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Impact of Distributed Generation on Distribution Contingency Analysis

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IMPACT OF DISTRIBUTED GENERATION ON DISTRIBUTION

CONTINGENCY ANALYSIS

By

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It is expected that increasing amounts of distributed generation (DG) will be connected to the power system in the future. Advances in technology, deregulation in the market to end the monopoly of the vertically integrated power utilities, alternative energy sources that are becoming more cost effective are encouraging the growth of this new technology. Although there are many advantages, there are many issues to be considered for the interconnection of DG's, like the sizing and siting of the DG. Since it is necessary that the voltages be within a specified limit, this problem of the siting and sizing of the DG has taken top priority as they affect the voltages and operations of the distribution power system. This thesis discusses a procedure for evaluating the impact of the site, size of the DG and also a change in the loading conditions of the system before and after the reconfiguration of the system due to the fault. Many feasible combinations of the size and site of a DG on the IEEE 13 and IEEE 37 node distribution feeder are analyzed, which resulted in large number of data from the load flow. The results and trends are presented.

DEDICATION

I would like to dedicate this thesis to my parents, Ms. K.Vijayalakshmi and Mr. K.V.Ramana Murthy, and my sister K.Suneetha, who have been my source of support and guidance, and have greatly motivated me to achieve all my goals.

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CHAPTER I

INTRODUCTION

1.1 Introduction

The electric utility industry is probably the largest and the most complex system in the world. Power systems can be divided into three parts, generation, transmission and distribution. Generation deals with the generation of electricity. The energy generated is transmitted through the transmission network to the substation and from there, it is distributed to the various industrial, commercial and residential areas. This was the old paradigm. Figure 1.1 gives a typical electric power system before deregulation.

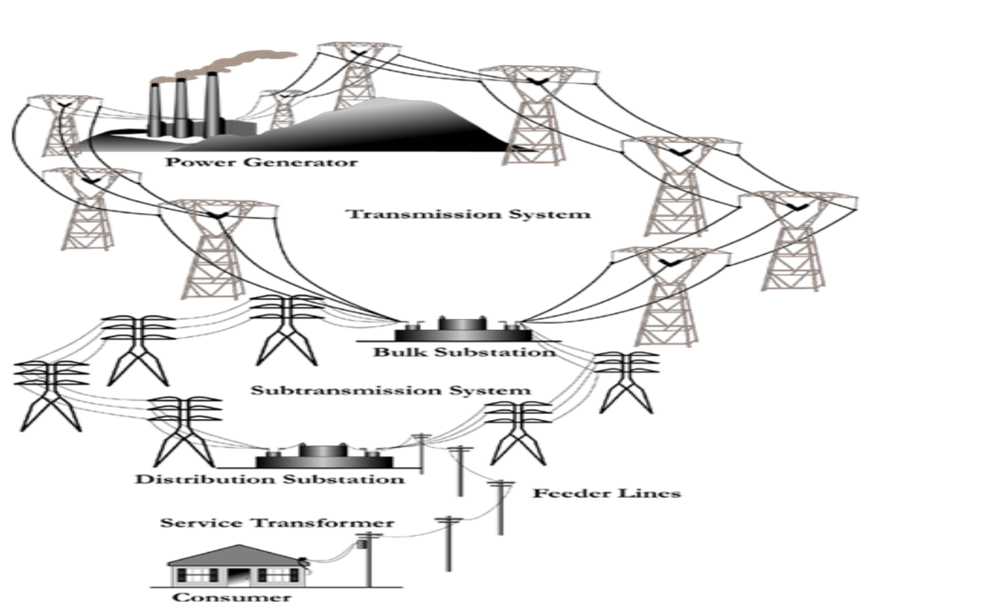

Figure 1.1 Typical electric power system [1]

The electric power industry is going through major changes from being an industry dominated by regulated monopolies to one featuring competitive electricity generation companies, common-carrier transmission organizations, and regulated distribution companies [1]. The centralized and regulated electric plants have been and will be the main source of energy but the utility deregulation and the incentives provided by the government to create a competitive market have created a high level of interest in the distributed energy resources. The DG's can provide the support needed to handle the incremental capacity of the grid and also to the user.

1.2 Growth and Benefits of Distributed Generation

The advances in technology have created a new trend for the growth of what is called the Distributed Generation. The generation facilities being huge plants (100s of MW) were usually located at far off places, away from populated areas, but the advancement of technology in a more cost effective way has led to the generation of electricity in the vicinity of the area where power is consumed. Not only this, but also the changes brought about by the government in many countries to end the monopoly of the vertically integrated power utilities has fostered this new technology. The increasing reliability expectations and also, the inability to add new transmission lines have become a driving force for the growth of distributed generation. All these reasons have created the need for a new area in power systems. This also provides an opportunity to effectively exploit the renewable energy, which is produced from replenishable resources available, abundantly in nature. Some of the renewable sources include geothermal, solar, biomass, wind and hydro. Distributed generation is very well suited to the above-mentioned technologies as it can be located close to the user and can be installed in small units according to the needs of the user and the customer.

The main advantages of the DG technology can be divided into three categories: customer benefits, supplier benefits and the general or national benefits [2]. From the customer's point of view, it guarantees the reliability of supply, acts as a back up power source during peak periods and also in places where it is difficult to set up a transmission or a distribution network. It also gives an opportunity for economic gains by self-generating during peak periods and results in uninterruptible power supply at a low cost. It provides flexibility of siting and also reduces the losses, increasing the economic gains due to its onsite capability.

From the suppliers' point of view, it reduces the risk of investment due to the flexibility of its size and site, increases the market competition especially in places unfriendly to set up a transmission or a distribution network and allows a low cost entry into the market.

This technology also provides some national benefits. The DG technology is relatively clean reducing the pollution. DG also provides a reliable and less expensive solution to the growing demand of electricity. It also creates job opportunities and enhances productivity due to the increased reliability and quality of the power supplied.

1.3 Distributed Generation and Voltage Support

The presence of a Distributed Generation (DG) can increase the reliability and, also, provide the necessary voltage support. DG helps reduce the burden on the source and in the process, also, improves the voltage profile of the distribution network.

These DG's cause a significant impact on the voltage profile of the system as a whole, especially in rural areas where the voltage swings and outages may be very common. However, there are possibilities of undesired changes in the voltage profile with the addition of the DG due to the over injection of the current due to the over size or the improper location of the DG, which creates a lot of scope for research on the size and the placement of the DG.

1.4 Faults and Reconfiguration

An electric power system behaves abnormally in the case of a fault. A fault is a phenomenon, which causes a short circuit. This sudden short circuit brings about many changes in the network. Although a fault is a very minor disturbance it must be attended to very quickly as it can lead to damage to equipment or a cascading effect. Reconfiguration is the process in which the system's topography is changed by altering the original structure of the layout after a fault. It can be a change in the breaker connection or a change in the switch status, such that the faulted sections are removed from the network to be repaired and the rest of the system is connected back to the supply to function normally. For this research, it is considered that the system is reconfigured after the occurrence of a fault.

1.5 DG Models

In solving a load flow problem, there are certain constraints that should be known prior to solving. There are four states in a power flow as follows, voltage magnitude, voltage angle, and the real and the reactive powers. Depending upon the variables known a priori the buses can be classified as PQ bus or a PV bus.

In a PQ bus the net powers (P and Q) are known with the unknowns being the voltage and the angle. At the PQ bus there is no generating facility. These buses are controlled by the automatic voltage regulator which keeps the voltage magnitude at a constant level by adjusting the field current of the generator and hence its reactive power output. In a PV bus the real power and the voltage are known and the reactive power and the angle are the unknowns.

A DG can be modeled as a PV or a PQ bus as described above. The DG can also be modeled as a negative load, which injects real and reactive powers into the system, independent of the system voltage. In this thesis the DG is modeled both as a PQ and a PV bus. The DG modeled as a PQ bus outputs power operating at a constant power factor whereas the DG modeled as a PV bus outputs power operating at a constant voltage, which is achieved by using voltage regulators. When the DG is modeled as a PV node the power flow solution determines the machines terminal voltages, and the currents injected by the machines will be a function of the terminal voltage. The DG can be seen as a voltage dependent current source in this mode of operation.

1.6 Contingency Analysis

Contingency analysis is defined as the study of the system when it is subjected to one fault. In general cases, industries consider the probability of occurrence of the fault to be (N-1), only one fault occurs where N can be the number of buses or lines. Depending upon that assumption different strategies are planned and the necessary corrective measures and decisions are taken. But there is always a possibility of more than one fault to occur. The research work in this thesis considers three contingencies.

1.7 Overview and Organization of Thesis

The research in this thesis deals with finding the best site and the size of a DG with respect to voltage profile. To do this a DG is placed on the IEEE 13 node distribution feeder and the IEEE 37 node distribution feeder to find the best site and size for the DG, such that it improves the voltage profile of the system. On the technical side, an analysis has been done to see the effects of the DG, before and after a fault, on the system voltage profile. This study does not take into account the type of fault since the analysis is done with the system reconfigured after the fault. The IEEE 13 node feeder, being a highly unbalanced feeder was chosen as it closely represents a real time distribution system, which is also unbalanced and the IEEE 37 node was chosen as it closely represents a shipboard power system.

This thesis is organized as follows; this chapter introduces the need for DG, system faults, and the reconfiguration of the system after the faults, and how this relates to the research work done. Chapter II gives the background information on the project and sheds light on the different DG technologies and unbalanced power flow studies. Chapter III discusses the work done in this field and how some issues can be further developed. Chapter IV states the problem and the two test cases studied, and provides general information on the test cases. The two test cases studied are the IEEE 13 and IEEE 37 node distribution feeders. Chapter V provides details on the approach to the problem and the procedure followed to see the impact of the size and the location of the

DG on each of the feeders and presents the results and the discussions of the above work. Finally, Chapter VI suggests the benefits of this research and the areas of potential future research.

CHAPTER II

BACKGROUND

2.1 Introduction

Power systems of modern day are growing to be extremely complex and large scale. The emerging power markets and increasing economic incentives have led to operation of the power system under more challenging conditions of reliability, security, stability and efficiency. The energy market today is fast changing due to the falling prices of alternative sources of energy and heavy deregulation. This chapter provides background information on the DG technologies and the unbalanced power flow.

2.2 Motivation for Distributed Generation

The energy market faces a tough task of supplying the entire demand with continuous supply of reliable energy. Generators cannot be overloaded, so a solution to the above problem could be the employment of Distributed Generators (DG). DG's, also, solve the problem of the increasing Transmission and Distribution costs (T&D) [3].

2.2.1 *Definition of Distributed Generation*

Distributed Generation is a new approach in the power industry. There are many definitions related to Distributed Generation, and it is called by different names in different places around the world. In Europe and Asia, "Decentralized Generation' is used, Anglo-American countries use the term " Embedded Generation" and the North American countries term it " Dispersed Generation". The Electric Power Research Institute defines Distributed Generation as generation from 'a few kilowatts up to 50MW'[4]. The Gas Research Institute defines it to be generation typically between 20-25 MW [5]. The purpose of Distributed Generation is to provide a source of active power generation close to the end user.

2.2.2 Issues with Distributed Generation

This new technology provides certain benefits compared to centralized generation. The DG's can support peak demand on certain lines for major customers, while the central generating plant continues to provide maximum power. This helps in reducing power shortages maintain the voltage profile during peak periods. Figure 2.1 gives a snapshot of the benefits that a DG can provide [6].

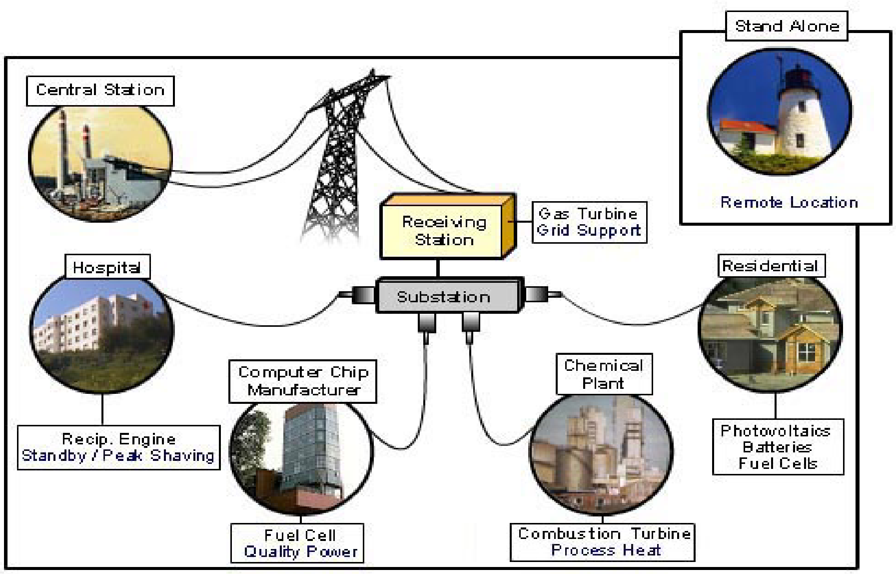

Figure 2.1 DG Benefits [6]

Having the DG closer to the load to be supplied decreases the losses compared to that of centralized generation, where the energy has to be supplied long distances. DG also provides a lower capital cost, as the units being employed are smaller. This technology can use renewable sources of energy and, hence, can be a source of green power [7]. It also provides for a local control, which is very useful in remote areas. It is easier to find sites for installing the DG's, since these plants require small plant sizes, shorter installation times and also the cost involved in the process is not as high. DG also provides the trade off options of choosing between the combinations of cost and reliability.

Deployment of DG has some disadvantages in spite of the mentioned advantages. DG requires a set of standards for interconnection. Also there is problem of reverse power flow, since the system is no more radial. Power quality and reliability are the other issues that have to be addressed. Also, the other issues to be addressed would be voltage and frequency issues [8] during islanding. IEEE 1547 [4] requires that the generator be disconnected from the grid in order to prevent an unintentional island. During a power outage, the transfer switch ensures that there is no back feed of electricity from the DG into the utility's electric distribution system as it may create safety issues for workers as well as extensive damage to equipment [6].

As there are markable advantages of installing these DG's, there are many signs of birth and growth of this new technology. This growth may lead to a huge technological change in the market, which will lead to the need for new tools to manage these systems. The past two decades have seen a drastic change in the market with the restructuring and deregulation in USA. The electricity usage has grown between 2-3% and the reserve margin has dropped to an alarming low of around 6%, which was over 20% in the early eighties [9]. Therefore, the rise of this new technology being so important, the optimal size and placement of a DG in the network will take high priority in the years to follow, as improper placement would lead to undesirable consequences. Therefore, some general trends were developed in this thesis, which would help future research on the best location and size of the DG in real time distribution systems.

2.2.3 DG Technologies

The DG can be associated with different technologies, such as renewable energy technology, combined heat and power technology and modular technology. Renewable energy resources are those, which cannot be depleted, such as the heat and light from the sun, force of the wind, organic matter, falling water, ocean energy and geothermal energy. Because of their abundance in nature these resources can be used to run generators, which reduces the depletion of other fuels.

Other technologies such as the micro hydro units, Photovoltaic units, diesel engines, fuel cells, battery storage, and solar energy consist of a number of small modules. This modular technology can be easily installed in a short period of time and the operation can start as soon as they are installed. Another advantage of using this modular technology is that the operation of each module is independent. For example, in case a module fails to operate the other modules are unaffected. This technology has an advantage of addition and removal of modules, as each is independent of the other [10-12].

The other technology is the combined heat and power technology. This technology uses waste heat from the generation of electricity for the making of steam, heating water or cooling of energy. These technologies make use of this heat, producing reusable thermal energy, thus, increasing the efficiency. Currently, the CHP plants are responsible for about 8% of the U.S electricity generation [13]. Table 2.1 gives an overview of the DG technologies and their key specifications [14].

Table 2.1 Options for DG technology [14]

Type	Size range (kW)	Electrical Efficiency (%)	Applications
Reciprocating Engines	5-7000	25-45	Backup power, base load, grid support and peak shaving
Fuel cell	1-10000	40-65	Co-generation, grid support
Photovoltaic Arrays	<1-100	5-15	Base load, peak shaving
Stirling Engines	1-25	12-20	Vehicles, Refrigeration, Aircraft, Space
Wind systems	Several kW-5000	20-40	Remote power, grid support
Micro Turbines	30-500	20-30	Stand-by power, power quality, reliability, peak shaving, and cogeneration
Biomass energy	5-10000	40-50	Co-generation, grid support

Much research is being done in the field of DG technologies. The next generation of DG technology will include turbines, fuel cells and reciprocating engines. More information about these technologies can be found in reference [6].

This thesis does not consider any particular type of DG technology but provides some general trends on the siting and sizing of a DG on two IEEE distribution feeders, which will pave the way to further development relating to a particular technology. The description of test cases will be given in chapter IV.

2.3 Load Flow

Load flow is fundamental and one of the most powerful tools for analysis of a power system. Load Flow has become powerful due to the fact that this tool is needed for designing a new power system, or for planning the extension of the existing system to accommodate the increased load demand. Load flow gives the voltages and phase angles at all the nodes and hence the power injection at all the buses and the power or current flowing through all the lines, whether it is a transmission network or a distribution network. Load flow also provides the feeder power losses, power loss in each line, and the KW and KVAR based on the specified model of the load for a distribution power flow.

