frequency Arresting Methodology to Prevent Power System Blackout**" submitted by Md. Arifur Kabir, ID No. 1014062110P, Session: October, 2014, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Science in Electrical and Electronic Engineering** on 2nd July, 2018.

BOARD OF EXAMINERS

1. ________________________________
Dr. Abdul Hasib Chowdhury — Chairman (Supervisor)
Professor
Department of Electrical and Electronic Engineering
BUET, Dhaka-1000, Bangladesh

2. ________________________________
Dr. Md. Shafiqul Islam — Member (Ex-officio)
Professor and Head
Department of Electrical and Electronic Engineering
BUET, Dhaka-1000, Bangladesh

3. ________________________________
Dr. Kazi Mujibur Rahman — Member
Professor
Department of Electrical and Electronic Engineering
BUET, Dhaka-1000, Bangladesh

4. ________________________________
Hamidur Rahman — Member
Associate Professor
Department of Electrical and Electronic Engineering
BUET, Dhaka-1000, Bangladesh

5. ________________________________
Dr. Tareq Aziz — Member (External)
Associate Professor
Department of Electrical and Electronic Engineering
Ahsanullah University of Science and Technology

Declaration

It is hereby declared that this thesis titled "A Dynamic-Adaptive Centralized Frequency Arresting Methodology to Prevent Power System Blackout" or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the Candidate

____

Md. Arifur Kabir

Acknowledgements

The author would like to express heartiest gratitude to his supervisor Dr. Abdul Hasib Chowdhury, Professor, Department of Electrical and Electronic Engineering, BUET, Dhaka, for his whole hearted support and co-operation to materialize this thesis. It is also acknowledged that without his advice, guidance and support this work would not have been possible.

Finally, I thank my parents, family and friends for their continuous inspiration towards the completion of this work.

Abstract

Several catastrophic global blackouts have occurred, including Bangladesh, in the last few years. Inefficient design of existing load shed schemes is one of the critical reasons to prevent larger blackout footprint. However, the analysis of recent blackouts suggests that voltage collapse and voltage-related problems are also important concerns in maintaining system stability. For this reason, both frequency and voltage need to be taken into account in blackout preventive load shedding schemes. In this context emergency controls that are used to prevent blackouts need to be revisited. It is difficult to prevent system blackouts entirely. However, protection and control procedures can be improved by using the emerging technologies to help reduce the geographical span of blackouts.

Conventional decentralized adaptive load shed schemes might be failed in some credible scenario because of change of demand pattern or network topology. The existing decentralized adaptive load shed scheme tries to estimate the disturbance severity and tries to shed the load accordingly but it goes without saying that the feeders under scheme are fixed and the scheme has no information about feeder load of a system. Due to the lack of enough adaptability to the operation state of the system, the successive estimation and approximation under frequency load shedding scheme will cause excessive cut or undercut problems inevitably.

A new dynamic adaptive load shedding methodology is introduced which helps to improve overall blackout protection including the tie lines security among zones with the help of phasor measurement unit (PMU). The methodology takes care of frequency and voltage stability in response of combinational disturbances of electric power system. The methodology involves measuring the power mismatch and relative disturbance magnitude with taking advantage from load damping factor as well as it decides the amount of load to be shed from each bus using the voltage sensitivities. The proposed methodology dynamically selects the feeders to shed the calculated loads from every PQ bus and any mismatch of calculated loads for a particular bus, the scheme corrects the calculated loads to the next adjacent bus in a more adaptive way, so that the total actual load shed size becomes very close to the calculated required load shed size and make the methodology based scheme more adaptive. Unlike other adaptive techniques it ensures the exact amount of load shed by selecting feeders in a dynamic manner to avoid over or under cut. The proposed methodology incorporates important real time power system stability parameters especially voltage, frequency, frequency decline rate, bus MW and Mvar during a situation where the power system would otherwise have become unstable. In the context of emerging technologies and sub-station communication standard based framework, the proposed methodology is not only limited to it but

also monitor and affirm the security of tie lines or interconnections among zones and the aim is to realize this methodology in practice.

To validate the proposed blackout mitigation methodology, it is scripted in python language and implemented on New England test system (IEEE 39 Bus) to execute in 'Digsilent PowerFactory' environment for all illustrative case studies. Comparisons of the adaptivity performance of proposed load shedding methodology based scheme with those of other decentralized adaptive schemes are also presented.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

UFLS	Under Frequency Load shedding
UVLS	Under Voltage Load shedding
LS	Load shedding
SFR	System Frequency Response
ROCOF	Rate of Change of Frequency
COI	Centre of Inertia
VSRI	Voltage Stability Risk Index
BMS	Blackout Mitigation Scheme
ANN	Artificial Neural Network
GA	Genetic Algorithm
GXP	Grid Exit Point
RES	Renewable Energy Sources
WAMCS	Wide Area Monitoring and Control Systems
PMU	Phasor Measurement Unit

CHAPTER 1

Introduction

1.1 Introduction

Load shedding is an emergency control operation. Various load shedding schemes have been used in the industry. Most of these are based on the frequency decline in the system. By considering only one factor, namely the frequency, in these schemes the results were less accurate. Although the earlier schemes were considerably successful, they lacked efficiency. They shed excessive load which was undesirable as it caused inconvenience to the customers. Improvements on these traditional schemes led to the development of load shedding techniques based on the frequency as well as the rate of change of frequency. This led to better estimates of the load to be shed thereby improving accuracy.

Recent blackouts have brought our attention to the issues of voltage stability in the system. Voltage decline can be a result of a disturbance. Its main cause, however, is insufficient supply of reactive power. This has led researchers to focus on techniques to maintain voltage stability. The loss of a generator causes an unbalance between the generated power and the load demand. This affects the frequency and voltage. Load shedding schemes must consider both these parameters while shedding load. By shedding the correct amount of load from the appropriate buses, the voltage profile at certain buses can be improved. After considering the parameters for load shedding, it is also necessary to have the suitable equipments for collecting system data so that the inputs for the shedding scheme are as accurate as the actual values. The measurement and recording equipments for analysis have undergone lots of developments. Usually, phasor measurement units (PMU) are used for measuring real time data.

The load shedding is on a priority basis, which means shedding less important loads, while expensive industrial loads are still in service. Thus the economic aspect plays an important part in load shedding schemes. Usually, a step wise approach is incorporated for any scheme. The total amount of load to be shed is divided in discrete steps which are shed as per the decline of frequency. For example, when the frequency decreases to the first pick up point a certain predefined percentage of the total load is shed. If there is a further decay in frequency and it reaches the second pickup point, another fixed percentage of the remaining load is shed. This process goes on further till the frequency increases above its lower limit.

Increasing the number of steps reduces the transients in the systems. The amount of load to be shed in each step is an important factor for the efficiency of the scheme. By reducing the load in each step the possibility of over shedding is reduced. While considering the amount of load to be shed and thestep amount, it is also important to take into account the reactive power requirements of each load. Quite often, disturbances such as a generator loss cause the voltage to decline. An effective way to restore voltage is to reduce the reactive power demand. Thus when loads absorbing a high amount of reactive power are first shed;the voltage profile can be improved.

Generally defined, the term 'frequency stability' refers to the ability of the power system to maintain steady acceptable frequency following a severe system event resulting in a large generation-load imbalance. Technically, the frequency stability is a system-wide phenomenon which primarily depends on the overall system response to the event and the availability of substantial power reserves. The sudden connection or disconnection of a large system load or generator unit can lead to system imbalance and a long-term distortion of the system. This load-generation gap is primarily protected by using the kinetic energy of rotating rotors of turbines, generators and motors [1]. If the gap remains in the system, the system frequency will change [2]. Because of time-difference frames for different systems, devising the frequency stability phenomenon is classified in two ways; one is short-term and other is long-term frequency stability. The short-term disturbance can be covered by using Load shed (LS) schemes, generator controls, and other protection devices for the first several seconds. The long term instability can be controlled by using other features, for example the prime mover energy supply for several minutes [3]. The nominal target frequency during normal operation is 50 Hz or 60 Hz. When generation (MW) and load (MW) are accurately in balance, the frequency is at nominal level. Multiple generators provide stable power to a single network and maintain the targeted frequency range. A large deviation of frequency can cause network instability, and even small deviations can undesirably affect sensitive end-use devices. The frequency deviations depend on the system topology of generation and load demand. The gap between generation and demand on a power network is the main cause of frequency deviations in the system [4]. The system frequency will decrease if supply is inadequate to meet demand; if supply exceeds demand the frequency will increase.

In large-scale integrated power systems, the mechanisms that might lead to voltage instability are to a certain extent interlinked with the rotor angle stability properties of the system, making the analysis of the instability phenomenon quite complicated [5]. Nevertheless, in the literature it is customary to distinguish between voltage and rotor angle stability phenomena. To facilitate the understanding of the various aspects of voltage instability mechanisms, the general and broad concept of 'voltage stability' is subdivided into two subcategories, namely Small and Large Disturbance Voltage Stability. These two concepts are defined as follows [6,7].

A power system is said to be small-disturbance voltage stable if it is able to maintain voltages identical or close to the steady values when subjected to small perturbations. And a power system is said to be large-disturbance voltage stable if it is able to maintain voltages identical or close to the steady values when subjected to large perturbations.

Thus, a voltage stable power system is capable of maintaining the post-fault voltages near the pre-fault values. If a power system is unable to maintain the voltage within acceptable limits, the system undergoes voltage collapse.

The importance of power system stability has been recognized at the early stage of the power system development [8]. The dimension and complexity of power systems have been gradually increasing over the years, making the power system stability phenomenon a more important and challenging problem. For instance, modern interconnected power systems are large, integrated, and have complex dynamic structures which are subject to constantly acting various (possibly overlapping) physical phenomena ranging from very fast ones such as transients due to lightening strokes to quite slow ones, such as, for instance, the dynamics of a boiler. A first step towards a better understanding of the power system stability phenomenon is to adequately define and categorize the various phenomena occurring in the power system. Normally, all power system phenomena are studied in the framework of three general structures, i.e., administrative, physical, and time-scale structures [9]. The administrative structure regulates the political organization of the power grid, i.e., it establishes the hierarchical structure of various layers of the power grid. The physical structure describes the main components of the power system, relations between them, control equipment, as well as the energy conversion principles. Finally, the time-scale structure categorizes the dynamic phenomena that occur in the power system according to the time scale of the underlying physical processes. The latter structure is arguably the most appropriate for studying the dynamics of the power system and hereby is adopted in this thesis. In general, all the phenomena can be divided in two large groups corresponding to fast and slow dynamics, depending on the time scale of the underlying physical processes triggering the mechanisms of power system instability. The concept of stability is one of the most fundamental concepts in most engineering disciplines. Due to the devastating impact that instabilities might cause in dynamical systems, numerous definitions of stability have been formulated, emphasizing its various aspects that reflect the manifestation of the system's stable state.

1.2 Motivation

Reliable and secure operation of large power systems has always been a primary goal for system operators. The new system structure following unbundling and deregulation requires very strong efforts in real-time assessing of system conditions and in the subsequent actions to protect power system [10].Technological development of industries and their growing infrastructure are stressing thepower industry to supply sufficient quality power. The generation capacity should increase inproportion to the increase of loads. Large power transfers across the gridlead to the operation of the transmission lines close to their limits. Additionally,generation reserves are minimal and often the reactive power is insufficient to satisfy theload demands. Due to these reasons power systems become more susceptible todisturbances and outages.

System frequency and bus voltage must be kept within tolerance level for a stable and reliable electrical power system. From a system stability view point both generation and demand need to be balanced. An unbalanced system can be identified by observing two important elements i.e. frequency and voltage. Frequency is considered a system-wide characteristic which is used to estimate unbalanced active power while voltage is a local feature used to determine unbalanced reactive power.

Some of the disturbances experienced by the power system are faults, loss of agenerator, tie-line and interconnection outage [11]-[13]. These disturbances vary in their intensity.At times these disturbances might cause the system to be unstable. For example, when agenerator is tripped suddenly, the system may become unstable. In general, load shedding can also be the amount of loads that must almost instantly be removed from a power system to keep the remaining portion of the system operational. This load reduction is in response to a system disturbance and consequent possible additional disturbances that result in a generation deficiency condition. As a resultit is necessary to study the system and monitor it in order to prevent it from becomingunstable. The two most important parameters to monitor are the system voltage andfrequency. Both the voltage at all the buses and the frequency must bemaintained within prescribed limits set by Grid Code to ensure that the systemremains stable. The frequency is mainly affected by the active power, while the voltage ismainly affected by the reactive power. The most load shedding schemas proposed so far used voltage and frequency parameters via under-frequency (UFLS) and under-voltage (UVLS) load shedding schemes, separately. The under-frequency and under-voltage relays are working in most of the power system without any coordination.

Specifically, the frequency is affected by the difference between the generatedpower and the load demand. This difference is caused due to disturbances which reducethe generation capacity of the system.

Due to loss of a generator, thegeneration capacity decreases while the load demand remains constant. If the othergenerators in the system are unable to supply the power needed, then the systemfrequency begins to decline. To restore the frequency within the prescribed limits a loadshedding scheme is applied to the system.In addition, the reactive power demand of the load affects the voltage magnitudeat that particular bus. Voltage stability refers to the ability of a power system to maintain steady voltages at all the buses in the system after being subjected to a disturbance from a given initial condition [14]. System blackout is the state when the system or large areas of it may completely collapse. This state is usually preceded by a sequence of cascading failure events that knock out transmission lines and generating units [15]. Voltage instability, in particular, results from the inability of the combined transmission and generation system to deliver the power requested by loads. It is a dynamic phenomenon largely drove by the load response to voltage changes. Load shedding is well known to be an effective countermeasure against voltage instability, especially when the system undergoes an initial voltage drop that is too pronounced to be corrected by generator voltages and switching on reactive power sources.

The importance of system security and stability has led to a long history of research on the load shedding topic. Because of its importance in preventing the complete collapse of the system and thereby reducing the number of customers affected by the events, hence load shedding has become an important topic of research and it has drawn attention of many researchers.

1.3 Problem Statement

As it is revealed by various studies, voltage collapse and highfrequency deviation are two primary causes of blackouts.The most load shedding schemes proposedso far used voltage and frequency parameters via under-frequency (UFLS) and under-voltage (UVLS) LS schemes, separately. The under-frequency and under-voltage load shedding schemes are working in most of the power system without any coordination.

When power system is in stable operation at normal frequency, the total mechanical power input from the prime movers to the generators is equal to the sum of all running loads, plus all real power losses in the system [16]. With a small disturbance, the frequency decay rate will be low and the turbine governor will quickly act to restore the frequency, provided the system has sufficient spinning reserve. However, if thedisturbance is large caused by generation loss, HVDC bipolar link or tie line/interconnector outage, because of the definite time response of the turbine speed-governor, spinning reserve provide little aid in short time recovery and the frequency may fall to a dangerous value for quick release of the kinetic energy before the turbine governor fully operates. The fast frequency decline, if left unattended or not arrested, will lead to system collapse [17]. As the last resort against system blackouts, UFLS schemes implemented today are mainly conventional and adaptive schemes. The former one is generally based on off-line simulation under selected scenario, shedding a predefined amount of load in case frequency and/or df/dt (ROCOF) fall below a certain threshold with a time delay[18]. The main goal of UFLS is to restore the active-power balance between generation and load by shedding proper amount of load. Though the concept of UFLS is simple, it encounters many problems when applied in power grids [19]. Although some scholars have tried to improve its flexibility [20], the possibility of excess or lack of control cannot be avoided yet. Due to the lack of enough adaptability to the operation state of the system, the traditional successive approximation under frequency load shedding method will cause excessive cut or undercut problems inevitably [21]. Most of the UFLS schemes implemented today are conventional static and semi-adaptive schemes. To date, methods for the design of these schemes consider known and constant step amounts. Step amounts might actually vary due to feeder load variation, feeder outages or breaker failures [10].

Adaptive UFLS measures the rate of change of frequency (ROCOF) to estimate the load shedding amount while knowing the system equivalent system inertia [8-9]. The idea of adaptive UFLS using the rate of frequency decline signal is already presented by some researches [8], [11], [12].Though the method is correct theoretically but cannot measure the exact power disparity. The difficulty in obtaining the accurate value of system inertia especially when the whole grid splits into several small islands reduces its practicality. After a generation outage, the parameters H_{eq}(System Inertia)and S_{eq}(Load demand) no longer remain constant and their amount of change and consequently the resulted error in the active power estimation will depend on the bulkiness of the lost generator. The assumption that feeder load variations are somehow proportional to the total demand variation is not realistic, since depending on the hour and the day, different customer types are fed by the feeders. Moreover, distributed generation such as PV can significantly alter the amount of active power flowing downwards through a feeder[22]. Besides these, in most cases ROCOF based adaptive UFLS does not consider load damping co-efficient, load variation, regional frequency response and dynamic correction of load shed amount for controlled and lesser load shed.

When a major event occurs,frequency deteriorates and tripping is initiated by the UFLSrelay when the system frequency falls below the pre-set threshold values and tripping signalsare sent to the relevant circuit breakers to trip the pre-selected feeders [23]. If UFLS scheme isnot effective and frequency continues to drop, generators will disconnect from the system andthere will be a high risk of system blackout.

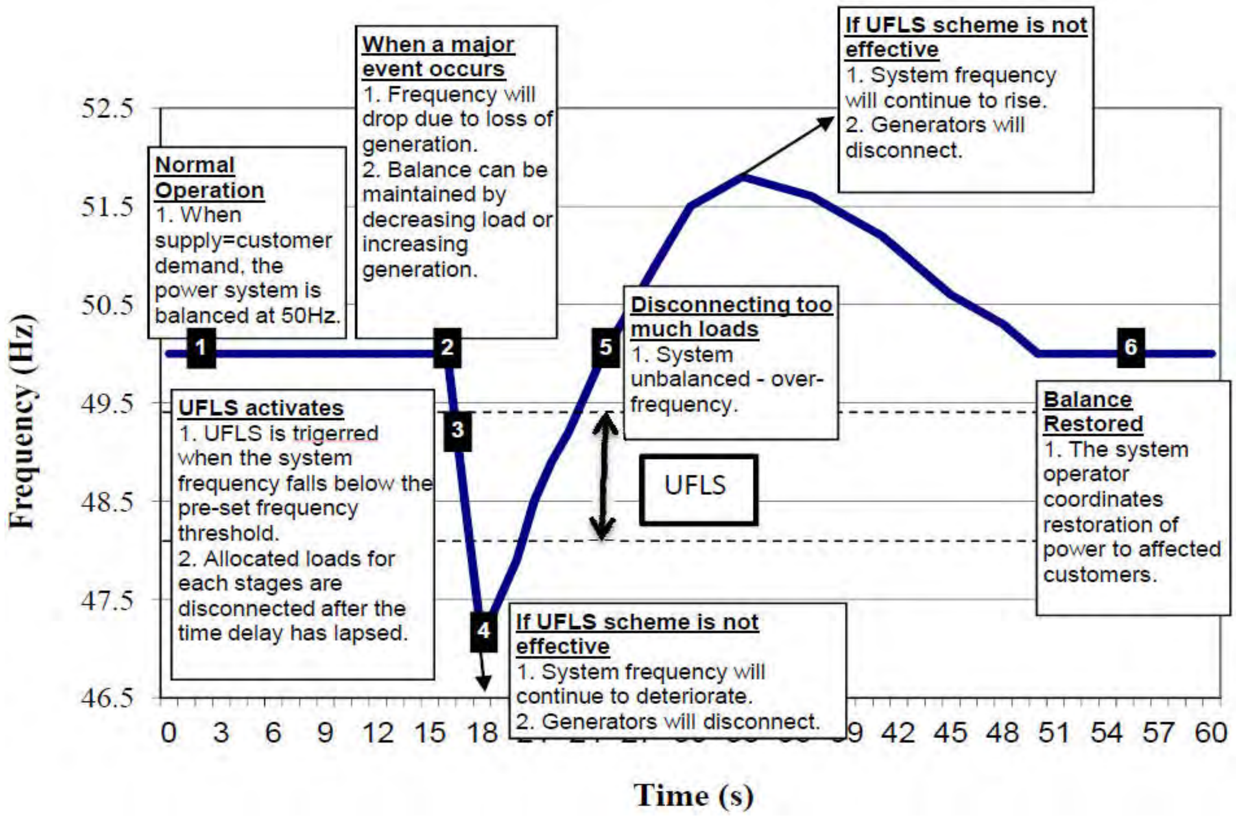

Figure 1.1: An example of frequency excursion [2]

However, if too much loads are disconnected, the system will go into over-frequencyand generators may disconnect as well. Therefore, it is an extremely involved task to design an dynamic-adaptive load shed methodology which will prevent a power system from frequency and voltage collapse.

Frequency stability and voltage stability are two main kinds of stabilities in power grids. Researchers studied the two problems independently in the past. However, few studies have been done on the relationship between these two kinds of instabilities. Moreover, coupling effects of voltage and frequency dynamic on the last line of defense in power grids have not been researched yet rigorously[24]. Some researchers find that only the system frequency response trend cannot be correctly decided only by initial active-power deficit [25]. Frequency stability and voltage stability are two main kinds of stabilities in power grids [26]. Conventionally, load-shedding schemes- under frequency load shedding (UFLS) and under voltage load shedding (UVLS), are designed independently and they constitute the last line of defense against frequency and voltage instabilities, respectively [27]. Some scholars find that the current load-shedding devices may show invalid when these two instabilities both come up [28]. Moreover, once severe contingencies occur such as generation loss or sudden tie line power outage, voltage and frequency deviations actually interact with each other owing to their coupling effects [29]. Though many literatures have reported about improvements on UFLS schemes and UVLS schemes [30-33] independently. But recently, few researches have been done on the voltage-frequency based last line of defense.

Application of centralized load-shedding algorithms toenhance adaptability of the schemes has been proposed insome references [34–35]. Wide area measurement systems (WAMS) using PMUs (Phasor Measurement Unit) are the most advanced form of monitoring as they are synchronized by a Global Positioning Satellite (GPS) system and give the operator in the control room a coherent and dynamic view of the network [36]. According to the WAMS data, the power changes of the generators and the transmission tie-lines, and the magnitude of the disturbance in a regional power grid can be obtained. However, in most cases,performance of the proposed methods in the case ofcombinational disturbances has not been analyzed.

In thisresearch work, acentralizeddynamic-adaptive load-shedding methodologyis proposed which iscapable of preventing system instability even forcombinational disturbances.In these methods, the required signalsare transmitted to the control centre and the appropriatedecision to shed load is made in this centre. Therefore areliable and fast communication link, which is currentlyavailable in most power systems, is vital in theseschemes. With the aid of communication system, there couldbe a lot of helpful information available for the controlled and lesser load-shedding.

1.4 Thesis Objectives and Possible Outcomes

The objectives of this thesis are:

i) To devise a dynamic-adaptive and centralized power system blackout protection methodology considering the system exact power discrepancy, load damping coefficient, regional frequency response, real-time feeder load variation and load bus ranking based on voltage sensitivity as local indicator to prioritize the load shedding.

ii) To develop a python scripting based test system modeling as well as a simulation framework to validate the proposed methodology at different credible scenarios and compare it with other adaptive techniques.

iii) To investigate that the proposed methodology ensures the controlled as well as comparatively lesser load shedding with taking care of voltage stability in response of combinational disturbances.

The possible outcome of this thesis work will be a robust dynamic-adaptive frequency decline arresting methodology that will ensure short-term frequency stability while taking care of voltage stabilityin response of combinational disturbances of electric power system. The proposed methodology will ensure controlled load shedding by selecting feeders dynamically irrespective of daily or seasonal load variation.

1.5 Outline of The Thesis

The main purpose of the thesis is to develop a dynamic-adaptive frequency decline arresting methodologyalong with taking care of voltage stability to preventsystem instability. The standard communication system is used in thedevelopment of the proposed scheme that could be implemented in practice. The overall thesis structure is identified as under:

Chapter 1. Introduction

In this chapter the thesis summarises the importance of frequency and voltage load shedding schemes as an emergrncy control to prevent power system blackout with a brief overview about the background research. It sets the outline of the thesis by explaining the important motivation and present problem which form the basis of the thesis. In addition, the objectives to undertake this research and possible outcomes are also clearly defined.

Chapter 2. Literature Review

This chapter is a comprehensive review of the literature related to the topics and researchobjectives. This chapter discusses the current strategies of load shed implementation procedure.Fundamental theory and operating principle practised in industries and different countries are also highlighted. This chapter also discusses the importance of power system emergency control, in particular voltage and frequency stability, which are needed to design a dynamic-adaptive load shed scheme.

Chapter 3. Proposed Dynamic-Adaptive Load Shedding Methodology

This chapter analyses, develops and providesablackout remedial methodology based on online real-time data acquisition infrastructure. This chapter is to develop and discuss a dynamic adaptive andcentralizedfrequency decline arresting methodology that will ensure frequency stability while taking care of voltage stability in response to combinational disturbances of electric power system including tie line (zonal interconnection) security. This chapter also shows how the proposed methodology ensures system stability by curtailing lesser load from different zones considering perturbation magnitudeand also provides the dynamic-adaptive load selection procedure.

Chapter 4. Test System Modeling

This chapter widely discusses the modeling of IEEE 39Bus test system. The modeling of every component of test system has been shown here. The exciter, governor, generator, transformer, transmission line and load modeling along with their static and dynamic data are also provided. Composite real-time loads are represented to calculate the frequency and voltage sensitivities of load. This chapter also shows the different zones of test system.

Chapter 5. Implementation of Proposed Methodology

This chapter demonstrates the validation of proposed methodology by implementing on IEEE 39 Bus test system. The simulation has been done by python coded power system scripting in Digsilent PowerFactory environment. Several cases are widely described by creating various worst but credible scenarios. This chapter also validates the tie line security sub-scheme of proposed methodology.

Chapter 6. Performance Comparison of Proposed Methodology

This chapter brings the superiority of proposed scheme into light compared to a widely used existing adaptive technique. Several worst but credible scenarios have been investigated where it upholds that the existing adaptive technique might be failed in some scenarios but proposed technique is not.

Chapter 7. Closure

The research outcomes are summarised in this chapter. The deliberated ideas and theories thatare employed in this thesis are highlighted. Recommendations for future work along with thelimitations of the thesis are also discussed.

CHAPTER 2

Load Shedding Methodologies

2.1 Introduction

Recently, the growing trends of electricity market provoking more stressed conditions are leading the power networks toward higher risk operational states [37]. To this end, an increase in the number of brown and blackouts is inevitable. As it is revealed by various studies, voltage collapse and high frequency deviation are two primary causes of blackouts [38]. These two phenomena are usually studied separately; however, they emerge simultaneously when a severe under frequency contingency (e.g., large generation rejection or heavy tie-line disconnection) occurs [39]. In this context, system protection schemes or remedial action schemes are accepted as effective mechanisms to detect abnormal or predetermined system conditions and mitigate potential threats in power systems [40]. Over the past decades, a broad range of system protection schemes have been designed based on local data because of limitations of communication infrastructures [41]. The main disadvantage of such local solutions is non-optimal and inadequate control actions, especially at the event of combinational disturbances. Recently, with the advent of wide-area measurement systems (WAMS), defense plans are becoming a common and optimal solution upon system-wide disturbances. Under frequency load shedding (UFLS) scheme as a particular type of system protection schemes is the last resort to stop declining frequency and to maintain security of the whole network following under frequency events. Needless to say, the main disadvantage of conventional UFLS scheme is to drop a non-optimal amount of loads encountering different contingencies [42]. In order to enhance the adaptability of conventional UFLS scheme, various methods including centralized and decentralized schemes have been suggested in the literature. The local class utilizes the derivation of bus frequency and voltage following the event [6]–[9]. For a different disturbance, these techniques change the amount and speed of load drops adaptively. Since the locations and settings of UFLS relays are acquired from offline studies,the main shortcoming of these methods is that the amount and location of load curtailments are non-optimal.

Under-frequency Load shedding (UFLS) is a common demand reduction measure taken by most energy utilities to mitigate frequency drop whenever there is dangerous imbalance between loads and generation due to disturbances to the system such as loss of generation or major transmission lines. UFLS is performed to force the perturbed system to a new equilibrium state, balancing load and generation, to minimize the risk of a further uncontrolled system separation and loss of generation and to prevent continuous frequency drop which may lead to total frequency collapse and prolonged system outage [43]. UFLS has to be well-coordinated between interconnected power systems and also with other system defense schemes such as Under-Frequency Capacitor Shedding (UFCS), Under-Frequency Generator Isolation (UFGI), Special Protection Scheme (SPS), Under-Voltage Load Shedding (UVLS) and other automatic actions that will kick in to arrest system from collapsing during abnormal frequency, voltage and/or power flow conditions [44]. For power system that has industrial and commercial customers with local generation connected to it, UFLS can detect onset of disturbance, isolate power systems by opening system ties and trip non-essential industrial loads to match total loss of generation. However, tripping these tie lines having active parallel generation reduces the beneficial impacts of load shedding because the sources of generation supporting system inertia are eliminated. Various UFLS load shedding schemes are used in the industry worldwide. UFLS can be classified into two main categories – fixed and adaptive. The fixed scheme sheds a pre-defined amount of loads when the system frequency falls below a certain threshold. Further load shedding is performed if the system frequency continues to deteriorate after activating the first stage of UFLS scheme. The total amount of load shed as a function of time is expressed as a sum of incremental step function [12]. The adaptive scheme sheds loads dynamically by taking into consideration severity of disturbances and system frequency-voltage characteristics and is proven to provide optimal amount of load shed thereby giving better frequency recovery, lower frequency overshoot and lesser frequency deviation [13]. However, simulation studies for system contingencies for three load step increments also show that the adaptive scheme only out-performs the fixed scheme for a medium amount disturbance [14].

Implementation of an integrated UFLS and UVLS scheme was proposed in [20] to keep power islands stable after power oscillations or out-of-step islanding. An interconnected grid system such as China was susceptible to large disturbances and has the tendency to go out-of-step. With the integrated scheme, a certain proportion of load would be shed when system splitting occurred whereby quantum of load shed was set according to the generation deficit of the area. UVLS would be activated if system voltage was low but frequency was high at the same time. The authors believed that this would improve the voltage profile, increase the generators' output power, and limit island frequency. Following system islanding, UFLS would be triggered when the island frequency was lower than the UFLS setting threshold whereas UVLS would work if the island voltage profile was lower than its setting value. Simulation results showed that the integrated measure could keep the island stable. In [21] and [22], the conventional non-adaptive under-frequency load-shedding scheme has been deemed inadequate to provide sufficient protection against system collapse. The authors in [23] proposed the use of three adaptive combinational load shedding methods to improve the operation of a conventional UFLS scheme to enhance power system stability following severe disturbances. Operation of the conventional and the proposed load shedding methods were simulated in an actual large network. Obtained simulation results confirmed that the proposed methods would provide considerable enhancement in the power system voltage stability margin, and by using the proposed algorithms, various power system blackouts could be prevented. Zhang and Wang proposed the use of a WAMS-based adaptive UFLS scheme using real-time online power system measurements in [24]. The scheme was proven to be capable of adapting its sensitivity to the current operating conditions thereby eliminating the need for making many assumptions necessary while tuning a conventional local scheme. In [25] a coordinated UFLS and UFCS scheme combining with automatic switching of shunt reactors was presented to optimize the performance of the existing UFLS scheme following major disturbances which resulted in large mismatch between load and generation. Fixed and switched shunt capacitors in service during normal operation for maintaining system voltage and dynamic MVAR reserve could generate surplus reactive power post operation of UFLS relays resulting in over voltage issues, generator under excitation and other undesirable conditions such as transformer saturation and ferro-resonance. UFLS scheme is a popular mitigation method used to arrest a power system from load-generation imbalance in various parts of the world such as Asia, Europe, Australasia, Africa, Middle East and the Americas. UFLS in these continents differ in terms of total load shed, number of UFLS blocks, average block amount and trip frequency deviation thresholds depending on their system amount, system inertia and generation mix.

The System Frequency Response (SFR) model has been widely used in computation of load-frequency response of a power system during system contingency. However in the classic SFR model, only inertia constant of generator and frequency information are considered and the impact of voltage dependence of loads is not taken into account although load characteristics have been proven to have significant influence on the dynamic behavior of power systems during low frequency oscillation and severe faults [26]. In more recent literature, SFR model incorporating frequency and voltage dependence load models is proposed and used in the design of optimal UFLS scheme.

UFLS operating philosophies consisting of three important areas namely trigger criteria; load characteristics and load shedding distribution have always been based solely on frequency parameters in the early days of implementation. Load shedding trigger based solely on frequency measurements is inadequate to determine the stability and “health” of a power system especially after islanding of an interconnected power system as an islanded power system following severe disturbances may experience low voltage with high frequency when an area being split from the main grid has large generation deficit [27]. The power system may be susceptible to voltage collapse as well, which will lead to total system blackout within shorter time duration as compared to a frequency collapse phenomenon. Hence, trigger condition considering voltage information and voltage stability criterions are introduced and implemented in UFLS schemes. Distribution of load shedding affects the minimum frequency deviation from nominal and steady-state frequency recovery following disturbances [28]. In the early days of UFLS implementation, fixed quantum of loads is shed at pre-determined locations based solely on system frequency information regardless of type of disturbance and all load buses are involved in sharing of total power imbalance without selection. Improvement in this area is introduced over the years to cater for combined frequency and voltage instabilities.

2.2 Literature Review

The Under-frequency Load Shedding (UFLS) scheme has been used by utility companies around the world to mitigate frequency drop caused by simultaneous or cascading tripping of transmission lines and/or generators in a power system. In the effort to devise an optimal load shedding scheme, it is imperative that investigations are done on the many factors that may affect the response of the scheme in the event of a system contingency. This paper starts by analysing the implementation of UFLS in various power utility companies in Asia, Europe, Australasia, South Africa, Middle East and the Americas. It is observed that UFLS in these continents differ in terms of total load shed, number of UFLS blocks, average block amount and trip frequency deviation thresholds depending on their system amount, system inertia and generation mix. This paper also looked at the usage of SFR models in the computation of UFLS and system parameters. Analysis on the SFR model showed that the impact of voltage dependence of loads was not taken into consideration in the early implementation of the model albeit load characteristics have significant influence on the dynamic behavior of power systems during low frequency oscillation and severe faults. SFR model incorporating frequency and voltage dependence load models was proposed later in literature and used in the design of an optimal UFLS scheme. Investigation was also conducted on UFLS operating philosophies in terms of load shedding trigger, power imbalance estimation and distribution of load shedding. UFLS operating philosophies based solely on frequency parameters is inadequate to determine the stability of a power system especially for an islanded power system following severe disturbances. The power system may be susceptible to voltage collapse as well, which will lead to total system blackout within shorter time duration as compared to a frequency collapse phenomenon. Load shedding to avoid frequency collapse is a conventional emergency approach in the power system stability area.

An automatic under frequency load shedding scheme is used by the Guam power industry [12]. It tries to minimize the load to be shed based on the severity of load unbalance and the availability of spinning reserves. It is based on the declining average system frequency. A similar scheme is incorporated between Cote d'Ivoire-Ghana-Togo-Benin [13]. It has established a five stage load shedding scheme with the first pick up frequency of 49.5 Hz (on a 50 Hz system) and the pickup frequency of the last stage is 47.7 Hz.

An intelligent adaptive load shedding scheme proposed by Haibo You et al [15] divides the system into small islands when a catastrophic disturbance strikes it. Further, an adaptive load shedding scheme is applied to it based on the rate of change of frequency decline.

Another scheme [16] uses the artificial neural networks to determine the most appropriate load shedding protection scheme. The inputs to the system are the desired probabilistic criteria concerning the system security or the amount of customer load interruptions. This scheme is an extended version of an existing sequential Monte Carlo simulation approach.

Terzia [21] talks about under frequency load shedding in two stages. During the first stage the frequency and rate of frequency changes of the system are estimated by non-recursive Newton-type algorithm. In the second algorithm, the magnitude of the disturbance is estimated using the simple generator swing equation.

In another approach Saffarianet al [22] have obtained results from an autonomous power system on the Greek Islands of Crete and the results are discussed in the paper. The method uses the Monte Carlo simulation approach for the settings of under frequency relays and selection of appropriate spinning reserve for an autonomous power system.

Another method [23] triggers the under frequency relays based on a dynamically changing intelligent load shedding scheme (ILS). The main components of this scheme are the knowledge base, disturbance list and the ILS computation engine. The knowledge base is the most important block. It is connected to the computation engine which sends trip signals to relays. The network models can be accessed by the knowledge base while monitoring the system. The knowledge base is trained and its output consists of system dynamic scenarios and frequency responses during disturbances. This trained knowledge base also monitors the system continuously for all operating conditions. The disturbance list consists of pre-specified system disturbances. Based on the inputs for the system and the continuous system updates, the knowledge base notifies the ILS engine to update its load shedding list.

The Public Service Company of New Mexico (PNM) has developed an under voltage load shedding scheme [9] to protect their system against fast and slow voltage instability. The scheme has been designed for two voltage instability scenarios. The first one is associated with the transient instability of the induction motors within the first 0-20 seconds. The second one is up to several minutes. This collapse may be caused due to the distribution regulators trying to restore voltages at the unit substation loads. According to the topology of the PNM system the Imported Contingency Load Shedding Scheme has been developed (ICLSS). This scheme uses distribution SCADA computers and consists of PLCs. The Albuquerque area system has been used for testing this method. Thirteen load shedding steps were required to correct the frequency deviation.

Terjiza presented a new approach to adaptive UFLS in [15]. In the initial stage, the frequency and the rate of frequency change were estimated using the non-recursive Newton-type algorithm and in the latter stage, the magnitude of disturbance was determined using the simplest expression of the generator swing equation. Combinational load shedding schemes gain popularity when the industry realizes the susceptibility of power systems to combinatorial frequency and voltage collapses. In [16], the authors presented two combinatorial algorithms to combine UFLS and UVLS schemes whereby locally measured frequency and voltage signals were used to determine distribution of load curtailment during severe disturbances. These methods known as V-F and dV-F load shedding schemes, were shown to increase adaptability of UFLS relay and reduce power system's susceptibility to voltage collapse by improving voltage stability margins whereby loads with lower voltage level and greater voltage decline were shed sooner. Voltage stability has become an issue in recent decades as power systems are getting more interconnected and heavily loaded [17], [18]. M. V. Suganyadevi and C. K. Babulal in [19] has defined voltage stability as "the ability of a power system to maintain steady state voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition".

The South West Power Pool, SPP, has the basic three step load shedding scheme based on under frequency relays [10]. In case the frequency decline cannot be curbed in three steps, additional shedding steps are carried out. Other actions may include opening lines, creating islands. These actions are carried out once the frequency drops below 58.7 Hz. The scheme is inherently automatic but in case it fails to achieve successful frequency restoration, manual load shedding is incorporated. As stated before, the members are required to shed loads in three steps. In the first step, 10% of the load but no more than 15% is required to be shed. In the second step 20% of the load but no more than 25% is required to be shed. The third step requires up to 30% but not more than 45% of the existing load to be shed.

Wee-Jen Lee [24] discuss about another intelligent load shedding based on microcomputers.The unique feature about this relay is the built in frequency setting and the time delay setting.Denis Lee Hau Aik, [25] suggests a method using the System Frequency Response SFR and the Under Frequency Load Shedding UFLS together to get a closed form expression of the system frequency such that the UFLS effect can be included in it. On doing this, the system and UFLS performance indicators can be calculated. Thus these indicators can be used efficiently in any further optimization techniques of SFR- UFLS model.

One such method has been discussed using the regression tree by Chang et al [26]. The regression tree is utilized to interpolate between recorded data to give an estimate of the frequency decline after a generator outage. It is a non parametric method which can select the system parameters and their relations which are most relevant to the load imbalance (due to generator outage) and the frequency decline. The case considered here is only a generator outage but this method can be applied to other forms of disturbances as well.

A Kalman filtering-based technique by A.A. Girgis et al [27] estimates frequency and its rate of change which is beneficial for load shedding. The noisy voltage measurements are used to estimate the frequency and its rate of change. A three-state extended Kalman filter in series with a linear Kalman filter is used in a two stage load shedding algorithm. The output of the three stage Kalman filter acts as the input to the linear Kalman filter. It is the second filter which identifies linear components of the frequency and its rate of change. The amount of load to be shed is calculated using the linear component of the estimated frequency deviation.

Another method uses Kalman filtering [28] to estimate the frequency and its rate of change from voltage waveforms. The buses are ranked based on their rate of change of voltage (dV/dt) values. The disturbance magnitude is calculated from the swing equation. The rate of change of frequency required for this equation is calculated using the Kalman filter. Once the total amount of load to be shed is estimated then the load to be shed from each bus is determined based on the PV analyses.

An optimization technique for load shedding [29] with distributed generation was developed. This technique converts differential equation into algebraic ones using the discretization method. Two cases are considered here; one with the distributed generation switched on to the system as a static model and the other case without the distributed generation on the grid. Both cases resulted in successful shedding of appropriate amount of load.

Li Zhang suggests a method [30] which designs under frequency relays using both the frequency and the rate of change of frequency (df/dt). The scheme has been designed for a 50 Hz Northeast China power system. Traditional schemes required only the frequency decay information. Here the rate of change of frequency is used as auxiliary information. The plots for the rate of change of frequency are oscillatory in nature. Hence a new scheme is devised in this paper which considers the integration of the rate of change of frequency (df/dt) to indicate the frequency drop. By integrating one is effectively measuring the area between two frequencies, fi-1 and fi. The schemes is made up of five load shedding steps for a 50 Hz system. These steps are from 50 to 49.2 Hz, 49.2 to 49 Hz, 49 to 48.8Hz, 48.8 to 48.6 Hz, 48.6 to 48.4 Hz. The amount of load to be shed in each step is decided by integrating the df/dt value in each step. The simulation results when compared with the old scheme with just the frequency decay show a definite improvement in system frequency due to the inclusion of rate of change of frequency (df/dt) in the new scheme.

The main idea in the paper proposed by Xiong et al [31] is the inclusion of on line load frequency regulation factors. Loads with smaller frequency regulation factors are shed first, followed by the ones with larger frequency regulation factors. The active power and load frequency relation is established in the paper.

Another scheme considering the rate of change of frequency is the adaptive load shedding algorithm in the paper by Seyedi et al [32]. Here the shedding is adapted as per the intensity of the disturbance. This intensity is determined based on the rate of change of frequency. Thus the main points observed while designing the scheme is that the speed of load shedding is increased if the rate of change of frequency (df/dt) values are high. Also, the number of load shedding steps and the amount of load to be shed in each step is increased if there is an increase in the rate of change of frequency (df/dt) values. The new method was tested on the HV network of the Khorasan province in Iran. The proposed method definitely showed improvements as compared to the conventional scheme.

Neural networks are proposed [33] to be used for an under frequency load shedding scheme. This intends to replace the conventional slow acting dynamic simulators by quick and efficient neural network engines. The general procedure is to identify the inputs for the neural networks, generations of data sets, designing NN and the evaluating the performance of neural nets. The variables used as inputs are the actual real power generation, available real power, actual load generation level prior to a disturbance, amount of the actual load being shed and the percentage of the polynomial load to be shed.

A SCADA based scheme has been proposed by Parniani et al [34]. The rate of change of frequency is useful in identifying the overload when a disturbance occurs and hence is helpful to estimate the amount of load to be shed. The SCADA based scheme overcomes the shortcomings of the previous adaptive UFLS scheme. Adding the df/dt equation for every generator, the post disturbance oscillation is obtained by SCADA. ΔPL is the disturbance magnitude in per unit. Now another variable $\Delta Pthr$ is defined. If a disturbance occurring at the weakest generator is less than this value then the absolute frequency of that generator is within the permitted limits. For a situation where the disturbance magnitude, ΔPL is less than $\Delta Pthr$ no load shedding is required. The maximum load shedding magnitude is equal to the difference between the disturbance magnitude and$\Delta Pthr$ (ΔPL - $\Delta Pthr$). The load to be shed is distributed inversely proportional to the generator inertia to make the load shedding effective.

An adaptive load shedding scheme which includes a self healing strategy is presented by Vittal et al [35]. The proposed scheme is tested on a 179 bus 20 generator test system. This self healing strategy comes into play when the system vulnerability is detected. The system then divides into self sustaining islands. After this islanding, load shedding based on the rate of change of requency is applied to the system. Due to this division, it becomes easier to restore load. A Reinforcement Learning scheme is discussed in the paper. The first is the controlled islanding which is done using the two-time scale method. It deals with the structural characteristics of the power systems and determines the interactions of the generators and their strong or weak coupling. Islanding causes two types of islands to be formed, the generation rich islands and the load rich islands. The load rich islands may have a further decline of frequency. This may result in the generator protection to trip the generators thus further declining the island's frequency. Thus a two layer load shedding strategy is employed for the load rich island. The first layer is based on the frequency decline approach. The second layer considers the rate of change of frequency. Due to the longer time delays and lower frequency thresholds for a frequency based scheme inadvertent load shedding is avoided. When the system disturbance is large and exceeds the signal threshold, the second layer comes into play. It sends a signal to discontinue the first layer of operation and continues with the load shedding based on rate of change of frequency.

Under voltage load shedding relays are set up to operate in case of low voltage conditions in the system. Disturbance affected systems may retain their stability post disturbance but still have low voltages at buses. In the following paragraphs the deficiencies in reactive power in various cases have been discussed which also may result in cases of voltage instabilities. In certain cases the voltages might be too close to the stability limits and collapse can be so fast that simple under voltage correction schemes are not effective. These low voltage conditions can be corrected by shedding appropriate amount of load from buses with the help of effective under voltage load shedding schemes. Lopes et all [36] suggest a method which carries out load shedding in case of two conditions. One, where the load shedding occurs due to a post disturbance low voltage condition and secondly, where the load shedding results due to the inability of the system to achieve a stable operating condition post disturbance. This method uses the load flow in order to decide the buses from which to shed load. The initial set of control actions are first carried out. These actions are capacitor switching, tap changing transformer and secondary voltage control.

Jianfeng et al [37] have developed a method with risk indices in order to decide which buses should be targeted for load shedding to maintain voltage stability. The buses with a high risk of voltage instability are considered first. This is estimated from the probability of a voltage collapse occurrence. The risk indices are the products of these probabilities and impact of voltage collapse.

Another method [38] dealing with the particle swarm approach for under voltage load shedding has been researched. The particle swarm Optimization concept is a group or cluster of particles in which each particle is known to have individual memory like an animal in its herd or flock. The flock is initiated with some initial velocity and the particles move in different directions to come up with the best solution. The best solution is shared with every particle of the group so that they can move from there on based on this new acquired knowledge. This same idea is used for under voltage load shedding to recognize the best possible load shedding scheme considering the system conditions and disturbance particular to that situation.

Ladhani and Rosehart [39] propose load modeling for an under voltage load shedding scheme. They also suggest offering economic incentives to customers for discontinuing the use of power during load control periods. This way the brunt of a sudden load shed is not borne by the customer alone. Also, systematic load control will lead to the stability of the system even when it is not faced with a disturbance.

There is another method for voltage control and setting up under frequency load shedding. It is proposed by Yorino et al [40] suggesting a new planning method for allocating the VAR using the FACTS devices. Here, the total economic cost for a voltage collapse along with its corrective control and load shedding are taken into account to come up with the optimum VAR planning scheme. Thus, the objective function is to minimize the cost while keeping in mind the voltage stability of the system.

Mozino [41] discusses the currently existing under voltage load shedding schemes. They are divided into two categories; decentralised and centralised. The decentralized load shedding involves setting relays at buses with loads to be shed and tripping the respective relays. The centralised scheme is more advanced. The relays are installed at the key bus locations and the information regarding which relays are to be tripped is sent to these relays from a main control centre. Thus the required load is shed from appropriate buses. Many of these schemes are referred to as “special protection” or “wide area” schemes.

The two categories mentioned above widely use as under voltage load shedding relays. These relays require logic and have to perform efficiently and accurately. Also, these relays must avoid false operation. Thus to satisfy the above requirements digital relays are being used for under voltage load shedding. Two schemes using digital relays are discussed in the paper by Mozina [41].

Single Phase UVLS Logic measures voltages on every phase. This scheme distinguishes between voltage collapse and fault induced low voltages. The voltage collapse is a balanced phenomenon, hence results in a reduction of voltage on all the three phases. Except for a three phase fault all the other faults are unbalanced. The relays trips when it identifies a voltage collapse and blocks the relay for a fault induced low voltage. Unbalanced faults usually induce negative sequence voltages which are detected and used for blocking the relay.

Positive sequence UVLS logic checks the positive sequence voltage with the set point value. Since the voltage collapse is balanced for all the three phases, the positive sequence voltage is equal to the three phase voltages. In case of a fault condition, the negative sequence voltage is utilised to block the relay.

Based on the 2004 blackout and the Voltage Assessment system for voltage instability the Hellenic Transmission System Operator (HTSO) decided to automate the load shedding process. The paper [42] two load shedding strategies are described. The first one is in Athens region and the second one is in Peloponnese area. For the first scheme in Athens, an event driven Special Protection Scheme (SPS) was set up. This scheme used the already existing protection scheme to check for overloads in the northern interconnections.

In the Peloponnese area automatic load shedding occurs when specific transmission lines trip. A manual load shedding procedure is to follow this automatic set up. At present this shedding scheme is implemented when two 150 KV lines starting from the Megalopolis area are disconnected. The manual load shedding increases the reliability of the protection system.

