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Optimizing The Size And Location Of Distributed Generators To Maximize The Grid Stability

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OPTIMIZING THE SIZE AND LOCATION OF DISTRIBUTED GENERATORS TO MAXIMIZE THE GRID STABILITY

By

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Distributed Generators (DGs) are being increasingly utilized in power system distribution networks to provide electric power at or near load centers. These are generally based on technologies like solar, wind and biomass and range from 10 kW to 50 MW. Research work carried out in this thesis relates to the optimal siting and sizing of DGs in order to maximize the system voltage stability and improve voltage profile. This has been formulated as an optimization problem and solved using LINGO software. Power flow equations have been embedded in the LINGO formulation, along with other operating constraints. The solution provides optimal values of the bus voltage magnitudes and angles, which have been utilized to compute a stability index. Finally, a multi-objective formulation has been developed to simultaneously optimize the size and placement of the DGs. The impact of the DGs on voltage stability and voltage profile has been studied on IEEE standard distribution test systems and verified using 'three-phase unbalanced power flow software' developed at Mississippi State University (MSU).

Results indicate that the sizing and siting of DGs are system dependent and should be optimally selected before installing the distributed generators in the system.

DEDICATION

I would like to dedicate this thesis to my parents and friends, who have been my continual support.

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CHAPTER I

INTRODUCTION

1.1 Introduction

Distributed Generation (DG) is the concept of decentralizing the power generation by placing small generating units at or near the load center. The electric power system is divided into three parts, generation, transmission and distribution subsystems. Traditionally the power at the generating units is supplied to the loads through transmission and distribution systems. During last few decades there have been many changes in the electric power industry due to development in distributed generation technologies, economic policy and restructuring. Fig 1.1 and 1.2 demonstrate the traditional and modern power system.

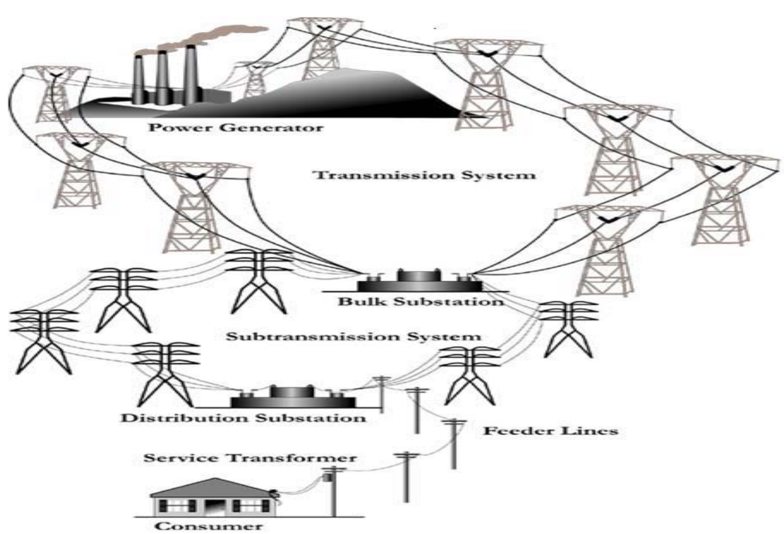

Figure 1.1 Traditional electric power system [1]