2.3.1 Transmission versus Distribution Power Flow

A distribution power flow differs from transmission power flow. A transmission power flow is looped, whereas the distribution power flow is not. Also, the transmission power flow is balanced, whereas, the distribution power flow is usually unbalanced. Transmission power flow assumes a resistance to the reactance ratio, which is lower, compared to a distribution power flow. The load and generation are constantly changing in a real power system and moreover the distribution power flow is radial as there is usually flow from the source to the load. Hence, an unbalanced distribution power flow is much more complex and many changes need to be made to the existing static power flow, since the assumptions made for the transmission power flow do not hold well for distribution power flow. Keeping these constraints of the transmission power flow in view the load flow equations in the software used in this thesis, are solved iteratively, as there are many non-linear equations involved for solving these equations.

Large numbers of DG's are being incorporated into the distribution network recently. Therefore, the distribution system is no longer a single source system, but has become a significant source of power from either end, as described in the above paragraph. The power flow required should be such that it allows for repetitive calculation of power flows and should be fast, reliable and efficient. The methods used in solving the three phase balanced power flow analysis and its models cannot be used here. The software used to perform this research was developed with an aim of satisfying these entire criteria. The new software was developed to tackle the problem of unbalanced distribution power flow with DG.

2.3.2 Description of the software

The unbalanced distribution power flow software provides the option of choosing to model the DG as a PV node or a PQ node. The software handles multiple sources. It includes the new models of lines, cables, transformers, switches, and capacitors and loads necessary for solving the unbalanced distribution power flow. This software allows for the simulation of multiple faults with variations in penetration levels of the DG's. Simulation of the fault, however, requires renumbering of the nodes. The outputs from the software are three phase line-line voltages for a delta system, and positive sequence voltages at all the three phase nodes. The output, also, includes currents flowing in all lines in the system, real and reactive power contributions from the DG, and total losses in the system. More details on this software developed by Khushalani and Schulz can be obtained in [15].

2.4 Summary

The chapter provides a general overview of the need for the use of DG's. The chapter provides details about the generation and growth of this new technology and gives a brief idea on the present DG technologies and the DG technologies of the future. The advantages and the disadvantages of employing a DG and the problems associated with the improper placement of the DG, which lays the foundation for finding the optimal size and place to deploy a DG are also discussed. This chapter also presented detailed information about the distribution power flow and how it differs from a transmission power flow and also, provides some general information on the software used in this thesis to find the best site and size of a DG on the two test cases. The next chapter gives an overview of the work done in this field and work for the future.

CHAPTER III

LITERATURE REVIEW

3.1 Introduction

This chapter reviews the previous work done on the impact of distributed generation on the voltage profile of a system and also reviews the research work done on the optimal siting and sizing of a DG in a network. It also includes literature on the placement and impact of a DG on a transmission and distribution network.

3.2 Changes in Power Flows with Distributed Generation

Conventionally, every distribution power system assumes the power flow from the source to the load. However, with the advent of the distributed generation this convention has changed, as the main source is no longer the only supplier of power. With the DG's in the system the power flow can be either from the source to the load, or from the load to the source, or either, depending on loading circumstances.

In a distribution system, the key information is the value of the voltage and current at all the nodes on the feeder. With this information the power flow can be performed and the flows on each of the lines in a distribution feeder can be known. In a distribution system, this key information can be obtained by the power flow analysis. However, the involvement of DG changes these system variables. This kind of decentralized environment, which causes the reversal of power flow, has to be dealt with as it causes very unconventional voltage profiles. Thus, the long time convention has changed with the presence of the DG in the network. Therefore, it becomes very important to study the impact of the DG on the voltage profile of the system during all the conditions.

3.3 Literature on the Distributed Generation Technology and its Impacts

Research has been done in the area of Distributed Generation for the past two decades. In paper [16], the development, energy resources, equipment and standards of the DG are discussed. The different DG technologies, sources of energy and the technical issues are discussed.

Menon and Nehrir, in paper [8], presented some issues regarding the use of DG's, islanding and islanding detection. Techniques on islanding detection and their drawbacks are discussed.

In paper [9], research was done on the types of loads used in residential applications, the characterization of the composite load characteristics, and a review of the availability of DG as a cost effective solution for residential applications is done.

A review of the impacts of DG on the system protection and coordination especially in cases where a DG is added to a distribution feeder with existing line reclosers is presented in reference [17]. Some problems are encountered due to the interconnection of the DG.

In paper [18] the authors describe the problems that arise due to the integration of distributed generation. In this paper they describe that the effect of DG on coordination will depend on size, type, and placement of DG. This paper explores the effect of DG on protective device coordination such as fuse-fuse, fuse-recloser and relay-relay. In each case, depending on size and placement of DG, there are some margins in which the coordination may hold and certain cases where no margin is available. These conditions are identified for each case through coordination graphs.

Papers [19-24] discuss the issues of planning of distributed generation and optimization of operation. They also discuss the reliability issues in distributed generation.

3.4 Distributed Generation and Analytical Methods

Many studies have been done on the impact of the Distributed Generation on the voltage profile. In reference [25] the authors present a methodology to investigate the impact of reliability, voltage profile and the losses in a distribution network. A power flow analysis was done with the DG units represented as PV buses. In this paper it is assumed that there are no frequency related issues i.e, the DG and the source are disconnected with the event of a fault and the DG is reconnected after the fault is isolated making the frequency related indices free from modifications. They determined the reliability, voltage profile, and the losses with respect to the SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index), the frequency and duration related indices. The evaluation of the reliability indices was based on analytical methods. A comparison of the voltages and the losses was done before and after the installation of the DG. This methodology was found to be useful in determining the impact of the size and the installation of the DG.

An analytical method to evaluate the optimal placement of the distributed generators in power systems with respect to power loss is studied in paper [26] by Wang and Nehrir. The proposed methods can be applied to radial as well as networked systems. The proposed method was validated on the IEEE 30-bus test system and simulations were carried out to verify the results on both radial and networked systems.

Rau and Yih-heui Wan, in paper [27] proposed a method to place the DG's at selected nodes of the system such that there is a reduction in the network losses, var losses or loadings on a selected line. An optimization method is presented to minimize the losses on the system.

In paper [28] analytical expressions were derived for the voltage profile of the radial distribution feeders containing DG units. This paper analyzes the impact of the DG on the voltage profile, where it is assumed that the substation voltage is held constant. The active and the reactive powers of the DG are also expressed as a function of the location of the DG. Analytical expressions for the voltage profile along a feeder with uniformly distributed load were derived with respect to the size and the distance of the DG from the substation. The DG size for the maximum allowable voltage was derived. This analysis was extended to the feeders with multiple DG units and feeders with distributed loads.

In paper [29] the optimal siting and sizing of the DG were determined using sensitivity analysis and security-constrained optimization. It is shown that a strategic placement of the DG improves both system security and reliability by improving the voltage profile and reducing the losses.

3.5 Literature on Tabu search

Engineering and technology have been continuously providing examples on different optimization problems. Tabu search (TS) is one such iterative process designed for finding the solution to optimization problems. TS was invented by Glover and has been used to solve a wide range of hard optimization problems such as job shop scheduling, graph coloring (related), the Traveling Salesman Problem (TSP) and the capacitated arc routing problem. Hansen has also sketched the basic ideas [30]. It has been proven that tabu search has now become an established and well-used technique to solve the variety of optimization problems.

Tabu search keeps track, not only of the current information, but also some of the information related for the next iteration. It is characterized by the ability to avoid local minima by using short-term memory of recent solutions. The research done using tabu search to find the optimal size and placement of the DG has been presented in the following paragraphs.

In paper [31] the authors present a Tabu search method to investigate the reduction in losses with the optimal placement of the DG's. However, it is assumed that the number of DG's and the capacity of DG's connected at each node are known. This paper discusses an implementation method of tabu search to give information on the reduction of losses by the optimal placement and size of the DG on the demand side of a power system.

In paper [32] a new optimization technique is presented based on the combination of genetic algorithms and tabu search method for the optimal allocation of dispersed generation resources in distribution networks. It investigates the reduction of losses with the optimal placement of the DG on the demand side of the power system. The problem is formulated to determine the allocation of the DG, which minimizes the losses with the assumptions that the number of the DG's and the total capacity of the DG's are known. Validation of this method was done on an IEEE 13-node and IEEE 34-node distribution feeders taking three different sizes and types of DG's.

3.6 Distributed Generation Penetration and Transient Stability

Large penetration of DG connected at the distribution level cannot be neglected as it may impact not only the distribution network, but also the whole system including the transient system stability [33]. A study on the affect of the addition of DG on the power system shows that the transient stability is affected differently with different penetration levels, DG technology and the fault duration [34]. The same study was done with the fault applied at all possible branches of the feeder in the paper [35]. To see the impact of the DG on the transient stability of the system, the analysis was done in two ways 1) with an increase in the load covered by the DG where the centralized generation is kept constant, and 2) with the reduction of the centralized generation (constant load) with the DG covering for the reduction in the load. Similar work has been done to investigate the effect of the DG on the transient stability of the system in [36-37].

3.7 Distributed Generation and Optimal Power Flow

More DG's are going to be connected on the distribution side of the network and hence there is increasing demand for an unbalanced distribution power flow, which has the capability to allocate resources needed to mitigate the voltage instability problems. The original power flow was designed for balanced systems and hence a lot of changes had to be made for the unbalanced power flow.

An approach for coordinating DG on the micro grid, which solves the resource allocation problem with the use of a voltage stability constrained optimal power flow, is presented in paper [7]. In this study, weak nodes vulnerable for voltage collapse were identified and a locational marginal price differential for the assessment of the impact of the DG is computed.

A technique based on genetic algorithm and Optimal Power Flow for the siting and the sizing of the DG is presented in paper [38]. The optimal siting and the sizing of the DG were found with the constraint as the minimization of the cost of the active and the reactive powers. The proposed procedure has been validated on a distribution system in Iran.

Paper [15] presents a developed three-phase unbalanced power flow algorithm including a DG. This power flow algorithm is validated on an IEEE 13 node distribution feeder. This paper demonstrates the effect of the DG on the voltages and currents at each node on the feeder.

A method to address the risk associated with an inappropriately sized or located plant is addressed in paper [39]. A technique is presented, which helps evaluate the available capacity on the system. In this technique the fixed power factor DG is modeled as a negative load, and an optimal power flow is performed, by shedding the negative load that maximizes capacity and identifies available headroom.

Paper [40] presents the study made on two distribution feeders to learn the effects of adding distributed generating units to the radial distribution feeders. This paper reviews the voltage profile improvement and the power loss decrement by the addition of DG on these feeders. Similar work has been done in this thesis to arrive at the best place for the voltage improvement and the power losses. The results obtained by performing the unbalanced power flow on the IEEE 13 node and IEEE 34 node feeders, like the voltages and losses were taken as the basis to determine the best place and size of the DG on each of these feeders.

3.8 Distributed Generation and Genetic Algorithms

Genetic algorithms have played a very important role for finding the optimal placement and size of a DG. Researchers have used genetic algorithms for finding the optimal placement and size of the DG.

A three-step procedure for establishing the best distributed generation siting and sizing on a MV distribution line, considering all the technical constraints like: feeder capacity limits, feeder voltage profile, and three-phase short circuit current in the network nodes, using genetic algorithms and decision theory was proposed by Celli and Pilo in paper [41].

A methodology, based on genetic algorithms which allows the planner to decide the best compromise between the cost of network upgrading, cost of power losses, cost of energy not supplied and the cost of energy required by the customers was proposed in paper [42].

Paper [43] presents the study of the design of reactive power supply of micro grids (a system of dispersed resources connected to a distribution feeder in this paper). The optimum allocation of reactive power necessary to maintain adequate voltages on a particular micro grid was obtained using a genetic algorithm.

An efficient method for Volt/Var control in radial distribution network taking DG into account is presented in paper [44]. In this paper the DG's are considered to be PV nodes. Minimization of losses is achieved by the Volt/Var control, which is achieved by controlling the Load Tap Changer (LTC), voltage regulators and capacitors, which are used to minimize the losses. A genetic algorithm was used to minimize the objective function and the validation was done on the IEEE 34 bus radial distribution feeder.

In this thesis, the impact of a DG on the distribution contingency analysis was done using the unbalanced distribution power flow software. A post fault evaluation on the voltage profile of the system was done to find the best size and the placement of a DG, when the load is reduced, due to an open circuit after a fault. The faulty section of the system was isolated and the system was reconfigured after a contingency. An analysis was also done to analyze the effect of the DG placement on the system with and without a contingency. The results and the trends obtained from the analysis are presented in the chapters to follow.

3.9 Summary

This chapter reviews the previous work done on the optimal size and placement of the DG on the network. It presents the different techniques used, like the genetic algorithms, decision theory, and optimal power flow to determine the optimal placement of the DG. The next chapter provides the details on the test cases used in this research work and also provides the approach taken to solve the problem.

CHAPTER IV

PROBLEM STATEMENT AND TEST CASES

4.1 Introduction

This chapter presents the problem statement and also the test cases on which this research was performed. Contingencies were created at different locations on the test feeders and the DG was placed at different locations on the feeder with different sizes modeled as a PV and a PQ node. It also provides details on the contingency locations, DG locations and DG sizes. The next section describes the problem statement in detail followed by a general overview and assumptions made on the test cases.

4.2 Problem Statement

Most distribution systems have been designed to operate with the main source as the only supplier of the loads with the power flowing from the source to the end of the feeder. However, DG involvement has changed the convention of the power flow being radial. Now the power flow can be reversed with the DG sending power in either direction from where it is placed, thus, disturbing the radiality. The power flow changes with change in DG location and size and loading conditions. A study can be done to see the impact of DG on criteria like voltage, losses and reliability, and economics, etc. It is paramount to focus on the optimal placement and size of a DG on a distribution system to keep the system in an economical and secured state. There has to be a trade off between the above criterions depending on the requirements of the situation. With rapid penetration of DG into distribution systems, it is critical to assess power system impacts accurately so that these DG units can be applied in a manner that avoids causing degradation of power quality, reliability, and control of the utility system. On the other hand, DG has great potential to improve distribution system performance and it should be encouraged. Thus, it has become imperative to study changes that DG brings with a change in its location or size and the loading conditions.

This chapter focuses on the test systems considered for this research, and the analysis done to achieve the results for the optimal size and placement of a DG on the test cases with respect to voltage and losses. This work was done on two feeders, which are unbalanced. The unbalanced power flow was run on both feeders for different cases and the situations created. A technical evaluation was done to look at the impacts of a change in the location, size of DG and also a change in the loading conditions due to the reconfigurations caused by faults, on the system voltage profile. This thesis deals only with changes in voltage profile of the DG before and after the reconfigurations caused by the faults and does not consider the type of fault as it is assumed that the system is reconfigured after the isolation of the fault. This study may help in finding some trends for the optimal size and location of the DG for bigger and real time systems in the future.

The research in this thesis focuses on the DG impacts after reconfiguration. It gives the analysis of the impact of the DG location and size on that state of the system, after a contingency with a change in the system topology and the loading conditions.

Research has been done on the steady state of a system and also after the system is stabilized after a fault. This thesis focuses mainly on the intermediate state of the system where a fault happens and faulty part of the system is isolated and the system is reconfigured to continue operation, and how the DG impacts the system voltage due to its size, placement and a change in the loading conditions due to the fault.

As mentioned in section 1.5 the DG is modeled both as a PQ and a PV node. The objective to find the optimal location for a DG in the distribution system that results in the least voltage deviations was done by taking the required voltage at each node to be 1.0 p.u, for all the DG nodes modeled as PV. The analysis was performed for three different sizes of DG, one-third, half, and two-thirds of total load capacity. Three different contingencies were considered with a DG placed at four different locations and modeled as a PV node and a PQ node.

4.3 IEEE/PES test cases

The following sections give a general overview of the test cases and the assumptions taken for this research. The topologies after the reconfiguration of the system after the fault are presented. The locations of the DG placements and the locations of the different contingencies created on the system are presented. The contingency locations in this thesis are selected randomly. It is selective prioritization as only three random locations are selected to look at the impact of the size, location and model of DG on the intermediate state of the system after a fault, with the system reconfigured after the removal of the faulty section and before restoration of the system. The impact of the DG was observed with the change in the system load after the fault. These locations were chosen such that an estimate of the best location among the chosen locations is obtained. It is not a contingency analysis done looking at all the possible faults, which would give the optimal location for the placement of the DG. This analysis gives the best placement of the DG at one of the selected DG locations.

4.3.1 IEEE 13-node feeder- Configuration

Figure 4.1 shows the general layout of an IEEE 13 node feeder.

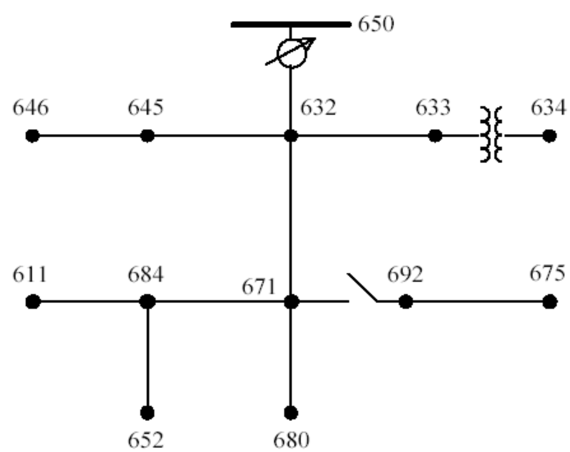

Figure 4.1 Layout of IEEE 13-node distribution feeder [45]

The IEEE 13 node feeder being a small feeder displays several characteristics. The key features of the feeder are as follows:

- Short and relatively highly loaded feeder for a 4.1 KV level.
- Overhead and underground lines with variety of phasing.

- Shunt capacitor banks.
- Inline transformer.
- Unbalanced spot and distributed loads.

