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Development of corrective actions for higher order contingencies

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DEVELOPMENT OF CORRECTIVE ACTIONS FOR HIGHER ORDER CONTINGENCIES

By

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This research work focuses on developing tools to take corrective actions based on sensitivity for multiple outages. Algorithms developed are Multiple Line Outage Bus Sensitivity Factor (MLOBSF), Multiple Line Outage Voltage Sensitivity (MLOVS), Multiple Generator Outage Bus Sensitivity Factor (MGOBSF) and Multiple Generator Outage Voltage Sensitivity (MGOVS) based on DC and AC load flow models. These developed algorithms were tested on three test systems; the six buses, thirty seven buses and the 137 buses actual utility test case. The test results demonstrate that given situational awareness the algorithms provide additional decision support that can be used for remedial actions and/or for recovery after multiple outages. Integrating these into a power system energy management system (EMS) will provide a tool for operators to have a better understanding of the system before and during an extreme condition.

DEDICATION

I would like to dedicate this research work to my parents, R. Ramgopal Rao and Padma, my grandfather R. Ranga Rao, my uncle A. Jagan Mohan Rao, my aunt A. Vijaya Lakshmi and my all time favorite cousin A. Karthik Suman. I would also like to dedicate this thesis to my friends for life J. Naveen and K. Pratyusha for their continuous support.

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CHAPTER I

INTRODUCTION

1.1 Introduction

The frequency of blackouts over the past decades has increased throughout the world. An investigation into the cause of these blackouts will lead to one of the factors being lack of situational awareness and decision support for the operating personnel at the control center during higher order contingencies. Additional root causes for the blackouts discussed in the literature are a reduced investment by the utilities in the transmission infrastructure, inherent nature of the interconnected utility system and operating near to its limits [1]. A decision support system with experience and simulation studies helps in making decisions quickly and in an effective manner especially at the time of higher order contingencies, thus reducing the occurrence of a blackout.

This thesis will focus on developing corrective actions for a power system network at the time of higher order contingencies, which can be used by the control center operator during multiple outages. Generally corrective actions for higher contingencies are taken based on the heuristic rule base developed using offline simulation studies and system expertise. These rule bases are system specific and depend on the topology of the power system network. This work relates to developing algorithms for corrective actions, which are independent of system topology.

1.2 Power system network overview

A power system network consists of generators, transmission lines, loads, buses, transformers and shunt capacitors. The normal operation of each and every element is very important for the proper functioning of the power system network. Generally utilities consist of hundreds to thousands of buses to which different transmission lines and other power system components are connected. The main aim of power system utility in general is to supply the power to load consistently without any discrepancies and also maintaining the reliability and stability of the network. It is important for utilities to frequently monitor the power system network to check that the limits are not violated as even small violations may lead to cascading outages.

There are different power flows tools which are available which continuously solve the power flow based on the information they get from sensors. These power flows give a snapshot of the power system network and its operating conditions and are used to monitor the system continuously. The general monitoring parameters are the bus voltages and phase angles at each bus. Power system measurements in conjunction with a state estimator give the estimate of the system to be monitored continuously, so that the operators can be well prepared in case of an emergency. There are also other parameters to be monitored in addition to the voltage and angles with increasing size and complexity of power system network, monitoring and control has become a daunting challenge in the recent years [2].

1.3 Operating states in power systems

Power systems generally have three operating states namely normal, emergency and restorative. The latter two operating states are reached when the operating conditions of a power system change [2]. A power system is said to be operating in normal state if all the loads in the system can be supplied by the generators which are present in the system without violating any operational constraints. Different operational constraints include upper and lower limits on the bus voltage magnitudes, line limits and economic aspects. Different states in power system during its operation are discussed in the next paragraphs.

A system is said to be in normal state if the system continues to remain in the normal state even after the occurrence of critical contingencies. Normal contingencies include a transmission line outage, a transformer outage or generator outage. If the system is found to be insecure then preventive controls can be determined typically by help of security constrained optimal power flow programs given a list of critical contingencies. The emergency state requires immediate corrective action to be taken by the operator to bring the system to the normal state. Restorative states include actions such as removing loads or lines to help in fix violations, which results in a reconfigured topology. The three states of the power system network explained are given in Figure 1.1 [2].

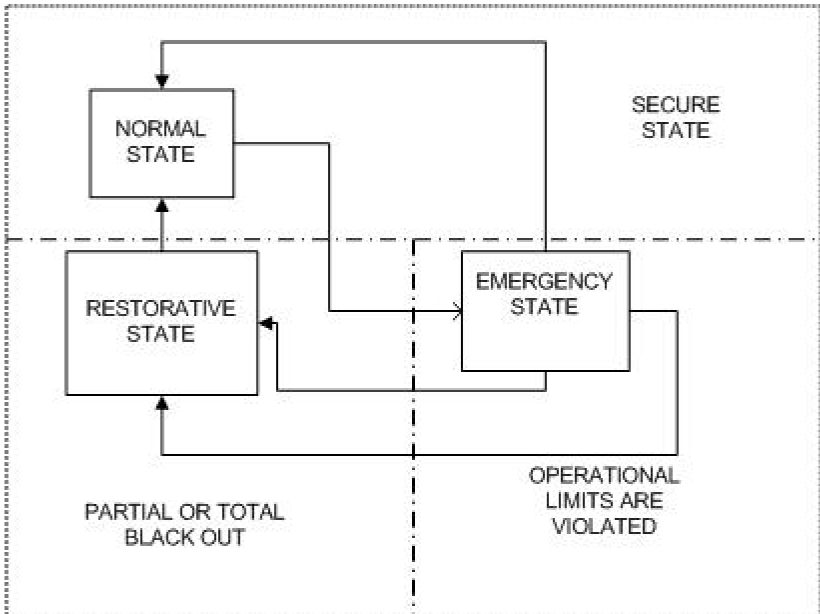

Figure 1.1 The operating states for a power system [2]

The main goal of the system operator is to maintain the system in normal secure state as the conditions vary during its operation. This job for the system operator requires continuous monitoring of system conditions, identification of the operating state and determination of the necessary preventive or corrective actions that need to be taken [2]. These actions are part of the security analysis of the system. Security analysis for the power system contains different steps; the first step is to monitor the power system state. This step involves acquisition of the measurements from all parts of the system and then processing them in order to determine the state of the system. Substations are equipped with different measurement units to acquire the data and sent it back to the control center. The types of these measurements are power flows, bus voltage, line current magnitudes, generator output, loads, switching capacitor values, transformer tap positions, and switching status information. The second step is doing a simulation study for contingency ranking/ evaluation and the third step is taking actions based on offline studies. Taking actions to maintain the power system in normal state (whenever it moves or tends to move to other states) as quickly as possible is the main objective of the corrective actions.

1.4 Research work contributions

Generally, Remedial Action Schemes (RAS) have been developed for single/double contingencies [3]. Most of the utilities uses RAS developed based on offline studies for list of critical contingencies. These RAS either utilize full AC power flow which takes lot of time for larger test cases during contingencies or DC power flow which does not give enough information about the system [4]. This research work contributes towards development of algorithms for corrective actions locations needed during multiple contingencies utilizing AC power flow for voltage related problems and DC power flow for line overloading problems. Developed algorithms are not limited to list of critical contingencies and can be applied in general. The formulation for the multiple line outages are taken from reference [5] and further extended to develop Multiple Line Outage Bus Sensitivity Factor (MLOBSF) and Multiple Generator Outage Bus Sensitivity Factor (MGOBSF) are developed to find the bus sensitivities. The Multiple Line Outage Voltage Sensitivity (MLOVS) and Multiple Generator Outage Voltage Sensitivity (MGOVS) algorithms are developed based on algorithms for single line outage utilizing AC power flow given in [6]. The contribution of this work is also to include the developed with heuristic thumb rule for RAS to suggest corrective actions to solve the violations due to multiple contingencies. The sensitive buses obtained using developed algorithms will help operator identify specific location for needed corrective actions.

1.5 Thesis objective

It is very important to maintain the power system security and operation in a normal state. Given situational awareness, developing a decision support system to take corrective actions is the objective of this work. A good decision support system reduces the time of reaction for the operators and helps them to prevent cascading outages. Whenever some component in the power system network goes out, it is very important to restore the system as early and as efficiently as possible. Due to the inherent nature of the inter-connectivity, a single element fault may cause problems in a wider area. Preparing the operating personnel for the extreme situations has become one of the major tasks of the utilities 'to do' list. Most of the utilities perform offline studies regularly to help prepare for any worst case scenarios. Experience indicates that loss of data and unpreparedness for the combination of critical contingencies has been main causes to not take the proper corrective actions on time by the operators. These corrective actions are generally system dependent.

The objective of thesis is to develop sensitivity based algorithms for multiple generator and branch contingencies. In this work sensitivity based indices are developed to suggest locations for needed corrective actions during multiple contingencies utilizing AC power flow for voltage related problems and DC power flow for line overloading problems, which makes this work superior to the existing corrective action schemes. The objective of thesis is also to develop thumb rules for RAS using offline studies for several contingencies. Final goal is to include the developed sensitivity based algorithms developed with thumb rule for RAS to suggest corrective actions to solve the violations due to multiple contingencies. The objective of this work is also to test and validate the developed algorithms using three test cases.

1.6 Thesis organization

The organization of this thesis is as follows. Chapter 2 gives the background information related to wide area monitoring and protection and different methods of remedial action schemes and their application to power systems security. The literature review and work done to date on these subjects is also included. Contingency analysis, different types of contingencies and the types of violations they cause are also explained in Chapter 2. Finally the need for corrective and preventive actions and the tools used to develop them are also discussed in Chapter 2. Chapter 3 explains the problem statement and algorithm formulation for the work done. Sensitivities based on DC and AC power flows and different test cases used for the work are explained in Chapter 3. Chapter 4 details the DC sensitivities in the case of any single line and multiple line outages. It explains the different terms, such as the Power Transfer Distribution Factor (PTDF), which are very important and will help in deriving the algorithm. It will define the mathematical problem formulation of the Multiple Line Outage Bus Sensitivity Factor (MLOBSF) algorithm and the applicability of the algorithm in taking the necessary preventive and corrective actions. Results on the test cases using the MLOBSF algorithm are also discussed in Chapter 4.

Chapter 5 explains AC sensitivities for the line outages. The application of Multiple Line Outage Voltage Sensitivity (MLOVS) algorithm on different test cases and their explanation is also given in chapter 5. Chapter 6 gives the explanation of the application of DC sensitivities for multiple generator outages. The Multiple Generator Outage Bus Sensitivity Factor (MGOBSF) algorithm, which helps in determining the impact on buses due to multiple generator outages, and the implementation of the algorithm on the test cases and results are also given. Chapter 7 deals with the Multiple Generator Outage Voltage Sensitivities (MGOVS) algorithm which provides the impact on the bus voltages due to multiple generator outages. Implementation of this algorithm on the test cases and the results are also given in this chapter. Flow charts for each algorithm are given in their respective chapters. Chapter 8 is the conclusions and future work chapter which discusses the work done in the thesis and suggested future work which can be done to extend the algorithms.

1.7 Summary

Multiple contingencies are happening frequently and there is a need for a tool to deal with these contingencies. The algorithms for multiple contingencies are very essential. The chapter discusses a brief introduction on tools to deal with multiple contingencies. The objective of thesis is also given in this chapter. Finally the organization of the thesis and glimpses at different chapters are given.

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CHAPTER II

BACKGROUND

2.1 Introduction

This chapter gives a brief discussion of key topics and previous work done related to the thesis subject. Different aspects of Wide Area Monitoring [1] of power system network and different aspects and characteristics related to it will be introduced based on the reviewed literature. The basics of contingency analysis, the types of violations will be presented in this chapter. Contingency analysis helps in preparing for possible outages in the system. Different Remedial Action Schemes (RAS), corrective and preventive actions which help in dealing with the contingency and remove the violations will also be discussed in this chapter.

2.2 Energy Management Systems and its applications

Energy Management systems (EMS) is a system of computer-aided tools for operators to monitor, control and optimize the performance of the electric grid. Contingency Analysis (CA), Automatic Generation Control (AGC), Load Forecasting (LF) and Optimal Power Flow (OPF) are some of the EMS applications. State estimation provides the required states of power system for EMS applications [2]. The data is acquired through different sensors and the processed through different stages as shown in figure 2.1. Power system monitoring and control are done by using the EMS applications.

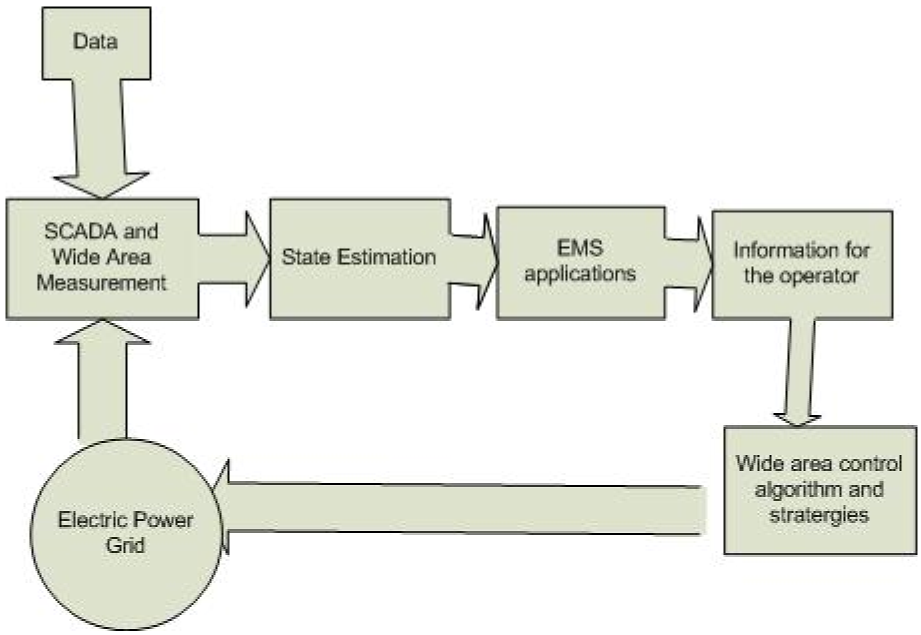

Figure 2.1 Power grid operation using EMS

Figure 2.1 gives different stages of operation using EMS applications. In this work it is assumed that the data is already available with the operator and the algorithms developed in this work are used for suggesting corrective actions to the operator.

2.3 Contingency analysis

Contingency analysis [3] gives the security status of the power system network and list of critical contingencies. Contingency analysis is achieved by running power flow cases after removing different elements of the power system network such as a transmission line, transformer, bus or generator. Contingency analysis helps us look at the system's vulnerable points and allows possibly determining a solution offline ahead of time, because the time available for the operator to react in real time situation is minimal.

Most of the EMS software available in the market has the contingency analysis option. Some of the main software, such as PowerWorld, PSS/E, and PSS/O are used by the operators at the control centers in utilities to run the contingency analysis ahead of time for system planning.

As mentioned above contingency analysis is achieved by removing different types of elements. Outage types and their importance are explained below.

2.3.1 Types of contingencies

Transmission lines, transformers, generators and buses are the key components of power system network. Different kind of contingencies that can happen based on these important components are discussed in this section. Due to physical vulnerability of a transmission line, it is most prone to the outages due to various reasons starting from sagging on to a tree to higher current flowing through it. The desired voltage level is maintained using the transformers which step up/down the voltage according to the requirements. A transformer outage is also one of the important outages in the system. During contingency analysis, transformers are generally considered as the transmission line outage with consideration of resistance and susceptance. It is very important to know the transformers and their functionalities when the load changes in the system, since they are responsible for the voltage profile in the network.

Generators are the source of power for the system. Loss of generation causes many problems in the system and may lead to a blackout.

Buses are the main components of the power system network, particularly because of their connections in the system. All the transmission lines, transformers and generators are connected to the rest of the system through the buses. An outage of the bus is typically an outage of all the elements connected to that bus, which becomes very huge loss if the number of elements connected to that bus is higher. A bus outage is thus considered to be critical.

Thus different types of contingencies and their study will help in better planning of the system and helps the operator in preparing for them. Some events can cause outage of multiple components in the system causing more loss compared to single contingencies.

2.3.2 Types of violations

Line contingency and generator contingency are generally most common type of contingencies. These contingencies mainly cause two types of violations [4]

i. *Low voltage Violations:*

This type of violation occurs at the buses. This suggests that the voltage at the bus is less than the specified value. The operating range of voltage at any bus is generally 0.95-1.05 p.u. Thus if the voltage falls below 0.95 p.u then the bus is said to have low voltage. And if the voltage rises above the 1.05 p.u mark the bus is said to have a high voltage problem. It is known that in the power system network generally reactive power is the reason for the voltage problems. Hence in the case of low voltage problems reactive power is supplied to the bus to increase the voltage profile at the bus and in the case of the high voltage reactive power is absorbed at the buses to maintain the system normal voltage. Different devices and their actions to deal with the voltage profile in the power system network are explained later in the chapter.

ii. Line MVA limits violations:

This type of contingency occurs in the system when the MVA rating of the line exceeds given rating. This is mainly due to the increase in the amplitude of the current flowing in that line. The lines are designed in such a way that they should be able to withstand 125% of their MVA limit. Based on utility practices, if the current crosses the 80-90 % of the limit, it is declared as an alarm situation. Different types of remedial actions to solve this problem are explained later in this chapter. Figure 2.2 shows the pie chart for a transmission line change its color, once the MVA for the line crossed 80% (although it may vary from system to system depending on their operation) due to outages in the system.

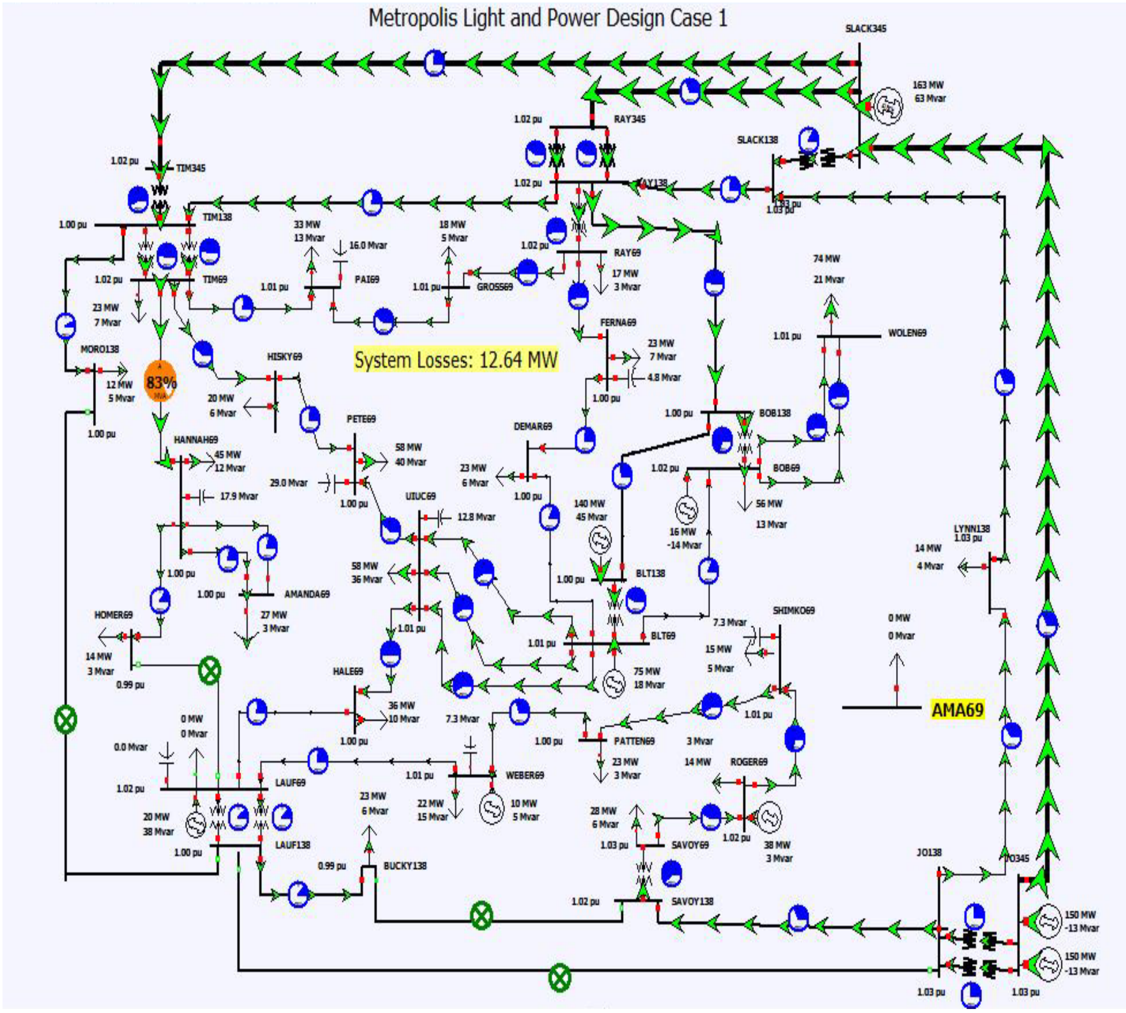

Figure 2.2 Line violations showing in as 87% of rating [18].

2.3.3 *Higher order contingencies*

The outages or contingencies are generally denoted in terms of numbers such as "N-n", where 'N' refers to the total number of elements of specific type in the system and 'n' refers to the number of those elements which are outaged. For example if one transmission line is outaged in the system then it is called an 'N-1' transmission line outage and if 3 elements are outaged in the system then it is called 'N-3' transmission line outage. Thus the outages with more than a single line outage are generally called higher order contingencies. The general tendency in the utilities in the North American region is to operate at the 'N-1' security level. That is the system must be able withstand the outage of the single element and still be able to work within normal operating conditions. Most of the remedial actions have been designed such that they will be able to solve the violations caused only due to the mostly 'N-1'. This thesis focuses on developing corrective actions for higher order contingencies.

A look into major outages in the power system industry throughout the world will clearly indicate the reasons for those outages are the cause of loss of multiple critical elements from the system. For example, in case of the Northeastern blackout which took place in August 2003, the cascading effect (which is caused by the multiple line outages) was the main reason. The cascading effect is the very result of the nature of the interconnected grid. Another example is the outage of the many elements in the southern region of the United States due to Hurricane Katrina. In this case too, it is the cascading effect which is once again is caused due to the multiple line outages damage (which ultimately results in line outages). These higher order contingencies will lead to huge loss of infrastructure, money etc. Thus a remedial action scheme designed for higher order contingencies is needed in order to prevent these losses to society.

2.4 Remedial actions schemes

Remedial Action Schemes (RAS) are the key components for any power system utility planning. These are the steps which the utilities need to take in order to get the system back to its normal operation. Remedial Action Scheme (RAS) as the name suggests are the necessary actions which need to be taken to solve the violations caused by a contingency. Remedial Action Schemes are also defined as Special Protection Schemes (SPS) or System Integration Schemes (SIS) in literature [4].

2.4.1 Classification of remedial action schemes

The RAS can be classified into the following categories:

i. Event based:

The event based RAS are instantaneous in their nature. The event based schemes detect the outage or fault in the system and initiate actions to solve the problem. The actions include shedding or tripping the load. These types of actions are used when actions need to be applied instantaneously in order to fully or partially mitigate the impact caused by the event.

ii. Parameter based:

The parameter based types of schemes detect the change in the parameters of the system, which indirectly gives an indication that there is problem with the system. This is an indirect way of detecting the system problems. This method is used to generally detect remote problems such as switching of breakers at the opposite end of the line and other significant sudden changes in the system which cause instabilities in the system. The measured parameters in the system that provide timely action include power angles.

iii. Response based:

The above mentioned two schemes can be termed as open loop since they just perform the action whenever there is a change in the system parameters or if there is an event but don't necessarily react according to the feedback. The response based schemes monitor the system response during disturbances by incorporating a closed loop response which enables it to react to actual system conditions. Response based scheme actions can be used to respond to magnitude of the disturbances but these types of actions are not as fast as the other two discussed earlier.

2.4.2 Types of remedial actions

Different types of available remedial actions which can be implemented to solve the contingencies are explained below.

i. Shunt capacitor switching:

This method is generally used to solve the low voltage problems that occur at the different buses in the system. As discussed, the low voltage problem is generally caused due to the lack of the reactive power supplied. The shunt capacitor is used to supply the necessary reactive power to the system to increase the voltage in the system and maintain it in the desired limits. Planning studies are needed to install them at the right locations to deal with the low voltage problem being caused in the system. The shunt capacitor at the necessary buses is thus switched on/off according the voltage profile requirement in the system.

ii. Generation Re-dispatch:

When the current flowing through the line is over a certain specified limit then the maximum amplitude violation occurs in the system. The limits are generally 80% of the line rating. Generation re-dispatch is then used to re-route the power to the load through changing generation at available generators. Knowledge of the system topology is essential to the operator for doing optimal and efficient generation re-dispatch.

iii. *Load shedding:*

Load shedding is generally done when other RAS methods are unable to solve the violations for the contingency. All the problems caused in the system are generally due to the excessive or sudden drop of the load.

iv. *Under load tap changing (ULTC)Transformer*

Under load tap changing is generally for the transformers in case of voltage problems. The transformers have different settings and varying these allows changing supplied voltage to the load or system.

v. *Distributed Generation:*

Distributed Generation (DG) is also seen as one of the alternatives for solving the line MVA limit violations. Distributed generation helps in reducing the MVA flow, since power can be generated nearer to the load. DG is typically a longer term solution.

vi. *Islanding:*

Intentional islanding is one of the concepts which researchers are considering for possible solution to solve higher order contingencies. Islanding helps separate the system with problems from rest of the system. An islanded system will operate on itself and the rest of the system will not be affected from the contingencies caused on the islanded parts of system. Intentional islanding combined with distributed generation is also seen as a possibility, since this reduces the risk of occurrence of blackouts (avoiding a cascading effect). Figure 2.4 shows a 37 bus system in PowerWorld which has been divided into six islands for ‘N-3’ contingency to solve the violations.

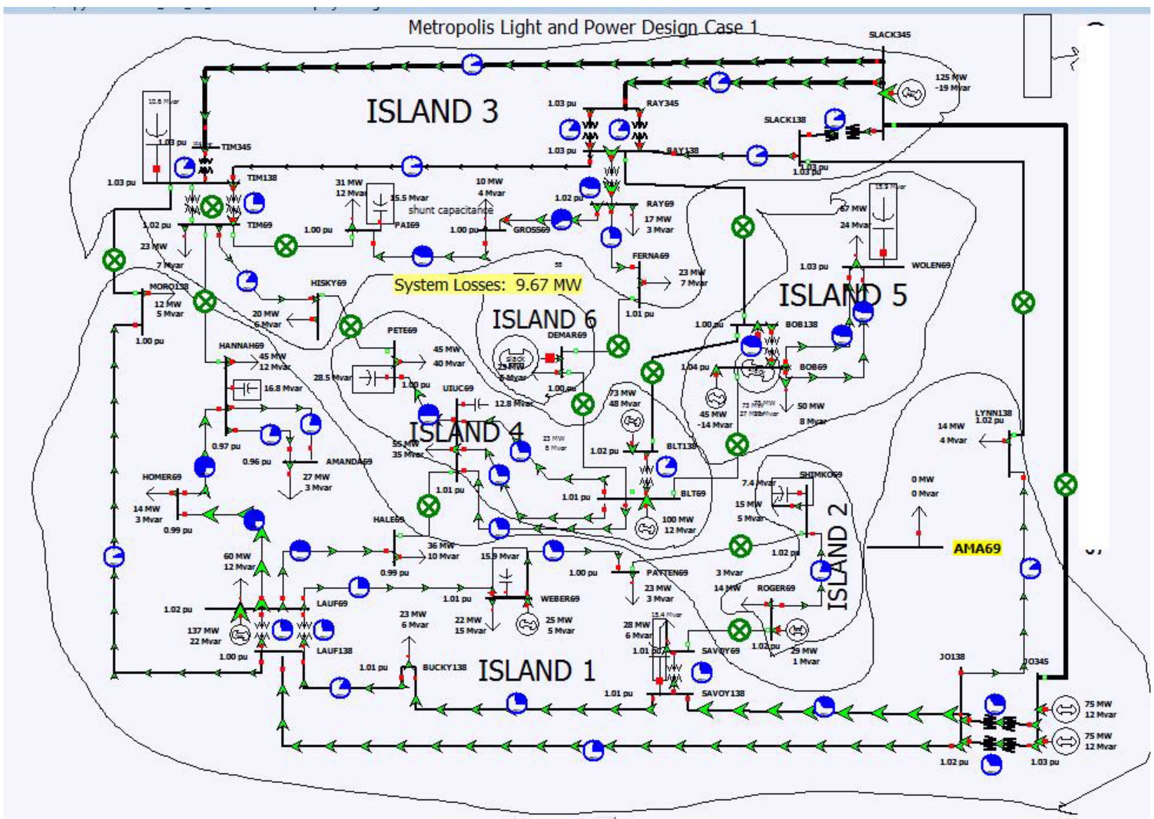

Figure 2.3 Six islands in the 37 bus system

Although islanding is an effective way of solving the violations many researchers have different opinions about intentional islanding since the more the system is interconnected the more it is stable and the less it is prone to oscillations.

Some of the other forms of remedial action schemes also include braking resistors, generator tripping, and static VAr control units.

2.4.3 Different remedial actions in literature

References [5] and [8] deal with the formulation of algorithm based on contingency screening done by fast de-coupled power flow method; the algorithm gives a performance index based on direct ranking which eliminates need for post outage voltages. Also they additionally predict buses in the sub-network where action needs to be taken. But these algorithms lack complete efficiency and information since they are based on the fast de-coupled load flow and also not able to predict the locations accurately. One more method which does contingency screening is explained in reference [10]. It utilizes ANN for calculating severity indices based on time domain simulation.

Reference [9] proposes a new method for generator re-scheduling; it provides a coherency index method based on contingency ranking. The sensitivities calculated by this method will be useful for taking remedial actions. The drawback of this method is that, sometimes it leads to instability resulting in further outage. A new method for sensitivity analysis to determine the voltage index during any contingencies is described in reference [14]. A severity index algorithm is developed which will help not only in contingency ranking but also to determine which contingency to act upon. This method is based on first order sensitivities and Eigenvalue analysis and the drawback of this method is that it is only used for the voltage ranking during contingency.

Basic details of contingency analysis (single contingency) on the system and the remedial actions which can be performed to solve these contingencies are explained in reference [6]. It is mainly targeted at academic purposes (which can be used in universities etc). Remedial action schemes such as load shedding, capacitor switching etc based on both AC and DC methods for single contingencies are discussed in reference [7]. It uses Linear Programming and hence only 4 to 5% of variables are taken into account in the overall system, which is not accurate.

Operating FACTS devices to take corrective and preventive actions for a single contingency in the system is discussed in reference [12]. The algorithm gives the nearest FACTS device to operate upon to solve for MW or voltage contingency without any generator re-scheduling or load shedding.

Distributed security constrained optimal power flow, for regions interconnected and especially in case of tie lines is described in reference [11]. LODF methodology is used in this method for providing the necessary constraints for the optimal power flow. The algorithm is implemented on a Korean power system network and describes safe operation of the network when the generators are taken out of service. This method has no contingency constraints which are inhibited for the optimal power flow. Hence this lacks the adaptability in case of contingencies especially at the tie-lines in the system. Genetic algorithm based optimal power flow for line outage is discussed in reference [15]. A phase shifting transformer is used to remove line overload violation. The location of phase shifter is obtained using sensitivity analysis method. This algorithm has the advantages over the traditional methods since it uses genetic factors such as mutation etc. Mathematical frame work to develop the corrective action capabilities for the power system network after an outage is occurs in the system is explained in reference [16]. The solution methodology is used for economic dispatch based on optimal power flow.

2.5 Remedial actions for higher order contingencies

As seen in the literature review, work has been to develop remedial actions for single branch outages or single generator outages. Some of them are taking more time by using the full AC power flow or optimal power flow for line outages or some of them are not sufficient to deal with voltage problems by using DC power flow for solving them. There are also methods which are flexible enough for applying different methods for different problems and are adaptable but are only designed for single contingencies.

The method developed in this thesis work will utilize DC power flow based sensitivity index in case of line overloading, and uses AC power flow based sensitivity index to deal with any voltages problems. Developed techniques are more efficient and take less time compared to using total full power flow. Also the work is concentrated on suggesting locations where corrective and preventive actions need to be taken. The most important use of these algorithms over the other is that all other algorithms developed in the past are only developed for single branch or single outages where as the algorithm developed in this work is totally useful for multiple branch as well as multiple generator outages. Developed algorithm is adaptable, faster, and flexible in dealing with higher order contingencies and developing corrective and preventive actions to solve the violations caused by them.