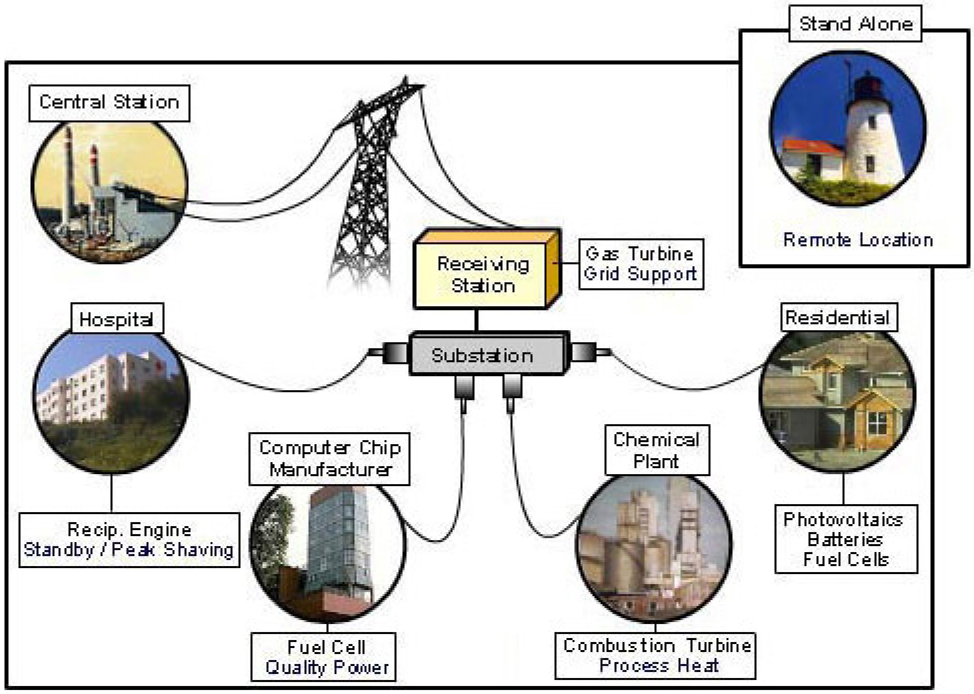

Figure 1.2 Power system with DG [2]

In several countries governments are providing incentives for establishing DG units. Though centralized power plants are the main source of power supply, DG technology is gaining wide spread interest in the electric power system due to its three major advantages: customer benefits, supplier benefits and global environmental.

1.2 Distributed Generation (DG) and its impact on the grid

DG is a small scale generation at or near the load center and usually ranges from 10kW to 50MW [3]. Though this technology was introduced several decades ago it is gaining wider applications and usage in recent years due to advancements in technology, environmental concerns, security and reliability. This technology could be beneficial especially at locations, where renewable resources are feasible and available as DG is based on wind, solar and biomass. This technology is a great opportunity to exploit the renewable energy resources around the world and provide clean energy, thus minimizing environmental pollution. If properly planned and implemented this technology could be beneficial to the power industry by providing necessary voltage support, stability, reliability and reducing the cost of future expansion. DG has both advantages as well as disadvantages; the advantages of DG can be divided in to three categories: supplier benefits, consumer benefits and national benefits [4]. The presence of DG necessitates new power flow techniques and protection strategies as it brings many changes in the system which is the major disadvantage of this technology.

From the customer point of view DG is beneficial in providing financial benefit for extra power generated. It also acts as a backup power supply especially during the times of natural calamities like hurricanes. If the available resources can be properly utilized DG can be major source of power at places where installing transmissions lines are not very feasible and are expensive to set up. DG also reduces the losses in the system which is a major concern in power transmission and distribution.

DG is beneficial to the suppliers by reducing the risk of investment due to the flexibility of its location and it increases the market competition with the possible low cost entry into the market. This technology also provides some environmental benefits by providing clean energy reducing the pollution. It also creates job opportunities and enhances productivity due to the increased reliability and quality of the power supplied.

The major disadvantages of DG are that when a DG is connected to the grid the power flow which is unidirectional in radial distribution network can become bidirectional due to the reverse power flow. Traditional power flow methods need to be modified to solve the load flow with DG. Inclusion of DG in the system also brings many changes in the system that demands additional protection, control and interconnection standards.

1.3 Size and location of DG and its importance

The size of DG is defined as the total power supplied by all the DG's connected to the system to the total load of the system. The size of the DG is expressed in terms of percentage penetration (% DG) which is as shown below

$$\%DG \qquad \frac{P_{DG}}{P_{Load}} \tag{1}$$

Where P_{DG} is the total power supplied by all the DG's.
P_{Load} is the total load of the system.

DG can be connected at several possible locations in the system. For instance in the IEEE 13 node distribution feeder there are five possible locations where DG can be placed, since in this work DG is modeled as a three phase node and it can be placed only at three phase nodes of the system.

The advantages of Distributed Generation can be enjoyed only by choosing the proper size of the DG and connecting it at the appropriate location in the system. DG has significant impact on the voltage profile of the system. Voltage profile is defined as the change in the voltage of the system as the load changes which are shown in the Figure 1.3.