4.3.2 Numbering of nodes before and after the contingency

This section shows the numbering of the system nodes for the power flow before and after the fault using the unbalanced power flow software. Figure 4.2 shows the IEEE 13-node feeder before a fault.

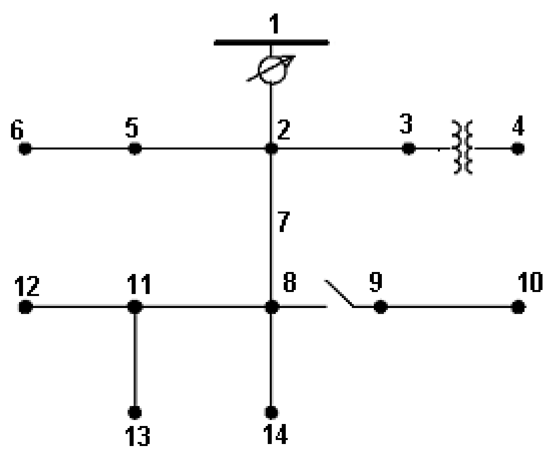

Figure 4.2 Numbering of the IEEE 13 node feeder before fault

Sometimes the main feeder supplies loads through distribution transformers tapped at several locations on the line. If every load point would be modeled as a node then there will be large number of nodes in the system. To handle this problem a dummy node was created between nodes 2 and 8 in the IEEE 13 node feeder. This dummy node is created at one-fourth length of the line from the sending node where two thirds of the load is connected and the other one-third of the load is connected at the receiving end [15].

The locations of the DG on this feeder are at nodes 3, 8, 10 and 14. These locations were chosen as the analysis with these locations could provide an estimate for the analysis at other locations on the feeder directly connected to the DG branch. The DG is placed only at the three phase nodes as the program can handle the DG modeled as a three-phase node.

The following figure shows the numbering of the IEEE 13 node feeder after reconfiguration of the system due to the fault.

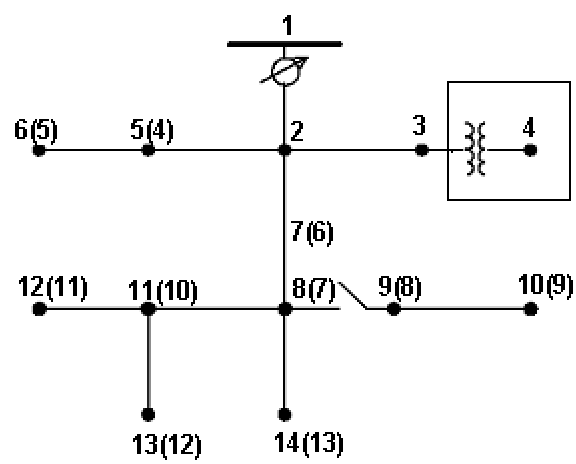

Figure 4.3 Numbering of the IEEE 13-node feeder after reconfiguration

Figure 4.3 shows a fault between nodes 3-4 where node 4 was removed to isolate the fault. The bracketed numbers show the change in the numbering from the previous numbering, after a fault. Similarly faults were created between nodes 2-5 and 8-11, where nodes 5 and 6 and 11, 12, and 13 have been removed respectively to isolate the fault in each case before the system was reconfigured. The numbering was done in a breadth first order, i.e., whenever a lateral branches of the main feeder the lateral is indexed before returning to the main feeder.

The same locations were chosen to place the DG before and after the reconfiguration of the system. The DG was placed at nodes 3, 8(7), 10(9) and 14(13), where the numbers in brackets represent the node number after the reconfiguration of the system due to the fault between nodes 3 and 4. Similarly, the DG was placed at the same nodes, for faults at the other two-locations.

The following table gives the renumbering of the nodes after the fault. It presents the renumbering of the nodes for all the fault cases discussed above. The blank spaces in the table indicate that those nodes have been removed after the fault.

Table 4.1 Numbering of nodes before and after the fault (13-node feeder)

Node Number	Original Numbering	Numbering after Reconfiguration		
		Fault btw 633-634	Fault btw 632-645	Fault btw 671-684
650	1	1	1	1
632	2	2	2	2
633	3	3	3	3
634	4	-	4	4
645	5	4	-	5
646	6	5	-	6
Distributed load Btw 632-671	7	6	5	7
671	8	7	6	8

692	9	8	7	9
675	10	9	8	10
684	11	10	9	-
611	12	11	10	-
652	13	12	11	-
680	14	13	12	11

4.3.3 IEEE 37-node Distribution Feeder

Figure 4.3 shows the general layout of an IEEE 37 node distribution feeder.

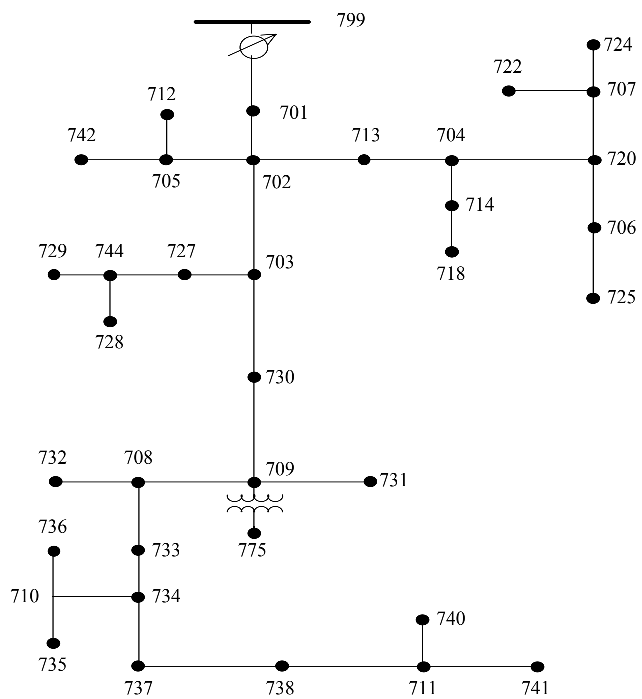

Figure 4.4 Layout of the IEEE 37-node feeder test case [45]

This feeder is characterized by

- Spot loads, single phase and three phase balanced and unbalanced loads, delta connected loads, constant KW, KVAR, constant Z, and constant I type loads.

- Three phase overhead and underground lines with different phasing of spaces.
- Substation transformer and a delta-delta inline transformer.

4.3.4 Numbering of the nodes before and after the fault

This section provides details on the numbering of the system nodes for the power flow before, and after the fault. Figure 4.5 shows the IEEE 37-node feeder before a fault.

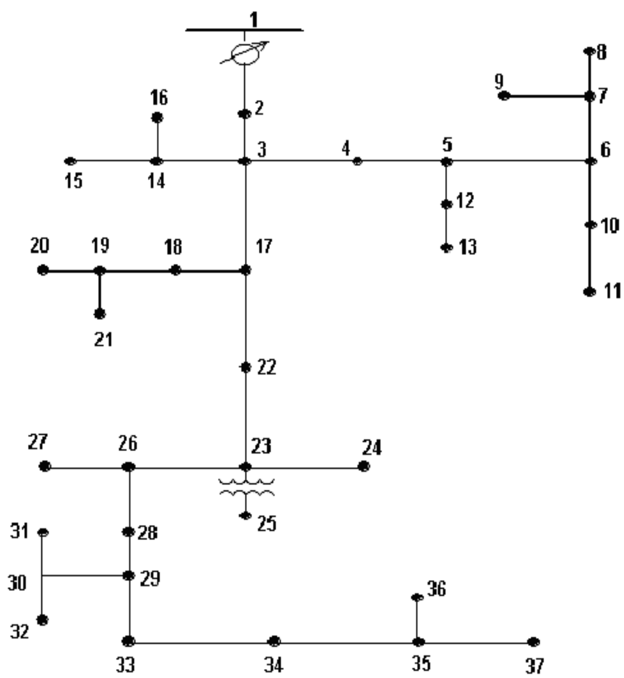

Figure 4.5 Numbering of the IEEE 37-node feeder before the fault

Figure 4.5 shows a fault between nodes 29-30 where nodes 30,31, and 32 were removed to isolate the fault. The bracketed numbers show the change in the numbering from the previous numbering, after a fault. Similarly faults were created between nodes 5-6 and 17-18 respectively, where nodes 6,7,8,9,10,11,12 and 18,19,20,21 have been removed to isolate the fault in each case before the system was reconfigured.

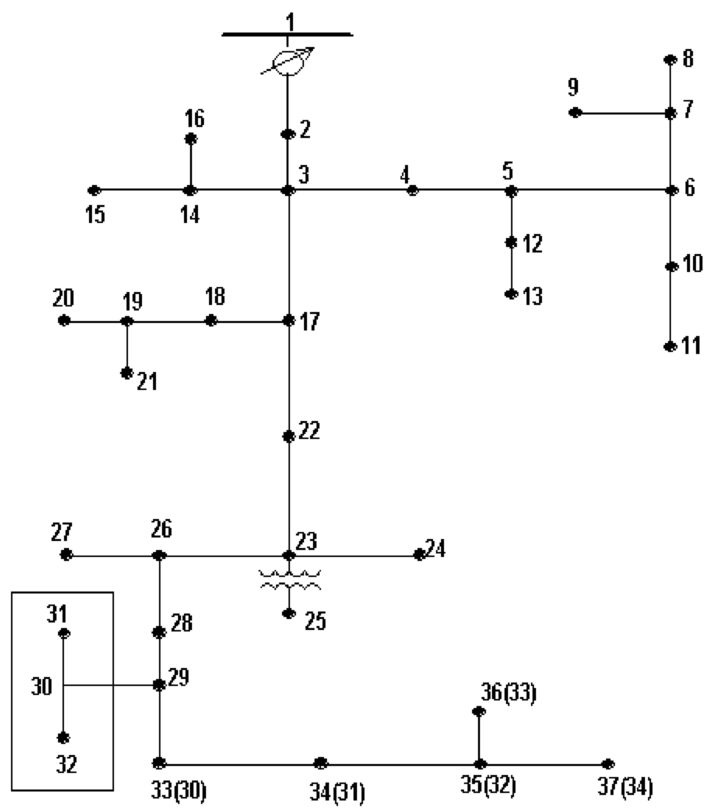

Figure 4.6 Numbering of the IEEE 37-node feeder after reconfiguration

The DG locations were chosen to be nodes 15, 23, 29 and 37 for the system before reconfiguration and the respective nodes after reconfiguration.

Table 4.2 gives the renumbering of the nodes after the fault for all the fault cases, discussed above. The blank spaces in the table indicate that those nodes have been removed after the fault.

Table 4.2 Numbering of nodes before and after the fault (37-node feeder)

Node Number	Original Numbering	Numbering after Reconfiguration		
		Fault btw 704-720	Fault btw 703-727	Fault btw 734-710
799	1	1	1	1
701	2	2	2	2
702	3	3	3	3
713	4	4	4	4
704	5	5	5	5
720	6	-	6	6
707	7	-	7	7
724	8	-	8	8
722	9	-	9	9
706	10	-	10	10
725	11	-	11	11
714	12	6	12	12
718	13	7	13	13
705	14	8	14	14
742	15	9	15	15
712	16	10	16	16

Table 4.2 (Continued)

703	17	11	17	17
727	18	12	-	18
744	19	13	-	19
729	20	14	-	20
728	21	15	-	21
730	22	16	18	22
709	23	17	19	23
731	24	18	20	24
775	25	19	21	25
708	26	20	22	26
732	27	21	23	27
733	28	22	24	28
734	29	23	25	29
710	30	24	26	-
736	31	25	27	-
735	32	26	28	-
737	33	27	29	30
738	34	28	30	31
711	35	29	31	32
740	36	30	32	33
741	37	31	33	34

4.4 Assumptions

The regulator was removed in order to clearly see the effects of the DG on the system voltage profile for both IEEE 13 and 37 node feeders.

4.5 Summary

The previous chapters and sections presented some background information in the field of DG's and the work done on finding the optimal size and placement of the DG's. Based on the information obtained, it is valuable to know the impact of size and placement of the DG's on test systems with a change in the loading conditions due to the reconfigurations after the fault.

This chapter presents details on the configuration and general overview of the test cases and, also a description of the problem. These two test cases were selected, as the IEEE 13 node feeder is highly loaded and unbalanced, whereas the IEEE 37 node feeder is ungrounded and lightly loaded, thus more likely representing a shipboard power system. The other difference between the feeders is that the 13-node feeder is wye connected and the 37-node feeder is delta connected. With the two test cases being very different from each other, the trends and results obtained may be useful for future research on any kind of a real time system with characteristics representing that of the above feeders. The following chapter provides an insight into the approach taken, results obtained, and an analysis and discussion of results.

CHAPTER V

APPROACH, RESULTS AND DISCUSSIONS

5.1 Introduction

This chapter presents the approach taken to perform this work. It provides details on the locations of the fault, the DG sizes, and the DG models. A flowchart of the work is also presented. The terminology used in this work is presented and also the criterion for the selection of the best location and size of the DG on the feeders is detailed. The procedure adopted is presented and finally, the results on the impact of the DG location, size and a change in loading conditions observed on the distribution contingency analysis are discussed.

5.2 Terminology

This section introduces the terminology used for the analysis performed in this thesis. The power flow resulted in multiple values for the voltages due to the different sizes, locations, models of the DG, and the different locations of the contingencies.

Contingency: A contingency in this thesis is taken to be a line contingency. In case a contingency was considered between two nodes then the nodes after the contingency were considered to be unavailable. For example if a fault occurred between nodes 704 and 720 on the IEEE 37 node feeder, then the nodes 720, 707, 724, 722, 702 and 725 are considered to be unavailable.

Size: The DG size is defined as the penetration of the DG with respect to the total load. The DG sizes are taken to be 1/3, 1/2 and 2/3 of the total load, with the total load on the IEEE 13 node feeder being 3.466 MW and on the IEEE 37 node feeder being 2.457MW.

5.3 Approach to the problem

The investigation for finding the best size and placement of the DG on each of test cases was done using the unbalanced power flow software developed by Khushalani and Schulz [15]. The analysis done using this software presents the trends for the optimal size and site of a DG with respect to voltage profile. When the power flow is run with this software, the results displayed are the voltages in volts, angle in degrees, current in amps and the positive, negative and zero sequence voltages. It also displays the total load on the system, and the contributions of the DG and the source towards the load.

The inputs for the study of the best size and placement of a DG on the IEEE 13 and 37 node distribution feeders were three different faults, three different sizes and four DG locations with the DG modeled as a PV node and a PQ node. The locations on the IEEE 13 node feeder considered for the study in this thesis are nodes 633, 671, 675 and 680, and the locations on the IEEE 37 node feeder are nodes 742, 709, 734 and 741. All the selected DG nodes are three phase since the program can handle three phase modeling of a DG. The sizes considered are 1/3, 1/2 and 2/3 of the total load. The faults considered for the IEEE 13 node case are faults between nodes 633-634, 632-645, and 671-684 and those for the IEEE 37 node are faults between 704-720, 703-727, and 734-710. Due to these combinations of inputs, like the different sizes, locations, and the models of the DG with the different contingency locations there was a large amount of data obtained from the power flow.

The same procedure was followed for each location and the results were obtained for each case. Thus, the power flow produced a large amount of data for each location on the feeders with a change in the model, size of the DG and location of the fault. The approach was taken such that all the possible combinations of the inputs were considered to arrive at the best location and size of the DG. The results were analyzed using the cumulative voltage deviation norm and the cumulative size norm, respectively for the best location and the size of the DG on each of these feeders. Figure 5.1 gives the flowchart of the work done to achieve the results.

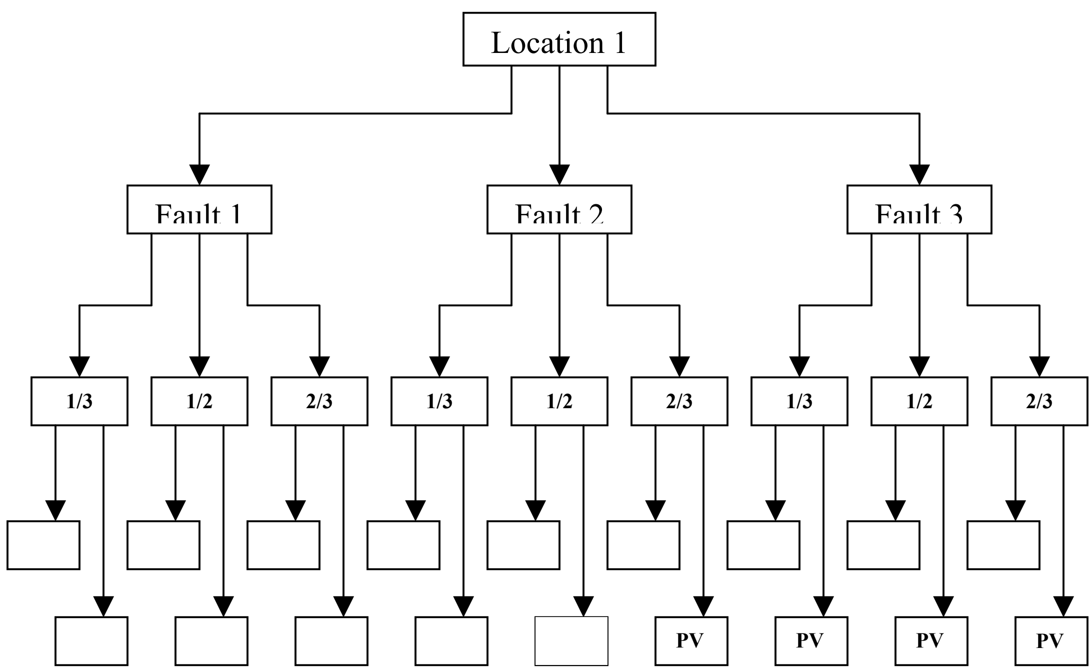

Figure 5.1 Flowchart of the work done

5.4 Cumulative Voltage Deviation Norm

The different DG sizes, locations, models and the different locations of the contingencies resulted in multiple values of voltages, which were difficult to handle. To handle these multiple values a cumulative voltage deviation norm was selected. In this thesis the positive sequence voltage is considered. This norm is defined to find the best location for the placement of the DG with respect to the voltage profile.