2.6 Need for corrective and preventive actions

Outages in the power system equipment may occur due to different reasons such as a fault on the system or due to damage of the equipment etc. In addition to the generally happening transmission line outages causalities can happen to transformers, generators, buses and also cables in case of underground transmission. If the outage is severe (such as multiple line outages for example), it may cause power deficiency to the rest of the power system network and may cause load- generation imbalance leading to cascading outages to collapse the entire power system.

Generally after the fault occurs in the system the relay operates to clear the fault, and taking the faulty component out of system if the fault persists. The utilities generally operate for N-1 outage, which explains the power system network should be able to operate in normal condition even though there is a single element outage in the system. If this single element outage is not dealt with adequately, it may lead to a cascading result affecting the entire system if any other element goes out in the system. Therefore it is required to restore the supply quickly to those un-faulted sections of the power system network for improving the system survivability.

It is required to suggest the corrective and preventive actions automatically when the cascading effect happens (which leads to higher order outages) so that system can be saved from total collapse. Corrective and preventive actions will help the operator at the control center to take the necessary actions quickly and effectively. In this work these actions are suggested using the methodology based on sensitivity.

2.7 Tools used for this work

This section presents details of software tools used in this research work.

2.7.1 PSS/E

PSS®E [17] is the software tool used by electrical transmission participants world-wide. The probabilistic analyses and advanced dynamics modeling capabilities included in PSS®E provide transmission planning and operations engineers a broad range of methodologies for use in the design and operation of reliable networks. PSS®E is the standard Siemens software offering for electrical transmission analysis that continues to be the technology of choice in an ever-growing market that exceeds 115 countries.

Since its introduction in 1976, the **P**ower **S**ystem **S**imulator for **E**ngineering tool has become the most comprehensive, technically advanced, and widely used commercial program of its type. It is widely recognized as the most fully featured, time-tested and best performing commercial program available.

PSS®E [17] is an integrated, interactive program for simulating, analyzing, and optimizing power system performance. It provides the user with the most advanced and proven methods in many technical areas, including:

- Power Flow

- Optimal Power Flow
- Balanced or Unbalanced Fault Analysis
- Dynamic Simulation
- Extended Term Dynamic Simulation
- Open Access and Pricing
- Transfer Limit Analysis
- Network Reduction
- Contingency Analysis

In this work, PSS/E is used to simulate the 137 bus utility system. Different levels of power flow results were obtained for the base case and during contingencies. Contingency analysis is performed on the system using PSS/E and the output is further used to develop the corrective and preventive actions and also to validate the results obtained from the MATLAB program.

2.7.2 PowerWorld simulator

PowerWorld [18] software version 11 is used as another tool in this work. Following basic features are available in PowerWorld in addition to many other.

Optimal Power Flow is a linear programming based optimal power flow package. Simulator OPF, an optional add-on to the base Simulator package, is ideally suited to determining how to mitigate constraints in the most economical fashion, and to report the cost of enforcing line constraints.

In addition to the above, the tools used for the work are contingency analysis tool which is used for running contingencies on the system if different types such as single contingency or multiple contingency.

The contingencies analysis gives a detailed list of events such as what caused the contingency, what are the violations due to, how much exactly is the deviation from the normal value and what type of violation it is. This helps a great deal especially in dealing with multiple contingencies and the basic nature of PowerWorld being more visual, will help the operator identify the problems quickly. The other features of PowerWorld include calculating the Power Transfer Distribution Factor (PTDF), Line Outage Distribution Factor (LODF) and Generation Shift Factor (GSF) which are important and have been used in this work for testing and validation of developed algorithms.

2.7.3 MATLAB /Simulink

MATLAB [19] is used in the work for developing the code based on the algorithms developed. MATLAB is helpful especially dealing with column and row operations of matrix based algorithms. The bus data and branch data and other details of the test case are given to the MATLAB as text file input which it is capable of reading. The output of the MATLAB can also be written into a text file depending upon the nature of the work. In this work the outputs are saved into an excel file to analyze the data. MATLAB is user friendly and it is very helpful in developing the code for different algorithms in this work.

2.8 Summary

The initial part of the chapter focuses on the Energy Management System and its applications in the power system network. The second part of the chapter focusses on remedial action schemes, defining different types of contingencies, and different methods to solve those contingencies. Literature review shows that so far RAS has been developed for single/double contingencies and the thesis focuses on remedial action schemes for multiple contingencies. Finally the tools used for developing the algorithms have also been explained in the chapter.

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CHAPTER III

PROBLEM FORMULATION AND SOLUTION ALGORITHM

3.1 Introduction

This chapter deals with basics of power flows and formulation of AC power flow and DC power flows needed for sensitivity algorithm development. The formulations and assumptions for obtaining the basic power flow equation for an ‘n’ bus system are explained. The problem has been defined and basis for developing sensitivities for contingencies based on these power flows have been presented. Test cases used in this study are also discusses here.

3.2 AC power flow

The basic power flow equation for any power system network is given by

$$I=[Y]\,E$$

In case of ‘n’ bus network this can be written as

$$\begin{bmatrix} I_1 \\ I_2 \\ . \\ . \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & . & . & Y_{1n} \\ Y_{21} & Y_{22} & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ Y_{n1} & . & . & . & Y_{nn} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ . \\ . \\ E_n \end{bmatrix} \qquad \text{.......................... (3.1)}$$

Where

‘I’ are the current injections at the buses.

‘E’ are the voltages at the buses.

‘Y’ is the admittance matrix

The equation for power at each node (bus) ‘*i*’ in a ‘N’ bus power system network can be written as

$$P_i + jQ_i = E_i I_i^*$$

Where

P is the real power

Q is the reactive power

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

Then equation for power can be written as

$$P_i + jQ_i = E_i \left(\sum_{k=1}^{N} Y_{ik} E_k \right)^*$$

We write the voltages in polar coordinates and hence get the two independent variables in this equation, one being voltage at the bus and other voltage angles. For every bus we write two equations, one is for real power and other for reactive power, given by equations 3.2 and 3.3

$$\Delta P_i = \sum_{k=1}^{N} \frac{\partial P_i}{\partial \theta_k} \Delta \theta_k + \sum_{k=1}^{N} \frac{\partial P_i}{\partial |E_k|} \Delta |E_k| \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

$$\Delta Q_i = \sum_{k=1}^{N} \frac{\partial Q_i}{\partial \theta_k} \Delta \theta_k + \sum_{k=1}^{N} \frac{\partial Q_i}{\partial |E_k|} \Delta |E_k| \quad \text{...............} \quad (3.3)$$

Equations 3.2 and 3.3 can be written in matrix format for all the buses as given by equation 3.4,

$$\begin{bmatrix} \Delta P_1 \\ \Delta Q_1 \\ \Delta P_2 \\ \Delta Q_2 \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} = \begin{bmatrix} \frac{\partial P_1}{\partial \theta_1} & \frac{\partial P_1}{\partial E_1} & \cdot & \cdot & \cdot \\ \frac{\partial Q_1}{\partial \theta_1} & \frac{\partial Q_1}{\partial E_1} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \\ \cdot & \cdot & & & \\ \cdot & \cdot & \cdot & \cdot & \cdot \end{bmatrix} \begin{bmatrix} \Delta \theta_1 \\ \Delta |E_1| \\ \cdot \\ \cdot \\ \cdot \end{bmatrix} \quad \text{..........} \quad (3.4)$$

where, the vector with real and reactive power differences is called the mismatch vector and the matrix with the partial differentiations of power (both real and reactive) to the voltages and voltage angles is called Jacobian matrix.

Chapters 5 and 7 utilize the basic power flow equations developed in this chapter and then extend these to develop the sensitivity based algorithm.

3.3 DC power flow

AC power flow gives full information about the system but cannot be used in real time for a larger system especially at the time of contingencies. DC power flow is an approximation of AC power flow and has been used widely to get faster response. In DC power flows, the reactive power Q is not considered in solving the load flow. The Q-V relationship from the normal power flow equation is eliminated and hence the Jacobian also changes to reflect only P- θ relationship Y bus becomes only the reactance matrix X in this case.

$$\begin{bmatrix} \Delta P_1 \\ \Delta P_2 \\ . \\ . \\ . \end{bmatrix} = \begin{bmatrix} X_{11} & . & . & . & X_{1n} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ X_{n1} & . & . & . & X_{nn} \end{bmatrix} \begin{bmatrix} \Delta \theta_1 \\ \Delta \theta_2 \\ . \\ . \\ . \end{bmatrix} \ldots\ldots\ldots\ldots\ldots \text{(3.5)}$$

Where,

θ_i = Angle at bus 'i'

θ_k = Angle at bus 'k'

The DC power flow is given by equation 3.6 to give information about real power. The DC power flow will not be able to provide any information about bus voltages, or MVA of the lines. The power flowing on each line using the DC power flow is given as,

$$P_{ik} = \frac{1}{x_{ik}}\left(\theta_i - \theta_k\right) \ldots\ldots\ldots\ldots\ldots\ldots \text{(3.6)}$$

And

$$P_i = \sum_{k=busesconnectedtoi}^{N} P_k$$

The DC power flow equation developed in this chapter has been extended in chapters 6 and 8 to get sensitivity information.

3.4 Problem statement and proposed work

The current power system networks of the utilities are designed to operate for the 'N-1' outages. Remedial Action Schemes (RAS) generally do not consider actions needed for multiple line outages and blackouts are generally caused by multiple outages. There is a lack of effective tools to deal with higher order contingencies.

This research will focus on finding the methodology to suggest the corrective actions using the DC flow based multiple line outage bus sensitivity factor algorithms and multiple generator bus sensitivity factor algorithms, as well as AC based multiple line outage voltage sensitivities and multiple generator outage voltage sensitivities. A rule base developed by utilities using offline studies is used to validate the developed algorithms.

Some of the common types of violations which are found in the higher order contingency analysis are:

- Low Voltage Violations
- Branch MVA Limit Violations

Some of the methods which are suggested for removing the violations are as follows:

- Switching Shunt Capacitor
- Generation Re-Dispatch
- Under load tap changing Transformer
- Load Shedding

The overall research objectives include: suggest actions and try to solve both types of violations mentioned using sensitivity based algorithms. Also a rule base for the above violations and methods to solve it based on offline studies, is developed for the different test cases which may help in developing the corrective actions.

The algorithms for single and multiple lines as well as generator outages (based on AC and DC sensitivities) are coded in MATLAB. The rule bases for corrective actions for different test cases were constructed based on the contingency analysis and offline studies done on the systems using PowerWorld and PSS/E.

Different test cases for validating these algorithms are the 6 bus [1], 37 bus system given in PowerWorld and the 137 bus utility system. Each of the system details are given in the Appendix.

3.5 Formulation of proposed algorithm

The thesis work focused on developing algorithms for multiple contingencies. Especially considering their impact and considering their frequency of occurrence, the work is focused on multiple line outages (figure 3.1) and multiple generator outages (figure 3.2).

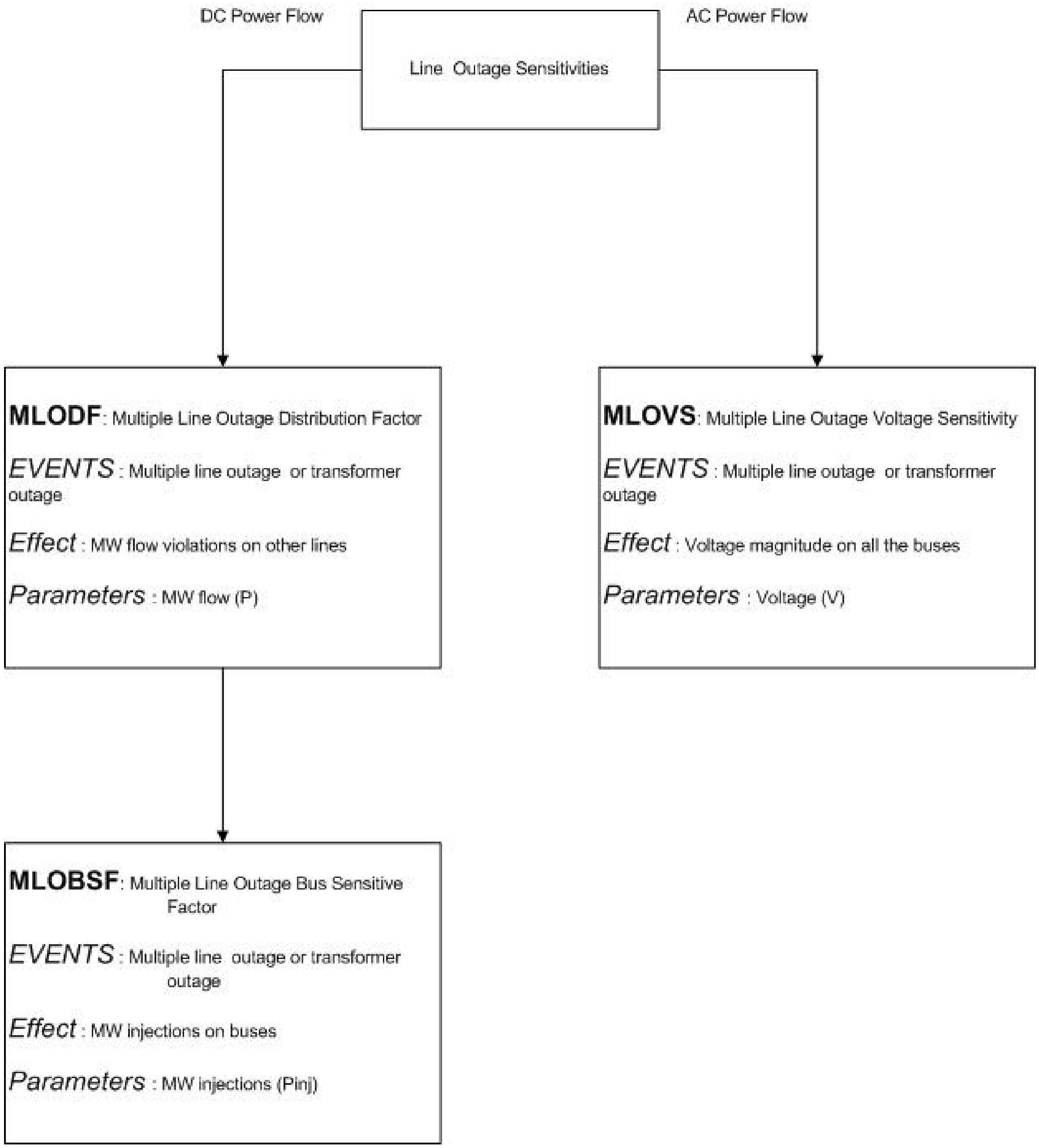

Figure 3.1 Algorithms for multiple line outages

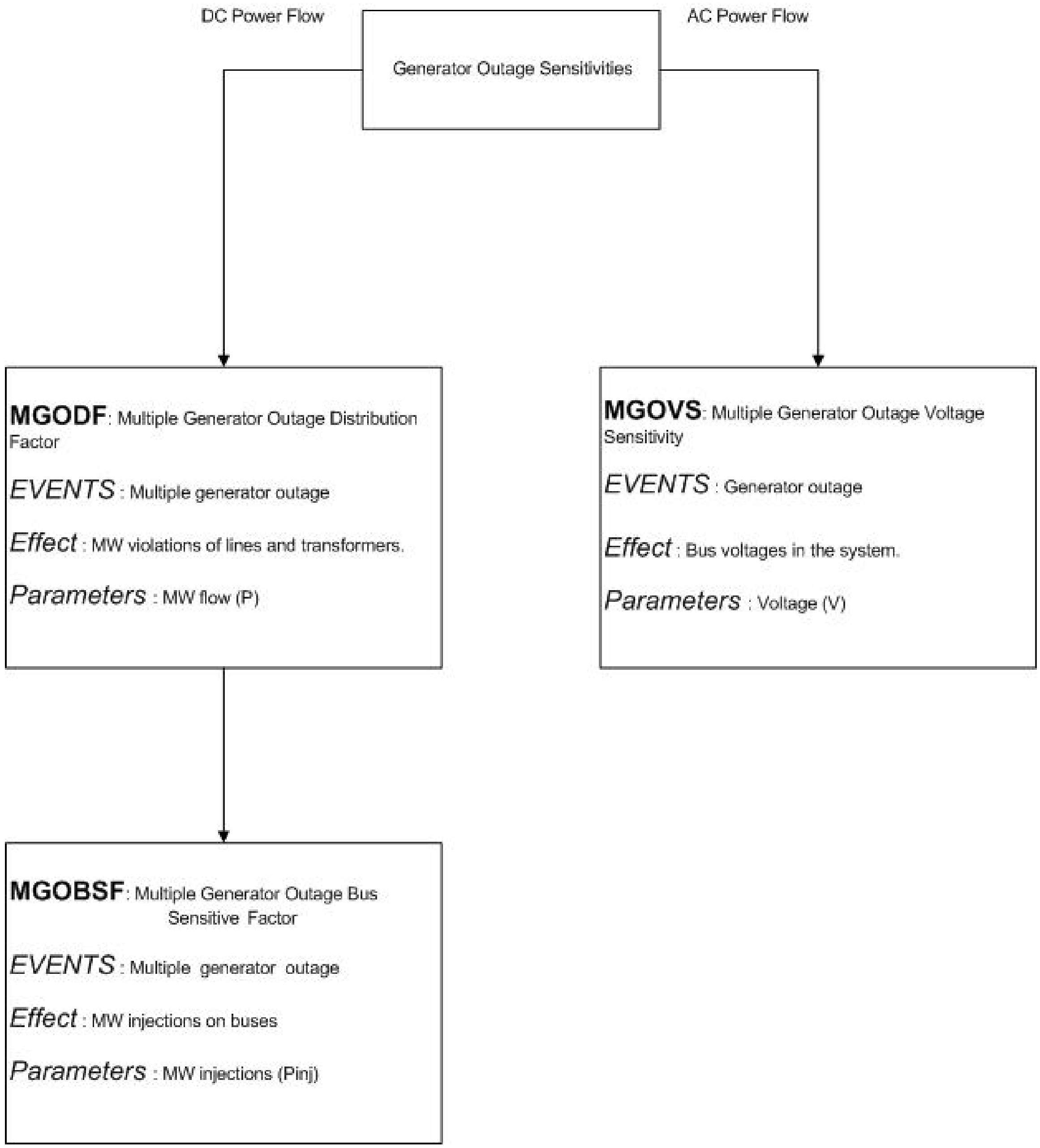

Figure 3.2 Algorithms for multiple generator outages

The algorithms are mainly divided based on the type of sensitivities

- Line sensitivities
- Generator Sensitivities

Further these sensitivities are divided into sub-categories based on the type of power flow which they will use.

3.5.1 Line sensitivities

The line sensitivities (figure 3.1) are developed based on AC and DC power flow calculations. Multiple Line Outage Distribution Factor algorithm (MLODF) is based on the DC power flow and it calculates the impact on all other transmission lined when multiple lines in a system are outaged. This algorithm is further developed to calculate Multiple Line Outage Bus Sensitivity Factor (MLOBSF) algorithm which will calculate the impact of line outages on the buses. The output of this algorithm provides an index which will then be used as input to rule base for RAS for corrective actions. The other types of line sensitivities are based on AC power flow. The Multiple Line Outage Voltage Sensitivity (MLOVS) algorithm is used to calculate the impact on the bus voltages on a system when multiple line outages occur in the system. This MLOVS algorithm will be used for calculating the sensitive buses for suggesting corrective actions. The general violations for any contingency are line overloading and bus voltages. Thus MLODF algorithm based on DC power flow will help solve the overloading problems and MLOVS algorithm based on AC power flow will help in solving the voltage problems for higher order branch contingencies.

3.5.2 *Generator sensitivities*

The generator sensitivities (shown in figure 3.2) are divided based on the type of power flow being used for the contingency. The Multiple Generators Outage Distribution Factor (MGODF) Algorithm is based on the DC power flow and is used for calculating the impact on the transmission lines in the system when multiple generator contingency happens in the system. The MGODF algorithm is further deduced to derive the Multiple Generator Outage Bus Sensitive Factor (MGOBSF) algorithm which gives the sensitive buses for the multiple generator outages based upon which corrective actions can be taken to solve these violations. The other algorithm developed is Multiple Generator Outage Voltage Sensitivity (MGOVS) algorithm and is used to calculate the impact on the bus voltages in the system when multiple generator contingency happens in the system. The MGOVS algorithm is based on full AC power flow and is more effective during the voltage violations during contingencies.

The developed tool will utilize combinations of offline and online calculations to suggest corrective actions. Figure 3.3 shows overall corrective action plan for higher order contingencies using developed algorithms.

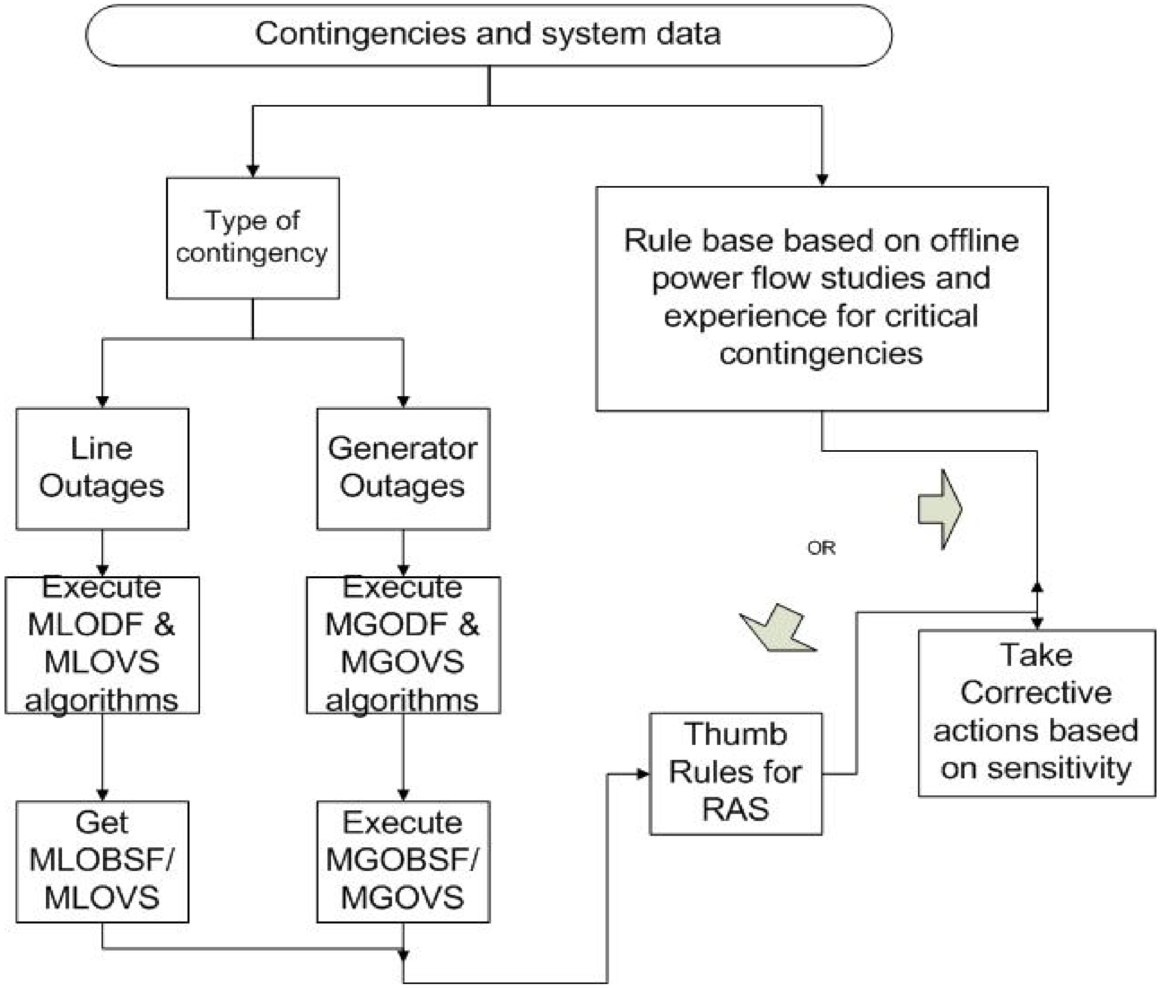

Figure 3.3 Online implementation of algorithms

As seen in figure 3.3 using the developed algorithms, corrective actions can be taken online for any multiple branch or generator contingencies. The input needed for algorithm would be the type of contingency, contingency details (online) and network data (off line) etc. This research work can be useful in real time online applications for multiple contingencies. It can be used as a tool by utilities during higher order contingencies as a quick and effective ways to solve the violations.

3.6 Test cases used in the work

There are three test cases which have been used in this work. First one is the 6 bus test case system [1]. This is re-built in the PowerWorld software with the given parameters.

The one line diagram for the test case built in PowerWorld in software is given in figure 3.4.

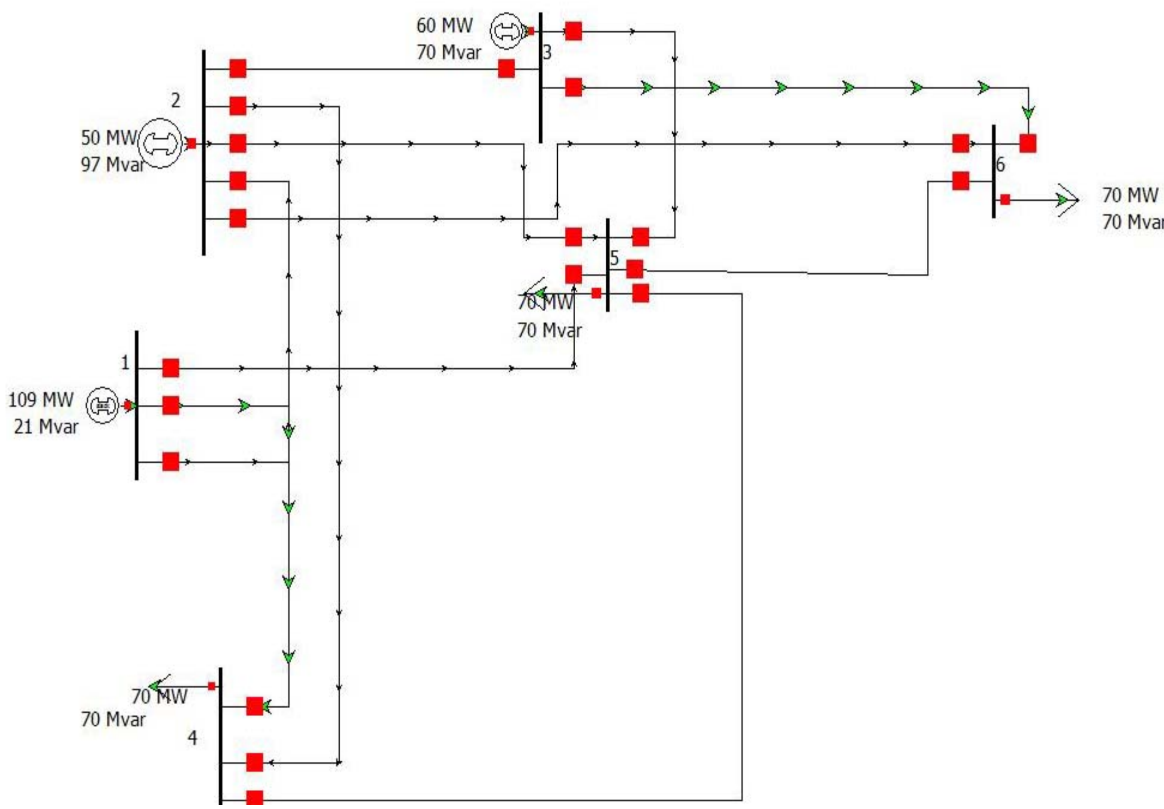

Figure 3.4 Six bus test case system

The six bus system has three generators and three loads. Bus number 1 is slack bus, bus number 2 and 3 are PV buses and bus number 4, 5 and 6 are PQ (load buses).

3.6.2 37 bus test case system

The 37 bus system has the following important specifications briefly:

The test system consists of

- 37 buses
- 9 generators
- 57 transmission lines (69kV, 138kV, 345kV)
- Real power load is 769.4MW and reactive power load is 277.2MVAR
- Generation 778.9 MW and 117.5 MVAR respectively.

The base case one line diagram for the 37 bus system in the PowerWorld software is given in figure 3.5, also the power flows on each line as well as the pie charts for the amount of power flowing through each line can also be seen in figure 3.5. The loads are given with an arrow mark, the generators in circular diagram, and different buses and transformers can also be seen in the picture. The shunt capacitor at some buses can also be seen from the figure.

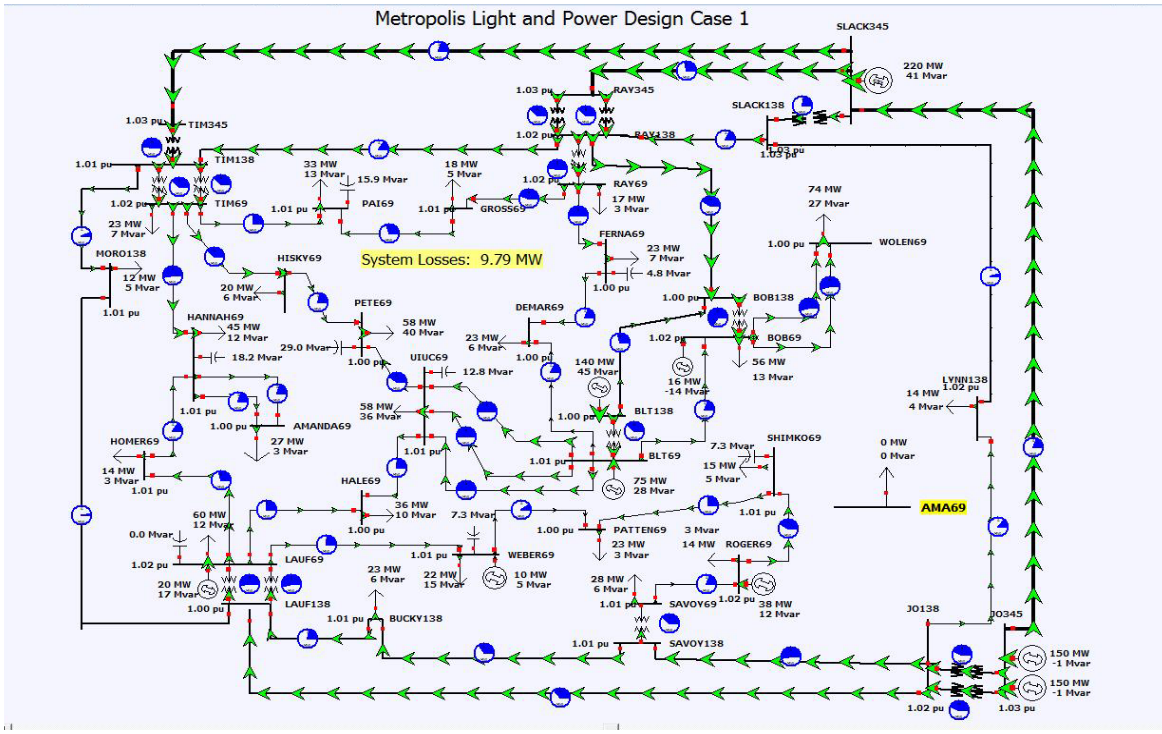

Figure 3.5 37 bus test case system

3.6.3 137 bus utility system

The 137 bus test case is a utility system. Detailed data for the system is not presented in this thesis due to a confidentiality agreement. A brief description for 137 bus utility system is given as follows:

- 12 generators
- 137 buses
- 159 transmission lines
- 31 transformers
- 90 loads

3.7 Rule base from offline simulation studies

The rule base is a set of rules defined by experience and knowledge gained by trying out different options available to solve the violations obtained from the contingencies through simulations. It is common for a utility to have a rule base for the most frequently occurring or most critical contingencies which affect the system performance. The rule base developed will look at all the aspects in developing a rule for each possible contingency so that not only the problem is solved but also solving it in most effective and optimum ways. The optimal solution will look at how to maintain the system stability and continuous operation to supply as many loads as possible without affecting the system normal operation. The typical formulation of the rule base consists of trying out different options through simulation studies and see if they are successful in removing the violations or not. There are several different actions need to be tried before actually coming with a rule or best possible solution for a contingency to remove the violations. And also one more important thing to be noted is that there may be multiple set of rules which may be possible for some contingencies and the rule base should be able to give the operator the choice to implement whatever is best at that point of time looking at different parameters which are important at any given time.