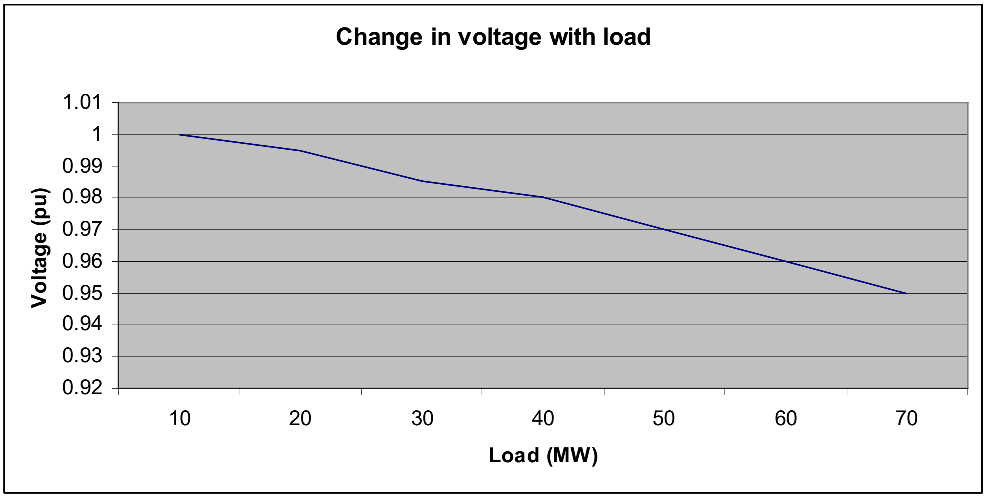

Figure 1.3 Change in voltage of the system with load

The presence of DG improves the voltage profile which is beneficial especially in rural areas where voltage swings and outages are more common. There are possibilities that over currents may be induced in the system due to oversizing and improper location of DG leading to undesired voltage profiles. The voltage stability of the system mainly depends on the voltage profiles and it is very essential that the power system should be stable at all times for reliable operation. Presence of DG in the system may improve or worsen the stability. It is essential to choose proper size and location of DG. Thus, there is a need for investigation of the DG impact on voltage stability.

1.4 Research work contributions

There is a need for research in the area of optimizing the size and location of DG that has to be connected to the grid. Several works were reported in the literature and most of them were based on minimizing the power losses and cost of generation. Voltage stability is an important aspect of power system and presence of DG may improve the stability or bring instability in the system depending on the size and location that has been selected. In reference [5] an attempt was made to find the best location and size by choosing limited penetration levels of DG and some possible locations. The best combination was reported by authors, at which the voltage support is maximum or voltage deviation is minimum. Extending the above work by including all feasible sizes and locations of DG and voltage stability analysis has been done in this work. The following contributions were made in this work

- Developed a mathematical formulation to find the optimal size and location of DG to maximize the voltage stability.
- Implemented developed formulation using commercially available tool LINGO successfully.
- Tested and verified the developed method using standard IEEE distribution systems.

1.5 Thesis objective

The research work in this thesis aims at finding the optimal size and location of the DG to maximize the grid stability. The IEEE 13 node and IEEE 37 node feeders are selected as test systems as these feeders are highly unbalanced and they closely represent actual terrestrial distribution systems. This work aims at finding the optimal size and location based on voltage support and stability. A formulation is developed in LINGO with the objective function to maximize the stability. The equality constraints of the formulation are power flow equations and the inequality constraints are the voltage limits, power supplied by the DG as well as load limits at all the nodes. Finally a multi objective function is developed that addresses voltage support, and voltage stability and the results are presented.

1.6 Thesis organization

This chapter introduces basic information about the Distributed Generation (DG) and its impact on the grid. It also gives an overview on importance of sizing and location as well as research contributions and objective of the thesis. Chapter 2 discusses some issues related to distributed generation, power flow analysis and voltage stability, different optimization approaches that were used earlier for sizing and location, test cases and software tools used. Chapter 3 gives the problem formulation and the solution algorithm. Chapter 4 gives details about the results obtained from the simulations for the test cases considered. Chapter 5 gives the conclusions and future work.

CHAPTER II

BACKGROUND

2.1 Introduction

The changes in technology, environmental concerns and motivation for economic benefit for deregulation have led to the development of Distributed Generation. This is also an excellent opportunity to exploit the renewable energy resources and supply clean power. The modern power system is extremely complex and interconnection of DG to the existing grid makes it even more complex. Inclusion of DG brings many changes in the power systems, which have to be dealt carefully. This chapter gives an overview of changes that DG brings in the system and some aspects like voltage stability, load flow analysis and different optimization approaches for size and location of the DG.