The cumulative voltage deviation norm per node is defined as " the normalized sum of the deviations of the obtained value from the desired value at every node on the feeder " with the desired value being 1.0 p.u and the obtained value being the value obtained from the three- phase unbalanced distribution power flow.

$$\text{Cumulative voltage deviation norm per node} = \frac{\sum_{n=1}^{K} |V_n - 1.0|}{K} \quad \text{-------Without a fault}$$

$$= \frac{\sum_{n=1}^{K-n_r} |V_n - 1.0|}{K - n_r} \quad \text{------- With a fault}$$

where V_n = positive sequence voltage at the nth node

K = the number of nodes on each feeder (14 for 13 node and 37 for 37 node)

and n_r = number of nodes that have been removed due to a line contingency

The norm given in the first equation is used for the cases without a fault and the second equation is used for that with a fault.

From the definition, it is clear that the node with the lowest voltage deviation is considered the best node for the placement of the DG, since it implies an improvement in the voltage profile of the system. Thus, the lowest cumulative voltage deviation indicates the best voltage profile.

5.5 Cumulative Size Norm

To handle the multiple results that are obtained due to various factors and to arrive at the best size for the best location of the DG on these feeders, the cumulative size norm is defined. It is selected as the criterion for sizing of the DG.

The cumulative size norm is defined as "the total cumulative voltage deviation obtained by adding the cumulative voltage deviations of all the equal sized DG's at the location selected to be the best for the placement of the DG".

Equal sized DG's were placed in one group and their cumulative voltage deviation was obtained. The cumulative voltage deviations for DG penetrations of 1/3, 1/2 and 2/3 of the total load are obtained.

From the definition of cumulative size norm, it is evident that the best size for a DG would be that value where the value of the sum of the cumulative voltage deviations of all the equal sized DG's is the least. It indicates that at that size the voltage profile has the least deviations considering the presence of the DG.

5.6 For calculating the P and Q for a PQ bus

To calculate the P and Q to model the DG as a PQ node, the power factor is considered fixed at 0.95. From the available data the P and Q for the PQ bus are calculated.

$$\text{Cos } \Phi = 0.95$$

$$\Rightarrow \quad \Phi = \cos^{-1}(0.95) = 18.194$$

We know that,

$$\text{Tan } \Phi = \frac{Q}{P}$$

$$\Rightarrow \quad Q = P * \text{Tan } \Phi$$

Table 5.1 below shows the three-phase P and Q values for the different DG sizes on the IEEE 13 node feeder.

Table 5.1 Values of P and Q for the 13-node feeder

Size	P (MW)	Q (MVAR)
1/3	1.155	0.379
1/2	1.733	0.569
2/3	2.310	0.759

Table 5.2 below shows the three-phase P and Q values for the different DG sizes on the IEEE 37 node feeder.

Table 5.2 Values of P and Q for the 37-node feeder

Size	P (MW)	Q (MVAR)
1/3	0.812	0.269
1/2	1.228	0.403
2/3	1.638	0.538

For modeling the DG as a PV node, the values of P in the above tables are used with the voltage fixed at 1.0 p.u. The DG is also modeled as a PV in both the test cases. The locations of the DG on the IEEE 13 and 37 node feeders were chosen such that the nodes directly connected to the DG connected node are not considered.

5.7 Case Scenarios

To observe the changes in voltage due to the impact of DG, the approach was divided into the following scenarios. The voltages, loads, currents, and the powers were noted in all the cases shown below.

Case 1: The base case i.e., without the DG and without the contingency.

Case 2: Without the DG and with the contingency.

Case 3: With the DG and without the contingency.

Case 4: With the DG and with the contingency.

Results were obtained for all the above case at each DG location with different sizes, models and the different fault locations. The next section presents the procedure followed to analyze the impact of the DG.

5.8 Procedure Followed

To observe the changes in voltage due to the impact of the DG the following procedure was adapted to get the cases described above. The voltages, loads, currents, and the powers were noted for all the cases. The procedure followed is given below.

1] The voltages were noted for the case without a fault and without a DG (Case 1).

2] The voltages were noted for the case with a fault but without a DG (Case 2). For this case a fault was considered between two nodes and the faulty section was isolated and the system was renumbered before the power flow was run.

3] The DG is placed at the four different locations on the feeder with one particular DG size. The voltages are noted, without any fault (Case 3) and with the DG modeled as a PQ, and a PV node.

4] A line contingency was created. The DG is placed at the four different locations on the feeder with the same DG size as in 3 above now taking the line contingency into account. The voltages are noted, with the DG modeled as a PQ, and a PV node (Case 4).

5] The voltages obtained for all the nodes (14 on 13-node feeder and 37 on 37-node feeder) were noted for all the cases.

6] The same procedure from [2-5] is followed with the other line contingencies and other sizes of the DG.

5.9 Impact of DG placement on the IEEE 13-node feeder

Figure 5.2 shows the locations of the contingencies, the branches removed due to the contingencies and the locations of the DG on the IEEE 13-node feeder. The faults are created between nodes, 633-634, 632-645, and 671-684, where the nodes inside the circle have been removed for each fault correspondingly. The DG was placed at 633, 671, 675 and 680. The regulator was removed to clearly see the effect of the DG on the system voltage. The following sections present the results and the analysis done on this feeder.

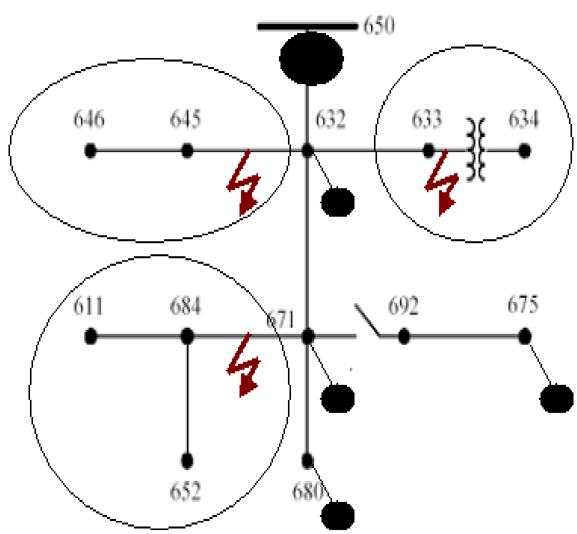

Figure 5.2 Contingency locations on the IEEE 13-node feeder

5.9.1 Effect of fault on system voltage

Table 5.3 summarizes the results of the cumulative voltage deviations before and after a fault.

Table 5.3 Cumulative voltage deviations with contingencies (13-node feeder)

Contingency location	No of nodes	Cumulative voltage deviations (p.u)	Cumulative voltage deviation per node (p.u)
Without fault	14	2.9217	0.2087
With fault between 633-634	13	2.7982	0.2152
With fault between 632-645	12	2.1558	0.1797
With fault between 671-684	11	1.1035	0.1003

Figure 5.3 shows the comparison between cases 1 and 2 with the different contingencies before the placement of the DG. A decrease in the cumulative voltage deviations was observed due to a drop in the load due to the contingency on the 13-node system. We can see that the voltage deviations have decreased from the base case irrespective of the location of the fault, which implies the increase in the voltages at all, the nodes, which can be accounted for the decrease in the load due to the fault.

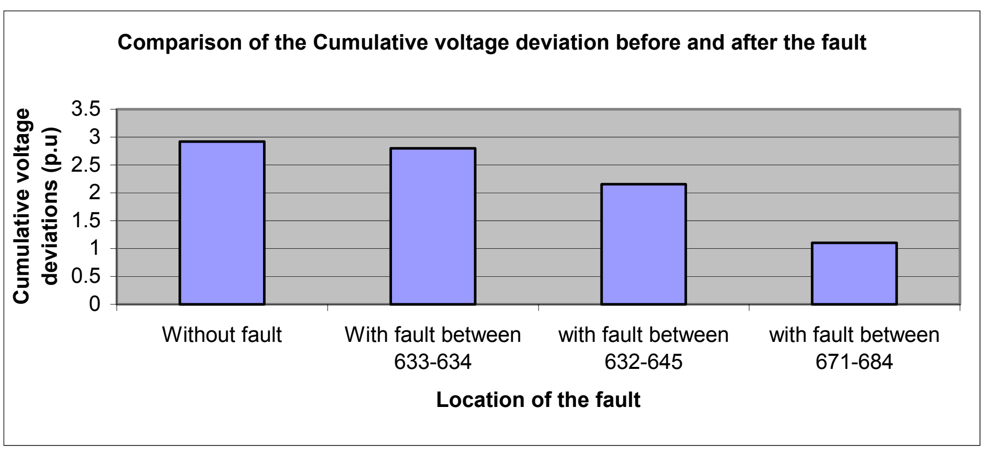

Figure 5.3 Voltage profile before and after the fault (13-node feeder)

5.9.2 Effect of the DG placement on the voltage profile without a fault

This section addresses the impact of the placement of DG units of different sizes and models at different locations on the feeder, without contingencies. Table 5.4 shows the changes in the voltages with the introduction of the DG into the system. The cumulative voltage deviation for case 1 was obtained to be 2.9217.

Table 5.4 Cumulative voltage deviations for Case 3 (13-node feeder)

DG Type	DG size	Cumulative voltage deviations (p.u)				Cumulative voltage deviations per node (p.u)			
		DG at 633	DG at 671	DG at 675	DG at 680	DG at 633	DG at 671	DG at 675	DG at 680
PQ	1/3	2.7927	2.7289	2.7234	2.7263	0.1995	0.1949	0.0430	0.1947
PQ	1/2	2.7309	2.6380	2.6307	2.6361	0.1951	0.1884	0.0263	0.1883
PQ	2/3	2.6700	2.5500	2.5413	2.5496	0.1907	0.1821	0.0192	0.1821
PV	1/3	2.7129	2.6132	2.6063	2.6068	0.1938	0.1867	0.0330	0.1862
PV	1/2	2.6115	2.4650	2.4778	2.5136	0.1865	0.1761	0.0280	0.1795
PV	2/3	2.6152	2.4332	2.4821	2.5109	0.1868	0.1738	0.0241	0.1794

Figure 5.4 shows the effect that the DG has on the improvement of the voltages before the fault. It shows the comparison between case 1 and case 3. From figure 5.4 it is evident that the presence of the DG in the system improves the voltage profile as compared to a system without a DG, independent of the DG model. However, a comparison between the two DG models shows that the deviations would be less with the DG modeled as a PV rather than as a PQ.

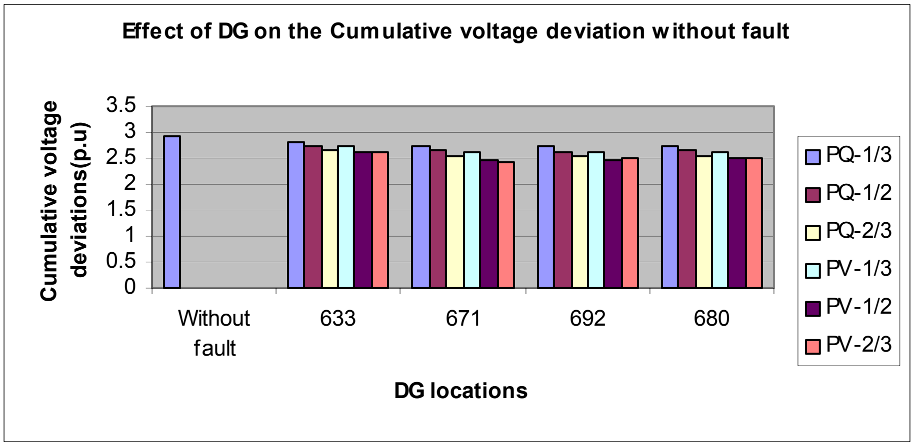

Figure 5.4 Voltage profile with and without the DG (13-node feeder)

5.9.3 Effect of the DG placement on the voltage profile in the presence of a fault

In this thesis it is considered that the system is reconfigured after the isolation of the fault. Three different contingencies are considered. Tables 5.5 and 5.6 present the different cases considered for arriving at the best place for the DG, after a fault. Contingencies are not considered for cases 0-2. In cases 3-5 the fault is located between nodes 633-634 (634 is not available) with three different DG sizes respectively. In cases 6-8 the fault is located between nodes 632-645 (645 and 646 are not available) with the three different DG sizes respectively. In cases 9-11 the fault is located between nodes 671-684 (684, 652 and 611 are not available) with the three different DG sizes respectively.

5.9.3.1 *<u>DG modeled as a PQ node</u>*

Table 5.5 presents the results obtained for the cumulative voltage deviations with the DG modeled as a PQ node at different DG locations and sizes with the different contingencies. It is clear that the voltage deviations are reduced when the DG is placed at node 675, modeled as a PQ node.

Table 5.5 Cumulative voltage deviations with the DG (PQ) placed at different nodes (13-node feeder)

Case	Dg size	Fault Location Between nodes	No of Nodes	Cumulative Voltage Deviations (p.u)				Cumulative Voltage Deviations per node (p.u)			
				DG at 633	DG at 671	DG at 675	DG at 680	DG at 633	DG at 671	DG at 675	DG at 680
0	1/3	-	14	2.7927	2.7289	2.7234	2.7263	0.1995	0.1949	0.1945	0.1947
1	1/2	-	14	2.7309	2.6380	2.6307	2.6361	0.1951	0.1884	0.1879	0.1883
2	2/3	-	14	2.6700	2.5500	2.5413	2.5496	0.1907	0.1821	0.1815	0.1821
3	1/3	633-634	13	2.6878	2.6195	2.6141	2.6168	0.2068	0.2015	0.2011	0.2013
4	1/2	633-634	13	2.6350	2.5353	2.5281	2.5331	0.2027	0.1950	0.1945	0.1949
5	2/3	633-634	13	2.5847	2.4537	2.4451	2.4528	0.1988	0.1887	0.1881	0.1887
6	1/3	632-645	12	2.0357	1.9730	1.9675	1.9702	0.1696	0.1644	0.1640	0.1642
7	1/2	632-645	12	1.9808	1.8896	1.8822	1.8873	0.1651	0.1575	0.1569	0.1573
8	2/3	632-645	12	1.9268	1.8087	1.7999	1.8076	0.1606	0.1507	0.1500	0.1506
9	1/3	671-684	11	0.9926	0.9500	0.9451	0.9470	0.0902	0.0864	0.0859	0.0861
10	1/2	671-684	11	0.9393	0.8777	0.8711	0.8748	0.0854	0.0798	0.0792	0.0795
11	2/3	671-684	11	0.8870	0.8077	0.7996	0.8056	0.0806	0.0734	0.0727	0.0732
Total Cumulative voltage deviations (p.u)				24.8633	23.8321	23.7481	23.8072	1.9451	1.8630	1.8562	1.8609

Figure 5.5 shows the comparison of the voltage deviation with respect to the location of the DG for all the cases given in Table 5.5. From Figure 5.5 and Table 5.5, it is evident that the best location of the DG modeled, as a PQ node is node 675, where the voltage deviations are the least when compared to those at other nodes.

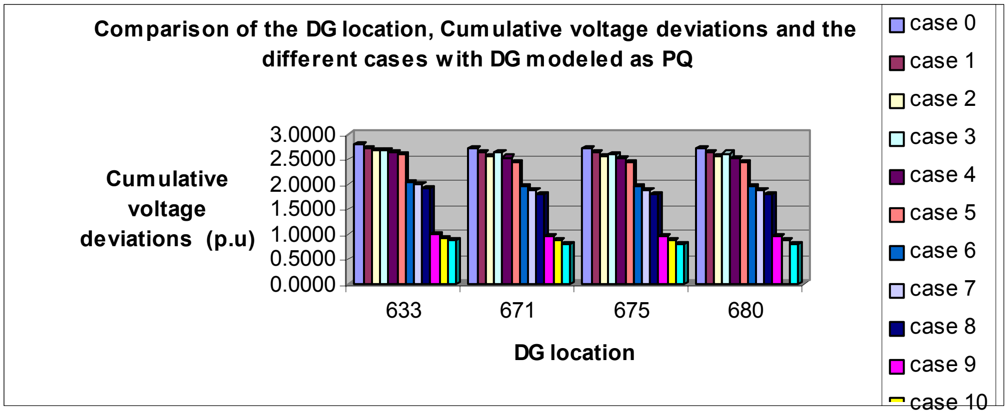

Figure 5.5 Comparison of the location of the DG, cumulative voltage deviations and the different case scenarios with the DG modeled as PQ (13-node feeder)

5.9.3.2 DG modeled as a PV node

Table 5.6 presents the results obtained for the cumulative voltage deviations with the DG modeled as a PV node with different sizes at different locations.