Example for Rule Base

As mentioned earlier the sample rule base developed for N-2 contingency on the 37 bus test case system will be given here.

3.7.1 N-2 contingency rule base for low voltage violations

Contingency: Line outage

Line 1: Branch TIM345 (1) TO SLACK345 (31) CKT 1 [2]

Line 2: Branch RAY138 (39) TO TIM138 (40) CKT 1

Voltages with limit violations

Limit Violations	Bus name	Bus voltage	Voltage limit	Bus kV
Bus Low Volts	TIM345 (1)	0.93	0.95	345.0
Bus Low Volts	MORO138 (3)	0.93	0.95	138.0
Bus Low Volts	TIM138 (40)	0.93	0.95	138.0

General Rule: Try all the capacitors around the buses (up to 4 buses).

- Try to switch on shunt capacitor at PAI 69(level 2) **failed** to solve violation.
- Try to increase generation Mvar at SLACK 345(level 2) from 33 Mvar to 45 Mvar –**failed**.
- Try to increase generation Mvar at LAUF 69(level 2) [2] from 33 Mvar to 45 Mvar –**failed.**
- Increase the shunt switching capacitor Mvar at HANNAH 69(level 2) from 18 Mvar to 28 Mvar, only **'one'** violation **solved** at MORO 138(level 2).
- Shunt capacitor of 25 Mvar at MORO 138 (level 1) **failed**.
- Shunt capacitor of 25 Mvar at TIM 345(level0) **solved** all **'3'** violations (MATLAB code based on sensitivities also validated this).

- Shunt capacitor of 25 Mvar at TIM 138(level0) **solved** all **‘3’** violations (MATLAB code based on sensitivities also validated this).

Note: All possibilities of trying to increase the Mvar at nearby generators and shunt capacitors at nearby buses have been tried. Some are not giving positive results and some are solving only one violation at MORO 138. Level 0 is having the capacitor on the same bus, level 1 is having capacitor one bus away and level 2 is having capacitor 2 buses away etc.

General Solution: To solve the problem, it is necessary to switch on the capacitor at TIM 138 or TIM 345 of 25 Mvar.

Solution: Capacitor of 25 Mvar at TIM138.

The N-2 transmission line contingency caused low voltages at three buses, the general method to remove the low voltage violations would be to switch on the capacitor bank near the violated buses, or increase the available Mvar or shed the load. Hence the methodology showed above looks at all the options mentioned to solve the violations. For example, if we look at the different rules mentioned, increasing the capacitance of the bus at PAI 69 has failed to solve the violations but installing the capacitance at the TIM 138 bus would solve the violations. Hence we can say that this rule base development studies may also be used for planning purpose in order to anticipate the future problems and be ready for them. As said earlier the rule base, the way the contingencies are approached and the way they are solved may be different for different contingencies but the common fundamental rule of actions are almost same.

The rule base developed for different contingencies on several systems based on offline studies is used for derivation of thumb rule for RAS. These thumb rule gives the prioritized actions which needs to be taken in case of violations due to multiple contingencies.

3.7.2 Thumb rules for RAS

The corrective actions are developed using the following thumb rules for remedial action schemes (RAS).

If voltage< voltage limit

1. Turn on the capacitor on the bus or the neighboring bus.
2. Supply the reactive power from the generator bus or nearby generator bus.
3. Shed the load/part of the load on the bus or neighboring bus.

If MW flow>MW limit

1. Generation re-dispatch from the sensitive generator bus
2. Shed the load the bus or neighboring bus.

The output of the developed algorithms is the list of top sensitive buses and these sensitive buses are used as probable locations for corrective actions using the above mentioned thumb rules. If the type of violation resulting for the contingencies is a low voltage violation then as mentioned above, first thing will be to look for the capacitor at most sensitive bus, and switch on the capacitor. If the top sensitive buses don't have the sensitive buses installed on them, then look for the buses which are one bus away from the sensitive buses and switch on the capacitor if there is any capacitor installed. Similar procedure is followed for two buses away from the sensitive bus to switch on the capacitor. If there is no capacitor at the sensitive buses (within the 2 bus range or if the problem still persists even after switching the capacitor) then other way to solve the contingencies is to supply the reactive power through the generator (if any) at these sensitive buses or through the generators nearby (up to 2 buses). The third and last preferable way to solve the violation followed in this work for low voltage problem is to shed the load at the sensitive buses or on the buses which are up to 2 buses away.

The other important type of violation is the MW limit violation. This is solved by using the MW flow rules given in thumb rules for RAS. If the MW flow on the line crosses the MW limit of the line then it is declared line overload. The list of top sensitive buses for the contingency are obtained from the developed algorithm. Using these top sensitive buses the violations are solved by using thumb rules for MW violation. If there is generator bus in the list of top sensitive buses the generation is increased or decreased depending on sign of sensitivity indices. Different combinations may be tried (within the top sensitive generator buses) to solve the problem. This may be done with up to two generator buses away from the sensitive bus. The other way to solve the line overload violation is shedding the load at the top sensitive bus. Load at the top sensitive buses or up to 2 buses away from sensitive buses is shed. Different combinations need to be tried out on the list of top sensitive load buses and shedding the load gradually based on indices and MW violations.

3.8 Summary

The basic power flow formulation and the reason for developing corrective actions based on sensitivity algorithms for a power system network was presented in this chapter. The explanations of developed algorithms for multiple contingencies are also given in this chapter. All the test cases that are used in the work and their details have been presented. Finally the rule base for the contingencies, development of thumb rule base and its implementation on a test case is also presented in this chapter.

3.9 References

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[2]. PowerWorld version 11.0 www.powerworld.com

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CHAPTER IV

DC SENSITIVITY FOR MULTIPLE LINE OUTAGES AND SIMULATION RESULTS

4.1 Introduction

This chapter deals with development of algorithms for multiple line outages and solving the violations caused by the multiple line outages. The algorithms developed in this chapter are based on DC power flow [1]. Initially a single line outage will be studied and then it will be extended to the multiple line outages in the power system based on reference [1].Work presented in the reference[1] was further developed to find the sensitivity of bus. The algorithms and flow charts for solving the single and multiple line outages based on DC power flow will be explained in this chapter.

4.2 Line Outage Distribution Factor

The Line Outage Distribution Factor (LODF) is one of the important linear sensitivity factors which plays a key role in finding the effect of the critical contingencies and hence suggesting possible preventative and corrective actions to solve the violations in the system. LODF [1] calculates the impact on all other transmission lines in a network when a single transmission line goes out in a system. LODF is being used as an important tool for calculating the outage impact i.e. how severe is the outage and how it impacts the system. LODF is based on the DC power flow and is less accurate compared to the full AC power flow. It only calculates the MW flow and doesn't give any information about MVAR of the line or the bus voltages. Also DC power flow is a one way to gain speed of solution in a contingency analysis procedure by creating an approximated model of the power systems. The Multiple Line Outage Distribution Factor (MLODF) calculates the impact on the transmission lines of the system when multiple lines are outaged in the system. LODF is widely used by industry, where not much as attention has been paid to the MLODF. The MLODF is very useful in calculating the impact on the system when higher order contingencies happen in the system. Depending on the type of contingency MLODF can be used for MVA limitations of line during the multiple outages. This chapter discusses in detail about MLODF and how it is calculated based on the DC power flow

4.2.1 Calculation of LODF

To calculate the LODF initially a line outage must be modeled which can be used for further derivations of LODF formulation. LODF formulation is summarized here from reference [1]. A line outage may be modeled by injecting equivalent power at both ends of the system, the line is actually left in the system but effect of its outage is modeled by injecting the equivalent MW or pre-contingency power flow through the each ends of the line. Suppose line k is from bus n to bus m. If the line is opened with help of circuit breaker no current flows in the system and line is completely isolated from the remaining power system network. To simulate this impact we inject power ΔP_n at bus n

and ΔP_m at bus m respectively. If $\Delta P_n = \tilde{P}_{nm}$ and $\Delta P_n = -\tilde{P}_{nm}$, since the power flowing through line zero , the current flowing through the line will also be zero even though the circuit breakers are closed and also the line is out with respect to the remaining part of the system. Since the power flow used is DC for calculation of LODF and since it is linear power-flow model we can write,

$$\Delta\theta = [X]\,\Delta P \text{ [1]............(4.1)}$$

Where,

$\Delta\theta$ = Change in bus phase angle with respect change in power injection ΔP

[X] = Reactance matrix

$$\Delta P = \begin{bmatrix} . \\ \Delta P_n \\ . \\ \Delta P_m \\ . \end{bmatrix}$$

Hence from above relation we can write

$$\Delta\theta_n = X_{nn}\Delta P_n + X_{nm}\Delta P_m$$

$$\Delta\theta_m = X_{mn}\Delta P_n + X_{mm}\Delta P_m$$

Here we have

θ_n, θ_m , P_{nm} are the initial phase angles of bus n and bus m and P_{nm} is the flow on line k from bus *n to* bus m

θ_n, θ_m, P_{nm} are the incremental changes resulting from the outage.

$\tilde{\theta}_n, \tilde{\theta}_m, \tilde{P}_{nm}$ are the phase angles for bus n and bus m power on line k after outage

When a line is outaged the power flowing through the line is equal to the incremental injections at the buses. Also let x_k be the reactance of the line k.

Therefore we can write

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

Where

$$\tilde{P}_{nm} = \frac{\left(\tilde{\theta}_n - \tilde{\theta}_m\right)}{x_k}$$

Then

$$\Delta\theta_n = (X_{nn} - X_{nm})\Delta P_n \quad \ldots\ldots\ldots\ldots\ldots\ldots.. (4.2)$$

$$\Delta\theta_m = (X_{mm} - X_{mn})\Delta P_m \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

and

$$\tilde{\theta}_n = \theta_n + \Delta\theta_n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

$$\tilde{\theta}_m = \theta_m + \Delta\theta_m \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.5)$$

Substituting the values of $\tilde{\theta}_n$ and $\tilde{\theta}_m$ in $\tilde{P}_{nm}$

and re- arranging the terms we get,

$$\tilde{P}_{nm} = \frac{(\theta_n - \theta_m)}{x_k} + \left(\frac{\Delta\theta_n - \Delta\theta_m}{x_k}\right)$$

Or in-terms of the reactance we can write

$$\tilde{P}_{nm} = \Delta P_{nm} + \left(\frac{(X_{nm} + X_{mm} - 2X_{nm})\Delta P_n}{x_k} \right) \text{....... (4.6)}$$

Then using the fact that $\tilde{P}_{nm} = \Delta P_n$

$$\Delta P_n = \frac{(P_{nm} * x_k)}{[x_k - (X_{nn} + X_{mm} - 2X_{nm})]} \qquad \text{............. (4.7)}$$

Now define the sensitivity factor δ as the ratio of change in phase angle to the power flowing through the line from bus *n* to bus *m*. We can write δ as

$$\delta_{i,nm} = \frac{\Delta\theta_i}{P_{nm}} \text{........... (4.8)}$$

If neither *n* nor *m* are the system reference buses,

Injections ΔP_n and ΔP_m are imposed at buses n and m. The change in phase angle at bus i due to these injections equal to

$$\Delta\theta_i = X_{in}\Delta P_n + X_{im}\Delta P_m$$

Then sensitivity factor δ can be written as

$$\delta_{i,nm} = \frac{(X_{in} - X_{im})x_k}{[x_k - (X_{nn} + X_{mm} - 2X_{nm})]} \text{............. (4.9)}$$

If *m* or *n* is the reference bus, only one injection is made. The sensitivity factor can be given as

$$\delta_{i,nm} = \frac{X_{in} * x_k}{(x_k - X_{mm})}, \text{ when } m \text{ is the reference bus.}$$

$$= \frac{-X_{in} * x_k}{(x_k - X_{mm})}, \text{ when } n \text{ is the reference bus.}$$

$$= 0 \qquad \text{when } i \text{ is the reference bus}$$

Now, Defining the symbol for Line Outage Distribution Factor (LODF) as d

$d_{l,k}$ Can be written as the LODF of the line l when the line k is outaged from the system

$d_{l,k}$ is defined as the ratio of the change in flow on line l to the flow on line k before outage

$$d_{l,k} = \frac{\Delta f_l}{f_k^o}$$

$$= \frac{(\Delta\theta_i - \Delta\theta_j)}{x_l f_k^o}$$

$$d_{l,k} = \frac{\left[\left(\frac{\Delta\theta_i}{P_{nm}}\right) - \left(\frac{\Delta\theta_j}{P_{nm}}\right)\right]}{x_l}$$

$$= \frac{(\delta_{i,nm} - \delta_{j,nm})}{x_l} \quad \text{…………..(4.10)}$$

If neither *i nor j is* a reference bus

We can write

$$d_{l,k} = \frac{\frac{x_k}{x_l}(X_{in} - X_{jn} - X_{im} + X_{jm})}{x_k - (X_{nn} + X_{mm} - 2X_{nm})} \text{ [1]} \quad \text{……………….. (4.11)}$$

Using the above expression the Line Outage Distribution Factor for the line l when the line k is outaged can be calculated.

Using the above formula the LODF algorithm is implemented for different test cases to find out the LODF and hence the bus sensitivities from it to suggest possible remedial actions for the system when contingencies occur in the system.

4.2.2 Algorithm for LODF

1. Input the branch data and bus data for the test case

2. Calculate the number of buses and number of branches from the data.

3. Define the slack bus and its corresponding number.

4. Calculate the susceptance matrix 'B' from the branch data

$$B = \frac{1}{x_{ij}}$$

Where x_{ij} is the reactance of the line between i, j buses.

5. Eliminate the corresponding rows and columns of the slack bus from the 'B' Matrix.

6. Calculate the inverse of the resultant matrix.

7. Append the slack bus rows and columns with zeros for the resultant zeros matrix and name it as 'X'.

8. Calculate the LODF $d_{l,k}$ of any line l when a line k is outaged in the system given by the equation 4.11

$$d_{l,k} = \frac{\frac{x_k}{x_l}\left(X_{in} - X_{jn} - X_{im} + X_{jm}\right)}{x_k - \left(X_{nn} + X_{mm} - 2X_{nm}\right)} \qquad \text{............ [1]}$$

9. Repeat the process for all the lines in the system.

10. Assign the impact on the line to the ‘from’ and ‘to’ buses of the line and cumulatively add together the impact on each bus and rank the buses according to their sensitivities.

Thus the LODF of all the lines in the system is calculated when a single line is outaged in the system. Sensitive buses thus obtained will be used for taking corrective and preventive action in the system.

4.2.3 Flow chart for LODF

The flow chart for LODF algorithm is shown in fig 4.1

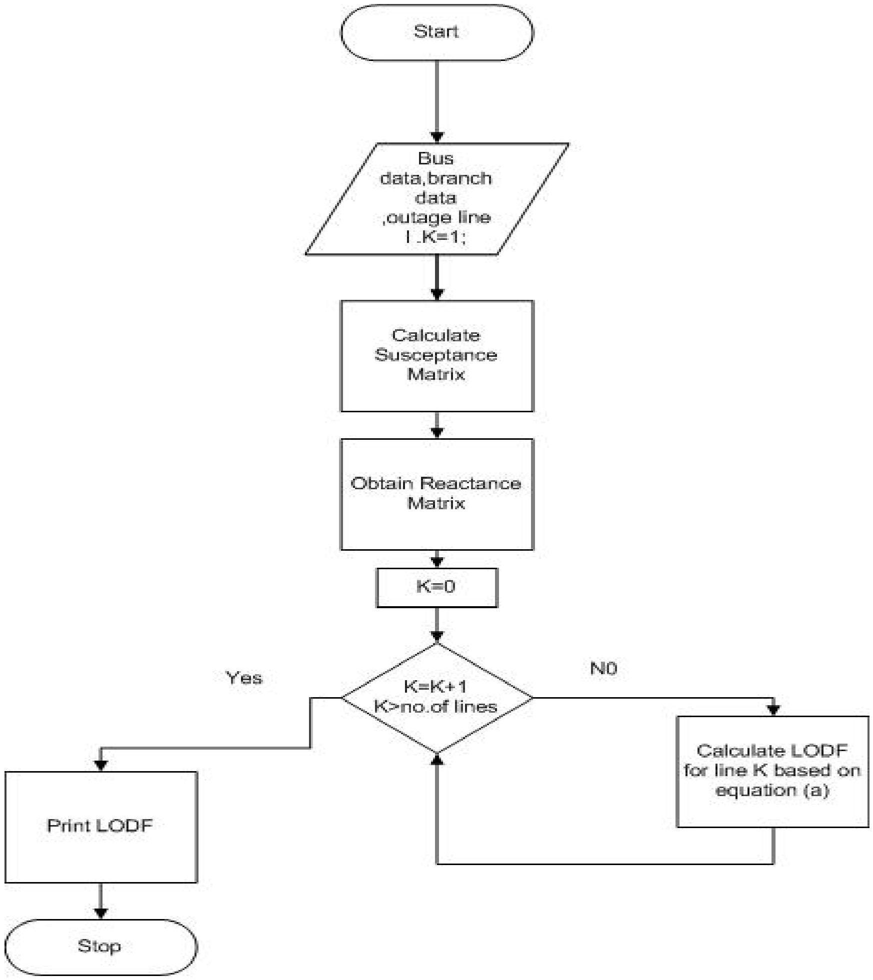


Figure 4.1 Flow chart for LODF

4.3 Multiple Line Outage Distribution Factor

Although the methodology presented in section 4.2 is very efficient in calculating the impact on the transmission lines in the network it is used only for single line outage. The main problem many utilities face today, especially due to the large inter-connection ties is the cascading effect which can result in the multiple line outages. In this scenario calculation of the line outage distribution factor for multiple outages is very important tool for taking any corrective and preventive actions during these higher order contingencies. MLODF has not been used much by the industry. In this section, focus is on deriving the MLODF and evaluating them and demonstrating how they are useful for multiple line outages based on reference [2].

The Multiple Line Outage Distribution Factor (MLODF) is based on the DC Power flow and will be explained in this section. MLODF addresses the MW limit violations caused by any higher order line contingency. MLODF is then further deduced to give Multiple Line Outage Bus Sensitivity Factor(MLOBSF). This MLOBSF gives a list of sensitive buses on which corrective and preventive actions can be taken to solve the violations due to higher order line contingencies. Since it is based on DC power flow the MLOBSF is not efficient in deriving the sensitive buses for the low voltage problems which are most frequently occurring violations in the system. Hence one more algorithm known as Multiple Line Outage Voltage Sensitivity (MLOVS) algorithm is developed to calculate the impact on the buses in the power system network as presented in next chapter.

To derive the expression for MLODF we have to explain and derive some important terms and formula first, which help as building factors for the derivation of MLODF.

4.3.1 Power Transfer Distribution Factor

Power Transfer Distribution Factor (PTDF) gives an index measurement of how transmission lines are affected when power is transferred from one bus to another bus in the power system network. The bus causing transfers may be any generator bus or slack bus, which transfers the power to other buses to supply the load. The bus giving the necessary power is called the seller bus and bus which receives the power is called the buyer bus. The whole process is termed as MW transaction. The derivation of expression for multiple LODF calculation from PTDF for a power system network is adopted from reference [2] and has been presented here. Equations from (4.12) to (4.26) have already been derived in reference [2] and they are explained here in detail.

Let us define PTDF as $\psi_{l_k}^{w}$

Where

$w = \{i, j, \Delta t\}$ i, j are the buses at each end of the line l_k.

Δt is the MW transaction on that line.

The relationship between the PTDF and LODF can be given as

$$\varsigma_{l_k}^{(l_m)} \overset{\Delta}{=} \frac{\psi_{l_k}^{w(l_m)}}{\left(1-\psi_{l_m}^{w(l_m)}\right)} \quad , l_k \neq l_m \quad [2] \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.12)$$

Where

l_m =line outages, l_k =line which is being monitored.

$\varsigma_{l_k}^{(l_m)}$ = LODF of the line l_k when the line l_m is outaged.

$\psi_{l_k}^{w(l_m)}$ = PTDF of the line l_k when line l_m is outaged.

As long as $\psi_{l_k}^{w(l_m)} \neq 1$, $\varsigma_{l_k}^{(l_m)}$ can be defined,

The outage of the line l_m results in change in topology of the system, which requires calculation of the PTDF's of the lines after the outage termed as post outage PTDF's. These are calculated using the equation 4.13

$$\psi_{l_k}^{w(l_m)} = \psi_{l_k}^{w} + \varsigma_{l_k}^{(l_m)} \psi_{l_m}^{w} \quad ,\ldots\ldots\ldots\ldots\ldots (4.13)$$

Define a line $l_1 = (i_1, j_1)$ where i_1 and j_1 are buses at each end of line l_1

Let f_{l_1} be the power flowing on the line l_1. For the outage of line l_1, the real power injection on each line in the post outage network connected to i_1 changes by the fraction of f_{l_1}.

This impact is simulated without actually taking a line out by adding an injection amount $\Delta t(l_1)$ on the line l_1 and net flow change of $(1-\psi_{l_1}^{w(l_1)})$ on all other lines connected to i_1, by selecting suitable transaction $\Delta t(l_1)$ we can satisfy the equation

$$(1-\psi_{l_1}^{w(l_1)})\Delta t(l_1) = f_{l_1} \quad [2]\ldots\ldots\ldots\ldots\ldots.. (4.14)$$

Now if we consider the outage of two lines l_1 and l_2, these impacts are simulated by taking into account the interactions between these two transactions, as mentioned for the single line outage by specifying the suitable values for $\Delta t(l_1)$ and $\Delta t(l_2)$ for satisfying the flowing equations for the two lines outage.

$$\left(1-\left(\psi_{l_1}^{w(l_1)}\right)^{(l_2)}\right)\Delta t(l_1) = \left(f_{l_1}\right)^{(l_2)} \quad \ldots\ldots\ldots\ldots\ldots (4.15)$$

$$\left(1-\left(\psi_{l_2}^{w(l_2)}\right)^{(l_1)}\right)\Delta t(l_2) = \left(f_{l_2}\right)^{(l_1)} \quad \ldots\ldots\ldots (4.16)$$

We can write the above two equations in matrix form using the relations 1 and 2 as

$$\left[I-\begin{bmatrix}\psi_{l_1}^{w(l_1)} & \psi_{l_1}^{w(l_2)}\\ \psi_{l_2}^{w(l_1)} & \psi_{l_1}^{w(l_2)}\end{bmatrix}\right]\begin{bmatrix}\Delta t(l_1)\\ \Delta t(l_2)\end{bmatrix}=\begin{bmatrix}f_{l_1}\\ f_{l_2}\end{bmatrix} \quad \text{...... (4.17)}$$

Since the above system is a linear system, we can solve the above equation to determine $\Delta t(l_1)$ and $\Delta t(l_2)$

.

Let α be the number of outages in the system.

Similarly using the inductive process to generalize the result for the case of multiple line outages, let us assume that $(\alpha-1)$ outages have taken place on the network and defining the set of $(\alpha-1)$ lines as $L_{(\alpha-1)}=\{l_1 \quad . \quad . \quad l_{(\alpha-1)}\}$, all these $(\alpha-1)$ outages are simulated and their transactions are given with the help of inductive process given for single line outage. Thus for these transactions we can write

$$\left[I-\phi_{L(\alpha-1)}\right]\Delta t_{(\alpha-1)} = f_{(\alpha-1)}$$

Where

$$\Delta t_{(\alpha-1)}=\left[\Delta t(l_1), \quad . \quad . \quad . \quad . \quad \Delta t(l_{(\alpha-1)})\right]^T, \quad f_{(\alpha-1)}=\left[f(l_1), \quad . \quad . \quad . \quad . \quad f(l_{(\alpha-1)})\right]^T$$

And

$$\text{a= } \phi_{L(\alpha-1)}=\begin{bmatrix}\psi_{l_1}^{w(l_1)} & . & . & . & . & . & \psi_{l_1}^{w(l_{(\alpha-1)})}\\ . & . & . & . & . & . & .\\ . & . & . & . & . & . & .\\ . & . & . & . & . & . & .\\ . & . & . & . & . & . & .\\ . & . & . & . & . & . & .\\ \psi_{l(\alpha-1)}^{w(l_1)} & . & . & . & . & . & \psi_{l_{(\alpha-1)}}^{w(l_{(\alpha-1)})}\end{bmatrix} \text{[2].... (4.18)}$$

The condition for the above equation to be true is that $\lfloor I - \phi_{L(\alpha-1)} \rfloor$ is non singular.

Now consider additional outage of line $l_\alpha \notin L_{(\alpha-1)}$. Now the total number of outaged lines are L_α. This can be written in set form as $L_\alpha = L_{(\alpha-1)} \cup \{l_\alpha\}$.

Repeating the procedure as we have done for the two lines outage analysis we can write $\Delta t_{(\alpha-1)}$ as

$$\left\lfloor I - \left(\psi_{L_{(\alpha-1)}}\right)^{l_\alpha} \right\rfloor \Delta t_{(\alpha-1)} = \left(f_{\alpha-1}\right)^{l_\alpha}$$

Now calculating the impact of $L_{(\alpha-1)}$ lines on l_α by $\Delta t_{(\alpha)}$ calculating as

$$\left\lfloor I - \left(\psi_{l_\alpha}^{w(l_\alpha)}\right)^{L(\alpha-1)} \right\rfloor \Delta t(l_\alpha) = \left(f_{(\alpha-1)}\right)^{L(\alpha-1)}$$

Where the super-script $L_{(\alpha-1)}$ denotes the network with $(\alpha-1)$ elements outaged.

Now let us re arrange the above two equations to get the result for α lines outaged in the system.

Let us define

$$b \stackrel{\Delta}{=} \left[\psi_{l_1}^{w(l_\alpha)} \quad . \quad . \quad . \quad \psi_{l_{(\alpha-1)}}^{w(l_\alpha)}\right]^T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.19)$$

$$c \stackrel{\Delta}{=} \left[\psi_{l_\alpha}^{w(l_1)} \quad . \quad . \quad . \quad \psi_{l_{(\alpha)}}^{w(l_{\alpha-1})}\right]^T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.20)$$

Substituting the values of *b* and *c* (where b is the vector of ptdf's of $\alpha-1$ lines for a α transfer and c is the ptdf's of α line for transfers of $\alpha-1$ lines. Expanding the terms, we get the simplified form for the final linear equation to solve the line outages

$$\lfloor I - \psi_{L_{(\alpha)}} \rfloor \Delta t_{(\alpha)} = f_{(\alpha)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.21)$$

Where

$$\psi_{L_{(\alpha)}} \stackrel{\Delta}{=} \begin{bmatrix} \psi_{L_{(\alpha-1)}} & b \\ c & \psi_{l_\alpha}^{w(l_\alpha)} \end{bmatrix} \text{..................} (4.22)$$

Define,

$$d = \psi_{l_\alpha}^{w(l_\alpha)} \text{..............................} (4.23)$$

Where,'d' is the PTDF of line alpha for transfer of power between buses which connect line alpha.

As long as $\lfloor I - \psi_{L_\alpha} \rfloor$ is non singular we can use the above expression to solve for $\Delta t_{(\alpha)}$ and α line outages can be simulated.

The above procedure [2] for specifying the appropriate values for the transactions will be used to develop the MLOBSF expression. Let us assume a line $l_k \notin L_{(\alpha)}$, let us define $\xi_{l_k}^{L(\alpha)}$, whose elements are the MLOBSFs with α lines outaged.

The change in the real power flow on line l_k with the interactions between the outaged lines fully considered can be given as

$$\left(f_{l_k}\right)^{L_{(\alpha)}} \stackrel{\Delta}{=} \left[\xi_{l_k}^{L_{(\alpha)}}\right]^T f_{(\alpha)} \;,\; l_k \notin L_{(\alpha)} \text{.................} (4.24)$$

The combined impacts on the line l_k of the α transactions with specified $\Delta t_{(\alpha)}$ can be written as

$$\left(\Delta f_{l_k}\right)^{L_{(\alpha)}} = \left\lfloor \psi_{l_k}^{w(l_1)}, \quad . \quad . \quad . \quad \psi_{l_k}^{w(l_{(\alpha)})} \right\rfloor \Delta t_{(\alpha)}$$

Define $$e = \left\lfloor \psi_{l_k}^{w(l_1)}, \quad . \quad . \quad . \quad \psi_{l_k}^{w(l_{(\alpha)})} \right\rfloor$$ …………… (4.25)

Where,

Each element of *e* is the PTDF of line *'k'* for the transfer of each line from 1 to alpha.

Substituting the value of $\Delta t_{(\alpha)}$ and assuming $\left\lfloor I - \psi_{L_\alpha} \right\rfloor$ is nonsingular we can write

$$\left(\Delta f_{l_k}\right)^{L(\alpha)} = \left\lfloor \psi_{l_k}^{w(l_1)}, \quad . \quad . \quad . \quad \psi_{l_k}^{w(l_{(\alpha)})} \right\rfloor \times \left[I - \psi_{L_\alpha} \right]^{-1} f_\alpha$$

It follows from the above equations that $\xi_{l_k}^{L(\alpha)}$ is the solution of

$$\left[I - \psi_{L_\alpha} \right]^T \xi_{l_k}^{L(\alpha)} = \left\lfloor \psi_{l_k}^{w(l_1)}, \quad . \quad . \quad . \quad \psi_{l_k}^{w(l_\alpha)} \right\rfloor^T$$ [2]……. (4.26)

Hence the MLOBSF for the α line outages can be found out using the above expression with the only condition being $\left\lfloor I - \psi_{L_\alpha} \right\rfloor$ is nonsingular.

Thus the MLODF is found out in case of multiple line outages.

The MLODF found from the above algorithm is then used to get list of top sensitive buses. MLODF of all the lines is attributed to the buses attached to the lines and the impact on each bus is cumulatively added. Thus we get list of buses and their respective sensitivities. This is called the Multiple Line Outage Bus Sensitive Factor (MLOBSF). The buses with their impacts are thus ranked according to the magnitude of impact on each bus in decreasing order. Thus a list of top sensitive buses will be found and these buses are the natural locations to act upon to take preventive and corrective actions in the system. The number of top sensitive buses which can be acted upon may vary from system to system. For example a 37 bus system may need 5 to 6 buses based on the sensitivity locations for taking corrective actions to solve the problem where as a 137 bus system may need higher number of bus sensitivity locations to solve the violations. The sensitive buses thus found are effective in dealing with these higher order contingencies to take corrective and preventive actions to solve the violations.

4.3.2 Algorithm for MLODF/MLOBSF

1. Input the Branch data and bus data for the test case
2. Calculate the number of buses and number of branches from the data.
3. Define the slack bus and its corresponding number.
4. Calculate the susceptance matrix 'B' from the branch data

$$B = \frac{1}{X_{i,j}}$$

   Where $X_{i,j}$ is the reactance of the line between i, j buses.

5. Eliminate the corresponding rows and columns of the slack bus from the 'B' Matrix.
6. Calculate the inverse of the resultant matrix.
7. Append the slack bus rows and columns with zeros for the resultant zeros matrix and name it as 'X'.

8. Find the Power Transfer Distribution Factor (PTDF) for all the lines when the power system is operating normally as well as when a single line out goes out in the in the system using the formula

$$PTDF_{ij,mn} = \frac{X_{im} - X_{jm} - X_{in} + X_{jn}}{x_{ij}}$$

Where

m is the seller bus and n is the buyer bus.

x_{ij} is the reactance of the transmission line connecting zone i and j

X_{im} Entry in the ith row and the mth column of the bus reactance matrix X.

9. Calculate the matrices a, b, c, d, and e mentioned in the formulation above.

10. Define $\alpha = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$

Where

α is the matrix with ptdf's of lines when their corresponding lines are outaged.

11. Calculate the MLODF of the remaining lines in the system using equation 4.26

$$MLODF = inv(I - \alpha) * e$$

12. Attribute the MLODF to the corresponding buses attached to the lines and cumulatively add them together to get the MLOBSF for all the buses in the system.

13. Rank the buses according to their sensitivities.

The Multiple Line Outage Bus Sensitive Factor is very important tool in the research to take corrective actions for higher order line contingencies. The MLOBSF is based on the MLODF algorithm; it is derived from the MLODF by using the MATLAB code. When the MLODF for all the lines is obtained , then the MLOBSF code goes through each of the line and its MLODF and then attributes this MLODF to the each ‘ from’ and ‘to’ bus in the system. This is process is repeated for all the buses in the system and the impact on each bus is cumulatively added together to get the list of buses and their sensitivities.

Suppose there is a line between bus ‘*i*´ and ‘*j’* and its MLODF is M1 and there is a line between bus ‘*i*´ and ‘*k’* and its MLODF is M2. Then the MLOBSF of buses *i, j, k* can be given as.