A load shedding scheme against long term voltage instability is proposed in the paper by Van Cutsem et al [43]. It uses distributed controllers which are delegated a transmission voltage and a group of loads to be controlled. Each controller acts in a closed loop, shedding loads that vary in magnitude based on the evaluation of its monitored voltage. Each controller acts on a set of electrically close loads and monitors the voltage V of the closest transmission bus in that area. The controller is rule based where the rules are simple if-then statements. If voltage reduces below V_{th} , then load will be shed equal to ΔP_{sh}. The controller decides to shed load based on the comparison between voltage V of that area to the threshold value V_{th} . This threshold value can be pre-decided by the operations personnel based on empirical system data.

An under frequency load shedding scheme incorporated by the Taiwan power system [17] considers various load models, for example, a single motor dynamic model, a two motor dynamic model and a composite dynamic model. This scheme calculates the dynamic D-factors, which are the coefficients of various load models depending on load frequency and voltage. A genetic algorithm load shedding scheme, called the Iterative Deepening Genetic Algorithm (IDGA) [18] sheds appropriate load at each sampling interval and minimizes the total losses of the system due to unnecessary load shedding. An Intelligent Load Shedding scheme [19] is introduced by Shokooh et al. This scheme has been installed at PT Newmont Batu Hijau, a mining plant in Indonesia. This scheme is computerized with a main server linked to PLCs distributed throughout the system. These PLCs notify the ILS server in case of disturbances anywhere in the system. Another method applied to the Northern Chilean system for testing purposes [20], considers optimizing the economic dispatch problem, fast spinning reserves and load shedding when a generator loss occurs in the system. This scheme uses the Bender's Decomposition Algorithm. It also considers the cost analysis of the system considering the load shedding cost and the spinning reserve cost. Most of the schemes used for Load shedding use two methods. Under frequency load shedding and under voltage load shedding.

There are different types of UFLS scheme comprising traditional, semi-adaptive, and adaptive [29, 30]. The traditional load shedding is often employed among the others, due to its simplicity in manufacturing of relays [41]. The traditional scheme curtails a specific amount of load when the frequency declines below a predetermined threshold. If this amount of load shed is enough, the frequency will become stable due to load-frequency control capability of generators, otherwise the frequency continuously declines slower than before. When the frequency crosses the next threshold, the next load shed stage is executed. This procedure is going on until the frequency drop is stopped or all the relevant relays to load shedding have acted [45]. The thresholds and the relevant amount of load shed are determined off-line, based on practical experiences and numerical simulations. Generally conservative settings are applied in traditional load shedding method due to the unknown scale of the disturbance [46]. Although this scheme is efficient during small disturbances, it cannot differentiate between the normal and abnormal oscillations. For example, in this scheme, the frequency fall due to a generator outage is treated same as frequency drop of a normal wind speed oscillation in a wind turbine. Therefore, it sheds relatively lesser loads at large disturbances, which generally cannot be seen as a comprehensive solution for widespread range of disturbances. In the traditional UFLS, the load shedding places are already determined independent of disturbance location. As, the load curtailment is not carried out necessarily at the areas with active or reactive power shortage, the risk of tie line over loading and voltage instability issues exists following an improper load shedding [35]. Load curtailment at locations with relatively lower voltage and hence greater reactive power requirement, will improve voltage stability of the overall system and consequently aid the system to retrieve its stability following a serious combinational event. In [47] a hierarchical genetic algorithm (GA) based technique was proposed to calculate the Under Frequency Load Shedding (UFLS) relay settings. The time delays and number of stages were considered as dependent and independent variables, respectively [47]. In [48], the fuzzy load model and the first fit heuristic were employed to calculate the relay settings. The load shed amount determined based on a closed form of voltage changes gradient in [49]. Selecting of demonstrative operation and incident scenarios was considered in layout of 81L UFLS relays in [50]. Several scenarios considering the intermittent nature of renewable energies and different outages were considered in calculation of shed load at each stage by taking into account of each scenario probability in [42].

The semi-adaptive load shedding scheme utilizes the frequency drop rate as an indicator of the active power shortcoming [4]. The amount of load shed is proportional to ROCOF when the frequency arrives to a specific threshold. Hence, this algorithm measures the ROCOF just after the threshold is crossed. Generally, the ROCOF value is employed only once at the first frequency threshold, the rest are treated as traditional scheme. The ROCOF thresholds and the amount of load shed at each stage are determined off-line based on simulation and experience. The scheme is adapted to the disturbance magnitude due to proportionality of load shed amount to the ROCOF. In adaptive load shedding the active power shortage can be estimated based on measured initial ROCOF, just after power imbalance occurred. The system generators do not decelerate at a same rate. Therefore, the frequency is not unique throughout the entire power system at least for first several cycles. To achieve the average frequency of the whole system, the Center of Inertia (COI) technique is used to get more accurate estimation [44, 51]. Moreover, it seems vital since the locally measured frequency does not contain precise information of system just after incident. Adaptive aspect of UFLS has been presented to enhance the performance of traditional load shedding methods in [46, 52–54]. All of these methods calculate the active power shortcoming, following an incident, based on the equivalent system model presented in [52]. However, only frequency data is employed in the load shedding strategy. By taking into account voltage dependency of loads and exploiting this fact in estimating active power deficit, the scheme was improved to some extent [36, 44]. Load characteristic dependency to voltage and frequency has been taken into account in [54] in order to anticipate the frequency decline after an event. Coordination of frequency and ROCOF in UFLS method has been employed under a self-healing strategy in [46].

The active power shortage can be estimated based on measured initial ROCOF, just after power imbalance occurred. The system generators do not decelerate at a same rate. Therefore, the frequency is not unique throughout the entire power system at least for first several cycles. To achieve the average frequency of the whole system, the Center of Inertia (COI) technique is used to get more accurate estimation [44, 51]. Moreover, it seems vital since the locally measured frequency does not contain precise information of system just after incident. Adaptive aspect of UFLS has been presented to enhance the performance of traditional load shedding methods in [46, 52–54]. All of these methods calculate the active power shortcoming, following an incident, based on the equivalent system model presented in [52]. However, only frequency data is employed in the load shedding strategy.

The adaptive schemes in [52, 53, 55] are based on using the initial frequency gradient following an event to determine the active power shortage in the power system. In the above research studies, the voltage information was not directly involved in load shedding application. A precise evaluation demonstrates that the total load shedding in the system is solely determined based on the frequency stability. The references [51, 55] equipped the adaptive load shedding scheme with the capability of determining the load shedding distribution using pre-fault V-Q sensitivity factors or voltage magnitude. The stability problem is the concern of all aforementioned methods in adaptive UFLS. However, in reference [56], it has been stated that occurrence of a severe contingency, in a highly stressed power system, may also lead it to the voltage instability. The UVLS scheme is triggered after load bus voltages fall down below a specific threshold. Practically, a voltage amplitude based UVLS plan is not secure enough versus voltage instability resulting from a severe event [51]. Ideally, a self-healing strategy should guarantee both voltage and frequency stability, following an event. Different indexes have been reported for voltage instability in [57–59]. These indexes need to on-line calculation of either the network admittance matrix [57,58] or a Thevenin equivalent of the power system [59] to predict voltage collapse. A Voltage Stability Risk Index (VSRI) which has been proposed in [37, 51], addresses the voltage instability by employing the time series data of bus voltages to determine the vulnerability of the power system at each bus after a contingency. Therefore, this scheme can be implemented by PMUs to evaluate the transient voltage stability of the power system. The main effort of [51] is to drive the control actions considering the voltage dynamic changes regardless of disturbance. The work carried out in [37] advocates of exploiting the reactive power together with active power directly in the load shedding process. This approach deals with the coordination of voltage and frequency information instead of independent methods.

In [47] a hierarchical genetic algorithm (GA) based technique was proposed to calculate the Under Frequency Load Shedding (UFLS) relay settings. The time delays and the number of stages were considered as dependent and independent variables, respectively [47]. In [48], the fuzzy load model and the first fit heuristic was employed to calculate the relay settings. Different LS methods including a fixed maximal load to shed and proportionality of shed load to the ROCOF were investigated in [49]. Calculation of UFLS relay setting based on Monte-Carlo simulation method for autonomous power systems were carried out in [50]. The main effort of [51] was focused on dynamically adjustment of the UFLS relay parameters using the frequency and ROCOF information, whereas the adaptive LS with even load shed at each stage may cause long-term transients. The authors in [52] have suggested the tuning of relay parameters according to practical conditions using an Artificial Neural Network (ANN). It should be noted that the scheme with only one stage of LS may result a serious overshoot frequency. The work reported in [53] utilizes ANNs to directly evaluate the parameters of most effective LS scheme considering system stability. There is the risk of over LS in case of following the single objective of maximum lowest frequency. The work carried out in [54] addresses the estimation of frequency and ROCOF using a non recursive Newton type procedure and in the next step, determination of the disturbance magnitude, whereas for estimation of the disturbance magnitude inertia constants should be known. Additionally, the minimization of total amount of shed load was not considered in [55–56]. The paper [57] developed an intelligent LS algorithm for scheduled islanding, accompanied by an algorithm for grid reconnection. That work also tried to determine the load shed amount based on a closed form of voltage changes gradient. Selection ofdemonstrative operation and incident scenarios was considered in layout of 81L UFLS relays in [58]. Large power systems, to some extent, deal with similar daily pattern of load, whereas microgrids experience significantly different scenarios due to intermittent behavior of renewable energies and this fact was not considered for traditional relays in [47,48,60,61], and adaptive relays in [59]. The schemes with single objective of minimal shed load [50] may lead to a significant undershoot in frequency. Reference [60] advocates calculation of load shed at each stage of under frequency relay (81L) in a stand-alone micro grid based on historical meteorological data and the Markov two-state model. Furthermore, the load shed is minimized and the lowest swing frequency is maximized using the genetic algorithm.

2.3 Load Shedding Fundamentals

The frequency stability and the voltage stability have attracted much attention due to worldwide blackouts [61-63]. The UFLS (under-frequency load shedding) and the UVLS (under-voltage load shedding), as the last defense line for guaranteeing the security and the stability of the power system, are widely studied in recent years [64].

Under frequency load shedding (UFLS) is a very important approach to prevent frequency decline. It should have capability not only to shed load under different operating conditions when local systems are connected to the main systems, but also capable to maintain the frequency stability when local systems are islands[65-66]. The frequency decline, caused by the power imbalance between generation and demand is considered as a serious problem. It may cause damage to the turbine blades, this in turn causes failures to plant because at low frequency (10 to 15% below normal) their auxiliary are not able to maintain normal output [67-69]. The primary method to bring back to the nominal frequency level is, to shed some amount of load. In power system protection scheme, the frequencies are widely used as a setting in UFLS design. Under frequency load shedding must be performed quickly to arrest power system frequency decline by decreasing power system load, to match available generating capacity [70]. The objective of an under-frequency load shedding scheme is to quickly recognize generation deficiency within any system and automatically shed a minimum amount of load [71]. At the same time provide a quick, smooth and safe transition of the system from the emergency situation to post emergency condition such that a generation-load balance is achieved and nominal system frequency is restored.

Frequency stability and voltage stability are two main kinds of stabilities in power grids [72-73]. Conventionally, load shedding schemes under frequency load shedding and under voltage load shedding are designed independently and they constitute the last line of defense against frequency and voltage instabilities, respectively [74]. Some scholars find that the current load-shedding devices may show invalid when these two instabilities both come up [3-4]. Moreover, once severe contingencies occur such as receiving end power grids disconnected from the main system, voltage and frequency deviations actually interact with each other owing to their coupling effects [75]. Though many literatures have reported about improvements on UFLS schemes and UVLS schemes[76-79], few researchers have been done on the voltage-frequency coupling and their effects on the traditional last line of defense. This paper theoretically analyses the significance of voltage-frequency coupling effects in view of system closed-up response diagram, and then simulation results based on typical test system validate the existence of the coupling and its significant effect on system response. Moreover, two dominant factors influencing the coupling effect are summarized and their influence is analyzed. Secondly, the effect of voltage-frequency coupling on the traditional last line of defense in power grids was researched. It is found that traditional protection schemes would fail to arrest system collapse when the coupling effect becomes strong.

.

When dealing with load-shedding, several items must be taken into account. The most important of them are [76] the definition of a minimum allowable frequency for secure system operation, the amount of load to be shed, the different frequency thresholds, the number and the amount of steps. The minimum allowable frequency is imposed by the limitations of ‘operation of system equipment. Specifically, the elements that are more sensitive to frequency drops are generators, auxiliary services and steam turbines [77]. Generators can operate at speeds much lower than steady state one, provided their MVA output is reduced. Power plant auxiliary services are more demanding than generators in terms of minimum allowable frequency: in fact, they begin to malfunction at a flequency of 57 Hz (47.5 Hz), while the situation becomes critical at 55-57 Hz (about 46-48 Hz). In that case, there is a cascade effect: the asynchronous motors of the auxiliary services are disconnected by their protections, Anyway, the steam turbine is the equipment more sensitive to frequency drops. Turbine natural frequencies are kept by design - far from the nominal speed, so that they are not likely to operate in a situation of resonance, which could destroy the turbine or cause a reduction of its life. It is safe to avoid that the frequency falls below 57 Hz (47.5 Hz): in fact, every commercial turbine can sustain up to 10 contingencies at 57 Hz (47.5 Hz) for one second without being jeopardized [60]. The economical limitations in the amount of spinning reserve, regulation and the intrinsic technical limits of some plants in terms of their ramping capability call for immediate remedial actions based on load shedding. The main features that a load shedding scheme must provide are [61]

l) The action has to be quick, so that the frequency drop is halted before a situation of danger has occurred. Unnecessary actions have to be avoided.

2) The protection system has to be liable and redundant, as a malfunction of it would surely lead to a major failure of the whole system.

3) The amount of load to be shed should always be the minimum possible, but anyway sufficient to restore the security of the grid and to avoid the minimum allowable frequency being exceeded.

The most intuitive method for checking the level of danger is measuring the average frequency of the grid: when the frequency falls below certain thresholds it is possible to obtain an indication on the risk for the system and consequently to shed a certain amount of load, The two main reasons for improving this simple scheme are that, if the disturbance is very large, the consequent frequency transient will be very quick, For load-shedding to be effective, it is wise to recognize the emergency situation as quickly as possible, On the other side, in case of small disturbances, the methodologies based only on frequency thresholds may result in an excessive amount of load shed[62]. For the two above reasons it is advisable to consider a new element of diagnosis, which is the derivative of the frequency (df/dt) or Rate of change of Frequency (ROCOF). This value has the meaning of speed at which the frequentcy is declining. By measuring the speed at which a certain frequency threshold is reached it is possible to estimate the danger of the current contingency and so to provide different load-shedding alternatives depending on the value of df/dt. Moreover, by knowing the initial value of df/dt (that is to say its value when the frequency begins to decline soon after a contingency) it is possible to estimate the disturbance and so to provide an adequate load-shedding.

Application of centralized load-shedding algorithms to enhance adaptability of the schemes has been proposed in some references [62]. However, in most cases, performance of the proposed methods in the case of combinational disturbances has not been analysed. In this research work, the main objective is to propose some centralised adaptive load-shedding algorithms which are capable of preventing system instability even for combinational disturbances. One of the important features of the proposed methods is their centralised nature. In these methods, the required signals are transmitted to the control centre and the appropriate decision to shed load is made in this centre. Therefore a reliable and fast communication link, which is currently available in most power systems, is vital in these schemes. With the aid of communication system, there could be a lot of helpful information available for the load-shedding system. Using this information, the load-shedding method would be capable of adaptively selecting frequency settings, time-delay settings as well as the amount and location of loads to be shed. Since dependence of loads upon voltage and frequency could prevent operation of UFLS relays, modeling these dependencies is important. In this research work, these dependencies have been considered using appropriate load models. Performances of the proposed load-shedding algorithms are analyzed using the simulated model of a real power system. The results of simulations confirm that using these algorithms various power system blackouts may be prevented.

2.3.1 Combinational Disturbances

An electric power system is a large interconnected system that produces, transmits and distributes electric energy to different consumers. Stability of the power system is of agreat concern, since it is subjected to different disturbances that may cause a local or complete system collapse if no adequate action is taken to prevent it. Therefore, many techniques have been developed to make the power system survive during disturbances and continue to operate [64]. One common disturbance is the imbalance between generation and load due to an overload situation caused by generator outage or loss of transmission lines. Power systems are forced to operate at ever-smaller reserve capacity and stability margins because of the demands of deregulated electricity markets. As a result, several blackouts have occurred in the recent years because of the system voltage and frequency instabilities. Consequently, improvement of the power system protection schemes has become a matter of serious concern for security of the electric utilities [63, 64]. Load shedding is a last-resort and effective tool to preserve the system stability when large disturbances such as major generation outages or important power transmission line outages occur in the system. Automatic load shedding in power systems is usually implemented using two independent under-frequency load shedding (UFLS) and under-voltage load-shedding (UVLS) schemes [65, 66]. One of the major weaknesses of the conventional load shedding methods is that in many cases they fail to protect the system against combinational disturbances. In such events, a combination of the disturbances causing frequency drop (such as major generation outages) and the disturbances causing severe voltage declines (such as transmission line outages) occurs. These cascading disturbances may happen because of power system faults and protection system malfunctions, and may eventually lead to system collapse through a frequency/voltage instability process. The conventional load-shedding schemes may fail to operate correctly following such events in two ways:

1. For such events, severe voltage declines at the load buses can decrease the active power consumption of the voltage dependent loads. As a result, the rate of frequency declineis decreased or even the frequency returns back towards its nominal value, while the system is prone to catastrophic failure because of voltage instability. In this situation the UFLS process is violated and a less than required amount of load is shed unexpectedly and/or the load-sheddingprocess is delayed. Examples of this phenomenon have been observed in Italy and North America blackouts [67].

2. Sometimes the combinational disturbances jeopardize the frequency and voltage stability of the system simultaneously. Depending on the location of disturbance, the voltage stability margin decreases in some areas of the system. However, in the conventional UFLS schemes the load shedding is performed from fixed pre-defined locations regardless of the disturbance location and the system condition. As a result, the voltage stability margin of the affected areas is not improved or even is deteriorated because of increased loading of some power transmission lines. This deficiency may eventually lead to power system voltage instability following a combinational disturbance.

2.3.2 Load Shedding Theory

A power system is subjected to a variety of disturbances such as small and large perturbations. A large disturbance could happen because of a major fault, loss of large generator units, loss of transmission major facilities or a significant increase of load. The stability problem associated with large perturbations is known as transient stability [69]. A power system may dynamically lose stability and cause catastrophic collapse of the whole system following contingencies. During transient instability events, the total power system mismatch can be calculated from total generated power and load power described as follows [70]:

$$\Delta P = \sum_{i=1}^{N} \Delta P_i = \frac{2\sum_{i=1}^{N} H_i}{f_n} \frac{df_c}{dt} = \xi \frac{df_c}{dt} \tag{2.1}$$

Where, $H_i$is the system equivalent inertia and

$$f_c = \sum_{i=1}^{N} H_i f_i \Big/ \sum_{i=1}^{N} H_i \text{ ,and } \xi = \frac{2}{f_n} \sum_{i=1}^{N} H_i \tag{2.2}$$

The frequency of the equivalent inertial center ($f\,c$) and constant ξ might be calculated in advance [14]. If all the generators are maintaining the same frequency $f_n$then $f_c = f_n$.

The total amount of load is ΔP that needs to be shed to maintain the system nominal frequency. The deviation of the system frequency (Δf) for dynamic frequency analysis is developed in [77] can be expressed as:

$$\Delta f = \frac{\Delta P}{D}\left(1 - e^{\frac{-Dt}{2H}}\right) \tag{2.3}$$

Where ΔP is per unit system load-generation imbalance discussed above, the total system equivalent inertia H , and equivalent load damping coefficient D is defined in [71] as follows:

$$H = \sum_{i=1}^{N} H_i \quad , \quad D = \sum_{i=1}^{N} D_i \tag{2.4}$$

Hence, the initial rate of change of frequency is defined in reference [72] as follows:

$$\frac{df}{dt} = \frac{\Delta P}{2H} \tag{2.5}$$

Where,

df/dt is the rate of change of frequency in Hz/s.

The frequency decay depends on two factors: the magnitude of overload ΔP , and the equivalent inertia H and system damping constant D. If the imbalance power decreases as the frequency decreases the final frequency described in [77] can be derived as follows:

$$f(t) = f_0\left(1+\frac{\Delta P}{D}\left(1-e^{\frac{-Dt}{2H}}\right)\right) \tag{2.6}$$

Where $f$is final the frequency, and $f_0$is the nominal frequency.

2.3.3 Load Shedding Operating Principle

In current practice, automatic LS schemes are widely used within the transmission network [5]. In the AUFLS relay is used either at the Grid Exit Point (GXP) or at the zone substation level. The substation level LS can be employed based on several principles. It is also possible to shed the load to prevent the system from blackout. This scheme is executed at the substation level and activated by a pre-setting criterion as outlined in the remedial action plan.

The LS decisions in the scheme described above are made by monitoring the frequency change over periods of several hundred milliseconds. Most system operators use the fixed frequency setting elements to define the time delay for the LS scheme. The relay operates if the frequency drops below the set value. Time delay used in this LS scheme should be sufficient to dominate any transient dip in frequency. Excessive time delay on the other hand may jeopardize system stability. The typical time delay settings vary between fractions of second to a second. For a large disturbance, where a rapid decline of system frequency is expected, the LS scheme should be improved by the frequency decay elements. The use of ROCOF elements for under-frequency LS schemes is unusual in practice and the majority of systems rely on under-frequency triggering elements. In general, the ROCOF relay is used for generator unit islanding protection.

It is very necessary to understand the rotor dynamics of machines to understand the load-frequency control of a system.

2.3.4 Rotor dynamics

Let us consider a three-phase synchronous alternator that is driven by a prime mover. The equation of motion of the machine rotor is given by [2.7].

$$J\frac{d^2\delta}{dt^2} = T_m - T_e = T_a \tag{2.7}$$

Where,

J is the total moment of inertia of the rotor mass in kg-m^2

T_m is the mechanical torque supplied by the prime mover in N-m

T_e is the electrical torque output of the alternator in N-m

$\delta$is the angular position of the rotor in radian

Neglecting the losses, the difference between the mechanical and electrical torque gives the net accelerating torque Ta. In the steady state, the electrical torque is equal to the mechanical torque, and hence the accelerating power will be zero. During this period the rotor will move at synchronous speed $\acute{\omega}_s$ in rad/s.The angular position Θ is measured with a stationary reference frame. To represent it with respect to the synchronously rotating frame, we define

$$\theta = \omega_s t + \delta \tag{2.8}$$

where δ is the angular position in rad with respect to the synchronously rotating reference frame. Taking the time derivative of the above equation we get

$$\frac{d\theta}{dt} = \omega_s + \frac{d\delta}{dt} \tag{2.9}$$

Defining the angular speed of the rotor as

$$\omega_r = \frac{d\theta}{dt} \tag{2.10}$$

We can write (2.13) as

$$\omega_r - \omega_s = \frac{d\delta}{dt} \tag{2.11}$$

We can therefore conclude that the rotor angular speed is equal to the synchronous speed only when *dδ/dt* is equal to zero. We can therefore term *dδ/dt* as the error in speed. Taking derivative of (2.15), we can then rewrite (2.16) as

$$J\frac{d^2\delta}{dt^2} = T_m - T_e = T_a \tag{2.12}$$

Multiplying both side of (2.16) by $\acute{\omega}_r$we get

$$J\omega_r\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \tag{2.13}$$

Where,

P_m, $P_e$and $P_a$respectively are the mechanical, electrical and accelerating power in MW.

We now define a normalized inertia constant as

$$H = \frac{Storedkineticenergyatsynchronousspeedinmega-jouls}{GeneratorMVArating} = \frac{J\omega_s^2}{2S_{rated}} \quad (2.14)$$

Substituting (12) in (10) we get

$$2H\frac{S_{rated}}{\omega_s^2}\omega_r\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \quad (2.15)$$

In steady state, the machine angular speed is equal to the synchronous speed and hence we can replace **ώr**in the above equation by ώ*s*. Note that in (13) P_m, $P_e$and $P_a$are given in MW. Therefore dividing them by the generator MVA rating *Srated* we can get these quantities in per unit. Hence dividing both sides of (13) by *Srated* we get

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_m - P_e = P_a \text{ per unit} \quad (2.16)$$

Equation (2.16) describes the behaviour of the rotor dynamics and hence is known as the swing equation. The angle δ is the angle of the internal emf of the generator and it dictates the amount of power that can be transferred. This angle is therefore called the "load angle". For a power system with NG generators, the swing equation of the ith generator can be formulated as follows [59]:

$$\frac{2H_i}{f_0}\cdot\frac{df_i}{dt} = P_{m_i} - P_{e_i} \qquad (i= 1,2,3\ldots) \quad (2.17)$$

Where,

H_i is the inertia time constant of the ith generator

P_{mi} is the mechanical power of the ith generator

P_{ei} is the electromagnetic power of the ith generator

f_0 is the rated frequency of the system

Thus, the total active power deficiency can be obtained as

$$\sum\left(\frac{2H_i}{f_0}\cdot\frac{df_i}{dt}\right) = \sum_{i=1}^{N_G}\left(P_{m_i} - P_{e_i}\right) \quad (2.18)$$

Rearranging (5) yields,

$$\frac{2\sum_{i=1}^{N_G}\left(H_i \frac{df_i}{dt}\right)}{f_0} = \sum_{i=1}^{N_G} P_{m_i} - \sum_{i=1}^{N_G} P_{e_i} = P_M - P_g \tag{2.19}$$

Where,

$P_M = \sum_{i=1}^{N_G} P_{m_i}$ ical Power

$P_g = \sum_{i=1}^{N_G} P_{e_i}$ is the total electromagnetic power

Equation (2.19) can be simplified as

$$\frac{2}{f_0}\frac{d}{dt}\left[\sum_{i=1}^{N_G}(H_i f_i)\right] = P_M - P_g \tag{2.20}$$

Substituting $H = \sum_{i=1}^{NG}(\mathrm{Hi})$ into (5) yields:

$$\frac{2H}{f_0}\cdot\frac{df}{dt} = P_M - P_g \tag{2.21}$$

Where,

$f_0 = \frac{\sum_{i=1}^{N_G}(H_i f_i)}{H}$ frequency of the system.

$H = \sum_{i=1}^{N_G} H_i$ ertia time constant of the equivalent system generator.

Hence, the swing equation of the equivalent system generator can be described as

$$\frac{df}{dt} = \frac{f_0}{2H}\Delta P_S \tag{2.22}$$

Where,

$\Delta P_S = P_M - P_g$ total active power imbalance in the system.

2.4 Power Balance

A transmission line is mainly inductive and its active power transfer is given by

$$P = \frac{V_1 V_2}{X_L}\cdot\sin\theta \tag{2.23}$$

where $V1$ and $V2$ [V]are the end voltage magnitudes, XL [Ω] the line reactance and θ [rad] the angle difference between $V1$ and $V2$.

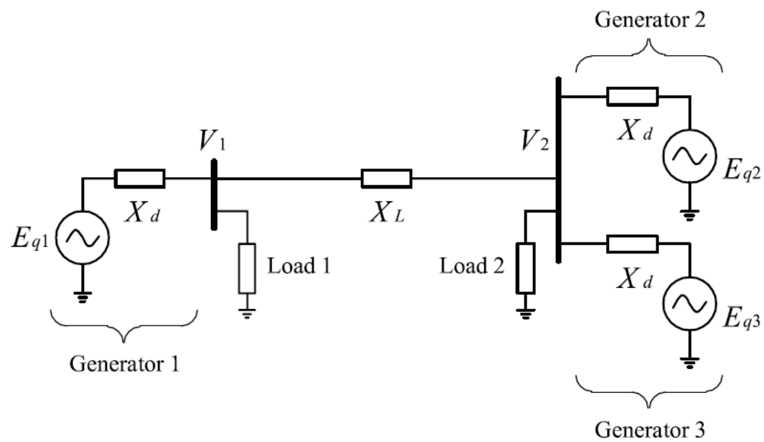

Figure 2.1: A simple power system

If generator 3 in Figure 2.1 is suddenly disconnected the angles of $V1$ and $V2$ will change rapidly as the power transfer over the line reactance $X_L$changes. The same expression as in (2.1) holds for a synchronous generator when ignoring saliency. $\boldsymbol{\delta}$is then the angle difference between the induced voltage Eq and the terminal voltage V.

$$P_e = \frac{E_q V}{X_d} \cdot \sin\delta \tag{2.24}$$

As the rotor in the generator has inertia, the angle of the induced voltage $Eq1$ cannot change rapidly. Hence, a reduced $V1$ angle (associated with e.g. loss of generator 3) implies an increased output power from the generator. The turbine governor cannot increase the input power instantaneously, hence the additional power has to be extracted from the kinetic energy stored in the rotor. The rotor speed decreases and so does the electrical frequency as well due to the strong connection between mechanical and electrical frequency in the synchronous generator. The mechanical system is described by

$$J\omega_{nom}\frac{d\omega}{dt} = P_{mech} - P_{el} \tag{2.25}$$

Which implies that a difference between mechanical power (P_{mech}) and electrical power (P_{el}) gives a change in speed. $J$is the rotor inertia and ω the rotor speed. If the electrical load Pel power is increased without increasing the mechanical power $P_{mech}$from the turbine a power unbalance arises and the speed of the generator decreases. Likewise, for the case with higher mechanical than electrical power, the rotational speed increases. An electrical frequency change (df/dt) is a measure of a power imbalance in the system. For a single generator, *J*may be replaced by an inertia constant *H* and the generator rated power S_n.

$$J = \frac{2S_n H}{\omega_{nom}^{2}}$$

Which leads to

$$\frac{2S_n H}{\omega_{nom}} \frac{d\omega}{dt} = P_{mech} - P_{el} \tag{2.26}$$

His given in seconds and is a measure of the time that a rotating generator can provide rated power without any input power from the turbine. Instead of using *J* for inertia SnHis used in this thesis from now on. This facilitates the calculations and it is easy to see the connection between rated power and inertia. It is also easy to calculate an equivalent inertia of a system comprising generators with different $S_n$and *H*. Equation (2.27) may then represent an equivalent of a power system with several synchronously connected rotating machines and the equivalent S_nHis calculated as

$$S_n H = S_{n1} H_1 + S_{n2} H_2 + \ldots + S_{nN} H_N \tag{2.27}$$

where S_{nN} and H_N is the rated power and inertia constant for generator N. Since the power system is supposed to handle a specific loss of production, i.e. the rating of the largest connected unit, it is preferable to use $S_n H$ instead of the inertia constant Has a measure of the system strength. It is then easy to relate the disturbance magnitude in MW to the system inertia in MWs.

An example of the frequency behavior following a loss of generation is shown in Figure 2.2. The primary frequency control is here obtained with hydropower units. Immediately after tripping one generator the remaining generators increase their output power by releasing kinetic energy stored in the rotor. The electrical output power is then higher than the mechanical turbine power and the generator speed and grid frequency decreases. This is between 0 sec. and 10 sec. in Figure 2.2.

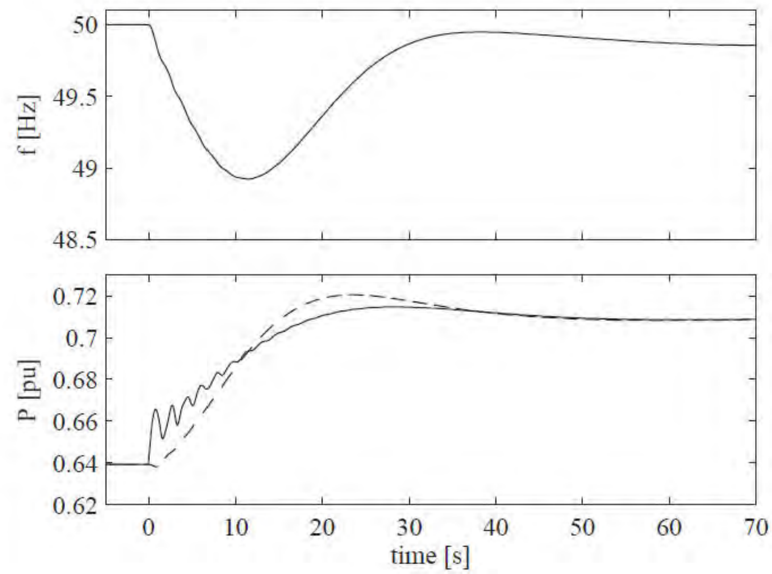

Figure 2.2: Frequency behavior following a generation loss

With a short delay the turbine gate opening is increased but due to the non-minimum phase characteristic of a hydro turbine the mechanical power is initially decreased prior to increasing. With increasing turbine power the rate of change of frequency is decreased. When the mechanical power is equal to electrical power the frequency nadir, i.e. the lowest frequency, is reached. After this point the mechanical power is higher than the electrical power, the kinetic energy previously released from the rotor is restored and the frequency is increased. Finally the frequency stabilizes at a value where the mechanical power and the electrical power are equal. This control action is called primary control.

2.5 Load Frequency Control

For large scale power systems which consist of inter-connected control areas, it is important to keep the frequency and inter area tie power near to the scheduled values. The input mechanical power is used to control the frequency of the generators and the change in the frequency and tie-line power are sensed, which is a measure of the change in rotor angle. A well designed power system should be able to provide the acceptable levels of power quality by keeping the frequency and voltage magnitude within tolerable limits. Changes in the power system load affects mainly the system frequency, while the reactive power is less sensitive to changes in frequency and is mainly dependent on fluctuations of voltage magnitude. So the control of the real and reactive power in the power system is dealt separately. The load frequency control mainly deals with the control of the system frequency and real power whereas the automatic

Voltage regulator loop regulates the changes in the reactive power and voltage magnitude. Load frequency control is the basis of many advanced concepts of the large scale control of the power system.

Automatic generation control (AGC) is very important issue in power system operation and control to ensure the supply of sufficient and reliable electric power with good quality. Owing to the continuous growth of electrical power system in amount and complexity with increasing interconnections, the problem of power and frequency oscillations due to unpredictable load changes, has become increasingly serious. These random load changes result in power generation-consumption mismatch, which in turn, affects the quality and reliability of electric power. These mismatches have to be corrected for generation and distribution of sufficient power. One of the important issues in the operation of power system is Automatic Generation Control (AGC). It helps in supplying adequate and consistent electric power with good quality. It is the secondary control in LFC which re-establishes the frequency to its nominal value (50 Hz) and sustains the interchange of power between areas (in case of more than one control area). For this the load demand in the generator prime mover set is increased or decreased in the form of kinetic energy, resulting in change of frequency. The transient in primary, secondary and tertiary control is of the order of seconds and minutes respectively Automatic generation control is to provide control signals to regulate the real power output of various electric generators within a prescribed area in response to changes in system frequency and tie-line loading so as to maintain the scheduled system frequency and established interchange with other areas. In other words the design of automatic generation controller depends upon various energy source dynamics involved in the AGC of the area.

If the load on the system is increased suddenly then the turbine speed drops before the governor can adjust the input of the steam to the new load. As the change in the value of speed diminishes the error signal becomes smaller and the positions of the governor and not of the fly balls get closer to the point required to maintain the constant speed. One way to restore the speed or frequency to its nominal value is to add an integrator on the way. The integrator unit will monitor the the average error over a period of time and will overcome the offset. Thus as the load of the system changes continuously the generation is adjusted automatically to restore the frequency to the nominal value. This scheme is known as automatic generation control. In an interconnected system consisting of several pools, the role of the AGC is to divide the load among the system, stations and generators so as to achieve maximum economy and reasonably uniform frequency.

2.5.1 Droop Control

Droop control is a control strategy commonly applied to generators for primary frequency control (and occasionally voltaqe control) to allow parallel generator operation (e.g. load sharing). Recall that the active and reactive power transmitted across a lossless line are:

$$P = \frac{V_1 V_2}{X} \cdot \sin \delta \tag{2.28}$$

$$Q = \frac{V_1}{X}\left(V_1 - V_2 \cos\delta\right) \tag{2.29}$$

Since the power angle δ is typically small, we can simplify this further by using the approximations cosδ = 1 and $\sin \delta \approx \delta$.

$$\delta \approx \frac{PX}{V_1 V_2} \tag{2.30}$$

$$\left(V_2 - V_1\right) \approx \frac{QX}{V_2} \tag{2.31}$$

From the above, we can see that active power has a large influence on the power angle and reactive power has a large influence on the voltage difference. Restated, by controlling active and reactive power, we can also control the power angle and voltage. We also know from the swing equation that frequency is related to the power angle, so by controlling active power, we can therefore control frequency. This forms the basis of frequency and voltage droop control where active and reactive power are adjusted according to linear characteristics, based on the following control equations:

$$f = f_0 - k_p\left(P - P_0\right) \tag{2.32}$$

$$V = V_0 - k_q\left(Q - Q_0\right) \tag{2.33}$$

Where,

f is the system frequency

f_o is the base frequency

$k\,p$ is the frequency droop control setting

P is the active power of the unit

P_0 is the base active power of the unit

V is the voltage at the measurement location

V_0 is the base voltage

Q is the reactive power of the unit

Q_0 is the base reactive power of the unit

k_q is the voltage droop control setting

The Equation (2.32) is plotted in the characteristic below:

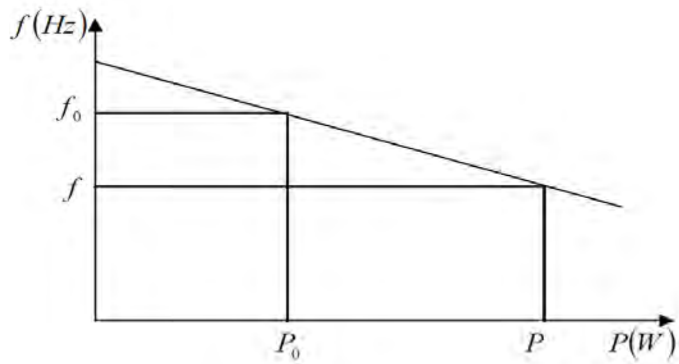

Figure 2.3:Frequency droop characteristic.

The frequency droop characteristic above can be interpreted as follows: when frequency falls from f_0 to f, the power output of the generating unit is allowed to increase from P_0 to P . A falling frequency indicates an increase in loading and a requirement for more active power. Multiple parallel units with the same droop characteristic can respond to the fall in frequency by increasing their active power outputs simultaneously. The increase in active power output will counteract the reduction in frequency and the units will settle at active power outputs and frequency at a steady-state point on the droop characteristic. The droop characteristic therefore allows multiple units to share load without the units fighting each other to control the load (called "hunting"). The same logic above can be applied to the voltage droop characteristic.

The Equation (2.33) is plotted in the characteristic below.

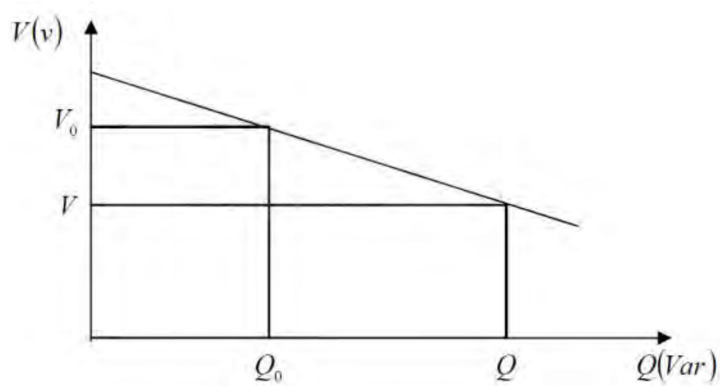

Figure 2.4:Voltage droop characteristic

When voltage falls from V0 to V the power output of the generating unit is allowed to increase from Q0 to Q . A voltage drop indicates an increase in reactive power demand and a requirement for more reactive power supply.

2.5.2 Droop Control Setpoints

Droop settings are normally quoted in % droop. The setting indicates the percentage amount the measured quantity must change to cause a 100% change in the controlled quantity. For example, a 5% frequency droop setting means that for a 5% change in frequency, the unit's power output changes by 100%. This means that if the frequency falls by 1%, the unit with a 5% droop setting will increase its power output by 20%.

2.5.3 The Inertia Constant (H)

Traditionally, power system operation is based on the assumption that electricity generation, in the thermal power plants, reliably supplied with fossil or nuclear fuels, or hydro plants, is fully dispatchable, i.e. controllable, and involves rotating synchronous generators. Via their stored kinetic energy they add rotational inertia, an important property of frequency dynamics and stability. The contribution of inertia is an inherent and crucial feature of rotating synchronous generators. Due to electro-mechanical coupling, a generator's rotating mass provides kinetic energy to the grid (or absorbs it from the grid) in case of a frequency deviation Δf . The kinetic energy provided is proportional to the rate of change of frequency Δf . The grid frequency f is directly coupled to the rotational speed of a synchronous generator and thus to the active power balance. Rotational inertia, i.e. the inertia constant H , minimizes Δf in case of frequency deviations. This renders frequency dynamics more benign, i.e slower, and thus increases the available response time to react to fault events such as line losses, power plant outages or large-scale setpoint changes of either generation or load units. Maintaining the grid frequency within an acceptable range is a necessary requirement for the stable operation of power systems. Frequency stability, and in turn stable operation, depend on the active power balance, meaning that the total power infeed minus the total consumption (including systems losses) is kept close to zero. In normal operation small variations of this balance occur spontaneously. Deviations from its nominal value f_o (50 Hz or 60 Hz depending on region) should be kept small, as damaging vibrations in synchronous machines and load shedding occur for larger deviations. This can influence the whole power system, in the worst case ending in fault cascades and black-outs. Low levels of rotational inertia in a power system, caused in particular by inverter-connected Renewable Energy Sources (RES), i.e. wind turbine and Photovoltaic (PV) units that as such do not provide any inertia, have implications on frequency dynamics. Frequency dynamics are becoming more important in power systems with low rotational inertia. This can lead to situations in which traditional frequency control schemes become, relatively spoken, too slow for preventing large frequency deviations and the impeding consequences of this. The loss of rotational inertia as such and the time-variance of inertia lead to new frequency instability phenomena in power systems. Frequency and power system stability may be at risk.Mathematically,

$$H = \frac{KE}{MVA} = \frac{\frac{1}{2}J\omega_m^2}{S_{base}}(Ws/VA = s) \tag{2.34}$$

Where,

K.E is the kinetic energy of rotating masses

MVA is the generator MVA rating

The typical values of inertia constant 'H' on different MVA bases are

(i) Steam turbines = 4-9 s
(ii) Gas turbines = 3-4 s
(iii) Hydro turbines = 2-4 s
(iv) Synchronous compensator = 1-1.5s

2.5.4 Frequency Response Indicators

When evaluating frequency response the important indicators are maximum frequency gradient (df/dt) as observed by ROCOF (Rate-Of-Change-Of-Frequency) and maximum frequency deviation as observed by underfrequency scheme. Both these quantities shall be kept as small as possible to prevent relays from tripping. df/dt, frequency deviation and frequency nadir are defined in Figure 2.5.

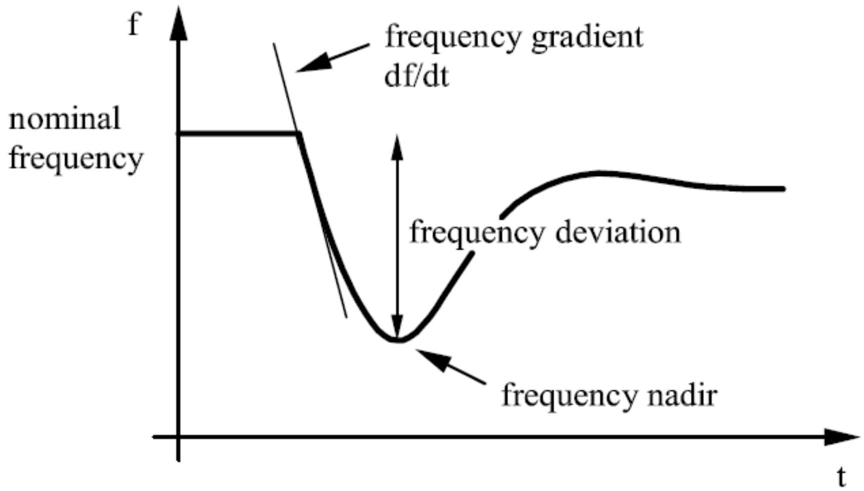

Figure 2.5: Frequency response indicators [2]

A generating unit is a rotating mechanical system, in which the rotation of a turbine shaft caused by some input mechanical power is transformed into electrical power. A mechanical torque is generated by the input mechanical power while an opposing electrical torque is caused by the load connected to the generator. If there is a change in the generation or demand, this imbalance will be reflected on the turbine speed, which results in a fluctuation of the system frequency. The swing equation of a generating unit defines the relationship between the active power imbalance and its frequency response. This equation in its simplest form is given by,

$$\frac{2H}{f_o}\frac{d\Delta f}{dt} = P_m - P_e = \Delta P \tag{2.35}$$

In Equation (2.35), *Pm* refers to the input mechanical power and *Pe* refers to the output electrical power in per unit, while *H* is the generator inertia constant in seconds, *fo* is the nominal frequency in Hz, and Δf is the frequency deviation from nominal in Hz. There are however many other parameters that significantly affect the frequency trajectory of a generating unit. These are discussed in the following subsections.

2.5.5 Load Damping

There are different kinds of electric loads in a power system. Resistive loads do not modify their power consumption when there are frequency fluctuations, but this is not the case of motor loads. Motor speeds vary according to the frequency of the input power supply. A motor load reduces its active power consumption when there is a decline in the system frequency. It is necessary to investigate the load damping on system frequency response. There is little work on the effect of the intrinsic load characteristics. With the increasingly large amount of frequency sensitive load for frequency regulation and the increasing interests in load models, it is important to examine the impact of load behaviors, namely the load-damping coefficient ‘D’ on the system frequency regulation. The dependence of power consumption on frequency for motor loads is defined by the relation,

$$\Delta P_{ml} = D\Delta f \tag{2.36}$$

P_{ml}refers to the change in active power consumed by motor loads and $\Delta \boldsymbol{f}$is the frequency deviation from nominal. The damping constant ***D*** is defined as the percent change in load for a one percent change in frequency. For example, a damping constant of 2% indicates that a 1% change in frequency would cause a 2% change in load. The sensitivity of loads to frequency changes should be included in the swing equation to accurately reflect the frequency response following a contingency. Figure 2.6 shows the frequency trajectory after a 25% generation loss contingency with and without considering load damping.

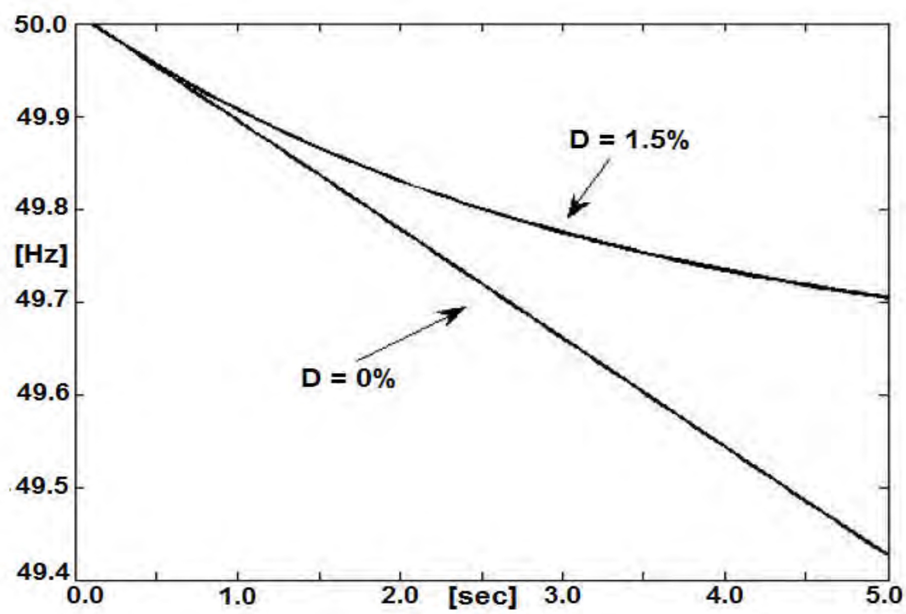

Figure 2.6: Typical damping effect on frequency excursion

It can be seen that the frequency decline is more severe when not considering the effect of load frequency dependence. Therefore, if the relay settings are found with the use of a model that does not include load damping, the resulting UFLS plan will be too conservative and may shed excess load.

2.5.6 Determination of Load Damping Constant (K)

The load power in a node may change with the variation of the voltage in this node or that of the frequency in the system or both. This is part of load characteristics. Generally, the load characteristic can be divided into static and dynamic. The static load characteristic is generally described as a quadratic polynomial or a power function, while the dynamic characteristic is generally described as a differential and algebraic equation set. In this work, the following load static characteristic model is employed.

$$\begin{cases} P_L = P_L^0[a_p(V_L/V_L^0)^2 + b_p(V_L/V_L^0) + c_p](1+K_{pf}\Delta f) \\ Q_L = Q_L^0[a_q(V_L/V_L^0)^2 + b_q(V_L/V_L^0) + c_q](1+K_{qf}\Delta f) \end{cases} \quad (2.37)$$

Where,

V_L^0 is the rated voltage magnitude of the load studied

V_L is the actual voltage magnitude of the load studied

P_L^0/Q_L^0 is the rated active/reactive load power

P_L/Q_L is the actual active/reactive load power

Δf is the frequency variation of the system

K_{pf}/K_{qf} is the frequency sensitivity factor of the active/reactive load power, and their values generally range from 0.0 to 3.0.The coefficients in Eqn. (2.37) should satisfy

$$\begin{cases} a_p + b_p + c_p = 1 \\ a_q + b_q + c_q = 1 \end{cases} \quad (2.38)$$

With Equation (2.38), the variation amount of active load power at the load node caused by a unit frequency variation, defined as the so-called K value, could be obtained as

$$K = \frac{\partial P_L}{\partial \Delta f} = P_L^0[a_p(V_L/V_L^0)^2 + b_p(V_L/V_L^0) + c_p]K_{pf} \quad (2.39)$$

It can be derived from Equation (2.39) that the same amount of frequency decline could lead to more active load power reduction for a larger value of K.