Table 5.6 Cumulative voltage deviations with the DG (PV) placed at different nodes (13-node feeder)

Case	Dg size	Fault Location Between nodes	No of nodes	Cumulative Voltage Deviations (p.u)				Cumulative Voltage Deviations per node(p.u)			
				DG at 633	DG at 671	DG at 675	DG at 680	DG at 633	DG at 671	DG at 675	DG at 680
0	1/3	-	14	2.7129	2.6132	2.6063	2.6068	0.1938	0.1867	0.1862	0.1862
1	1/2	-	14	2.6115	2.4650	2.4778	2.5136	0.1865	0.1761	0.1770	0.1795
2	2/3	-	14	2.6152	2.4332	2.4821	2.5109	0.1868	0.1738	0.1773	0.1794
3	1/3	633-634	13	2.6184	2.5122	2.5054	2.5057	0.2014	0.1932	0.1927	0.1927
4	1/2	633-634	13	2.5900	2.3911	2.4629	2.4562	0.1992	0.1839	0.1895	0.1889
5	2/3	633-634	13	2.5953	2.3891	2.4308	2.4538	0.1996	0.1838	0.1870	0.1888
6	1/3	632-645	12	1.9665	1.8688	1.8620	1.8623	0.1639	0.1557	0.1552	0.1552
7	1/2	632-645	12	1.9192	1.7497	1.7842	1.8126	0.1599	0.1458	0.1487	0.1511
8	2/3	632-645	12	1.9224	1.7464	1.7867	1.8089	0.1602	0.1455	0.1489	0.1507
9	1/3	671-684	11	0.9224	0.8528	0.8464	0.8461	0.0839	0.0775	0.0769	0.0769
10	1/2	671-684	11	0.8490	0.7341	0.7660	0.7928	0.0772	0.0667	0.0696	0.0721
11	2/3	671-684	11	2.7129	2.6132	2.6063	2.6068	0.0777	0.0668	0.0657	0.0721
Total Cumulative voltage deviations (p.u)				24.1772	22.4905	22.7328	22.9631	1.8901	1.7556	1.7746	1.7936

From Figure 5.6, it is evident that the best location for the placement of the DG modeled as a PV node is node 671 where the voltage deviation norm is the least when compared to the deviations at other nodes.

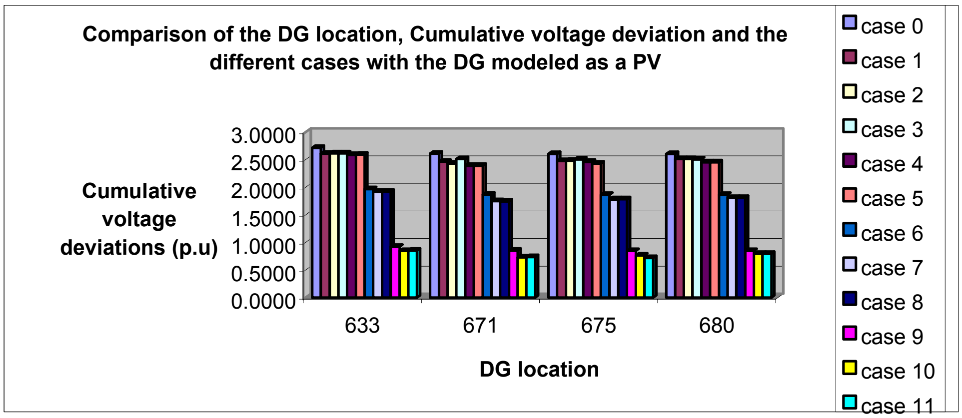

Figure 5.6 Comparison of the location of the DG, cumulative voltage deviations and the different case scenarios with the DG modeled as PV (13-node feeder)

5.9.4 Comparison of the DG models and the DG location

From Figures 5.5 and 5.6 we can see that the optimal location to place the DG with respect to voltage deviation is different for different models of the DG. Table 5.7 gives a snapshot of the best location to place the DG according to the DG model and the size with respect to the voltage deviations.

For the DG modeled as a PQ, node 675 gives better results, whereas, node 671 gives better results for DG as a PV node. From Tables 5.5 and 5.6, comparison of these two models shows that modeling the DG as a PV node, would lessen the deviations as compared to modeling it as a PQ node as the voltage deviations are smaller at every DG location with the DG as a PV node, as compared to the DG as a PQ node.

Table 5.7 Best locations for different DG models (13-node feeder)

Fault Location	DG size	Best location with DG as a PQ Node	Best location with DG as a PV Node
Without fault	1/3	675	675
	1/2	675	671
	2/3	675	671
633-634	1/3	675	675
	1/2	675	671
	2/3	675	671
632-645	1/3	675	675
	1/2	675	671
	2/3	675	671
671-684	1/3	675	680
	1/2	675	671
	2/3	675	671

5.9.5 Comparison of the DG size

Cumulative size norm is selected as criterion for sizing of the DG. The best size of the DG will be that size where the total cumulative voltage deviation is the least. It indicates that at that size the voltage profile is good.

The best size will be selected at node 671, since this node is selected as the best location to place the DG. Now the three faults with the DG placed at node 671 with the three different DG sizes and different contingency locations are analyzed. Equal sized

DG's were placed in one group and their cumulative voltage deviation was obtained. The voltage deviations of cases 0,3,6 and 9 from Table 5.6 with the DG at node 671 are added to get the cumulative voltage deviation with a DG penetration of 1/3rd of the total load. Similarly cumulative voltage deviations for DG penetrations of 1/2 and 2/3 of the total load are obtained. The results for the DG size are given in Table 5.8 below.

Table 5.8 Best size of the DG at node 671 (13-node feeder)

Contingency cases	Cumulative Voltage Deviations (p.u)			Cumulative Voltage Deviations per node (p.u)		
	1/3	1/2	2/3	1/3	½	2/3
Without fault	2.6132	2.4650	2.4332	0.1867	0.1761	0.1738
633-634	2.5122	2.3911	2.3891	0.1932	0.1839	0.1838
632-645	1.8688	1.7497	1.7464	0.1557	0.1458	0.1455
671-684	0.8528	0.7341	0.7349	0.0775	0.0667	0.0668
Total Cumulative Voltage Deviation (p.u)	5.5104	5.1933	5.1177	0.6131	0.5725	0.5699

Figure 5.7 gives a graphical representation of Table 5.8 above. It can be observed that the best size for the placement of the DG at node 671 will be 2/3 of the total load.

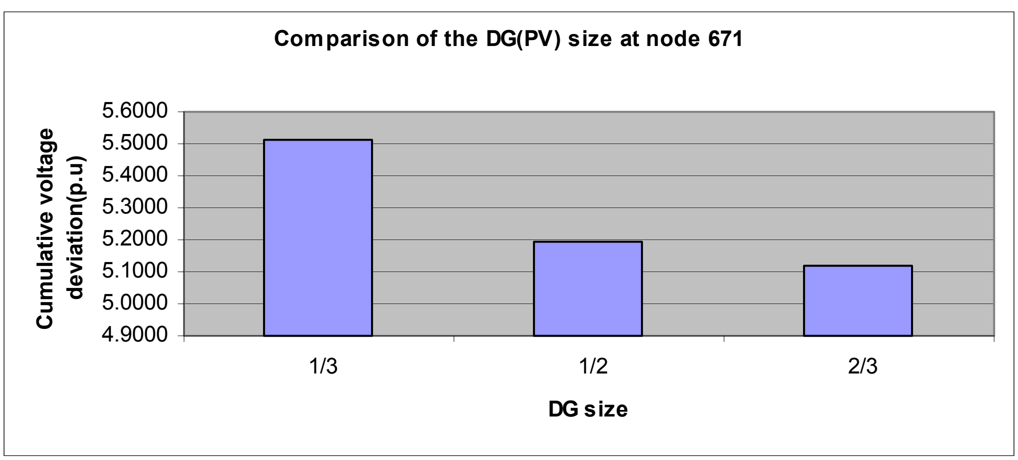

Figure 5.7 Comparison of the size of the DG with DG at node 671

5.10 Impact of DG placement on the IEEE 37 node feeder

Figure 5.8 shows the locations of the contingencies, the branches removed due to the contingencies and the locations of the DG on the IEEE 37-node feeder. The faults are created between nodes, 704-720, 703-727, and 734-710 where the nodes inside the circle have been removed for each fault respectively. The DG was placed at 742, 709, 734 and 741. The regulator was removed to clearly see the effect of the DG on the system voltage. The following sections present the results and the analysis done on this feeder.

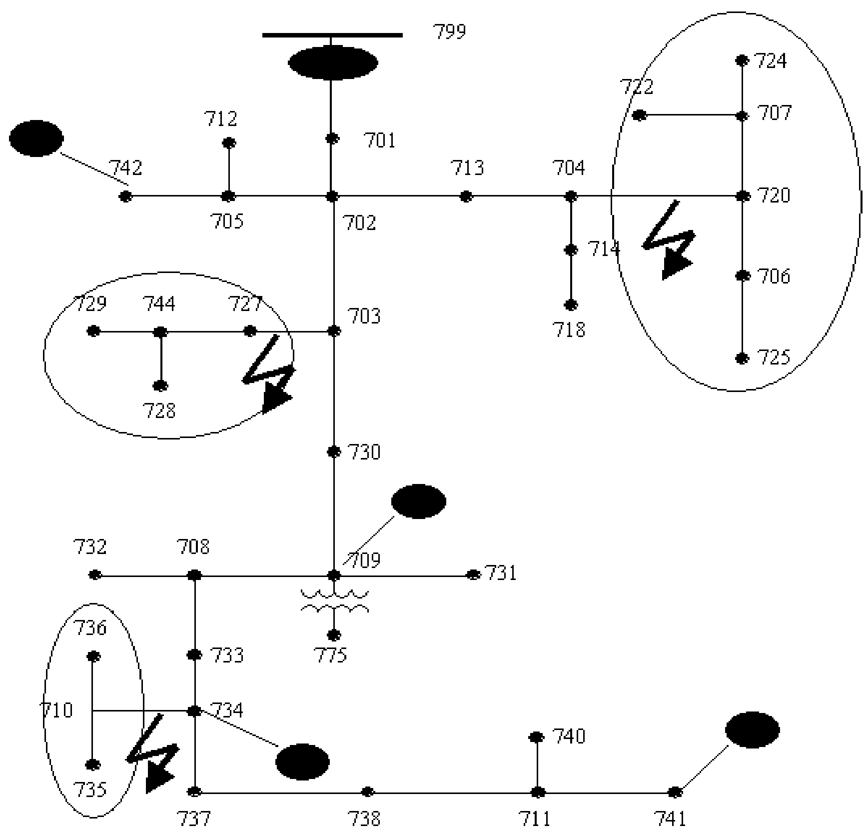

Figure 5.8 Contingency locations on the IEEE 37-node feeder

5.10.2 Effect of fault on system voltage

Whenever a fault occurs, the voltages at all the nodes change due to the change in the loading conditions as a result of contingency. The effects of the faults at various locations on the voltage deviations in the system without a DG are discussed in this section. Table 5.9 presents the values of the cumulative voltage deviations for the different contingencies.

Table 5.9 Cumulative voltage deviations with contingencies (37-node feeder)

Contingency location	No of nodes	Cumulative voltage deviations (p.u)	Cumulative voltage deviation per node (p.u)
Without fault	37	1.0737	0.0290
With fault between 704-720	31	0.8144	0.0263
With fault between 703-727	33	0.8717	0.0264
With fault between 734-710	34	0.8846	0.0268

Figure 5.9 shows the comparison between Cases 1 and 2 with the contingencies at different places. A decrease in the voltage deviation can be observed for all the considered contingencies. We can see that the voltage deviations have decreased from the base case irrespective of the location of the fault. However, the change in the voltage deviation is different for different faults as the loss of load in each case is different. This increase in the voltage can be accounted for by the decrease in the load, due to the fault.

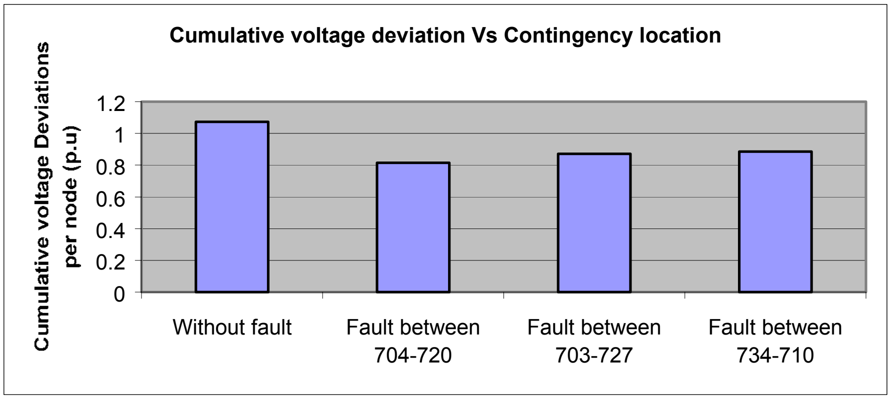

Figure 5.9 Voltage deviations before and after the fault (37-node feeder)

5.10.3 Effect of the DG placement on the voltage profile without a contingency

This section addresses the impact of the type, size, and placement of the DG units at different locations on the feeder without a contingency.

Table 5.10 shows the changes in the cumulative voltage deviations for the different types, sizes, and locations of the DG on the system. The cumulative voltage deviation without the DG was observed to be 1.0737 p.u or 0.0767 p.u per node.

Table 5.10 Cumulative voltage deviations for Case 3 (37-node feeder)

DG Type	DG size	Cumulative voltage deviations (p.u)				Cumulative voltage deviations per node (p.u)			
		DG at 742	DG at 709	DG at 734	DG at 741	DG at 742	DG at 709	DG at 734	DG at 741
PQ	1/3	0.8251	0.6810	0.6025	0.5603	0.0589	0.0486	0.0430	0.0400
PQ	1/2	0.7038	0.4859	0.3682	0.3717	0.0503	0.0347	0.0263	0.0266
PQ	2/3	0.5992	0.2885	0.2692	0.3538	0.0428	0.0206	0.0192	0.0253
PV	1/3	0.7461	0.5582	0.4620	0.4997	0.0533	0.0399	0.0330	0.0357
PV	1/2	0.7922	0.3097	0.3919	0.4740	0.0566	0.0221	0.0280	0.0339
PV	2/3	0.7048	0.3448	0.3374	0.5068	0.0503	0.0246	0.0241	0.0362

Figure 5.10 shows the effect the DG has on the improvement of the voltages regardless of the size, type or location of the DG. It shows the comparison between cases 1 and 3 with different DG sizes, models and locations. It is evident that the presence of the DG in the system improves the voltage profile as compared to a system without a DG, independent of other factors. However, the DG modeled as a PV node gives less voltage deviations than those with the DG modeled as PQ.

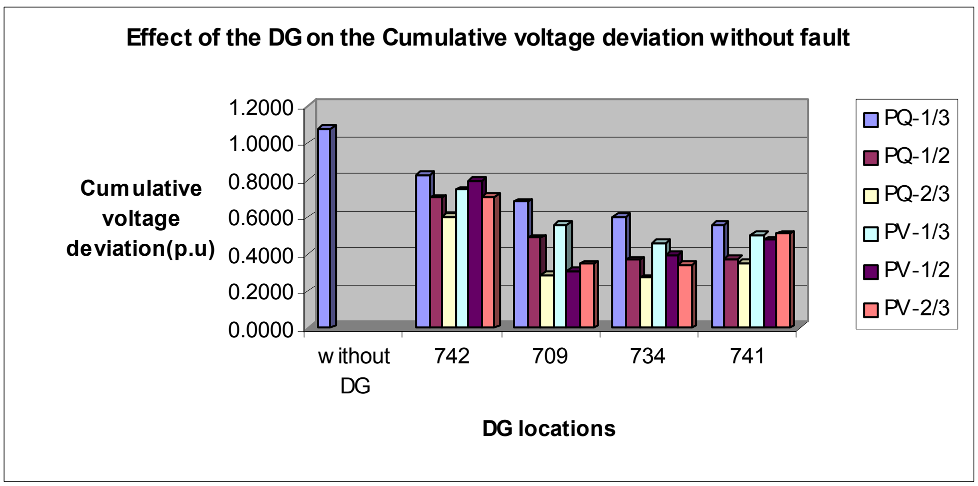

Figure 5.10 Voltage profile with and without the DG (37-node feeder)

5.10.4 Effect of the DG placement on the voltage profile after the contingency

This section discusses the effect of the DG and the contingency on the system. In this thesis, it is considered that the system is reconfigured after the isolation of the fault. Three different locations for the contingencies are considered. Tables 5.11 and 5.12 give the different cases considered for arriving at the best location for the DG, after a fault. Contingency is not considered for cases 0-2 and in cases 3-5 the fault is located between nodes 704-720 (720,707,724,722,706 and 725 are not available) with three different DG sizes. In cases 6-8 the fault is located between nodes 703-727 (727,744,729 and 728 are not available) with the three different DG sizes. In cases 9-11 the fault is located between nodes 734-710 (710,736 and 735 are not available) with the three different DG sizes. The cumulative voltage deviation obtained with the DG at the four locations, nodes 742, 709, 723 and 741 is given for all the cases.

5.10.4.1 DG modeled as a PQ node

Table 5.11 presents the results obtained for the Cumulative Voltage deviations with the DG modeled as a PQ node at different DG locations and sizes, with and without contingencies. From Table 5.11, it is clear that the voltage deviations are the least at node 741 with the DG modeled as a PQ node.