MLOBSF of bus ‘*i*´ = M1+M2

MLOBSF of bus ‘*j’* = M1

MLOBSF of bus ‘*k’* = M2

The above procedure is repeated for all the buses in the system and their respective sensitivities. Then these buses are ranked according to their absolute value of their sensitivities such that we get the list of top sensitive buses on which corrective actions can be taken. Thus we get MLOBSF for any ‘n’ bus system for higher order line contingencies.

4.3.3 Flow chart for MLODF/MLOBSF

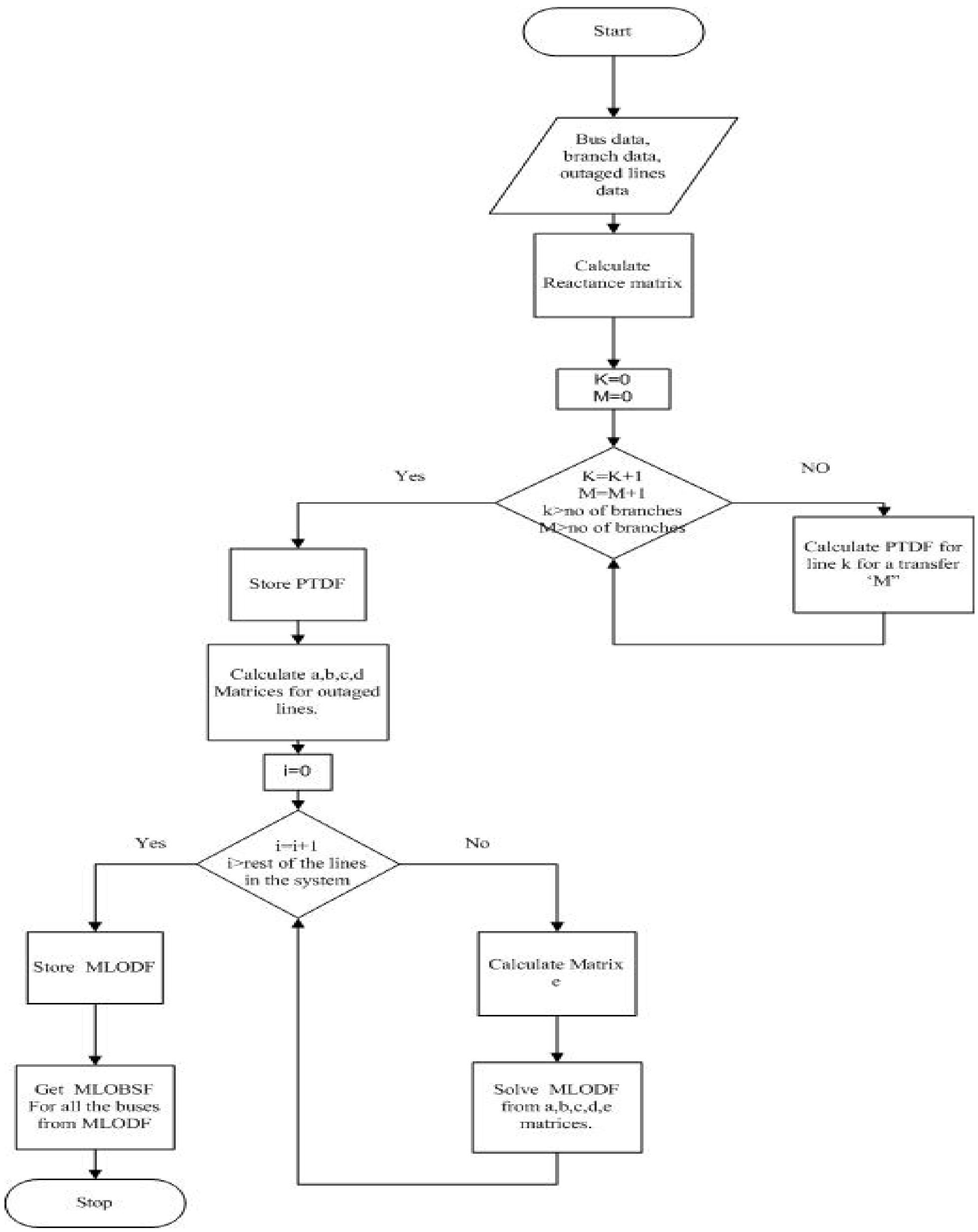


Figure 4.2 Flow chart for MLODF/MLOBSF

4.4 Implementation of algorithm on test cases

This section deals with implementing the MLODF/MLOBSF algorithm for N-2 and N-3 line contingencies on the test cases and results are also given. The three test cases used are 6 bus system, 37 and 137 bus test case systems. The details of these test cases are given in chapter 2. Results and corrective and preventive actions taken to solve the violations are given below.

4.4.1 N-2 line contingency

N-2 line outage is performed on all the test cases and the violations are then solved by using the corrective and preventive actions developed based on the MLODF/MLOBSF algorithm code in MATLAB. Figure 4.3 shows the N-2 contingency on the six bus test case system.

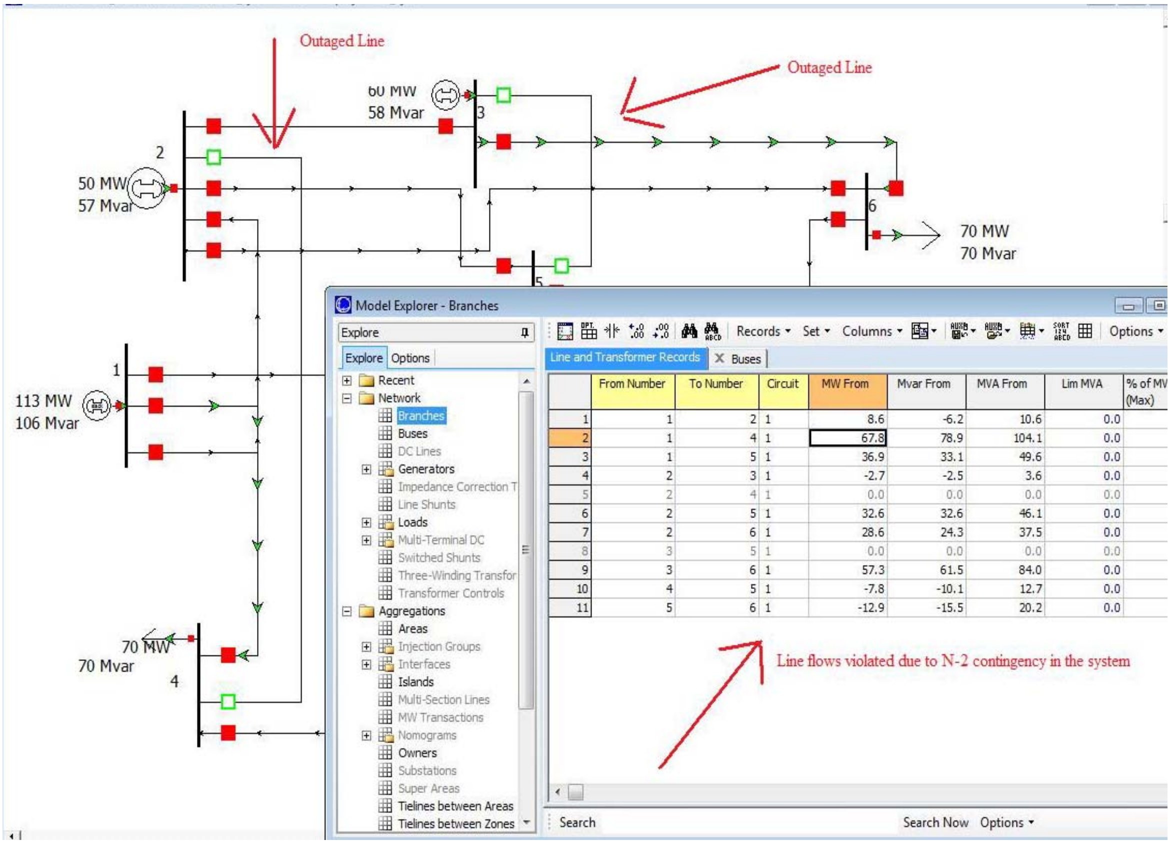


Figure 4.3 N-2 line contingency showing line flow violations

Figure 4.3 shows the N-2 contingency on the six bus system. The two lines outaged are the line 5 (2-4) and line 8 (3-5), as shown by the arrows in figure. The power flows on rest of the lines after the outage are also shown by the arrows in figure 4.3. Some of the lines have been carrying the power more than the limit. Action should be taken to solve these MVA violations. The MLODF/MLOBSF program for the above contingencies gives the ranking of sensitive buses, where action needs to be taken as shown in table 4.1.

Table 4.1 Sensitive buses N-2 contingency on 6 bus system

Bus No.	Sensitivity
2	0.01947
4	0.01798
3	0.01454
5	0.01125
1	0.00943
6	0.00567

.

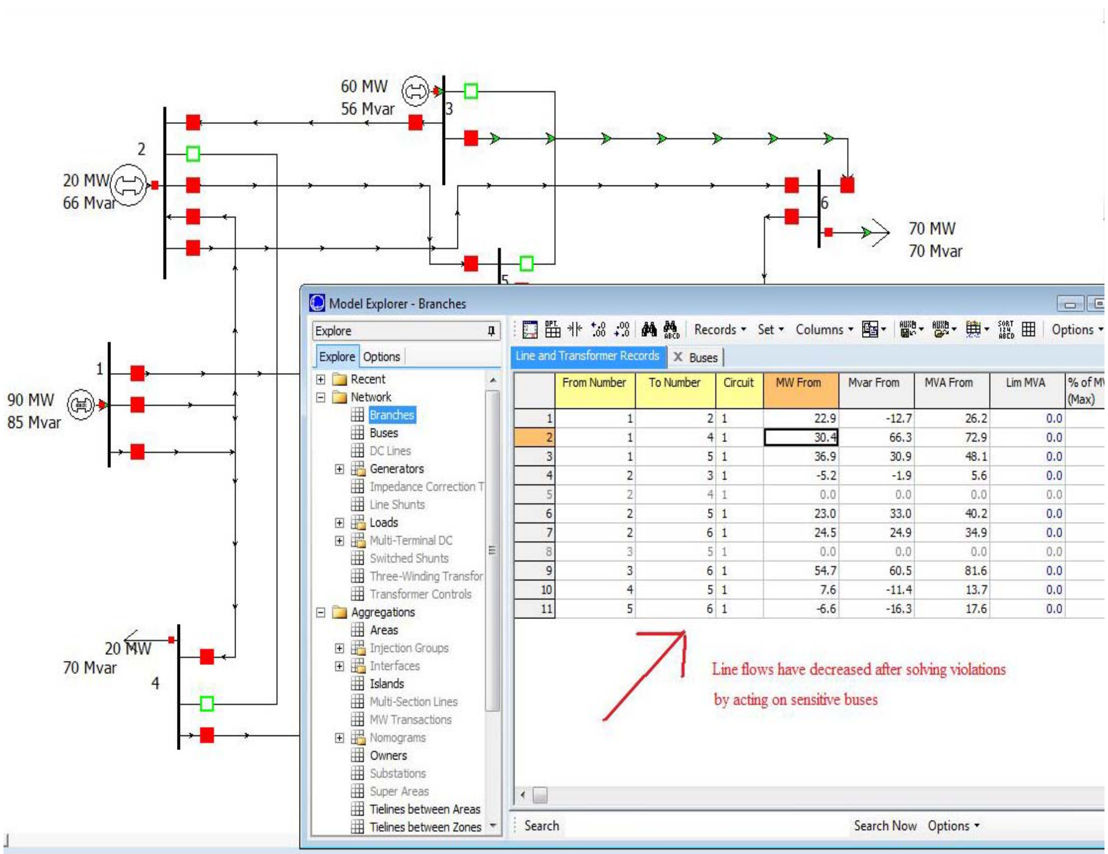


Figure 4.4 After violations (line flows) are solved for N-2 line contingency.

As seen from the table 4.1 the top three sensitive buses are the buses 2, 4, 3. The action taken on the buses are decreasing the generation at the bus 2 to 20 MW, shedding the load at bus 4 to 20 MW, and decreasing the generation at bus 3 to 50 MW. As a result the flows on all the lines in the system have been brought back to normal operating range as shown by the arrow in the figure. Thus the corrective actions taken based on the MATLAB code has resulted in solving the N-2 line contingency on the six bus system. Note that these actions will be given as option to the operator and it is up to the operator to take the final decision.

4.4.2 N-3 line contingency on six bus system

N-3 Line contingency has been performed on the six bus system to once again validate the MLODF/MLOBSF algorithm. The three lines outaged are lines 5 (2-4), 8(3-5) and 11(5-6). The post outage flows are shown by the arrows in figure 4.5.

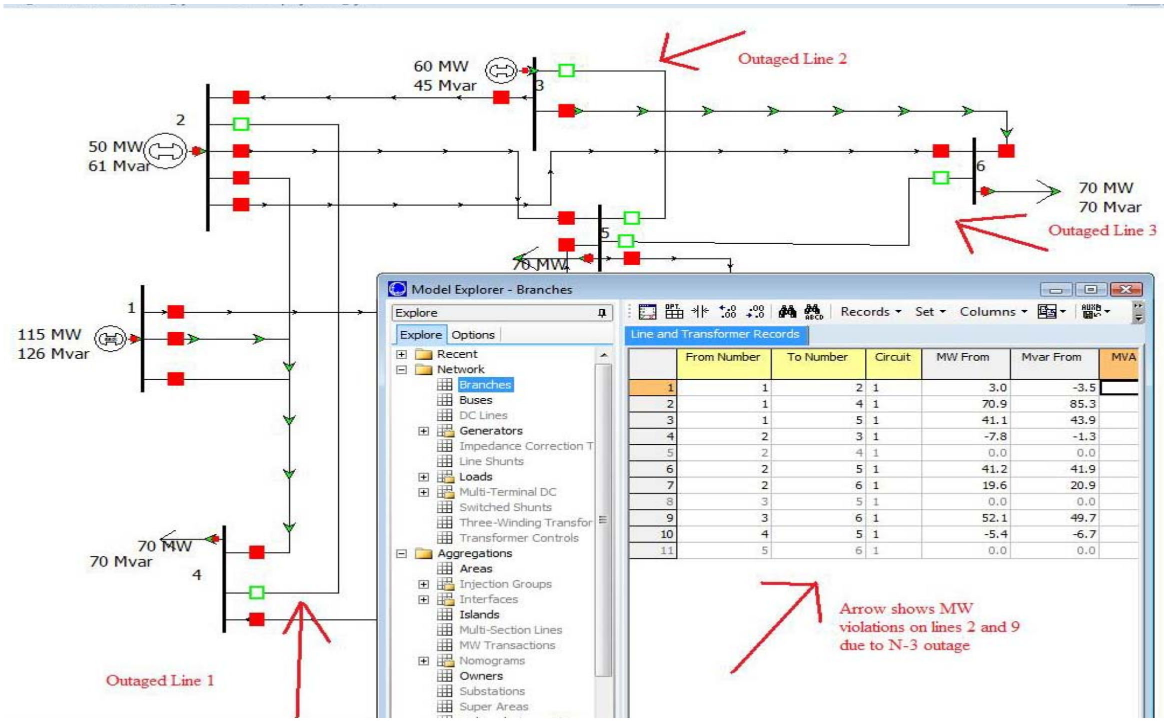


Figure 4.5 N-3 line contingency on 6 bus system showing line flow violations

We can see the outaged lines (pointed in arrows) and post outage with MVA violations in figure 4.5. The MATLAB code for this N-3 contingency has given the following buses as the most sensitive buses.

Table 4.2 Sensitive buses N-3 contingency on 6 bus system

Bus No.	Sensitivity
6	0.09440
2	0.06351
5	0.03777
3	0.01664
4	0.00913
1	0.00341

As shown in table 4.2 above the sensitive buses are buses 6, 2 and 5. By shedding the load at buses 6 and 5 and by decreasing the generation at bus number 2 the flows on the lines have been brought back to normal state. Hence the violations have been solved for the N-3 line contingency using the corrective actions based on developed MATLAB code. The sensitive buses on which action and corrected flow are shown in figure 4.6.

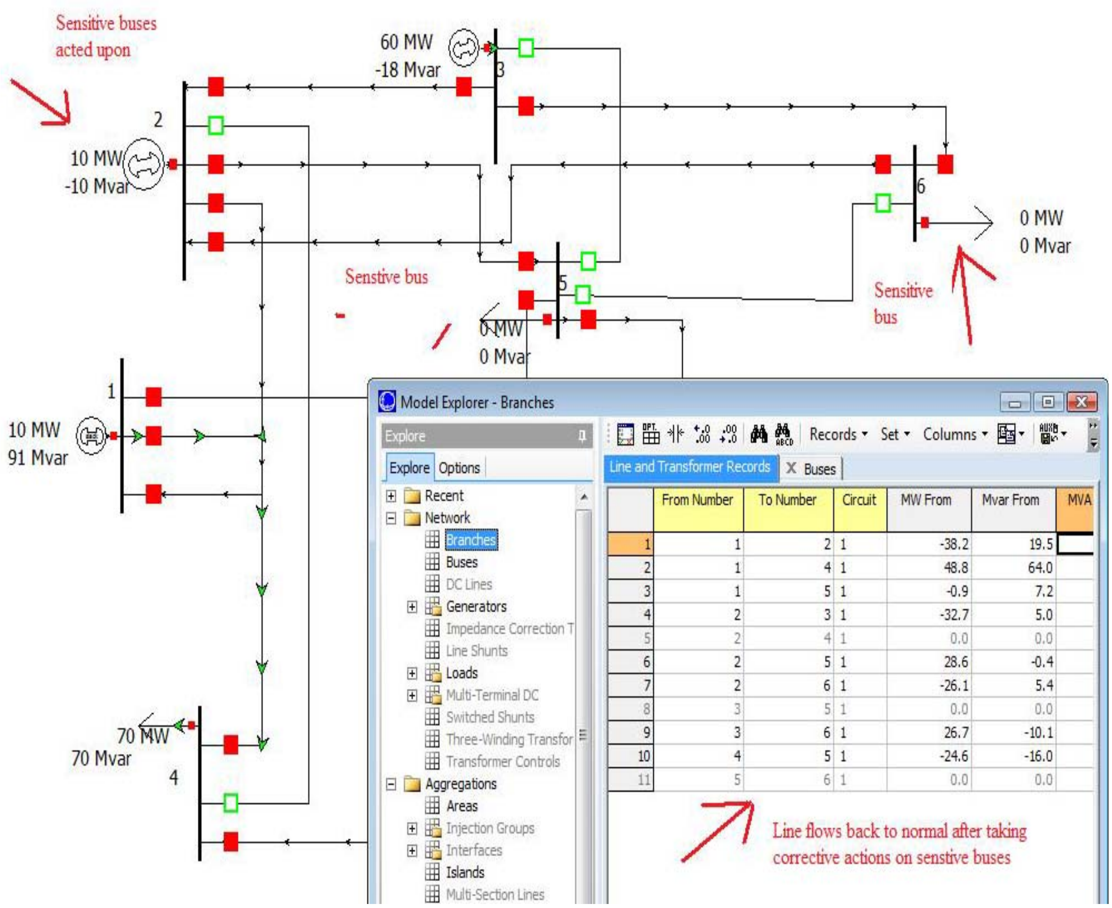


Figure 4.6 Corrective actions taken on sensitive buses.

4.4.3 N-2 line contingency on 37 bus systems

The lines outaged are lines 20 (15-54) and 22(15-54) which are the two of the three lines between buses 15 and 54. As a result the third line between the buses 15-54 gets over loaded. The one line diagram in figure 4.7 shows the post outage condition of the system.

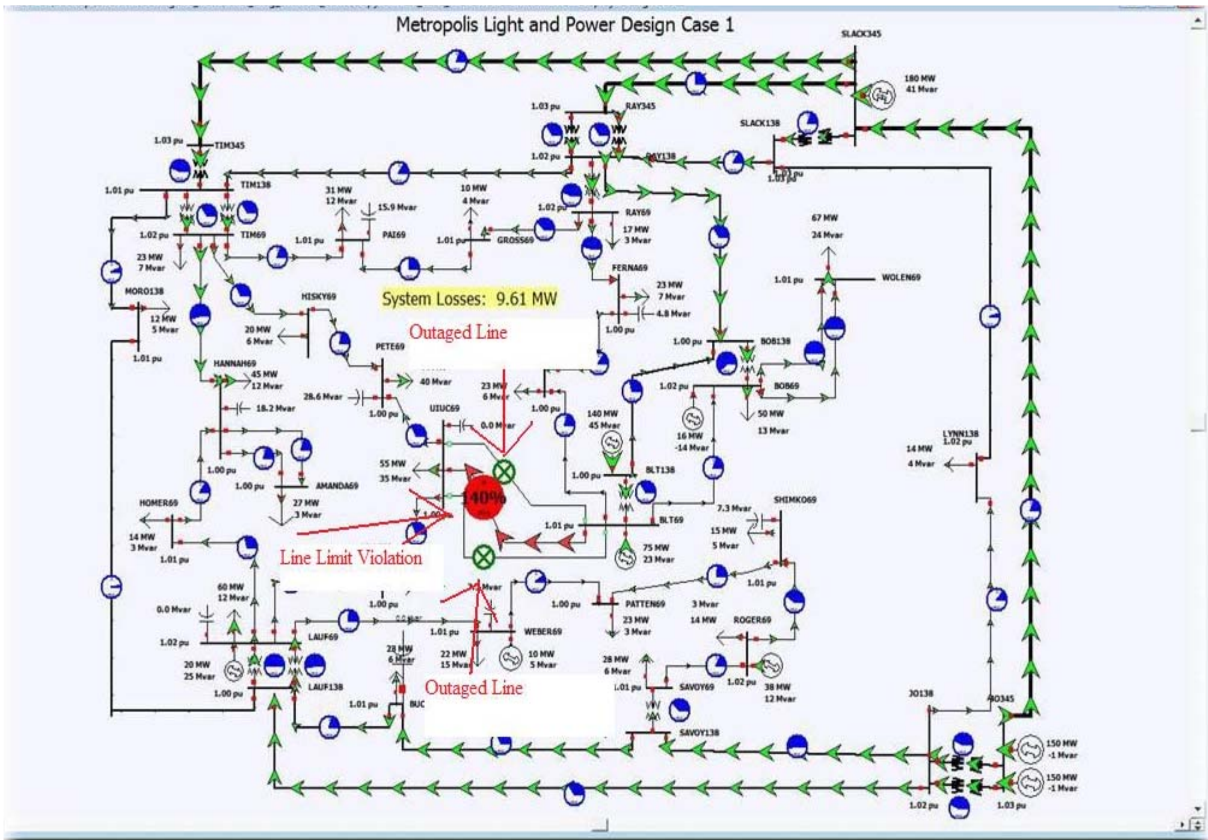


Figure 4.7 N-2 line violations on 37 bus system.

The sensitive buses for the above contingency given by the MATLAB code are given in table 4.3

Table 4.3 Sensitive buses N-2 contingency on 37 bus system

Bus No	Sensitivity
15	0.8700
54	0.8381
16	0.310 1
24	0.2681
47	0.2141

As seen from table 4.3 the top sensitive buses are 15, 54, 16, 24 and 47 of which most of them have loads on them hence the corrective actions could be shed the load as minimum as possible to remove these violations for this contingency.

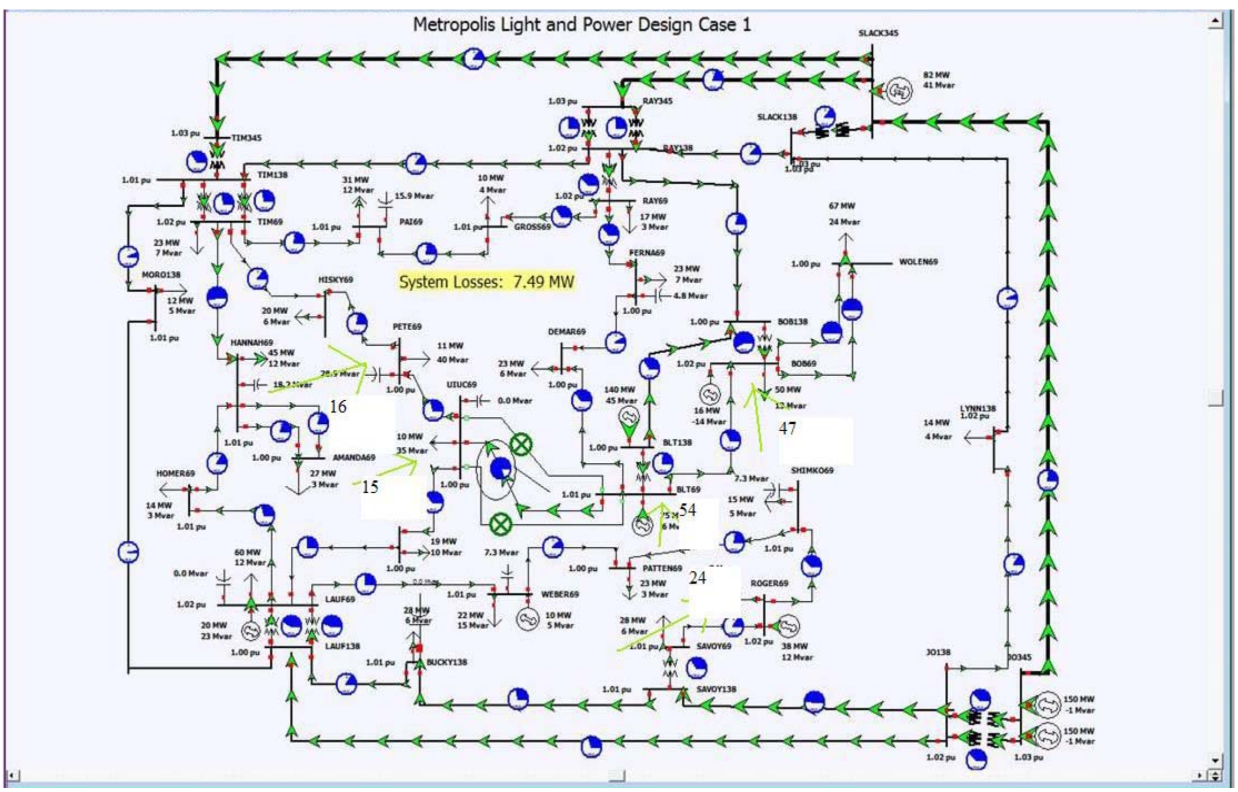


Figure 4.8 N-2 line violations solved after action taken on 37 bus system.

As shown by the arrows in figure 4.8, acting upon the sensitive buses given by the MATLAB code, (which are load buses mostly), helped remove the violations. One of the sensitive buses is bus number 54 which is a generator bus and hence the generation of amount 15 MW is re-routed from this generator bus to the load at bus number 16 such that the line is not overloaded, and hence it also helped in removing the violations. The bus number and the buses on which the actions have been taken are indicated in the figure4.8. This figure also shows the overloaded line coming back to its normal operating limits as a result of these actions taken. Thus the N-2 violations have been solved for 37 bus system using the corrective actions. Now let us look at the N-3 Line contingency on the 37 bus system.

4.4.4 N-3 line contingency on 37 bus system

The three lines that are outaged are 30(21-48), 43(33-32) and 50(39-47). As a result lines 31(21-48 ckt 2), 9(10-13), 51(41-44) are overloaded as shown by the arrows in figure 4.9. The outaged lines are also shown in the same figure 4.9.

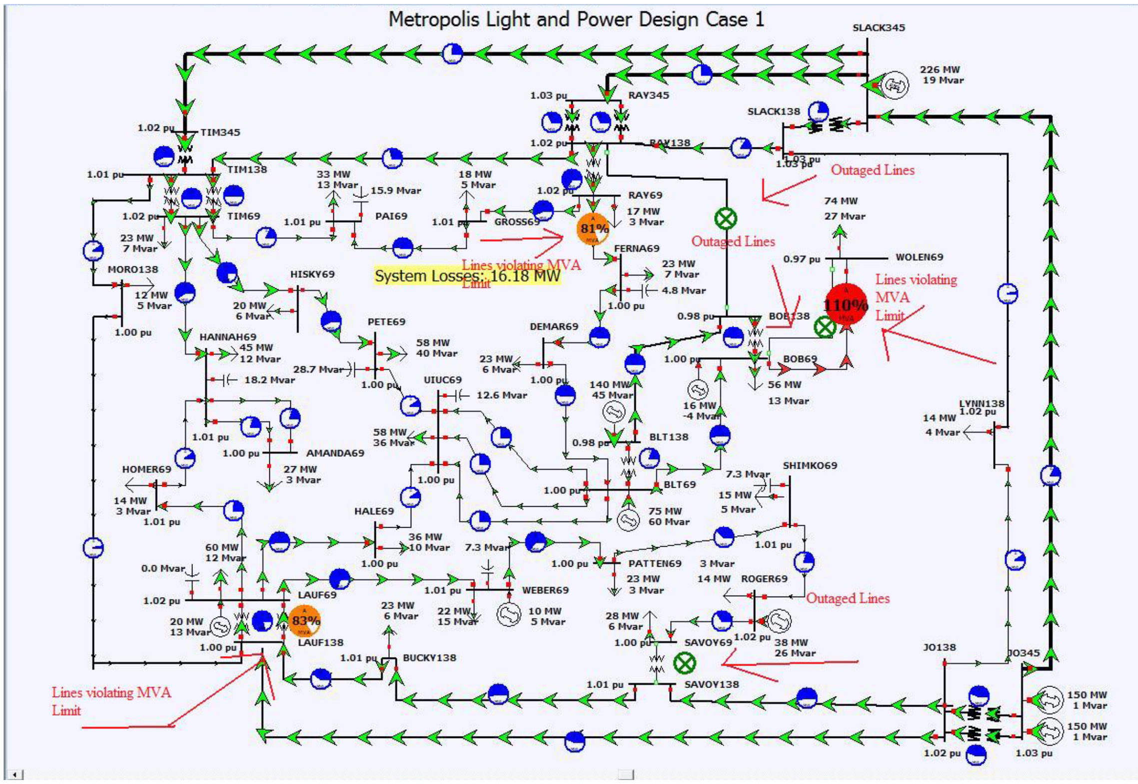


Figure 4.9 N-3 line violations on 37 bus system.

The MATLAB MLODF/MLOBSF code for this N-3 contingency gave the sensitive buses as shown in the table 4.4.

Table 4.4 Sensitive buses for N-3 contingency on 37 bus system

Bus No	Sensitivity
21	0.09278
16	0.07313
54	0.05973
44	0.05632
13	0.04779
48	0.04507
24	0.04288

As shown by MATLAB code bus 21 is the top sensitive bus. The load is shed at bus 21 from 75MW to 50 MW and all the three violations are solved. There also other ways to solve the violations but since 48 is only supplied only through the line 21-48 ckt 2, so there is no other alternative to solve this overloaded line violation except for shedding the load at the bus 48.

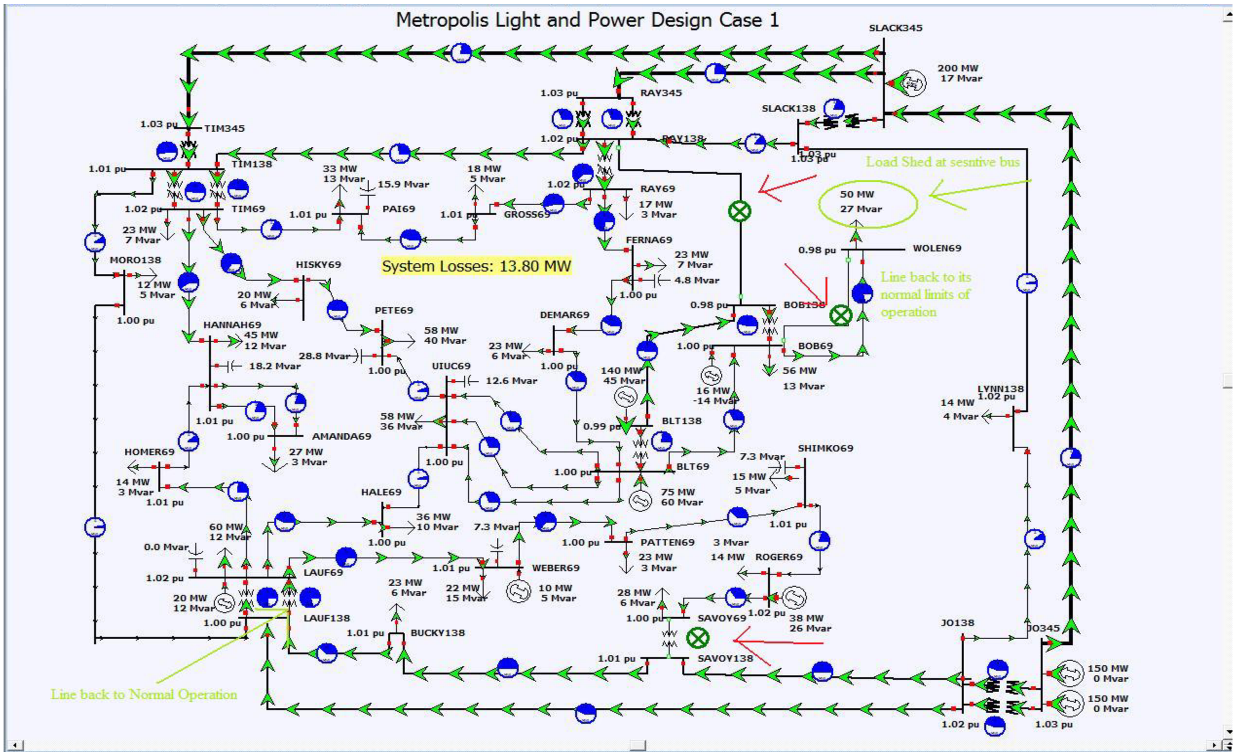


Figure 4.10 Actions taken on N-3 line contingency and solved violations on 37 bus system.