2.5.7 Response and Event Based System Protection Schemes

In this type of system protection schemes, response of the system to disturbances is used in decision making. Input signals of the system in this method may be voltage, frequency or any other signal of the system. UFLS and under-voltage load-shedding (UVLS) schemes are popular methods in this class [65].

In this method, decision is based on the state of specific elements in the system such as important transmission lines or generators. This method usually requires a communication link to transmit the state of important elements to the control centre and under-frequency relays. For instance, one of the methods proposed in this paper is an event-based method. In this method, UFLS scheme is based on the outage of generators. Whenever a generator is tripped, a signal is transmitted to the control centre. The decision-making system in the control centre determines the amount of load to be shed based on the location of the tripped generator. The algorithm could be extended for the outage of tie lines as well.

2.5.8Comparison of Centralized and Distributed Load Shedding Schemes

The following points include comparison between centralized and distributed load-shedding schemes.

1. In the centralised schemes, various parameters of the system could be used for decision making. For example, frequency, voltage, reactive power of generators, status of important generators or transmission lines and other required parameters may be used. Thus, it is possible to make a more appropriate and complete decision.

2. In the centralised schemes, the decision-making system is aware of the situation of the whole system. Therefore in this system, it is possible to preserve stability of the system more efficiently, especially after large disturbances.

3. In the centralised schemes, it is easily possible to implement both UFLS and UVLS schemes using the same hardware.

4. Reliability of distributed schemes may be higher than that of the centralised schemes, since in the centralised schemes, failure of a component might result in failure of the whole UFLS system. This shortcoming of the centralised schemes may be compensated by redundancy in communication and control equipments.

5. Although operation of centralised schemes is dependent on the communication facilities, since in these schemes, measuring equipments are located only at a few locations some capital may be saved. This way, a part of the communication link cost will be compensated. In addition, some of the communication system infrastructure may already be available for other operational purposes and could concurrently be used for load shedding [16].

In [63] different types of centralized load shedding have been introduced to rank and select the best loads to interrupt during voltage or frequency stability. Centralized load shedding is supposed to be the best solution for coordination of dispersed loads and generators in power system [64]. However, centralized method needs to collect and transmit the measured information and to distribute the decisions throughout the system. This strategy has several disadvantages such as implementation expenses of communication system and vulnerability of communication link due to eventually natural failures or Cyber Security attacks, which have been introduced in [66]. Besides, the centralized scheme is unable to adapt itself to any structural changes in power system configuration, therefore it should be redesigned again when any load, generator or transmission line is installed or removed. The stochastic and variable nature of Renewable Energy Sources (RES) causes intermittent behavior of them in connection to the power system. Alteration of power system topology proliferates the duty of centralized control schemes. As distributed approach is able to prevail these weaknesses, decentralized control scheme seems to be a better solution to deal with RESs and to reach a more affordable and reliable power system. Nowadays, Multi Agent System (MAS) is widely used as a suitable solution for decentralized control algorithms [67]. The MAS can process the distributed data and tolerate single point failures, which make it faster in decision and operation and more efficient in duty distribution. A decentralized MAS load shedding algorithm has been proposed in [66] to achieve an effective load shedding scheme based on collected global information. The global information are earned based on information exchange merely between neighbor agents. Total generation and demand can be identified accurately. The load shedding commands can be issued according to the available information. In the decentralized load shedding, decisions are made based on locally measured voltage and frequency signal at the relevant relay. In this method, load shed are determined based on the failure place either directly or indirectly. On the other hand, as the load shedding process is taken place utilizing locally measured information, no communication system is required. Therefore, implementation of these methods is much more easy and affordable than the centralized load shedding approaches which require rapid communication links [35].

2.5.9 Role of PMU in Power System Stability

Standard [68] defines the synchrophasor as a complex number representation of either a voltage or a current, at the fundamental frequency, using a standard time reference. The power system variables are measured by phasor measurement units (PMUs) and are broadcasted with the Wide Area Monitoring and Control Systems (WAMCS). Therefore, the power system stability issues may be supervised more carefully than before. PMUs are able to dedicate synchronized measurements, which include the magnitude and phase angle of voltages, currents, frequency and ROCOF [69]. These collected information may aid to trace the dynamical behavior and provide useful data for both voltage and frequency stability evaluation. Additionally, the phase angle data ease early and more accurate recognition of voltage instability. However, they have not been utilized yet in current load shedding schemes [69].

2.6 Summary

In this chapter, different load shedding methods were classified in term of being centralized/distributed from a control strategy aspect of view, adaptive/non-adaptive capability regarding online updating of its parameters based on the measured power system variables and the last, but not the least, flexibility to overcome unpredicted changes of power system structure/topology. Most of centralized methods introduced in this chapter are based on the SFR method. Furthermore, almost all of adaptive methods are solely based on frequency data to estimate the active power deficit and cannot pin point the event location. Therefore, the load shedding is uniformly fulfilled in whole power system regardless of event location, resulting interruption of the loads that are inside the safe regions with the voltage inside the normal range. In the decentralized load shedding, which is properly investigated in the existing literatures and at the present, the settings of protection relays are determined manually, offline, constant and independent of event location and magnitude, based on simulation and/or practical experiences of utility operators, which may not be a comprehensive countermeasure for all possible combinational and cascading events.

CHAPTER 3

Proposed Dynamic-Adaptive Load Shedding Methodology

3.1 Introduction

The various conventional schemes, under frequency schemes and under voltage load shedding schemes have been discussed in chapter 2. These give an insight about the technological advancement achieved in this area. The proposed scheme in this thesis incorporates frequency and voltage together and tries to overcome some of the disadvantages faced by the conventional and adaptive schemes present in the industry.

The blackout protection scheme based on only offline simulation is not guaranteed for successful work in real time situation without knowing the current condition of real time network. To overcome this problem the proposed scheme has taken all important state variables to be checked for strict and controlled load shedding [4]. The technique proposed in this paper is a heuristic one that considers magnitude of frequency upset, load damping factor, frequency deviation, rate of change of frequency (ROCOF), weak bus ranking due to reactive power imbalance and minimum load shed to decide the above parameters. It develops a comprehensive solution to the short term frequency instability for any power system amount. Conventionally, load shedding schemes under frequency load shedding (UFLS) and under voltage load shedding (UVLS) are designed independently and they constitute the last line of defense against frequency and voltage instability. In this paper, we propose a new adaptive load shedding method that considers frequency and voltage stability assessment simultaneously.

The proposed blackout remedial methodology is a dynamic-adaptive and centralized blackout protection methodology considering the system exact power discrepancy, load damping coefficient, real-time feeder load variation, regional frequency response, controlled load shedding and load bus ranking based on voltage sensitivity as local indicator to prioritize the load shedding. The possible outcome of this methodology will be a robust dynamic-adaptive frequency decline arresting scheme that will ensure short-term frequency stability along with taking care of voltage stability.

The main features of the proposed methodology of this paper which distinguish the proposed method from other industry used methods are as the following:

1) The methods are centralized, therefore there may be various useful parameters available in the decision making process.

2) In these methods, in contrast to the most of the other adaptive methods, voltage of sub-transmission buses has a very important role in the load shedding system. This way the load shedding scheme is sensitive to both frequency and voltage. This characteristic enables the load shed scheme to prevent voltage collapse as well as frequency instability in numerous cases.

3) Intelligent and dynamic selection of loads for controlled load shedding is another important feature of the proposed methodology. In thismethodology,more loads will be shed from higher perturbed zone and from weaker bus within a zone. This characteristic has the highest impact on the robustness of these methods during combinational disturbances.

4) In the proposed methods the amount of load to be shed is determined adaptively and it is completely proportional to the magnitude of disturbance following the bus ranking. This way the problems of under-shedding and over-shedding existing in the conventional UFLS method are overcome.

5) In this dynamic-adaptive methods of this work, the scheme also monitors the power flow of tie-lines after contingency.

This way a fast response is obtained for large disturbances and, as the results of python coded simulations verify, several grid system collapses may be prevented.

Thus, the new approach can enhance the recovered steady state with respect to frequency stability, voltage stability and load ability, while also ensuring a good transient behavior, for the same total active power curtailment, compared to the existing load shedding methods.

3.2 Proposed Load Shedding Methodology

Frequency decline happens due to disturbance in power system. Sometimes the system can stabilize itself by its inertial reserve or the system can be made stable through primary governor action control. But for large disturbance spinning reserve control through governor action is too late to arrest rapidly declining frequency [5]. In that case, under frequency load shedding becomes the only inevitable step to prevent subsequent tripping of lines and generators which can lead to blackout. Sometimes load shedding also cannot stabilize the frequency and for that case proper network islanding technique becomes urgent. That's why UFLS system must have to be robust and compatible with the system.

Major questions about any load shedding scheme are, how much of the network loads must be dropped and where must be the location of load drops. These questions are reasonable; nevertheless, the first and short answer is unsatisfying: it depends. In this work, these questions are comprehensively answered in details.

The proposed methodology presumes the following conditions.

(i) The power system has several area or zones and a National Control Centre.

(ii) Every zone has defined boundary. Zones are defined usually based on geographical proximity of generators.

(iii) High speed communication infrastructure (fiber optic) belongs to the power system.

(iv) PMU are installed at every candidate PQ and PV/slack buses only.

(v) The load power in a node may change with the variation of voltage and frequency in this node.

(vi) The minimum and maximum threshold frequency of a power system is determined by machine endurance frequency, grid code, power quality and etc. The threshold frequency, f_{TH} is defined as that limiting frequency below which the power system may embrace frequency instability.

Following state variables of interest are,

(1) Frequency

(2) Rate of change of frequency

(3) Load Bus Voltage

(4) Plant's Active Power

(5) Load Bus Reactive Power

3.2.1Main Scheme of Proposed Methodology

The proposed methodology has three parts namely

i) Main scheme

ii) FVSI Subroutine

iii) Tie line monitoring scheme

The proposed methodology is described here sequentially as follows.

Step-1: Taking sample of active power (**P_{gi}**) and frequency (**f_{gi}**) at every power plant's HT bus. The HT Bus is connected to the secondary of unit transformer. At steady state, all plant's generation frequency are essentially same, that means,

$$f_{g1} = f_{g2} = f_{g3} = \ldots\ldots = f_{gj} = f_{sys}. \quad (3.1)$$

Where,

f_{g1} - Frequency of Generator-1

f_{gi} - Frequency of Generator- i

f_{sys} -WholeSystem Frequency at healthy condition

Step-2: Every power plant's current sample and previous sample of active power are compared to reckon tolerable generation loss. Then the equation becomes.

$$\frac{P_{gi}(n-1)-P_{gi}(n)}{P_{gi}(n-1)} \times 100\,\% < \varepsilon \qquad \text{for stable case} \quad (3.2)$$

Where,

n - Current sample

$(n-1)$ - Previous sample

i - Number of generators (1, 2, 3…)

The value of ε is critical which may trigger frequency instability. Protection engineers can set it from their empirical knowledge and experience. The setting of ε may be coordinated with primary control and secondary control. Intentional or scheduled generation ramp rate should be lower than ε**.**The scheme stores current n^{th} sample value erasing the $(n-2)^{th}$ sample data. Therefore just previous power and frequency sample data are saving always.

It is to be noted that, sometimes the output of a power station may drop suddenly for a while for any valid reason such as lightning during inclement weather. But this is not a real generation loss. So, to encounter this issue, the current sample can be checked two times more with the sample taken just before the disturbance. The way it works is as follows

When the Equation (3.2) becomes false, then the proposed blackout preventive methodology executes the Equation (3.4) two times more just to be sure about real MW loss.

$$P_{gi}\,(n\text{-}1) = P_{healthy\_i} \tag{3.3}$$

$$\frac{P_{healthy\_i} - P_{gi}(n)}{P_{healthy\_i}} \times 100\ \% < \varepsilon \tag{3.4}$$

Where,

$P_{gi}(n)$-Current sample of active power of generator- i

$P_{healthy\_i}$ -Sample taken just before the disturbance of generator- i

If the imbalance is false for total three times then the blackout preventive methodology will understand that the step-2 is false and it is a real generation loss.

Step-3: If Equation (3.2) or (3.4) in step-2 is true (no confirmed generation loss) for every power plant then it executes the FVSI subroutine where load bus are always being ranked from weakest to strongest dynamically by using voltage stability index. Here we have used FVSI (Fast Voltage Stability Index). FVSI is a tool for bus ranking and widely use in voltage stability analysis. The details of FVSI have been discussed in FVSI subroutine section.

Operator of load dispatch center may understand the system condition and be helped from load bus ranking. If step-2 is false (generation loss found) then next subsequent steps will be executed.

Step-4: Generation loss (>ε) triggers the short-term frequency instability. If step-2 is false (Confirmed generation loss found) for any power plant then to prevent the short-term frequency instability, the scheme will determine the following parameters in subsequent steps.

- Asses the need for load shed
- Total amount of required load shed
- Location of load shed
- Disturbance severity of each location/area

- Amount of load shed for each perturbed area
- Distribute the area wise load shed amount from weak to strong bus
- Monitor whether the amount of load shed are strictly maintained

After understanding the confirmed generation loss or tie line outage, the scheme will assess the real need of load shed.

$$\Delta P = P_{loss} = P_{gi}(n) - P_{gi}(n-1) \tag{3.5}$$

$$\Delta f = \Delta P / D \tag{3.6}$$

$$(f_{sys} - \Delta f) >= f_{TH} \tag{3.7}$$

Where,

D - Load Damping Factor, usually varies between 1% to 3%

P_{loss} -Themagnitude of generation loss

f_{TH} - Lower frequency threshold limit.

Equation (3.5) gives the magnitude of generation loss but the generation loss is not necessarily the amount of load shed. The scheme will first check what extent the system frequency will go down without shedding any loadby Equation (3.5) to (3.6). Load damping factor (D) of the system must have to be known for successful operation. If not known, conservative value for D can be considered. There are different kinds of electric loads in a power system. Resistive loads do not modify their power consumption when there are frequency fluctuations, but this is not the case of motor loads. Motor speeds vary according to the frequency of the input power supply. A motor load reduces its active power consumption when there is a decline in the system frequency. It is necessary to investigate the load damping on system frequency response. There is little work on the effect of the intrinsic load characteristics. With the increasingly large amount of frequency sensitive load for frequency regulation and the increasing interests in load models, it is important to examine the impact of load behaviors, namely the load-damping coefficient (D) on the system frequency regulation. The dependence of power consumption on frequency for motor loads is defined by the relation,

$$\Delta P_{ml} = D\Delta f \tag{3.8}$$

ΔP_{ml} refers to the change in active power consumed by motor loads and Δf is the frequency deviation from nominal. The damping constant (*D*) is defined as the percent change in load for a one percent change in frequency. For example, a damping constant of 2% indicates that a 1% change in frequency would cause a 2% change in load. The sensitivity of loads to frequency changes should be included in the swing equation to accurately reflect the frequency response following a contingency. Figure3.2 shows the frequency trajectory after a generation loss contingency with and without considering load damping factor (D).

It can be seen from Figure 3.1 that the frequency decline is more severe when not considering the effect of load frequency dependence. Therefore, if a methodology or scheme is found with a model that does not include load damping (D), then the load shedding scheme may shed unnecessarily excess load and scheme might be worsen the system stability own self. This reflects the importance of including load damping in the blackout preventive scheme.

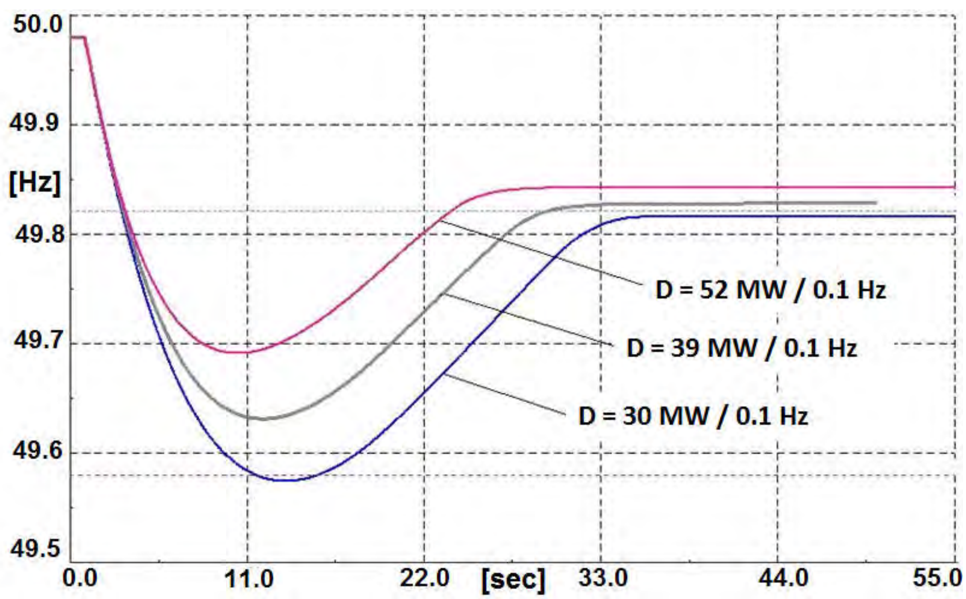

Figure 3.1: Frequency response for different values of 'D'

Step-5: If Equation (3.7) is true**,** then no need to shed the load else determine the amount of load shed (P_{shed}) for the whole system. From the frequency distance between pre-disturbance frequency and threshold frequency, the scheme will take an advantage for determining the lesser amount of load shed. The scheme will determine the load shed amount by Equation (3.9).

$$P_{shed} = [\, f_{TH} - (f_{sys} - \Delta f)\,] \times D \quad (3.9)$$

Where,

P_{shed} - Amount of power to be shed in megawatt (MW)

f_{TH} - Lowerthreshold frequency.

P_{shed} is eventually less than P_{loss}. Now the total load shed (P_{shed}) size will be divided among all zones across the whole system according to their disturbance magnitude.

The threshold frequency of a power system (f_{TH}) is determined by machine endurance frequency, grid code, power quality and etc. The threshold frequency, (f_{TH}) is defined as that limiting frequency below which the power system may embrace frequency instability and under frequency load shedding triggered by BRS is activated. Some equipment is very much sensitive to frequency drops that are motors, generators, steam turbines and auxiliary services. Auxiliary services are more sensitive to frequency drop than generators and these begin to malfunction usually at 47.5 Hz for 50 Hz system (57 Hz in case of 60 Hz) and in critical situation, cascaded effect is occurred at 45-47 Hz (55-57 Hz in 60 Hz system) [8].

Step-6: It is reasonable to imagine an equivalent generation unit at each area/zone that describes the average behavior of all the generators of that zone. Usually the machines in the same geography are coherent. This equivalent unit is called COI (Centre of Inertia) machine [23].The frequency of COI **[f_{COI_z}]** of respective areas can be determined by Equation (3.10).

$$f_{COI\_Z} = \frac{\sum_{i=1}^{i=m} H_i f_{gi}(n)}{\sum_{i=1}^{i=m} H_i} \tag{3.10}$$

Where,

z - Zone numbers

m -Machine numbers

H_i- Inertia of i[th] generator

f_{gi}-Frequency ofi[th] generator

Step-7: In this step, it will now determine to what extent a zone is disturbed because of active power imbalance. The rate of change of average frequency decline (df_{coi_z} / dt) of a zone indicates the magnitude of upset caused by generation loss. Higher slope means larger disturbance, consequently larger amount of load will be shed of that zone.

$$\frac{df_{COI\_Z}}{dt} = \frac{f_{sys} - f_{COI\_z}}{t_{sys} - t(n)} \tag{3.11}$$

Where,

t(n)- Current sample time

$f_{COI\text{-}Z}$- Frequency of a zone at time *t(n)*

f_{sys}-SystemFrequency prior to the disturbance

t_{sys} - Time of sample of f_{sys}

Definitely, the area of generation loss will experience highest rate of frequency decline and other zones will experience perturbation according to their electrical distance and machine inertia. Higher slope means higher disturbance, consequently higher load will be shed in that zone.

Step-8: Since the total load shed amount (P_{shed}) will be distributed among all zones of whole power system according to the severity of the disturbance. Hence the zonal load shed weight (W_z) has to be computed with Equation (3.12).

$$W_z = \frac{df_{COI\_z}/dt}{\sum_{z=1}^{z=p}(df_{COI\_z}/dt)} \tag{3.12}$$

Where, z represents zones or areas in a power system.

Step-9: After computing the zonal load shed weight (W_z),the amount of zonal load shed ($Load_z$) for every zone will be defined as follows.

$$Load_z = W_z \times P_{shed} \tag{3.13}$$

Now the zonal load shed amounts are finalized to recover short-term frequency stability. But every zone may have several substations and many feeders at each substation. Now question remains that which feeders of which substations will be shed in a zone that is equivalent to $Load_z$?

Like traditional and semi-adaptive scheme, the proposed methodology does not say only L% load have to be shed [6]. Rather it makes possible and assure L% load shed. In any scheme, the load shed is executed by opening the feeder circuit breakers. Feeders' power flow varies peak to off-peak daily and seasons to seasons. Even the daily load curves in same season are not always same. Since the traditional and semi-adaptive schemes do not measure the state of MW flow of medium voltage (MV) distribution bus or load shedding bus, hence as a consequence under or over tripping (load shed) might be occurred in response to short term frequency instability and these schemes might not be able to recover the frequency stability [7].Therefore, the load-shedding scheme must be tailored to adapt the changes in the power system such as generation loss, an increase in demand and changing operating condition. So the scheme settings developed based on offline simulation might not work in real time situation. To overcome this problem the proposed methodology will have to inspect the system states and keep knowledge of power flow at each MV feeder or load shedding feeder.

Step-10: To avoid unexpected load shedding and to care voltage stability, the scheme will shed more loads at weaker bus and less loads at comparatively stronger bus in a zone. But the total load shed in PQ buses of a specified zone must be equal (or very close) to that zonal load shed amount ($Load_z$). Bus stands here for medium voltage (MV) distribution bus or load shedding bus. Several methods have been found in literature survey for bus ranking but FVSI (Fast Voltage Stability Index) is taken here. Therefore, the load-shed amount for each bus (B_{zk}) in a zone is calculated by Equation (3.14).

$$B_{zk} = FVSI_{z\_k} \times Load_z \quad (3.14)$$

Where, z represents zones and k represents bus or substation numbers within a zone.
The distribution buses are already ranked by FVSI in the subroutine-A during healthy state. The FVSI is taken into account for taking care of voltage stability as well as the power grid operator can know the system strongest to weakest bus.

Step-11: Now the scheme selects circuit breakers of bus feeders so that the summation of power flow (P_i) of selected feeders is close to bus load shed amount (B_{zk}).

$$B_{zk} \approx \sum P_i \quad (3.15)$$

Where, i represents the selected feeders to the bus.

Step-12: Here, the dynamic correction of bus load shed amount of sub-stations within a zone is performed. The scheme checks in step-11 whether the total power flow (ΣP_i) of selected bus feeders are close to bus load shed amount (B_{zk}) or not. If any difference ε_b is found then the difference adjusted to the next substation load shed amount& updates it.

For substation-1 (k=1),

$$B_{z1} - \sum_{i=1} P_i = \pm\varepsilon_b \quad (3.16)$$

The difference is added to the next substation (k=2) load shed amount and is modified.

$$B_{z2} = B_{z2} \pm \varepsilon_b \quad (3.17)$$

Similarly, it will select feeder circuit breakers of all substation buses with dynamic correction (considering the feeder power flow) in a zone for controlled and lesser load shedding.

Step-13: Now the scheme checks the total power flow of all selected feeders in a zone, whether it is very close to calculated area/zonal load shed amount or not. It is another checkpoint for ensuring controlled load shedding. If ΣB_{zk} is not very close to $Load_z$ or the scheme finds any deviation then the next zone load shed size will be modified by the deviation.

$$Load_{z1} - \sum_{k=1} B_{zk} = \pm\varepsilon_z \tag{3.18}$$

$$Load_{z2} = Load_{z2} \pm \varepsilon_z \tag{3.19}$$

The dynamic correction of sub-station and zonal load shed amount is done in two steps so that total load shed amount is controlled and cannot go far beyond the value of P_{shed}, which is determined in step-5.

Step-14: Step - 10 to 13 are repeated to select circuit breakers of distribution or load shedding feeders of all zones in the whole power system.

Step-15: The scheme finally sends the trip signals to all selected feeder circuit breakers of all zones of whole power system through the network using the communication infrastructure (Fiber Optic) to arrest the rapid frequency decline and to prevent the short-term frequency instability along with a care of voltage stability. Then it just triggers the tie-line (Zonal Interconnection) monitoring sub-scheme that runs once after activation and the main scheme goes back to step-1 for repetition of above steps of main scheme.

In healthy condition, the scheme will be measuring and updating the required aforesaid state variables as well as executing following subroutine for bus ranking and thus reckoning voltage stability. As mentioned in following subroutine, bus ranking can be done in many ways but in the test power system FVSI (Fast Voltage Stability Index) is used for bus ranking. The scheme keeps dynamic records of FVSI of all sub-station PQ buses. In all zones, sub-station PQ buses are ranked according to the FVSI. Higher value of FVSI means weaker bus and lower value of FVSI means strong bus.

3.2.2FVSI Subroutine

If Equation (3.2) or (3.4) in step-2 is true or the scheme does not find any confirmed generation loss then main scheme calls FVSI subroutine to rank all PQ buses from weaker to stronger within zones. Sequential steps of FVSI subroutine are described below:

Step-A1: The following state variables are read from PQ buses (Load shedding) of grid exit substations only

i) Bus voltage (V_{zk})
ii) Reactive power (Q_{zk}) coming to the distribution bus.

Where, *z* represents zones and *k* represents bus or substation numbers within a zone. Load bus voltage and reactive power are measured for accounting voltage stability.

Step-A2: For ranking of PQ buses based on voltage stability index to take care of combinational disturbance, any kind of voltage or line stability index can be used. But we have considered here widely used Fast Voltage Stability Index (FVSI) as a local indicator for PQ bus ranking within a zone.

$$FVSI_{zk} = \frac{4.Z^2.Q_{zk}}{V_s^2.X} \tag{3.20}$$

Where,

Z - line impedance

X - line reactance

Q_{zk}- Reactive power flow at the kth bus.

V_s- Sending end voltage.

Step-A3: All FVSI of PQ buses within a zone are normalized as follows

$$FVSI_{Z\_k} = \frac{FVSI_{zk}}{\sum_{k=1}^{k=p}(FVSI_{zk})} \tag{3.21}$$

Where,

$FVSI_{zk}$-Fast voltage stability index (FVSI) of bus-k of zone-z.

$FVSI_{Z\_k}$- Normalized Fast voltage stability index (FVSI) of bus-k of zone-z.

P - Total bus number within a zone

Step-A4: All PQ buses are ranked according to their normalized FVSI within their own zone. The normalized FVSI ($FVSI_{Z\_k}$) values of respective buses will be used in main scheme to distribute the zonal load shed size among PQ buses within zones after generation loss.

In the proposed methodology, probability of over-frequency is lower than that of the conventional or tradional method. Moreover, since the proposed methods are centralized, they are flexible enough to be able to include more intelligence. Therefore some more appropriate functions related to over-frequency phenomenon or load loss may easily be added to the methods to adopt appropriate corrective actions in the case of frequency rise.

3.2.3 Tie Line Monitoring Scheme

Tie line monitoring scheme activates only by the step-15 of main scheme and it executes once after activation. This value added sub-scheme is for tie line (Zonal Interconnection) monitoring after disturbance and it prudently selects some additional feeder for load shed if the tie-line becomes overloaded.

The main scheme works well at each case of different disturbance and heal the power system from frequency instability taking care of voltage by controlled and less load shedding. However controlled load shedding never assures that the tie lines and interconnections among areas or zones will not be overloaded, although the system is stable in frequency. After dynamic and controlled load shedding, even there is a little possibility to overload the tie lines among zones but we cannot say stoutly and certainly that no interconnection will be overloaded. When the scheme sent trip signals to all dynamically selected feeders then the power flow redistributes in the system. If the interconnection lines among areas are overloaded and trip by protective relay then the system may be endangered again and may loss the stability in terms of voltage and frequency. So, in this connection, it is also very important to monitor the interconnection lines among areas from the point of power system security. In our developed methodology, the scheme can perform the security constrained dynamic and controlled load shedding. After dynamic selection of feeders and sending trip signals to all circuit breakers, the scheme checks the tie line power flow (Either sending end MVA or line Current) of that area only where the generation is curtailed. Actually, in most cases when the generation loss occurs in the load rich area then the tie-line might be overloaded. In that case tie-line monitoring sub-scheme will assure the security of tie-line by shedding some additional feeders. This sub-scheme executes the following sequential steps.

Step-1: After getting signal from step-15 of main scheme, a time delay (T_{wait})is introduced for selected circuit breakers by main scheme to switch off and also to redistribute the power flow through tie-lines.

The T_{wait} counts the opening time, arching time of circuit breaker, signal transmit time from control centre to the most distant circuit breaker and some oscillation time. The value of oscillation time of T_{wait} can be determined by offline dynamic simulation but the value of T_{wait} should not be more than the thermal runway time ($T_{thermal}$) of tie lines as follows.

$T > T_{wait} < T_{thermal}$

Step-2: After elapsing the T_{wait} time, this sub-scheme measure either sending end MVA (MVA_{flow}) or current (I_{flow}) and then compares the magnitude of measured MVA or current with the known value of line thermal (I_{Limit}) or stability limit (MVA_{Limit}).

$$I_{flow} \geq I_{Limit} \text{or } MVA_{flow} \geq MVA_{Limit} \tag{3.22}$$

Where,

I_{flow} / MVA_{flow} - Sending end Current/MVA flowing through the line

I_{Limit} / MVA_{Limit} - Line rated ampacity/capacity of the line

Step-3: If the measured quantity is higher than the known limit value then this sub-scheme computes the quantity of load has to be shed (L_{T_shed}) at receiving zone by the Equation (3.23) otherwise returns to the first step of main scheme.

$$L_{T\_shed} = [I_{measured} - I_{Limit}] \times V_{measured} \times 1.732 \tag{3.23}$$

Where,

L_{T_shed} - Amount of load has to be shed

$I_{measured}$ - Measured current through the tie line

I_{Limit} - Thermal Limit of the tie line

$V_{measured}$ - Measured bus voltage.

Step-4: Now the scheme will shed more loads at weaker bus and less loads at comparatively stronger bus in receiving zone according to the bus ranking prior to disturbance, although the FVSI might change after disturbance. The sub-scheme now divides the L_{T_shed} within receiving zone following the Equation (3.23).

$$B_{zk} = FVSI_{z\_k} \times L_{T\_shed} \tag{3.24}$$

Where, z represents zones and k represents bus or substation numbers within a receiving zone. The distribution buses are already ranked by FVSI in the FVSI Subroutine during healthy state. The FVSI is taken into account for taking care of voltage stability as well as the power grid operator can know the system strongest to weakest bus.

Step-5: Now the scheme selects circuit breakers of all substation buses in a receiving zone according to (B_{zk}) for controlled and lesser load shedding so that the summation of power flow of selected feeders is close to load shed amount (L_{T_shed}).

$$L_{T\_shed} \approx \sum B_{zk} \tag{3.25}$$

Where, z represents the receiving zone and k represents bus or substation numbers within this zone. Similarly, it will select feeder circuit breakers of all substation buses with dynamic correction (considering the feeder power flow) in a receiving zone for controlled and lesser load shedding.

After executing the tie line monitoring scheme, it restarts from 1st step of main scheme and always takes care of electric power system to prevent wide spread blackout. The flowchart of complete methodology is shown in Figure 3.2.

3.3 Communication Requirements

Powerful and reliable communication infrastructure is present in most of the today's modern power systems. The present communication links could transfer various power system signals fast and reliably. Even for the unlikely event of disconnection of the communication media between two points of the system, the required data could be transmitted indirectly through other redundant system nodes. Communication networks, presently used in power systems, are mainly applied for monitoring and tele-protection functions. They may concurrently be used for the centralized UFLS schemes as well. Moreover, as the interest in expansion of communication networks for power system increases, these methods could be implemented in future with minimum additional costs.

3.3.1 Data Transmission Link

In the load-shedding methodology proposed above that the event and measured signals of the system must be transmitted to the control centre through a reliable communication link is a fundamental requirement of these methodology. Fortunately, reliable and fast communication links are available in most of the present-day power systems. In [22], several communication links have been introduced. Metallic cable for local in-building applications, fiber-optic cable, power-line carrier (PLC), satellite, leased service, Very High Frequency (VHF) and Ultra High Frequency (UHF) radio and microwave radio are important communication media which may be used in power system applications. The suitable technologies for power system communication may be listed as follows [24].

i)Fiber-optic cable: This may be the most important communication link for power applications. It has considerably improved since its inception in 1970 [22]. Losses ,0.3 db/km, immunity to electromagnetic interference, immunity to ground potential rise, high channel capacity and low operating cost are important advantages of fiber-optic cables. These advantages lead to increasing demand for this technology. For instance, in Bangladesh, several thousand kilometers of these cables have been installed during recent years [25] in form of OPGW (Optical fiber ground wire). The most appropriate technology for our proposed methodology is Fiber-optic network.

ii)Microwave radio: Microwave radio is a term to describe UHF radio systems operating at frequencies above 1 GHz[24]. Microwave equipments are generally more expensive and more complex than fibre-optic equipments. Vulnerability to poor weather conditions and line-of-sight clearance requirement are other disadvantages of this technology. On the other hand, high channel capacity and high data transmission rates are important advantages of this communication link.

iii) UHF radio: The frequency band of UHF radio is in the range of 400 and 900 MHz. Lower prices and possibility of propagation over non-line-of-sight paths are important advantages of UHF radio over microwave radio. Conversely, channel capacity and data transmission rate of UHF are lower than those of microwave.

iv)Power-line carrier: PLC communication system has been used in power systems for a few decades. It provides the most common protective communication link in many countries. Although PLC can usually provide a versatile communication link, its performance might be degraded due to high impulse noise associated to short-circuit fault and lightning.

3.3.2 Tasks of Communication Link

The main tasks of communication link may be summarized as follows.

i) To transmit measured signals of the system to the control centre:

Frequency with time stamp of each PV bus must be sent to the control centre. Since the algorithm needs to calculate Δf and Pshed for the adaptation of frequency and load shedding amount, a reliable and fast communication link is required for this purpose. Maximum 100 ms delay may be tolerated in order that efficiency of the algorithms would not be reduced. To transmit the outage signal of generators: Whenever a generator/tie-line is tripped, a signal must be sent to the control centre indicating generator/tie-line outage. This signal must be sent as fast as possible in order that the loads to be shed are quickly selected by the adaptive load-shedding algorithm. If the delay of communication link would be in the range of one electrical cycle, the load-shedding operation will be acceptably fast. This speed is obtainable with the present day communication links such as fiber-optic communication link.

ii) To transmit trip signals to the suitable loads:

Once all loads to be shed are selected by the adaptive load-shedding algorithm, trip commands must be sent from the control centre to the proper loads. These trip commands must be transmitted as fast as possible. In this case, similar to the previous section, delays in the range of one cycle are acceptable. Ordinary communication links used in power systems such as PLC or radio link is acceptable but fiber-optic communication link is advisable for this purpose.

iii) To transmit the amount of active power of generators and loads:

Since both load-shedding algorithms require the amount of loads and also the second algorithm requires the amount of active power of each generator, these values must also be transmitted to the control centre every few minutes but instantly with time stamp when perturbation occurs.

3.3.3 Time Delay

For a successful load shedding method, right amount of load will be shed at right location definitely within right time. So time delay from the time of disturbance happening to final load shedding (t_{shed}) is very important and plays a prominent role in both frequency and voltage stability analysis. In this way, typical delays for different components of the load rejection process based on wide area infrastructure are given in Table 3.1 according to the equipment of Huawei Technologies Co., Bangladesh. As it can be seen, the total delay of 280 ms seems to be reasonable; nevertheless, in this paper, 400 ms is taken into account for the total delay of data gathering, computation, and trip signal transmission. Note that for tuning the new method in a real application, if the communication latency is available for a power network, $t_{\mathbf{shed}}$ is assumed to be equal to its value plus 100 ms as the safety margin. Otherwise, it is set to a typical value of t_{shed} = 250 ~ 300 ms.

Table 3.1: Delay calculation according to Huawei Technologies Co., Bangladesh

Sl. No.	Components of total delay	Typical time delay (ms)
1.	Time to read parameters/Measurements	<60
2.	Round-trip communication medium latency	<150
3.	Load circuit breaker operation	<30
4.	Computational burden of the method	<40
	Total delay (t_{shed})	**<280**

From the above explanation and discussion of developed methodology, the following unique features of the new scheme are evident:

(i) Measuring exact power disparity;
(ii) Shedding less loads in comparison to other techniques;
(iii) Extending the system frequency response (SFR) model incorporating dynamic load dependency to frequency and voltage conditions;

(iv) Considering a comprehensive load model for frequency and voltage stability assessments;

(v) Satisfying both dynamic and steady state frequency limitations;

(vi) Ensuring sufficient voltage stability margins;

(vii) Taking decision on real time system perturbation;

(viii) Requiring lower computational burden;

(ix) Taking in count voltage stability criteria for specifying the distribution of load curtailments;

The new dynamic-adaptive load shedding methodology can be adopted as a part of a defense plan against both voltage and frequency instability threats for a power system of any size.

CHAPTER 4

Test System Modeling

4.1 Introduction

"Obtaining maximum benefits from installed assets on an interconnected power system is becoming increasingly dependent on the coordinated use of automatic control systems. The ability to optimize the configuration of such control devices and their settings is dependent on having an accurate power system model, as well as controllers themselves" [23].

This compendious but neat quotation from a CIGRE report is cited here to signify the importance of having an accurate model of the system studied. Modern power systems are characterized by complex dynamic behaviors which are due to their amount and complexity. As the amount of a power system increases, its dynamic processes become more challenging for analysis as well as for an understanding of its underlying physical phenomena. Power systems, even in their simplest form, exhibit nonlinear and time-varying behaviors. Moreover, there is a wide variety of equipment in today's power systems. Though the kinds of equipment found in today's power systems are well-established and quite non-uniform in design, their precise modeling plays an important role in analysis and simulation studies of a whole system. Different approaches to system modeling lead to different analytical results and accuracy. Improper models may result in over-estimated stability margins which can be disastrous for system operation and control. This chapter is therefore devoted to describe the models of relevant power system components to a justified extent for IEEE-39 bus test system.

4.2 Test System Modeling

IEEE-39 bus test system which is also known as New England test system [9]. This system is widely used for power system stability studies. The system contains 39 buses with 10 generators. It has 19 load points totaling 6150.1 MW and 1233.9 Mvar. All the generators are modeled as 4th order synchronous generator model with IEEE type-2 exciter. A simple turbine governor is used in every generator except generator 1 which is an aggregation of large number of generators. The transmission lines of 345 kV and loads are modeled with typical system data. This test system is mostly used to study stability and power market problems.

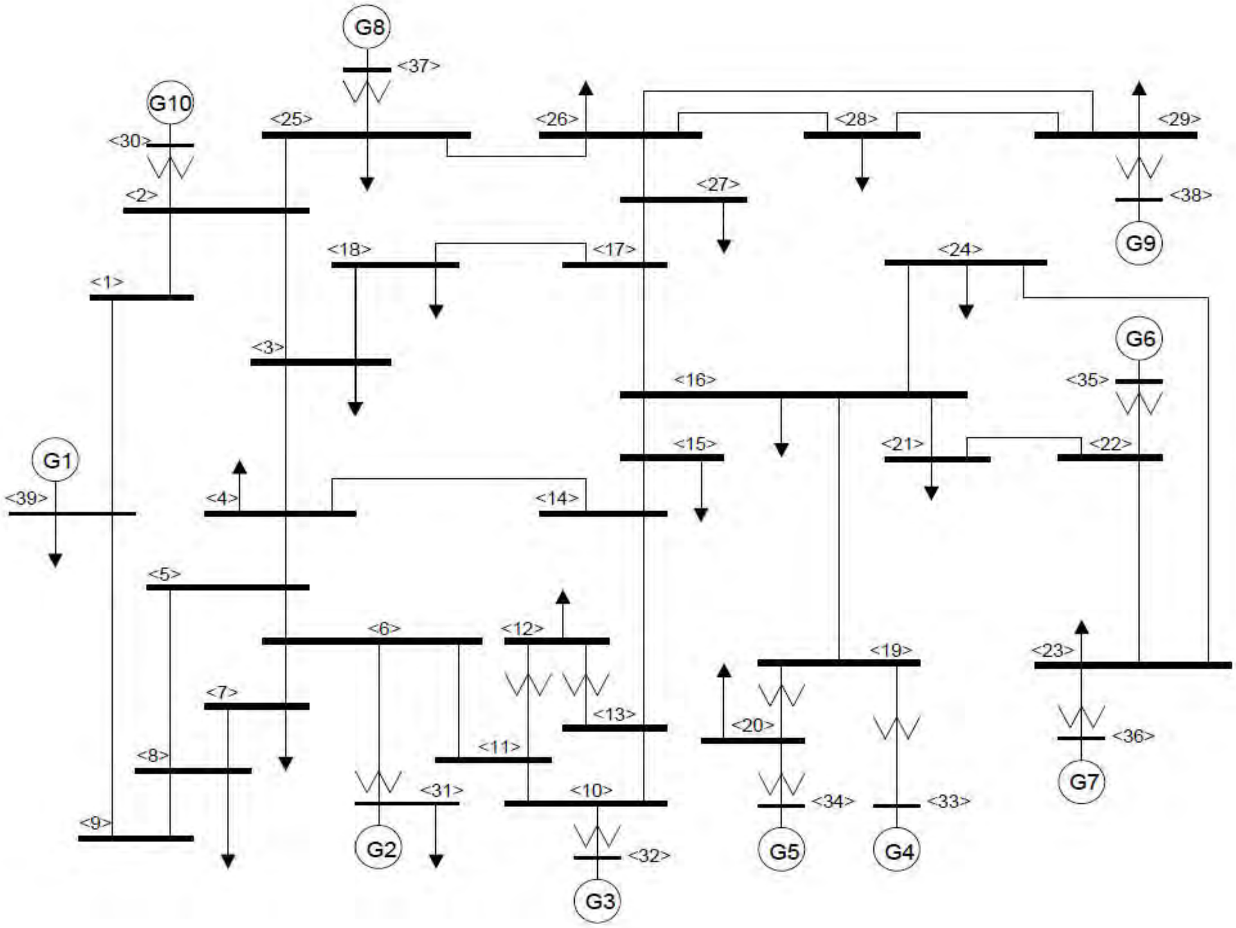

Figure 4.1: IEEE 39 Bus Test System (Modified) with zones

Figure 4.1 represents the IEEE 39 Bus Test System (Modified) with zones and the power system components of this test system have been modeled as follows.

4.2.1 Generators

Generator analysis was carried out using a fourth-order model, as shown in the equations below. Equations 1 through 4 model the generator, while the remaining equations relate various parameters.

$$\dot{E}'_q = \frac{1}{T'_{do}}(-E'_q - (x_d - x'_d)I_d + E_{fd}) \tag{4.1}$$

$$\dot{E}'_d = \frac{1}{T'_{qo}}(-E'_d + (x_q - x'_q)I_q) \tag{4.2}$$

$$\dot{\delta} = \omega$$

$$\dot{\omega} = \frac{1}{M}(T_{mech} - (\phi_d I_q - \phi_q I_d) - D_\omega) \tag{4.3}$$

$$
\left.\begin{aligned}
0 &= r_a I_d + \phi_q + V_d \\
0 &= r_a I_q - \phi_d + V_q \\
0 &= -\phi_d - x'_d I_d + E'_q \\
0 &= -\phi_q - x'_q I_q - E'_d
\end{aligned}\right\} \tag{4.4}
$$

$$
\left.\begin{aligned}
0 &= V_d \sin\delta + V_q \cos\delta - V_r \\
0 &= V_q \sin\delta - V_d \cos\delta - V_i \\
0 &= I_d \sin\delta + I_q \cos\delta - I_r \\
0 &= I_q \sin\delta - I_d \cos\delta - I_i
\end{aligned}\right\} \tag{4.5}
$$

Generator Parameter values for the test system (IEEE 39 Bus) model are shown in Table 4.1 and 4.2 on the system base MVA.The step-up unit transformers data of generators for test system modeling has been shown in Table 4.1.

Table 4.1: Generator Transformer Data of IEEE 39 Bus Test System

Bus No.		**Rated Power (MVA)**	**R (pu)**	**X(pu)**
From	**To**			
12	11	450	0.0072	0.196
12	13	450	0.0072	0.196
6	31	1000	0	0.250
10	32	1000	0	0.200
19	33	1000	0.007	0.142
20	34	600	0.0054	0.108
22	35	1000	0	0.143
23	36	1000	0.005	0.272
25	37	1000	0.006	0.232
2	30	1000	0	0.181
29	38	1000	0.008	0.156
19	20	1400	0.0098	0.1932

The static and dynamic data of generators for test system modeling has been shown in Table 4.2.

Table 4.2: Generator Data of IEEE 39 Bus Test System

Unit No.	**Rated Power (MW)**	**H (sec)**	**Ra (pu)**	**x'd (pu)**	**x'q (pu)**	**Xd (pu)**	**Xq (pu)**	**T'do (sec)**	**T'qo (sec)**	**Xl (pu)**
1	10000	5.000	0.000	0.600	0.800	2.000	1.900	7.000	0.700	0.300
2	1000	3.030	0.000	0.697	1.700	2.950	2.820	6.560	1.500	0.350
3	1000	3.580	0.000	0.531	0.876	2.495	2.370	5.700	1.500	0.304
4	1000	2.860	0.000	0.436	1.660	2.620	2.580	5.690	1.500	0.295
5	600	4.333	0.000	0.792	0.996	4.020	3.720	5.400	0.440	0.324
6	1000	3.480	0.000	0.500	0.814	2.540	2.410	7.300	0.400	0.224
7	1000	2.640	0.000	0.490	1.860	2.950	2.920	5.660	1.500	0.322
8	1000	2.430	0.000	0.570	0.911	2.900	2.800	6.700	0.410	0.280
9	1000	3.450	0.000	0.570	0.587	2.106	2.050	4.790	1.960	0.298
10	1000	4.200	0.000	0.310	0.080	1.000	0.690	10.200	0.000	0.125

4.2.2 Excitation System

All generators in the system are equipped with automatic voltage regulators (AVRs). We chose to use static AVRs with E_{fd} limiters. The model for this controller is shown in Figure 4.2.

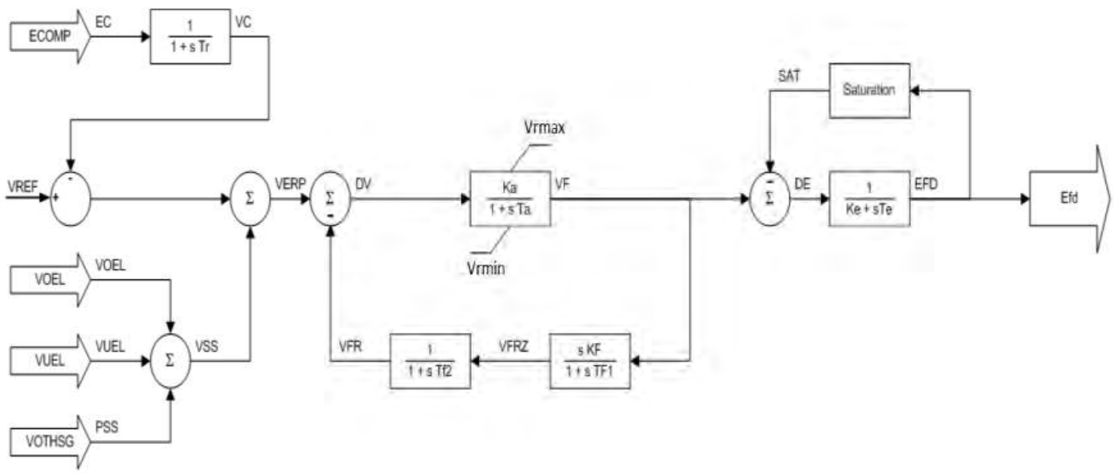

Figure 4.2: IEEE type 2 excitation system block diagram

The setting values of different parameters for IEEE type 2 excitation system are tabulated in table 4.3.

Table 4.3: IEEE type 2 excitation system parameters settings

Sl No.	Parameters Name	Parameters Unit	Parameters Description	Parameters value
1	Tr	Seconds	Filter time constant	0.3
2	Ka	pu	Regulator gain	30
3	Ta	Seconds	Regulator time constant	0.5
4	Vrmin	pu	Minimum voltage regulator outputs	0.5
5	Vrmax	pu	Maximum voltage regulator outputs	1.2
6	Ke	pu	Exciter constant related to self-excited field	0.5
7	Te	Seconds	Exciter time constant, integration rate associated with exciter control	0.5
8	KF	pu	Feedback gain	0.1
9	TF1	Seconds	Feedback time constant 1	0.9
10	TF2	Seconds	Feedback time constant 2	0.7
11	E1	pu	Exciter alternator output voltages back of commutating reactance at which saturation is defined	3.0
12	SE1	pu	Exciter saturation function value at the corresponding exciter voltage, E1, back of commutating reactance	0.03
13	E2	pu	Exciter alternator output voltages back of commutating reactance at which saturation is defined	4
14	SE2	pu	Exciter saturation function value at the corresponding exciter voltage, E2, back of commutating reactance	0.09

4.2.3 Speed Governor

IEEE Type 2 Speed-Governor Model is used in modeling of all governors for IEEE 39 bus test system.