Table 5.11 Cumulative voltage deviations with the DG (PQ) placed at different nodes (37-node feeder)

Case	Dg size	Fault Location Between nodes	No of nodes	Cumulative Voltage Deviations (p.u)				Cumulative Voltage Deviations per node(p.u)			
				DG at 742	DG at 709	DG at 734	DG at 741	DG at 742	DG at 709	DG at 734	DG at 741
0	1/3	-	37	0.8251	0.6810	0.6025	0.5603	0.0223	0.0184	0.0163	0.0151
1	1/2	-	37	0.7037	0.4859	0.3682	0.3716	0.0190	0.0131	0.0100	0.0100
2	2/3	-	37	0.5992	0.2884	0.2692	0.3538	0.0162	0.0078	0.0073	0.0096
3	1/3	704-720	31	0.8144	0.4606	0.3820	0.3398	0.0263	0.0149	0.0123	0.0110
4	1/2	704-720	31	0.5768	0.6636	0.3914	0.1742	0.0186	0.0214	0.0126	0.0056
5	2/3	704-720	31	0.4351	0.1264	0.1751	0.2602	0.0140	0.0041	0.0056	0.0084
6	1/3	703-727	33	0.6488	0.5200	0.4414	0.3991	0.0197	0.0158	0.0134	0.0121
7	1/2	703-727	33	0.5448	0.3451	0.2289	0.2684	0.0165	0.0105	0.0069	0.0081
8	2/3	703-727	33	0.4624	0.1952	0.2570	0.3418	0.0140	0.0059	0.0078	0.0104
9	1/3	734-710	34	0.6552	0.5382	0.4843	0.4413	0.0193	0.0158	0.0142	0.0130
10	1/2	734-710	34	0.7074	0.6090	0.5524	0.5068	0.0208	0.0179	0.0162	0.0149
11	2/3	734-710	34	0.4559	0.2107	0.2580	0.3446	0.0134	0.0062	0.0076	0.0101
Total Cumulative voltage deviations (p.u)				7.4288	5.1241	4.4104	4.3619	0.2201	0.1517	0.1303	0.1283

Figure 5.11 shows the graphical representation of the table 5.11.

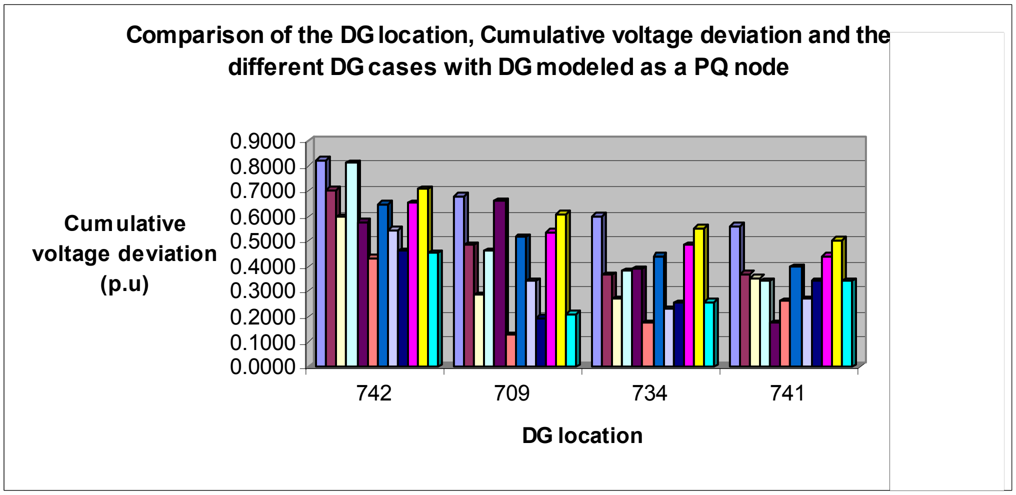

Figure 5.11 Comparison of the location of the DG, cumulative voltage deviation and the different case scenarios with the DG modeled as PQ (37-node feeder)

5.10.4.2 *<u>DG modeled as a PV node</u>*

Table 5.12 presents the results obtained for the voltage deviations with the DG modeled as a PV node at different locations and sizes. From Table 5.12, it is clear that the voltage deviations are the least at node 734 with the DG modeled as a PV node.

Table 5.12 Cumulative voltage deviations with the DG (PV) placed at different nodes (37-node feeder)

0	1/3	-	37	0.7461	0.5582	0.4620	0.4997	0.0202	0.0151	0.0125	0.0135
1	1/2	-	37	0.7921	0.3096	0.3918	0.4740	0.0214	0.0084	0.0106	0.0128
2	2/3	-	37	0.7048	0.3447	0.3373	0.5068	0.0190	0.0093	0.0091	0.0137
3	1/3	704-720	31	0.5929	0.3516	0.2560	0.3216	0.0191	0.0113	0.0083	0.0104
4	1/2	704-720	31	0.5768	0.6775	0.2246	0.3025	0.0186	0.0219	0.0072	0.0098
5	2/3	704-720	31	0.5729	0.2032	0.1509	0.3236	0.0185	0.0066	0.0049	0.0104
6	1/3	703-727	33	0.6289	0.4117	0.3163	0.4221	0.0191	0.0125	0.0096	0.0128
7	1/2	703-727	33	0.6188	0.3154	0.2925	0.3679	0.0188	0.0096	0.0089	0.0111
8	2/3	703-727	33	0.6069	0.3297	0.2183	0.3916	0.0184	0.0100	0.0066	0.0119
9	1/3	734-710	34	0.6220	0.4298	0.3642	0.4681	0.0183	0.0126	0.0107	0.0138
10	1/2	734-710	34	0.6245	0.3239	0.3535	0.4211	0.0184	0.0095	0.0104	0.0124
11	2/3	734-710	34	0.5986	0.2856	0.2767	0.4540	0.0176	0.0084	0.0081	0.0134
				7.6853	4.5409	3.6441	4.9530	0.2273	0.1351	0.1069	0.1459

Figure 5.12 shows the graphical representation of Table 5.12.

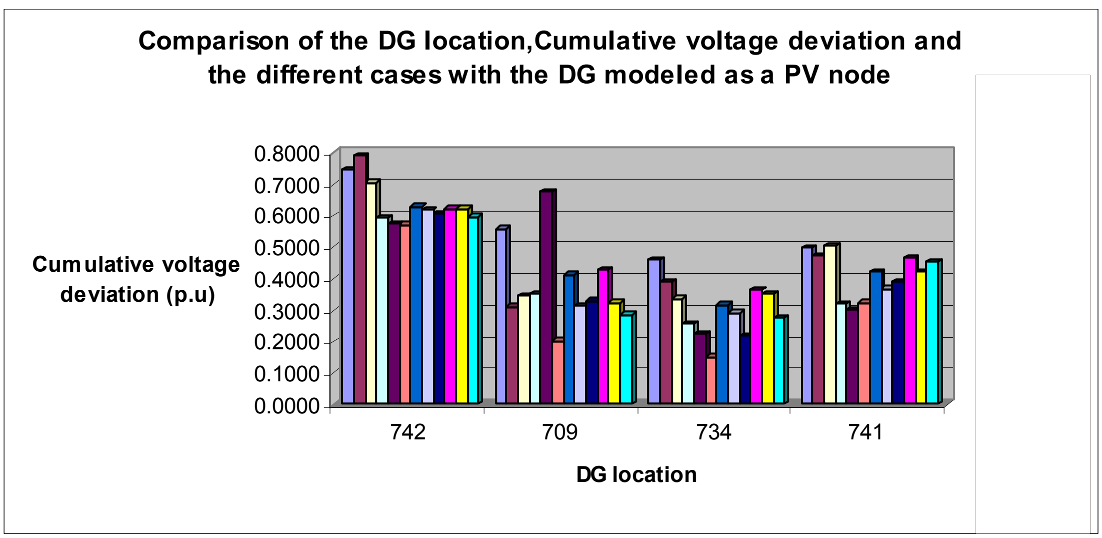

Figure 5.12 Comparison of the location of the DG, cumulative voltage deviation and the different case scenarios with the DG modeled as PV (37-node feeder)

5.10.5 Comparison of the DG models and the DG location

Table 5.13 gives a snapshot of the best location to place the DG according to the DG model and the size with respect to the voltage deviations. We can observe that the best location to place the DG to reduce the voltage deviations changes with the change in the DG type and size. Node 741 gives better results for the DG modeled as a PQ node whereas node 734 gives better results for DG modeled as a PV node., as a PV node would lessen the cumulative voltage deviation norm as compared to modeling the DG as a PQ node as is evident from tables 5.11, 5.12 and 5.13. The voltage deviations at node 734 with DG as PV are smaller than the deviations at node 741 with DG as PQ.

Table 5.13 Best locations for different DG models (37-node feeder)

Fault Location	DG size	Best location with DG as a PQ Node	Best location with DG as a PV Node
Without fault	1/3	741	734
	1/2	734	709
	2/3	734	734
704-720	1/3	741	734
	1/2	741	741
	2/3	734	734
703-727	1/3	741	734
	1/2	734	734
	2/3	709	734
734-710	1/3	741	734
	1/2	741	709
	2/3	709	734

5.10.6 Comparison of the DG size

Analysis similar to that done for the IEEE 37 node feeder is done for the IEEE 13 node feeder to find the best size at the best location. The best size for placing the DG at node 734 is selected using the cumulative size norm. Equal sized DG's were placed in one group and the sum of their cumulative voltage deviations irrespective of the different contingency cases were obtained. For example, the sum of the cumulative voltage deviations of cases 0,3,6 and 9 with the DG modeled as a PV node at node 734 are added to get the total cumulative voltage deviations for 1/3rd DG penetration. Similarly total cumulative voltage deviations for DG penetrations of 1/2 and 2/3 of the total load are obtained by adding cases 1,4,7 and 10, and 2,5,8 and 11 respectively. The results for the DG size are shown in Table 5.14.

Table 5.14 Best size of the DG at node 734 (37-node feeder)

Contingency cases	Cumulative Voltage Deviations (p.u)			Cumulative Voltage Deviations per node (p.u)		
	1/3	1/2	2/3	1/3	1/2	2/3
Without fault	0.4620	0.3918	0.3373	0.0125	0.0106	0.0091
704-720	0.2560	0.2246	0.1509	0.0083	0.0072	0.0049
703-727	0.3163	0.2925	0.2183	0.0096	0.0089	0.0066
734-710	0.3642	0.3535	0.2767	0.0107	0.0104	0.0081
Total Cumulative Voltage Deviation (p.u)	1.3985	1.2624	0.9832	0.0411	0.0371	0.0287

Figure 5.13 gives a graphical representation of the above table. It can be observed that a DG penetration of 2/3 of the total load placed at node 734 would give the least total cumulative voltage deviations.

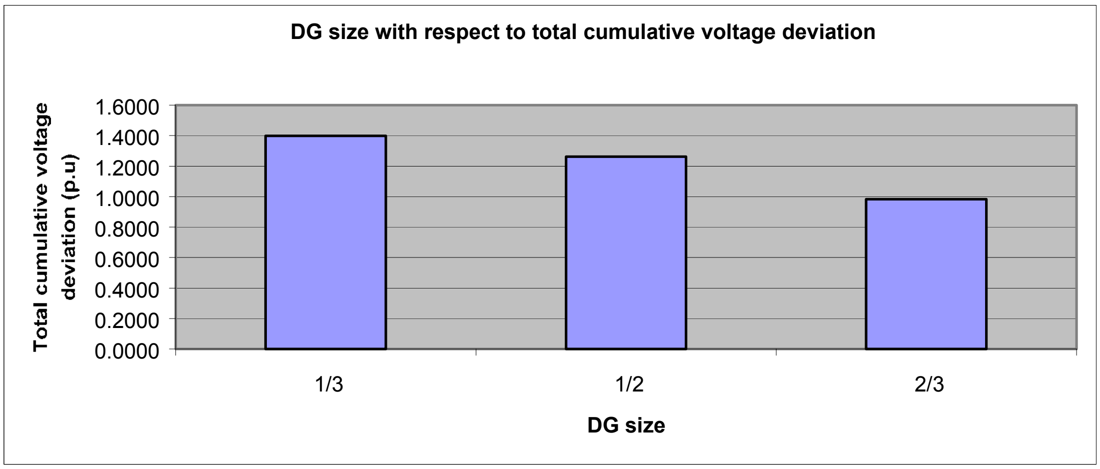

Figure 5.13 Comparison of the size of the DG with DG at node 734 (37-node feeder)

5.11 Summary

This chapter has discussed the various results obtained from the unbalanced power flow. A comparison between the voltage profile of the network with and without DG is presented. Also, the effects of the DG on the system before and after the fault are analyzed. The effects of the DG location and size on the voltages at the nodes are discussed and a comparison of the DG models was done to look at the model, which gives better results for reduction in the voltage deviations on the feeders. The next chapter gives the conclusions drawn from the results shown in this chapter and outlines the future work in this area.

CHAPTER VI

CONCLUSIONS AND FUTURE WORK

6.1 General Conclusions

Research work in this thesis presented an opportunity to look at the impacts of the DG on the distribution contingency analysis. The majority of the previous work focused on looking at the impact of the DG size and location on the system voltage without a fault or after the system is restored from the fault. This thesis focused on looking at the system voltages in the presence of a DG with the system configured after the removal of the faulty part of the system and before the restoration of the system. This reconfiguration caused a change in the loading conditions due to the removal of a part of a system due to the contingency. Also, majority of the previous work dealt with the balanced systems for simplicity. In this thesis, the power flow designed to handle the unbalanced distribution systems was used. However, this thesis focused on the assessment of the size and the location impact of the DG with a change in the loading conditions due to a contingency on unbalanced distribution systems. The optimal location and the size of the DG were selected from the results obtained from the unbalanced distribution power flow. A contingency analysis was done taking three contingencies, three different sizes and four different locations for the DG on each of the feeders with the power flow run taking both the models of the DG, i.e., PQ and PV into consideration and then the results were analyzed for the best location and size of the DG.

Previous work mostly modeled DG as a PQ node only. DG was modeled as a PQ node with negative injections into the network for simplicity. Here the DG was modeled also as a PV node and a comparison of the models was done to see the effect of the DG model on the system before and after the fault. The work done in Reference [3] used the DG as a PQ node and the placement of the DG was analyzed with a single variable optimization. This thesis presented the results for the DG modeled not only as a PQ node but also as a PV node. Further, different variables such as the DG size, model and also the location of the contingency were also considered for this work.

However, this kind of work is not feasible on large systems as it is difficult to handle the different cases and the different inputs.

6.2 Conclusions from this research

The following conclusions can be drawn from the results presented in the previous chapter.

1) The system voltages increased for a fault in the system as compared to the system without a fault. As the faulty part is removed from the system, the load on the system reduces increasing the voltages at all the nodes.
2) The voltage deviations on the system reduced considerably with the presence of the DG in the system irrespective of the type of the DG. However a comparison of the voltage deviations show that modeling the DG as a PV node reduces the deviations further.

3) The results also showed that placing the DG at the junction nodes or at the downstream nodes reduced the deviations more considerably than with the DG placed at upstream nodes on the feeder, as the DG placed further away from the source helped in providing voltage support to the downstream nodes. It can be seen that the even with the reconfigured system DG placed further away from the source helped increase the voltage at all the downstream nodes.
4) A comparison of the voltage deviations at certain nodes on the feeder with the reconfigured system for both the DG models showed that the best location to place the DG changes with DG model as the best location obtained for both the models was different. However, a DG modeled as a PV node gave lesser deviations at all the nodes as compared to the DG modeled as a PQ, as the DG modeled as a PV was able to control the voltages at the nodes reducing the voltage deviations as compared to the DG modeled as a PQ. Also, according to the way the PQ and PV nodes are defined, it is known that the PV model has some voltage control to keep the voltages within the limits whereas in the PQ model there is no control for the voltage. Thus, for large DG's the PV model is better than the PQ model to reduce the voltage deviations.
5) It can also be seen that the best location of the DG may be size dependent.
6) The best size of the DG at the best location has proven to be a DG penetration of 2/3 of the total load.

6.3 Future Work

This research work analyzed the impact of the DG on the distribution contingency analysis of the IEEE 13 and 37 node systems. These systems were chosen since the IEEE 13 node system is highly unbalanced, like the real time distribution systems and the IEEE 37 node feeder is ungrounded and lightly loaded like the shipboard power system. Future work would be to look at the location and size of the DG using real time system data. This work incorporated only one DG. Future work could be to look at the presence of two or more DG's and the impact of the size, location and the model of the DG on that system with two DG's considering the losses along with the voltage as discussed in this work. This work can also be extended to look at the response of the system for the impact of the size, location and model with the different DG technologies.

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APPENDIX A

TEST CASES

Data of IEEE 13-node feeder

Figure A.1 shows the general layout of an IEEE 13 node feeder.

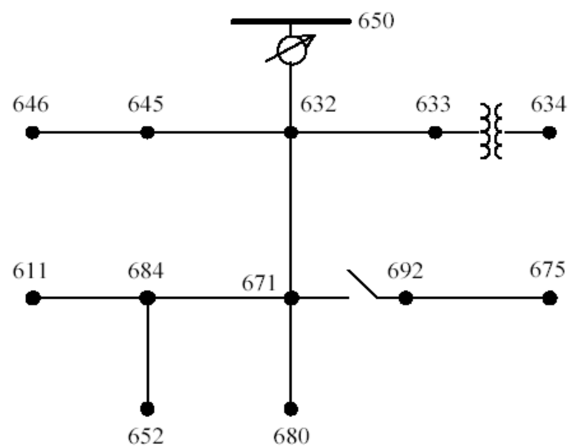

Figure A.1 Layout of IEEE 13-node distribution feeder [45]

Details of the various components of the IEEE 13-node feeder are given below.

Load Models

There are both spot and distributed loads on this feeder. Loads are both single phase and three phased, connected in both wye and delta. There are different codes for different models. The table below gives the kind of load and load model.