As seen from pointed arrows in the figure 4.10 the lines have come to normal operating limits as marked by arrows after taking suggested actions.

4.4.5 N-2 line contingency on the 137 bus utility system

The two lines which are outaged for the N-2 (line) contingency on the 137 bus utility system are

Line 13 (4-7 ckt 1) and line 14 (4-7 ckt 2). As a result the lines which crossed the MVA limits, are line 22(8-12) and line 23 (8-124) which are shown in table 4.6. The MLODF/MLOBSF algorithm gave the following buses as the top sensitive buses.

Table 4.5 Sensitive buses N-2 contingency on 137 bus system

Bus No.	Sensitivity
8	0.4015
6	0.4015
18	0.2560
19	0. 2560
14	0.1941
126	0.1574

After reducing the generation at the top most sensitive bus (8) and also shedding load at the top three sensitive buses(6,18,19) the MW on the lines have come back to within its operational limits. As seen in the table 4.6, the MVA limit of the lines are 120 MVA and all lines flows are within operating limits.

Table 4.6 Violated lines for N-2 contingency on 137 bus system.

Line No.	Base case Flow(MVA)	Post Outage(MVA)	After Action on sensitive buses
22 (8-12)	86.5	180.0	104.1
23 (8-124)	79.7	200.0	95.9

The procedure is also verified with the rule base book developed by the utility based on offline simulation. Rule base also mentions reducing generation at the bus 8 and shedding loads at buses 6, 18, 19, if this contingency happens.

4.4.6 N-3 line contingency on 137 bus utility system

The three lines which are outaged are 47 (19-70), 48 (19-74) and 49(19-118) and as a result the line 129 (79-126) is overloaded. The MLODF/MLOBSF algorithm for this contingency gave the following top sensitive buses as shown in table 4.7

Table 4.7 Sensitive buses N-3 line contingency on 137 bus system.

Bus No.	Sensitivity
76	0. 7612
20	0. 7446
81	0. 4392
79	0. 3925
21	0.3723
83	0.3525

After shedding the loads at the bus 76 and bus number 20 the MVA on the line has been reduced from 26.7 to 14.2, which is in limit for the line with rating of 30 MVA. In this case also the actions developed are in agreement with the ones which are suggested in the rule base book, developed by utility. The flows on the overloaded line at different stages are given in the below table 4.8.

Table 4.8 Violated lines for N-3 contingency on 137 bus system.

Line No .Name	Base Case Flow	Post Outage	After acting on sensitive
129 (79-126)	-13.6	-26.7	-14.2

MLODF/MLOBSF algorithm is implemented on all three different test cases for higher order contingencies, and corrective actions have been developed to remove the violations. Obtained results are also validated with offline simulation based rule base.

4.5 Summary

The sensitivity factors for single and multiple line outages have been derived in this chapter. The line outage distribution factor and multiple line outage distribution factors are based on DC power flow and are generally used for quicker calculations. The MLODF algorithm based on literature was further developed to obtain multiple line outage bus sensitive factors used for solving the MVA violations on the lines (in case of multiple lines contingency) in quick and effective way. The algorithms have been implemented on 6, 37 and 137 test case systems. The results obtained are used to develop corrective actions which in turn are useful in solving violations for higher order line contingencies.

4.6 References

[1] Allen J.Wood, Bruce F.Wollenburg, "Power Generation Operation and Control", 2nd edition, pp. 421-433. John Wiley and sons Inc.

[2] T. Guler, G. Gross, M. Liu, "Generalized Line Outage Distribution Factors", Power Systems, IEEE Trans. Vol. 22, Issue 2, May 2007 pp.879 – 881.

CHAPTER V

AC SENSITIVITY FOR MULTIPLE LINE OUTAGES AND SIMULATION RESULTS

5.1 Introduction

The previous chapter dealt with the line outage sensitivities pertaining to DC power flow. Although they are fast and efficient one thing they lack is providing information about the impact on the bus voltages due to these outages. Hence a method described as Multiple Line Outage Voltage Sensitivity (MLOVS) based on AC power flow was utilized to give the impact on the bus voltages due to multiple line outages in the system.

This chapter deals with developing the algorithm which provides the impact on bus voltages due to multiple line outages. The Single Line Outage Voltage Distribution Factor (LOVDF) is described and explained in [1]. Impact on the bus voltages in the system when a single line outage takes place in the power system network has been explained using LOVDF in [1]. This methodology is then further enhanced and extended to give the effect on the bus voltages due to multiple line outages in the system in this thesis. Hence this methodology is named as Multiple Line Outage Voltage Sensitivity (MLOVS). This algorithm is based on full AC power flow and hence gives information about the bus voltages during these outages. The next sections describe the MLOVS algorithm and its implementation on different test cases to derive top sensitive buses, and help in taking corrective actions to solve the violations.

5.2 Multiple Line Outage Voltage Sensitivity

Chapter 4 presented the Multiple Line Outage Distribution Factors (MLODF) based on DC power flow. These factors are effective, provide a good approximation of the system state and provide top sensitive buses to take action on. Since MLODF is based on DC power flow it cannot give any useful information for the low voltage violation, which is major concern and frequently occurring problem. Hence the MLOVS algorithm has been developed to predict the sensitive buses to eliminate these low voltage violations. Using the index obtained from the MLOVS algorithm sensitive buses can be predicted and actions can be taken on these buses to solve the low voltage problems.

The MLOVS is based on the AC power flow which is generally a full Newton Raphson Load Flow (NRLF) Method. Suppose there is a line *l* between buses *r* and *s* and it is outaged from the system. The impact on the voltage of bus *i*, characterized by LOVDF [1] of bus *i* can be then defined as

$$\left(LOVDF\right)_{i-l} = \frac{\Delta V_{i-l}}{P_{rs}^{o}} \quad \ldots\ldots\ldots\ldots\ldots (5.1)$$

Where, $\Delta V_{i-l} = V_{i-l} - V_{l}^{o}$

P_{rs}^{o} = Pre outage real power flow on line-*l*.

Equations (5.1) and (5.2) are given in reference [1] for single line outage. Based on these the further equations have been developed in this work to derive MLOVS. The MLOVS is also developed on the same basis as the normal LOVDF [1]. To take corrective actions, we are interested in top sensitive buses. Top sensitive buses are those where voltage changes most due to multiple line outages and these top sensitive buses are characterized by MLOVS. MLOVS is based on Full power flow Jacobian matrix. NRLF method utilizes the Jacobian matrix and its dimensions are dependent on the type of buses (slack, PV, PQ). Initially NRLF is run for the given test case system and the values of the voltages, P and Q are calculated after reaching the given tolerance value. Then the full Jacobian is calculated irrespective of the type of bus except for the slack bus in the system. Suppose there are N number of buses in the system then the size of the full Jacobian (J_{full}) would be (2N-2) X (2N-2). This full Jacobian is constructed by extending the already existing normal Jacobian for the NRLF. The post voltage values are then calculated by using the following formula,

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} S_T \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots (5.2)$$

Where,

$\Delta\delta$ are the change in phase angles of the buses except for the slack bus.

ΔV is the change in the bus voltages except for the slack bus.

S_T is the inverse of the Full Jacobian matrix.

ΔP is mismatch vector for real power for all buses except for slack bus.

ΔQ is mismatch vector for reactive power for all buses except for slack bus.

Given solved power flow, values of the mismatch vector should be zero (almost zero or near to specified tolerance value). To find the change in voltages, the entries in mismatch vectors would be calculated based on the bus numbers between which the lines are outaged.

Let us assume there are two lines *l* (between the buses *r* and s) and *m* (between buses *x* and *y*) which are outaged. After the outage, power flow Jacobian will change due to change in the topology of the system. But to re-calculate this Jacobian again is time consuming and especially at the time of contingencies it is very critical to do it as fast as possible. The method presented in [1] assumes fictitious generators at the buses of the lines which are outaged. These generators generate power opposite in magnitude to the power flowing from the bus such that the net power flowing on the lines will be zero to simulate the lines are outage. To get the voltage change for all the buses, there is need of extending the existing Jacobian to full Jacobian. Now the entries in the mismatch vector, assuming fictious generator at each bus of the outaged lines can be given as:

For line *l* outage, $\Delta P_r = P_{rs}^o$, $\Delta P_s = P_{sr}^o$, $\Delta Q_r = Q_{rs}^o$, $\Delta Q_s = Q_{sr}^o$

For line *m* outage, $\Delta P_x = P_{xy}^o$, $\Delta P_y = P_{yx}^o$, $\Delta Q_x = Q_{xy}^o$, $\Delta Q_y = Q_{yx}^o$

Thus the angle and voltage change vector can be calculated by substituting these values in the mismatch vector and using the formula, which is given below.

$$\begin{bmatrix} \Delta\delta_2 \\ \vdots \\ \Delta\delta_n \\ \Delta V_2 \\ \vdots \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} J_{1(N-1*N-1)} & J_{2(N-1*N-1)} \\ J_{3(N-1*N-1)} & J_{4(N-1*N-1)} \end{bmatrix} \begin{bmatrix} \Delta P_r \\ \Delta P_s \\ \Delta P_x \\ \Delta P_y \\ \Delta Q_r \\ \Delta Q_s \\ \Delta Q_x \\ \Delta Q_y \end{bmatrix} \ldots\ldots\ldots\ldots\ldots..(5.3)$$

Rest of the values of the mismatch vector will be taken as zero. Using the above formula we calculate the change in phase angles of the buses ($\Delta\delta$) and the change in the bus voltages (ΔV) for all the buses except the slack bus. Thus the change in the bus voltages for a given contingency can be calculated. Now using these changes in the phase angles of the buses MLOVS for all the buses can be calculated. The MLOVS for bus *i* can be given as

$$(MLOVS)_{i-l,m} = \Delta V_{i-l,m} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(5.4)$$

Where,

'i' is any bus

'l', 'm' are two lines outaged in the system

Thus the MLOVS gives an estimation of the impact on the bus *i* when multiple lines are outaged from the system following similar approach based on the above equation magnitude.

The buses with top rank (with higher sensitivities) are the buses, where actions need to be taken, such as switching the capacitor, shedding the load or generation change. The number of top buses to be taken may vary, for smaller systems such as 37 bus system the top five buses may be enough to take possible corrective actions, where as for bigger systems the number of top ranked buses may increase up to 15 buses.

The algorithm for finding out the list of sensitive buses for multiple line outages based on the MLOVS can be summarized as follows:

5.2.1 Algorithm for MLOVS

1. Input the branch data and bus data for the test case.

2. Calculate the number of buses and number of branches from the data also the type of the buses (PQ or PV).

3. Set all the voltages at all the buses to 1pu (un-less given) and all the angles at the buses to zero degree.

4. Calculate the admittance matrix ‘Y’ from the branch data, real and reactive power injections at each bus from bus data.

5. Set the tolerance, calculate the initial mismatch vectors and set error as maximum of absolute value of mismatch.

6. Calculate the Jacobian matrix based on the number of PQ buses and then repeat the process until the desired tolerance is met.

7. Calculate the power flows on the lines using the updated voltage and phase angles.

8. Construct a full Jacobian by extending the already obtained Jacobian to all the buses except for the slack bus and find its inverse and name is as S_T.

9. Get the outaged lines and their "from" and "to" buses.

10. Use the formulation given by equation (5.3) for the entries of mismatch vector to set up the mismatch vector.

11. Calculate the changed phase angles and bus voltages for the contingency using the equation 5.2

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} S_T \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

12. Calculate the MLOVS for bus i using the equation 5.4

$$(MLOVS)_{i-l,m} = \Delta V_{i-l,m}$$

13. Find out the top most sensitive buses.

    Note: Steps 1 to 7 are used to solve the AC power flow on the system from reference [1].

5.2.2 Flow chart for MLOVS

The flow chart for the algorithm is given in figure 5.1

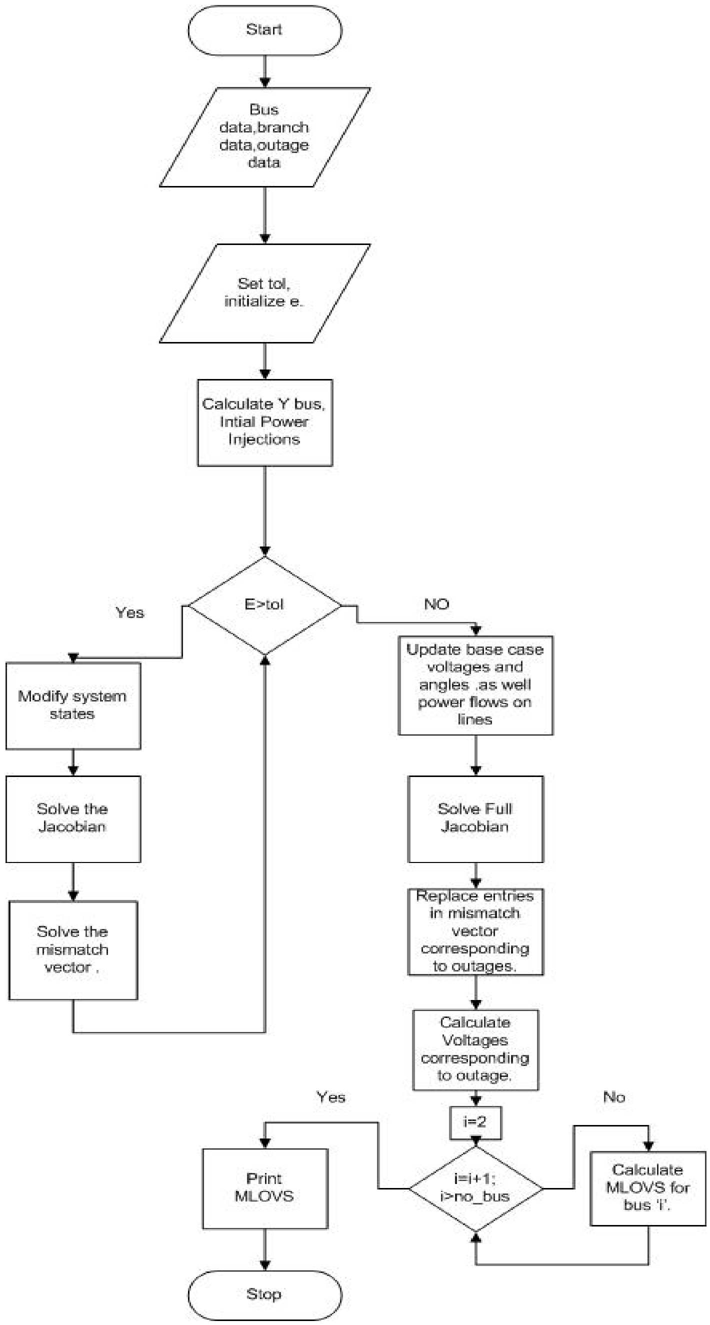


Figure 5.1 Flowchart for MLOVS

Thus using the above algorithm the MLOVS is calculated which is helpful in solving the low voltage violations due to higher order line contingencies.

5.3 Implementation on test cases

This section deals with implementing the MLOVS algorithm for N-2 and N-3 line contingencies on the test cases and the impact on the bus voltages are observed in the given results. The three test cases used are 6 bus system, 37 and 137 bus test case systems. The details of these test cases are given in appendix.

5.3.1 N-2 line contingency on six bus system

The two lines that are outaged are lines 4(2-3) and line 5 (2-4). As a result there is low voltage on bus number 4. The outaged lines and the low voltage on bus 4 can be seen in figure 5.2. As seen in figure 5.2 the voltage on bus number 4 is reduced to 0.8434p.u. The MATLAB MLOVS algorithm for this contingency gave the following buses as the most sensitive buses.

Table 5.1 Sensitive buses for N-2 Line Contingency on 6 bus system.

Bus no	sensitivity
2	0.0046
3	0.0032
4	0.0126
5	0.0054
6	0.0044

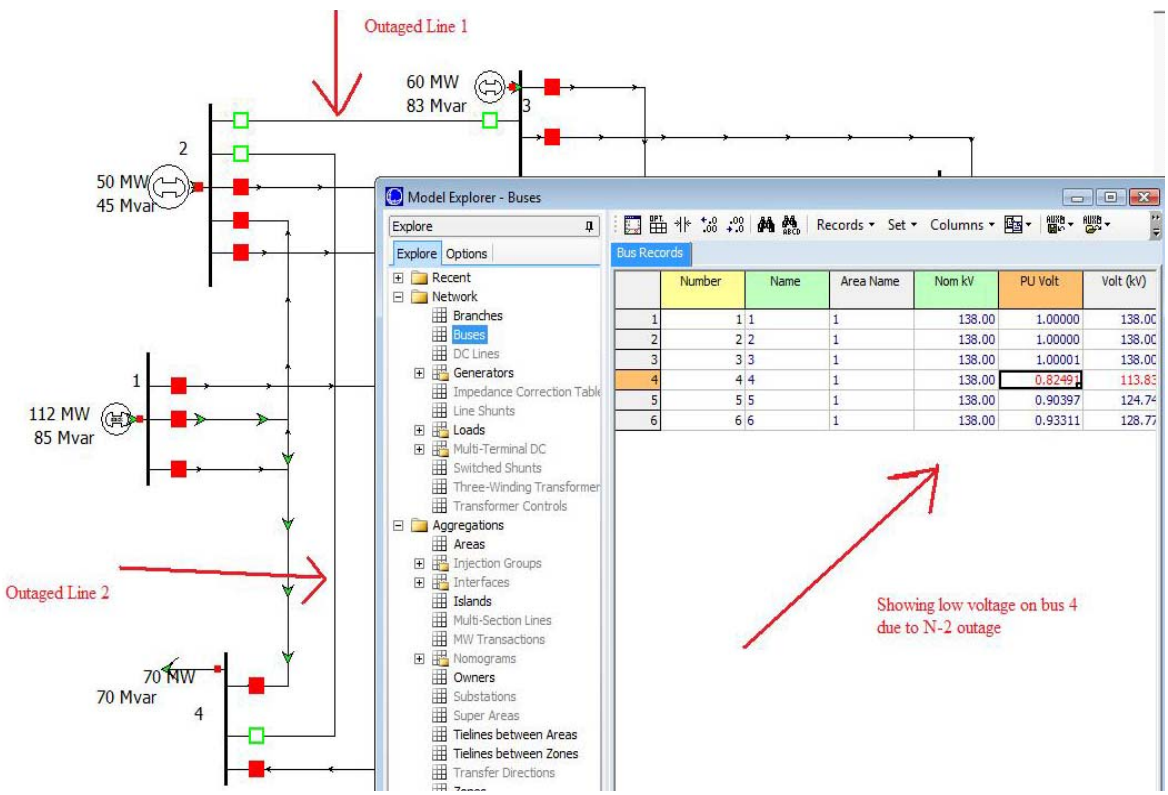


Figure 5.2 N-2 line outage on 6 bus system showing voltage violations.

As seen in table 5.1 the Algorithm gave bus number 4 as sensitive bus and when a capacitor (42.5Mvar) is installed at bus 4 the low voltage violation (from **0.8428 p.u** to **0.9217 p.u**)is removed as seen in the figure 5.3.

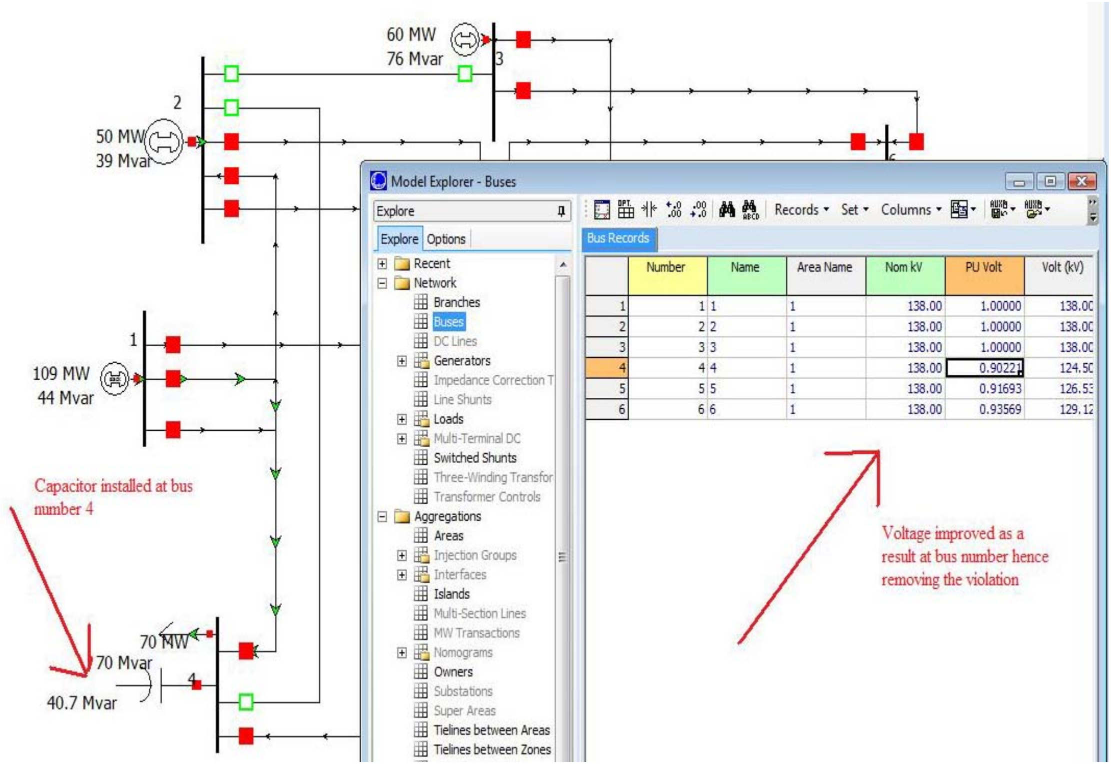


Figure 5.3 N-2 line outage solving violations using capacitor.

5.3.2 N-3 line contingency on 6 bus system

The three lines outaged for the N-3 contingency are shown in table 5.2

Table 5.2 Lines which are outaged on 6 bus system

Line No.	From	To
5	2	4
8	3	5
11	5	6

The diagram for the three lines outage is shown in figure 5.4

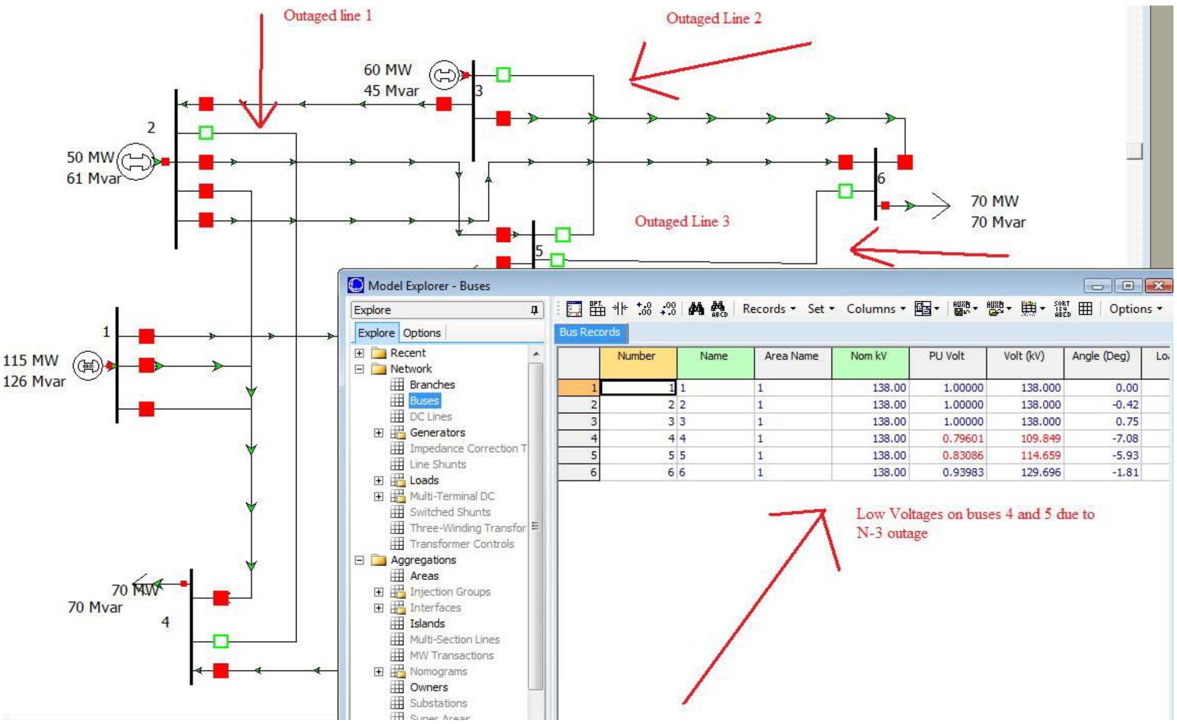


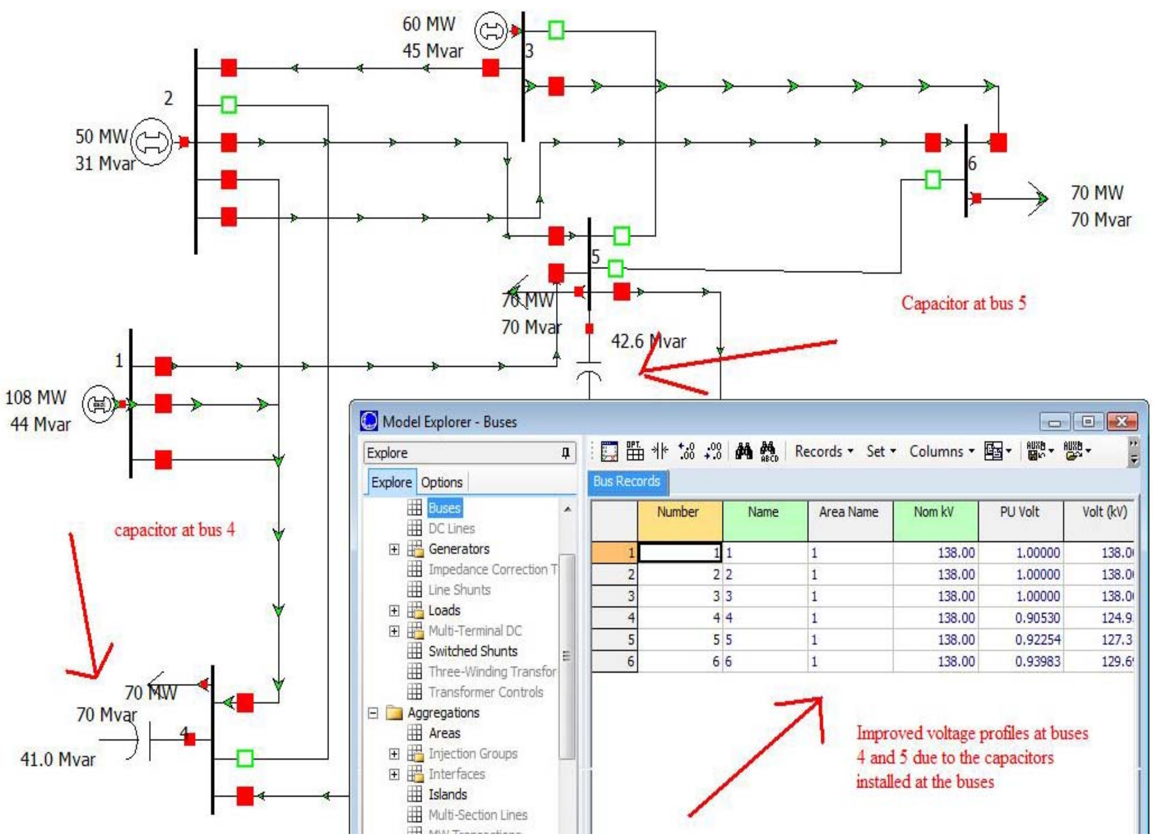
Figure 5.4 N-3 line outage and low voltages on buses.

The MLOVS algorithm gave the buses shown in table 5.3 as the most sensitive buses for these contingencies.

Table 5.3 Sensitive buses for N-3 line contingency

Bus No	Sensitivities
2	0.0061
3	0.0073
4	0.0102
5	0.0110
6	0.0070

As seen buses 4 and 5 are the top most sensitive buses, hence by placing a shunt capacitors of 40MVar each the low voltage are solved, the installation of 40MVar capacitors at buses 4 and 5 can be seen in the figure 5.5.



	Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)
1	1	1	1	138.00	1.00000	138.0
2	2	2	1	138.00	1.00000	138.0
3	3	3	1	138.00	1.00000	138.0
4	4	4	1	138.00	0.90530	124.9
5	5	5	1	138.00	0.92254	127.3
6	6	6	1	138.00	0.93983	129.6

Figure 5.5 N-3 Line outage solving violations using capacitors at buses 4 and 5.

As seen in figure 5.6, one more scenario when a capacitor is installed at bus number 4 of value 140MVar solves the violation as shown in figure 5.6. Thus MLOVS solves low voltage violations for N-2 and N-3 line contingencies.