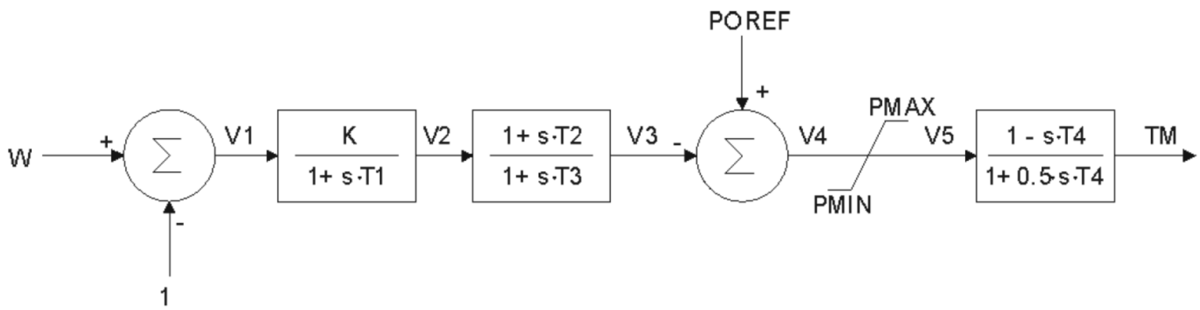

Figure 4.3: IEEE Type 2 speed-governing model

The setting values of different parameters for IEEE type 2 speed-governing model are tabulated in table 4.4.

Table 4.4: IEEE type 2 speeed-governor parameters setting

Sl No.	Parameters Name	Parameters Unit	Parameters Description	Parameters value
1	K	pu	Governor gain	10
2	T1	Seconds	Governor lag time constant	50
3	T2	Seconds	Governor lead time constant	5.0
4	T3	Seconds	Gate actuator time constant	0.5
5	T4	Seconds	Water starting time	1
6	PMAX	pu	Gate maximum	0.3
7	PMIN	pu	Gate minimum	3

4.2.4 Transmission Line

Network line impedances and line lengths data for the test system is shown in the following Table 4.5.

Table 4.5: Transmission Line Data

Bus No.		R1 (pu)	X1 (pu)	B1 (pu)	km	R1 (ohm/km)	X1 (ohm/km)	B1 (uS/km)	R0 (ohm/km)	X0 (ohm/km)	B0 (uS/km)
From	To										
1	2	0.0035	0.0411	0.6987	275.5	0.032	0.373	1.015	0.318	1.119	0.609
1	39	0.001	0.025	0.75	167.6	0.015	0.373	1.790	0.149	1.119	1.074
2	3	0.0013	0.0151	0.2572	101.2	0.032	0.373	1.017	0.321	1.119	0.610
2	25	0.007	0.0086	0.146	57.6	0.304	0.373	1.013	3.036	1.119	0.608
3	4	0.0013	0.0213	0.2214	142.8	0.023	0.373	0.620	0.228	1.119	0.372
3	18	0.0011	0.0133	0.2138	89.1	0.031	0.373	0.959	0.308	1.119	0.576
4	5	0.0008	0.0128	0.1342	85.8	0.023	0.373	0.626	0.233	1.119	0.375
4	14	0.0008	0.0129	0.1382	86.5	0.023	0.373	0.639	0.231	1.119	0.384
5	6	0.0002	0.0026	0.0434	17.4	0.029	0.373	0.996	0.287	1.119	0.598
5	8	0.0008	0.0112	0.1476	75.1	0.027	0.373	0.786	0.266	1.119	0.472
6	7	0.0006	0.0092	0.113	61.7	0.024	0.373	0.733	0.243	1.119	0.440
6	11	0.0007	0.0082	0.1389	55.0	0.032	0.373	1.011	0.318	1.119	0.607
7	8	0.0004	0.0046	0.078	30.8	0.032	0.373	1.012	0.324	1.119	0.607
8	9	0.0023	0.0363	0.3804	243.3	0.024	0.373	0.625	0.236	1.119	0.375
9	39	0.001	0.025	1.2	167.6	0.015	0.373	2.865	0.149	1.119	1.719
10	11	0.0004	0.0043	0.0729	28.8	0.035	0.373	1.012	0.347	1.119	0.607
10	13	0.0004	0.0043	0.0729	28.8	0.035	0.373	1.012	0.347	1.119	0.607
13	14	0.0009	0.0101	0.1723	67.7	0.033	0.373	1.018	0.332	1.119	0.611
14	15	0.0018	0.0217	0.366	145.4	0.031	0.373	1.007	0.309	1.119	0.604
15	16	0.0009	0.0094	0.171	63.0	0.036	0.373	1.086	0.357	1.119	0.651
16	17	0.0007	0.0089	0.1342	59.7	0.029	0.373	0.900	0.293	1.119	0.540
16	19	0.0016	0.0195	0.304	130.7	0.031	0.373	0.930	0.306	1.119	0.558
16	21	0.0008	0.0135	0.2548	90.5	0.022	0.373	1.126	0.221	1.119	0.676
16	24	0.0003	0.0059	0.068	39.5	0.019	0.373	0.688	0.190	1.119	0.413
17	18	0.0007	0.0082	0.1319	55.0	0.032	0.373	0.960	0.318	1.119	0.576
17	27	0.0013	0.0173	0.3216	116.0	0.028	0.373	1.109	0.280	1.119	0.666
21	22	0.0008	0.014	0.2565	93.8	0.021	0.373	1.093	0.213	1.119	0.656
22	23	0.0006	0.0096	0.1846	64.3	0.023	0.373	1.148	0.233	1.119	0.689
23	24	0.0022	0.035	0.361	234.6	0.023	0.373	0.616	0.234	1.119	0.369
25	26	0.0032	0.0323	0.513	216.5	0.037	0.373	0.948	0.370	1.119	0.569
26	27	0.0014	0.0147	0.2396	98.5	0.036	0.373	0.973	0.355	1.119	0.584
26	28	0.0043	0.0474	0.7802	317.7	0.034	0.373	0.982	0.338	1.119	0.589
26	29	0.0057	0.0625	1.029	418.9	0.034	0.373	0.983	0.340	1.119	0.590
28	29	0.0014	0.0151	0.249	101.2	0.035	0.373	0.984	0.346	1.119	0.590

4.2.5 Power and Voltage Setpoints

Table 4.6 contains power and voltage setpoint data for base network of IEEE 39 Bus test system. Generator 2 is the swing node, and Generator 1 represents the aggregation of a large number of generators. Since the following data are for base network hence load values and generations are changed rather different in different scenarios.

Table 4.6: Power and Voltage Setpoints

Bus	**Type**	**Voltage**	**Load**		**Generator**		
		pu	MW	MVar	MW	MVar	Unit
1	PQ	-	0	0	0	0	-
2	PQ	-	0	0	0	0	-
3	PQ	-	322	2.4	0	0	-
4	PQ	-	500	184	0	0	-
5	PQ	-	0	0	0	0	-
6	PQ	-	0	0	0	0	-
7	PQ	-	233.8	84	0	0	-
8	PQ	-	522	176	0	0	-
9	PQ	-	0	0	0	0	-
10	PQ	-	0	0	0	0	-
11	PQ	-	0	0	0	0	-
12	PQ	-	7.5	88	0	0	-
13	PQ	-	0	0	0	0	-
14	PQ	-	0	0	0	0	-
15	PQ	-	320	153	0	0	-
16	PQ	-	329	32.3	0	0	-
17	PQ	-	0	0	0	0	-
18	PQ	-	158	30	0	0	-
19	PQ	-	0	0	0	0	-
20	PQ	-	628	103	0	0	-
21	PQ	-	274	115	0	0	-
22	PQ	-	0	0	0	0	-
23	PQ	-	247.5	84.6	0	0	-
24	PQ	-	308.6	92	0	0	-
25	PQ	-	224	47.2	0	0	-
26	PQ	-	139	17	0	0	-
27	PQ	-	281	75.5	0	0	-
28	PQ	-	206	27.6	0	0	-
29	PQ	-	283.5	26.9	0	0	-
30	PV	1.0475	0	0	250	-	Gen10
31	PV	0.982	9.2	4.6	-	-	Gen2
32	PV	0.9831	0	0	650	-	Gen3
33	PV	0.9972	0	0	632	-	Gen4
34	PV	1.0123	0	0	508	-	Gen5
35	PV	1.0493	0	0	650	-	Gen6
36	PV	1.0635	0	0	560	-	Gen7
37	PV	1.0278	0	0	540	-	Gen8
38	PV	1.0265	0	0	830	-	Gen9
39	PV	1.03	1104	250	1000	-	Gen1

4.2.6 Load Modeling

In power systems, electrical load consists of various different types of electrical devices, from incandescent lamps and heaters to large arc furnaces and motors. It is often very difficult to identify the exact composition of static and dynamic loads in the network. The load composition can also vary depending on factors such as the season, time of day etc. A common polynomial ZIP load model is used to study the test system stability as follows.

$$\mathbf{P} = P_0[\, a_1 + a_2 \left(\frac{U}{U0}\right)^1 + (1 - a_1 - a_2)\left(\frac{U}{U0}\right)^2 \,]\,(1+K_{pf}\Delta f) \quad (4.6)$$

$$\mathbf{Q} = Q_0[\, a_3 + a_4 \left(\frac{U}{U0}\right)^1 + (1 - a_3 - a_4)\left(\frac{U}{U0}\right)^2 \,]\,(1+K_{qf}\Delta f) \quad (4.7)$$

Where,

U_0 is the rated voltage magnitude of the load studied;

U is the actual voltage magnitude of the load studied;

P_0/Q_0 is the rated active/reactive load power;

P/Q is the actual active/reactive load power;

Δf is the frequency variation of the system;

K_{pf}/K_{qf} is the frequency sensitivity factor of the active/reactive load power ;

The frequency and voltage dependency of loads are considered to reflect the scenario of real time power system. The subscript '0' indicates the Operating Point values as defined on the Load Flow page of the load element dialog.

Table 4.7: Exponent value for ZIP load model

Sl.	Exponent	Constant
1	0	Power
2	1	Current
3	2	Impedance

Table 4.7 shows the values for the exponents in order to model constant power, constant current and constant impedance load. The relative proportion of each coefficient can be freely defined using the coefficientsa_1, a_2, a_3 and a_4.

In our all studies on test system, we have put

$a_1 = a_2 = a_3 = a_4 = 0$ *{ To make the constant impedance load }*

K_{pf} =K_{qf} = 1.5 { It means 1% change in frequency will cause 1.5% change in active/reactive load }

But the values of P_0 and Q_0 are varied in our studies because of voltage and frequency sensitivities.

4.3 Test System withZones

Every power system is divided in several operational zones or areas. Zones or areas are usually formed based on geographical proximity of generation and loads. It can be assumed that generators in a zone are coherent. In our test system, there are six zones. Zones are shown in the following Figure 4.4.

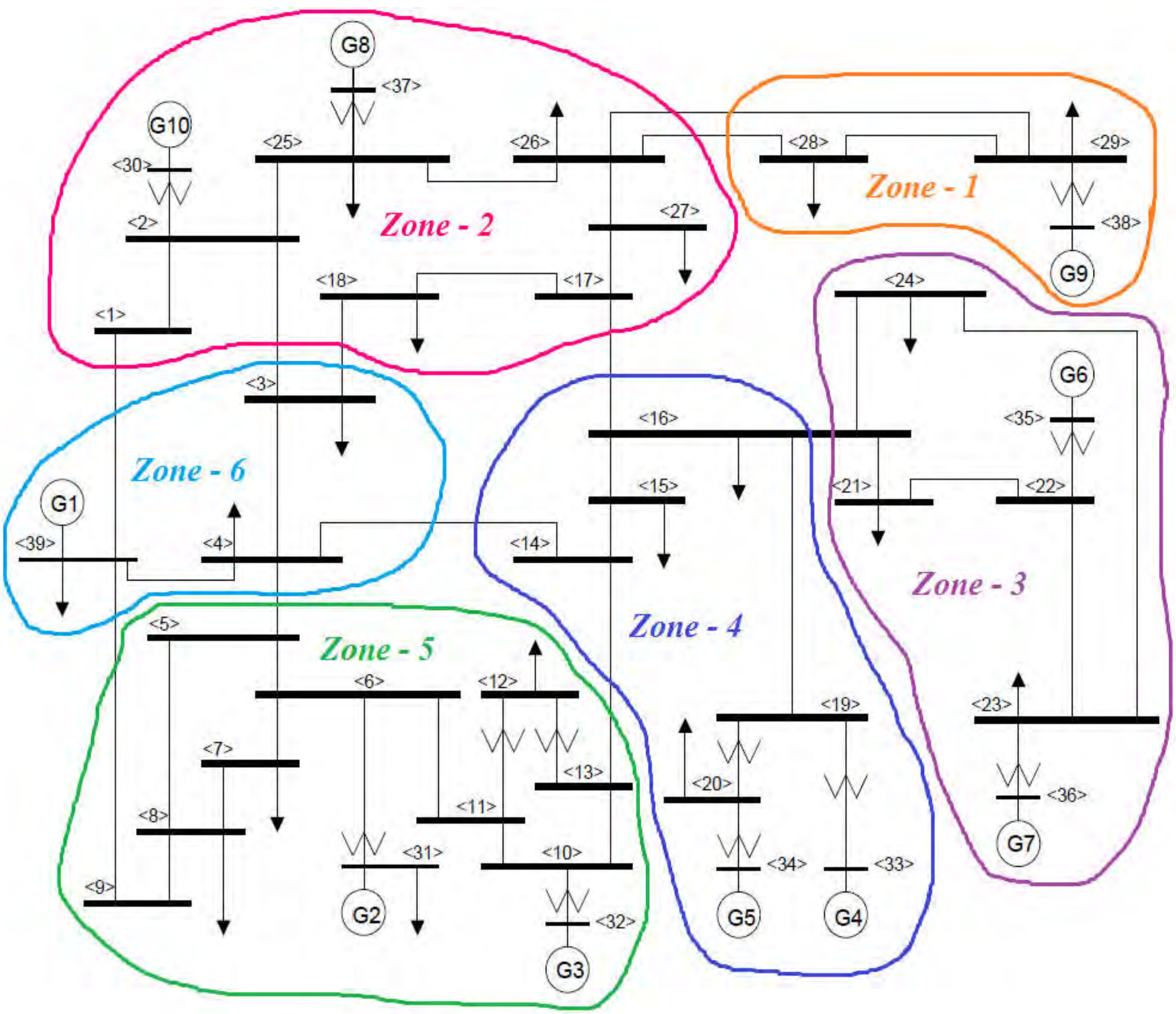

Figure 4.4: IEEE 39 Bus Test System (Modified) with zones

4.4 Tool for Simulation

In this work, Python scripting and DIgSILENT PowerFactory software are used. PowerFactory software allows smooth integration of Python language with existing systems.

DIgSILENT PowerFactory has set standards and trends in power system modeling, analysis and simulation. The proven advantages of PowerFactory software are its overall functional integration, its applicability to the modeling. PowerFactory offers a complete suite of functions for studying large interconnected power systems and addressing these emerging needs. Its fast and robust simulation algorithms can be applied to any AC or DC network topology and support the simulation of new technologies. PowerFactory is also perfectly suited to transmission system operation planning.

The Python scripting language can be used in PowerFactory to perform the following actions:

• Automate tasks

• Create user defined calculation commands

• Integrate PowerFactory into other applications

Since the proposed methodology is dynamic-adaptive and the load shed amount along with fedders are prudently selected hence the user-defined transient simulation in PowerFactory will not do work here. Python scripting is very strong tool for controlled simulation and analysis in PowerFactory software. That's why, writing the python script for implementing the proposed method will be a great task. The DSL (Digsilent Simulation Language) will be used for power plant modeling where the generator will be equipped with turbine-governor and exciter/AVR. Then the whole Blackout remedial methodology will be validated under different credible scenarios in "Digsilent PowerFactory" environment by python scripting.

CHAPTER 5

Implementation of Proposed Methodology

5.1 Introduction

Satisfactory operation of a power system requires balance in both the active and reactive power which corresponds to two equilibrium points: frequency and voltage. When either of the two balances is broken and reset at a new level, the equilibrium points will float. Grid blackouts experienced around the world in recent years shows that power systems require careful consideration of stability problems and needs more effective and robust blackout remedial strategies. The blackout protection scheme based on only offline simulation is not guaranteed for successful work in real time situation without knowing the present state variables of real time network. To overcome this problem the proposed methodology has taken all important state variables to be checked for strict and controlled load shedding [4]. The technique proposed in this section is a heuristic one that considers magnitude of frequency upset, load damping factor, frequency deviation, rate of change of frequency (ROCOF), bus ranking for taking care voltage stability and controlled load shed. It develops a comprehensive solution to the short term frequency instability for any power system amount.

The proposed methodology is tested here through python scripting based computer simulation. For network modeling and simulation, a powerful transmission system study software named ‘Digsilent PowerFactory’ is used. This software has many strong and useful features including ‘Digsilent programming Language (DPL)’, Digsilent Simulation Language (DSL). Exciter and Governor-turbine of our test system are modeled by using DSL. Digsilent PowerFactory also supports python scripting. Python scripting is now widely used to take control over the time domain simulation for power system analysis. The scripting language approach intrinsically promotes the reusability of the code and is suitable for quickly developing small applications and/or extensions of existing projects.

In this research, each step of proposed blackout remedial methodology is coded by python scripting language and the the script is called from as well as executed by Digsilent PowerFactory. Digsilent PowerFactory shows calculation in each step from measuring and updating the required state variables to final feeder selection of every zone. This software also shows the frequency dynamics of the whole system before and after tripping the selected feeders.

There are fourdifferent case scenarios we have considered for validation of proposed methodology. Case scenarios are;

- Case-1: 600 MW Loss
- Case-2: 900 MW Loss
- Case-3: 1200 MW Loss
- Case-4: Tie Line Security

The above scenarios show that the methodology works for small to larger perturbation and justify the robustness of the proposed methodology. In all the cases we observe that the methodology works successfully with taking care of frequency as well as voltage stability and tries to arrest the frequency before the threshold point with reduced load shed.

5.2 Implementation of proposed Methodology

The detail description of Test System modeling is in chapter-4. The proposed scheme is implemented sequentially. The following things are presumed before implementation of proposed methodology based on centralized state variables monitoring.

(i) The power system has six zones.

(ii) Every zone has defined boundary. Zones are defined here based on geographical proximity of generators.

(iii) High speed communication system (Fiber optic) belongs to the power system.

(iv) PMU are installed at every candidate PQ and PV/Slack Buses only.

(v) The load power in a node may change with the variation of the frequency in this node. This is part of load characteristics and called as load damping factor (D). Since the value of 'D'varies from 1% - 3% hence it is assumed that the value of 'D' for the test system is 1.5% . It means 1% change in frequency will cause 1.5% change in active load.

(vi) The minimum and maximum threshold frequency of a power system is determined by machine endurance frequency, Grid code, power quality, empirical knowledge on system behavior and etc. The threshold frequency, f_{TH} is defined as that limiting frequency below which the power system may embrace frequency instability. Here it is assumed, the proposed method will assure that the nadir point of frequency transient will not go below the threshold frequency (fTH) 49.1 Hz for the test system.

(vii) The critical power disparity value (ε) in step-2 is determined based on empirical knowledge, experience, generator amount and etc. The value of 'ε' is critical which will trigger frequency instability. It indicates generation's real power change in percentage. Intentional or scheduled generation ramp rate should be lower than 'ε'**.** For our cases, it is assumed 0.15 or 15% for all generator Buses.

(viii) The allowable disparity between estimated and actual load shed amount at zonal level ($Ɛ_z$) and Bus level ($Ɛ_b$) is assumed here one MW.

.

The following state variables are monitored centrally:

a) Frequency.
b) Rate of Change of Frequency (ROCOF).
c) PQ Bus voltage and reactive power.
d) PV Bus active power.

There are four cases studied on New England test system to understand the novelty of the proposed methodology. The first case will be described here in details to focus on every step of proposed methodology and case two and three will prove that the proposed method works well for any amount of perturbation.

5.2.1 Case-1: 600 MW Loss

In this scenario 600 MW generation outage is happened in zone-3. Total generation is 6243 MW and all transmission lines are in operation. In healthy condition, buses are ranked according to

```
Load ID : z2_s27_13 = 50.00 MW & 10.00 MVAR
Load ID : z2_s27_12 = 30.00 MW & 11.00 MVAR
Load ID : z2_s27_11 = 70.00 MW & 20.00 MVAR
Load ID : z2_s27_16 = 60.00 MW & 20.00 MVAR
Load ID : z2_s27_15 = 21.00 MW & 5.00 MVAR
Load ID : z2_s27_14 = 50.00 MW & 10.00 MVAR
Bus V = 0.977598
Bus Q = 75.999999
FVSI z2_s27 = 0.047714
---------------------
Load ID : z3_s16_17 = 29.00 MW & 1.00 MVAR
Load ID : z3_s16_16 = 100.00 MW & 10.00 MVAR
Load ID : z3_s16_15 = 20.00 MW & -0.00 MVAR
Load ID : z3_s16_12 = 70.00 MW & 5.00 MVAR
Load ID : z3_s16_13 = 50.00 MW & 5.00 MVAR
Load ID : z3_s16_14 = 30.00 MW & 5.00 MVAR
Load ID : z3_s16_11 = 30.00 MW & 6.00 MVAR
Bus V = 0.970215
Bus Q = 32.000000
FVSI z3_s16 = 0.020397
---------------------
Load ID : z3_s21_16 = 74.00 MW & 23.00 MVAR
Load ID : z3_s21_15 = 20.00 MW & 10.00 MVAR
Load ID : z3_s21_14 = 30.00 MW & 15.00 MVAR
Load ID : z3_s21_13 = 50.00 MW & 23.00 MVAR
Load ID : z3_s21_12 = 30.00 MW & 14.00 MVAR
Load ID : z3_s21_11 = 70.00 MW & 30.00 MVAR
Bus V = 0.952903
Bus Q = 115.000000
FVSI z3_s21 = 0.075989
---------------------
Load ID : z3_s22_11 = 100.00 MW & 20.00 MVAR
Load ID : z3_s22_12 = 30.00 MW & 5.00 MVAR
Load ID : z3_s22_13 = 70.00 MW & 15.00 MVAR
Load ID : z3_s22_15 = 20.00 MW & 5.00 MVAR
Load ID : z3_s22_14 = 30.00 MW & 5.00 MVAR
Bus V = 0.982603
Bus Q = 50.000000
FVSI z3_s22 = 0.031072
---------------------
Load ID : z3_s23_16 = 20.00 MW & 20.00 MVAR
Load ID : z3_s23_15 = 15.00 MW & 4.00 MVAR
Load ID : z3_s23_14 = 50.00 MW & 10.00 MVAR
Load ID : z3_s23_13 = 50.00 MW & 15.00 MVAR
Load ID : z3_s23_11 = 82.00 MW & 25.00 MVAR
Load ID : z3_s23_12 = 30.00 MW & 11.00 MVAR
Bus V = 0.970584
Bus Q = 85.000000
FVSI z3_s23 = 0.054138
Load ID : z3_s24_11 = 120.00 MW & 25.00 MVAR
Load ID : z3_s24_12 = 73.00 MW & 15.00 MVAR
Load ID : z3_s24_13 = 50.00 MW & 13.00 MVAR
Load ID : z3_s24_16 = 15.00 MW & -0.00 MVAR
Load ID : z3_s24_15 = 20.00 MW & 5.00 MVAR
Load ID : z3_s24_14 = 30.00 MW & 10.00 MVAR
Bus V = 0.959222
Bus Q = 68.000000
FVSI z3_s24 = 0.044343
---------------------
Load ID : z4_s14_11 = 110.00 MW & 40.00 MVAR
Load ID : z4_s14_12 = 85.00 MW & 20.00 MVAR
Load ID : z4_s14_13 = 55.00 MW & 15.00 MVAR
Load ID : z4_s14_14 = 45.00 MW & 10.00 MVAR
Load ID : z4_s14_16 = 25.00 MW & 5.00 MVAR
Load ID : z4_s14_15 = 30.00 MW & 10.00 MVAR
Bus V = 0.952720
Bus Q = 100.000000
FVSI z4_s14 = 0.066103
---------------------
Load ID : z4_s15_11 = 100.00 MW & 45.00 MVAR
Load ID : z4_s15_12 = 70.00 MW & 30.00 MVAR
Load ID : z4_s15_13 = 55.00 MW & 30.00 MVAR
Load ID : z4_s15_14 = 45.00 MW & 20.00 MVAR
Load ID : z4_s15_16 = 20.00 MW & 13.00 MVAR
Load ID : z4_s15_15 = 30.00 MW & 15.00 MVAR
Bus V = 0.935028
Bus Q = 153.000000
FVSI z4_s15 = 0.105001
---------------------
Load ID : z4_s20_11 = 200.00 MW & 50.00 MVAR
Load ID : z4_s20_12 = 100.00 MW & 23.00 MVAR
Load ID : z4_s20_13 = 78.00 MW & -0.00 MVAR
Load ID : z4_s20_14 = 50.00 MW & -0.00 MVAR
Load ID : z4_s20_17 = 150.00 MW & 30.00 MVAR
Load ID : z4_s20_15 = 30.00 MW & -0.00 MVAR
Load ID : z4_s20_16 = 20.00 MW & -0.00 MVAR
Bus V = 0.959811
Bus Q = 103.000000
FVSI z4_s20 = 0.067084
---------------------
Load ID : z5_s7_11 = 35.00 MW & 10.00 MVAR
Load ID : z5_s7_12 = 34.00 MW & 20.00 MVAR
Load ID : z5_s7_13 = 50.00 MW & 14.00 MVAR
Load ID : z5_s7_15 = 20.00 MW & 10.00 MVAR
Load ID : z5_s7_14 = 90.00 MW & 30.00 MVAR
Bus V = 0.957612
Bus Q = 84.000000
FVSI z5_s7 = 0.054961
```

Figure 5.1: FVSI of PQ Buses in output window of PowerFactory with Bus's feeder load

the FVSI and FVSI is calculated in FVSI Subroutine. FVSI Subroutineis coded by python scripting in PowerFactory environment and FVSI values are printed on output window of PowerFactory along with the feeder's load of respective buses as shown in Figure 5.1 and 5.2. In the output window, FVSI z2_s27means that, the voltage index is for bus no.27 and the bus is in zone-2.

```
Load ID : z1_s28_14 = 50.00 MW & 6.00 MVAR
Load ID : z1_s28_13 = 20.00 MW & 4.00 MVAR
Load ID : z1_s28_12 = 30.00 MW & 4.00 MVAR
Load ID : z1_s28_11 = 60.00 MW & 6.00 MVAR
Load ID : z1_s28_15 = 30.00 MW & 4.00 MVAR
Load ID : z1_s28_16 = 16.00 MW & 2.00 MVAR
Load ID : z1_s28_17 = 10.00 MW & 1.00 MVAR
Bus V = 1.018745
Bus Q = 26.999999
FVSI_s28 = 0.015609
---------------------
Load ID : z1_s29_16 = 80.00 MW & 7.00 MVAR
Load ID : z1_s29_15 = 33.00 MW & 3.00 MVAR
Load ID : z1_s29_14 = 50.00 MW & 20.00 MVAR
Load ID : z1_s29_11 = 70.00 MW & 7.00 MVAR
Load ID : z1_s29_12 = 30.00 MW & 3.00 MVAR
Load ID : z1_s29_13 = 50.00 MW & 4.00 MVAR
Bus V = 1.020501
Bus Q = 43.999999
FVSI_s29 = 0.025350
---------------------
Load ID : z2_s18_12 = 30.00 MW & 6.00 MVAR
Load ID : z2_s18_13 = 23.00 MW & 6.00 MVAR
Load ID : z2_s18_15 = 30.00 MW & 6.00 MVAR
Load ID : z2_s18_14 = 25.00 MW & 6.00 MVAR
Load ID : z2_s18_11 = 50.00 MW & 6.00 MVAR
Bus V = 0.975227
Bus Q = 30.000000
FVSI z2_s18 = 0.018926
---------------------
Load ID : z2_s25_12 = 60.00 MW & 7.00 MVAR
Load ID : z2_s25_11 = 40.00 MW & 15.00 MVAR
Load ID : z2_s25_14 = 50.00 MW & 7.00 MVAR
Load ID : z2_s25_13 = 50.00 MW & 15.00 MVAR
Load ID : z2_s25_15 = 24.00 MW & 3.00 MVAR
Bus V = 1.005443
Bus Q = 47.000000
FVSI z2_s25 = 0.027896
---------------------
Load ID : z2_s26_12 = 30.00 MW & 4.00 MVAR
Load ID : z2_s26_11 = 50.00 MW & 6.00 MVAR
Load ID : z2_s26_16 = 11.00 MW & 1.00 MVAR
Load ID : z2_s26_15 = 15.00 MW & 2.00 MVAR
Load ID : z2_s26_14 = 10.00 MW & 1.00 MVAR
Load ID : z2_s26_13 = 20.00 MW & 3.00 MVAR
Bus V = 1.008320
Bus Q = 17.000000
FVSI z2_s26 = 0.010032
```

```
Load ID : z5_s8_15 = 20.00 MW & 9.00 MVAR
Load ID : z5_s8_14 = 30.00 MW & 7.00 MVAR
Load ID : z5_s8_13 = 50.00 MW & 10.00 MVAR
Load ID : z5_s8_12 = 70.00 MW & 20.00 MVAR
Load ID : z5_s8_11 = 100.00 MW & 40.00 MVAR
Load ID : z5_s8_19 = 47.00 MW & 20.00 MVAR
Load ID : z5_s8_18 = 90.00 MW & 30.00 MVAR
Load ID : z5_s8_17 = 100.00 MW & 40.00 MVAR
Load ID : z5_s8_16 = 15.00 MW & -0.00 MVAR
Bus V = 0.936471
Bus Q = 176.000000
FVSI z5_s8 = 0.120413
---------------------
Load ID : z5_s12_11 = 41.00 MW & 20.00 MVAR
Load ID : z5_s12_12 = 15.00 MW & 5.00 MVAR
Load ID : z5_s12_13 = 25.00 MW & 10.00 MVAR
Load ID : z5_s12_14 = 25.00 MW & 10.00 MVAR
Load ID : z5_s12_16 = 10.00 MW & 5.00 MVAR
Load ID : z5_s12_15 = 7.00 MW & 4.00 MVAR
Bus V = 0.983709
Bus Q = 54.000000
FVSI z5_s12 = 0.033482
---------------------
Load ID : z6_s3_12 = 50.00 MW & -0.00 MVAR
Load ID : z6_s3_13 = 100.00 MW & -0.00 MVAR
Load ID : z6_s3_14 = 25.00 MW & -0.00 MVAR
Load ID : z6_s3_15 = 15.00 MW & -0.00 MVAR
Load ID : z6_s3_17 = 90.00 MW & -0.00 MVAR
Load ID : z6_s3_16 = 12.00 MW & -0.00 MVAR
Load ID : z6_s3_11 = 30.00 MW & 3.00 MVAR
Bus V = 0.980451
Bus Q = 3.000000
FVSI z6_s3 = 0.001872
---------------------
Load ID : z6_s4_17 = 150.00 MW & 30.00 MVAR
Load ID : z6_s4_16 = 20.00 MW & -0.00 MVAR
Load ID : z6_s4_15 = 30.00 MW & 14.00 MVAR
Load ID : z6_s4_14 = 50.00 MW & 20.00 MVAR
Load ID : z6_s4_13 = 80.00 MW & 30.00 MVAR
Load ID : z6_s4_11 = 100.00 MW & 50.00 MVAR
Load ID : z6_s4_12 = 70.00 MW & 40.00 MVAR
Bus V = 0.931222
Bus Q = 184.000000
FVSI z6_s4 = 0.127310
Load ID : z6_s39_14 = 50.00 MW & 5.00 MVAR
Load ID : z6_s39_13 = 84.00 MW & 2.00 MVAR
Load ID : z6_s39_12 = 90.00 MW & 20.00 MVAR
Load ID : z6_s39_11 = 150.00 MW & 50.00 MVAR
Load ID : z6_s39_15 = 30.00 MW & 3.00 MVAR
Load ID : z6_s39_16 = 20.00 MW & 2.00 MVAR
Load ID : z6_s39_17 = 15.00 MW & 3.00 MVAR
Load ID : z6_s39_19 = 40.00 MW & 12.00 MVAR
Load ID : z6_s39_18 = 25.00 MW & 3.00 MVAR
Bus V = 0.981752
Bus Q = 100.000000
FVSI z6_s39 = 0.062251
```

Figure 5.2: FVSI of PQ Buses in output window of PowerFactory with Bus's feeder load

From the above python script generated FVSI data, the scheme finds the the actual value of FVSI [$\mathbf{FVSI_{zk}}$] and normalized value of FVSI [$\mathbf{FVSI_{z\_k}}$] and bus ranking according to their [$\mathbf{FVSI_{z\_k}}$] within a zone. The buses are ranked from weakest to strongest. The methodology coded by python scripting automatically keep the data and dynamically update the voltage indexing data for bus ranking in a zone as shown in Table 5.1.

Table 5.1: Bus ranking according to the voltage stability index in a zone

Sl.	Zone No.	Zone PQ Bus No.	$FVSI_{zk}$	$FVSI_{z\_k}$	Bus Ranking
1.	Zone -1	Bus 28	0.015609	0.381094	2
		Bus 29	0.02535	0.618906	1
2.	Zone-2	Bus 18	0.018926	0.180993	3
		Bus 25	0.027896	0.266770	2
		Bus 26	0.010032	0.095941	4
		Bus 27	0.047714	0.456296	1
3.	Zone-3	Bus 16	0.020397	0.090276	5
		Bus 21	0.075989	0.336326	1
		Bus 22	0.031072	0.137523	4
		Bus 23	0.054138	0.239615	2
		Bus 24	0.044343	0.196260	3
4.	Zone-4	Bus 14	0.066103	0.277525	3
		Bus 15	0.105001	0.440833	1
		Bus 20	0.067084	0.281642	2
5.	Zone-5	Bus 7	0.054961	0.263150	2
		Bus 8	0.120413	0.576538	1
		Bus 12	0.033482	0.160312	3
6.	Zone-6	Bus 3	0.001872	0.009781	3
		Bus 4	0.12731	0.665034	1
		Bus 39	0.062251	0.325184	2

To understand the robustness of proposed methodology, let 600 MW generation is lost suddenly at 0.1 sec of generator-7 (G-7) in zone-3. According to the equation (4.2) of Step-2, the power imbalance is greater than critical power disparity value **[ε].** So,the proposed scheme understands that it is a real MW loss and then calculates the total load shed amount($\mathbf{P_{shed}}$) by equation (4.8) of Step-5.

```
Gen Loss = 600.000000
System Load shed size = 446.000000 to arrest frequency before 49.1Hz & taking D=1.5%
```

$P_{shed}$is eventually less than generation loss (600 MW). The scheme calculates whole system load shed amount(P_{shed}) is 446 MW to keep the frequency within threshold frequency (f_{TH}) 49.1 Hz. The Magnitude of Load shed is minimum and accurate to prevent the blackout. Now the total load shed(446 MW) will be distributed across the whole power system according to the disturbance magnitude in each area/zone. The Scheme then computes to what extent each zone is perturbed because of power mismatch in the system.

Definitely, Zone-3 will experience highest rate of frequency decline and other zones will experience perturbation according to their electrical distance and machine inertia. Higher slop means higher disturbance, consequently higher load will be shed in that zone. The scheme computes the disturbance magnitude by using equation (3.9) and (3.10) as follows in PowerFactory environment. The df/dt values of each zone are also tabulated in Table 5.2.

```
df/dt_coi of Zone-1 -0.008863
df/dt_coi of Zone-2 -0.010110
df/dt_coi of Zone-3 -0.030433
df/dt_coi of Zone-4 -0.020086
df/dt_coi of Zone-5 -0.010760
df/dt_coi of Zone-6 -0.001532
```

We can see in Figure 5.3 that, since the generation loss occurs in zone-3, hence the rate of COI frequency decline in zone-3 is highest and the disturbance severity is lowest in zone-6 as it is electrically more distant from the disturbance source.

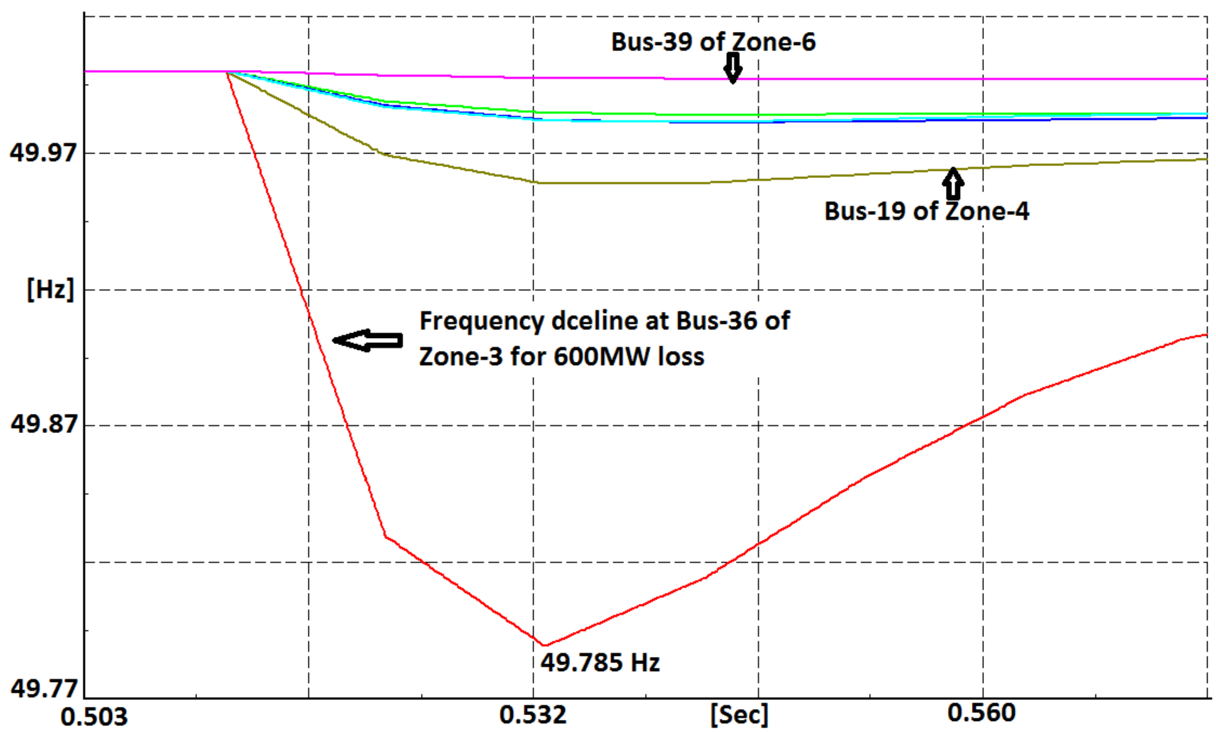

Figure 5.3: Frequency decline of different buses of different Zones for case-1

Zonal rate of COI frequency decline is a good indicator to understand the severity of disturbance. So, more disturbed zone will contribute more in load shedding. According to the depth of perturbation of each zone just after sudden generation loss, the scheme calculates the zonal/area disturbance weight by using the equation (3.11) of step-8 as follows in PowerFactory environment. The disturbance weight of each zone is also tabulated in Table 5.2.

```
Zone-1 disturbance Weight =  = 0.108376
Zone-2 disturbance Weight =  = 0.123614
Zone-3 disturbance Weight =  = 0.372107
Zone-4 disturbance Weight =  = 0.245601
Zone-5 disturbance Weight =  = 0.131567
Zone-6 disturbance Weight =  = 0.018734
```

It is evident that disturbance weight for zone-3 is highest as the disturbance happened in this area. So, highest portion of total load shed amount (P_{shed}) will be applied for that zone. Similarly, the disturbance weight for zone-6 is the lowest as the zone is electrically more distant from disturbed zone. So, lowest portion of total load shed amount(P_{shed}) will be applied for zone-6. By using equation (3.12) of step-9**,** the zonal load shed amounts are finalized by the scheme to recover short-term frequency stability in PowerFactory environmentas follows.

```
Gen Loss = 600.000000
System Load shed size = 446.000000 to arrest frequency before 49.1Hz & taking D=1.5%
Zone-1_LS =  = 48.000000 MW
Zone-2_LS =  = 55.000000 MW
Zone-3_LS =  = 166.000000 MW
Zone-4_LS =  = 110.000000 MW
Zone-5_LS =  = 59.000000 MW
Zone-6_LS =  = 8.000000 MW
```

Table 5.2 shows all calculation from disturbance severity to zonal load shed amount at a glance.

Table 5.2: Zonal Load shed amount

Zone No.	**Rate of Frequency Decline**	**Zonal Disturbance Weight [W_z]**	**Zonal Load Shed Amount [$Load_z$]**
Zone-1	-0.0088630	0.108376	48 MW
Zone-2	-0.0101097	0.123614	55 MW
Zone-3	-0.0304330	0.372107	166 MW
Zone-4	-0.0200860	0.245601	110 MW
Zone-5	-0.0107601	0.131567	59 MW
Zone-6	-0.0015320	0.018734	8 MW
	Total Load Shed Amount[P_{shed}]		**446 MW**

Now the zonal load shed amount will be distributed among the PQ buses of respective zones according to their voltage stability index. Weakest bus will shed most load and strongest bus will shed less load.

All PQ buses within a respective zone will shed load according to their ranking in Table 5.1 to take care of combinational disturbance. But the total load shed in PQ buses of a specified zone must be equal (or very close) to that zonal load shed amount($Load_z$). Therefore, the scheme computes the load-shed amount for each bus(B_{zk}) in a zone by equation (3.13) of step-10.

The distribution of zonal load shed amount within their own PQ buses is tabulated in Table 5.3. The python coded script automatically calculates all PQ buses load shed amount from zonal load shed amountto take care of combinational disturbance.

Table 5.3: Bus load shed amount according to their FVSI

Sl.	Zone No.	Zonal Load Shed Amount [$Load_z$]	Zone PQ Bus No.	$FVSI_{z\_k}$	Bus Ranking in zone	Bus Load Shed Amount[B_{zk}]
1.	Zone -1	48 MW	Bus 28	0.381094	2	18 MW
			Bus 29	0.618906	1	30 MW
2.	Zone-2	55 MW	Bus 18	0.180993	3	10 MW
			Bus 25	0.266770	2	15 MW
			Bus 26	0.095941	4	05 MW
			Bus 27	0.456296	1	25 MW
3.	Zone-3	166 MW	Bus 16	0.090276	5	15 MW
			Bus 21	0.336326	1	56 MW
			Bus 22	0.137523	4	23 MW
			Bus 23	0.239615	2	40 MW
			Bus 24	0.196260	3	33 MW
4.	Zone-4	110 MW	Bus 14	0.277525	3	31 MW
			Bus 15	0.440833	1	48 MW
			Bus 20	0.281642	2	31 MW
5.	Zone-5	59 MW	Bus 7	0.263150	2	16 MW
			Bus 8	0.576538	1	34 MW
			Bus 12	0.160312	3	09 MW
6.	Zone-6	08 MW	Bus 3	0.009781	3	00 MW
			Bus 4	0.665034	1	05 MW
			Bus 39	0.325184	2	03 MW

Since the scheme is sanctioned already the PQ buses load shedding amount in above hence the scheme will now find the feeder or feeders at respective buses close to their sanctioned load shed amount. It is really a big task to select the feeders dynamically to fit the load shed amount correctly.

For example, we can see in Table 5.3, 30MW loads have to shed from bus-29 as it is a weakest bus and ranked one in zone-1. The scheme will find the feeders to fit 30MW from the look-up table of feeders connected to bus-29. Now let us see the feeders load connected to bus-29 just before disturbance. From Figure 5.2, we find that there are six feeders connected to bus -29. Feeder names and loads ofbus-29 are tabulated below in Table 5.4. The scheme finds that Z1_S29_L2 feeder of bus-29 has 30MW load, so the scheme selects this feeder for shedding.

Table 5.4: Feeder loads of bus-29

Feeder Data of Bus - 29			
Sl.	**Feeder Name**	**Feeder MW**	**Feeder MVar**
1	Z1_S29_L1	70 MW	07 MVar
2	Z1_S29_L2	30 MW	03 MVar
3	Z1_S29_L3	50 MW	04 MVar
4	Z1_S29_L4	50 MW	20 MVar
5	Z1_S29_L5	33 MW	03 MVar
6	Z1_S29_L6	80 MW	07 MVar

Then the scheme finds that the sanctioned load shed amount for bus-28 of zone-1 is 18MW in aforementioned Table 5.3. Then the scheme searches feeder for 18MW on bus-28 but there is no feeder worth of 18MW connected to bus-28. Table 5.5 shows that there are seven feeders but no one feeder has 18MW load. In that case the scheme will take the *Z1_S28_L3* feeder from bus-28 because this feeder load is closest to the sanctioned load. Since the selected feeder load is 2MW greater than the sanctioned load cut-off then the scheme will now modify the sanctioned load shed amount for next adjacent bus by deducting 2MW.

Table 5.5: Feeder loads of bus-28

Feeder Data of Bus - 28			
Sl.	**Feeder Name**	**Feeder MW**	**Feeder MVar**
1	Z1_S28_L1	60 MW	06 MVar
2	Z1_S28_L2	30 MW	04 MVar
3	Z1_S28_L3	20 MW	04 MVar
4	Z1_S28_L4	50 MW	06 MVar
5	Z1_S28_L5	30 MW	04 MVar
6	Z1_S29_L6	16 MW	02 MVar
7	Z1_S29_L7	10 MW	01 MVar

In this way, the scheme will modify and update the sanctioned bus load shed amount dynamically. Thus the scheme selects circuit breakers of bus feeders so that the summation of power flow of selected feeders is close to bus load shed amount and then checks the total power flow (ΣP_i)of selected bus feeders are close to bus load shed amount(B_{zk}) by equation (3.14) in step-11. For ensuring controlled load shedding, the scheme applies another checkpoint at zone level. It also checks,whether the total power flow of zone's feeders are close to zonal load shed amount($Load_z$) by using equation (3.17) and (3.18) of step-13. For example, from Table 5.3, we have seen that the scheme has calculated zonal load shed amount for zone-3 ($Load_3$) is 166MW. But the actualload shed amount is 163 MW after selecting feeders shown in Table

5.7. So, the scheme finds 3MW imbalance and then modify the next load shed amount for zone-4 ($Load_4$). The load shedamount for zone-4 is 110MW from Table 5.3.

Table 5.6: Selected load shed feeders of zone-3

Feeder Data of Zone- 3				
Sl.	**Feeder Name**	**Feeder MW**	**Feeder MVar**	**Sanctioned Load shed amount[$Load_3$] for Zone-3**
1	z3_s21_l1	70 MW	30 MVar	166 MW
2	z3_s22_l5	20 MW	05 MVar	
3	z3_s24_l2	73 MW	15 MVar	
	Total	**163 MW**	**50 MVar**	

Since the scheme finds 3MW imbalance from zone-3 hence this 3MW will be adjusted with zone-4 by using Equation (3.16) and (3.17) of step-13. The zone-4 load shed amount [$Load_4$] 110MW will be modified to 113MW. After modifying and updating the zonal load shed amount for zone-4, the 113MW will be distributed to the PQ buses according to their voltage based ranking.

Table 5.7: Selected load shed feeders of zone-4

Feeder Data of Zone- 4					
Sl.	**Feeder Name**	**Feeder MW**	**Feeder MVar**	**Sanctioned Load shed amount for Zone-4**	**Modified Load shed amount for Zone-4**
1	z4_s14_l5	30 MW	10 MVar	110 MW	113 MW
2	z4_s15_l3	55 MW	30 MVar		
3	z4_s20_l5	30 MW	10 MVar		
	Total	**115 MW**	**50 MVar**		

It is evident from Table 5.7 that the sanctioned load shed amount of zone-4 is modified from 110MW to 113MW and actual load cut-off is 115MW as shown in below python generated ouput. Thus all zones load shed amount will be adjusted and modified in a dynamic way.

```
Sheded Feeder List
['0', 'z1_s28_l3', 'z1_s29_l2', 'z2_s25_l5', 'z2_s27_l2', 'z3_s21_l1', 'z3_s22_l5',
       'z3_s24_l2', 'z4_s14_l5', 'z4_s15_l3', 'z4_s20_l5', 'z5_s8_l9', 'z5_s12_l6']

Sheded Feeder MW
[0, 20, 30, 24, 30, 70, 20, 73, 30, 55, 30, 47, 10]
```

The scheme finally creates an array of all selected feeders for full power system as shown in above. Then finally the scheme sends the trip signals to all the circuit breakers connected to the selected feeders and the actual load shed for whole system is 449MW whereas it was estimated 446MW.