2.2 Issues related to Distributed Generation

Distributed Generation provides certain benefits when compared to the centralized generation station. DG provides necessary voltage support during the peak periods helping to reduce the power outages. These units are mainly connected at or near the load centers hence reducing the losses compared to the power transmitted over long distances. It is easier to find site for installing these units as they require small plant sizes and shorter installation times. Above all the major advantage of DG is that they can make use of locally available energy sources like solar, wind and biomass etc to generate power

[6]. This technology is especially beneficial in the states, which have abundant resources of solar, biomass and wind energy. DG reduces the cost of future expansion which is the major concern for the utilities [6] and also helps in providing power to the remote areas where installing transmission lines is very difficult and expensive.

Apart from the benefits mentioned above DG also have some disadvantages. With the presence of DG the power flow is no longer unidirectional as there will be flow of power from the load end to the source end. This reversal of power flow brings many changes in the system and various aspects like protection issues, voltage issues, frequency issues and an operational issue has to be considered [7]. Distribution systems have traditionally been designed as radial systems and the insertion of DG at the downstream of the loads changes the radial nature of the distribution system and necessitates the additional protection schemes. The other major issue that has to be considered is islanding. As defined in IEEE STD 1574-2003 [8] an island is a condition where a part of the grid is energized only by DG when it is isolated from the main power system feeder and during unintentional or unplanned islanding all the issues mentioned above should be addressed.

The DG is based on different technologies like renewable energy, combined heat and power and modular technology. Renewable energy resources include solar, wind and organic wastes like biomass and geothermal. Combined heating and power (CHP), which is also, referred to as cooling, heating and power uses the waste heat for producing thermal energy to increase the efficiency. CHP technology is being widely used these days and currently about 8% of U.S electricity is supplied from CHP plants [9]. Modular technology includes photovoltaic units, fuel cells, batter and storage and they can be installed in a short period and start operation immediately. Several works have been reported in literature [4] to [7] in making use of these DG technologies efficiently and analyzing the effect of DG when it is connected to the grid. This thesis work addresses the effect of DG on the stability of the grid where at the same time finding the optimal size and location of DG.

2.3 Load flow analysis with DG

Load flow or power flow is the important tool in any power system application, as it is needed for planning and operation of the system. Some applications in distribution systems like distribution automation, state estimation and optimization problems need fast power flow solutions. Distribution systems originate at the substation level and extend to the customer sites and they are typically radial in nature. High R/X ratio of the distribution systems makes it even more ill conditioned hence traditional power flow methods need to be modified for the distribution systems. With the DG technology growing rapidly it is of primary importance to study the impact of DG on the grid before installing it. There are not many specialized feasible tools in the industry to study the impacts of the DG and modified power flow analysis makes this study simpler. Distribution systems are highly unbalanced due to the loads and inherent nature of the distribution system. Unbalanced power flow is complex compared to balanced power flow and needs several changes in the traditional power flow. Taking all the constraints of the distribution systems the power flow developed should be fast, efficient and reliable.

A Monte Carlo based power flow algorithm that integrates the features of DG is proposed in [10]. The uncertainties in both the location and states of DG units are carefully incorporated into the Newton Raphson power flow equations and employed to find the power flow solution of a typical distribution system with DG. A novel approach to the distribution load flow problem has been proposed based on object oriented modeling and Newton Raphson power flow. These two are applied to radial system and in [11] this method has been extended to incorporate DG and run the power flow to get the voltage profile. This approach has the flexibility of handling different models of the distribution systems. In [12] the authors present a three phase unbalanced power flow algorithm including DG. This algorithm is based on forward and backward method and is validated for IEEE 13 node feeder.

The software used in this research work is unbalanced power flow algorithm and has the ability to include DG in any distribution system and gives the voltage profile of the system. DG can be modeled as either PQ or PV node, when DG is modeled as PQ it produce power at constant power factor and when modeled as PV node it outputs power operating at constant voltage. This software has the ability to handle multiple DG's and from the power flow obtained different analysis can be made on the system to see the impacts of DG. The data from the power flow can be used to find the stability of the system, power losses and also see the effects of reconfiguration.