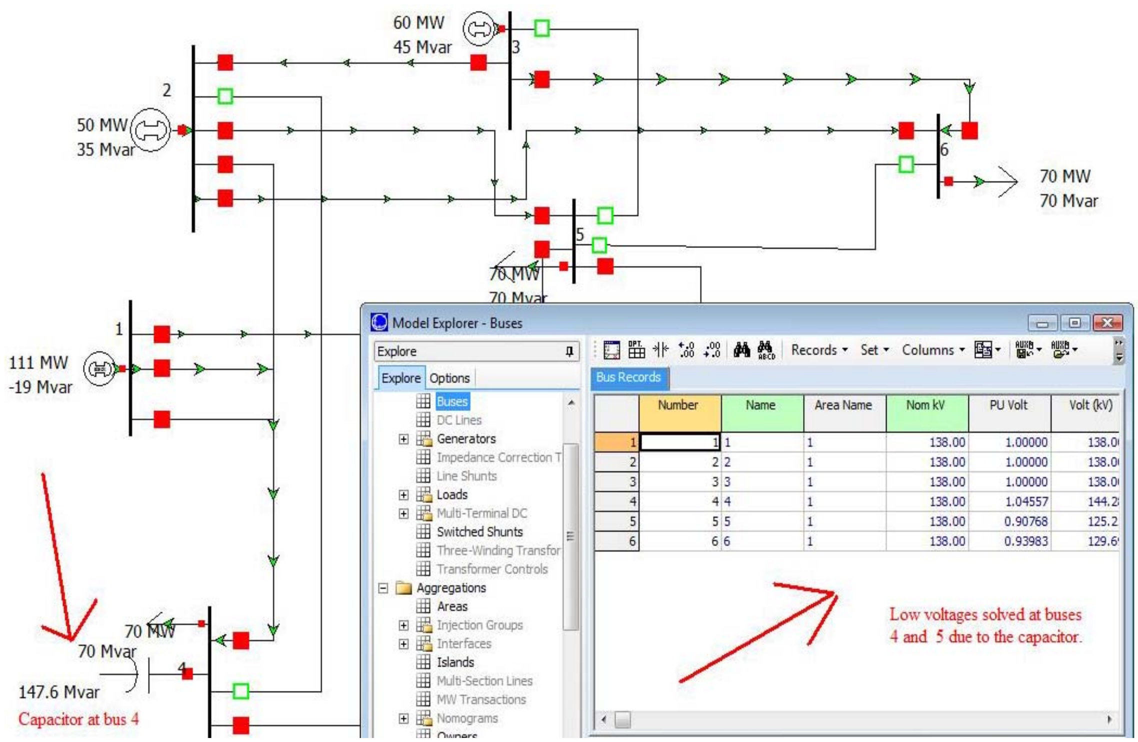


Figure 5.6 N-3 line outage solving violations using capacitor at bus 4

5.3.3 N-2 line contingency on 37 bus system

The two lines outaged are the lines 36 (32-29) and line 40(41-30) and as a result the low voltages are on the buses 30, 32 and 33. The outaged lines and as a result the low voltages on the buses can be given shown in figure 5.7

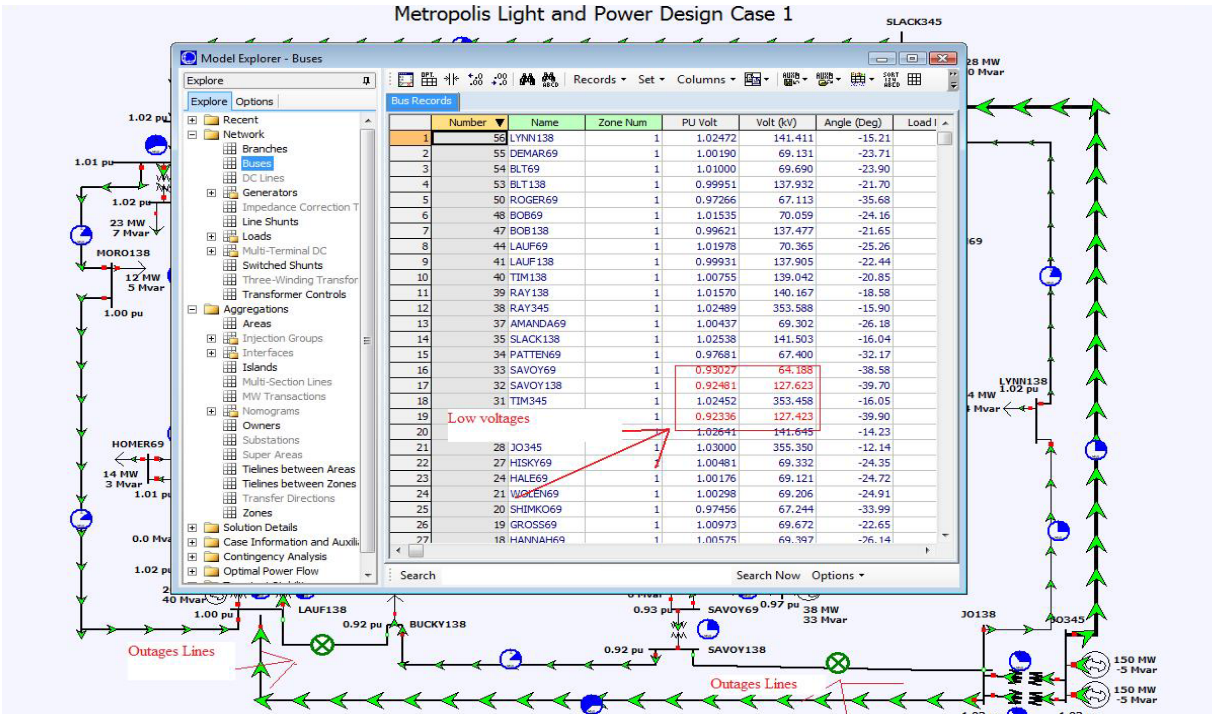


Figure 5.7 N-2 line outage violations

The sensitive buses given by MLOVS algorithm for this contingency are shown in table 5.4.

Table 5.4 Sensitive buses for N-2 line outage for 37 bus system

Bus No.	Sensitivity
31	0.7453
32	0.6433
29	0.4920
40	0.3957
28	0.2200

There are couple of ways to solve the violations by using the top most sensitive buses, one of the ways would be take the second most sensitive bus (bus number 32) and shed the load on it from 28 MW to 10 MW and hence all the violations are solved. The post outage voltages of the three buses and the voltage after the actions have been taken can be given in the table 5.5, and also the figure 5.8 shows the same.

Table 5.5 Voltages on limit violated buses for N-2 line outage

Bus No	Post Outage Voltage	Voltage After Taking
30	0.93027	0.97615
32	0.92482	0.97752
33	0.92336	0.98263

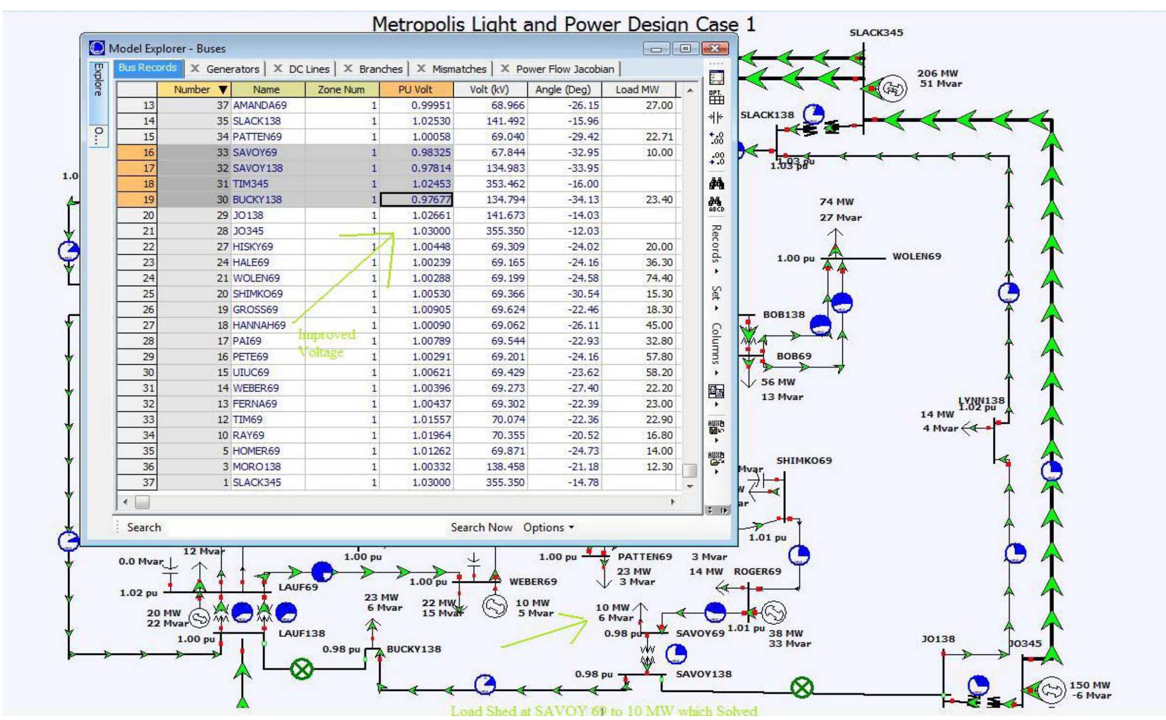


Figure 5.8 N-2 line outage violations solved by taking actions on the system

Thus N-2 line contingency low voltages violations are solved by taking actions based on the MLOVS algorithm.

5.3.4 N-3 line contingency for 37 bus system

Table 5.6 Three lines outaged in 37 bus system

Line No	From	To
7	5	18
37	32	29
41	30	41

As result once again the three buses which have the low voltages are buses 30, 32, 33. The MATLAB MLOVS gives sensitive buses for this contingency are given in table 5.7.

Table 5.7 Sensitive buses for N-3 line contingency on 37 bus system

Bus No.	Sensitivity
31	0..6598
32	0.5694
29	0.4361
40	0.3503
28	0.1946
30	0.1551

The two ways in which this contingency can be solved by using the sensitive buses are

1. Taking top sensitive bus (number 31) which has capacitor and the capacitance is increased from 7.2 to 20 and hence the 3 violations are solved (shown in fig 5.9).

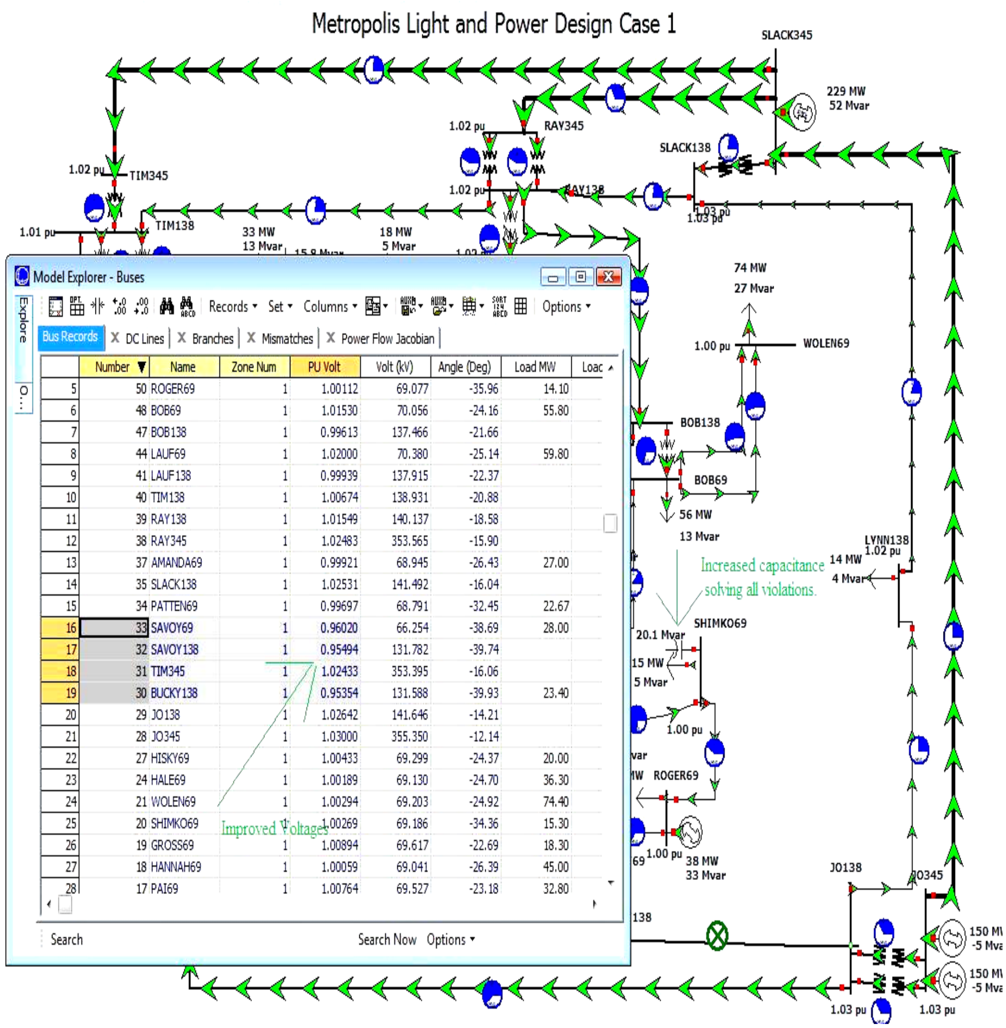


Figure 5.9 N-3 line outage violations solved by taking actions on the system

As shown in the figure 5.9 after increasing the capacitance at bus number 31 low voltage violations are solved.

2. The second way of solving this violation is to shed the load at bus number 20 and hence the violations are solved. This can be shown in the figure 5.10

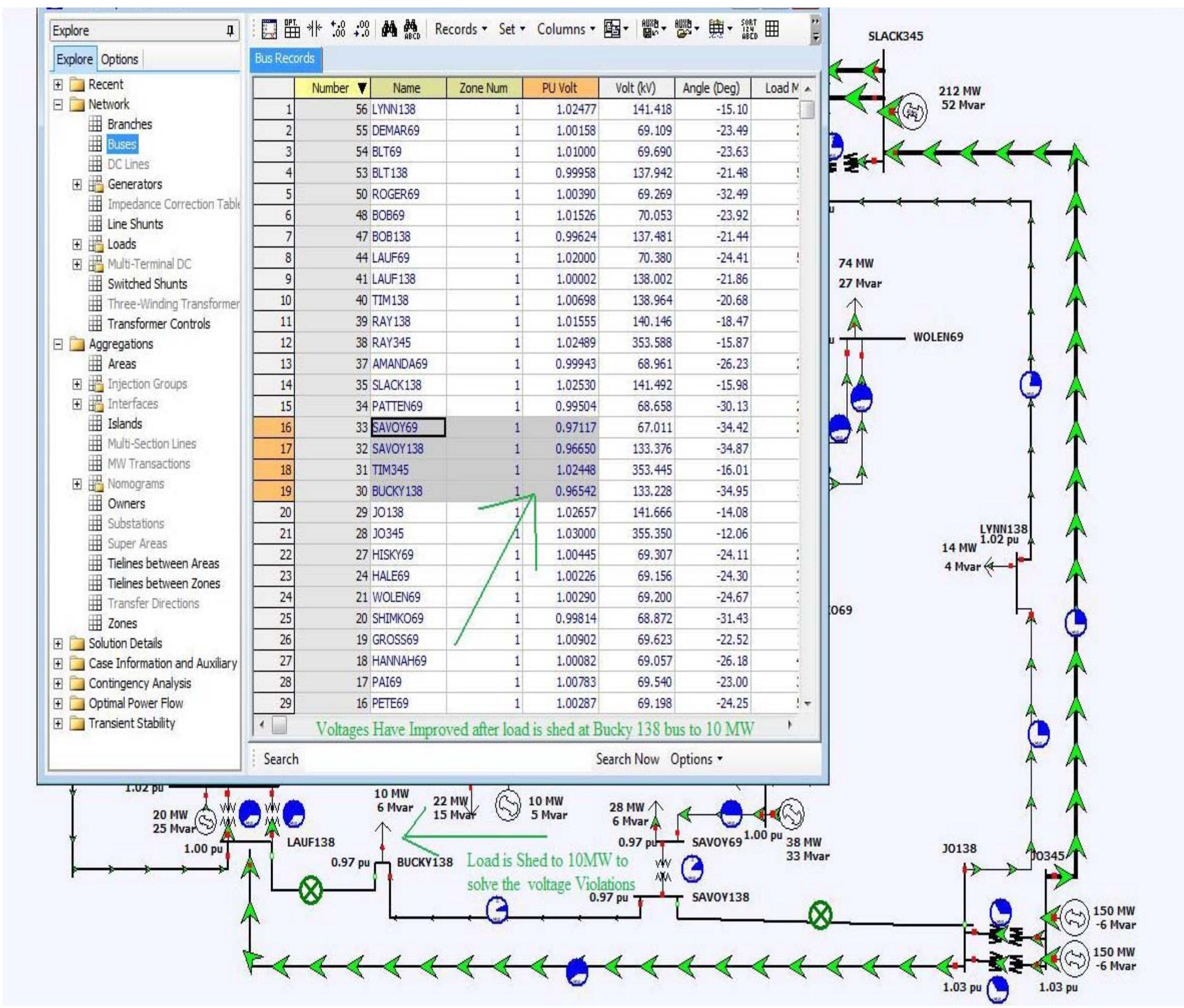


Figure 5.10 N-3 line outage violations solved by taking actions on the system

Thus the low voltage violations for N-3 contingency on the 37 bus system are solved by taking the actions based on the MLOVS algorithm.

5.3.5 N-2 line contingency on 137 bus utility system

The two lines outaged are two transformers: 3-4 (ckt 1 and ckt 2). As a result the low voltages are on many buses since these transformers are very critical. The MLOVS gives sensitive buses for this contingency as shown in table 5.8. Now actions are needed on these buses, some of which have capacitance and some of which have load attached to them. By switching on the capacitances of the capacitor buses and then shedding the load optimally for the other buses the low voltage violations are solved, this can be shown in the table 5.9 in which the post outage voltages as well the voltages of the buses after the actions are taken on the sensitive buses are given.

Table 5.8 Sensitive buses for N-2 line contingency on 137 bus system

Bus No	Sensitivity
34	0.0426
3	0.0422
33	0.0394
112	0.0370
40	0.0338
36	0.0257
66	0.0256
65	0.0246
35	0.0170
32	0.0152
23	0.0152
130	0.0146
129	0.0128
22	0.0120
2	0.0109
1	0.0109
95	0.0108
57	0.0108
94	0.0096

Table 5.9 Low voltage buses for N-2 Line contingency on 137 bus system

Bus No	Post	Voltage
23	0.8864	1.0248
24	0.8508	1.0234
25	0.8508	0.9654
28	0.934	0.9757
33	0.8223	1.0255
34	0.7953	1.0288
35	0.793	1.0254
36	0.8442	1.0253
37	0.8392	1.0255
38	0.91	0.96
41	0.801	1.0277
51	0.9485	0.9752
52	0.9401	0.9689
56	0.9289	0.9806
57	0.9217	0.9661
64	0.9067	0.971
65	0.9276	0.9812
95	0.9041	0.9545
96	0.8581	0.9998
97	0.9038	0.9542
99	0.9285	0.9803
102	0.9277	0.9697
104	0.8865	0.9546
107	0.9313	0.9671
108	0.9277	0.9637
129	0.8824	0.951
131	0.8608	1.022
134	0.9377	0.9755
135	0.9353	0.9733

As seen from the table 5.9, low voltages have improved considerably after taking actions on the sensitive buses specified by the MLOVS code. Some of the contingencies both the actions (capacitor switching as well as load shedding) have been done to improve the voltage profile.

5.3.6 N-3 contingency on 137 bus utility system

The three lines outaged are line 162- (78-121), line120 (78-72), line 28(78-10). The affected buses and their post outage voltages after taking actions are given in table 5.11. Table 5.10 gives the top sensitive buses calculated by MLOVS code.

Table 5.10 Sensitive buses for N-3 line contingency on 137 bus system

Bus No	Sensitivity
72	0.0470
75	0.0380
10	0.0377
92	0.0372

It is assumed that no capacitor is switched on at any buses before the lines are outaged for N-2 case, where as for this case some capacitors are assumed switched on in base case. We have less number of buses with low voltages in this case. This particular case is specifically chosen from the rule base given by the utility to validate the MLOVS algorithm and actions taken on the buses. Actions based on the MLOVS algorithm match the actions suggested by the rule base book in case of this contingency. The voltages of the buses in different scenarios for this contingency are given in table 5.11.

Table 5.11 Low voltage buses for N-2 Line contingency on 137 bus system

Bus No	Post Outage	After switching
10	0.9470	0.9603
72	0.9456	0.9900
78	0.9490	0.9944
32	0.9402	0.9611

Thus the action taken based on the MLOVS algorithm agrees with rules suggested by the rule base book to solve this violation.

5.4 Summary

The MLOVS algorithm is very useful especially when finding the impact on the bus voltages during a multiple line outage in the system. The algorithm utilizes full AC power flow and hence gives detailed information about the bus voltages. The algorithm is derived in this chapter and the flow charts are also explained. This algorithm is implemented on 6,37 and 137 bus test case systems and the results are used to develop the corrective actions and to remove the violations caused due to these higher order line contingencies.

5.5 References

[1]. Ashwini Kumar, "Available Transfer Capability and Congestion Determination", Doctoral dissertation, pp. 70-75, 2003, Indian Institute of Techonolgy, Kanpur, Advisor: Dr.S.C.Srivastava, Dr.S.N.Singh.

CHAPTER VI

DC SENSITIVITY FOR GENERATOR OUTAGES AND SIMULATION RESULTS

6.1 Introduction

This chapter deals with the impact on the power system network when a single /multiple generator outage(s) take place in the system. The Generator Outage Distribution Factor (GODF) is the index based on the DC power flow which will be helpful in determining the impact on the power system network when the generators in the system are outaged. The theory behind the (GODF), the formulation for the single Generator Outage Distribution Factor or normally called as Generator Shift Factor (GSF) and finally the need for the Multiple Generator Outage Distribution Factor (MGODF) and its formulation are explained in this chapter in detail.

Linear sensitivity factors generally make it easy to study these outages which are otherwise are very complex equations and difficult to solve [1]. The Generator Outage Distribution Factor (GODF) is the one of the sensitive factor which helps in determining the impact on lines when power injected from a bus changes. This change in power may be due to different factors such as outage of generator or change in generation. GODF can be a very valuable tool to evaluate the impact and to take necessary actions. A look at the literature over the years indicates that there hasn't been much work focused on the

GODF and their usefulness towards the power system monitoring and control with multiple outages. Reference [1] defines the GODF, the formulation to calculate the single impact (such as single generator outage), and how to use this factor during the contingency analysis.

The Generator Outage Distribution Factor can also be used to detect the island formation and also in identifying the causal factors (the factors which cause it) which when multiple line outages take place in the system. Authors in [3] explain how GODF combined with other sensitive factors can be used to determine the topology of the system such that islands can be formed in the system. This is also an important step towards dealing with extreme higher order contingencies since the argument of islanding the system during the extreme higher order contingencies will help prevent the cascading and hence may prevent black-out.

6.2 Generator Outage Distribution Factor

The research done for finding out the Generator Outage Distribution Factor (GODF) has been divided into two phases. One phase is finding out the GODF from the PowerWorld software which has the in-built GODF software tool and for single as well as multiple generation outages and use them to form a rule base and the second phase consists of formulating the process of finding out the GODF using the MATLAB software for the same 37 bus system . Work has also been done for finding out the GODF for the multiple generator outages. The final phase is to compare the results from the MATLAB and PowerWorld and validate the algorithm developed such that it can be implemented on any test case system.

The first phase for determining the Generator Outage Distribution Factor for the 37 bus system is explained below.

The 37 bus system is shown in figure 6.1 and it has 9 generators supplying the loads. The system has 45 transmission lines, 769.5 MW of real power load, 277.2MVAR of reactive load, 778.9 MW of real power generation and 117.5 MVAR of reactive generation. The injection or change in injection at any bus due to a generator outage is calculated by using the GODF. As seen from figure 6.2 the GODF is calculated by selecting generator outage and then calculating the impact on the transmission lines. The impact is then attributed to buses in the system and then buses are ranked based on their magnitude of impact.

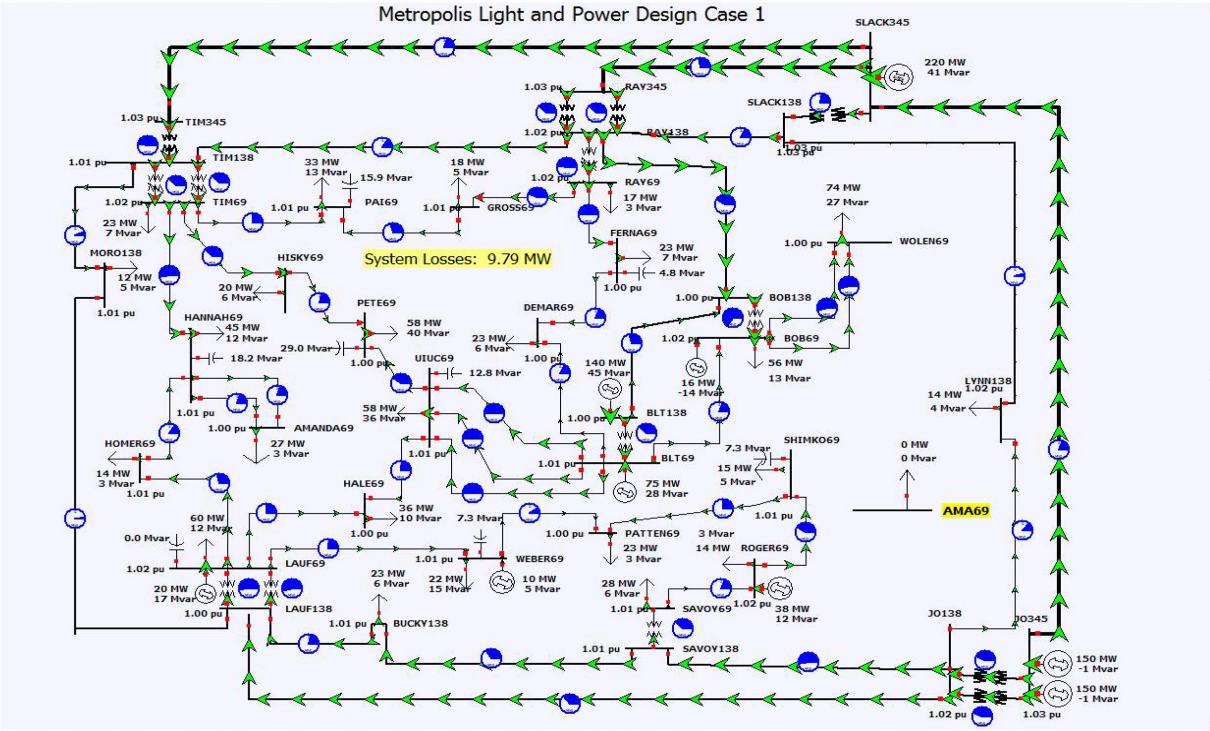


Figure 6.1 37 bus test case system.

6.2.1 *GODF in PowerWorld*

Figure 6.2 shows how GODF can be calculated in PowerWorld software. The user has the option of choosing the lines for which the GODF needs to be calculated. The GODF as explained earlier will calculate the effect of each generator outage in the system on the transmission lines. In the figure 6.2 the GODF for line between buses 1(TIM 345) and 31(SLACK 345) are calculated for all single generator outage, where the slack bus is the bus number 31. Table 6.1 in figure 6.2 shows all the list of generators in the system and their respective impact (when outaged) on the line between buses 1(TIM 345) and 31(SLACK 345).

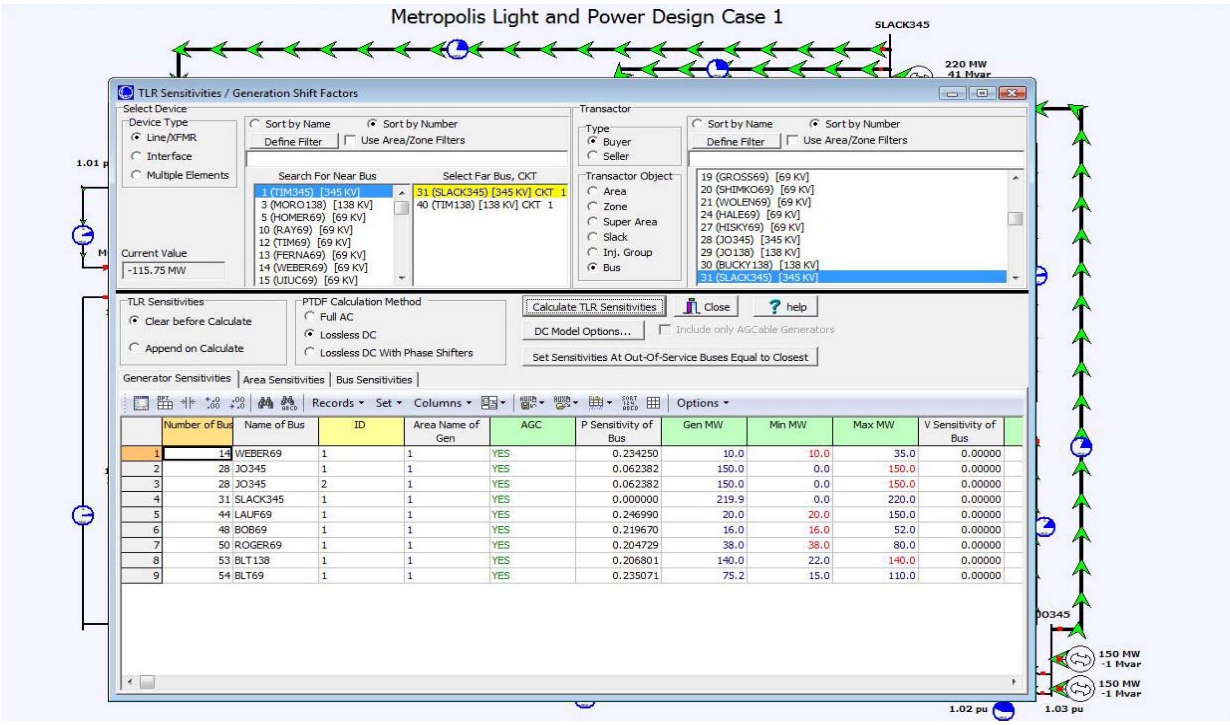


Figure 6.2 Calculation of GODF in PowerWorld

These GODF's will help the user to determine which lines are being most affected by the generator's outage and hence actions can be taken appropriately.

6.2.2 Formulation for GODF

In this section formulation for GODF algorithm have been presented. MATLAB software is used to implement the algorithm. The DC power flow and approximation is used for calculating these factors. Equations from (6.1) to (6.4) have been developed in reference [1] for single generator outage. Based on these equations algorithm, MGODF has been developed in this work which is explained in section 6.3.

The Generator Outage Distribution Factor is denoted by $a_{l\,i}$, and it is defined as

$$a_{li} = \frac{\Delta f_l}{\Delta P_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6.1)$$

Where

l = index of the line for which monitoring is done,

i = index of the generator bus in the system,

$\Delta f_l =$ Change in power (MW) on line l when a generator outage occurs at bus i.

$\Delta P_i =$ Change in MW generation at bus i.

The slack bus which is also known as the reference bus is always assumed to supply/absorb necessary power needed when a generator is outaged in the system. The change in generation is thus always compensated by the slack bus which in this case is ΔP_i.

Thus $a_{l\,i}$ can be defined as the change in the sensitivity of power flow on line l to change in generation at bus i. In practical terms the lost generation will always be picked up by all the generators in the system as there is no real slack bus generator. When we derive the expressions for the GODF, we assume that the slack bus takes up the change in generation due to loss of a generator in the system. We first consider the above case and then extend it to the case when the rest of the generators also contribute in taking up the generation in the system.

If the generator is generating P_i^o MW and if it is outaged, then the change in generation taken up by the slack bus can be given as ΔP_i. This will have impact on change of power flow on all the lines of the transmission lines in the system, which can be given in terms of the GODF a_{li}. Therefore for a transmission line l the power flowing on it when the generator at bus i is lost can be given as

$$\hat{f}_l = f_l^o + a_{li}\Delta P_i \quad \text{For l=1.....No. of lines in the system.}$$

Where,

$\hat{f}_l$ = post power flow on line l after the generator at the bus i is outaged.

f_l^o = power flowing on the line l before the outage of the generator at bus i.

Using these sensitive factors the post outage flow on a line can be calculated without the generator actually being outaged from the system. This helps in planning of the system and also identifying most sensitive lines as well as buses in the system which need to be strengthened, so that system can remain to operate in its normal conditions during any contingency. This also helps in contingency screening and to determine which lines are being overloaded when a particular generator goes out in the system and thus further actions can be planned in order to supply the load in different ways possible without overloading the line.

In the above scenario we assumed that the loss of generation due to a generator outage will be taken up by the slack bus but in reality the generation loss would be picked up by all the generators in the system. Since the generators are independent of each other the effect of simultaneous changes in the generators can be calculated using the super position principle. Thus several generating buses would participate in picking up the generation lost at the bus *i*. Generally the remaining generators in the system would pick up the generation in proportion to their maximum generation. Proportion of generation pick up at bus j due to loss of generation at bus i can be given as

$$\gamma_{ji} = \frac{P_j^{\max}}{\sum\limits_{\substack{k \\ k \neq i}} P_k^{\max}}$$

Where

$P_k^{\max}$ = maximum available MW rating for generator k

γ_{ji} = the factor with which the generator at k picks up generator when a generator at i is outaged.

The derivation of the formula for calculating the Generator Outage Distribution Factor given in reference [1] is explained below. The GODF is calculated based on the DC power flow on the system. The DC model gives us the advantage that apart from being fast in its calculations due to its linear nature, it also gives a good approximate of the system and its status. Thus the DC model of the system as mentioned earlier can be written as

$$\Delta\theta = [X]\Delta P \quad \text{………………….. (6.2)} \quad [1]$$

Where

$\Delta\theta$ = Change in set of bus phase angle due to change in power injections

X = Reactance Matrix formed by inverse of the transmission line reactance's

ΔP = Change in set of power injections or perturbations.

As we assumed earlier the swing bus takes up the necessary power to supply the circuit, hence the sum of power injections at the swing bus is equal to the sum of the power injections at all other buses in the system.

Thus to calculate the GODF at bus i we assume that change in power injection at bus i is equal to +1 and the corresponding compensating swing bus power injection as -1. This indirectly represents that a pu increase in power at bus i is compensated by a pu decrease in power at the swing bus. Thus the change in phase angles can be written as the derivatives of the phase angles of the bus with respect to the power injections at the bus i.

Therefore the power flow on line l can be written as

$$f_l = \frac{(\theta_n - \theta_m)}{x_l} \quad \text{..................} \; (6.3)$$

Where

m is the from bus of the line l

n is the to bus of the line l

x_l is the reactance of the line l.