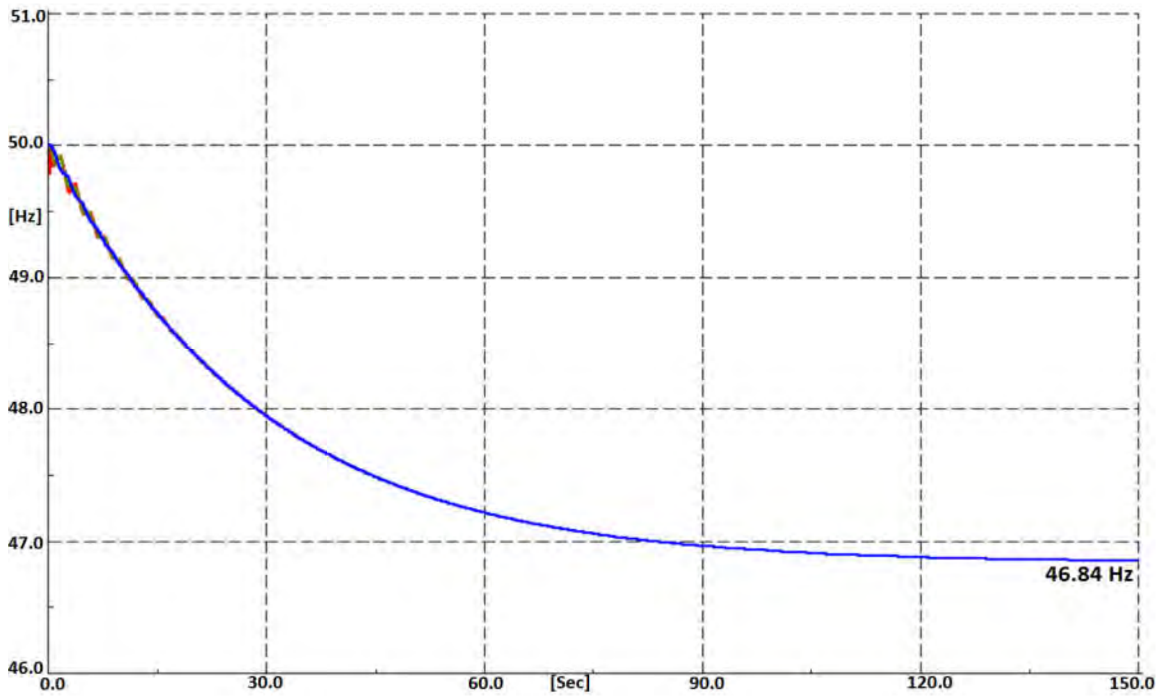

Figure 5.4: Frequency excursion without proposed scheme for Case-1

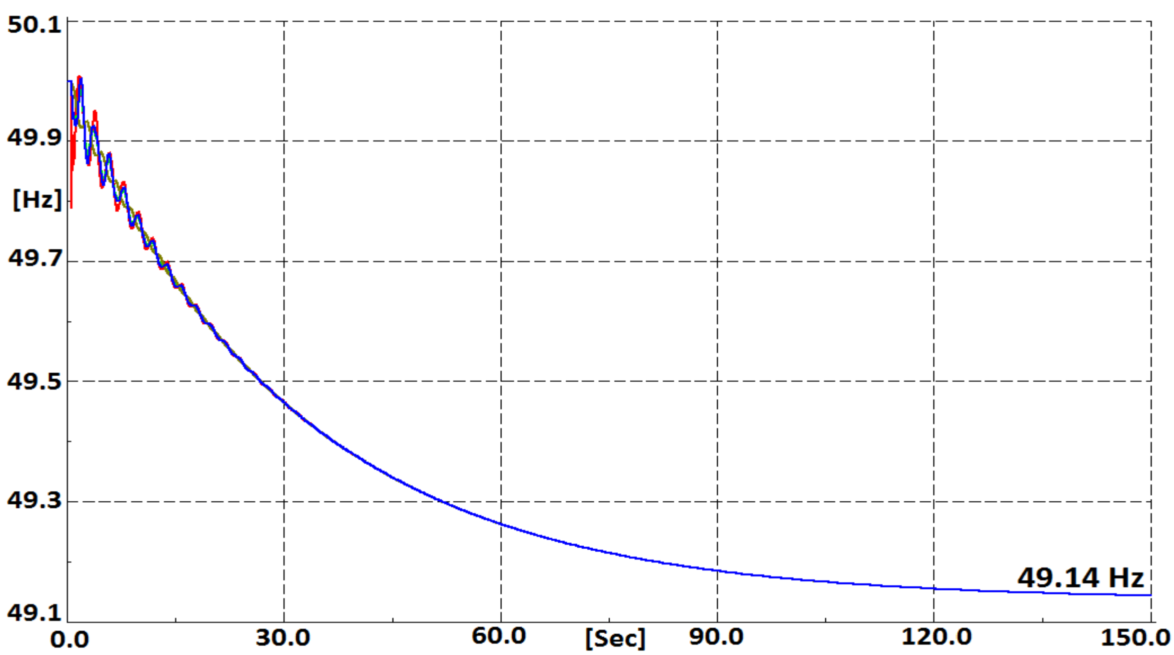

Figure 5.5: Frequency excursion with proposed scheme for Case-1

Figure 5.4 shows the frequency curve without the proposed methodology based scheme. The curve shows that frequency without scheme goes down to 46.84 Hz. Actually in real time at that frequency, power system will experience blackout because of under-frequency setting of generators.

The frequency curve of test system with the proposed scheme is shown in Figure 5.5 after sending all trip signals. In the controlled simulation the trip signals are sent to all circuit breakers of selected feeders after 400 ms but it is described in chapter-4 that practically it will take around less than 300ms. In this controlled simulation, deploying our scheme, we find that the scheme successfully arrest the frequency before the lower threshold frequency of 49.1 Hz. In Figure 5.9, we see that the frequency rests at 49.14 Hz.

A part of sheded feeders of case-1 by proposed methodology based scheme in python scripted simulation is shown in Figure 5.6

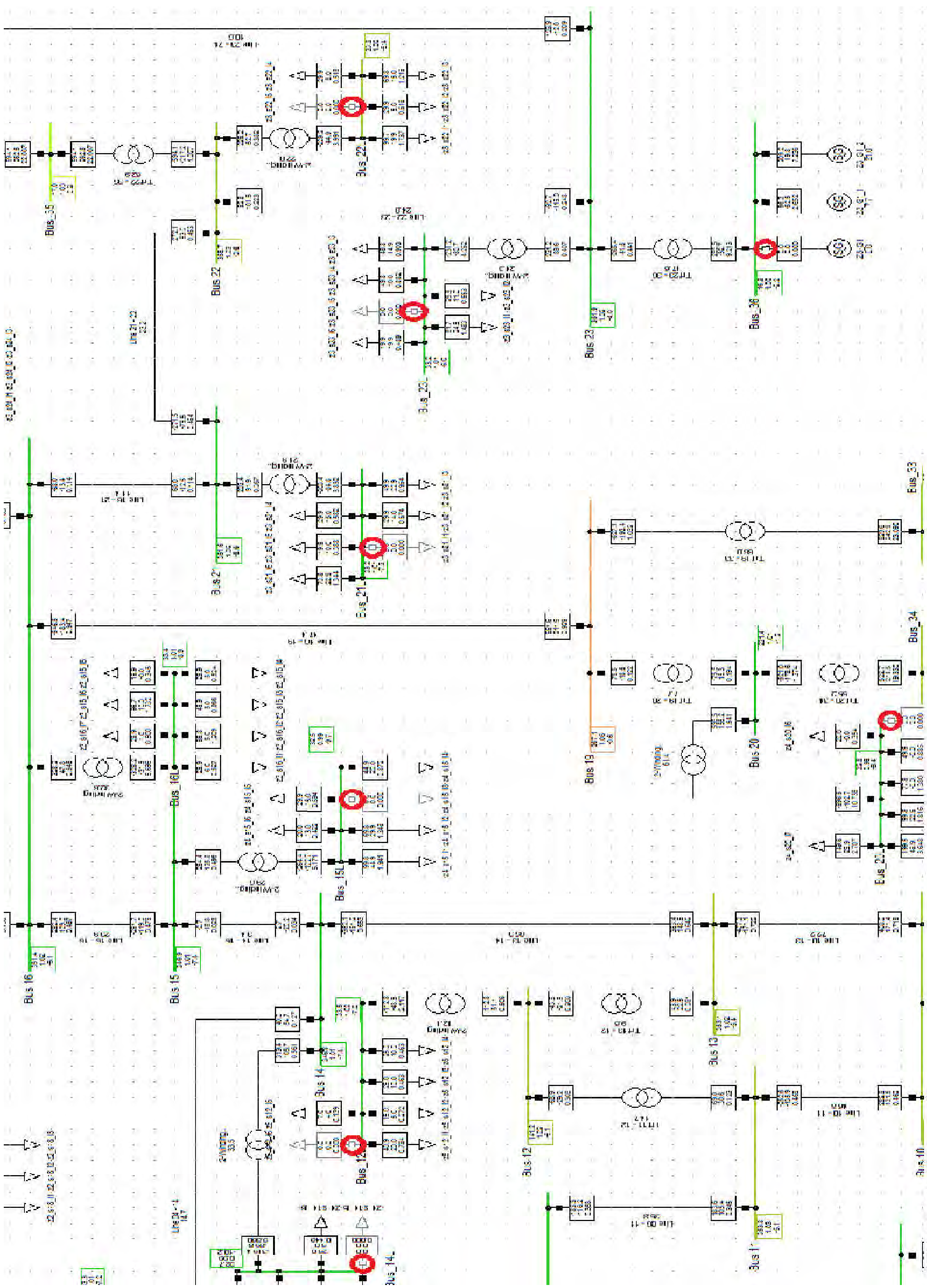

Figure 5.6:A part of sheded feeders of case-1 in python scripted simulation

5.2.2 Case-2: 900 MW Loss

In this scenario 900 MW generation outage has been happened in zone-3. Total generation was 6345 MW before generation loss and all transmission lines are in operation. The details of calculation of sequential steps of proposed methodology in the test system are discussed already in case-1. So, the details of scheme calculation will not be discussed in this case-2. But only the results will be shown here. The focus of this case is on the scheme validation that the proposed method will work for any amount of disturbance. In healthy condition, buses are ranked according to their FVSI. The bus voltage (pu) and FVSI are shown in Table 5.8.

Table 5.8: FVSI, Bus Voltage (pu) and Bus MVar for all load buses

Sl.	Zone No.	Zone PQ Bus No.	Bus Voltage (pu)	Bus MVar	FVSI
1	Zone -1	Bus 28	1.018485	27	0.015617
2		Bus 29	1.020237	44	0.025363
3	Zone-2	Bus 18	0.974899	30	0.018939
4		Bus 25	1.005307	47	0.027903
5		Bus 26	1.008086	17	0.010037
6		Bus 27	0.977334	76	0.047740
7	Zone-3	Bus 16	0.969962	32	0.020408
8		Bus 21	0.952732	115	0.076016
9		Bus 22	0.982528	50	0.031076
10		Bus 23	0.970514	85	0.054146
11		Bus 24	0.958992	68	0.044364
12	Zone-4	Bus 14	0.952018	100	0.066200
13		Bus 15	0.934628	153	0.105091
14		Bus 20	0.959777	103	0.067089
15	Zone-5	Bus 7	0.955624	84	0.055190
16		Bus 8	0.934957	176	0.120804
17		Bus 12	0.982918	54	0.033536
18	Zone-6	Bus 3	0.980059	3	0.001874
19		Bus 4	0.930368	184	0.127544
20		Bus 39	0.981752	100	0.062251

After disturbance, the proposed methodology based scheme then estimate the total load shed amount and disturbance weight according to the severity for whole power system and these are tabulated in Table 5.9. The powerfactory shows the total load shed amount and disturbance weight in its output as follows. It also shows that the scheme will shed 745MW because of 900MW loss to arrest the frequency within threshold value.

```
Gen Loss = 900.000000
System Load shed size = 745.000000 to arrest frequency before 49.1Hz & taking D=1.5%
```

```
Zone-1 disturbance Weight =  = 0.114603
Zone-2 disturbance Weight =  = 0.114603
Zone-3 disturbance Weight =  = 0.359454
Zone-4 disturbance Weight =  = 0.248563
Zone-5 disturbance Weight =  = 0.141681
Zone-6 disturbance Weight =  = 0.021097
```

```
df/dt_coi of Zone-1 -0.018218
df/dt_coi of Zone-2 -0.018218
df/dt_coi of Zone-3 -0.057142
df/dt_coi of Zone-4 -0.039513
df/dt_coi of Zone-5 -0.022523
df/dt_coi of Zone-6 -0.003354
```

It is to be noted that because of 900MW generation outage the scheme has estimated the total load shed amount of 745MW. According to disturbance weight the total load shed amount is distributed in all zones in PowerFactory environment as follows.

```
Zone-1_LS =  = 85.000000 MW
Zone-2_LS =  = 85.000000 MW
Zone-3_LS =  = 268.000000 MW
Zone-4_LS =  = 185.000000 MW
Zone-5_LS =  = 106.000000 MW
Zone-6_LS =  = 16.000000 MW
```

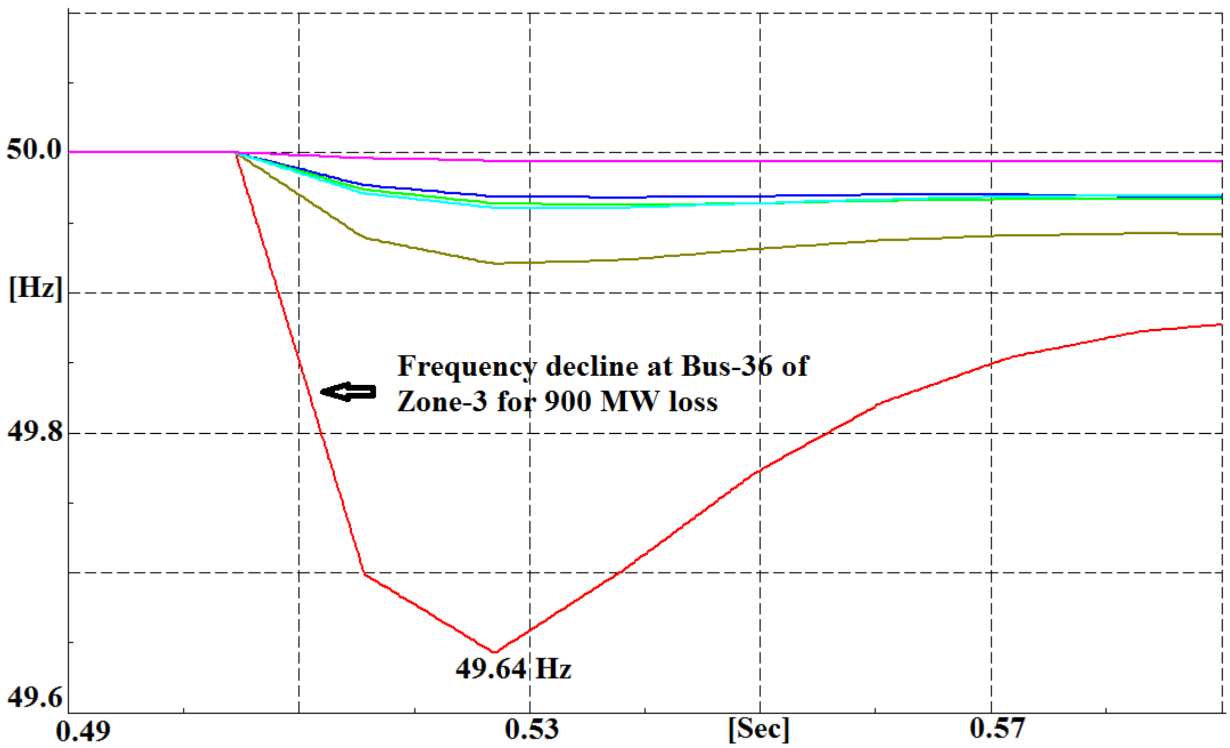

Figure 5.7: Frequency decline of different Zones for case-2

Figure 5.7 shows that the decline of mean frequency of zone-3 is highest because it faces generation loss of 900 MW. Consequently, this zone will shed more loads as it is perturbed most. The proposed methodology based scheme finally selects the following feeders and sends trip signals to the circuit breakers of selected feeders. Point to be noted here is that the estimated load was 745MW in Table 5.9 but

Table 5.9: Zonal Load shed amountfor case-2

Zone No.	Rate of Frequency Decline	Zonal Disturbance Weight [W_z]	Zonal Load Shed Amount [$Load_z$]
Zone-1	-0.018218	0.114603	85
Zone-2	-0.018218	0.114603	85
Zone-3	-0.057142	0.359454	268
Zone-4	-0.039513	0.248563	185
Zone-5	-0.022523	0.141681	106
Zone-6	-0.003354	0.021097	16
	Total Load Shed Amount[P_{shed}]		**745 MW**

the practical load shed is 746MW as shown in below python generated output. It is caused because of dynamic and real time feeder selection for controlled load shedding.

```
Total actual shed= 746.00
Sheded Feeder List
['0', 'z1_s28_12', 'z1_s29_14', 'z2_s18_13', 'z2_s25_15', 'z3_s16_12',
 'z3_s21_16', 'z3_s22_12', 'z3_s22_15', 'z3_s23_14', 'z3_s23_15',
 'z3_s23_14', 'z3_s23_15', 'z3_s24_13', 'z4_s14_13', 'z4_s15_12',
 'z5_s7_11', 'z5_s8_12', 'z5_s12_12', 'z6_s39_17']

Sheded Feeder MW
[0, 30, 50, 23, 24, 70, 74, 30, 20, 50, 15, 50, 55, 70, 50, 35, 70, 15, 15]
```

The python generated output in the output window of Digsilent PowerFactory is shown above, where finally selected feeders name and MWs are listed in arrays. The frequency excursion curves after disturbance with and without proposed scheme are shown below in Figure 5.8 and Figure 5.9 respectively.

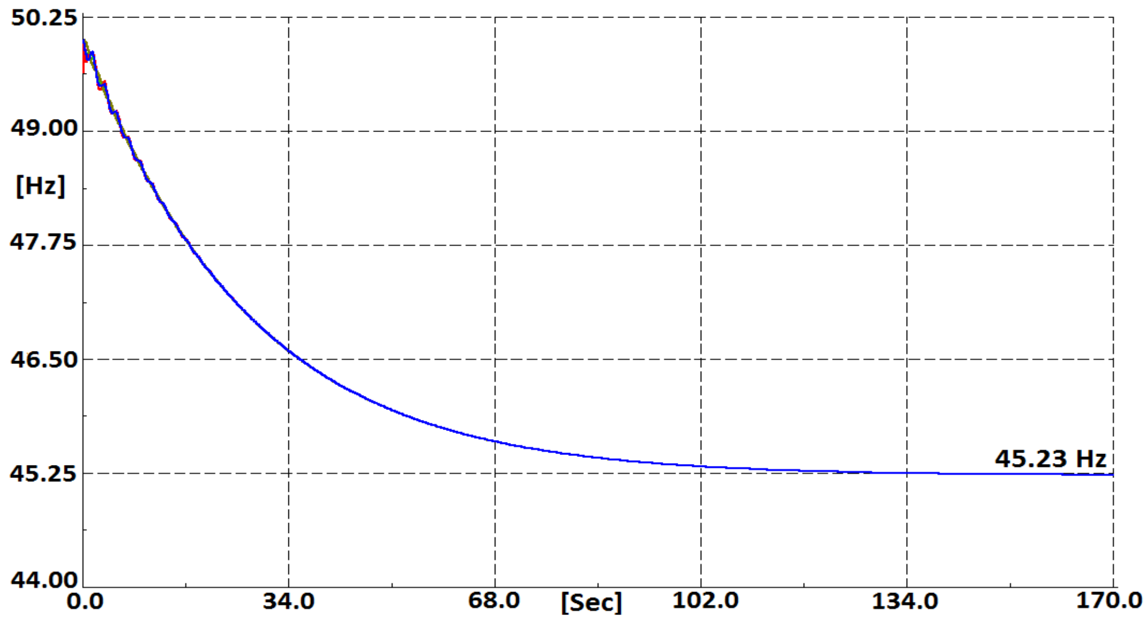

Figure 5.8: Frequency excursion without scheme for Case-2

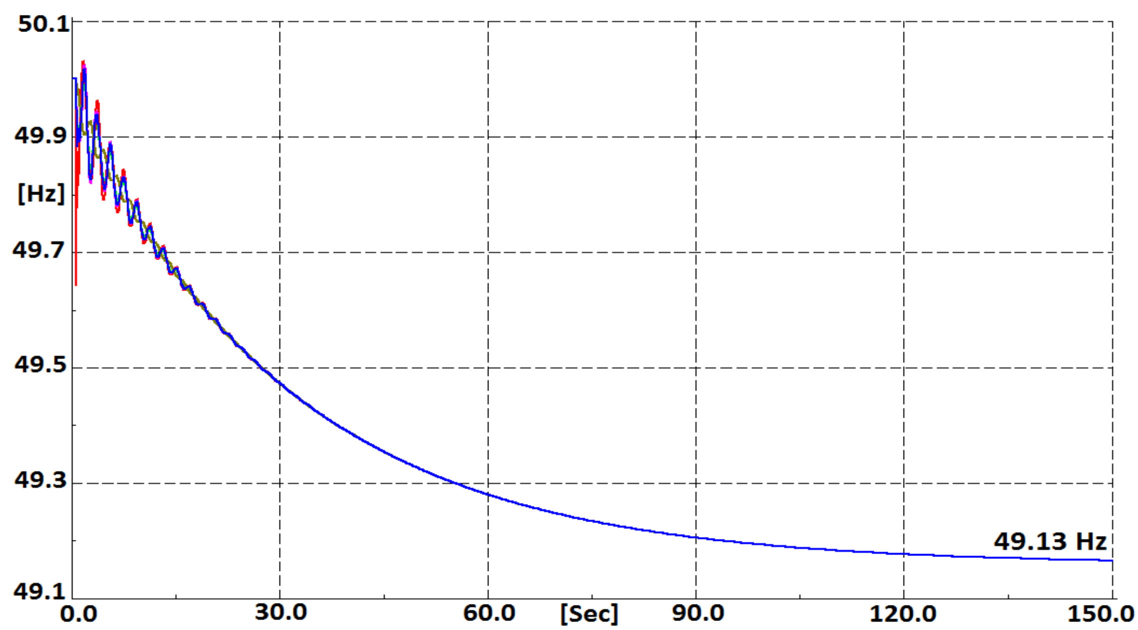

Figure 5.9: Frequency excursion with proposed methodology for Case-2

Figure 5.10presents a part of simulated network in Digsilent PowerFactory. It has been shown in the following figure that the proposed scheme has tripped the circuit breakers of selected feeders to heal the power system from instability. The red circled circuit breakers are opened after tripping signals are sent by the proposed methodology based scheme. Before perturbation all circuit breakers were closed.

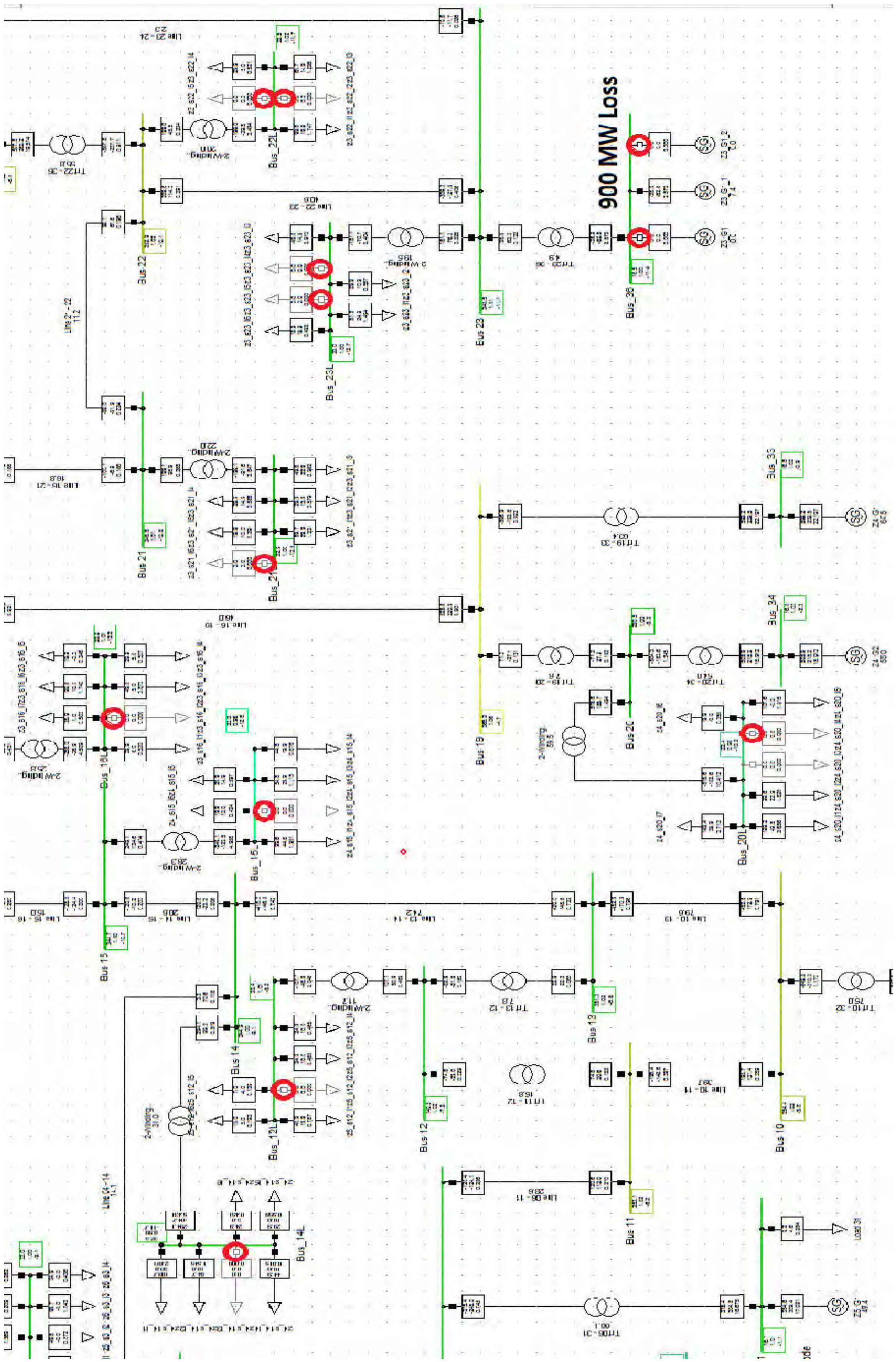

Figure 5.10: A part of sheded feeders of case-2 in python scripted simulation

5.2.3 Case-3: 1200 MW Loss

In this scenario 1200 MW generation outage is occurred in zone-3. Total generation was 6314 MW and 2397 MVar before generation loss and all transmission lines are in operation. The details of calculation of sequential steps of proposed methodology in the test system are discussed already in case-1. So, the details of scheme calculation will not be discussed in this case-3. But only the results will be shown here. The focus of this case-3 is on the scheme validation that the proposed method works for any amount of disturbance. In healthy condition, buses are ranked according to their FVSI. The Bus voltage (pu) and FVSI are shown in Table 5.10.

Table 5.10: FVSI, Bus Voltage (pu) and Bus total MVar for all PQ (Load)Buses

Sl.	Zone No.	Zone PQ Bus No.	Bus Voltage (pu)	Bus MVar	FVSI
1.	Zone -1	Bus 28	1.010868	27	0.015854
		Bus 29	1.012496	44	0.025752
2.	Zone-2	Bus 18	0.965057	30	0.019327
		Bus 25	1.002783	47	0.028044
		Bus 26	1.001263	17	0.010174
		Bus 27	0.968651	76	0.048599
3.	Zone-3	Bus 16	0.958013	32	0.020920
		Bus 21	0.940141	115	0.078066
		Bus 22	0.974327	50	0.031602
		Bus 23	0.961184	85	0.055202
		Bus 24	0.945443	68	0.045645
4.	Zone-4	Bus 14	0.943524	100	0.067398
		Bus 15	0.921722	153	0.108054
		Bus 20	0.958056	103	0.067330
5.	Zone-5	Bus 7	0.951345	84	0.055687
		Bus 8	0.930029	176	0.122087
		Bus 12	0.977370	54	0.033918
6.	Zone-6	Bus 3	0.972024	3	0.001905
		Bus 4	0.922374	184	0.129764
		Bus 39	0.981752	100	0.062251

The proposed methodology based scheme keeps the calculated FVSI in an array as follows to use in calculation after perturbation and for ranking the PQ buses in a zone to take care of voltage stability.

```
FVSI_arry=
[0, 0.015853536689428276, 0.025752384760217257, 0.01932707880444807, 0.02804367028094383,
    0.010174288727901487, 0.048599267830079465, 0.020919856582185675, 0.07806614124353244,
    0.031602016634350034, 0.05520223816007783, 0.04564462637479403, 0.06739767735883116,
    0.10805436548508043, 0.06732974067329947, 0.05568712674243307, 0.12208731676826055,
    0.03391777713021671, 0.001905101148855667l, 0.12976415330917546, 0.06225120544230507]
```

After perturbation happening, the proposed methodology based scheme quickly estimate total load shed amount and then normalized disturbance weight also. According to disturbance weight the total load shed amount is distributed in all zones as follows in python scripted PowerFactory output.

```
Gen Loss = 1200.000000
System Load shed size = 1046.000000 to arrest frequency before 49.1Hz & taking D=1.5%
Zone-1 disturbance Weight =  = 0.106019        df/dt_coi of Zone-1 -0.006548
Zone-2 disturbance Weight =  = 0.106019        df/dt_coi of Zone-2 -0.006548
Zone-3 disturbance Weight =  = 0.390039        df/dt_coi of Zone-3 -0.024088
Zone-4 disturbance Weight =  = 0.266030        df/dt_coi of Zone-4 -0.016430
Zone-5 disturbance Weight =  = 0.113207        df/dt_coi of Zone-5 -0.006992
Zone-6 disturbance Weight =  = 0.018686        df/dt_coi of Zone-6 -0.001154
```

It is to be noted from above PowerFactory output that because of 1200MW generation loss the scheme has estimated the total load shed amount 1046MW.Frequency decline in different Zones after disturbance is shown inFigure 5.11.According to disturbance weight the total load shed amount is distributed in all zones as shown in Table 5.11. The zonal load shed amounts calculated by scheme in python scripted PowerFactory environment are shown below.

```
Zone-1_LS =  = 111.000000 MW
Zone-2_LS =  = 111.000000 MW
Zone-3_LS =  = 408.000000 MW
Zone-4_LS =  = 278.000000 MW
Zone-5_LS =  = 118.000000 MW
Zone-6_LS =  = 20.000000 MW
```

Table 5.11: Zonal Load shed amountfor case-3

Zone No.	Rate of Frequency Decline	Zonal Disturbance Weight [W_z]	Zonal Load Shed Amount [$Load_z$]
Zone-1	-0.006548	0.106019	111
Zone-2	-0.006548	0.106019	111
Zone-3	-0.024088	0.390039	408
Zone-4	-0.016430	0.266030	278
Zone-5	-0.006992	0.113207	118
Zone-6	-0.001154	0.018686	20
	Total Load Shed Amount[P_{shed}]		**1046 MW**

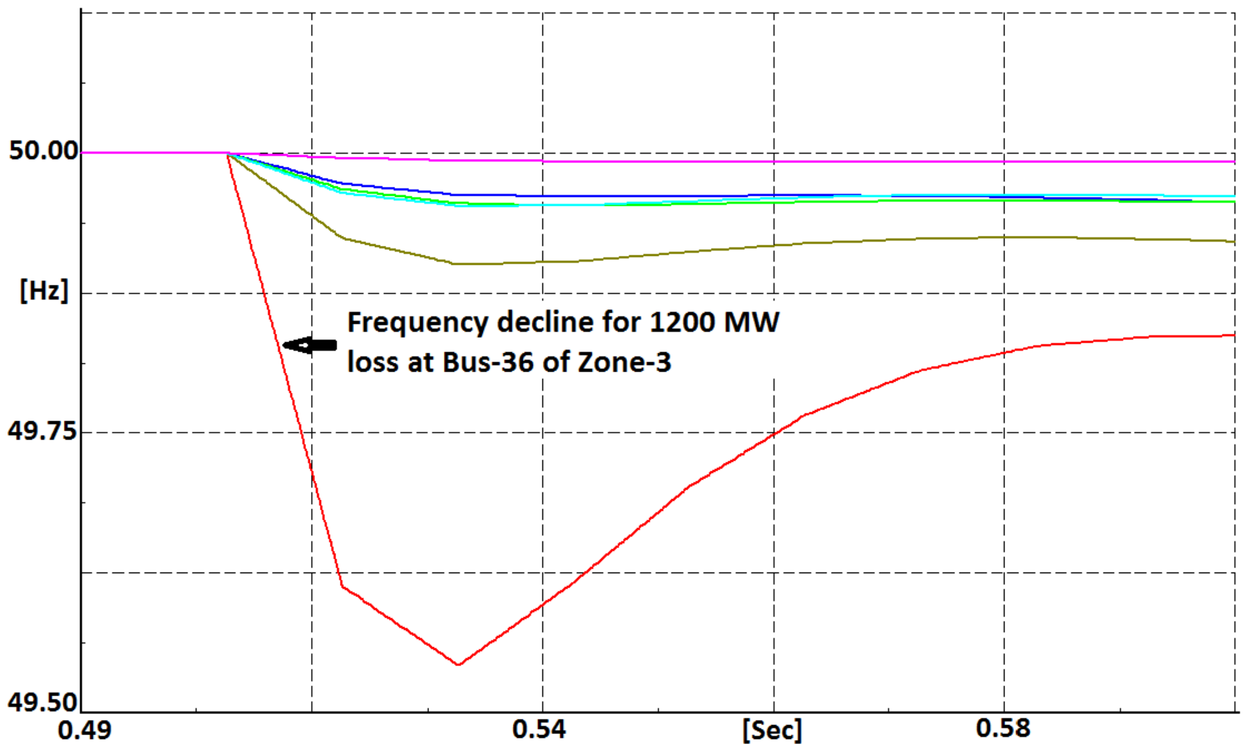

Figure 5.11:Frequency decline in different Zones for case-3

The scheme finally selects the following feeders and sends trip signals to the circuit breakers of selected feeders. Point to be noted here, we have seen that the estimated load was 1046 MW in Table 5.11 but the practical load shed is 1044 MW as shown in below python generated output. It is caused because of dynamic and prudent feeder selection in controlled simulation environment.

```
Total actual shed= 1044.00
Sheded Feeder List
['0', 'z1_s29_16', 'z1_s29_12', 'z2_s18_13', 'z2_s25_15', 'z2_s26_15',
 'z2_s27_13', 'z3_s16_14', 'z3_s21_16', 'z3_s21_11', 'z3_s23_11',
 'z3_s23_14', 'z4_s14_11', 'z4_s14_13', 'z4_s15_11', 'z4_s20_12',
 'z4_s20_13', 'z5_s7_13', 'z5_s12_11', 'z5_s12_13', 'z6_s3_15', 'z6_s4_16']
Sheded Feeder MW
[0, 80, 30, 23, 24, 15, 50, 30, 74, 70, 82, 50, 110, 55, 100, 100, 0, 50, 41, 25, 15, 20]
```

Figure 5.12 shows that the proposed scheme has tripped the circuit breakers of selected feeders to heal the power system from instability. The red circled circuit breakers are opened after tripping signals are sent by the scheme. Before perturbation all circuit breakers were closed.

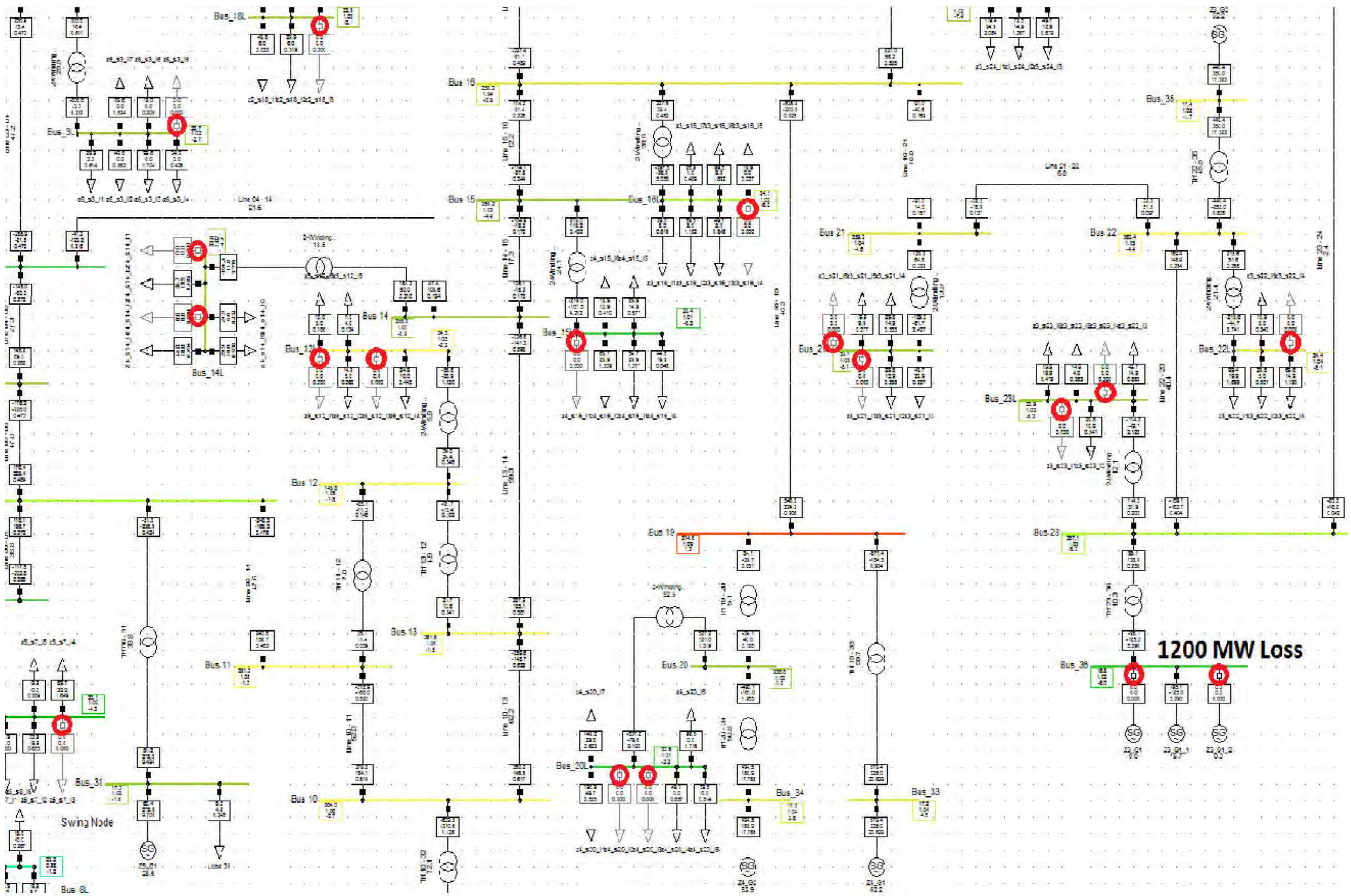

Figure 5.12:A part of sheded feeders of case-3 in python scripted simulation

The implementation of proposed methodology in PowerFactory environment shows that it can arrest the system frequency within the threshold level of frequency for 1200MW loss and the system becomes stable at 49.09 Hz. The frequency excursion curves after disturbance with and without proposed scheme are shown below.

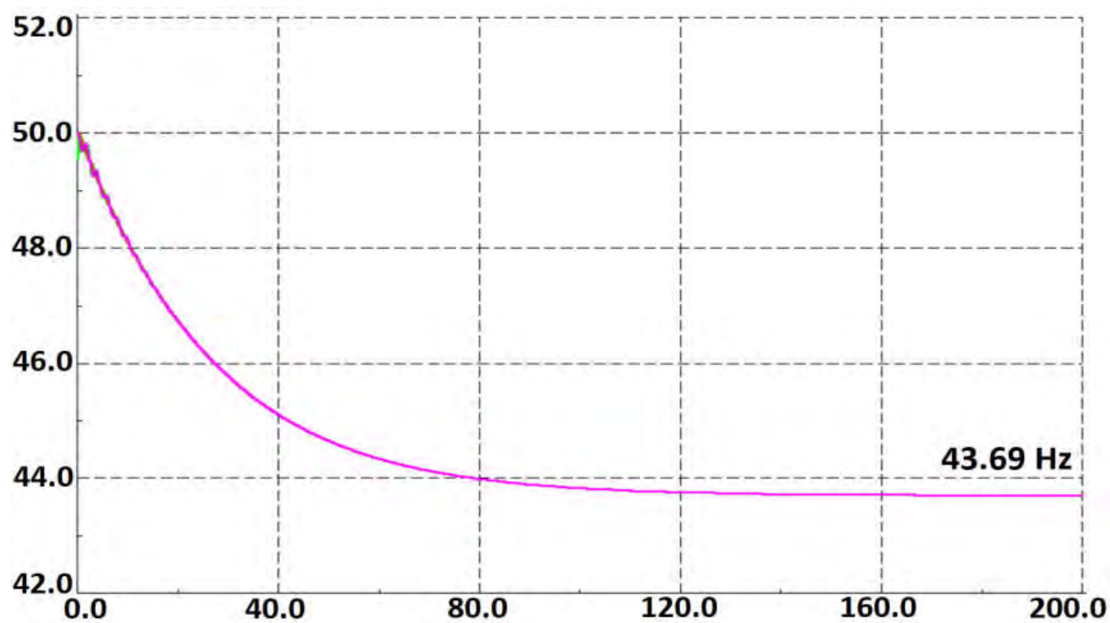

Figure 5.13: Frequency excursion without scheme for Case-3

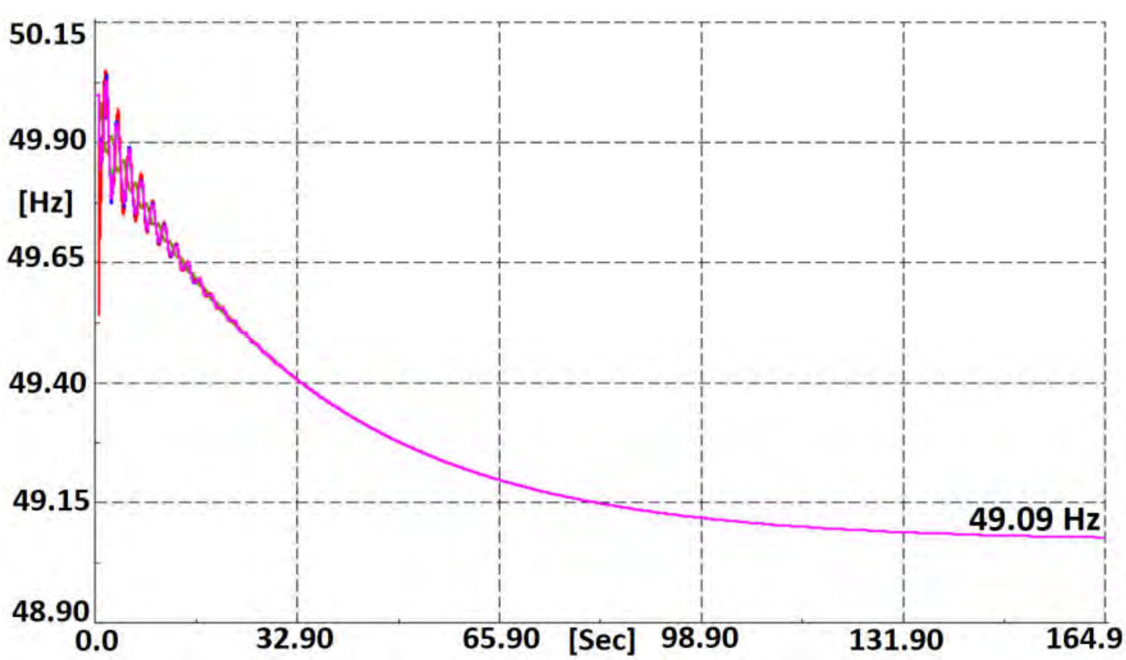

Figure 5.14: Frequency excursion with proposed scheme for Case-3

5.2.4 Case-4: Tie LineSecurity

From case-1 to case-3 we have seen that the methodology works well at all cases of different disturbances and heal the power system from frequency instability with taking care of voltage by controlled and lesser load shedding. But controlled load shedding never assures that the tie lines and interconnections among areas or zones will not be overloaded, although the system is stable in frequency. After dynamic and controlled load shedding, even there is a little possibility to overload the tie lines among zones but we cannot say stoutly and certainly that no tie line will be overloaded. When the scheme sent trip signals to all dynamically selected feeders then the power flow redistributes in the system. If the interconnection lines among areas are overloaded and trip by protective relay then the system may be endangered again and may loss the stability in terms of voltage and frequency. So, in this connection, it is also very important to monitor the interconnection lines among areas from the point of power system security. In our developed methodology, the scheme can perform the security constrained dynamic and controlled load shedding. After dynamic selection of feeders and sending trip signals to all circuit breakers, the scheme checks the tie line power flow (Either sending end MVA or line Current) of that area only where the generation is curtailed. Actually, in most cases when the generation loss occurs in the load rich area then the tie-line might be overloaded.

To understand the security constrained tie-line monitoring and security function of the proposed methodology a credible case-4 scenario is developed. In this scenario, the thermal current limit of 345KV interconnection line between bus 26 of zone-2 and bus 29 of zone-1 is set at 400A. Another tie line current between bus 26 of zone-2 and bus 28 of zone-1 is set at 500A. During python scripted simulation, 400 MW generation loss is happened in zone-1 at 500ms. Total generation is 6748 MW and 1828 MVar before generation loss and all transmission lines are in operation. The details of calculation of sequential steps of proposed methodology in the test system are discussed already in case-1. So, the details of scheme calculation will not be discussed in this case-4. But only the final results will be shown here. The focus of this case-4 is on the scheme validation that the proposed method works for any amount of disturbance with security constrained tie-line monitoring. After the disturbance, the scheme sanctioned the zonal load shed amount following the disturbance severity. The zonal load shed amounts calculated by scheme in python scripted PowerFactory environment are shown below.

```
Gen Loss = 400.000000
System Load shed size = 235.000000 to arrest frequency before 49.1Hz & taking D=1.5%
Zone-1_LS =  = 142.000000 MW
Zone-2_LS =  = 37.000000 MW
Zone-3_LS =  = 10.000000 MW
Zone-4_LS =  = 23.000000 MW
Zone-5_LS =  = 14.000000 MW
Zone-6_LS =  = 9.000000 MW
```

As we have seen already in previous cases, the zonal load shed amount is distributed among the PQ buses according to their busranking because weak bus will shed more loads than strong bus. The selected feeders and their MWs are as follows by the proposed methodology based scheme.

```
Total actual shed= 239.00
Sheded Feeder List
['0', 'z1_s28_13', 'z1_s29_14', 'z2_s18_13', 'z2_s26_14',
      'z2_s27_15', 'z4_s15_16', 'z5_s8_15', 'z6_s39_17']

Sheded Feeder MW
[0, 40, 90, 23, 10, 21, 20, 20, 15]
```

The implementation of proposed methodology in PowerFactory environment shows that it can arrest the system frequency within the threshold level of frequency for 400MW loss and the system rests at 49.11 Hz. The frequency excursion curves after disturbance with proposed scheme is shown below in Figure 5.15.

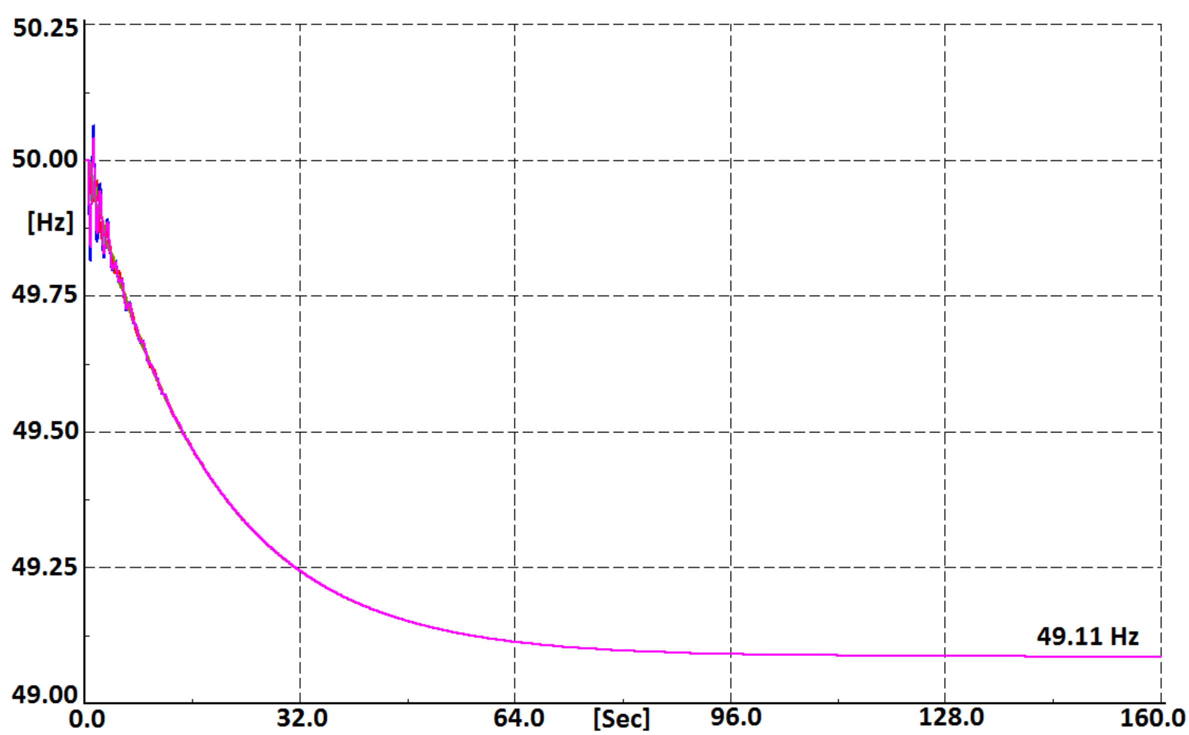

Figure 5.15: Frequency excursion with proposed scheme for Case-4

The following Figure 5.16 shows that before disturbance, the current at receiving end is 222amps through the interconnecting line between bus-26 and bus-29. But just after the disturbance the current of that line increase to 528 amps as shown in Figure 5.17.