2.4 Voltage stability analysis with DG

Voltage stability is the ability of the power system to maintain steady voltages at all the buses of the system after being subjected to some disturbance. The modern power system is challenged with increasing load demands and distribution systems including a combination of loads like industrial, commercial and residential. These loads change constantly and a change in the load with unfavorable conditions may bring instability in the system.

Distributed generation is gaining great interest due to its technical and economical benefits to the power industry. In recent years a larger number of DG's are being employed especially at the critical load ends to reduce the burden on the main feeder. One of the main benefits of employing DG in the system is that it improves the voltage profile and it helps in improving the stability of the system. DG may also have negative impacts on the stability of the system due to the oversizing and improper location creating scope for research in this area. The presence of DG affects on both transient and steady state (static) voltage stability of the system. In static analysis voltage stability margin is found based on the power flow and in transient analysis voltage stability is assessed considering the effect of various control equipment in the system [13].

In this work static analysis is used to find the voltage stability of the system and for this a proper stability index that calculates the voltage stability margin for the distribution systems is selected. A voltage stability index is a mathematical formulation that calculates the proximity of a bus to voltage collapse and identifies the node that is vulnerable and takes necessary actions. In [14], static voltage stability analysis was done using indices that are derived from Singular Value Decomposition (SVD) of the system Jacobian matrix. These indices determine the sensitivity of voltages and angles to small perturbations. It also describes continuation method which finds the power flow solutions starting at the base load and leading to the system stability. In [15], voltage stability analysis is done for distribution systems with embedded generators using PV and QV curves. Power World Simulator was used to evaluate the impact of embedded generators on the grid with respect to critical voltage variations and voltage collapse margins. In [16], voltage stability analysis for radial distribution networks was done by developing a new stability index using which the node that is at the verge of collapse can be identified. A modified load flow analysis was used for the voltage stability analysis and this method incorporates variations in load pattern at each nodes. In [17], a new technique to determine the voltage stability of load buses is proposed. The voltage stability index is derived from the voltage equation of two-bus network, which finds the node that is more prone to collapse.

In this work the stability index derived in [17] is used to do the voltage stability analysis as this index considers the node voltages and angles to find the nodes that are prone to collapse. The voltage profile obtained from the power flow analysis and stability index are used to study the voltage stability limits of the system. The details about the stability index considered are given in Chapter 3.

2.5 Optimization approaches for sizing and location of DG

DG has many technical benefits to the grid but these benefits can be optimized only if proper size of DG is connected at proper location. Large numbers of DG's are being installed at possible locations and the stability of the grid is mainly affected by the size and location of the DG. There are possibilities of undesired changes in voltage profile in the presence of DG due to injection of overcurrents due to oversizing and improper location of DG creating needs for investigation in this area.

In [5], DG's were placed on IEEE 13 node feeder and IEEE 37 node feeder and power flow was run to get the voltage profile of the system. By considering different combinations of DG sizes and locations the voltage deviations were calculated using the voltage norms. It was found in this work that presence of DG reduced the voltage deviations in the system. The results showed that placing DG at junction nodes or at the downstream nodes reduced the deviations more than when DG was placed on upstream nodes. A DG modeled as PV node gave lesser voltage deviations at all the nodes than compared to DG modeled as PQ node. In [5] the best size of the DG at best location is proven to be the DG penetration of 2/3 of the load. Voltage support was taken into account to find the best size and location but this work did not consider all possible sizes and locations of the DG.

In [18], two new approaches were proposed to determine the suitable size and location of DG to minimize the power losses in the distribution systems. The sensitivity of real and reactive power losses with respect to DG size and location are studied. This study revealed that maximum benefits can be obtained from DG only by proper planning. Optimal DG size and location varies for different system depending on the type of loads and system configuration. In [19], a genetic algorithm based DG placement approach was presented to minimize the total real power losses in the system. A genetic algorithm toolbox gives the optimal size and location as outputs and the results of this analysis were verified using power flow analytical tools for distribution system analysis.