Table A.1 Load Models and Codes [45]

Code	Connection	Model
Y-PQ	Wye	Constant Kw and Kvar
Y-I	Wye	Constant Current
Y-Z	Wye	Constant Impedance
D-PQ	Delta	Constant Kw and Kvar
D-I	Delta	Constant Current
D-Z	Delta	Constant Impedance

All the loads are specified in Kw and Kvar.

Spot load data

The spot load data for the IEEE 13 node feeder is given in Table A.2.

Table A.2 Spot load data [45]

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 Kw	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
634	Y-PQ	160	110	120	90	120	90
645	Y-PQ	0	0	170	125	0	0
646	D-Z	0	0	230	132	0	0
652	Y-Z	128	86	0	0	0	0
671	D-PQ	385	220	385	220	385	220
675	Y-PQ	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	Y-I	0	0	0	0	170	80
	TOTA L	1158	606	973	627	1135	753

Distributed Load Data

A distributed load is served at the mid point of a segment. The load may be three-phase, two-phase or single-phase. It can be connected in wye (phase to neutral) or delta (phase to phase). It can be modeled as constant power and reactive power, constant current, constant impedance or any combination of the three. The distributed load data is given in Table A.3.

Table A.3 Distributed load data [45]

Node A	Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3
		Model	kW	kVA	kW	kVAr	kW	kVAr
632	671	Y-PQ	17	10	66	38	117	68

Shunt capacitor banks

The capacitor bank details for the IEEE 13 node feeder are given in Table A.4.

Table A.4 Capacitor bank data [45]

Node	Ph-A	Ph-B	Ph-C
	kVAr	KVAr	kVAr
675	200	200	200
611			100
Total	200	200	300

Overhead line spacing data

Each line is given a different configuration. A code is given for each line to match it with the tower data. The overhead line spacing data is given in Table A.5.

Table A.5 Overhead line Spacing [45]

Spacing ID	Type
500	Three-phase, 4wire
505	Two-phase, 3wire
510	Single-phase, 2 wire

Overhead and underground line data

Underground line configuration data is given below in Table A.6.

Table A.6 Underground line configuration data [45]

CONFIG.	PHASING	CABLE	NEUTRAL	SPACE ID
606	A B C N	250,000 AA, CN	NONE	515
607	A N	1/0 AA, TS	1/0 CU	520

Overhead line configuration data is given below in Table A.7.

Table A.7 Overhead line configuration data [45]

CONFIG.	PHASING	PHASE	NEUTRAL	SPACING
		ACSR	ACSR	ID
601	B A C N	556,50026/7	4/0 6/1	500
602	C A B N	4/0 6/1	4/0 6/1	500
603	C B N	1/0	1/0	505
604	A C N	1/0	1/0	505
605	C N	1/0	1/0	510

Transformer Data

Transformers can be located at either end node of any segment. Single-phase transformers may be connected in a wye system only and are connected phase-to-neutral. The ratings, high-low values of voltage at both sides of the transformers are given along with their R, X settings in the following Table A.8.

Table A.8 Transformer data [45]

	kVA	kV-high	kV-low	R - %	X - %
Substation	5,000	115 - D	4.16 Gr. Y	1	8
XFM -1	500	4.16 – Gr.W	0.48 – Gr.W	1.1	2

Line segment Data

A radial feeder consists of *segments.* A segment is a three-phase or single-phase overhead or underground line that may have a *distributed load* associated with it. A segment is defined by its end nodes, length (distance between the nodes in feet) and the *Z-Model.* The line segment data used for the test feeder are shown in Table A.9.

Table A.9 [45]   Line segment data

Node A	Node B	Length(ft.)	Config.
632	645	500	603
632	633	500	602
633	634	0	XFM-1
645	646	300	603
650	632	2000	601
684	652	800	607
632	671	2000	601
671	684	300	604
671	680	1000	601
671	692	0	Switch
684	611	300	605
692	675	500	606

Data of IEEE 37-node Distribution Feeder

Figure A.2 shows the general layout of an IEEE 37 node distribution feeder.

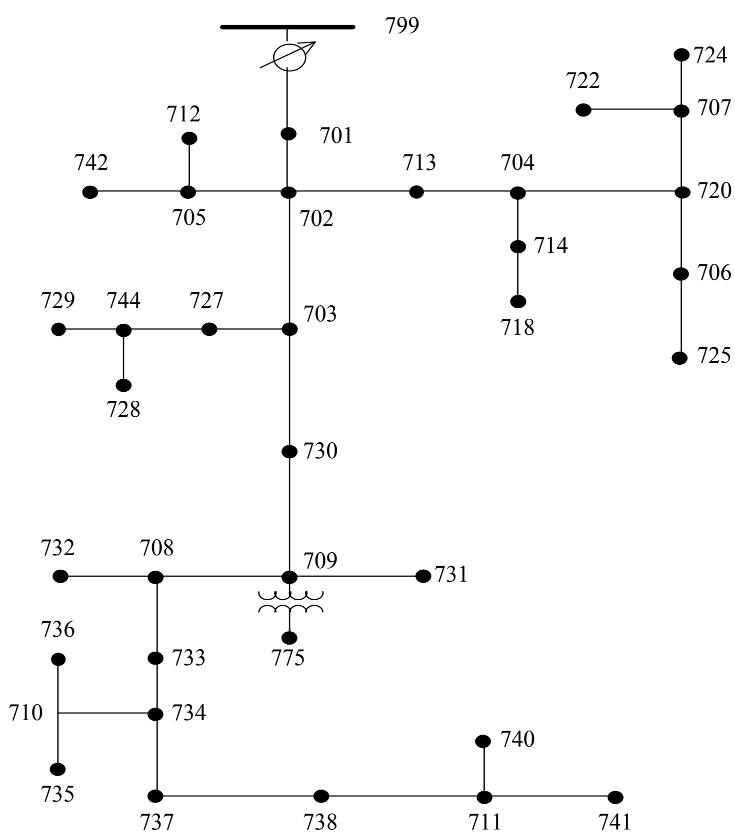

Figure A.2 Layout of the IEEE 37-node feeder test case [45]

The IEEE 37-node feeder is characterized by the data given below.

4.3.1 Underground Cable Configurations

The underground cable configurations for the IEEE 37 node feeder are given in Table 4.10.

Table A.10 Underground cable configuration data [45]

Config	Phasing	Cable	Spacing ID
721	A B C	1,000,000 AA, CN	515
722	A B C	500,000 AA, CN	515
723	A B C	2/0 AA, CN	515
724	A B C	#2 AA, CN	515

Line Segment Data

The line segment data for the IEEE 37 node feeder is given are Table A.11 below.

Table A.11 Line segment data [45]

Node A	Node B	Length (ft)	Config
701	702	960	722
702	705	400	724
702	713	360	723
702	703	1320	722
703	727	240	724
703	730	600	723
704	714	80	724
704	720	800	723
705	742	320	724
705	712	240	724

Table A.13 (Continued)

706	725	280	724
707	724	760	724
707	722	120	724
708	733	320	723
708	732	320	724
709	731	600	723
709	708	320	723
710	735	200	724
710	736	1280	724
711	741	400	723
711	740	200	724
713	704	520	723
714	718	520	724
720	707	920	724
720	706	600	723
727	744	280	723
730	709	200	723
733	734	560	723
734	737	640	723
734	710	520	724

Table A.13 (Continued)

737	738	400	723
738	711	400	723
744	728	200	724
744	729	280	724
775	709	0	XFM-1
779	701	1850	721

Load Models

There are only spot loads on this feeder. Loads are delta connected. This feeder has both single phase and three phase loads.

Table A.12 Load models [45]

Code	Connection	Models
D-PQ	Delta	Constant Kw and Kvar
D-I	Delta	Constant current
D-Z	Delta	Constant impedance

Spot load data

Spot load data for the feeder is given in Table A.13 below

Table A.13 Spot load data [45]

Node	Load Model	Ph-1 KW	Ph-1 Kvar	Ph-2 KW	Ph-2 Kvar	Ph-3 KW	Ph-3 Kvar
701	D-PQ	140	70	140	70	350	175
712	D-PQ	0	0	0	0	85	40
713	D-PQ	0	0	0	0	85	40
714	D-I	17	8	21	10	0	0
718	D-Z	85	40	0	0	0	0
720	D-PQ	0	0	0	0	85	40
722	D-I	0	0	140	70	21	10
724	D-Z	0	0	42	21	0	0
725	D-PQ	0	0	42	21	0	0
727	D-PQ	0	0	0	0	42	21
728	D-PQ	42	21	42	21	42	21
729	D-I	42	21	0	0	0	0
730	D-Z	0	0	0	0	85	40
731	D-Z	0	0	85	40	0	0
732	D-PQ	0	0	0	0	42	21
733	D-I	85	40	0	0	0	0
734	D-PQ	0	0	0	0	42	21
735	D-PQ	0	0	0	0	85	40
736	D-Z	0	0	42	21	0	0
737	D-I	140	70	0	0	0	0
738	D-PQ	126	62	0	0	0	0
740	D-PQ	0	0	0	0	85	40
741	D-I	0	0	0	0	42	21
742	D-Z	8	4	85	40	0	0
744	D-PQ	42	21	0	0	0	0
Total		727	357	639	314	1091	530

Transformer data

This feeder has an inline transformer and a substation transformer. The data for these transformers are given in Table A.14 below

Table A.14   Transformer data [45]

Transformer Type	KVA	KV-High	KV-Low	R-%	X-%
Substation	2,500	230D	4.8 D	2	8
Inline	500	4.8D	.480D	0.09	1.81

APPENDIX B

RESULTS FROM POWER FLOW

IEEE 13 node feeder

Case 1: Without DG without fault (Base case)

Table B.1 Magnitude of current in amps and angle in degrees

1	591.76	440.44	626.22	-29.635	-142.51	91.754
2	591.76	440.44	626.22	-29.635	-142.51	91.754
3	87.144	64.427	67.783	-38.103	-159.28	80.198
4	755.25	558.37	587.45	-38.103	-159.28	80.198
5	0	148.59	66.355	0	-143.3	57.26
6	0	66.355	66.355	0	-122.74	57.26
7	505.73	231.1	507.71	-28.181	-137.39	97.537
8	499.98	210.55	468.2	-28.115	-135.94	98.444
9	246.55	65.1	191.02	-20.572	-58.394	105.16
10	220.49	65.1	136.39	-8.7445	-58.394	105.77
11	58.815	0	70.895	-39.733	0	118.61
12	0	0	70.895	0	0	118.61
13	58.815	0	0	-39.733	0	0
14	0	0	0	0	0	0

Table B.2 Magnitude of line-neutral voltages in volts and angle in degrees

1	2403.9	2401.5	2404	0.04547	-119.99	120.02
2	2297.5	2379.4	2268.1	-2.7477	-121.86	117.62
3	2289.7	2374.6	2261.7	-2.8225	-121.91	117.63
4	257.09	268.64	255.34	-3.5946	-122.41	117.07
5	0	2356.4	2263.4	0	-122.05	117.65
6	0	2352.1	2258.4	0	-122.13	117.7
7	2277.9	2384	2241.2	-3.4906	-122.02	117.09
8	2218.5	2404.3	2163.7	-5.8854	-122.52	115.62
9	2219.2	2404.3	2163.8	-5.8852	-122.52	115.61
10	2201.9	2410.2	2158.2	-6.1591	-122.71	115.65
11	2214.3	0	2158.6	-5.9097	0	115.51
12	0	0	2153.6	0	0	115.36
13	2200.1	0	0	-5.837	0	0
14	2218.8	2404.4	2163.7	-5.8856	-122.53	115.62

Table B.3 Magnitude of voltage in p.u and angle in degrees

1	1.0009	0.99988	1.0009	0.04547	-119.99	120.02
2	0.95657	0.99067	0.94433	-2.7477	-121.86	117.62
3	0.95333	0.98868	0.9417	-2.8225	-121.91	117.63
4	0.92768	0.96937	0.92137	-3.5946	-122.41	117.07
5	0	0.9811	0.94238	0	-122.05	117.65
6	0	0.97933	0.94028	0	-122.13	117.7
7	0.94842	0.99258	0.93315	-3.4906	-122.02	117.09
8	0.92368	1.0011	0.90087	-5.8854	-122.52	115.62
9	0.92397	1.0011	0.90093	-5.8852	-122.52	115.61
10	0.91679	1.0035	0.8986	-6.1591	-122.71	115.65
11	0.92193	0	0.89876	-5.9097	0	115.51
12	0	0	0.89666	0	0	115.36
13	0.91604	0	0	-5.837	0	0
14	0.9238	1.0011	0.90086	-5.8856	-122.53	115.62

Table B.4 Magnitude of positive, negative and zero sequence voltages in p.u and angle in degrees

1	1.0006	0.00024787	.00050819 0	0.023247	-27.132	80.604
2	0.96384	0.011652	0.016939	-2.3239	120.13	-95.852
3	0.96121	0.01158	0.017455	-2.363	120.46	-97.749
4	0.93944	0.012201	0.01918	-2.9718	130.87	-103.07
5	0.64116	0.32224	0.31931	-2.1995	175.81	179.81
6	0.63987	0.32096	0.31931	-2.2157	175.77	179.81
7	0.958	0.014637	0.022902	-2.794	126.25	-93.862
8	0.94159	0.023992	0.042255	-4.2154	136.05	-94.015
9	0.94171	0.023923	0.042235	-4.2162	135.96	-93.882
10	0.93934	0.025296	0.044701	-4.356	137.17	-98.462
11	0.60685	0.31001	0.29699	-5.2091	-63.973	53.5
12	0.29889	0.29889	0.29889	-4.6423	-124.64	115.36
13	0.30535	0.30535	0.30535	-5.837	-5.837	-5.837
14	0.94164	0.023962	0.042264	-4.2162	135.94	-93.983

Total Load in the system in term of P and Q= 3.3212e+006 +1.9801e+006i

Source P and Q= 3.5389e+006 +1.8224e+006

Case 2: Without DG with fault between 633-634

Table B.5 Magnitude of current in amps and angle in degrees

1	502.24	377.08	556.44	-27.776	-139.34	93.518
2	502.24	377.08	556.44	-27.776	-139.34	93.518
3	0	0	0	0	0	0
4	0	147.99	65.973	0	-143.04	57.541
5	0	65.973	65.973	0	-122.46	57.541
6	502.24	229.6	504.54	-27.776	-136.96	97.924
7	496.55	209.13	465.35	-27.709	-135.48	98.851
8	244.02	65.338	189.75	-19.974	-57.924	105.7
9	218.29	65.338	135.13	-7.9813	-57.924	106.4
10	59.383	0	70.913	-39.363	0	119
11	0	0	70.913	0	0	119
12	59.383	0	0	-39.363	0	0

Table B.6 Magnitude of line-neutral voltages in volts and angle in degrees

1	2402.8	2401.6	2403.6	0.028595	-120	120.02
2	2317.6	2386.1	2284.2	-2.4308	-121.57	117.75
3	2317.6	2386	2284.2	-2.4308	-121.57	117.75
4	0	2363.2	2279.6	0	-121.76	117.78
5	0	2359	2274.6	0	-121.84	117.83
6	2298.8	2390.8	2257.5	-3.1574	-121.74	117.23
7	2239.9	2411	2180.7	-5.5154	-122.23	115.76
8	2240.5	2411	2180.8	-5.5152	-122.23	115.76
9	2223.5	2416.9	2175.2	-5.7862	-122.42	115.79
10	2235.7	0	2175.6	-5.5398	0	115.66
11	0	0	2170.6	0	0	115.5
12	2221.4	0	0	-5.4672	0	0
13	2240.2	2411.1	2180.6	-5.5157	-122.23	115.76

Table B.7 Magnitude of voltage in p.u and angle in degrees

1	1.0004	0.99991	1.0008	0.028595	-120	120.02
2	0.96497	0.99348	0.95106	-2.4308	-121.57	117.75
3	0.96497	0.99345	0.95103	-2.4308	-121.57	117.75
4	0	0.98395	0.94912	0	-121.76	117.78
5	0	0.98218	0.94704	0	-121.84	117.83
6	0.95713	0.99541	0.93991	-3.1574	-121.74	117.23
7	0.93261	1.0039	0.90794	-5.5154	-122.23	115.76
8	0.93286	1.0039	0.90799	-5.5152	-122.23	115.76
9	0.92577	1.0063	0.90568	-5.7862	-122.42	115.79
10	0.93083	0	0.90583	-5.5398	0	115.66
11	0	0	0.90374	0	0	115.5
12	0.92489	0	0	-5.4672	0	0
13	0.93271	1.0039	0.90792	-5.5157	-122.23	115.76

Table B.8 Magnitude of positive, negative and zero sequence voltages in p.u and angle in degrees

1	1.0004	0.00015351	0.0003525	0.016103	-60.191	94.675
2	0.96982	0.010929	0.015229	-2.0788	119.87	-88.616
3	0.9698	0.010918	0.015228	-2.0789	119.79	-88.612
4	0.64435	0.32455	0.32011	-1.989	176.24	179.81
5	0.64307	0.32329	0.3201	-2.0051	176.2	179.81
6	0.9641	0.013882	0.02119	-2.543	125.96	-88.15
7	0.94786	0.023165	0.040372	-3.9486	136.3	-90.812
8	0.94796	0.023106	0.040357	-3.9493	136.22	-90.692
9	0.94564	0.024456	0.04265	-4.0884	137.47	-95.589
10	0.61219	0.31171	0.30065	-4.9501	-63.623	53.674
11	0.30125	0.30125	0.30125	-4.4954	-124.5	115.5
12	0.3083	0.3083	0.3083	-5.4672	-5.4672	-5.4672
13	0.9479	0.023139	0.040382	-3.9493	136.21	-90.785
1	1.0004	0.00015351	0.0003525	0.016103	-60.191	94.675