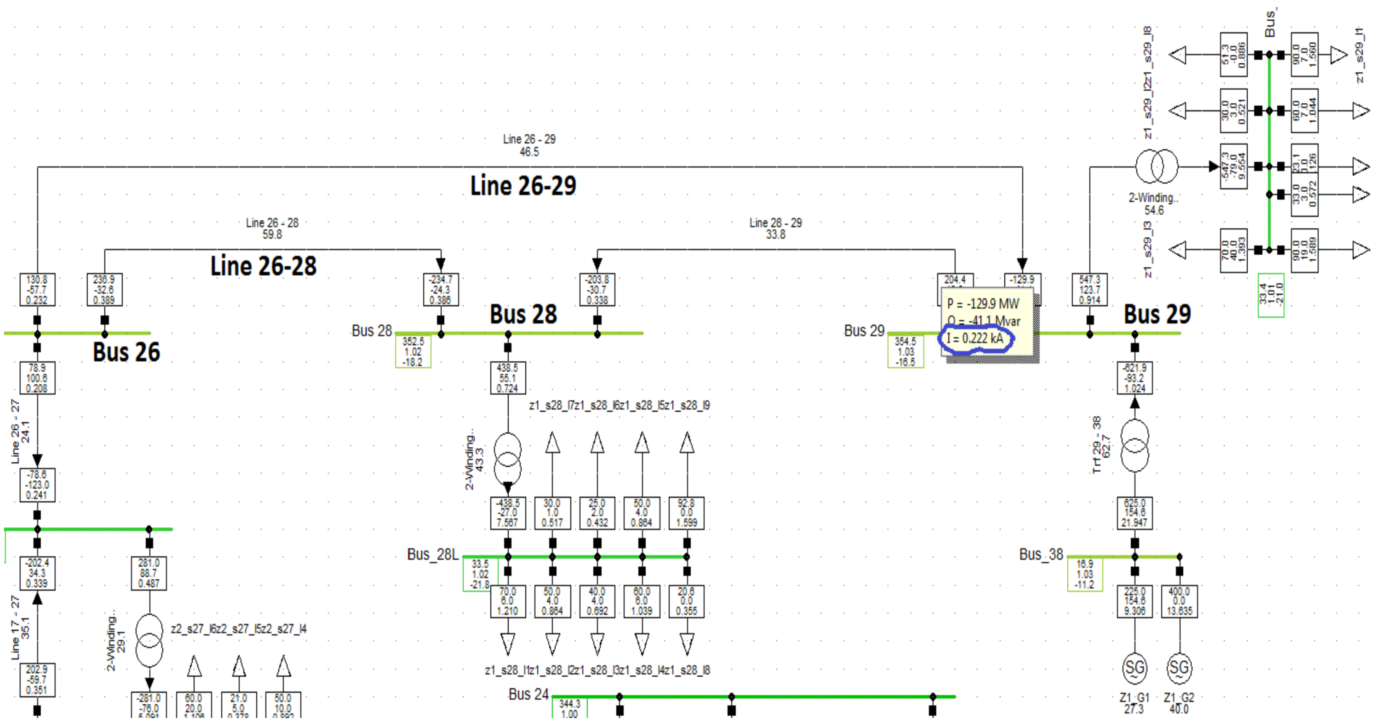

Figure 5.16: Current through line 26-29 before disturbance

Right after generation loss in zone-1, the color of line 26-29 and line 26-28 turn to red in simulation as an indication of overload of line. After automatic tripping of selected feeders as shown in Figure 5.18 by the scheme after 400 ms, the current flow through the line 26-29 and line 26-28 reduce but still remain in overload condition. The current flow of line 26-29 after tripping of dynamically selected feeders comes down to 451 amperes from 528 amperes as well as the current flow of tie line 26-28 also reduces to 596 amperes from 691 amperes as shown in the following Figure 5.18.

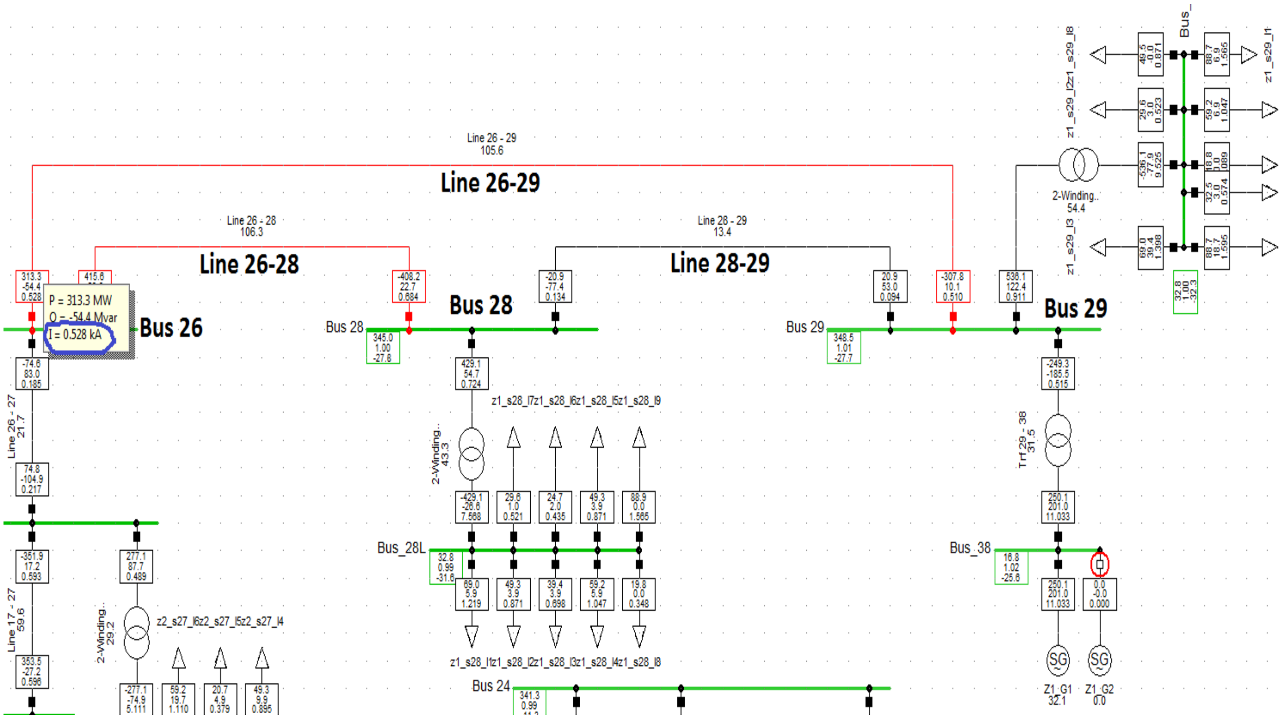

Figure 5.17: Current through line 26-29 and line26-28 right after disturbance

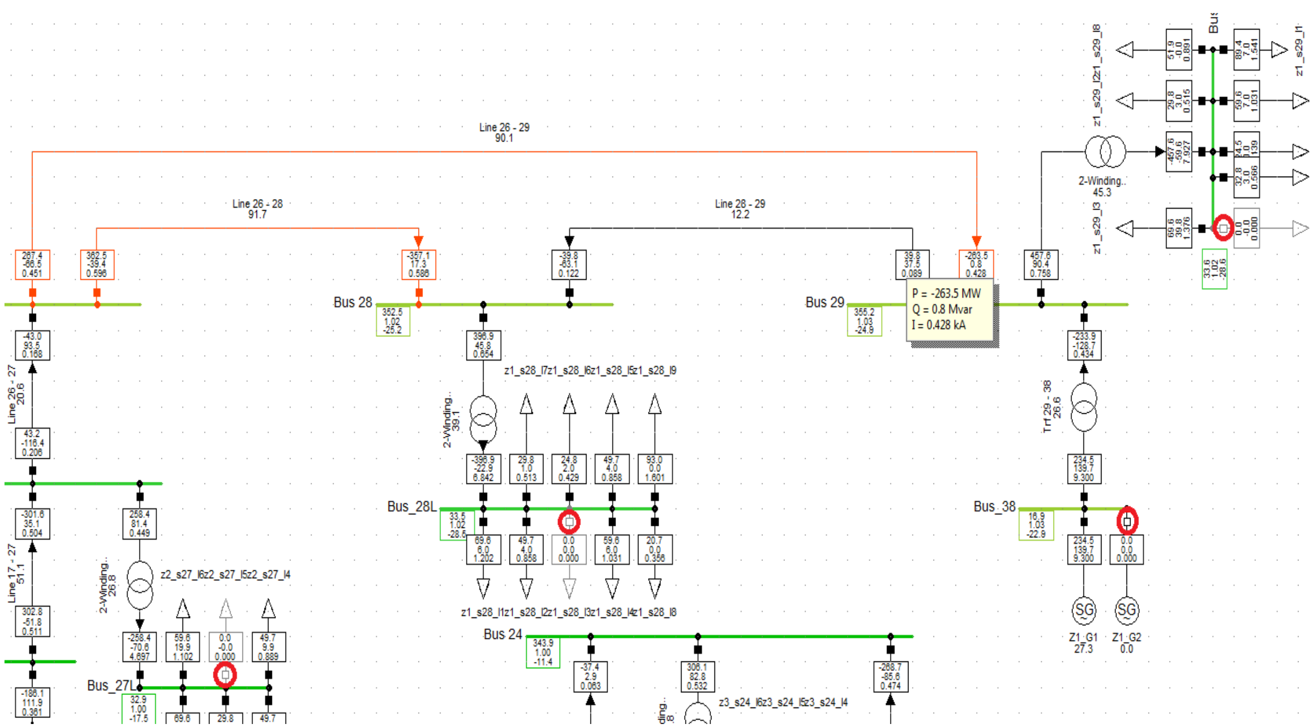

Figure 5.18: Current through line 26-29 and line 26-28 right after load shed

It is evident from the Figure 5.18 that the line 26-29 and line 26-28 are remained in overload condition, although the current flow through the lines are reduced due to load shed. Since the current flows through the said lines are reduced hence the line colors are turned to orange from red color. In this condition, if the additional loads are not sheded in the zone-1 then the said lines will be tripped by protective relay and the system will be endangered again. That's why the scheme will calculate the amount of load (L_{T_shed}) for further load shedding according to the Equation (3.23).Then the scheme again dynamically selects the feeders for further load shedding from the bus 28 and bus 29. The scheme selects and trips the circuit breaker of additional three feeders as shown below to prevent overloading and over-current protection tripping of tie lines.

```
------Tie Line Monitoring------
For line_26_29 shed = 30.949643 MW
Sheded Feeder List
['0', 'z1_s29_12', 'z1_s29_15']
For line_26_28 shed = 58.875730 MW
Sheded Feeder List
['0', 'z1_s28_13']
```

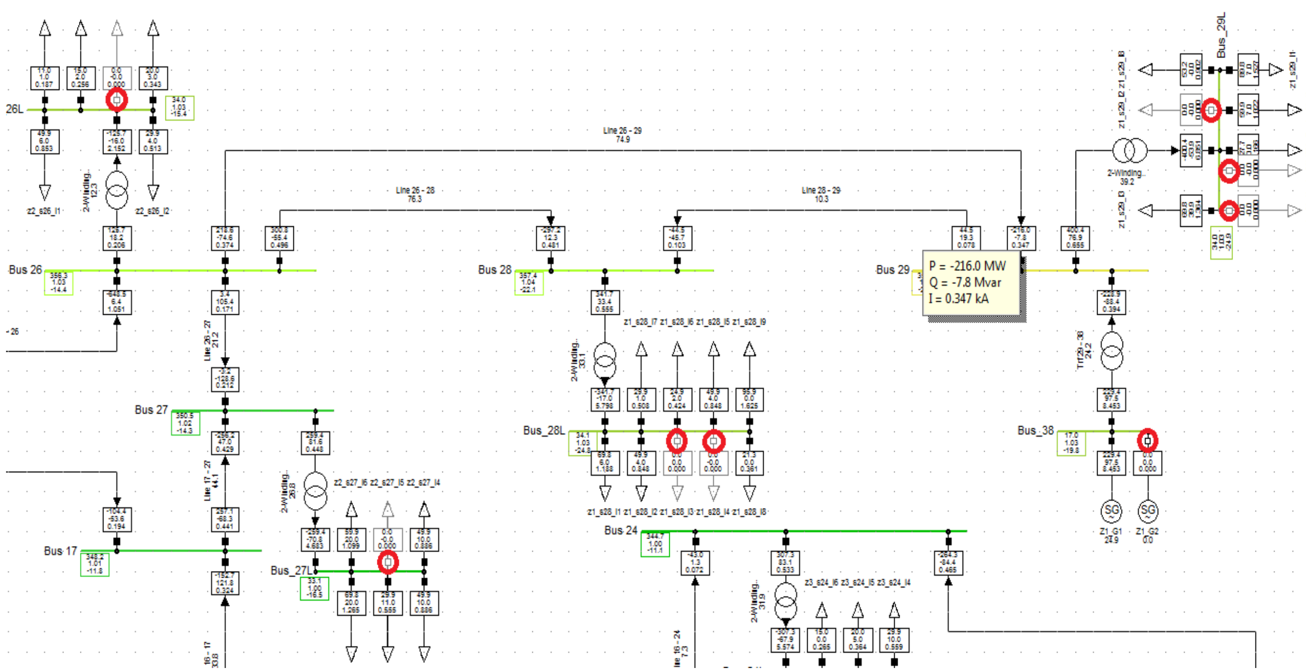

Figure 5.19: Additional Load shed for Tie-line security

The scheme further sheds load as shown in Figure 5.19 to keep the tie-line power flow beneath line thermal or stability limit. The additionally selected feeders are sheded and line power flows come into secure region. Thus the proposed methodology heals the whole power system in secure manner.

CHAPTER 6

Performance Analysis of Proposed Methodology

6.1 Introduction

The best load shedding scheme in power systems is the one that considers power system constraints and separates the least possible load in the shortest time from the network for stability protection. Currently most of the UFLS schemes used in the world are conventional UFLS [4]. The conventional UFLS sheds predefined amount of load when the frequency reaches a setting threshold after a constant time-delay. All the parameters of conventional UFLS are predefined based on off-line simulations under selected scenarios. Although some scholars have tried to improve its flexibility [5-6], the possibility of excess or lack of control cannot be avoided yet. To overcome drawbacks of conventional UFLS, adaptive schemes were developed based on system frequency response model (SFR) [7]. Adaptive UFLS measures the rate of change of frequency (ROCOF) to estimate the load shedding amount from the system equivalent system inertia [8-9]. Though the method is correct theoretically, the difficulty in obtaining the accurate value of system inertia especially when the whole grid splits into several small islands reduces its practicality. Beside this, most of the adaptive under frequency load shedding schemes (AUFLS) do not consider the load variation or on/off condition of those feeders, which are connected to the relays. For that reason, under shed of loads or unnecessary and extra loads might get separated from the network. Along with the above, most of the decentralized AUFLS are not designed to take care of voltage stability or to confront combinational disturbances. For that reason, an uncoordinated and non-optimal load shedding scenario is performed in the system. The proposed centralized dynamic-adaptive under frequency load shedding scheme possesses advantages of both traditional and adaptive UFLS and simultaneously protecting power system against frequency and voltage instabilities, following combinational disturbances.

In this chapter, to compare the performance of proposed methodology based scheme, a generic decentralized adaptive scheme will be implemented on same IEEE 39 bustest system and then the performance of proposed scheme will be compared with that generic adaptive schemefor more understanding about the robustness of proposed methodology.In chapter-5, we have shown already that our proposed methodology works for all amounts of disturbances. From the following analysis of performance, we shall observe that the decentralized adaptive scheme might not protect the power system from blackout in some credible scenarios because of under and over cut of load where as the proposed methodology works in all scenarios successfully.

6.2 Description of Generic Adaptive Protection Scheme

Throughout this book, we have considered the IEEE39 bus test system for our proposed methodology validation. Now for performance comparison of proposed methodology, firstly we shall implement a usually used adaptive under frequency load shedding scheme (AUFLS) on our IEEE39 bus test system. The decentralized AUFLS works based on rate of change of frequency (ROCOF) and under frequency (U/F) relays. To implement a generic AUFLS, we have selected widely used SPAF-140C relay from PowerFactory library. SPAF-140C relay hasfour frequency stages each of them with a different frequencythreshold and separate operate times. The df/dt threshold is common to all stages.

The settings for SPAF-140C relays are carefully determined by offline simulation under different credible scenarios. This implemented generic AUFLS works well without tie-line monitoring in every scenario that we have developed in chapter-5 for our proposed methodology validation. Even though, we have found some events under specific scenarios when this generic AUFLS,implemented on IEEE39 bus test system, might not work successfully but our proposed methodology based scheme would not fail. The settings of generic AUFLS implemented on IEEE39 bus test system are as follows.

Table 6.1: Relay logic and settings

Sl.	Stage name	Logic Settings	MW Shed
1	ROCOF 1st Stage	i) fre1<=49.04 ii) df/dt => 0.02	150 MW
2	ROCOF 2nd Stage	i) fre2<=49.04 ii) df/dt => 0.03	245 MW
3	ROCOF 3rd Stage	i) fre3<=49.04 ii) df/dt => 0.04	355 MW
4	U/F 1st Stage	i) fre1<=49.04	210 MW
5	U/F 2nd Stage	i) fre2<=49.02	155 MW

Relays are connected to different feeders in this way so that, they can shed monitored feeders according to set logics. After a generation loss, The ROCOF in each area and even in each PQ busis not same rather it is different in different zones, That's why *df/dt*'s are not same in whole power system and the feeders connected to the relays are not necessarily shed always. It is true that the *df/dt* of perturbed area right after disturbance is always higher than any other area in a power system. Then the electro-mechanical oscillation caused by perturbation propagates to other area depending on the electrical distances and the inertia of other areas.

6.3 Base Scenario 1

Base case network scenario-1 is a scenario on which our proposed method and above said AUFLS work successfully. In case study-2 of chapter-5, we have seen that the proposed methodology arrest system frequency before the threshold level at 49.13Hz after 900MW generation loss. It is evident from the Figure 6.1 that the implemented AUFLS also arrest the system frequency within safe (threshold) limit at the cost of load shed of following feeders as shown in Table 6.2. This is our base scenario for comparison-1.The feeders are disconnected from the system according to the relay logic settings shown in Table 6.1.

Table 6.2: Sheded feeders by AUFLS after 900MW generation loss

Sl.	Feeder name	MW	MVAR
1	Z3_S21_L1	70	30
2	Z5_S7_L1	35	10
3	Z3_S16_L1	30	6
4	Z3_S24_L2	73	15
5	Z4_S15_L2	70	30
6	Z4_S14_L5	30	10
7	Z3_S23_L1	82	25
8	Z3_S22_L3	70	15
9	Z3_S21_L6	75	23
10	Z6_S3_L1	30	3
11	Z1_S28_L1	60	6
12	Z2_S25_L1	40	15
13	Z2_S27_L2	30	11
14	Z5_S12_L2	15	5
15	Z6_S3_L2	50	0
16	Z4_S14_L3	55	15
	Total	**815**	**219**

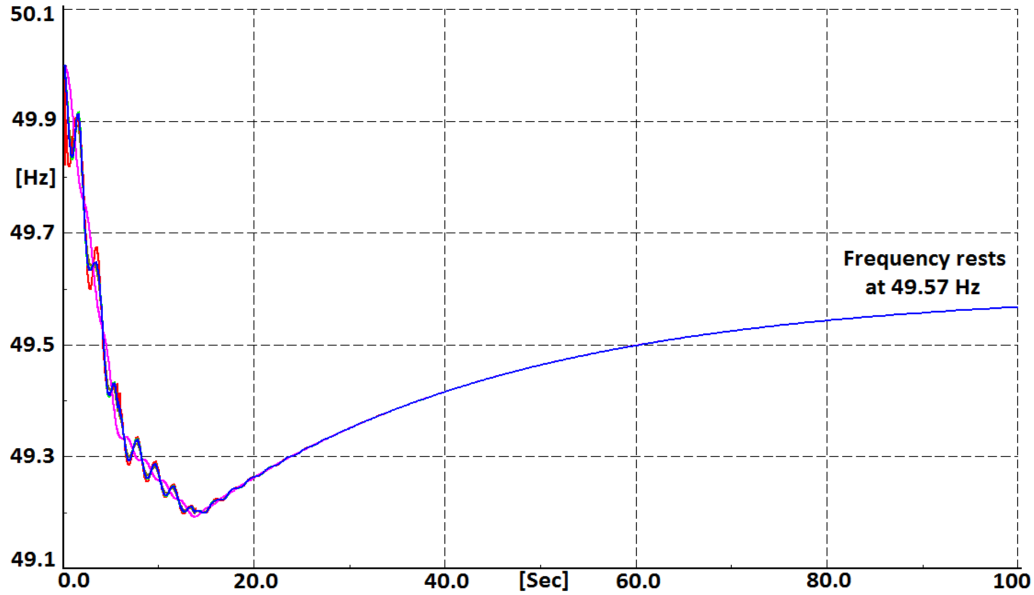

Figure 6.1: Frequency response with AUFLS for base scenario 1

Due to generation loss of 900 MW, some buses see the higher *df/dt* than the ROCOF 3rd stage and sheds load. Additionally both stages of under frequency relays are also operated as well as the system is healed from the frequency instability. For the same scenario the proposed methodology based scheme also works prudently at the cost of load shed of following feeders as we have seen in chapter-5.Feeders list by proposed methodology based scheme for 900MW generation loss is shown again in below.

```
Total actual shed= 746.00
Sheded Feeder List
['0', 'z1_s28_12', 'z1_s29_14', 'z2_s18_13', 'z2_s25_15', 'z3_s16_12',
      'z3_s21_16', 'z3_s22_12', 'z3_s22_15', 'z3_s23_14', 'z3_s23_15',
      'z3_s23_14', 'z3_s23_15', 'z3_s24_13', 'z4_s14_13', 'z4_s15_12',
      'z5_s7_11', 'z5_s8_12', 'z5_s12_12', 'z6_s39_17']

Sheded Feeder MW
[0, 30, 50, 23, 24, 70, 74, 30, 20, 50, 15, 50, 55, 70, 50, 35, 70, 15, 15]
```

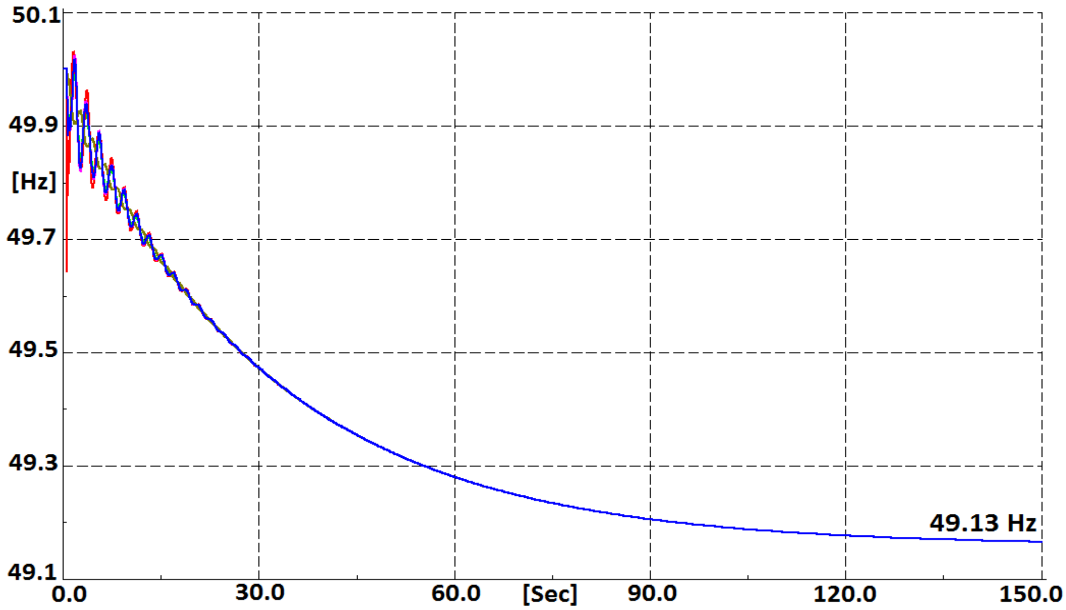

Figure 6.2:Frequency excursion with proposed scheme for 900MW generation loss

Since the implemented AUFLS does not have the true knowledge of feeder load variation and feeder's circuit breaker on-off status hence in some credible scenarios we are afraid that it might fail.

i) Comparison-1: Under-Frequency

In this comparison-1, we shall bring some change in our test system and try to compare our proposed methodology to the implemented AUFLS after 900MW generation loss and this comparison will take out the under-frequency issue in light that the implemented AUFLS tries to arrest the frequency decline in the following scenario but cannot arrest finally.

Now we will change feeders load in a way that the circuit breakers of two feeders will open and the loads of open feeders will transfer to other feeders which are not under AUFLS. We have selected two feeders "Z3_S21_L1" and "Z3_S22_L3" for switching off from Table 6.2 and the loads of "Z3_S21_L1" and "Z3_S22_L3" are transferred to the feeders "Z3_S16_L7" and "Z3_S22_L2" respectively. The feeders load before and after variation has been shown in Table 6.3.

Table 6.3: Feeders load before and after variation

Feeders Load at base scenario				
Sl.	**Feeder Name**	**MW**	**MVar**	**Feeder Status**
1	Z3_S21_L1	70	30	On
2	Z3_S22_L3	70	15	On
3	Z3_S16_L7	29	1	On
4	Z3_S22_L2	30	5	On
Feeders Load at the scenario of comparison-1				
Sl.	**Feeder Name**	**MW**	**MVar**	**Feeder Status**
1	Z3_S21_L1	0	0	Off
2	Z3_S22_L3	0	0	Off
3	Z3_S16_L7	99	31	On
4	Z3_S22_L2	100	20	On

It is worth mentioning that these two feeders "Z3_S16_L7" and "Z3_S22_L2" are not under AUFLS or we can assume that the relays of these two feeders are temporarily disabled for some valid reasons.

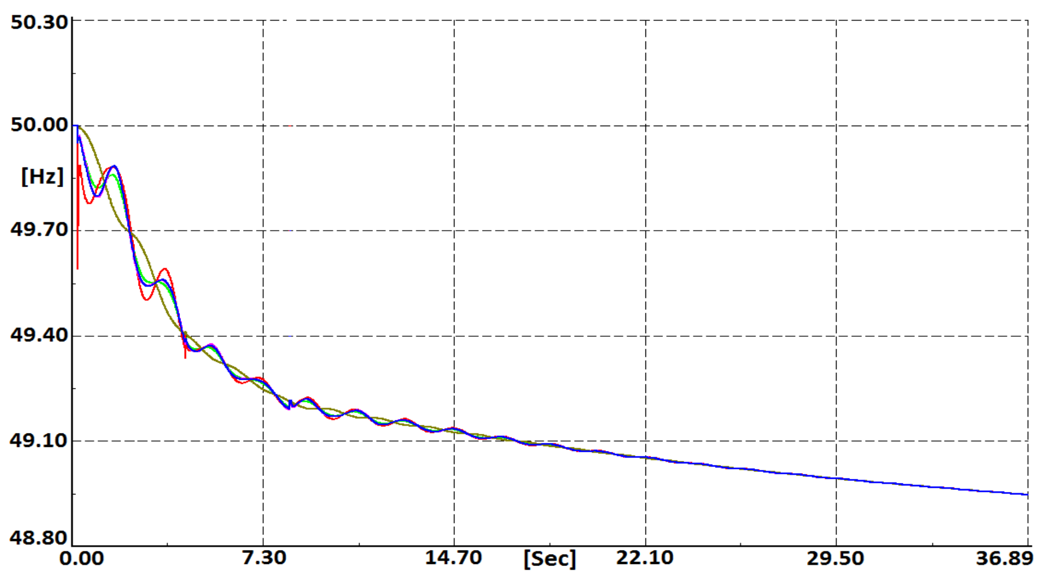

Figure 6.3: Frequency response after load variation with AUFLS

In this scenario, the simulation shows that, the implemented AUFLS on IEEE 39bus test system is no longer able to arrest the system frequency within safe limit and system falls in frequency instability. The frequency response of this scenario is shown above in Figure 6.4.

The instability (Under frequency) takes place because of load variation and implemented AUFLS has no knowledge of variation of power flow through the feeders under protection. The system was supposed to be healed by the 2nd stage of df/dt based and under-frequency based relay of implemented AUFLS but it did not happen because for maintenance purpose some loads under df/dt based relay were transferred to the other feeders which were not currently under implemented AUFLS for some valid reason.

So, from the above it is clear that, the implemented AUFLS might not work for every credible scenario, even though the generation loss is same for each scenario. Now we want to look at our proposed methodology, how it does act in this above said scenario. We find that, our python coded frequency arresting technique arrest the frequency decline before threshold level at the cost of load shed of prudently selected feeders of different zones as follows.

```
Gen Loss = 900.000000
System Load shed size = 745.000000 to arrest frequency before 49.1Hz & taking D=1.5%
Zone-1_LS =  = 85.000000 MW
Zone-2_LS =  = 85.000000 MW
Zone-3_LS =  = 268.000000 MW
Zone-4_LS =  = 185.000000 MW
Zone-5_LS =  = 105.000000 MW
Zone-6_LS =  = 16.000000 MW

Total actual shed= 749.00
Sheded Feeder List
['0', 'z1_s28_12', 'z1_s29_14', 'z2_s18_13', 'z2_s25_15', 'z3_s21_16', 'z3_s21_13',
      'z3_s23_11', 'z3_s23_14', 'z3_s24_13', 'z4_s14_13', 'z4_s15_12', 'z4_s20_14',
      'z5_s7_11', 'z5_s8_12', 'z5_s12_12', 'z6_s39_17']

Sheded Feeder MW
[0, 30, 50, 23, 24, 75, 50, 82, 50, 50, 55, 70, 50, 35, 70, 20, 15]
```

From above we observe that our proposed methodology sheds 749 MW loads in this above said scenario for 900MW loss but it sheded 746MW for same amount of generation loss in base scenario. Another important thing is found in comparison that our proposed methodology automatically rearranges feeder selection with respect to the different scenarios. The frequency response with our proposed technique in this case is shown in Figure 6.4.

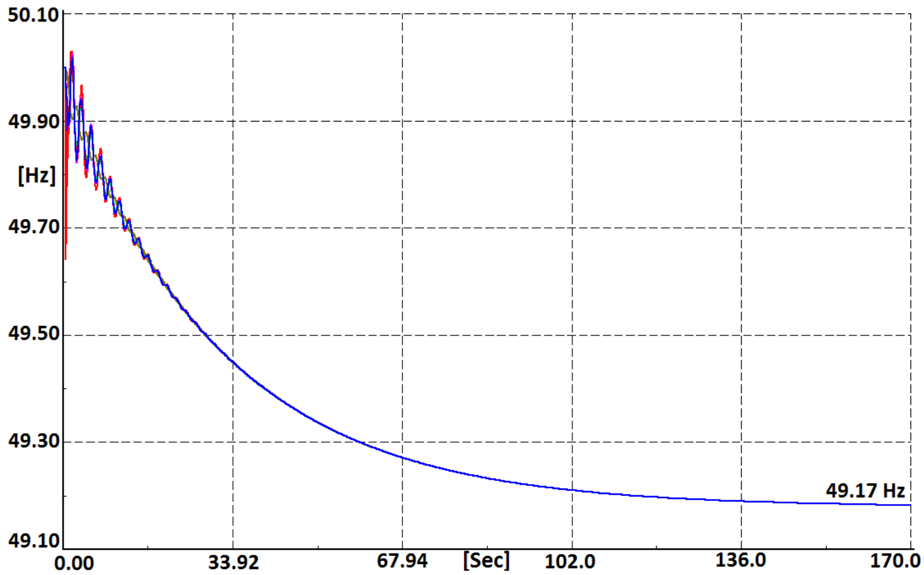

Figure 6.4: Frequency response after load variation with proposed method.

ii) Comparison-2: Over-Frequency

In this comparison-2, we shall bring some change in our base test system and try to compare our proposed methodology to the implemented AUFLS after 900MW generation loss and this comparison will take out the over-frequency issue in light that the implemented AUFLS tries to keep the frequency in the following scenario but over-frequency happens finally due to overload shed.

Now we shall increase the load of selected two feeders which are under AUFLS and other feeder's load of the test system will remain same. The increased load of the selected feeders will be catered by the slack machine. The selected two feeders are "Z2_S27_L2" and "Z5_S12_L2". The feeders load before and after increment has been shown in Table 6.4.

Table 6.4: Feeders load before and after increment

Feeders Load at base scenario				
Sl.	Feeder Name	MW	MVar	Feeder Status
1	Z2_S27_L2	30	11	On
2	Z5_S12_L2	20	5	On
Feeders Load at the scenario of comparison-2				
Sl.	Feeder Name	MW	MVar	Feeder Status
1	Z2_S27_L2	100	30	On
2	Z5_S12_L2	90	30	On

It is worth mentioning that these two feeders “Z2_S27_L2” and “Z5_S12_L2”are under AUFLS and we can assume that the loads of these two feeders are temporarily increased for some valid reasons. In this scenario, the simulation shows that, the implemented AUFLS on IEEE 39 bus test system no longer able to arrest the system frequency within safe limit due to over load shed and system fails as frequency rise. As a result frequency instability happens in the system. The frequency response with AUFLS of this scenario of comparison-2 is shown in Figure 6.5.

So, from the above discussion it is clear that, the implemented AUFLS might not work for every credible scenario, even though the generation loss is same for each scenario. Now we want to look at our proposed methodology, how it does act in this above said scenario of comparison-2. We find that, our python coded frequency arresting scheme arrest the frequency decline before threshold level at the cost of load shed of prudently selected feeders of different zones as follows.

```
Total actual shed= 737.00
Sheded Feeder List
['0', 'z1_s28_12', 'z1_s29_14', 'z2_s18_13', 'z2_s26_13', 'z2_s27_13', 'z3_s16_15',
     'z3_s21_16', 'z3_s21_15', 'z3_s22_12', 'z3_s24_11', 'z4_s14_13', 'z4_s15_12',
     'z4_s20_14', 'z4_s20_13', 'z5_s7_12', 'z5_s8_13', 'z5_s12_13', 'z6_s39_17']
Sheded Feeder MW
[0, 30, 50, 23, 20, 50, 20, 75, 20, 30, 120, 55, 70, 50, 0, 34, 50, 25, 15]
```

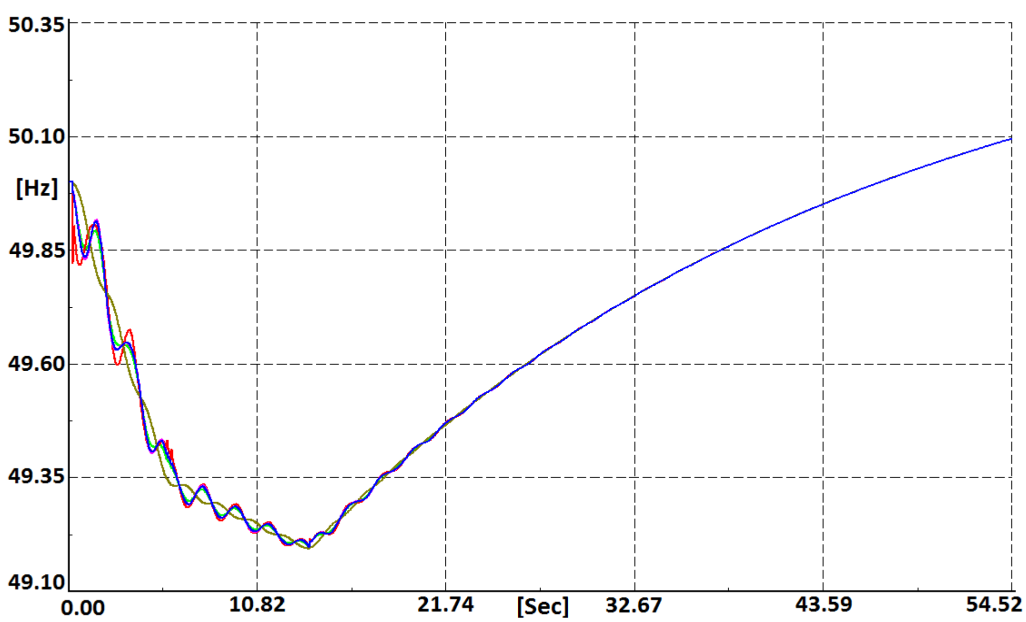

Figure 6.5: Frequency excursion after load increment with AUFLS

The important thing found in the comparison is that our proposed methodology automatically rearranges feeder selection in a dynamic manner for adaptation with different scenarios. The frequency response with our proposed technique in this case is shown in Figure 6.6.

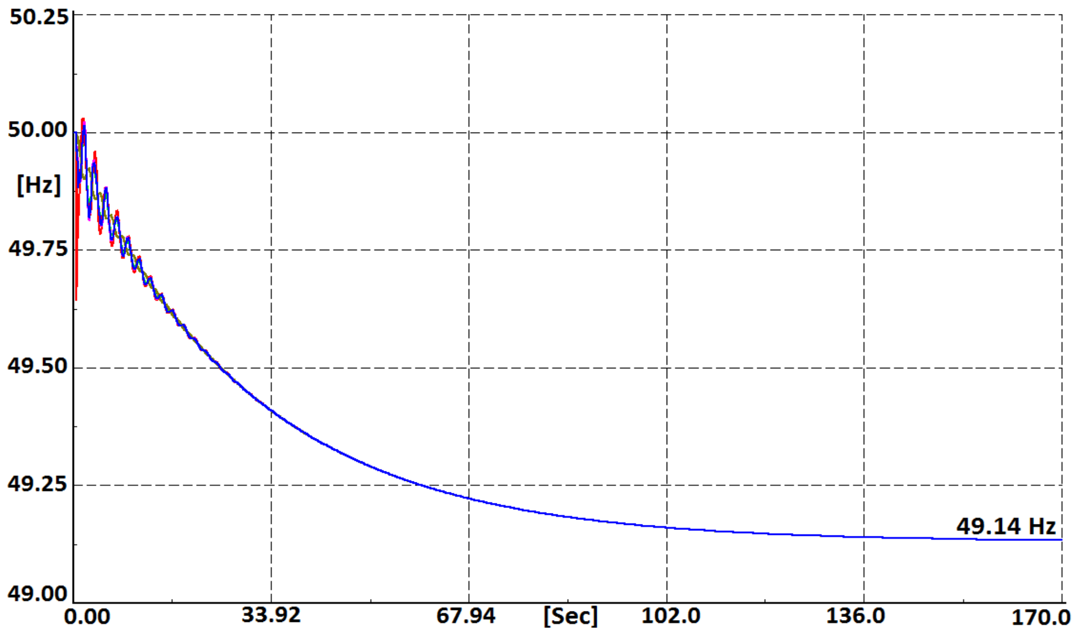

Figure 6.6: Frequency response after load increment with proposed method

6.4 Base Scenario 2

Base case network scenario-2 is a scenario of 600MW generation loss on which our proposed method and above said AUFLS work successfully. In case study-1 of chapter-5, we have seen that the proposed methodology arrest system frequency before the threshold level at 49.14Hz after 600MW generation loss. It is evident from Figure 6.7 that the implemented AUFLS also arrest the system frequency within safe limit at the cost of load shed of following feeders as shown in Table 6.5. This is our base scenario for comparison-3.The feeders are disconnected from the system according to the logic settings shown in Table 6.1.

Table 6.5: Sheded feeders by AUFLS after 600MW generation loss

Sl.	Feeder name	MW	MVAR
1	Z3_S21_L1	70	30
2	Z5_S7_L1	35	10
3	Z3_S16_L1	30	6
4	Z3_S24_L2	73	15
5	Z4_S15_L2	70	30
6	Z4_S14_L5	30	10
7	Z3_S21_L6	75	23
8	Z6_S3_L1	40	13
9	Z1_S28_L1	60	6
10	Z2_S25_L1	40	15
	Total	**523**	**158**

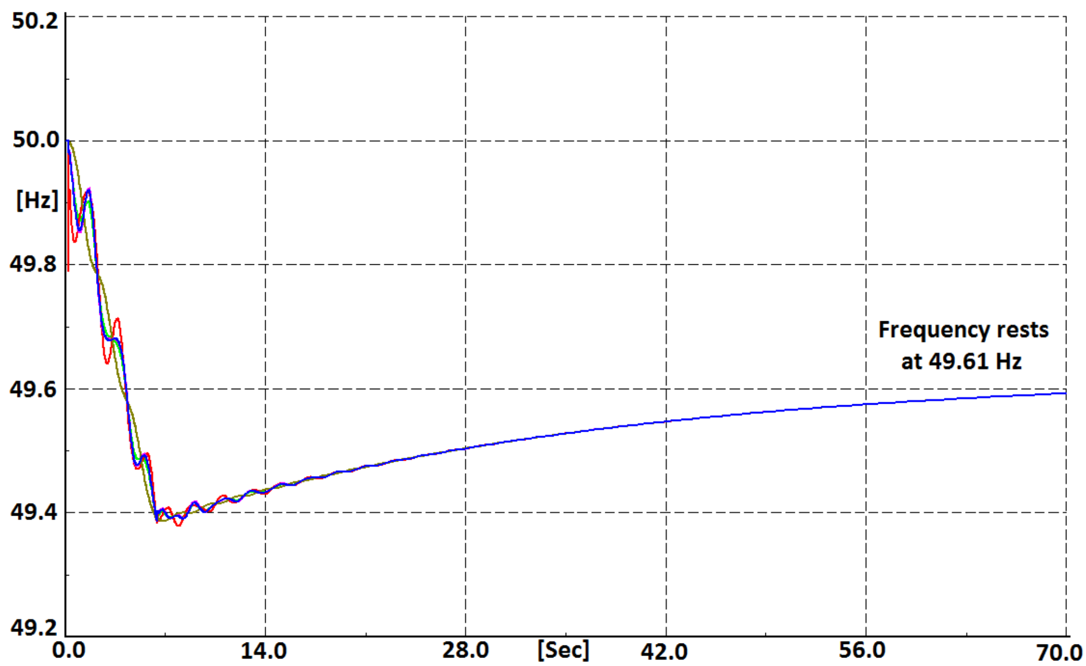

Figure 6.7: Frequency response with AUFLS for base scenario

Due to generation loss of 600 MW, some buses see the higher *df/dt* than the ROCOF 1st and 2nd stage and sheds load but no bus sees *df/dt* equal to or higher than ROCOF 3rd stage. Additionally first stage of under frequency relays are also operated as well as the system is healed from the frequency instability. For the same scenario the proposed methodology based scheme also works prudently at the cost of load shed of following feeders as we have seen in chapter-5. Figure 6.8 shows the frequency response with proposed methodology for 900MW generation loss.

```
Gen Loss = 600.000000
System Load shed size = 446.000000 to arrest frequency before 49.1Hz & taking D=1.5%
Zone-1_LS =  = 48.000000 MW
Zone-2_LS =  = 55.000000 MW
Zone-3_LS =  = 166.000000 MW
Zone-4_LS =  = 110.000000 MW
Zone-5_LS =  = 59.000000 MW
Zone-6_LS =  = 8.000000 MW

Sheded Feeder List
['0', 'z1_s28_13', 'z1_s29_12', 'z2_s25_15', 'z2_s27_12', 'z3_s21_11', 'z3_s22_15',
       'z3_s24_12', 'z4_s14_15', 'z4_s15_13', 'z4_s20_15', 'z5_s8_19', 'z5_s12_16']

Sheded Feeder MW
[0, 20, 30, 24, 30, 70, 20, 73, 30, 55, 30, 47, 10]
```

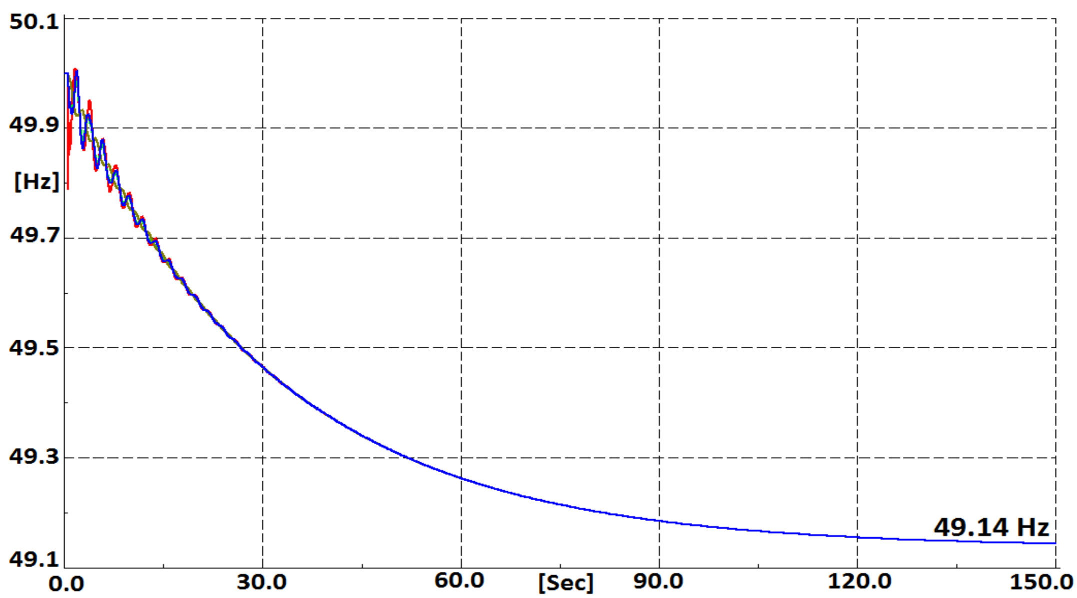

Figure 6.8:Frequency response with proposed methodology for 900MW generation loss

Since the implemented AUFLS does not have the true knowledge of feeder load variation and feeder's circuit breaker on-off status hence in some credible scenarios we are afraid that it might fail.

i) Comparison-3: Over-Frequency

In this comparison-3, we shall bring some change in our test system and try to compare our proposed methodology to the implemented AUFLS after 600MW generation loss and this comparison will take out the under-frequency issue in light that the implemented AUFLS tries to arrest the frequency decline in the following scenario but cannot arrest finally.

Table 6.6: Feeders load before and after inter-transfer

Feeders Load at base scenario 2				
Sl.	Feeder Name	MW	MVar	Feeder Status
1	Z3_S21_L1	70	30	On
2	Z3_S24_L2	73	15	On
3	Z2_S27_L2	30	11	On
4	Z5_S12_L2	15	5	On
Feeders Load at the scenario of comparison-3				
Sl.	Feeder Name	MW	MVar	Feeder Status
1	Z3_S21_L1	0	0	Off
2	Z3_S24_L2	0	0	Off
3	Z2_S27_L2	100	41	On
4	Z5_S12_L2	88	20	On

Now we will change feeders load in a way that the circuit breakers of two feeders will open and the loads of open feeders will transfer to other feeders which are under AUFLS unlike comparison-1. We have selected two feeders “Z3_S21_L1” and “Z3_S24_L2” for switching off from Table 6.2 and the loads of “Z3_S21_L1” and “Z3_S24_L2” are transferred to the feeders “Z2_S27_L2” and “Z5_S12_L2” respectively. The feeders load before and after inter-transfer has been shown in Table 6.6.

It is worth mentioning that these two feeders “Z3_S21_L1” and “Z3_S24_L2” are switched off but they were under df/dt based relay of AUFLS and we can assume that the loads of these two feeders are temporarily transferred to “Z2_S27_L2” and “Z5_S12_L2” for some valid reasons. Now the feeders “Z2_S27_L2” and “Z5_S12_L2” are carrying additional power and they are under AUFLS. In this scenario, the simulation shows that, the df/dt based relay and under-frequency based relay of implemented AUFLS on IEEE 39bus test system, both are giving efforts together to make the system frequency stable but no longer able to arrest the system frequency within safe limit due to over load shed by 2nd stage of AUFLS and system fails as frequency rise.

The instability (Over frequency) takes place because of load variation and implemented AUFLS has no knowledge of variation of power flow through the feeders under protection. The system was supposed to be healed by the 1st stage of df/dt based and under-frequency based relay of implemented AUFLS but it did not happen because some loads under df/dt based relay were transferred to the other feeders those were under under-frequency based relay for maintenance period. As a result frequency instability happens in the system. The frequency response with AUFLS of this scenario of comparison-3 is shown in Figure 6.9.