$\Delta\theta_n$ = phase angle of the bus n

$\Delta\theta_m$ = phase angle of the bus m.

Substituting the above values in finding the GODF we can write a_{li} as

$$a_{li} = \frac{df_l}{dP_i}$$

$$= \frac{d}{dP_i}\left[\frac{(\theta_n - \theta_m)}{x_l}\right]$$

$$= \frac{1}{x_l}\left(\frac{d\theta_n}{dP_i} - \frac{d\theta_m}{dP_i}\right)$$

$$= \frac{1}{x_l}\left(X_{ni} - X_{mi}\right) \quad \text{........................} \; (6.4)$$

Where

$\frac{d\theta_n}{dP_i} = X_{ni}$ = n^{th} row and i^{th} column element in the reactance matrix X

$\frac{d\theta_m}{dP_i} = X_{mi}$ = m^{th} row and i^{th} column element in the reactance matrix X

x_l is the reactance of the line l between buses m and n.

Using the equation (1) we can calculate the GODF of the all the transmission lines when a single generator is outaged in the system.

6.2.3 Algorithm for GODF

1. Input the branch data, bus data and generator data (if provided) for the test case system.
2. Calculate the number of buses and number of branches from the data.
3. Define the slack bus and its corresponding bus number.
4. Get the number of generator buses and the index of the generator buses from the generator data.
5. Calculate the susceptance matrix 'B' from the branch data

$$B = \frac{1}{X_{i,j}}$$

Where $X_{i,j}$ is the reactance of the line between i, j buses.

6. Eliminate the corresponding rows and columns of the slack bus from the 'B' Matrix.
7. Calculate the inverse of the resultant matrix.

8. Append the slack bus rows and columns with zeros for the resultant zeros matrix and name it as ‘X’.

9. Calculate the GODF a_{li} for the line l when generator i is outaged using the equation 6.4

$$a_{li} = \frac{1}{x_l}\left(X_{ni} - X_{mi}\right)$$

10. Repeat the procedure for each generator in the system calculating its outage impact on all the transmission lines.

11. Attribute the impact on the lines to the buses connected and rank the buses according to their magnitude of impact.

Thus the GODF of all the lines in the system is calculated when a single generator is outaged in the system.

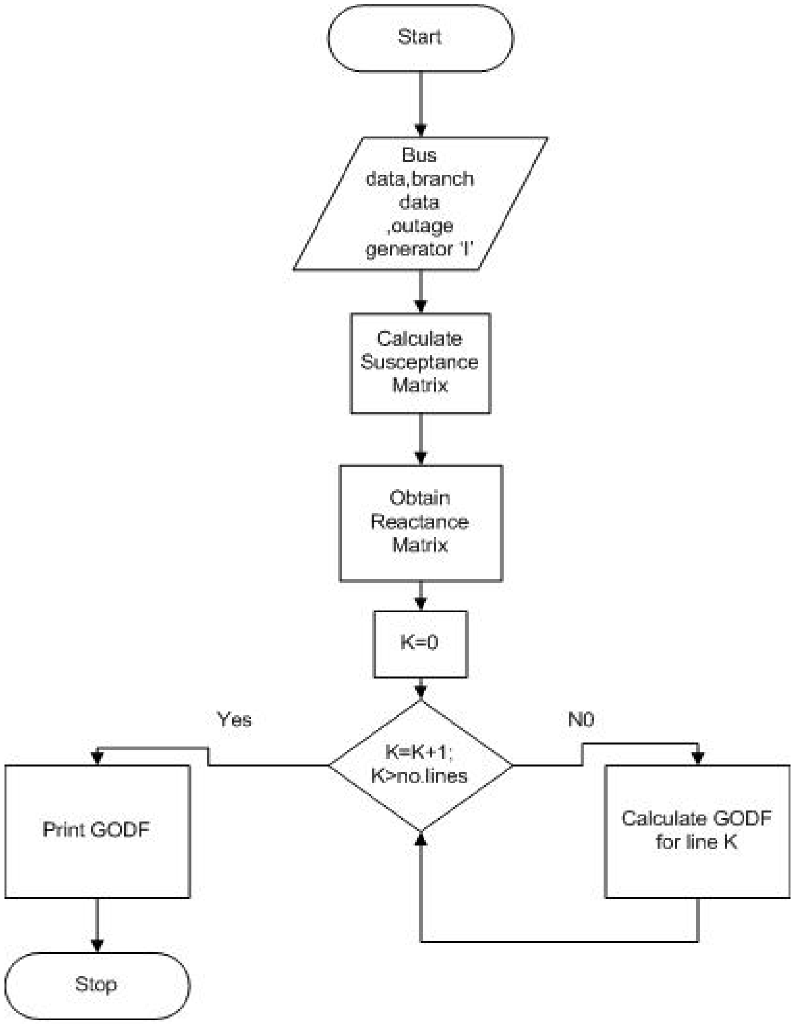


Figure 6.3 Flow chart for GODF

6.3 Multiple Generator Outage Distribution Factor

In general a blackout happens due to multiple number of generators outage resulting in higher order contingencies. GODF was extended to help in determining the impact on the transmission lines in case of a multiple generator outage. The multiple generator outage not only gives the user an idea on how to plan about the multiple generators but also gives a good measure of actions which can be taken. MGODF would help in determining the sensitive buses, which further will help in taking corrective actions which is our ultimate goal.

As seen above the single generator outage is considered and the expressions for its sensitivity factors have been derived and calculated. The derivation of formula for the multiple generator outage will also go on the same lines as the previous one. The multiple Generator Outage Distribution Factors are mainly calculated on the fact that each generator output is independent of each other and hence the effect of two generators outage can be calculated by using the superposition theorem, which gives the effect on the transmission lines when these generators are outaged. Thus in simple terms,

We can write,

MGODF of line *l* for generator at bus *a* is 'G1'

And MGODF of line *l* for generator at bus *b* is '*G2*'

Base case MW of generator G1 is 'MW1'

Base case MW of generator G2 is 'MW2'

Then the GODF of the line *l* when both the generators at buses *a* and *b* are outaged can be calculated using the superposition theorem which is nothing but the GODF of line *l* when 'a' is outaged multiplied by its MW and adding the product to GODF of line *l* when generator 'b' *is* outaged .This gives the impact on line *l* when both generators are outaged.

The mathematical formula can be written as

MGODF impact on line *l* = G1*MW1+G2*MW2

This formula is repeated for ‘n’ generators based on superposition theorem which can be written as

MGODF impact on line l = G1*MW1+G2*MW2+……… (6.5)

The slack bus GODF will always be considered as zero, since the outage of slack bus will lead to almost shutting down the system mathematically and hence very critical. In all these cases the slack bus is assumed to functioning in the system and supply the necessary load to the system. Now looking at the algorithm for the Multiple GODF we find it an extension to the normal GODF algorithm, where the GODF of the individual generators (which are to be outaged) is multiplied with their respective base case generation and added together to calculate the whole impact on the transmission lines. The MGODF thus is obtained for each transmission line. And then this MGODF is converted to Multiple Generator Outage Bus Sensitive Factors (MOGBSF) by attributing the MGODF of each line to each from and to buses of the line. And then the MGOBSF of each bus is added cumulatively together. The list of top sensitive buses is then updated. Hence we get the most sensitive bus which is affected by this contingency and actions can be taken on this bus to remove the violations.

The MGODF found from the above algorithm is then used to get a list of top sensitive buses. MGODF of all the lines is attributed to the buses attached to the lines and the impact on each bus is cumulatively added. Thus we get list of buses and their respective sensitivities. This is called the Multiple Line Outage Bus Sensitive Factor (MGOBSF). The buses with their impacts are thus ranked according to the magnitude of impact on each bus in decreasing order. Thus a list of top sensitive buses will be found and these buses are the natural locations to act upon to take corrective actions in the system. The number of top sensitive buses which can be acted upon may vary from system to system. For example a 37 bus system may need 5 to 6 buses for taking corrective actions to solve the problem where as a 137 bus system may need higher number of buses to solve the violations. But the sensitive buses thus found are effective in dealing with these higher order contingencies to take corrective actions to solve the violations

6.3.1 Algorithm for MGODF/MGOBSF

1. Input the branch data, bus data and generator data (if provided) for the test case system.
2. Calculate the number of buses and number of branches from the data.
3. Define the slack bus and its corresponding number.
4. Get the number of generator buses and the index of the generator buses from the generator data.
5. Define the number of generator outages and their index.
6. Calculate the susceptance matrix 'B' from the branch data

$$B = \frac{1}{x_{i,j}}$$

Where $x_{i,j}$ is the reactance of the line between i, j buses.

7. Eliminate the corresponding rows and columns of the slack bus from the 'B' Matrix.

8. Calculate the inverse of the resultant matrix.

9. Append the slack bus rows and columns with zeros for the resultant zeros matrix and name it as 'X'.

10. Calculate the GODF a_{li} for the line l when generator i is outaged using the formula

$$a_{li} = \frac{1}{x_l}\left(X_{ni} - X_{mi}\right)$$

11. Multiply GODF of the specified generators with their respective base case generation and add together to calculate the multiple generator outage impact using equation 6.5

12. Repeat the procedure for combination of the generators mentioned in the step 4 and calculate the impact on all the transmission lines in the system.

13. Convert the MGODF to MGOBSF by attributing the impact on the line to its from and to buses.

14. Rank the list of top sensitive buses for taking corrective actions.

The flow chart will be for the MGODF will be given below:

6.3.2 Flowchart for MGODF/MGOBSF

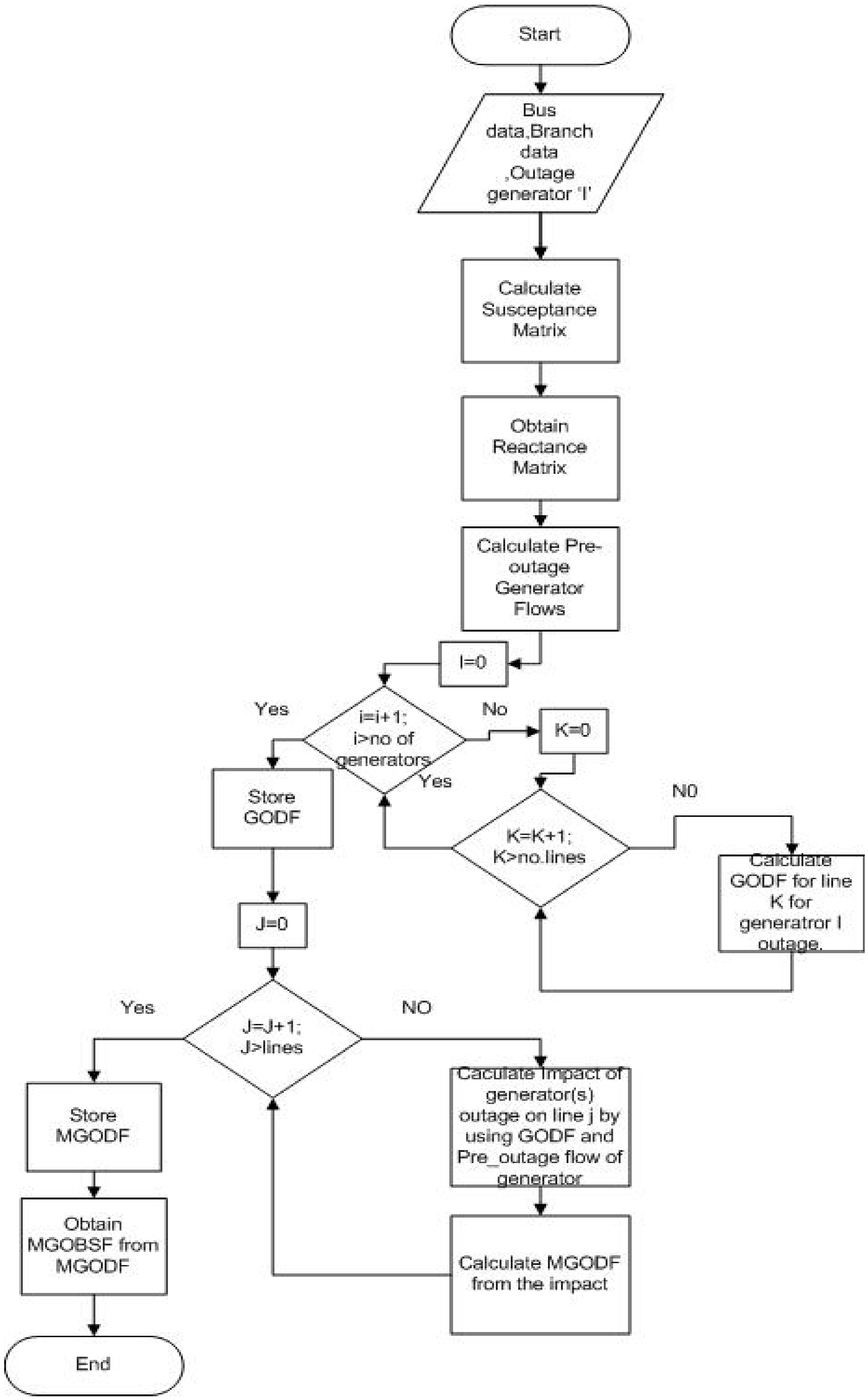


Figure 6.4 Flow Chart for MGODF

Deducing the impact on the buses from the transmission lines will give the sensitive buses for each type or each combination of generator outages. This sensitive buses will give the user an idea on which bus to react (which may be switching capacitor, load shedding, etc) to take proper corrective actions.

The test cases and the implementation of the single GODF as well as MGODF algorithm on those test cases and the results are explained in following sections.

The Multiple Line Outage Bus Sensitive Factor is very important tool in the research to take corrective actions for higher order line contingencies. The MGOBSF is based on the MGODF algorithm; it is derived from the MGODF by using the MATLAB code. When the MGODF for all the lines is obtained , then the MGOBSF code goes through each of the line and its MGODF and then attributes this MGODF to the each ' from' and 'to' bus in the system. This is process is repeated for all the buses in the system and the impact on each bus is cumulatively added together to get the list of buses and their sensitivities.

Suppose there is a line between bus '*i*´ and '*j*' and its MGODF is G1 and there is a line between bus '*i*´ and '*k*' and its MGODF is G2. Then the MGOBSF of buses *i, j, k* can be given as.

MGOBSF of bus '*i*´ = G1+G2

MGOBSF of bus '*j*' = G1

MGOBSF of bus '*k*' = G2

The above procedure is repeated for all the buses in the system and their respective sensitivities. Then these buses are ranked according to their absolute value of their sensitivities such that we get the list of top sensitive buses on which corrective actions can be taken. Thus we get MGOBSF for any ‘n’ bus system for higher order line contingencies.

6.4 Implementation on test cases

As seen above the algorithm will be implemented on the three test cases for N-2 and N-3 contingencies and corrective actions will be taken to remove the violations.

6.4.1 N-2 generator outage on 6 bus system

The one line diagram for the six bus system after the outage of generator 2 and generator 3 are given in figure 6.5

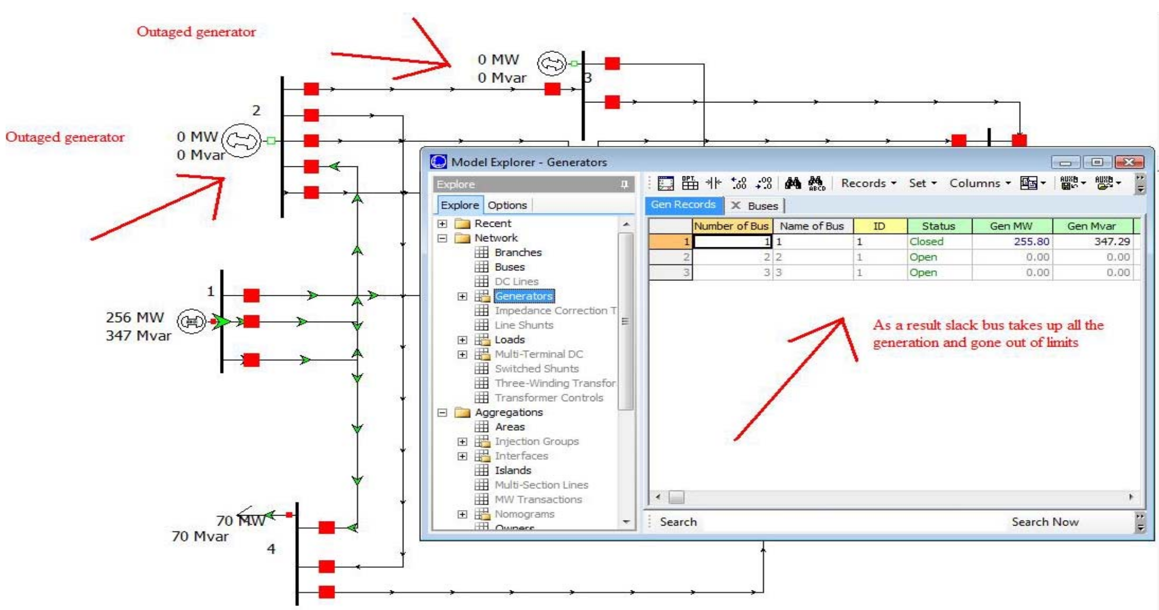


Figure 6.5 N-2 generator outage on 37 bus system.

As seen from figure 6.5, the two generator’s in the system are outaged and the load is taken up by the slack bus as a result the generation of the slack bus has gone out of limits . The MGODF code for this contingency gave the most sesnitve buses as shown in table 6.1.

Table 6.1 Sensitive buses for N-2 generator contingency on 6 bus system.

Bus No.	Sensitivity
1	0.60000
5	0.06775
4	0.004104
2	0.03525
3	0.00512

As pointed out in the table5.1most senstive bus is slack bus since it is the only generator bus left in the system to supply all the load . To solve this contingency there s no other way but to shed the load at the top senstive buses 5 and 4 and as a result the generation of the slack bus will decraese to it normal operating level. This can be seen in the figure 6.6

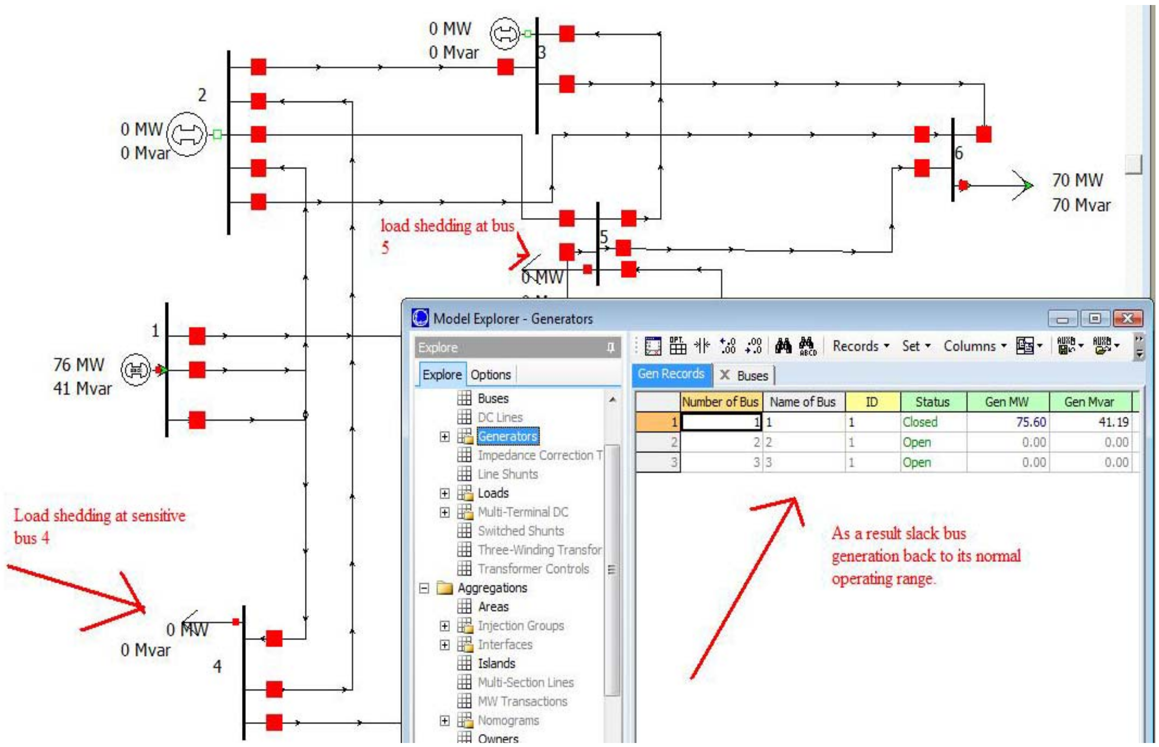


Figure 6.6 N-2 generator solved violations on 6 bus system.

N-3 Contingency is not possible on the 6 bus system since it has only 3 generators and if all the generators are outaged it will not function.

6.4.2 N-2 generator contingency on 37 Bus System

The N-2 contingency on the 37 bus system is not resulting in any violation hence the N-2 generator contingency is not done on the system. The system may be so desgined that it should be able to withstand the N-2 generator outage from the system.

6.4.3 N-3 generator contingency on 37 bus system

The three generators outaged are the generators at bus number 14,44 and54 respectively.

The one line diagram after the outage of three generators in the 37 bus system are given in figure 6.7

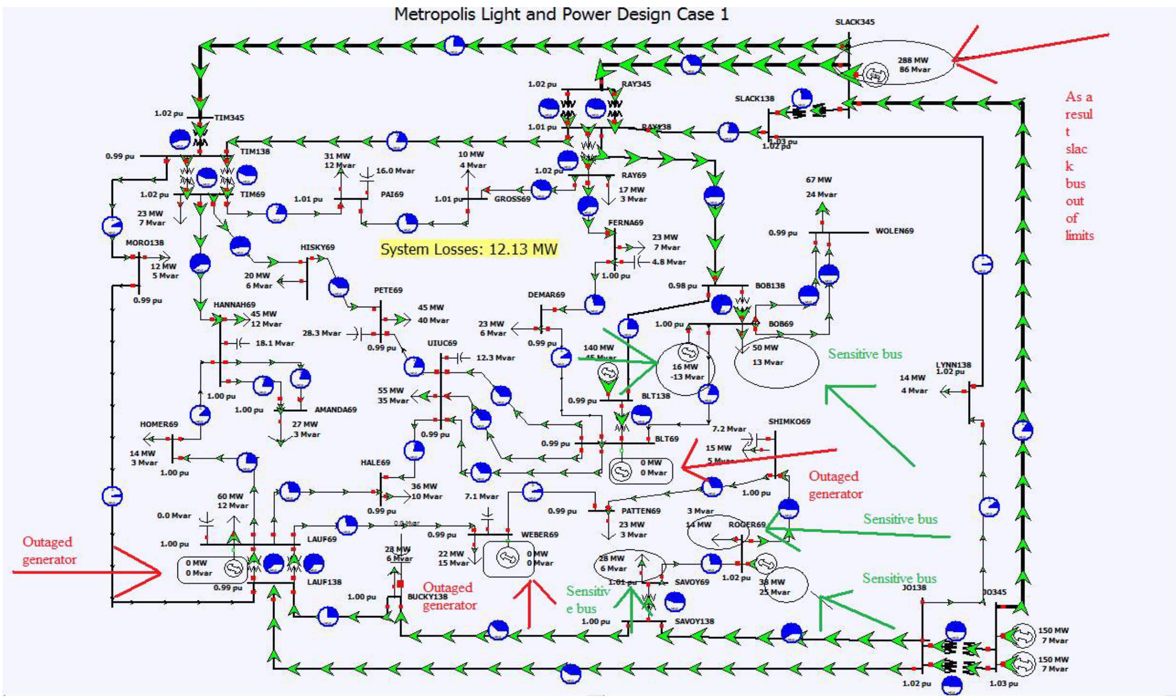


Figure 6.7 N-3 generator outage on 37 bus system.

As seen from figure 6.7 three generators are outaged as shown in marked rectangular shape. As a result the slack bus generation has exceeded its limits which are also shown in the figure 6.7. The MLOBSF code for this contingency gave the buses as the most sensitive buses to act upon as shown in table 6.2.

Table 6.2 Sensitive buses for N-3 generator contingency on 37 bus system.

Bus No	Sensitivity
1	1.050
48	0.855
50	0.752
31	0.631
32	0.510

The table 6.2 shows the sensitive buses of which some are generator buses and some are load buses. This contingency can thus be solved by two methods by the action taken on the generator buses or at load buses, increasing the generation of the two generation buses 48 and 50 to their maximum limit the slack bus generation has come down to its normal operating level, this scenario can be seen in figure 6.8.

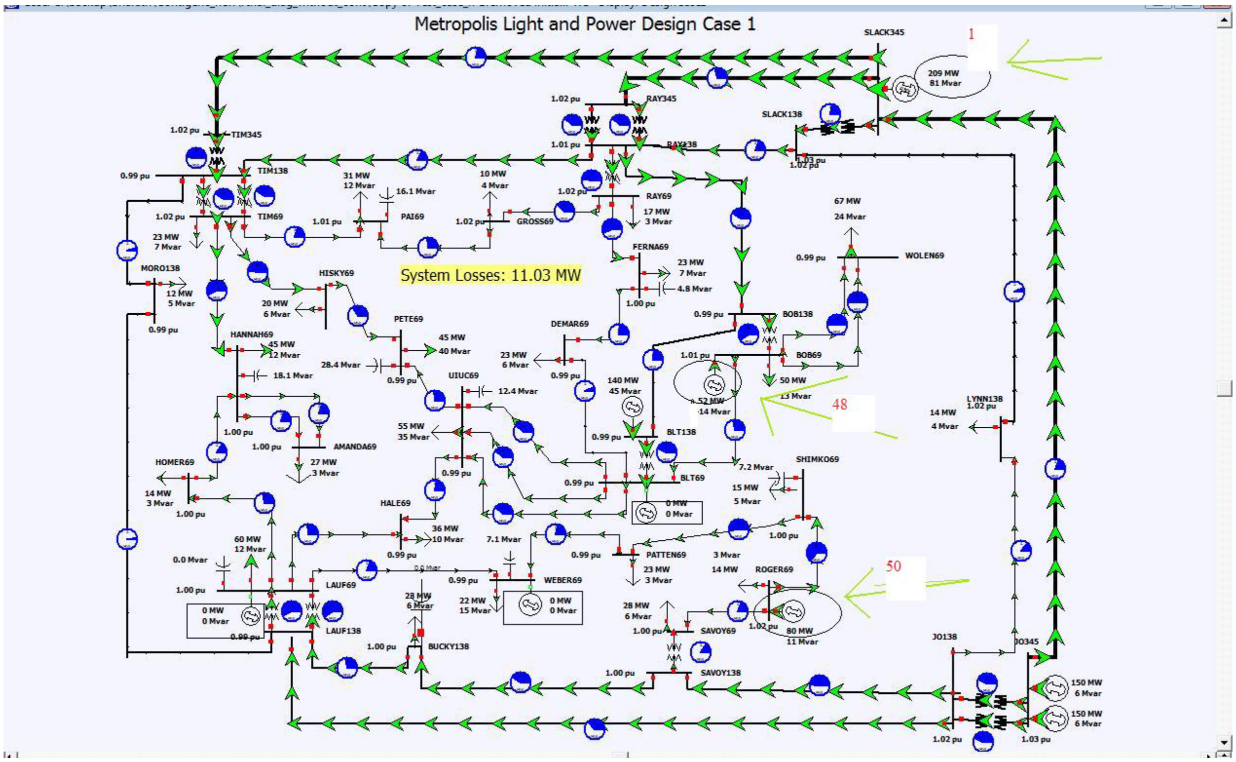


Figure 6.8 N-3 generator solving violations on 37 bus system.

The next method is to act on the load buses which are 48, 50, and 32 and shedding the load at the buses will also result in normal operation of the system, as seen in figure 6.9.

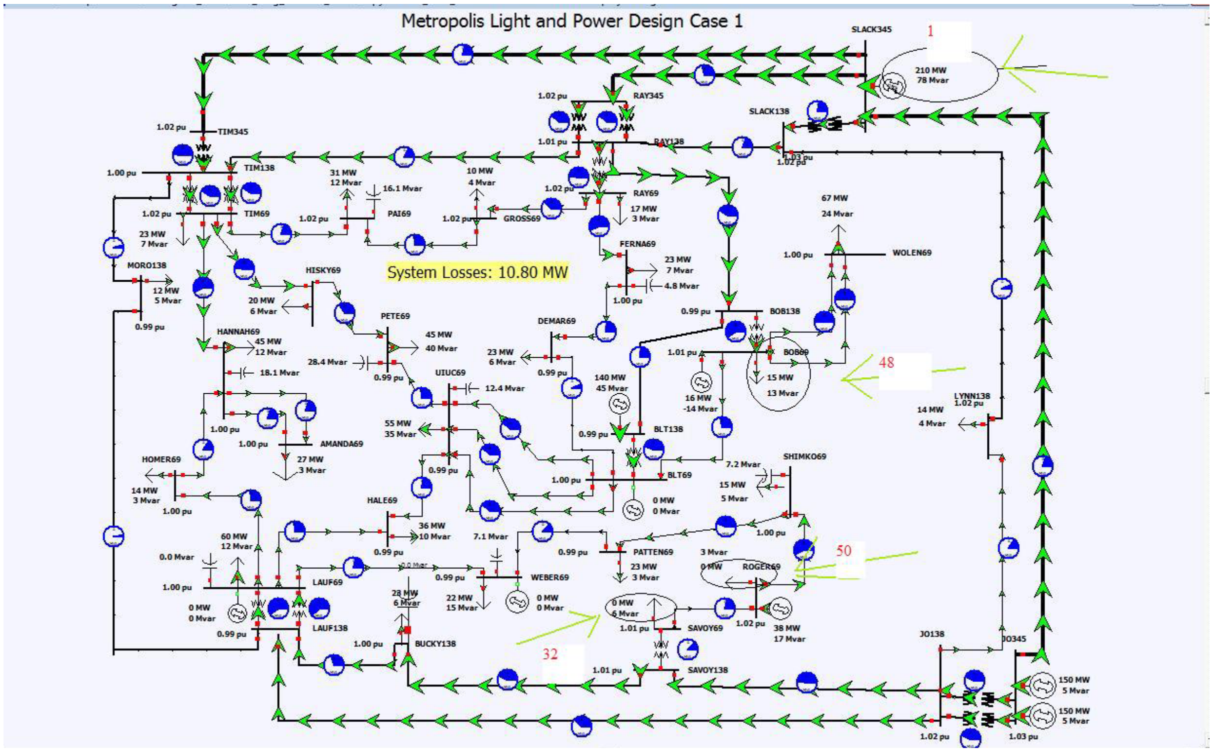


Figure 6.9 N-3 generator solving using load shedding on 37 bus system.

Thus the MGODF/MGOBSF algorithm is used to help develop corrective actions for the N-3 generator contingency on the 37 bus system.

6.4.4 N-2 contingency on 137 bus utility system

The two generators which are outaged for the 137 bus system are one generator at bus number 8 and other generator at bus no 123. As a result the lines between 5 and 8 are overloaded. The MGODF/MGOBSF for this outage gave the buses as shown in table 6.3 as the most sensitive buses upon which action need to be taken.

Table 6.3 Sensitive buses for N-2 generator contingency on 137 bus system.

Bus No	Sensitivity
9	0.4642
75	0.34331
4	0. 3375
11	0.2512
126	0. 1861

By shedding the loads optimally the flows on the lines between buses 5 and8 is brought back into its operating limits which can be shown in table 6.4.

Table 6.4 Flows on violated lines for N-2 generator contingency on 137 bus system.

Line NO	Base Flow	Post Outage	After acting on switching.
(5-8) ckt 1	105.4	-147.4	-106.6
5-8) ckt 2	-105.7	148.2	-106.2

Thus N-2 generator violation is solved by using MGODF/MGOBSF algorithms by taking necessary actions.

6.4.5 N-3 generator contingency on 137 bus utility system

The three generators outaged are the three generators at the bus number 123. As a result the line between buses 1 and 106 is over loaded. The MGODF/MGOBSF for this outage gave the most sensitive buses upon which action need to be taken, as seen in table 6.5.

Table 6.5 Sensitive buses for N-3 generator contingency on 137 bus system.

Bus No	Sensitivity
1	0.430
11	0.388
75	0.3195
9	0.3179
14	0. 2871
126	0.1784
34	0.1339

By increasing the generation at bus no 1 and re-routing the power , and also shedding the load at the other sensitive buses the flow on the line has been brought back to its normal operating range which are shown in table 6.6.

Table 6.6 Flows on violated lines for N-3 generator contingency on 137 bus system.