Total Load in the system in term of P and Q= 2.9269e+006 +1.6937e+006i

Source P and Q= 3.1188e+006 +1.4596e+006i

Case 3: With DG (at 671 modeled as PQ with 1/3 penetration of the total load) without fault

Table B.9 Magnitude of current in amps and angle in degrees

1	403.17	266.51	430.99	-30.332	-142.21	91.463
2	403.17	266.51	430.99	-30.332	-142.21	91.463
3	85.804	63.972	66.705	-37.322	-158.43	81.006
4	743.63	554.42	578.11	-37.322	-158.43	81.006
5	0	147.24	65.602	0	-142.44	58.223
6	0	65.602	65.602	0	-121.78	58.223
7	318.18	60.716	314.23	-28.452	-124.51	100.26
8	312.53	42.838	275.76	-28.369	-111.85	102.02
9	239.21	66.207	186.06	-18.194	-55.902	108.24
10	213.95	66.207	131.5	-5.8934	-55.902	109.47
11	60.544	0	70.972	-38.09	0	121.28
12	0	0	70.972	0	0	121.28
13	60.544	0	0	-38.09	0	0
14	0	0	0	0	0	0

Table B.10 Magnitude of line-neutral voltages in volts and angle in degrees

1	2402.8	2401.7	2402.4	0.017708	-119.99	120
2	2331.2	2395.6	2303.2	-1.9925	-121.01	118.41
3	2323.5	2390.8	2296.7	-2.0646	-121.06	118.42
4	261.1	270.55	259.47	-2.8137	-121.56	117.88
5	0	2372.8	2298.6	0	-121.2	118.44
6	0	2368.6	2293.6	0	-121.28	118.49
7	2319.7	2404.1	2283.7	-2.5422	-120.96	118.09
8	2283.7	2435.5	2231.5	-4.2428	-120.84	117.33
9	2284.1	2435.5	2231.5	-4.2431	-120.84	117.33
10	2267.5	2441.3	2226.3	-4.5072	-121.02	117.35
11	2279.3	0	2226.5	-4.2665	0	117.22
12	0	0	2221.5	0	0	117.07
13	2264.8	0	0	-4.1938	0	0

Table B.11 Magnitude of voltage in p.u and angle in degrees

1	1.0004	0.99995	1.0003	0.017708	-119.99	120
2	0.97062	0.99741	0.95895	-1.9925	-121.01	118.41
3	0.96743	0.99544	0.95627	-2.0646	-121.06	118.42
4	0.94218	0.97627	0.93627	-2.8137	-121.56	117.88
5	0	0.98793	0.95703	0	-121.2	118.44
6	0	0.98617	0.95496	0	-121.28	118.49
7	0.96582	1.001	0.95085	-2.5422	-120.96	118.09
8	0.95085	1.014	0.9291	-4.2428	-120.84	117.33
9	0.95098	1.014	0.92912	-4.2431	-120.84	117.33
10	0.9441	1.0164	0.92694	-4.5072	-121.02	117.35
11	0.94902	0	0.92702	-4.2665	0	117.22
12	0	0	0.92496	0	0	117.07
13	0.94296	0	0	-4.1938	0	0

Table B.12 Magnitude of positive, negative and zero sequence voltages in p.u and angle in degrees

1	1.0002	5.213e-005	0.00022996	0.0083006	-11.775	49.525
2	0.97564	0.00895	0.015053	-1.5252	125.63	-90.185
3	0.97302	0.0089263	0.015515	-1.5651	125.94	-92.295
4	0.95153	0.0096946	0.017025	-2.1586	138.5	-98.642
5	0.64832	0.32603	0.32253	-1.3773	177.05	-179.79
6	0.64704	0.32477	0.32253	-1.3935	177.02	-179.79
7	0.97249	0.011486	0.020804	-1.7928	133.16	-88.026
8	0.96437	0.019272	0.038539	-2.546	145.1	-89.06
9	0.96442	0.019237	0.038535	-2.5465	145.07	-88.994
10	0.96219	0.020616	0.040742	-2.6839	146.08	-94.01
11	0.6253	0.31975	0.30568	-3.5304	-62.392	55.279
12	0.30832	0.30832	0.30832	-2.9264	-122.93	117.07
13	0.31432	0.31432	0.31432	-4.1938	-4.1938	-4.1938
14	0.96439	0.019254	0.038544	-2.5467	145.06	-89.041

Total Load in the system in term of P and Q= 3.342e+006 +1.9932e+006i

Source P and Q= 2.3382e+006 +1.2262e+006i

DG P and Q= 1.155e+006 + 3.79e+0

Case 4: With DG (with 1/3 DG penetration at 671 with DG modeled as a PQ node) with fault

Table B.13 Magnitude of current in amps and angle in degrees

1	316.59	204.32	363.62	-28.041	-136.82	93.833
2	316.59	204.32	363.62	-28.041	-136.82	93.833
3	0	0	0	0	0	0
4	0	146.66	65.237	0	-142.19	58.496
5	0	65.237	65.237	0	-121.5	58.496
6	316.59	59.884	312.69	-28.041	-123.59	100.76
7	310.99	42.223	274.55	-27.957	-110.49	102.57
8	236.92	66.447	184.94	-17.625	-55.449	108.75
9	211.99	66.447	130.4	-5.1647	-55.449	110.09
10	61.088	0	70.993	-37.75	0	121.64
11	0	0	70.993	0	0	121.64
12	61.088	0	0	-37.75	0	0
13	0	0	0	0	0	0

Table B.14 Magnitude of line-neutral voltages in volts and angle in degrees

1	2402.2	2401.7	2402.2	0.0073526	-119.99	120
2	2351.1	2402.2	2318.8	-1.685	-120.73	118.54
3	2351.1	2402.2	2318.8	-1.685	-120.73	118.54
4	0	2379.5	2314.2	0	-120.92	118.57
5	0	2375.3	2309.3	0	-121	118.62
6	2340	2410.9	2299.4	-2.2231	-120.68	118.22
7	2304.3	2442.2	2247.7	-3.9027	-120.56	117.46
8	2304.5	2442.2	2247.7	-3.903	-120.56	117.46
9	2288.2	2447.9	2242.5	-4.1645	-120.74	117.48
10	2299.8	0	2242.7	-3.9264	0	117.36
11	0	0	2237.8	0	0	117.21
12	2285.2	0	0	-3.8538	0	0
13	2304.4	2442.2	2247.7	-3.9034	-120.56	117.46

Table B.15 Magnitude of voltage in p.u and angle in degrees

1	1.0002	0.99997	1.0002	0.0073526	-119.99	120
2	0.97888	1.0002	0.96545	-1.685	-120.73	118.54
3	0.97888	1.0002	0.96544	-1.685	-120.73	118.54
4	0	0.99074	0.96354	0	-120.92	118.57
5	0	0.98899	0.96148	0	-121	118.62
6	0.97426	1.0038	0.95739	-2.2231	-120.68	118.22
7	0.95941	1.0168	0.93584	-3.9027	-120.56	117.46
8	0.95951	1.0168	0.93586	-3.903	-120.56	117.46
9	0.95271	1.0192	0.9337	-4.1645	-120.74	117.48
10	0.95756	0	0.93377	-3.9264	0	117.36
11	0	0	0.93172	0	0	117.21
12	0.95144	0	0	-3.8538	0	0
13	0.95945	1.0168	0.93584	-3.9034	-120.56	117.46

Table B.16 Magnitude of positive, negative and zero sequence voltages in p.u and angle in degrees

1	1.0001	3.8867e-005 0	0.0001228	0.0042177	-116.65	46.774
2	0.98148	0.0082492	0.013628	-1.2854	125.56	-81.475
3	0.98147	0.0082434	0.013628	-1.2854	125.52	-81.465
4	0.65142	0.32832	0.32329	-1.17	177.46	-179.78
5	0.65015	0.32707	0.32328	-1.1861	177.42	-179.78
6	0.97842	0.010769	0.019385	-1.5493	133.32	-81.523
7	0.97041	0.018552	0.036958	-2.2959	145.83	-85.488
8	0.97045	0.018525	0.036956	-2.2963	145.81	-85.433
9	0.96825	0.019887	0.03897	-2.433	146.82	-90.789
10	0.6304	0.32139	0.30917	-3.2932	-62.069	55.434
11	0.31057	0.31057	0.31057	-2.7928	-122.79	117.21
12	0.31715	0.31715	0.31715	-3.8538	-3.8538	-3.8538
13	0.97042	0.018538	0.036963	-2.2964	145.81	-85.472
1	1.0001	3.8867e-005 0	0.0001228	0.0042177	-116.65	46.774

Total Load in the system in term of P and Q= 2.9475e+006 +1.7067e+006i

Source P and Q= 1.9249e+006 +8.8483e+005i

DG P and Q= 1.155e+006 + 3.79e+00

Case 3: With DG (at 671 modeled as PV with 1/3 penetration of the total load) without fault

Table B.17 Magnitude of current in amps and angle in degrees

1	372.56	246.26	400.06	-20.54	-125.34	100.78
2	372.56	246.26	400.06	-20.54	-125.34	100.78
3	85.228	63.45	66.177	-37.494	-158.47	80.905
4	738.64	549.9	573.53	-37.494	-158.47	80.905
5	0	146.07	65.067	0	-142.5	58.139
6	0	65.067	65.067	0	-121.86	58.139
7	292.09	94.445	297.51	-15.659	-69.885	113.71
8	286.74	93.51	262.87	-15.319	-57.121	117.44
9	235.95	67.555	183.63	-18.183	-55.09	108.73
10	211.07	67.555	129.14	-5.663	-55.09	110.32
11	61.345	0	71.019	-38.434	0	121.56
12	0	0	71.019	0	0	121.56
13	61.345	0	0	-38.434	0	0
1	372.56	246.26	400.06	-20.54	-125.34	100.78

Table B.18 Magnitude of line-neutral voltages in Volts and angle in degrees

1	2402.8	2401.5	2402.4	0.021293	-119.99	120
2	2346	2414.5	2320.8	-2.1751	-121.06	118.3
3	2338.4	2409.8	2314.3	-2.2463	-121.11	118.31
4	262.87	272.78	261.54	-2.9856	-121.6	117.78
5	0	2391.9	2316.2	0	-121.25	118.33
6	0	2387.7	2311.2	0	-121.33	118.38
7	2338.4	2427.6	2305.7	-2.7676	-121.03	117.96
8	2314	2473	2266.6	-4.5874	-120.95	117.11
9	2314.3	2473	2266.7	-4.5882	-120.95	117.11
10	2298.1	2478.7	2261.6	-4.8477	-121.13	117.13
11	2309.5	0	2261.7	-4.6106	0	117.01
12	0	0	2256.8	0	0	116.86
13	2294.8	0	0	-4.538	0	0

Table B.19 Magnitude of voltage in p.u and angle in degrees

1	1.0004	0.99989	1.0003	0.021293	-119.99	120
2	0.97679	1.0053	0.96627	-2.1751	-121.06	118.3
3	0.97362	1.0033	0.96358	-2.2463	-121.11	118.31
4	0.94854	0.9843	0.94374	-2.9856	-121.6	117.78
5	0	0.99587	0.96436	0	-121.25	118.33
6	0	0.99413	0.96231	0	-121.33	118.38
7	0.97359	1.0108	0.95998	-2.7676	-121.03	117.96
8	0.96345	1.0296	0.94372	-4.5874	-120.95	117.11
9	0.96358	1.0296	0.94374	-4.5882	-120.95	117.11
10	0.95681	1.032	0.94165	-4.8477	-121.13	117.13
11	0.96158	0	0.94167	-4.6106	0	117.01
12	0	0	0.93962	0	0	116.86
13	0.95544	0	0	-4.538	0	0

Table B.20 Magnitude of positive, negative and zero sequence voltages in p.u and angle in degrees

1	1.0002	7.59E-05	0.00025069	0.010181	-6.7024	54.045
2	0.98275	0.0091113	0.015821	-1.6388	131.25	-90.912
3	0.98014	0.0090891	0.01629	-1.678	131.49	-92.917
4	0.95882	0.010049	0.017796	-2.2626	143.14	-98.971
5	0.65341	0.3289	0.32476	-1.4558	176.96	-179.85
6	0.65214	0.32765	0.32475	-1.4716	176.92	-179.85
7	0.98137	0.011803	0.021747	-1.9332	138.38	-88.761
8	0.9786	0.020126	0.040028	-2.7658	149.57	-89.637
9	0.97865	0.020091	0.040026	-2.7665	149.55	-89.573
10	0.97649	0.021479	0.042203	-2.9024	150.22	-94.35
11	0.63435	0.32499	0.30947	-3.8096	-62.796	55.126
12	0.31321	0.31321	0.31321	-3.14	-123.14	116.86
13	0.31848	0.31848	0.31848	-4.538	-4.538	-4.538
14	0.97863	0.020107	0.040032	-2.767	149.56	-89.615

Total Load in the system in term of P and Q= 3.3525e+006 +1.9997e+006i

Source P and Q= 2.3345e+006 +6.8592e+005i

DG P = 1.155e+006

Q injected by DG = 8.6648e+005

Case 4: With DG (with 1/3 DG penetration at 671 with DG modeled as a PV node) with fault.

Table B.21 Magnitude of current in amps and angle in degrees

1	290.78	194.91	337.24	-15.239	-114.8	105.06
2	290.78	194.91	337.24	-15.239	-114.8	105.06
3	0	0	0	0	0	0
4	0	145.52	64.714	0	-142.25	58.41
5	0	64.714	64.714	0	-121.59	58.41
6	290.78	93.954	296.58	-15.239	-69.235	114.19
7	285.47	93.161	262.29	-14.899	-56.443	117.96
8	233.73	67.778	182.59	-17.609	-54.654	109.23
9	209.17	67.778	128.12	-4.9285	-54.654	110.93
10	61.888	0	71.042	-38.093	0	121.9
11	0	0	71.042	0	0	121.9
12	61.888	0	0	-38.093	0	0
13	0	0	0	0	0	0

Table B.22 Magnitude of line-neutral voltages in volts and angle in degrees

1	2402.2	2401.6	2402.2	0.0084405	-119.99	120
2	2365.9	2420.8	2336.1	-1.8705	-120.78	118.43
3	2365.9	2420.8	2336.1	-1.8705	-120.78	118.43
4	0	2398.3	2331.5	0	-120.96	118.46
5	0	2394.2	2326.6	0	-121.04	118.5
6	2358.6	2434	2321.1	-2.449	-120.74	118.09
7	2334.5	2479.2	2282.4	-4.2458	-120.66	117.24
8	2334.8	2479.2	2282.4	-4.2466	-120.66	117.24
9	2318.7	2484.9	2277.4	-4.5038	-120.84	117.26
10	2330	0	2277.5	-4.2692	0	117.14
11	0	0	2272.6	0	0	116.99
12	2315.1	0	0	-4.1965	0	0
13	2334.6	2479.2	2282.4	-4.2473	-120.66	117.24

Table B.23 Magnitude of voltage in p.u and angle in degrees

1	1.0002	0.99991	1.0002	0.0084405	-119.99	120
2	0.98506	1.0079	0.97265	-1.8705	-120.78	118.43
3	0.98506	1.0079	0.97264	-1.8705	-120.78	118.43
4	0	0.99856	0.97076	0	-120.96	118.46
5	0	0.99683	0.96871	0	-121.04	118.5
6	0.98201	1.0134	0.96639	-2.449	-120.74	118.09
7	0.97199	1.0322	0.95028	-4.2458	-120.66	117.24
8	0.97209	1.0322	0.95031	-4.2466	-120.66	117.24
9	0.96541	1.0346	0.94823	-4.5038	-120.84	117.26
10	0.9701	0	0.94824	-4.2692	0	117.14
11	0	0	0.9462	0	0	116.99
12	0.96391	0	0	-4.1965	0	0
13	0.97204	1.0322	0.95029	-4.2473	-120.66	117.24

Table B.24 Magnitude of positive, negative and zero sequence voltages in p.u and angle in degrees

1	1.0001	4.52E-05	0.00013408	0.0052894	-83.329	48.179
2	0.98852	0.0083969	0.014383	-1.4008	131.68	-82.44
3	0.98851	0.0083932	0.014384	-1.4008	131.64	-82.432
4	0.65643	0.33118	0.32544	-1.2496	177.36	-179.84
5	0.65518	0.32994	0.32544	-1.2655	177.32	-179.84
6	0.9872	0.011086	0.020307	-1.6907	138.87	-82.366
7	0.9845	0.019416	0.038419	-2.5158	150.44	-86.032
8	0.98454	0.019388	0.038419	-2.5164	150.43	-85.98
9	0.98241	0.020759	0.040404	-2.6517	151.08	-91.077
10	0.6394	0.32655	0.31297	-3.5743	-62.467	55.27
11	0.3154	0.3154	0.3154	-3.0113	-123.01	116.99
12	0.3213	0.3213	0.3213	-4.1965	-4.1965	-4.1965
13	0.98452	0.019401	0.038423	-2.5168	150.43	-86.014
1	1.0001	4.52E-05	0.00013408	0.0052894	-83.329	48.179

Total Load in the system in term of P and Q= 2.9579e+006 +1.7132e+006i

Source P and Q= 1.9228e+006 +3.5011e+005i

DG P and Q= 1.155e+006

Q injected by DG = 8.6648e+005

Other power flows:

Similarly all the cases are obtained at each location, size of the DG with both the models and the different contingencies.

The power flow was run in the same way for the IEEE 37-node feeder also with the different locations, sizes, models of the DG and the different locations of the contingencies.