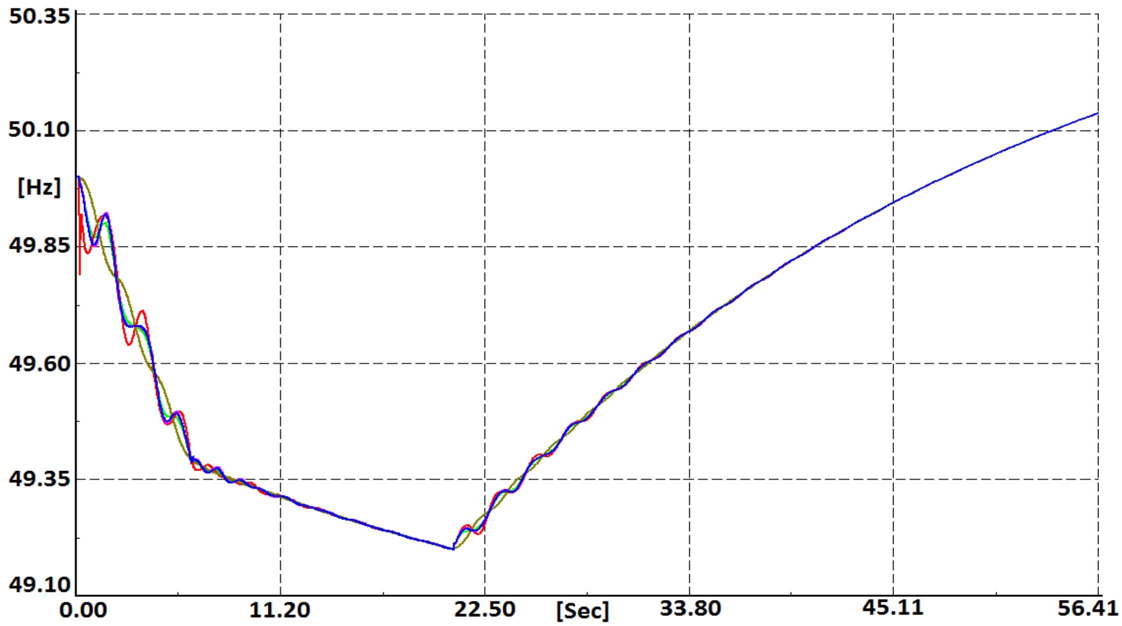

Figure 6.9: Frequency excursion with AUFLS for the scenario of comparison-3

So, from the above it is clear that, the implemented AUFLS might not work for every credible scenario, even though the generation loss is same for each scenario. Now we want to look at our proposed methodology, how it does act in this above said scenario of comparison-3. We find that, our python coded frequency arresting technique arrest the frequency decline before threshold level at the cost of load shed of prudently selected feeders of different zones as follows.

```
Gen Loss = 600.000000
System Load shed size = 444.000000 to arrest frequency before 49.1Hz & taking D=1.5%
Zone-1_LS =  = 48.000000 MW
Zone-2_LS =  = 55.000000 MW
Zone-3_LS =  = 167.000000 MW
Zone-4_LS =  = 110.000000 MW
Zone-5_LS =  = 56.000000 MW
Zone-6_LS =  = 8.000000 MW
Total actual shed= 450.00
Sheded Feeder List
['0', 'z1_s28_13', 'z1_s29_12', 'z2_s26_13', 'z2_s27_15', 'z3_s16_17', 'z3_s21_13',
      'z3_s22_15', 'z3_s23_14', 'z3_s24_14', 'z4_s14_15', 'z4_s15_14', 'z5_s7_13',
      'z5_s8_14', 'z5_s12_16', 'z6_s39_17']

Sheded Feeder MW
[0, 20, 30, 20, 21, 29, 50, 20, 50, 30, 30, 45, 50, 30, 10, 15]
```

Figure 6.10 shows that the frequency decline is arrested with proposed methodology based scheme before threshold value of lower frequency after load inter-transfer.

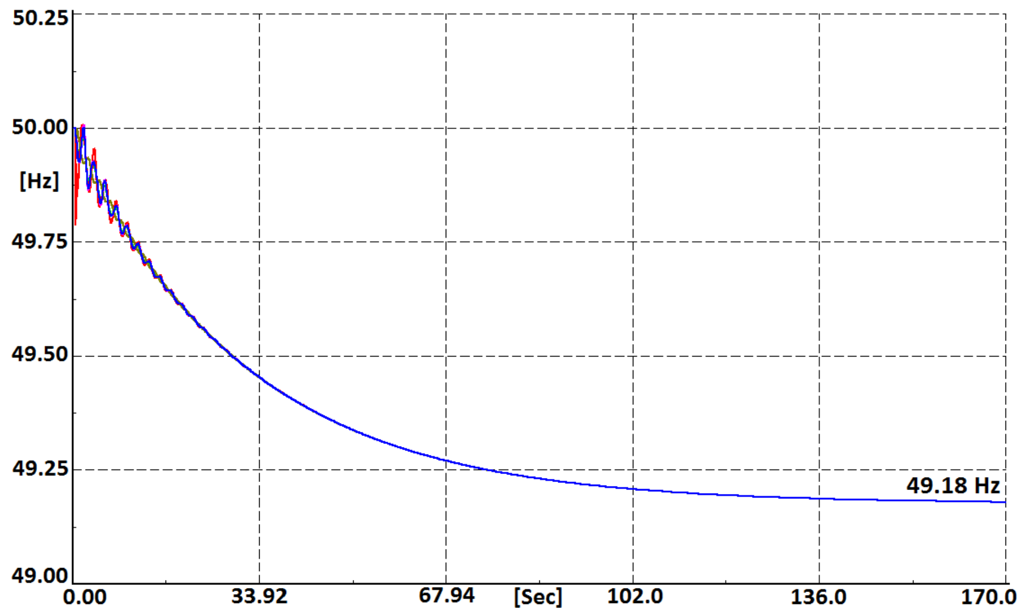

Figure 6.10: Frequency response after load inter-transfer with proposed method

The important thing found in this comparison is that our proposed methodology based scheme automatically rearranges feeder selection in a dynamic manner for adaptation with the different scenarios. The frequency response with our proposed methodology based scheme in this case is shown above in figure 6.10.

6.5 Conclusion

From the detail discussion and comparison of proposed methodology with conventional AUFLS we can come into the conclusion that since our proposed method for frequency stability is dynamically adaptive and keep the knowledge of necessary state variables hence this system will work in any type of credible network scenario irrespective of power system of any size.

CHAPTER 7

Closure

7.1Introduction

This chapter recapitulates the main results obtained in the framework of this project by providing general conclusions and discussions on the key findings, which is followed by suggestions for possible extensions of the work reported in this thesis.

7.2 Conclusions

The main focus of this thesis has been placed upon the formulation of a methodology for preventing a power system blackout by correcting frequency and voltage caused by generation loss or cross border tie-line outage. Frequency stability and voltage stability are two main kinds of stabilities in power grids. Researchers studied the two problems independently in the past. However, few studies have been done on the relationship between these two kinds of instabilities. We put forward a dynamic-adaptive frequency arresting technique which structure is introduced in details. Simulations based on typical system validate the effectiveness and adaptability of the proposed method compared with the other last line of defense applied in power grid. The scheme is simple and does not involve complicated calculations. It has also improved the voltage profile because more loads shed happen at weaker bus. The conventional load shedding schemes along with other adaptive schemes reviewed in chapter 2 were a strong basis for developing the proposed scheme. They provided details of the schemes which are already in practice in the industry as well as the schemes which are still being tested on a research level. The proposed scheme has been an effort to formulate a methodology for preventing a power system blackout considering the frequency and voltage as input variables for deciding and dividing the amount of load to be shed. Based on the observations and results obtained for the above test cases, it can be said that shedding the load based on the voltage sensitivities definitely improves the frequency and voltage. The case studies give satisfactory improvements in the frequency plot. This frequency is arrested and restored within safe limit.

There have been several cases considered in this thesis. From case-1 to case-3 of chapter-6, we have observed that the python coded proposed methodology in “Digsilent Powerfactory” works successfully in any pattern of load variation for any size of power system. In every case the proposed methodology sheds less amount of load for any type of disturbance amount and always sheds more loads proportionately at weaker buses following the bus ranking during healthy condition. That's why the proposed methodology not only arrest and restore the frequency but also makes the power system voltage stable.

In case-4 of chapter-5, the controlled simulation in "Digsilent Powerfactory" also confirms that the python coded proposed methodology also works successfully for zonal interconnection security. The python coded scheme always checks those interconnection lines connected to perturbed zone after every controlled load shedding and shed additional but least amount of load to rescue the line overloading which might trip the interconnecting lines. So this methodology provides security constrained dynamic adaptive load shedding scheme.

The communication requirements and latency time are also widely discussed. It shows that around 300ms is required to complete the total load shed without additional load shed for tie line monitoring. In simulation all breakers are tripped after 400ms as a conservative approach and simulation confirms that the test power system heals from instabilities at every case.

Along with the above, the proposed method is compared to widely used traditional and df/dt based adaptive technique to find the superiorities of proposed method. In chapter-7, it has been brought into light that the decentralized adaptive technique may fail in some credible scenarios because of load variation but the proposed method is not. Beside of this, it also has been shown in chapter-6 that existing adaptive techniques might not arrest the frequency when one or more feeders under df/dt relay are off for maintenance or any other reason but the proposed method can take back the frequency within safe limit.

7.3Future Work

The proposed methodology is confirmed by python scripted simulation in "Digsilent PowerFactory" Environment but the proposed methodology is applied to standard distribution and transmission network. The research has achieved some developments, but there are still some areas needing attention for future improvements. Based on the outcomes reported from this thesis, the author identifies two areas that have potential for future research as discussed next.

An extension of proposed methodology for market-based deregulated power system is another future direction. There is a definite scope for improving and modifying the scheme by fine tuning the algorithm by scoping to design an integrated scheme where both large and small loads can participate into a market-based program. Economical considerations need to be considered before shedding the load since certain loads cannot be kept offline. Also depending on the current market conditions the prices might vary. This needs to be kept in mind before initializing the load shedding scheme. This thesis proposed a method where only large scale loads at grid exit point can participate in the load shed programs without having prior agreement with the system operator. But it has not demonstrated a load control IED to control household loads. The future direction would be to integrate these elements and implement an ICT-based single platform where large loads as well as household loads can contribute to system operations. This ICT platform should expand seamlessly between distribution networks to the household level.

The LV network also is shifting from a passive to an active network. The active energy source will be available at downside of the distribution LV transformers. The shifting paradigm will change the unidirectional power to a bi-directional power flow, creating an extra burden in the design of a protection and control mechanism for an LV network. Therefore, the infrastructure of an automation platform in a LV network would be the other significant area of research including designing a new LS scheme.

References

[1] M.Q Ahsan, A.H.Chowdhury, S. S. Ahmed, I. H. Bhuyan, and H. Rahman, "Technique to Develop Auto Load Shedding and Islanding Scheme to Prevent Power System Blackout," in *IEEE Transactionson Power Systems,* Vol. 27, February 2012, pp. 198-205.

[2] M.Arifur Kabir, M.H.Hasan, S.M.Chowdhury, and A.H.Chowdhury, "Frequency Transient Analysis of Countrywide Blackout of Bangladesh Power System on 1st November, 2014," in *International Conference on Advances in Electrical Engineering*, Vol. 11, December 2015, pp. 267-270.

[3] A.H.Chowdhury, and S. S. Ahmed, "A study on low grid voltage problem near Rooppur nuclear power plant," in *International Conference on Electrical and Computer Engineering,* December 2014, pp. 289- 292.

[4] M.Arifur Kabir, M.H.Hasan, S.M.Chowdhury, and A.H.Chowdhury, "Analysis of Real Time Frequency Transients and Inertia Estimation of Bangladesh Power System," in *International Conference on Computer and Information Technology*, Vol. 7, December 2015, pp. 116-121.

[5] M. R. Haque, and A.H.Chowdhury, "Frequency characterization of Bangladesh Power System,"*International Conference on Electrical and Computer Engineering,* December 2016, pp. 341-344.

[6] M.K. M. Rabby, A.H.Chowdhury, M. A. Azamand and M. A. Towfiq, "Bifurcation analysis to identify voltage collapse in bangladesh power system," in *International Conference on informatics, Electronics and Vision,* May 2013.

[7] M. Zin, M. Hafiz, and Aziz, M., "A Review on Under frequency Load shedding scheme On TNB System, " in *International Power & Energy Conference*, Vol. 11, November 2004, pp. 170 – 174.

[8] Song, Z., Junyong, L., Youbo, L., Bazargan, L., and Liang,W., "A Method for design of UFLS scheme with Dynamic Correction , " in *Energy and Power Engineering*, Vol. 19, July 2013, pp. 442-447.

[9] Delfino, B., Massucco, S., Morini, A., Scalera, P., and Silvestro, F., "Implementaion and comparison of different under frequency load shedding schemes," in *IEEE Power Engineering Society*, vol. 3, July 2001, pp.307-312.

[10] Anderson, P.M., and Mirheydar, M., "An adaptive method for setting underfrequency load

shedding relays, ” in *IEEE Transactions on Power System*, vol. 7, May 1992, pp. 647-655.

[11] Rudez, U., and Mihalic, R., “Monitoring the first derivative to improve adaptive Under frequency load shedding schemes, ” in *IEEE Transactions on Power System*, vol. 26, May 2011, pp.37-42.

[12] Sigrist, L., and Rouco, L., “Design of UFLS schemes taking into account load variation”, in *Power Systems Computation Conference*, Vol. 5, August 2014, pp. 1-7.

[13] Mingchui, D., Chinwang, L., and Chikong,W., “Adaptive Under-Frequency Load Shed ding,” in *IEEE Transactions on Power System*, Vol. 13, December 2008, pp. 823-828.

[14] Zin, M., Hafiz, M., and Aziz, M., “A Review on Under frequency Load shedding scheme On TNB System, ” in *International Power & Energy Conference*, Vol. 11, November 2004, pp. 170 – 174.

[15] You, H., Vittal, V., and Yang, Z., “Self–healing in power systems: An approach using islanding and rate of frequency decline-based load shedding,” in *IEEE Transactions on Power Systems*, Vol. 18, February 2003, pp.121-128.

[16] Rudez, U., and Mihalic, R., “WAMS Based Under frequency Load Shedding with Short-Term Frequency Prediction”, in *IEEE Transactions on Power Delivery*, Vol. 31, February 2016, pp.137-142.

[17] Parniani, M., and Nasri, A., “SCADA based under frequency load shedding integrated with rate of frequency decline,” in *IEEE Power Engineering Society*, Vol. 24, June 2006, pp.63-68.

[18] Yang, H., and Zhang, B., “Voltage-frequency coupling effect in power grids and a novel load shedding scheme against it,” in *IEEE Region 10 Conference*, Vol. 19, October 2013, pp. 1-4.

[19] *A. Huang, G.M., and Nair, N.C, “Detection of dynamic voltage collapse,” in Power Engineering Society Summer Meeting, Vol. 3, July 2002, pp. 1284-1289.*

[20] Tang, J.J, Liu, J.Q., Ponci, F., and Monti, A., “Adaptive load shedding based on combined frequency and voltage stability assessment using synchrophasor measurements,” in *IEEE Transactions on Power System*, Vol. 28, May 2013, pp. 2035-2047.

[21] Ghaleh, A.P., Pasand, M.S., and Saffarian, A., “Power system stability enhancement using a adaptive combinal load-shedding algorithm,” in *IET Generation Transmission and Distribution*, Vol. 5, May. 2011, pp. 551-560.

[22] B. Saffarian, A., and Pasand, M.S.,“Enhancement of Power System Stability Using Adaptive Combinational Load Shedding Methods*,”* in *IEEE Transactions on Power System,* Vol. 26,

October 2010, pp. 1010-1020.

[23] D. H. A. Lee, "A General-Order System Frequency Response Model incorporating Load Shedding: Analytic Modelling and Applications," in *IEEE Transactions on Power System*, vol. 21, no.2, pp. 709 – 717, 2006.

[24] Power Systems Relaying Committee, IEEE Power Engineering Society, "IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration", *IEEE Standard C37.117-2007*, 2007.

[25] B. Delfino, S. Massucco, A. Morini, P. Scalera, and F. Silvestro, "Implementation and comparison of different under-frequency load shedding scheme", *Power Engineering Society Summer Meeting* , 2001.

[26] CIGRE, Technical Report38.01.07, "Analysis and Control of Power System Oscillations,"December 1996.

[27] M. S. Pasand, and H. Seyedi, "New Centralized Adaptive Under Frequency Load Shedding Algorithms," Large Engineering Systems Conference on Power Engineering, 2007.

[28] H. Seyedi, and M. S. Pasand, "New Centralised Adaptive Load-Shedding Algorithms to Mitigate Power System Blackouts," in *IET Generation, Transmission & Distribution*, vol. 3, no. 1, pp. 99-114, 2009.

[29] A. Saffarian, M. S. Pasand, and H. Asadi, "Performance Investigation of New Combinational Load Shedding Schemes," in*Joint International Conference on Power System Technology* and *IEEE Power India Conference* (POWERCON 2008), 2008.

[30] Y. Welhazi, T. Guesmi, I. B. Jaoued, and H. H. Abdallah, "Power System Stability Enhancement Using FACTS Controllers in Multimachine Power Systems", in *Journal of Electrical Systems*, vol. 10, no. 3, pp. 276-291, 2014.

[31] R. Z. Davarani, and R. Ghazi, "Optimal Simultaneous Coordination of PSS and TCSSC using Multi Objective Genetic Algorithm," in *Journal of Electrical Systems*, vol. 9, no. 4, pp. 410-421, 2013.

[32] M. V. Suganyadevi, and C. K. Babulal, "Fast Assessment of Voltage Stability Margin of a Power System," in *Journal of Electrical Systems*, vol. 20, no. 3, pp. 305-316, 2014.

[33] Y. Liu, W. Zhang, and Z. Yu, "Measures to Keep Islands Stable after Power Oscillation or Out of Step Islanding," in *International Conference on Advances in Power System Control*,

Operation and Management (APSCOM 2009), 2009.

[34] A. Saffarian, and M. S. Pasand, "Enhancement of Power System Stability Using Adaptive Combinational Load Shedding Methods," in *IEEE Transactions on Power Systems*, vol. 26, no. 3, pp. 1010-1020, 2011.

[35] A. P. Ghaleh, M. S. Pasand, and A. Saffarian, "Power System Stability Enhancement using a New Combinational Load-Shedding Algorithm," in*IET Generation, Transmission & Distribution*, vol. 5, no. 5, pp. 551-560, 2011.

[36] Z. Zhang, and Z. C. X. Wang, "Study on Emergency Control Based on Regional Frequency Response Model", in *International Conference on Advanced Power System Automation and Protection*, 2011.

[37] H. Samet, and M. Rashidi, "Coordinated Under Frequency Load and Capacitor Shedding for Bulk Power Systems,"in *IET Generation, Transmission & Distribution*, vol. 7, no. 8, pp. 799-812, 2013.

[38] A. Sauhats, V. Chuvychin, V. Strelkovs, R. Petrichenko, and E. Antonov, "Underfrequency Load Shedding in Large Interconnection", in *IEEE Grenoble Power Tech* (POWERTECH), 2013.

[39] Y-W. Au, and K-M. Yung, "Emergency Control and Restoration of Power System under Disturbance", Proceedings of the 4th *International Conference on Advances in Power System Control, Operation and Management* (APSCOM-97), 1997.

[40] L. E. Ling, and N. M. Vong, "Special Load Shedding Scheme to Enhance System Stability of Small Power System", in *International Conference on Power System Technology,* 2006.

[41] W. Pimjaipong, T. Junrussameevilai, and N. Maneerat, "Blackout Prevention Plan–The Stability, Reliability and Security Enhancement in Thailand Power Grid,"in *IEEE/PES Transmission and Distribution Conference and Exhibition: Asia and Pacific*, 2005.

[42] S. Imai, and T. Yasuda, "UFLS Program to Ensure Stable Island Operation," in*IEEE PES Power Systems Conference and Exposition*, 2004.

[43] S.-J. Huang, and C.-C. Huang, "An Automatic Load Shedding Scheme Including Pumped Storage Units," in*IEEE Transactions on Energy Conversion*, vo. 15, no. 4, pp. 427-432, 2000.

[44] L. E. Ling, V. Wong, and N. M. Vong, "Wide Area Protection (WAP) as an Enhanced Load Shedding Scheme to Mitigate Loss of Supply to Load Center," in *Conference of the Electric Power Supply Industry* (CEPSI) 2010, 2010.

[45] Y. Lu, W-S. Kao, and Y-T. Chen, "Study of Applying Load Shedding Scheme with Dynamic D-

Factor Values of Various Dynamic Load Models to Taiwan Power System," in*IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1976-1984, 2005.

[46] K. U. Z. Mollah, M. Bahadornejad, and N. K. –C. Nair, "Automatic Under-Frequency Load Shedding in New Zealand Power System – A Systematic Review", in *Australasian Universities Power Engineering Conference* (AUPEC), 2011.

[47] U. Rudez, and R. Mihalic, "Dynamic Analysis of Transition into Island Conditions of Slovenian Power System Applying Underfreuqency Load Shedding Scheme," in*IEEE Bucharest Power Tech Conference*, 2009.

[48] S. Lindahl, G. Runvik, and G. Stranne, "Operational Experience of Load Shedding and New Requirements on Frequency Relays", in *Developments in Power System Protection*, 1997.

[49] R. V. Fernandes, S. A. B. de Almeida, F. P. Maciel Barbosa, and RuiPestana, "Load Shedding – Coordination between the Portuguese Transmission Grid and the Distribution Grid with Minimization of Loss of Distributed Generation," in *IEEE Bucharest Power Tech Conference*, 2009.

[50] WECC, "WECC Coordinated Off-Nominal Frequency Load Shedding and Restoration Requirements", 2003.

[51] H. H. Wong, J. C. Flores, Y. Fang, and R. P. Baldevia Jr., "Guam Power Authority Automatic Underfrequency Load Shedding Study", in *International Conference on Energy Management and Power Delivery*, 1995.

[52] FRCC, Florida Reliability Coordinating Council, "FRCC Handbook", 2008.

[53] MAAC, Mid Atlantic Area Council, "MAAC Protective Relaying Philosophy and Design Standards", 1997.

[54] Y. R. Omar, I. Z. Abidin, S. Yusof, H. Hashim, H. A. Abdul Rashid, "Under Frequency Load Shedding (UFLS): Principles and Implementation," in Proceedings of *IEEE International Conference on Power and Energy*, 2010.

[55] R. M. Maliszewski, R. D. Dunlop, and G. L. Wilson, "Frequency Actuated Load Shedding and Restoration Part I – Philosophy," in *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-90, no. 4, pp. 1452-1459, 1971.

[56] M. L. Chan, R. D. Dunlop, and F. Schweppe, "Dynamic Equivalents for Average System Frequency Behavior Following Major Disturbances," in*IEEE Transactions on Power Apparatus*

and Systems, vol. PAS-91, no. 4, pp. 1637-1642, 1972.

[57] P. M. Anderson, and M. Mirheydar, "A Low-Order System Frequency Response Model," in *IEEE Transactions on Power Systems*, vol. 5, no. 3, pp. 720-729, 1990.

[58] P. M. Anderson, and M. Mirheydar, "An Adaptive Method for Setting Underfrequency Load Shedding Relays", in *IEEE Transactions on Power Systems*, vol. 7, no. 2, pp. 647-655, 1992.

[59] Y. Halevi, and D. Kottick, "Optimization of Load Shedding System," in *IEEE Transactions on Energy Conversion*, vol. 8, no. 2, pp. 207-213, 1993.

[60] V. Chin, Z. Y. Dong, T. K. Saha, J. Ford, and J. Zhang, "Adaptive and Optimal Under Frequency Load Shedding," in *Australasian Universities Power Engineering Conference* (AUPEC'08), 2008.

[61] C. Wu, L. Gao, and Y. Dai, "Simulation and Optimization of Load Shedding Scheme for Islanded Power System", in *International Conference on Power System Technology*, 2010.

[62] H. Y. Yu, and Z. Y. Dong, "Optimal Decentralized Load Curtailment by utilizing NMPA with Distributed Generations", in *IEEE PES ISGT* ASIA 2012, 2012.

[63] Y. R. Bhavanam, and M. Shahrazad, "Impact of Increased Distributed Generation on Fault Levels and the Network Equipment," in*Journal of Electrical Systems*, vol. 10, no. 2, pp. 209-222, 2014

[64] O. Shariati, A. A. MohdZin, A. Khairuddin, M. Pesaran, and M. R. Aghamohammadi, "An Integrated Method for Under Frequency Load Shedding Based on Hybrid Intelligent System-Part I: Dynamic Simulation," in*Asia-Pacific Power and Energy Engineering Conference* (APPEEC), 2012.

[65] G. Wang, H. Xin, D. Gan, N. Li, and Z. Wang, "*An Investigation into WAMS-based Under-Frequency Load Shedding*", in IEEE Power and Energy Society GeneralMeeting, 2012.

[66] J. Tang, J. Liu, F.Ponci, and A. Monti, "Adaptive Load Shedding Based on Combined Frequency and Voltage Stability Assessment Using Synchrophasor Measurements", in *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 2035-2047, 2013.

[67] H. You, V. Vittal, and Z. Yang, "Self-Healing in Power Systems: An Approach Using Islanding and Rate of Frequency Decline-Based Load Shedding," in*IEEE Transactions on Power Systems*, vol. 18, no. 1, pp. 174-181, 2003.

[68] V. V. Terzija, “Adaptive Underfrequency Load Shedding Based on the Magnitude of the Disturbance Estimation”, in *IEEE Transactions on Power Systems*, vol. 21, no. 3, pp. 1260-1266, 2006.

[69] L. Sigrist, I. Egido, and L. Rouco, “Principles of a Centralized UFLS Scheme for Small Isolated Power Systems,” in*IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 1779-1786, 2013.

[70] Power Systems Relaying Committee, IEEE Power Engineering Society, “*IEEE Guide for the Application of Protective Relays Used for Abnormal Frequency Load Shedding and Restoration*”, 2007.

[71] A. Li, and Z. Cai, “A Method for Frequency Dynamics Analysis and Load Shedding Assessment Based on the Trajectory of Power System Simulation,” in *International Conference on Electric Utility Deregulation and Restructuring and Power Technologies* (DRPT2008), 2008.

[72] Y. Lu, W-S. Kao, and Y-T. Chen, “Study of Applying Load Shedding Scheme with Dynamic D-Factor Values of Various Dynamic Load Models to Taiwan Power System,” in *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1976-1984, 2005.

[73] M. La Scala, M. Trovato, and C. Antonelli, “On-line Dynamic Preventive Control: An Algorithm for Transient Securirty Dispatch,” in*IEEE Transactions on Power Systems*, vol. 13, no. 2, pp. 601-610, 1998.

[74] K. Seethalekshmi, S. N. Singh, and S. C. Sriastava, “A Synchrophasor Assisted Frequency and Voltage Stability Based Load Shedding Scheme for Self-Healing of Power System”, in *IEEE Transactions on Smart Grid*, 2011.

[75] IEEE StdC37.118.1-2011 “IEEE standard for synchrophasor measurements for power systems,” (Revision of IEEE Std C37.118-2005), pp. 1–61, 2011.

[76] A. G. Phadke and J. S. Thorp, “*Synchronized phasor measurements and their applications*,” Springer, 2008.

[77] B. Hoseinzadeh, F. Faria Da Silva, and C. Bak, “Decentralized power system emergency control in the presence of high wind power penetration,” in *PES General Meeting Conference Exposition*, 2015 IEEE, pp. 1–5, 2015.