Line No.	Base Case Flow	Post Outage	After acting on sensitive buses
1-106	33.5	45.8	31.4

Thus the N-3 Generator Contingency is solved for the 137 bus utility system using the MGODF/MGOBSF algorithm.

6.5 Summary

Generators are very critical to any power systems operations. This chapter deals with single and multiple generator outages based on DC power flow method called as MGODF/MGOBSF algorithm. The formulation, algorithm and flowchart for MGODF/MGOBSF are given in this chapter. This algorithm calculates the impact on the sensitive buses in the system when multiple generator outages take place in the system. These lists of top sensitive buses are natural locations to take corrective actions and solve the violations. MGODF algorithm is implemented successfully on 6, 37 and 137 bus test case systems to solve the violations

6.6 References

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CHAPTER VII

AC SENSTIVITIES FOR MULTIPLE GENERATOR OUTAGES AND SIMULATION RESULTS

7.1 Introduction

The previous chapter dealt with the generator outage sensitivities pertaining to DC power flow. Although they are fast and efficient, they lack to provide information about the impact on the bus voltages due to generator outages. Hence a method described as Multiple Generator Outage Voltage Sensitivity (MGOVS) is described in this chapter which gives the impact on the bus voltages due to multiple generator outages in the system.

The Single Generator Outage Voltage Distribution Factor (GOVDF) is described and explained in [1]. This explains the impact on the bus voltages in the system when a single generator outage takes place in the power system network. This methodology is then further enhanced and extended in this thesis to give the effect on the bus voltages due to multiple generator outages in the system. This methodology is named as MGOVS which is Multiple Generator Outage Voltage Sensitivity. This algorithm is based on full AC power flow and hence gives total information about the bus voltages during these outages. The next sections describe the MGOVS algorithm and its implementation on different test cases in this work to derive sensitive buses, which help in taking corrective actions to solve the violations.

7.2 Multiple Generator Outage Voltage Sensitivity

Chapter 5 presented the algorithm for multiple line outages and developed MLOVDF. The algorithm for MGOVS was developed on the same line to know the impact on the voltage of the buses in power system due to multiple generator outage.

Reference [1] provides information about deriving the Single Generator Outage Voltage? Distribution Factor (GOVDF). The impact of single generator outages is calculated using the GOVDF algorithm. The MGOVS algorithm is developed similarly on the lines of GOVDF algorithm, and is based on AC power flow method. MGOVS algorithm is used to calculate the impact of multiple generator outages in the system.

Suppose at bus *q* there is a generator which is outaged from the system. The impact on the voltage of bus *i*, which is the GOVDF [1] of bus *i* can be then be given as

$$(GOVDF)_{i-q} = \frac{\Delta V_{i-q}}{P_q^o} \quad \text{.......................} \ (7.1)$$

Where, $\Delta V_{i-q} = V_{i-q} - V_i^o$

P_q^o = Pre outage real power generation of generator at bus *q*.

The MGOVS is developed on the same based on GOVDF [1]. MGOVS is calculated based on full Jacobian matrix and pre-outage generation MW.

NRLF is run for the given test case system and the values of the voltages, P, and Q are calculated based on power flow. Then the full Jacobian is calculated irrespective of the type of bus except for slack bus in the system which is taken as bus numbered as one. Suppose there are N number of buses in the system then size of the Full Jacobian would be (2N-2) X (2N-2). Thus the full Jacobian is constructed by extending the already existing Jacobian used for the NRLF. The change in voltage and angle are then calculated by using the following formula,

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = [S_T] \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

Where,

$\Delta\delta$ Change in phase angles of the buses except for the slack bus.

ΔV Change in the bus voltages except for the slack bus.

S_T Inverse of the Full Jacobian matrix.

ΔP Mismatch vector for real power for all buses except for slack bus.

ΔQ Mismatch vector for reactive power for all buses except for slack bus.

All the entries in the mismatch vector should be almost zero based on solved power flow. When calculating the change in phase angle and change in voltages the entries in mismatch vector should be modified based on the bus numbers on which generators are outaged.

Let us assume there are two generators at buses i and j which are outaged. Now the entries in the mismatch vector, corresponding to the generator buses would be pre-outage generation of each generator.

For generator at *i* outage, $\Delta P_i = P_i^o$, $\Delta Q_i = Q_i^o$,

For generator at *j* outage, $\Delta P_j = P_j^o$, $\Delta Q_j = Q_j^o$

Where,

P_i^o = Pre-outage real power generation of generator at bus '*i*'

Q_i^o = Pre-outage reactive power generation of generator at bus '*i*'

P_j^o = Pre-outage real power generation of generator at bus '*j*'

Q_j^o = Pre-outage reactive power generation of generator at bus '*j*'

Thus the voltage and angle change vector can be calculated by substituting these values in the mismatch vector and using the formula, given in equation 7.2

$$\begin{bmatrix} \Delta\delta_2 \\ . \\ . \\ \Delta\delta_n \\ \Delta V_2 \\ . \\ . \\ \Delta V_n \end{bmatrix} = \begin{bmatrix} J_{1(N-1*N-1)} & J_{2(N-1*N-1)} \\ J_{3(N-1*N-1)} & J_{4(N-1*N-1)} \end{bmatrix} \begin{bmatrix} \Delta P_i \\ . \\ \Delta P_j \\ . \\ \Delta Q_i \\ . \\ \\ \Delta Q_j \end{bmatrix} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7.2)$$

Other elements of the mismatch vector will be zero. Using the above equation 7.2 change in phase angles of the buses ($\Delta\delta$) and the change in the bus voltages (ΔV) is calculated for all the buses except the slack bus. The MGOVS for bus *k* can be given as

$$\left(MGOVS\right)_{k-i,j} = \Delta V_{k-i,j} \quad \text{........................... (7.3)}$$

A similar procedure is repeated for multiple generators to calculate their impact on all the buses in the system. This MGOVS would help in finding the top sensitive buses where corrective actions can be taken.

The magnitudes of MGOVS for all the buses are obtained and ranked. The buses with top rank (with higher sensitivities) are the buses where actions such as switching the capacitor, shedding the load or generation re-dispatch will be taken to solve the violations due to the contingencies. The number of top buses to be taken may vary, for smaller systems such as 37 bus system the top five buses may be enough to take corrective actions, where as for bigger systems the number of top ranked buses may be needed up to 15 buses. MGOVS are very useful and helpful to take quick and effective actions in a fast way.

The algorithm for finding out the list of sensitive buses for multiple line outage based on the MGOVS can be given as follows:

7.2.1 Algorithm for MGOVS

1. Input the branch data and bus data for the test case.
2. Calculate the number of buses and number of branches from the data also the type of the buses (PQ or PV).

3. Set all the voltages at all the buses to 1pu (un-less given) and all the angles at the buses to zero degree.

4. Calculate the admittance matrix 'Y' from the branch data, real and reactive power injections at each bus from bus data.

5. Set the tolerance, calculate the initial mismatch vectors and set error as maximum of absolute value of mismatch.

6. Calculate the Jacobian matrix based on the number of PQ buses and then repeat the process until the desired tolerance is met.

7. Calculate the power flows on the lines using the updated voltage and phase angles.

8. Construct a full Jacobian by extending the already obtained Jacobian to all the buses except for the slack bus and find its inverse and name is as S_T.

9. Get the generator outaged and the corresponding buses.

10. Use the formulation mentioned above for the entries of mismatch vector to and set up the mismatch vector.

11. Calculate the changed phase angles and bus voltages for the contingency using the formula

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = [S_T] \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

12. Calculate the MGOVS for bus i using the equation 7.3

$$\left(MGOVS\right)_{k-i,j} = \Delta V_{k-i,j}$$

13. Get the MGOVS for all the buses in the system.

14. Rank the buses according to their sensitivity factors to take actions.

7.2.2 Flow chart for MGOVS

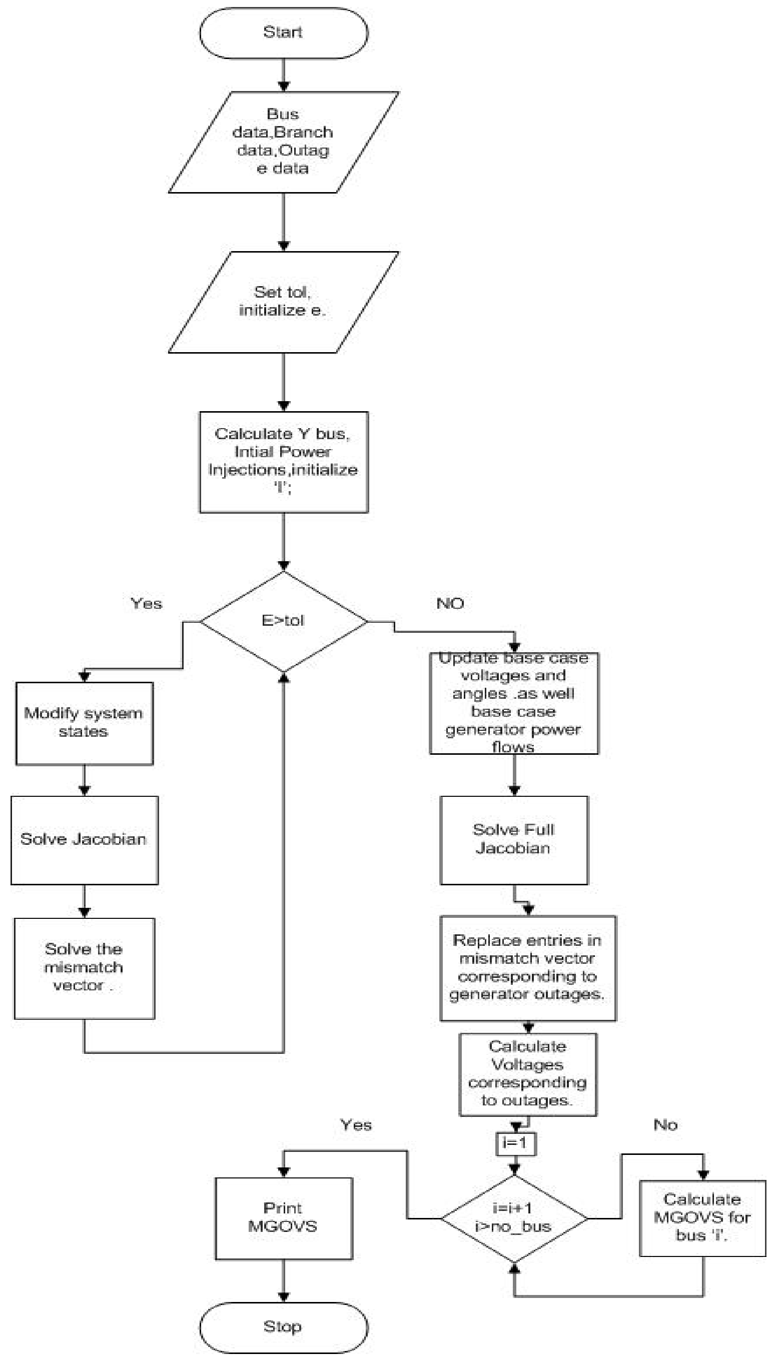

Figure 7.1 Flow chart for MGOVS

7.3 Implementation on test cases

7.3.1 N-2 generator outage in 6 bus system

The two generators outaged are generators at buses two and three, and as a result all the bus voltages in the system are violated. The sensitive buses suggested by the MGOVS algorithm for these contingencies are given in table 7.1

Table 7.1 Sensitive buses for N-2 generator contingency on 6 bus system.

Bus No	Sensitivity
3	1.1086
6	1.0748
2	0.8136
5	0.8096
4	0.6230

As seen from table 7.1 bus three is the most sensitive bus and since only one generator is left in the system even after shedding load at bus 6 and 5 the low voltages still persist. And hence the only way to solve this low voltage problem is either shed all the loads, since the only generator system cannot supply all the load to get back the voltages to normal operating range which can be seen in table 7.2.

Table 7.2 Low voltage buses for N-2 generator contingency on 6 bus system

Bus No	Post Outage Voltage	Voltage After Actions are
1	1.00000	1.00000
2	0.69249	0.96631
3	0.59364	1.07000
4	0.69782	0.95698
5	0.61633	0.95618
6	0.54419	0.97073

N-3 generator outage is not possible since there are only three generators in the system.

7.3.2 N-2 generation contingency on 37 bus system

The system does not show any violation for N-2 generator contingency, although with the loss of major generators such as the ones at bus number 20 the lowest voltage at the buses is 0.9732 as compared to the normal operating voltage which is 1.0273.

7.3.3 N-3 generator contingency on 37 bus System

The three generators which are outaged are at bus numbers 48, 53 and54 and as a result low voltages are resulted at buses 47 and 53 as shown in figure 7.2. The MGOVS algorithm for these contingencies gave the following buses as the most sensitive buses (table 7.3).

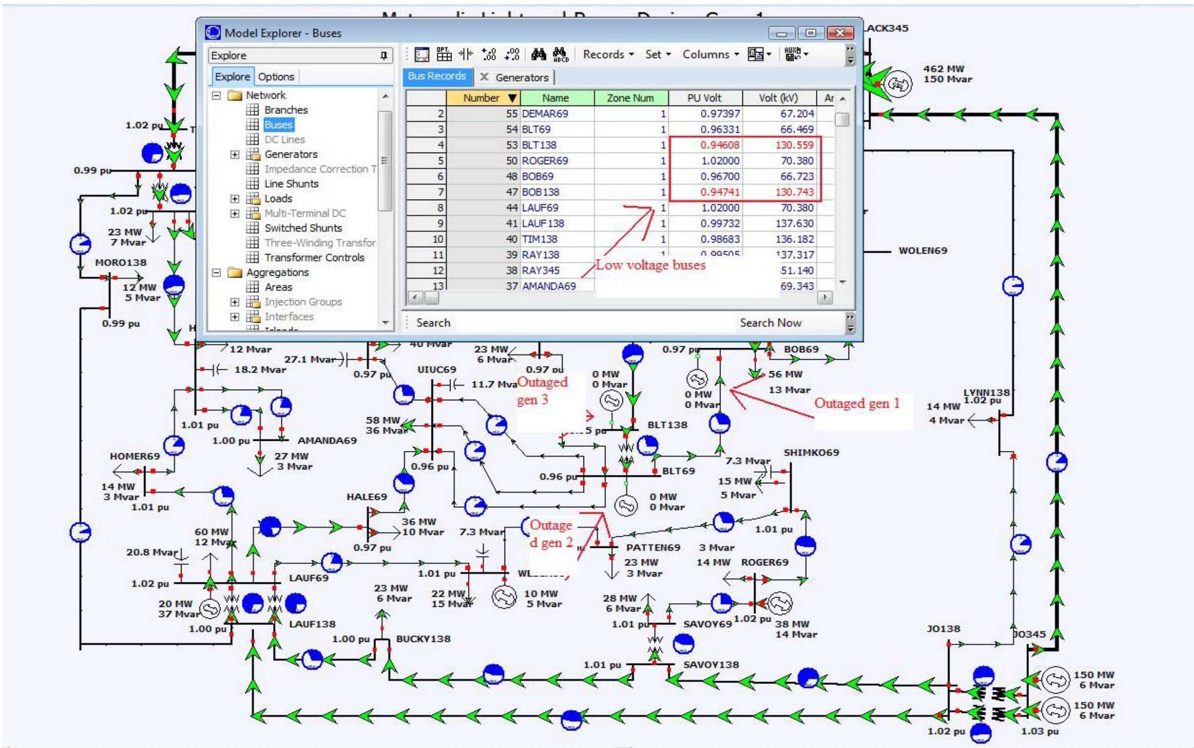

Figure 7.2 N-3 generator outage violations on the 37 system

Table 7.3 Sensitive buses for N-3 generator contingency on 37 bus system.

Bus No	Sensitivity
20	0.1226
14	0.1194
54	0.1138
50	0.1124
53	0.1021
47	0.0982

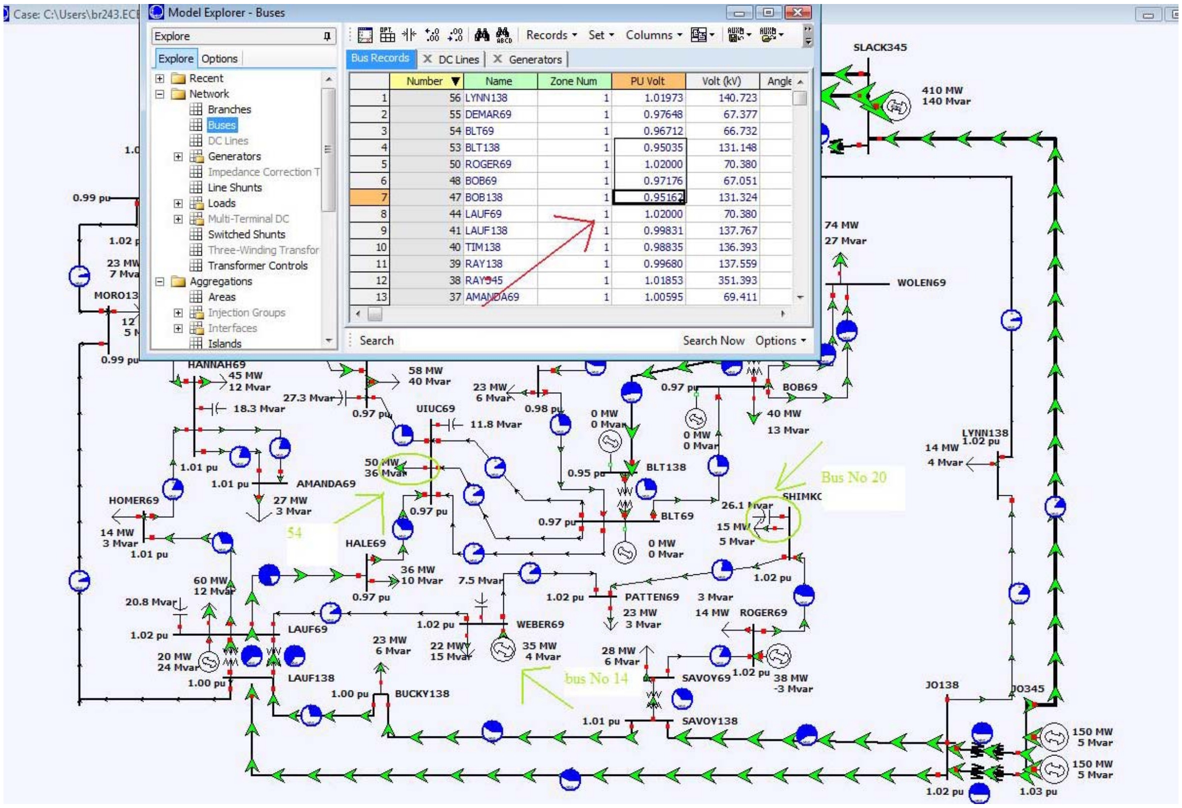

Figure 7.3 N-3 generator outage violations by taking actions.

After taking actions on the top sensitive buses such as increasing the capacitance at bus number 20, shedding the load at bus number 54 and 47 , and increasing the generation at bus number 14 , the voltages are brought back to their normal operating limits as shown in figure 7.3. Thus the MGOVS algorithm gives suggestions for corrective actions needed for N-3 generator contingency.

7.3.4 N-2 generator contingency on 137 bus utility system.

The two generators outages are generator at bus 7 and generator at bus 10. The top sensitive bus list obtained by MATLAB MGOVS for these contingencies can be given are given in table 7.4

Table 7.4 Sensitive buses for N-2 generator contingency on 137 bus system

Bus No	Sensitivity
9	0.0800
81	0.0690
82	0.0675
68	0.0625
108	0.0616
78	0.0611
86	0.0606
6	0.0605
71	0.0601
67	0.0593
74	0.0590
109	0.0584
92	0.0580
126	0.0578
125	0.0577
77	0.0576
69	0.0574
75	0.0546
70	0.0545
117	0.0542
76	0.0542
18	0.0540
17	0.0535

From the table 7.4, taking actions on the sensitive buses (such as switching on capacitor buses given in the list, shedding the load at other buses given in the list) the low voltage of the buses is removed. Different options can be tried to remove the voltage violations of the buses such as shedding only load, or switching on only the capacitor buses, or doing both actions such as switching on as well as shedding some load, these scenarios may be taken depending on the situation and the voltage profile needed. After taking actions (such as shedding load at the sensitive buses and also switching on the capacitors at the sensitive buses) the voltages of the buses are shown in table 7.5.table below.

Table 7.5 Violated buses for N-2 generator contingency on 137 bus system.

Bus No	Post outage voltage	Voltage after only load shedding	Combination of load and capacitor switching
24	0.9339	0.9539	0.9855
25	0.9464	0.954	0.9691
33	0.9383	0.9557	0.9844
52	0.9451	0.9547	0.9642
56	0.949	0.9666	0.9852
58	0.9189	0.9528	0.9801
62	0.9309	0.9541	0.9771
64	0.9299	0.9536	0.9787
65	0.9443	0.962	0.9818
82	0.9398	0.964	0.9927
91	0.9393	0.9511	0.957
96	0.9152	0.9528	0.9802
97	0.9429	0.951	0.964
99	0.9486	0.9663	0.9849
104	0.9243	0.9511	0.9755
107	0.9472	0.9676	0.9841
108	0.9437	0.9676	0.9807
129	0.9235	0.9514	0.9763
130	0.9368	0.9554	0.985
131	0.9367	0.9553	0.9849
136	0.9277	0.9537	0.9789

As seen from the table 7.5 the low voltages can be removed by load shedding or capacitor switching on the sensitive buses specified by the MGOVS algorithm.

7.3.5 N-3 generator contingency on 137 bus utility system

The generators which are outaged are generators at buses 3, 6 and 11. The top sensitive buses given by the MGOVS algorithm for these contingencies are given in table 7.6.

Table 7.6 Sensitive buses for N-3 generator contingency on 137 bus system

Bus No	Sensitivity
135	0.1604
63	0.1594
61	0.1577
64	0.1567
103	0.1564
10	0.1556
128	0.1554
98	0.1544
55	0.1544
95	0.1517
57	0.1510
59	0.1487
71	0.1431
51	0.1429
92	0.1394
77	0.1392

Some of the buses shown in table 7.7 are the capacitance buses, some of them are the generator buses and some of them are the load buses. Thus there are several ways in which actions can be taken using the above sensitivity to solve the low voltage violations caused by the N-3 generator contingencies. Some ways include only shedding the load at the sensitive buses or only switching on the capacitances at the sensitive buses or doing the combination of both. Once again depending on the situation, one needs to choose optimal actions. Some of the actions (such as load shedding at the top sensitive buses or capacitance switching at top buses or shedding some amount of load and switching on the capacitance if both are present at the same bus etc.) and the respective voltage of the buses in different situations are given in table 7.7.

Table 7.7 Violated buses for N-3 generator contingency on 137 bus system

Bus No	Post Outage Voltage	Voltage after Load shedding and Capacitor switching
24	0.9333	0.9854
25	0.9473	0.9661
33	0.9376	1.0285
52	0.9445	1.021
56	0.9484	1.0343
58	0.9182	1.0371
62	0.9303	1.0365
64	0.9293	1.0378
65	0.9437	1.0385
96	0.9146	1.0371
91	0.9388	1.009
99	0.9481	1.0343
104	0.9237	1.0368
108	0.9442	0.9641
128	0.9229	1.0369
130	0.9361	1.0344
136	0.9361	1.0380

Thus the low voltages at the buses are fixed by taking actions based on the MGOVS.

7.4 Summary

Generators are key to normal operation of power system network. The MGOVS algorithm is very useful especially when finding the impact on the bus voltages during a multiple generator outage in the system. The algorithm utilizes full AC power flow and hence gives detailed information about the bus voltages. The algorithm is derived in this chapter and the flow charts are also explained. This algorithm is implemented on 6, 37 and 137 bus test case systems and the results are used to develop the corrective actions to remove the violations caused due to these higher order generator contingencies.

7.5 References

[1]. Ashwini Kumar, “Available Transfer Capability and Congestion Determination”, Doctoral dissertation, pp. 70-75, 2003, Indian Institute of Technology, Kanpur, Advisors: Dr.S.C.Srivastava and Dr.S.N.Singh.

CHAPTER VIII

CONCLUSIONS AND FUTURE WORK

8.1 Introduction

The present day power systems are prone to multiple contingencies being highly interconnected and complex. Study of multiple contingencies and associated remedial actions has received less attention by the power industry. This chapter summarizes the work developed in this thesis to deal with the impact of multiple contingencies in the power system networks. The chapter also identifies future scope for research work, which can be carried out, to improve the suggested algorithms further.

8.2 Research work contributions and conclusions

Remedial control actions are required to be planned by operating personnel to avoid system entering into emergency state under major outages. The need for effective corrective schemes arises under contingencies in the system. Although there are several remedial action schemes suggested in the literature for the single (N-1) contingency cases, very few efforts have been made in developing the schemes for multiple contingencies. This thesis deals with developing corrective actions for higher order contingencies. In interconnected practical power system, higher order contingencies may happen more frequently. Therefore, it is necessary that the utilities be prepared for these contingencies prevent loss of service.

This thesis has developed four different algorithms to determine corrective actions under multiple contingencies, in order to remove major system violations caused by these contingencies. These algorithms have been referred as Multiple Line Outage Distribution Factor (MLODF) algorithm, Multiple Line Outage Voltage Sensitivity (MLOVS) algorithm, Multiple Generator Outage Distribution Factor (MGODF) algorithm, and Multiple Generator Outage Voltage Sensitivity (MGOVS) algorithm. Of these, the MLODF and the MGODF algorithms are based on DC power flow and are used to solve the MW violations (line overloads) and the MLOVS and the MGOVS algorithms are based on full AC power flow model and are used to solve the voltage violations caused in the system. The above algorithms are quite fast and can be used for real time applications for taking corrective actions. These algorithms have been implemented on three test systems, a six bus system test system, a thirty seven bus test system and a 137 bus utility system. The algorithms have been successfully implemented on these test systems for N-2 and N-3 contingencies (line outages and generator outages). The corrective actions obtained through the combination of proposed algorithms and thumb rule RAS effectively remove the limit violations in the system. The results obtained through the proposed algorithms are found to be quite accurate and thus, this work provides new tool for developing remedial control actions for higher order contingencies.

8.3 Future work

The proposed algorithms determine corrective actions effectively for the line and generator outages. These algorithms can be further extended for the bus outages, which will lead to simulating a combination of line and generator outages.

The data obtained from the Phasor measurement units (PMU's) can be used to improve the accuracy of the algorithms in taking accurate corrective actions.

The MLODF and MGODF algorithms can also be modified based on AC power flow based models to enhance the accuracy, which will also lead to a single tool for dealing with violations under all types of higher order contingencies. In addition, other types of remedial actions such as intentional islanding and under load tap changing actions may be included in the proposed algorithms.

8.4 Summary

Four different algorithms for dealing with the higher order contingencies and removing the associated limit violations are developed. This chapter has summarized the features of these algorithms and results of test cases. The possible future works which need to be done to make the algorithms more effective are also outlined in this chapter.

APPENDIX A

TEST CASES DATA

A.1 Six bus system bus data

Table A.1 Six bus data

No	Type	V	P_{gen}	P_{load}	Q_{gen}	Q_{load}	Delta
1	0	1.05	0	0	0	0	0
2	1	1.05	0.5	0.0	0	0.0	0
3	1	1.07	.6	0	0	0	0
4	2	1	0	0.7	0	0.7	0
5	2	1	0	0.7	0	0.7	0
6	2	1	0	0.7	0	0.7	0

Table A. 2 Six bus branch data

No	Type	V	P_{gen}	P_{load}	Q_{gen}	Q_{load}	Delta
1	0	1.05	0	0	0	0	0
2	1	1.05	0.5	0.0	0	0.0	0
3	1	1.07	.6	0	0	0	0
4	2	1	0	0.7	0	0.7	0
5	2	1	0	0.7	0	0.7	0
6	2	1	0	0.7	0	0.7	0

A.2 37 bus system branch data

Table A.3 37 bus system bus data

Bus no	Actual	Type	V	Angle	Pgen	Pload	Qload	Qgen
1	1	0	1.05	0	220			0
2	3	2	1	0		12.3	5	
3	5	2	1	0		14	3.2	
4	10	2	1	0		16.8	2.5	
5	12	2	1	0		22.9	6.5	
6	13	2	1	0		23	7	
7	14	1	1	0	10	22.2	15.2	0
8	15	2	1	0		36.3	36.3	
9	16	2	1	0		57.8	40.4	
10	17	2	1	0		32.8	12.9	
11	18	2	1	0		45	12	
12	19	2	1	0		18.3	5	
13	20	2	1	0		15.3	5	
14	21	2	1	0		74.4	26.8	
15	24	2	1	0		36.3	10.4	
16	27	2	1	0		20	6	
17	28	1	1	0	300			0
18	29	2	1	0				
19	30	2	1	0		23.4	6.2	
20	31	2	1	0				
21	32	2	1	0				
22	33	2	1	0		28	6	
23	34	2	1	0		22.7	3	
24	35	2	1	0				
25	37	2	1	0		27	3	
26	38	2	1	0				
27	39	2	1	0				
28	40	2	1	0				
29	41	2	1	0				
30	44	1	1	0	20	59.8	12.3	0
31	47	2	1	0	-	-		
32	48	1	1	0	16	55.8	12.5	0
33	50	1	1	0	38	14.1	3	0
34	53	1	1	0	140	59.5	27.8	0
35	54	1	1	0	76	12.5	5.7	0
36	55	2	1	0		23	6.15	
37	56	2	1	0		14	3.7	

Table A.4 37 bus system branch data

Line No.	From	To	Ckt ID	R	X	B
1	31	1	1	0.00117	0.017	0.182
2	31	40	1	0.001	0.0623	0
3	3	40	1	0.0048	0.0368	0.0182
4	3	41	1	0.00902	0.0571	0.0135
5	5	18	1	0.03133	0.07675	0.0015
6	5	44	1	0.03463	0.08253	0.0016
7	10	13	1	0.03375	0.0789	0.0012
8	10	19	1	0.0405	0.0953	0.0021
9	10	39	1	0.00106	0.03949	-0.0041
10	12	17	1	0.02172	0.06935	0.0019
11	12	18	1	0.02747	0.08909	0.0019
12	12	27	1	0.0142	0.07557	0.0695
13	12	40	1	0.00107	0.04039	-0.0042
14	12	40	2	0.00107	0.04039	-0.0042
15	13	55	1	0.02216	0.0904	0.0017
16	14	34	1	0.02625	0.06429	0.0012
17	14	44	1	0.04211	0.08545	0.0474
18	15	16	1	0.01953	0.02582	0.0206
19	15	24	1	0.01835	0.02845	0.0221
20	15	54	1	0.00846	0.00465	0.021
21	15	54	2	0.00855	0.0047	0.0213
22	15	54	3	0.00859	0.00472	0.0214
23	16	27	1	0.00366	0.01312	0.046
24	17	19	1	0.02703	0.03613	0.002
25	18	37	1	0.01017	0.00559	0.0253
26	18	37	2	0.01017	0.00559	0.0253
27	20	34	1	0.02423	0.05862	0.0011
28	20	48	1	0.02133	0.0521	0.0009
29	20	50	1	0.0424	0.07509	0.0008
30	21	48	1	0.01824	0.04236	0.0075
31	21	48	2	0.01829	0.04246	0.0078
32	24	44	1	0.03993	0.09965	0.002
33	28	29	1	0.00087	0.051	0
34	28	29	2	0.00087	0.051	0
35	1	28	1	0.00224	0.03268	0.35

Table A.4 Continued

36	32	29	1	0.0103	0.05681	0.016
37	29	41	1	0.01868	0.1259	0.0356
38	56	29	1	0.00771	0.0544	0.0138
39	30	32	1	0.00225	0.0134	0.004
40	30	41	1	0.00735	0.04395	0.0123
41	35	31	1	0.00087	0.051	0
42	1	38	1	0.00075	0.01092	0.117
43	33	32	1	0.0025	0.0723	0
44	33	50	1	0.0502	0.101	0.0025
45	35	39	1	0.01028	0.07253	0.0176
46	35	56	1	0.01243	0.07847	0.0192
47	39	38	1	0.00094	0.05107	-0.0127
48	39	38	2	0.00095	0.05116	-0.0124
49	39	40	1	0.01161	0.08085	0.0225
50	39	47	1	0.00775	0.05244	0.0154
51	44	41	1	0.0025	0.07144	-0.0045
52	44	41	2	0.00244	0.06829	-0.006
53	48	47	1	0.0192	0.03925	-0.0035
54	47	53	1	0.00204	0.00692	0.1601
55	48	54	1	0.01473	0.036	0.0744
56	54	53	1	0.00134	0.04988	-0.0004
57	54	55	1	0.06246	0.08246	0.0325