Appendix A

Python Script for Test System

```
# First go to "Creating events / Generator Trip" section,Then put'event
Time,Zone_trip,Gen_name'

#Gen_name='Z3_G1_1';zone_trip=3;
Gen_name1='Z3_G1';Gen_name2='Z3_G1_2';zone_trip=3;# Zone_trip=2 means, zone-2
Generator tripped

import powerfactory
app = powerfactory.GetApplication()

#***********************************************
#   From feeder_selection_v5_edit
#***********************************************
def check_ls(a1,b1):   # a1= Feeder MW & b1= Load Shed amount for a Bus
    if(a1>0.1): # If feeder MW is not zero
        c1=0;#app.PrintPlain('>> a1 = %d & b1 = %d'%(a1,b1));
        if (b1<=2 and abs(a1-b1)<=1.5): ok=1;
        elif ((b1>2) and (b1<=4) and abs(a1-b1)<=2): ok=1;
        elif ((b1>4) and (a1<=b1*1.5) and abs(a1-b1)<=5): ok=1;
        elif ((b1>=6) and (a1<=10)): ok=1;
        else:
            #ok=0;
            c1=a1+c1;#app.PrintPlain('>> c1 =%d & shed amount= %d'%(c1,b1));
            if (b1<=2 and abs(c1-b1)<=1.5): ok=1; c1=0;
            elif ((b1>2) and (b1<=4) and abs(c1-b1)<=2): ok=1;c1=0;
            elif ((b1>4) and (a1<=b1*1.5) and abs(c1-b1)<=5): ok=1;c1=0;
            else: ok=0;

    else: ok=0;
    return ok;

def row_column(): # It returns the row & column no. of pre-disturbance sheet
    #   -  Zone-1
    if (zone_bus_seq[p]==2): rw=3;col=3;
    elif(zone_bus_seq[p]==5): rw=3;col=7;
    #   -  Zone-2
    elif(zone_bus_seq[p]==8): rw=13;col=3;
    elif(zone_bus_seq[p]==11): rw=13;col=7;
    elif(zone_bus_seq[p]==14): rw=13;col=11;
    elif(zone_bus_seq[p]==17): rw=13;col=15;
    #   -  Zone-3
    elif(zone_bus_seq[p]==20): rw=22;col=3;
    elif(zone_bus_seq[p]==23): rw=22;col=7;
    elif(zone_bus_seq[p]==26): rw=22;col=11;
    elif(zone_bus_seq[p]==29): rw=22;col=15;
    elif(zone_bus_seq[p]==32): rw=22;col=19;
```

```
    #   -  Zone-4
    elif(zone_bus_seq[p]==35): rw=32;col=3;
    elif(zone_bus_seq[p]==38): rw=32;col=7;
    elif(zone_bus_seq[p]==41): rw=32;col=11;
    #   -  Zone-5
    elif(zone_bus_seq[p]==44): rw=42;col=3;
    elif(zone_bus_seq[p]==47): rw=42;col=7;
    elif(zone_bus_seq[p]==50): rw=42;col=11;
    #   -  Zone-6
    elif(zone_bus_seq[p]==53): rw=54;col=3;
    elif(zone_bus_seq[p]==56): rw=54;col=7;
    elif(zone_bus_seq[p]==59): rw=54;col=11;
    return rw,col;

def fdr_name(rw1,col1,no):
    ws = wb.get_sheet_by_name('Pre-disturbance_Data');
    aa=ws.cell(row=rw1-1+no,column=col1-1).value;
    bb=ws.cell(row=rw1-1+no,column=col1).value;
    ws = wb.get_sheet_by_name('Feeder_selection');
    return aa,bb;


# making up a dictionary--> SS name/LS MW/Bus Fdr nos.
zone_bus_ls = {'1':'Bus_28L','2':0,'3':7,
               '4':'Bus_29L','5':0,'6':6,
               #----- zone-2 -----------
               '7':'Bus_18L','8':0,'9':5,
               '10':'Bus_25L','11':0,'12':5,
               '13':'Bus_26L','14':0,'15':6,
               '16':'Bus_27L','17':0,'18':6,
               #----- zone-3 -----------
               '19':'Bus_16L','20':0,'21':7,
               '22':'Bus_21L','23':0,'24':6,
               '25':'Bus_22L','26':0,'27':5,
               '28':'Bus_23L','29':0,'30':6,
               '31':'Bus_24L','32':0,'33':6,
               #----- zone-4 -----------
               '34':'Bus_14L','35':0,'36':6,
               '37':'Bus_15L','38':0,'39':6,
               '40':'Bus_20L','41':0,'42':7,
               #----- zone-5 -----------
               '43':'Bus_7L','44':0,'45':5,
               '46':'Bus_8L','47':0,'48':9,
               '49':'Bus_12L','50':0,'51':6,
               #----- zone-6 -----------
               '52':'Bus_3L','53':0,'54':7,
               '55':'Bus_4L','56':0,'57':7,
               '58':'Bus_39L','59':0,'60':9,
               }
zone_load_bus_no=[0,2,4,5,3,3,3];

#**********************************************
#   From feeder_selection_v5_edit  End
#**********************************************

#For transient Simulation
ldf = app.GetFromStudyCase("ComLdf")
```

```
ini = app.GetFromStudyCase('ComInc')
sim = app.GetFromStudyCase('ComSim')

# Initialization of Transient Simulation
ldf.Execute()

#Excel file opening
from openpyxl import load_workbook
wb = load_workbook('D:\My Study\Thesis_Frequency Stability\my python
program\Thesis_IEEE_39.xlsx')
ass=wb.get_sheet_names()
ws = wb.get_sheet_by_name('Pre-disturbance_Data')

'''
#----Relay Deactivating---------------
loads=app.GetCalcRelevantObjects('*.ElmRelay')
relay=['0']

for load in loads:
    aa=load.GetAttribute('outserv')
    #load.outserv=1
    if (aa==0):
       fedr_nam=load.cbranch
       relay.append(fedr_nam.loc_name);
       load.outserv=1
'''



# ---------------------------------------------------------------------------
-------
# ---------------------------------------------------------------------------
-------
FVSI_arry=[0];Gen_nam_list=[0];Gen_MW_list=[0];
#Writing Load data(MW & MVAR) in excel of Zone-1 before perturbation

AllObj=app.GetCalcRelevantObjects()   #get list of all objects

grid=app.GetCalcRelevantObjects('Grid.ElmNet');
app.PrintPlain('%%%%%%%%%%%');
grid_Gen_mw=grid[0].GetAttribute('c:GenP');grid_Gen_mvar=grid[0].GetAttribute
('c:GenQ');
grid_Load_mw=grid[0].GetAttribute('c:LoadP');grid_Load_mvar=grid[0].GetAttrib
ute('c:LoadQ');
app.PrintPlain('Total Generation MW = %f'%grid_Gen_mw);
app.PrintPlain('Total Load MW = %f'%grid_Load_mw);
app.PrintPlain('%%%%%%%%%%%');

ws.cell(row=1, column=1, value="Zone-1")
loads=app.GetCalcRelevantObjects('z1_s28*.ElmLod')  #Filter the set with all
lines starting with â€™z1_s29â€™
lim=2;col_lim=2;load_tp=0;load_tq=0;fvsi_row=0;fvsi_col=0;gen_mw=0;gen_mvar=0
;

ws.cell(row=lim, column=col_lim, value="Feeder")
ws.cell(row=lim, column=col_lim+1, value="MW")
ws.cell(row=lim, column=col_lim+2, value="MVAR")
```

```
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim, value=name)
    ws.cell(row=lim+1, column=col_lim+1, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+2, value=round(load_q))
    lim=lim+1;
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
    #app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(load.loc_name,load.GetAttribute('m:P:bus1'),load.GetAttribute('m:Q:bus
1')))
line_no=lim;
ws.cell(row=lim+1, column=col_lim+1, value=load_tp)
ws.cell(row=lim+1, column=col_lim+2, value=load_tq)
load_zp=load_tp;load_zq=load_tq
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_28L.ElmTerm');
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");fvsi_row=fvsi_row+2;fvsi_col=fvsi_col+2;
ws.cell(row=fvsi_row,column=fvsi_col, value="Zone-1");
ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s28");carry_on=4*0.15*load_tq/(bus_u**2*1000);
ws.cell(row=fvsi_row+1,column=fvsi_col+2,
value=carry_on);FVSI_arry.append(carry_on);
app.PrintPlain('FVSI_s28 = %f'%carry_on);app.PrintPlain('--------------------
-');
ws = wb.get_sheet_by_name('Pre-disturbance_Data');


loads=app.GetCalcRelevantObjects('z1_s29*.ElmLod')
lim=2;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+4, value="Feeder")
ws.cell(row=lim, column=col_lim+5, value="MW")
ws.cell(row=lim, column=col_lim+6, value="MVAR")

for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+4, value=name)
    ws.cell(row=lim+1, column=col_lim+5, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+6, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
    #app.PrintPlain('Load ID : %s = %.2f MW & %0.2f MVAR
'%(name,load_p,load_q))
if(line_no<lim): line_no=lim;
ws.cell(row=lim+1, column=col_lim+5, value=load_tp)
ws.cell(row=lim+1, column=col_lim+6, value=load_tq)
```

```
#line_no=lim
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_29L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s29");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);
app.PrintPlain('FVSI_s29 = %f'%carry_on);app.PrintPlain('--------------------
-');
ws = wb.get_sheet_by_name('Pre-disturbance_Data');

load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;lim=2;
ws.cell(row=lim,column=col_lim+6+3, value="Gen.");
ws.cell(row=lim,column=col_lim+6+4, value="Load");
ws.cell(row=lim+1,column=col_lim+6+2, value="Total MW");
ws.cell(row=lim+2,column=col_lim+6+2, value="Total MVAR");

ws.cell(row=lim,column=col_lim+6+6, value="Gen. Name");
ws.cell(row=lim,column=col_lim+6+7, value="MW");
ws.cell(row=lim,column=col_lim+6+8, value="MVAR");

ws.cell(row=lim+1,column=col_lim+6+4, value=load_zp);  # writing Total load
MW
ws.cell(row=lim+2,column=col_lim+6+4, value=load_zq);  # writing Total load
MVAR

load_sp=load_zp;load_sq=load_zq;load_zp=0;load_zq=0;

gens= app.GetCalcRelevantObjects("Z1*.ElmSym");load_tp=0;load_tq=0;lim=2;
for gen in gens:
    load_p=gen.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp;
    Gen_nam_list.append(gen.loc_name);Gen_MW_list.append(round(load_p));
    load_q=gen.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+6+6, value=gen.loc_name)
    ws.cell(row=lim+1, column=col_lim+6+7, value=load_p)
    ws.cell(row=lim+1, column=col_lim+6+8, value=load_q)
    lim=lim+1;
lim=2;
ws.cell(row=lim+1,column=col_lim+6+3, value=load_tp); # Zonal Gen MW
ws.cell(row=lim+2,column=col_lim+6+3, value=load_tq); # Zonal Gen MVAR
gen_mw=gen_mw+load_tp;gen_mvar=gen_mvar+load_tq;

# Writing Load data(MW & MVAR)in excel of Zone-2 before perturbation
line1=line_no;lim=line1+3;col_lim=2;load_tp=0;load_tq=0;
ws.cell(row=lim-1, column=1, value="Zone-2")
ws.cell(row=lim, column=col_lim, value="Feeder")
ws.cell(row=lim, column=col_lim+1, value="MW")
ws.cell(row=lim, column=col_lim+2, value="MVAR")

loads=app.GetCalcRelevantObjects('z2_s18*.ElmLod')
for load in loads:
```

```
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim, value=name)
    ws.cell(row=lim+1, column=col_lim+1, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+2, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=col_lim+1, value=load_tp)
ws.cell(row=lim+1, column=col_lim+2, value=load_tq)
load_zp=load_tp;load_zq=load_tq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_18L.ElmTerm');
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");fvsi_row=fvsi_row+2;fvsi_col=2;
ws.cell(row=fvsi_row,column=fvsi_col, value="Zone-2");
ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s18");carry_on=4*0.15*load_tq/(bus_u**2*1000);
ws.cell(row=fvsi_row+1,column=fvsi_col+2, value=carry_on);
FVSI_arry.append(carry_on);
app.PrintPlain('FVSI z2_s18 = %f'%carry_on);app.PrintPlain('-----------------
----');
ws = wb.get_sheet_by_name('Pre-disturbance_Data');


loads=app.GetCalcRelevantObjects('z2_s25*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+4, value="Feeder")
ws.cell(row=lim, column=col_lim+5, value="MW")
ws.cell(row=lim, column=col_lim+6, value="MVAR")

for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+4, value=name)
    ws.cell(row=lim+1, column=col_lim+5, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+6, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
ws.cell(row=lim+1, column=col_lim+5, value=load_tp)
ws.cell(row=lim+1, column=col_lim+6, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_25L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;
```

```
ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s25");carry_on=4*0.15*load_tq/(bus_u**2*1000);
ws.cell(row=fvsi_row+1,column=fvsi_col+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z2_s25 = %f'%carry_on);app.PrintPlain('-----------------
----');


loads=app.GetCalcRelevantObjects('z2_s26*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+8, value="Feeder")
ws.cell(row=lim, column=col_lim+9, value="MW")
ws.cell(row=lim, column=col_lim+10, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+8, value=name)
    ws.cell(row=lim+1, column=col_lim+9, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+10, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
ws.cell(row=lim+1, column=col_lim+9, value=load_tp)
ws.cell(row=lim+1, column=col_lim+10, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_26L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s26");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z2_s26 = %f'%carry_on);app.PrintPlain('-----------------
----');


loads=app.GetCalcRelevantObjects('z2_s27*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+12, value="Feeder")
ws.cell(row=lim, column=col_lim+13, value="MW")
ws.cell(row=lim, column=col_lim+14, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+12, value=name)
    ws.cell(row=lim+1, column=col_lim+13, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+14, value=round(load_q))
```

```
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
ws.cell(row=lim+1, column=col_lim+13, value=load_tp)
ws.cell(row=lim+1, column=col_lim+14, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_27L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s27");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z2_s27 = %f'%carry_on);
app.PrintPlain('---------------------');


load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;lim=line1+3;
ws.cell(row=lim,column=col_lim+14+3, value="Gen.");
ws.cell(row=lim,column=col_lim+14+4, value="Load");
ws.cell(row=lim+1,column=col_lim+14+2, value="Total MW");
ws.cell(row=lim+2,column=col_lim+14+2, value="Total MVAR");

ws.cell(row=lim,column=col_lim+14+6, value="Gen. Name");
ws.cell(row=lim,column=col_lim+14+7, value="MW");
ws.cell(row=lim,column=col_lim+14+8, value="MVAR");

ws.cell(row=lim+1,column=col_lim+14+4, value=load_zp);  # writing Total MW
ws.cell(row=lim+2,column=col_lim+14+4, value=load_zq);  # writing Total MVAR
load_sp=load_sp+load_zp;load_sq=load_sq+load_zq;load_zp=0;load_zq=0;

gens= app.GetCalcRelevantObjects("Z2*.ElmSym");load_tp=0;load_tq=0;
for gen in gens:
    load_p=gen.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp;
    Gen_nam_list.append(gen.loc_name);Gen_MW_list.append(round(load_p));
    load_q=gen.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+14+6, value=gen.loc_name)
    ws.cell(row=lim+1, column=col_lim+14+7, value=load_p)
    ws.cell(row=lim+1, column=col_lim+14+8, value=load_q)
    lim=lim+1;
lim=line1+3;
ws.cell(row=lim+1,column=col_lim+14+3, value=load_tp);
ws.cell(row=lim+2,column=col_lim+14+3, value=load_tq);
gen_mw=gen_mw+load_tp;gen_mvar=gen_mvar+load_tq;

# Writing Load data(MW & MVAR)in excel of Zone-3 before perturbation
line1=line_no;lim=line1+3;load_tp=0;load_tq=0;col_lim=2;
ws.cell(row=lim-1, column=1, value="Zone-3")
ws.cell(row=lim, column=col_lim, value="Feeder")
ws.cell(row=lim, column=col_lim+1, value="MW")
ws.cell(row=lim, column=col_lim+2, value="MVAR")
loads=app.GetCalcRelevantObjects('z3_s16*.ElmLod')
```

```
load_tp=0;load_tq=0
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim, value=name)
    ws.cell(row=lim+1, column=col_lim+1, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+2, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
ws.cell(row=lim+1, column=col_lim+1, value=load_tp)
ws.cell(row=lim+1, column=col_lim+2, value=load_tq)
load_zp=load_tp;load_zq=load_tq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_16L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");fvsi_row=fvsi_row+2;fvsi_col=2;
ws.cell(row=fvsi_row,column=fvsi_col, value="Zone-3");
ws.cell(row=fvsi_row+1,column=fvsi_col+1, value="FVSI_s27");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z3_s16 = %f'%carry_on);app.PrintPlain('-----------------
----');


loads=app.GetCalcRelevantObjects('z3_s21*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+4, value="Feeder")
ws.cell(row=lim, column=col_lim+5, value="MW")
ws.cell(row=lim, column=col_lim+6, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+4, value=name)
    ws.cell(row=lim+1, column=col_lim+5, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+6, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
ws.cell(row=lim+1, column=col_lim+5, value=load_tp)
ws.cell(row=lim+1, column=col_lim+6, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_21L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s27");
```

```
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z3_s21 = %f'%carry_on);app.PrintPlain('-----------------
----');


loads=app.GetCalcRelevantObjects('z3_s22*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+8, value="Feeder")
ws.cell(row=lim, column=col_lim+9, value="MW")
ws.cell(row=lim, column=col_lim+10, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+8, value=name)
    ws.cell(row=lim+1, column=col_lim+9, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+10, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
ws.cell(row=lim+1, column=col_lim+9, value=load_tp)
ws.cell(row=lim+1, column=col_lim+10, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_22L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s22");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z3_s22 = %f'%carry_on);app.PrintPlain('-----------------
----');


loads=app.GetCalcRelevantObjects('z3_s23*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+12, value="Feeder")
ws.cell(row=lim, column=col_lim+13, value="MW")
ws.cell(row=lim, column=col_lim+14, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+12, value=name)
    ws.cell(row=lim+1, column=col_lim+13, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+14, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
```

```
ws.cell(row=lim+1, column=col_lim+13, value=load_tp)
ws.cell(row=lim+1, column=col_lim+14, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_23L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s23");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z3_s23 = %f'%carry_on);app.PrintPlain('-----------------
----');


loads=app.GetCalcRelevantObjects('z3_s24*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+16, value="Feeder")
ws.cell(row=lim, column=col_lim+17, value="MW")
ws.cell(row=lim, column=col_lim+18, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+16, value=name)
    ws.cell(row=lim+1, column=col_lim+17, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+18, value=round(load_q))
    lim=lim+1;app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q));
ws.cell(row=lim+1, column=col_lim+17, value=load_tp)
ws.cell(row=lim+1, column=col_lim+18, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_24L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s24");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z3_s24 = %f'%carry_on);app.PrintPlain('-----------------
----');


load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;lim=line1+3;
ws.cell(row=lim,column=col_lim+18+3, value="Gen.");
ws.cell(row=lim,column=col_lim+18+4, value="Load");
ws.cell(row=lim+1,column=col_lim+18+2, value="Total MW");
ws.cell(row=lim+2,column=col_lim+18+2, value="Total MVAR");
```

```
ws.cell(row=lim,column=col_lim+18+6, value="Gen. Name");
ws.cell(row=lim,column=col_lim+18+7, value="MW");
ws.cell(row=lim,column=col_lim+18+8, value="MVAR");

ws.cell(row=lim+1,column=col_lim+18+4, value=load_zp);  # writing Total MW
ws.cell(row=lim+2,column=col_lim+18+4, value=load_zq);  # writing Total MVAR
load_sp=load_sp+load_zp;load_sq=load_sq+load_zq;load_zp=0;load_zq=0;

gens=
app.GetCalcRelevantObjects("Z3*.ElmSym");load_tp=0;load_tq=0;lim=line1+3;
for gen in gens:
    load_p=gen.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp;
    Gen_nam_list.append(gen.loc_name);Gen_MW_list.append(round(load_p));
    load_q=gen.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+18+6, value=gen.loc_name)
    ws.cell(row=lim+1, column=col_lim+18+7, value=load_p)
    ws.cell(row=lim+1, column=col_lim+18+8, value=load_q)
    lim=lim+1;
lim=line1+3;
ws.cell(row=lim+1,column=col_lim+18+3, value=load_tp);
ws.cell(row=lim+2,column=col_lim+18+3, value=load_tq);
gen_mw=gen_mw+load_tp;gen_mvar=gen_mvar+load_tq;

# Writing Load data(MW & MVAR)in excel of Zone-4 before perturbation
line1=line_no;lim=line1+3;load_tp=0;load_tq=0;col_lim=2;
ws.cell(row=lim-1, column=1, value="Zone-4")
ws.cell(row=lim, column=col_lim, value="Feeder")
ws.cell(row=lim, column=col_lim+1, value="MW")
ws.cell(row=lim, column=col_lim+2, value="MVAR")
loads=app.GetCalcRelevantObjects('z4_s14*.ElmLod')
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim, value=name)
    ws.cell(row=lim+1, column=col_lim+1, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+2, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=col_lim+1, value=load_tp)
ws.cell(row=lim+1, column=col_lim+2, value=load_tq)
load_zp=load_tp;load_zq=load_tq;
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_14L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");fvsi_row=fvsi_row+2;fvsi_col=2;
ws.cell(row=fvsi_row,column=fvsi_col, value="Zone-
4");ws.cell(row=fvsi_row+1,column=fvsi_col+1, value="FVSI_s14");
```

```
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z4_s14 = %f'%carry_on);app.PrintPlain('-----------------
----');

loads=app.GetCalcRelevantObjects('z4_s15*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+4, value="Feeder")
ws.cell(row=lim, column=col_lim+5, value="MW")
ws.cell(row=lim, column=col_lim+6, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+4, value=name)
    ws.cell(row=lim+1, column=col_lim+5, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+6, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=col_lim+5, value=load_tp)
ws.cell(row=lim+1, column=col_lim+6, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_15L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s15");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z4_s15 = %f'%carry_on);app.PrintPlain('-----------------
----');

loads=app.GetCalcRelevantObjects('z4_s20*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+8, value="Feeder")
ws.cell(row=lim, column=col_lim+9, value="MW")
ws.cell(row=lim, column=col_lim+10, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+8, value=name)
    ws.cell(row=lim+1, column=col_lim+9, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+10, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
```

```
ws.cell(row=lim+1, column=col_lim+9, value=load_tp)
ws.cell(row=lim+1, column=col_lim+10, value=load_tq)
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_20L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s20");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z4_s20 = %f'%carry_on);app.PrintPlain('-----------------
----');

load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;lim=line1+3;
ws.cell(row=lim,column=col_lim+10+3, value="Gen.");
ws.cell(row=lim,column=col_lim+10+4, value="Load");
ws.cell(row=lim+1,column=col_lim+10+2, value="Total MW");
ws.cell(row=lim+2,column=col_lim+10+2, value="Total MVAR");

ws.cell(row=lim,column=col_lim+10+6, value="Gen. Name");
ws.cell(row=lim,column=col_lim+10+7, value="MW");
ws.cell(row=lim,column=col_lim+10+8, value="MVAR");

ws.cell(row=lim+1,column=col_lim+10+4, value=load_zp);  # writing Total MW
ws.cell(row=lim+2,column=col_lim+10+4, value=load_zq);  # writing Total MVAR
load_sp=load_sp+load_zp;load_sq=load_sq+load_zq;load_zp=0;load_zq=0;


gens=
app.GetCalcRelevantObjects("Z4*.ElmSym");load_tp=0;load_tq=0;lim=line1+3;
for gen in gens:
    load_p=gen.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp;
    Gen_nam_list.append(gen.loc_name);Gen_MW_list.append(round(load_p));
    load_q=gen.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+10+6, value=gen.loc_name)
    ws.cell(row=lim+1, column=col_lim+10+7, value=load_p)
    ws.cell(row=lim+1, column=col_lim+10+8, value=load_q)
    lim=lim+1;
lim=line1+3;
ws.cell(row=lim+1,column=col_lim+10+3, value=load_tp);
ws.cell(row=lim+2,column=col_lim+10+3, value=load_tq);
gen_mw=gen_mw+load_tp;gen_mvar=gen_mvar+load_tq;


# Writing Load data(MW & MVAR)in excel of Zone-5 before perturbation
line1=line_no;lim=line1+3;load_tp=0;load_tq=0;col_lim=2;
ws.cell(row=lim-1, column=1, value="Zone-5")
ws.cell(row=lim, column=col_lim, value="Feeder")
ws.cell(row=lim, column=col_lim+1, value="MW")
ws.cell(row=lim, column=col_lim+2, value="MVAR")
loads=app.GetCalcRelevantObjects('z5_s7*.ElmLod')
for load in loads:
```

```
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim, value=name)
    ws.cell(row=lim+1, column=col_lim+1, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+2, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=col_lim+1, value=load_tp)
ws.cell(row=lim+1, column=col_lim+2, value=load_tq)
load_zp=load_tp;load_zq=load_tq;
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_7L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");fvsi_row=fvsi_row+2;fvsi_col=2;
ws.cell(row=fvsi_row,column=fvsi_col, value="Zone-
5");ws.cell(row=fvsi_row+1,column=fvsi_col+1, value="FVSI_s7");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z5_s7 = %f'%carry_on);app.PrintPlain('------------------
---');

loads=app.GetCalcRelevantObjects('z5_s8*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+4, value="Feeder")
ws.cell(row=lim, column=col_lim+5, value="MW")
ws.cell(row=lim, column=col_lim+6, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+4, value=name)
    ws.cell(row=lim+1, column=col_lim+5, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+6, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=col_lim+5, value=load_tp)
ws.cell(row=lim+1, column=col_lim+6, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_8L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s8");
```

```
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z5_s8 = %f'%carry_on);app.PrintPlain('------------------
---');

loads=app.GetCalcRelevantObjects('z5_s12*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+8, value="Feeder")
ws.cell(row=lim, column=col_lim+9, value="MW")
ws.cell(row=lim, column=col_lim+10, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+8, value=name)
    ws.cell(row=lim+1, column=col_lim+9, value=round(load_p))
    ws.cell(row=lim+1, column=col_lim+10, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=col_lim+9, value=load_tp)
ws.cell(row=lim+1, column=col_lim+10, value=load_tq)
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_12L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s12");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z5_s12 = %f'%carry_on);app.PrintPlain('-----------------
----');

load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;lim=line1+3;
ws.cell(row=lim,column=col_lim+10+3, value="Gen.");
ws.cell(row=lim,column=col_lim+10+4, value="Load");
ws.cell(row=lim+1,column=col_lim+10+2, value="Total MW");
ws.cell(row=lim+2,column=col_lim+10+2, value="Total MVAR");

ws.cell(row=lim,column=col_lim+10+6, value="Gen. Name");
ws.cell(row=lim,column=col_lim+10+7, value="MW");
ws.cell(row=lim,column=col_lim+10+8, value="MVAR");

ws.cell(row=lim+1,column=col_lim+10+4, value=load_zp);  # writing Total MW
ws.cell(row=lim+2,column=col_lim+10+4, value=load_zq);  # writing Total MVAR
load_sp=load_sp+load_zp;load_sq=load_sq+load_zq;load_zp=0;load_zq=0;


gens=
app.GetCalcRelevantObjects("Z5*.ElmSym");load_tp=0;load_tq=0;lim=line1+3;
for gen in gens:
```

```
    load_p=gen.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp;
    Gen_nam_list.append(gen.loc_name);Gen_MW_list.append(round(load_p));
    load_q=gen.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+10+6, value=gen.loc_name)
    ws.cell(row=lim+1, column=col_lim+10+7, value=load_p)
    ws.cell(row=lim+1, column=col_lim+10+8, value=load_q)
    lim=lim+1;
lim=line1+3;
ws.cell(row=lim+1,column=col_lim+10+3, value=load_tp);
ws.cell(row=lim+2,column=col_lim+10+3, value=load_tq);
gen_mw=gen_mw+load_tp;gen_mvar=gen_mvar+load_tq;


# Writing Load data(MW & MVAR)in excel of Zone-6 before perturbation
line1=line_no;lim=line1+3;load_tp=0;load_tq=0;col_lim=2;
ws.cell(row=lim-1, column=1, value="Zone-6")
ws.cell(row=lim, column=col_lim, value="Feeder")
ws.cell(row=lim, column=col_lim+1, value="MW")
ws.cell(row=lim, column=col_lim+2, value="MVAR")
loads=app.GetCalcRelevantObjects('z6_s3_*.ElmLod')
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=2, value=name)
    ws.cell(row=lim+1, column=3, value=round(load_p))
    ws.cell(row=lim+1, column=4, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=3, value=load_tp)
ws.cell(row=lim+1, column=4, value=load_tq)
load_zp=load_tp;load_zq=load_tq;
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_3L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");fvsi_row=fvsi_row+2;fvsi_col=2;
ws.cell(row=fvsi_row,column=fvsi_col, value="Zone-
6");ws.cell(row=fvsi_row+1,column=fvsi_col+1, value="FVSI_s3");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z6_s3 = %f'%carry_on);app.PrintPlain('------------------
---');

loads=app.GetCalcRelevantObjects('z6_s4*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+4, value="Feeder")
ws.cell(row=lim, column=col_lim+5, value="MW")
ws.cell(row=lim, column=col_lim+6, value="MVAR")
for load in loads:
```

```
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=6, value=name)
    ws.cell(row=lim+1, column=7, value=round(load_p))
    ws.cell(row=lim+1, column=8, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=7, value=load_tp)
ws.cell(row=lim+1, column=8, value=load_tq)
load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_4L.ElmTerm')
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s4");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z6_s4 = %f'%carry_on);app.PrintPlain('------------------
---');

loads=app.GetCalcRelevantObjects('z6_s39*.ElmLod')
lim=line1+3;load_tp=0;load_tq=0;
ws.cell(row=lim, column=col_lim+8, value="Feeder")
ws.cell(row=lim, column=col_lim+9, value="MW")
ws.cell(row=lim, column=col_lim+10, value="MVAR")
for load in loads:
    name=load.loc_name
    load_p=load.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp
    load_q=load.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=10, value=name)
    ws.cell(row=lim+1, column=11, value=round(load_p))
    ws.cell(row=lim+1, column=12, value=round(load_q))
    lim=lim+1
    app.PrintPlain('Load ID : %s = %.2f MW & %0.2f
MVAR'%(name,load_p,load_q))
ws.cell(row=lim+1, column=11, value=load_tp)
ws.cell(row=lim+1, column=12, value=load_tq)
if(line_no<lim): line_no=lim;
# FVSI Calculation
bus=app.GetCalcRelevantObjects('Bus_39L.ElmTerm');
bus_u=bus[0].GetAttribute('m:u');app.PrintPlain('Bus V =
%f'%bus_u);app.PrintPlain('Bus Q = %f'%load_tq);
ws = wb.get_sheet_by_name("FVSI");
fvsi_row=fvsi_row+1;ws.cell(row=fvsi_row+1,column=fvsi_col+1,
value="FVSI_s39");
carry_on=4*0.15*load_tq/(bus_u**2*1000);ws.cell(row=fvsi_row+1,column=fvsi_co
l+2, value=carry_on);
```

```
FVSI_arry.append(carry_on);ws = wb.get_sheet_by_name('Pre-disturbance_Data');
app.PrintPlain('FVSI z6_s39 = %f'%carry_on);app.PrintPlain('-----------------
----');

load_zp=load_tp+load_zp;load_zq=load_tq+load_zq;lim=line1+3;
ws.cell(row=lim,column=col_lim+10+3, value="Gen.");
ws.cell(row=lim,column=col_lim+10+4, value="Load");
ws.cell(row=lim+1,column=col_lim+10+2, value="Total MW");
ws.cell(row=lim+2,column=col_lim+10+2, value="Total MVAR");

ws.cell(row=lim,column=col_lim+10+6, value="Gen. Name");
ws.cell(row=lim,column=col_lim+10+7, value="MW");
ws.cell(row=lim,column=col_lim+10+8, value="MVAR");

ws.cell(row=lim+1,column=col_lim+10+4, value=load_zp);  # writing Total MW
ws.cell(row=lim+2,column=col_lim+10+4, value=load_zq);  # writing Total MVAR
load_sp=load_sp+load_zp;load_sq=load_sq+load_zq;load_zp=0;load_zq=0;

gens=
app.GetCalcRelevantObjects("Z6*.ElmSym");load_tp=0;load_tq=0;lim=line1+3;
for gen in gens:
    load_p=gen.GetAttribute('m:P:bus1')
    load_tp =load_p+load_tp;
    Gen_nam_list.append(gen.loc_name);Gen_MW_list.append(round(load_p));
    load_q=gen.GetAttribute('m:Q:bus1')
    load_tq=load_q+load_tq
    ws.cell(row=lim+1, column=col_lim+10+6, value=gen.loc_name)
    ws.cell(row=lim+1, column=col_lim+10+7, value=load_p)
    ws.cell(row=lim+1, column=col_lim+10+8, value=load_q)
    lim=lim+1;
lim=line1+3;
ws.cell(row=lim+1,column=col_lim+10+3, value=load_tp);
ws.cell(row=lim+2,column=col_lim+10+3, value=load_tq);
gen_mw=gen_mw+load_tp;gen_mvar=gen_mvar+load_tq;

line1=line_no;lim=line1+3;
ws.cell(row=lim+1,column=3, value="Sys Lod MW");ws.cell(row=lim+2,column=3,
value="Sys Lod MVAR");
ws.cell(row=lim+1,column=4,
value=round(grid_Load_mw));ws.cell(row=lim+2,column=4,
value=round(grid_Load_mvar));
ws.cell(row=lim+1,column=7, value="Sys Gen MW");ws.cell(row=lim+2,column=7,
value="Sys Gen MVAR");
ws.cell(row=lim+1,column=8, value=grid_Gen_mw);ws.cell(row=lim+2,column=8,
value=grid_Gen_mvar);

#Saving Excel File
wb.save('D:\My Study\Thesis_Frequency Stability\my python
program\Thesis_IEEE_39.xlsx')
# ------------------------------------------------------------------
# ------------------------------------------------------------------

# Adding monitoring variables
elmres = app.GetFromStudyCase('All calculations.ElmRes')
terminal = app.GetCalcRelevantObjects("Bus_38.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz','m:Pflow')
terminal = app.GetCalcRelevantObjects("Bus_37.ElmTerm")
```

```
elmres.AddVars(terminal[0],'m:dfedt','m:fehz','m:Pflow')
terminal = app.GetCalcRelevantObjects("Bus_30.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz')
terminal = app.GetCalcRelevantObjects("Bus_36.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz')

terminal = app.GetCalcRelevantObjects("Bus_35.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz','m:Pflow')
terminal = app.GetCalcRelevantObjects("Bus_33.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz','m:Pflow')
terminal = app.GetCalcRelevantObjects("Bus_34.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz','m:Pflow')
terminal = app.GetCalcRelevantObjects("Bus_31.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz')
terminal = app.GetCalcRelevantObjects("Bus_32.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz')
terminal = app.GetCalcRelevantObjects("Bus_39.ElmTerm")
elmres.AddVars(terminal[0],'m:dfedt','m:fehz')

# For Tie line
tie_line = app.GetCalcRelevantObjects("Line 26 - 29.ElmLne")
elmres.AddVars(tie_line[0],'m:U11:bus1')
elmres.AddVars(tie_line[0],'m:I1:bus1')
tie_line = app.GetCalcRelevantObjects("Line 26 - 28.ElmLne")
elmres.AddVars(tie_line[0],'m:U11:bus1')
elmres.AddVars(tie_line[0],'m:I1:bus1')


# Creating events / Generator Trip
event_time=0.5;
Shc_folder = app.GetFromStudyCase('IntEvt');
EventSet = Shc_folder.GetContents();

if(len(EventSet)>0):
    for i in range(0,len(EventSet)):
        EventSet[i].Delete();

Shc_folder.CreateObject('EvtSwitch', Gen_name1+' Trip');
EventSet = Shc_folder.GetContents();
evt = EventSet[0];evt.time =event_time;
sym = app.GetCalcRelevantObjects(Gen_name1+'.ElmSym')
evt.p_target = sym[0]

Shc_folder.CreateObject('EvtSwitch', Gen_name2+' Trip');
EventSet = Shc_folder.GetContents();
evt = EventSet[1];evt.time =event_time;
sym = app.GetCalcRelevantObjects(Gen_name2+'.ElmSym')
evt.p_target = sym[0]




# Initialization & Transient Simulation Running
ini.Execute()
sim.Execute()
#evt.Delete()
```

```
#Get Result file ElmRes
script=app.GetCurrentScript()
res=script.GetContents('All_calc.ElmRes')
res=res[0][0]

#Loading of Result file into memory
app.ResLoadData(res)


#Get number of rows and columns
NrCol=app.ResGetVariableCount(res)
NrRow=app.ResGetValueCount(res,0)

#print results
app.PrintPlain('ElmRes has %i rows and %i Columns'%(NrRow,NrCol))


#_________________________________________________________________
# Calculating df/dt of Zone-1 Buses
dfdt_z=0.0;
app.PrintPlain('----------------Zone-1/SS-29----------------------------')
ws = wb.get_sheet_by_name('dfdt')
terminal = app.GetCalcRelevantObjects("Bus_29L.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');#app.PrintPlain('dfdt=
%i'%ColIndex1)

ColIndex2=app.ResGetIndex(res,terminal[0],'b:tnow');#app.PrintPlain('Time =
%i'%ColIndex2)
for i in range(NrRow):                              # Determining event time
array no.
    sim_time=app.ResGetData(res,i,ColIndex2);#app.PrintPlain(sim_time)
    if(abs(sim_time[1]) >= (event_time+.02)):
        start_time=i;break
app.PrintPlain('Time @ %d = %f'%(start_time,sim_time[1]))


app.PrintPlain('----------------Zone-1/PS-1----------------------------')
ws.cell(row=1, column=1, value="Zone-1")
ws.cell(row=2, column=2, value="Z1_G1")
terminal = app.GetCalcRelevantObjects("Bus_38.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=2;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-1<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=2, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt =
%f'%val[1])
       lim=lim+1
dfdt=-1*dfdt/5;dfdt_z=dfdt;
ws.cell(row=lim+1, column=2, value=dfdt)
ws.cell(row=2, column=3, value="df/dt_coi");ws.cell(row=3, column=3,
value=dfdt_z);
app.PrintPlain('df/dt of Z1_Bus_38_gen Bus %f'%(dfdt))
```

```
app.PrintPlain('df/dt_coi of Zone-1 %f'%(dfdt_z))
app.PrintPlain('-------------------------------------------------------')


app.PrintPlain('----------------Zone-2/PS-1----------------------------')
ws.cell(row=1, column=6, value="Zone-2")
ws.cell(row=2, column=7, value="Z2_G1")
terminal = app.GetCalcRelevantObjects("Bus_37.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=2;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-1<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=7, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt = 
%f'%val[1])
       lim=lim+1
#if (Gen_name!="Z2_G1"): dfdt=-1*dfdt/5;dfdt_z=dfdt;
#else: dfdt=0;
ws.cell(row=lim+1, column=7, value=dfdt)
app.PrintPlain('df/dt of Z2_Bus_30_gen Bus %f'%(dfdt))
app.PrintPlain('--------------------------------------------------------')

app.PrintPlain('----------------Zone-2/PS-2----------------------------')
ws.cell(row=2, column=8, value="Z2_G2")
terminal = app.GetCalcRelevantObjects("Bus_30.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=2;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-1<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=8, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt = 
%f'%val[1])
       lim=lim+1
#dfdt=-1*dfdt/5;dfdt_z=(dfdt_z+dfdt)/2;
#if (Gen_name!="Z2_G2"): dfdt=-1*dfdt/5;dfdt_z=(dfdt_z+dfdt)/2;
#else: dfdt=0;

ws.cell(row=lim+1, column=8, value=dfdt)
ws.cell(row=2, column=9, value="df/dt_coi");ws.cell(row=3, column=9, 
value=dfdt_z);
app.PrintPlain('df/dt of Z2_Bus_37_gen Bus %f'%(dfdt))
app.PrintPlain('df/dt_coi of Zone-2 %f'%(dfdt_z))
app.PrintPlain('--------------------------------------------------------')

app.PrintPlain('----------------Zone-3/PS-1----------------------------')
dfdt_z=0.0;lim=12;dfdt=0.0;
ws.cell(row=1, column=11, value="Zone-3")
ws.cell(row=2, column=12, value="Z3_G1")
terminal = app.GetCalcRelevantObjects("Bus_36.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=2;dfdt=0.0;
```

```
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-1<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=12, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt = 
%f'%val[1])
       lim=lim+1
dfdt=-1*dfdt/5;
ws.cell(row=lim+1, column=12, value=dfdt)
app.PrintPlain('df/dt of Bus 35 %f'%(dfdt))
app.PrintPlain('---------------------------------------------------------')


app.PrintPlain('----------------Zone-3/PS-2----------------------------')
ws.cell(row=2, column=13, value="Z3_G2")
terminal = app.GetCalcRelevantObjects("Bus_35.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=2;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-1<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=13, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt = 
%f'%val[1])
       lim=lim+1
dfdt=-1*dfdt/5;dfdt_z=(dfdt_z+dfdt)/2;
ws.cell(row=lim+1, column=13, value=dfdt)
ws.cell(row=2, column=14, value="df/dt_coi");ws.cell(row=3, column=14, 
value=dfdt_z);
app.PrintPlain('df/dt of Bus-36 %f'%(dfdt))
app.PrintPlain('df/dt_coi of Zone-3 %f'%(dfdt_z))
app.PrintPlain('---------------------------------------------------------')


app.PrintPlain('----------------Zone-4/PS-1----------------------------')
ws.cell(row=13, column=1, value="Zone-4")
ws.cell(row=14, column=2, value="Z4_G1")
terminal = app.GetCalcRelevantObjects("Bus_33.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=14;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-13<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=2, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt = 
%f'%val[1])
       lim=lim+1
dfdt=-1*dfdt/5;dfdt_z=dfdt;
ws.cell(row=lim+1, column=2, value=dfdt)
app.PrintPlain('df/dt of Bus 33 %f'%(dfdt))
app.PrintPlain('---------------------------------------------------------')
```

```
app.PrintPlain('----------------Zone-4/PS-2----------------------------')
ws.cell(row=14, column=3, value="Z4_G2")
terminal = app.GetCalcRelevantObjects("Bus_34.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=14;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-13<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=3, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt =
%f'%val[1])
       lim=lim+1
dfdt=-1*dfdt/5;dfdt_z=(dfdt_z+dfdt)/2;
ws.cell(row=lim+1, column=3, value=dfdt)
app.PrintPlain('df/dt of Z3_S1_gen Bus %f'%(dfdt))
ws.cell(row=14, column=4, value="df/dt_coi");ws.cell(row=15, column=4,
value=dfdt_z);
app.PrintPlain('df/dt_coi of Zone-4 %f'%(dfdt_z))
app.PrintPlain('------------------------------------------------------')
app.PrintPlain('------------------------------------------------------')


app.PrintPlain('----------------Zone-5/PS-1----------------------------')
dfdt_z=0.0;
ws.cell(row=13, column=6, value="Zone-5")
ws.cell(row=14, column=7, value="Z5_G1")
terminal = app.GetCalcRelevantObjects("Bus_31.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=14;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-13<=5)):
       val=app.ResGetData(res,i,ColIndex1);
       dfdt=dfdt+abs(val[1])
       ws.cell(row=lim+1, column=7, value=float(val[1]))
       app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt =
%f'%val[1])
       lim=lim+1;
dfdt=-1*dfdt/5;dfdt_z=dfdt;
ws.cell(row=lim+1, column=7, value=dfdt)
app.PrintPlain('df/dt of Bus-31 %f'%(dfdt))
app.PrintPlain('------------------------------------------------------')


app.PrintPlain('----------------Zone-5/PS-2----------------------------')
ws.cell(row=14, column=8, value="Z5_G2")
terminal = app.GetCalcRelevantObjects("Bus_32.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=14;dfdt=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-13<=5)):
       val=app.ResGetData(res,i,ColIndex1);
```

```
        dfdt=dfdt+abs(val[1])
        ws.cell(row=lim+1, column=8, value=float(val[1]))
        app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt =
%f'%val[1])
        lim=lim+1
dfdt=-1*dfdt/5;dfdt_z=(dfdt_z+dfdt)/2;
ws.cell(row=lim+1, column=8, value=dfdt)
ws.cell(row=14, column=9, value="df/dt_coi");ws.cell(row=15, column=9,
value=dfdt_z);
app.PrintPlain('df/dt of Bus-32 %f'%(dfdt))
app.PrintPlain('df/dt_coi of Zone-2 %f'%(dfdt_z))
app.PrintPlain('-------------------------------------------------------')


app.PrintPlain('----------------Zone-6/PS-1----------------------------')
ws.cell(row=13, column=11, value="Zone-6")
ws.cell(row=14, column=12, value="Z6_G1")
terminal = app.GetCalcRelevantObjects("Bus_39.ElmTerm")
ColIndex1=app.ResGetIndex(res,terminal[0],'m:dfedt');
lim=14;dfdt=0.0;dfdt_z=0.0;
for i in range(start_time,NrRow):
    sim_time=app.ResGetData(res,i,ColIndex2);
    if ((abs(sim_time[1]) > event_time)  &  (lim-13<=5)):
        val=app.ResGetData(res,i,ColIndex1);
        dfdt=dfdt+abs(val[1])
        ws.cell(row=lim+1, column=12, value=float(val[1]))
        app.PrintPlain('Time = %f'%sim_time[1]);app.PrintPlain('dfdt =
%f'%val[1])
        lim=lim+1
dfdt=-1*dfdt/5;dfdt_z=dfdt;
ws.cell(row=lim+1, column=12, value=dfdt)
ws.cell(row=14, column=13, value="df/dt_coi");ws.cell(row=15, column=13,
value=dfdt_z);
app.PrintPlain('df/dt of Bus-39 %f'%(dfdt))
app.PrintPlain('df/dt_coi of Zone-6 %f'%(dfdt_z))
app.PrintPlain('-------------------------------------------------------')


#---------------------------------------------------------------------------
-----
#Saving Excel File
wb.save('D:\My Study\Thesis_Frequency Stability\my python
program\Thesis_IEEE_39.xlsx')

    #****************Feeder Shedding event generation**************
#---------------------------------------------------------------------------
-----
#----Zonal weight & shed amount calculation----------------------------------
-------

cal_load_shed=0;fre_lim=49.1;Gen_loss=0;ws = wb.get_sheet_by_name('dfdt')

# Zonal weight following Regional Response

dfdt_t=ws.cell(row=3,column=3).value
+ws.cell(row=3,column=9).value+ws.cell(row=3,column=14).value
```

```
dfdt_t=dfdt_t+ws.cell(row=15,column=4).value
+ws.cell(row=15,column=9).value+ws.cell(row=15,column=13).value
app.PrintPlain('dfdt_COI_Total = %f'%dfdt_t);app.PrintPlain('-----------------
-');
z_w=[0.0,0.0,0.0,0.0,0.0,0.0,0.0];
z_w[1]=ws.cell(row=3,column=3).value/dfdt_t;
z_w[2]=ws.cell(row=3,column=9).value/dfdt_t;
z_w[3]=ws.cell(row=3,column=14).value/dfdt_t;
z_w[4]=ws.cell(row=15,column=4).value/dfdt_t;
z_w[5]=ws.cell(row=15,column=9).value/dfdt_t;
z_w[6]=ws.cell(row=15,column=13).value/dfdt_t;

for i in range(1,7):    # writing weight in dfdt sheet
    z_str='z'+str(i)+'_w';
    ws.cell(row=23+i, column=2, value=z_str);
    ws.cell(row=23+i, column=3, value=z_w[i]);
    z_str='Zone-'+str(i)+' disturbance Weight = ';
    app.PrintPlain('%s = %f'%(z_str,z_w[i]));
app.PrintPlain('-----------------');

ws = wb.get_sheet_by_name('Load_Shed_amount')
for i in range(1,7):
    ws.cell(row=4+i, column=2, value='z'+str(i)+'_w');
    ws.cell(row=4+i, column=3, value=z_w[i]);


app.PrintPlain('Gen_nam_list =');app.PrintPlain(Gen_nam_list);
app.PrintPlain('Gen_MW_list =');app.PrintPlain(Gen_MW_list);

# Total Load Shed sizing including 'D=1.5%'
for i in range(1,len(Gen_nam_list)):
    #app.PrintPlain(Gen_name); app.PrintPlain(Gen_nam_list[i]);
    if ((Gen_name1) == Gen_nam_list[i]):
        Gen_loss=Gen_MW_list[i];break;

for i in range(1,len(Gen_nam_list)):
    #app.PrintPlain(Gen_name); app.PrintPlain(Gen_nam_list[i]);
    if ((Gen_name2) == Gen_nam_list[i]):
        Gen_loss=Gen_loss+Gen_MW_list[i];break;



app.PrintPlain('Gen Loss = %f'%round(Gen_loss));

D=load_sp*0.013/(50*0.01); del_fss=Gen_loss/D; # 220 MW (10%) tripped

if ((50-del_fss)<49.10):  # Threshold ,fth=49.1 Hz
    shed_amount= (49.13-(50-del_fss))*D;#ws =
wb.get_sheet_by_name('Feeder_selection');
    ws['B2']='Total Calcu. shed(MW) = ';ws['E2']= round(shed_amount);
    app.PrintPlain('System Load shed amount = %f to arrest frequency before
49.1Hz & taking D=1.5%%'%round(shed_amount));


    for i in range(1,7):    # writing Zone wise shed amount in
Load_Shed_amount sheet
        z_str='Z'+str(i)+'_LS';
```

```
        ws.cell(row=4+i, column=5, value=z_str);
        ws.cell(row=4+i, column=6, value=round(z_w[i]*ws['E2'].value));
        ws.cell(row=4+i, column=7, value='MW');
        z_str='Zone-'+str(i)+'_LS = ';
        app.PrintPlain('%s = %f MW'%(z_str,round(z_w[i]*ws['E2'].value)));
    app.PrintPlain('-----------------');


    # app.PrintPlain(FVSI_arry);
    # Bus shed amount in a zone following FVSI
    fvsi_bus=[0.0,0.0,0.0,0.0,0.0,0.0,0.0];

    app.PrintPlain('FVSI_arry=');app.PrintPlain(FVSI_arry);
    dfdt=FVSI_arry[1]+FVSI_arry[2];

ws['B15']='FVSI_Bus_28L';ws['C15']=(FVSI_arry[1]/dfdt);ws['E15']=round(ws['C1
5'].value*ws.cell(row=5, column=6).value);ws['F15']='MW';

ws['B16']='FVSI_Bus_29L';ws['C16']=(FVSI_arry[2]/dfdt);ws['E16']=round(ws['C1
6'].value*ws.cell(row=5, column=6).value);ws['F16']='MW';

    dfdt=FVSI_arry[3]+FVSI_arry[4]+FVSI_arry[5]+FVSI_arry[6];
    ws['B17']='FVSI_Bus_18L';ws['C17']=(FVSI_arry[3]/dfdt);
    ws['E17']=round(ws['C17'].value*ws.cell(row=6,
column=6).value);ws['F17']='MW';

ws['B18']='FVSI_Bus_25L';ws['C18']=(FVSI_arry[4]/dfdt);ws['E18']=round(ws['C1
8'].value*ws.cell(row=6, column=6).value);ws['F18']='MW';

ws['B19']='FVSI_Bus_26L';ws['C19']=(FVSI_arry[5]/dfdt);ws['E19']=round(ws['C1
9'].value*ws.cell(row=6, column=6).value);ws['F19']='MW';

ws['B20']='FVSI_Bus_27L';ws['C20']=(FVSI_arry[6]/dfdt);ws['E20']=round(ws['C2
0'].value*ws.cell(row=6, column=6).value);ws['F20']='MW';

    dfdt=FVSI_arry[7]+FVSI_arry[8]+FVSI_arry[9]+FVSI_arry[10]+FVSI_arry[11];

ws['B21']='FVSI_Bus_16L';ws['C21']=(FVSI_arry[7]/dfdt);ws['E21']=round(ws['C2
1'].value*ws.cell(row=7, column=6).value);ws['F21']='MW';

ws['B22']='FVSI_Bus_21L';ws['C22']=(FVSI_arry[8]/dfdt);ws['E22']=round(ws['C2
2'].value*ws.cell(row=7, column=6).value);ws['F22']='MW';

ws['B23']='FVSI_Bus_22L';ws['C23']=(FVSI_arry[9]/dfdt);ws['E23']=round(ws['C2
3'].value*ws.cell(row=7, column=6).value);ws['F23']='MW';

ws['B24']='FVSI_Bus_23L';ws['C24']=(FVSI_arry[10]/dfdt);ws['E24']=round(ws['C
24'].value*ws.cell(row=7, column=6).value);ws['F24']='MW';

ws['B25']='FVSI_Bus_24L';ws['C25']=(FVSI_arry[11]/dfdt);ws['E25']=round(ws['C
25'].value*ws.cell(row=7, column=6).value);ws['F25']='MW';

    dfdt=FVSI_arry[12]+FVSI_arry[13]+FVSI_arry[14];

ws['B26']='FVSI_Bus_14L';ws['C26']=(FVSI_arry[12]/dfdt);ws['E26']=round(ws['C
26'].value*ws.cell(row=8, column=6).value);ws['F26']='MW';
```

```
ws['B27']='FVSI_Bus_15L';ws['C27']=(FVSI_arry[13]/dfdt);ws['E27']=round(ws['C
27'].value*ws.cell(row=8, column=6).value);ws['F27']='MW';

ws['B28']='FVSI_Bus_20L';ws['C28']=(FVSI_arry[14]/dfdt);ws['E28']=round(ws['C
28'].value*ws.cell(row=8, column=6).value);ws['F28']='MW';

    dfdt=FVSI_arry[15]+FVSI_arry[16]+FVSI_arry[17];

ws['B29']='FVSI_Bus_7L';ws['C29']=(FVSI_arry[15]/dfdt);ws['E29']=round(ws['C2
9'].value*ws.cell(row=9, column=6).value);ws['F29']='MW';

ws['B30']='FVSI_Bus_8L';ws['C30']=(FVSI_arry[16]/dfdt);ws['E30']=round(ws['C3
0'].value*ws.cell(row=9, column=6).value);ws['F30']='MW';

ws['B31']='FVSI_Bus_12L';ws['C31']=(FVSI_arry[17]/dfdt);ws['E31']=round(ws['C
31'].value*ws.cell(row=9, column=6).value);ws['F31']='MW';

    dfdt=FVSI_arry[18]+FVSI_arry[19]+FVSI_arry[20];

ws['B32']='FVSI_Bus_3L';ws['C32']=(FVSI_arry[18]/dfdt);ws['E32']=round(ws['C3
2'].value*ws.cell(row=10, column=6).value);ws['F32']='MW';

ws['B33']='FVSI_Bus_4L';ws['C33']=(FVSI_arry[19]/dfdt);ws['E33']=round(ws['C3
3'].value*ws.cell(row=10, column=6).value);ws['F33']='MW';

ws['B34']='FVSI_Bus_39L';ws['C34']=(FVSI_arry[20]/dfdt);ws['E34']=round(ws['C
34'].value*ws.cell(row=10, column=6).value);ws['F34']='MW';

    #Saving Excel File
    wb.save('D:\My Study\Thesis_Frequency Stability\my python
program\Thesis_IEEE_39.xlsx')


#****************************************************************************
**************
    #                           From feeder_selection_v5_edit

#****************************************************************************
**************

    for i in range(1,21):  # Updating load shedding MW
        zone_bus_ls[str(2+(i-1)*3)]=ws.cell(row=14+i, column=5).value;

    ws = wb.get_sheet_by_name('Pre-disturbance_Data')

    lst=[0];lst1=[0]; fdr_nam=['0'];fdr_MW=[0];
    z_s=[0];   # z_s keep only feeder no. of a S/S those to be cut
    z_s_n=[0]; # keeping all feeder no. of all S/S those to be cut
    print(z_s_n);

    # Creating zone sequence
    if(zone_trip==1):

zone_bus_seq=[0,2,5,8,11,14,17,20,23,26,29,32,35,38,41,44,47,50,53,56,59]; #
Load Shed MW in zone_bus_ls array.
    elif(zone_trip==2):
```

```
zone_bus_seq=[0,8,11,14,17,2,5,53,56,59,20,23,26,29,32,35,38,41,44,47,50];
    elif(zone_trip==3):

zone_bus_seq=[0,2,5,8,11,14,17,20,23,26,29,32,35,38,41,44,47,50,53,56,59];
    elif(zone_trip==4):
       zone_bus_seq=[0,26,29,32,8,11,14,17,20,23,2,5];

    # finding the closest one
    a1=0;carry_on=0;p1=1;col_no=2;rw=0;col=0;zone_buff=0;z_ls1=0;

    for p in range(1,21):
        okay=2;row_no=3;op=zone_bus_seq[p];
        z_ls1=zone_bus_ls[str(op)];
        z_ls=zone_bus_ls[str(op)]-carry_on;
        app.PrintPlain('------------------------------------');
        app.PrintPlain('z_ls1 = %f & Carry_p = %f & z_ls =
%f'%(z_ls1,carry_on,z_ls));carry_on=0;

        if (z_ls<=0):
                carry_on=z_ls;
                ws.cell(row=row_no, column=col_no, value=zone_bus_ls[str(op-
1)]); # Bus name
                ws.cell(row=row_no, column=col_no+1, value='Lod Shed');
                ws.cell(row=row_no, column=col_no+2,
value=str(zone_bus_ls[str(op)])+' MW');
                ws.cell(row=row_no+1, column=col_no+1, value='carry_p =');
                ws.cell(row=row_no+1, column=col_no+2, value=str(carry_on)+'
MW');
                ws.cell(row=row_no+3, column=col_no+2, value='Skipped');
                carry_on=-z_ls;


        else:
bus_no=zone_bus_ls[str(op+1)]; # bus_no actually bus total feeders no.
                carry_on1=carry_on;

                #--- Array formation to find closest to load shed amount
                ws = wb.get_sheet_by_name('Pre-disturbance_Data');
                rw,col=row_column();
                for i in range(1,bus_no+1):
                    lst.append(i);
                    #app.PrintPlain('Load MW = %f'%(round(ws.cell(row=rw+i-
1,column=col).value)));
                    lst1.append(round(ws.cell(row=rw+i-1,column=col).value))
# Feeder MW



                ws = wb.get_sheet_by_name('Feeder_selection');

                op=zone_bus_seq[p];
                ws.cell(row=row_no, column=col_no, value=zone_bus_ls[str(op-
1)]); # Bus name
                ws.cell(row=row_no, column=col_no+1, value='Lod Shed');
                ws.cell(row=row_no, column=col_no+2,
value=str(zone_bus_ls[str(op)])+' MW');
```

```
                ws.cell(row=row_no+1, column=col_no+1, value='carry_p=');
                ws.cell(row=row_no+1, column=col_no+2, value=str(carry_on)+'
MW');


                a=abs(lst1[1]-z_ls);a1=1;


                for i in range(1,bus_no): # finding closest feeder among all
feeders of a bus
                    b=lst1[i+1]-z_ls; app.PrintPlain('Load MW =
%f'%(lst1[i+1]));
                    if(abs(b)<abs(a)):
                       a=abs(b);a1=i+1;
                aa1,bb1=fdr_name(rw,col,lst[a1]); # want to know closest
feeder

                if((lst1[a1]-z_ls)>0): # if the closest value is bigger than
shed amount
                    okay=check_ls(lst1[a1],z_ls); # How big the closest load
is.
                    if(okay==1):
                       okay=2;fdr_nam.append(aa1);fdr_MW.append(bb1);
                       ws.cell(row=row_no+2,column=col_no+1, value=aa1);

ws.cell(row=row_no+2,column=col_no+2,value=str(lst1[a1])+"MW");
                       carry_on=lst1[a1]-z_ls;app.PrintPlain('%s = %f MW &
Carry_on = %f'%(aa1,bb1,carry_on));
                    else:
                       carry_on=carry_on-z_ls;
                       ws.cell(row=row_no+3, column=col_no+2, value='O/R');
                       app.PrintPlain('%s = %f MW but O/R & Carry_on =
%f'%(aa1,bb1,carry_on));


                else:  # if the closest value is smaller than shed amount

aa1,bb1=fdr_name(rw,col,lst[a1]);fdr_nam.append(aa1);fdr_MW.append(bb1);
                    ws.cell(row=row_no+2, column=col_no+1, value=aa1);

ws.cell(row=row_no+2,column=col_no+2,value=str(lst1[a1])+"MW");
                    z_ls=z_ls-lst1[a1];app.PrintPlain('%s = %f MW & next z_ls
= %f'%(aa1,bb1,z_ls));
                    lst1.remove(lst1[a1]);lst.remove(lst[a1]);

                    app.PrintPlain('Next z_ls = %f'%(z_ls));
                    a=abs(lst1[1]-z_ls);a1=1;
                    for i in range(1,bus_no-1):
                        b=lst1[i+1]-z_ls; app.PrintPlain('Load MW =
%f'%(lst1[i+1]));
                        if(abs(b)<abs(a)):
                          a=abs(b);a1=i+1;
                    aa1,bb1=fdr_name(rw,col,lst[a1]); # want to know closest
feeder

                    if((lst1[a1]-z_ls)>0): # if the closest value is bigger
than shed amount
```

```
                        okay=check_ls(lst1[a1],z_ls); # How big the closest
load is.
                        if(okay==1):
                            okay=2;

aa1,bb1=fdr_name(rw,col,lst[a1]);fdr_nam.append(aa1);fdr_MW.append(bb1);
                            ws.cell(row=row_no+3, column=col_no+1,
value=aa1);

ws.cell(row=row_no+3,column=col_no+2,value=str(lst1[a1])+"MW");
                            carry_on=lst1[a1]-z_ls;app.PrintPlain('%s = %f MW
& Carry_on = %f'%(aa1,bb1,carry_on));
                        else:
                            carry_on=carry_on-z_ls;
                            ws.cell(row=row_no+3, column=col_no+2,
value='O/R/S');
                            app.PrintPlain('%s = %f MW but O/R/S & Carry_on =
%f'%(aa1,bb1,carry_on));

                    else:

aa1,bb1=fdr_name(rw,col,lst[a1]);fdr_nam.append(aa1);fdr_MW.append(bb1);
                        ws.cell(row=row_no+3, column=col_no+1, value=aa1);

ws.cell(row=row_no+3,column=col_no+2,value=str(lst1[a1])+"MW");
                        carry_on=lst1[a1]-z_ls;
                        app.PrintPlain('%s = %f MW & Carry_on =
%f'%(aa1,bb1,carry_on));



        col_no=col_no+4;lst=[0];lst1=[0];#print(z1_s2);
        ws.cell(row=row_no+3, column=col_no+1, value='carry=');
        ws.cell(row=row_no+3, column=col_no+2, value=str(carry_on)+' MW');



    ws['H18']='Total Actual shed=';load_q=0;load_p=13;


    for i in range(1,len(fdr_MW)):
        load_q=load_q + fdr_MW[i];

    ws['J18']=load_q;app.PrintPlain('Total actual shed= %0.2f'%load_q)
    app.PrintPlain("Sheded Feeder List");app.PrintPlain(fdr_nam);
    app.PrintPlain("Sheded Feeder MW");app.PrintPlain(fdr_MW);

    #Saving Excel File
    wb.save('D:\My Study\Thesis_Frequency Stability\my python
program\Thesis_IEEE_39.xlsx')



#*****************************************************************************
**************
    #                        From feeder_selection_v5_edit
```

```
#************************************************************************
**************

    #***************Feeder Shedding event generation**************
    ini.Execute();
    Shc_folder = app.GetFromStudyCase('IntEvt');

    for i in range(1,len(fdr_nam)):
       Shc_folder.CreateObject('EvtSwitch', fdr_nam[i]);

    EventSet = Shc_folder.GetContents();
    event_time=0.5;
    for i in range(1,len(fdr_nam)):
        qq=fdr_nam[i]+'.ElmLod';load1=app.GetCalcRelevantObjects(qq);
        EventSet[i+1].p_target=load1[0];
        EventSet[i+1].time=0.8;

    #ini.Execute();

    sim.Execute();

else:
    app.PrintPlain("No Load Shed Required");



'''

#************************************************************************
**************
    #                          Tie line monitoring

#************************************************************************
**************
app.PrintPlain('------Tie Line Monitoring------')

fedr_nam=['0'];fedr_MW=[1.0];fedr1_nam=['0'];fedr_shed_nam=['0'];

tie_26_28=app.GetCalcRelevantObjects('Line 26 - 28.ElmLne');
line_26_28_amp=tie_26_28[0].GetAttribute('m:I1:bus1');
volt=tie_26_28[0].GetAttribute('m:U1:bus1');
z_ls= 3*volt*(line_26_28_amp-0.5);app.PrintPlain('For line_26_28 shed =
%f'%z_ls);


fedr=app.GetCalcRelevantObjects('z1_s28_l*.ElmLod');
for i in range(0,len(fedr)):  # collecting all feeder Name & MW connected to
Bus
    fedr_nam.append(fedr[i].loc_name);
    bb1=fedr[i].GetAttribute('m:P:bus1');
    fedr_MW.append(bb1);
app.PrintPlain('All Feeder of S28
Bus');app.PrintPlain(fedr_nam);app.PrintPlain(fedr_MW)
```

```
for i in range(1,len(fdr_nam)): # finding already sheded feeder name from
sheded feeder list
    lim=fdr_nam[i].find('z1_s28')
    if (lim>=0):
        fedr1_nam.append(fdr_nam[i])
app.PrintPlain('Sheded Feeder of S28 Bus');
app.PrintPlain(fedr1_nam);


for i in range(1,len(fedr1_nam)): # Deleting already sheded feeder name & mw
    app.PrintPlain('fedr_nam Length= %d'%len(fedr_nam))
    for j in range(1,len(fedr_nam)-1):
        app.PrintPlain('i= %d & j= %d'%(i,j))
        if (fedr1_nam[i]==fedr_nam[j]):
            app.PrintPlain('Removed fedr_nam=%s & fedr_MW=%f and index=
%d'%(fedr_nam[j],fedr_MW[j],j))
            fedr_nam.remove(fedr_nam[j]);
            app.PrintPlain('Removed index= %d & MW= %f'%(j,fedr_MW[j]))
            fedr_MW.remove(fedr_MW[j])
app.PrintPlain(fedr_nam);app.PrintPlain(fedr_MW)

a=abs(fedr_MW[1]-z_ls);a1=1; # finding closest feeder among all feeders of a
bus
for i in range(1,len(fedr_MW)-1):
    b=fedr_MW[i+1]-z_ls; #app.PrintPlain('i = %d & lst1[i+1] = %f & P =
%d'%(i,lst1[i+1],p));
    if(abs(b)<abs(a)):
       a=abs(b);a1=i+1;

fedr_shed_nam.append(fedr_nam[a1])

if((fedr_MW[a1]-z_ls)<0): # if the closest value is smaller than shed amount
   z_ls= z_ls-fedr_MW[a1];
   fedr_MW.remove(fedr_MW[a1]);fedr_nam.remove(fedr_nam[a1])
   a=abs(fedr_MW[1]-z_ls);a1=1;
   for i in range(1,len(fedr_MW)-1):
       b=fedr_MW[i+1]-z_ls; #app.PrintPlain('i = %d & lst1[i+1] = %f & P =
%d'%(i,lst1[i+1],p));
       if(abs(b)<abs(a)):
          a=abs(b);a1=i+1;
   fedr_shed_nam.append(fedr_nam[a1])

for i in range(1,len(fedr_MW)): # making empty the list
    fedr_MW.pop();
    fedr_nam.pop();
    app.PrintPlain(fedr_MW);app.PrintPlain(fedr_nam)

for i in range(1,len(fedr1_nam)): # making empty the list
    fedr1_nam.remove(fedr1_nam[i]);

app.PrintPlain(fedr_nam);app.PrintPlain(fedr_MW)
#***************************************************************************
********
tie_26_29=app.GetCalcRelevantObjects('Line 26 - 29.ElmLne');
line_26_29_amp=tie_26_29[0].GetAttribute('m:I1:bus1');
volt=tie_26_29[0].GetAttribute('m:U1:bus1');
```

```
z_ls= 3*volt*(line_26_29_amp-0.4);app.PrintPlain('For line_26_29 shed =
%f'%z_ls);

fedr=app.GetCalcRelevantObjects('z1_s29_l*.ElmLod');
for i in range(0,len(fedr)):  # collecting all feeder Name & MW connected to
Bus
    fedr_nam.append(fedr[i].loc_name);
    bb1=fedr[i].GetAttribute('m:P:bus1');
    fedr_MW.append(bb1);

for i in range(1,len(fdr_nam)): # finding already sheded feeder name from
sheded feeder list
    lim=fdr_nam[i].find('z1_s29')
    if (lim>=0):
        fedr1_nam.append(fdr_nam[i])


for i in range(1,len(fedr1_nam)): # Deleting already sheded feeder name & mw
    for j in range(1,len(fedr_nam)):
        if (fedr1_nam[i]==fedr_nam[j]):
            fedr_nam.remove(fedr_nam[j])
            fedr_MW.remove(fedr_MW[j]);break;
app.PrintPlain(fedr_nam);


a=abs(fedr_MW[1]-z_ls);a1=1; # finding closest feeder among all feeders of a
bus
for i in range(1,len(fedr_MW)-1):
    #app.PrintPlain('i= %d'%(i))
    b=fedr_MW[i+1]-z_ls;
    if(abs(b)<abs(a)):
       a=abs(b);a1=i+1;

fedr_shed_nam.append(fedr_nam[a1])

if((fedr_MW[a1]-z_ls)<0): # if the closest value is smaller than shed amount
   z_ls= z_ls-fedr_MW[a1];
   fedr_MW.remove(fedr_MW[a1]);fedr_nam.remove(fedr_nam[a1])
   a=abs(fedr_MW[1]-z_ls);a1=1;
   for i in range(1,len(fedr_MW)-1):
       b=fedr_MW[i+1]-z_ls; #app.PrintPlain('i = %d & lst1[i+1] = %f & P =
%d'%(i,lst1[i+1],p));
       if(abs(b)<abs(a)):
          a=abs(b);a1=i+1;
   fedr_shed_nam.append(fedr_nam[a1])

app.PrintPlain(fedr_shed_nam)

#****************Feeder Shedding event generation for Tie line***************
ini.Execute();
Shc_folder = app.GetFromStudyCase('IntEvt');

app.PrintPlain('Eventset_pre=%d'%len(EventSet));
for i in range(1,len(fedr_shed_nam)):
    Shc_folder.CreateObject('EvtSwitch', fedr_shed_nam[i]);

EventSet = Shc_folder.GetContents();
```

```
#app.PrintPlain('Eventset_after=%d'%len(EventSet));
a1=len(EventSet)-len(fedr_shed_nam);
for i in range(1,len(fedr_shed_nam)):
    qq=fedr_shed_nam[i]+'.ElmLod';load1=app.GetCalcRelevantObjects(qq);
    app.PrintPlain(load1[0]);app.PrintPlain('i=%d'%i);
    EventSet[a1+i].p_target=load1[0];
    EventSet[a1+i].time=1.0;

    #ini.Execute();

sim.Execute();
'''

'''
#----Relay activating---------------
for i in range(1,len(relay)):
    loads=app.GetCalcRelevantObjects('*.ElmRelay')
    for load in loads:
        name=load.cbranch;
        if (relay[1]==name.loc_name):
            relay.remove(relay[1]);
            load.outserv=0;
            break;
'''
```