In [20], an algorithm based on tabu search is employed to determine the optimal allocation of DG in the distribution systems. This study gives the extent to which the distribution system losses can be reduced if DG's are optimally allocated on demand side of the system. A Fuzzy – GA method was presented in [21] for the DG placement with an objective to reduce the power losses and cost of generation and the constraints being the location and size of DG's. In this approach the idea is to transform the fuzzy nonlinear objective and constraints into equivalent multi- objective function and solve the problem using genetic algorithm. In paper [22] Hereford Ranch Algorithm is used to find the optimal size and location of the DG with the objective of minimizing the power losses in the distribution system. In this study the power loses were minimized showing the importance of sizing and location.

An algorithm using the Primal Dual Interior Point (PDIP) method and optimal power flow is employed in [23] for the purpose of finding the optimal size and location of DG for solving power loss problem. The equality constraints are solved in a non linear manner based on Karush- Kuhn-Tucker (KKT) conditions. This algorithm was tested for 10 –bus and 42-bus radial distribution systems using MATLAB. A combination of Genetic Algorithm and Simulated Annealing is applied to solve the problem of finding optimal size and location of DG in [24]. The problem is to minimize the total cost of generation and energy losses for a fixed number of DG's and specific total capacity of the DG. A multiagent based dispatching scheme is developed in [25] for dispatching the distributed generators on a distribution feeder to provide necessary voltage support. The test results showed that it coordinates the reactive power dispatch among the DG's to provide voltage support during a contingency.

It is seen from the literature review that many attempts were made to solve the optimization problem related to size and location of the DG. Most of the research related to size and location was aimed at minimizing the real power losses of the system, energy losses and cost of generation. Less work has been done related to the voltage support and stability which is also a major concern of the power systems. This work aims at finding the optimal size and location of the DG such that stability of the grid is maximized using the unbalanced power flow software and LINGO. The details related to the software tools used are explained in the later sections of this chapter.

2.6 Test cases

IEEE radial distribution feeders are used for this study and the data of these feeders is obtained from the IEEE test case archive for distribution feeders [26]. These feeders are highly unbalanced and closely represent the real time distribution systems. In this work IEEE 13 node feeder and IEEE 37 node feeders are used as the test cases to study the impact of size and location DG's. The details of the test cases are given in the following sections.

2.6.1 IEEE 13 node feeder

Figure 2.1 shows the layout of the IEEE 13 node feeder

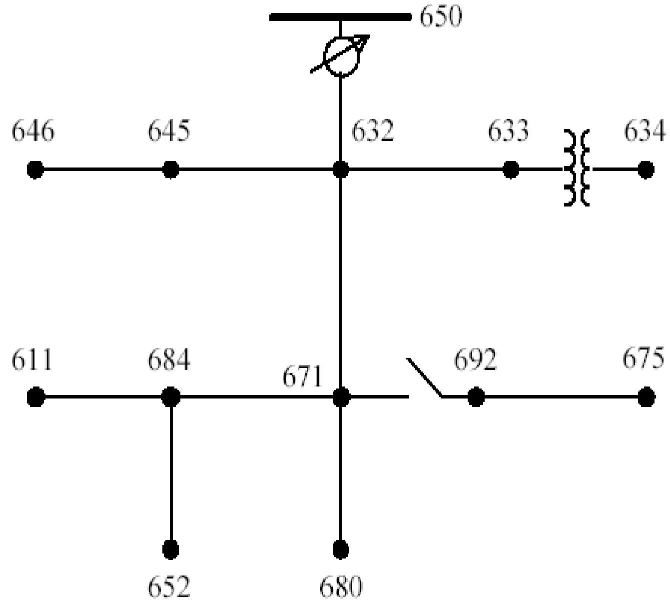

Figure 2.1 IEEE 13 node feeder

The features of IEEE 13 node feeder are as follows:

- It is short and highly loaded feeder for 4.1kV level with the total load on the system being 3.466MW.
- It is highly unbalanced feeder.
- It has spot loads, distributed loads, single phase and three phase unbalanced loads, wye and delta connected, constant kW, kVAR, constant Z and constant I type loads.
- It has overhead and underground lines with single phase and three phase and different spacing between them.
- A substation transformer that is delta – grounded wye connected and an inline transformer that is grounded wye – grounded wye connected.

- Balanced three phase capacitor and single phase capacitor.

2.6.2 IEEE 37 node feeder

Figure 2.2 shows the layout of IEEE 37 node feeder

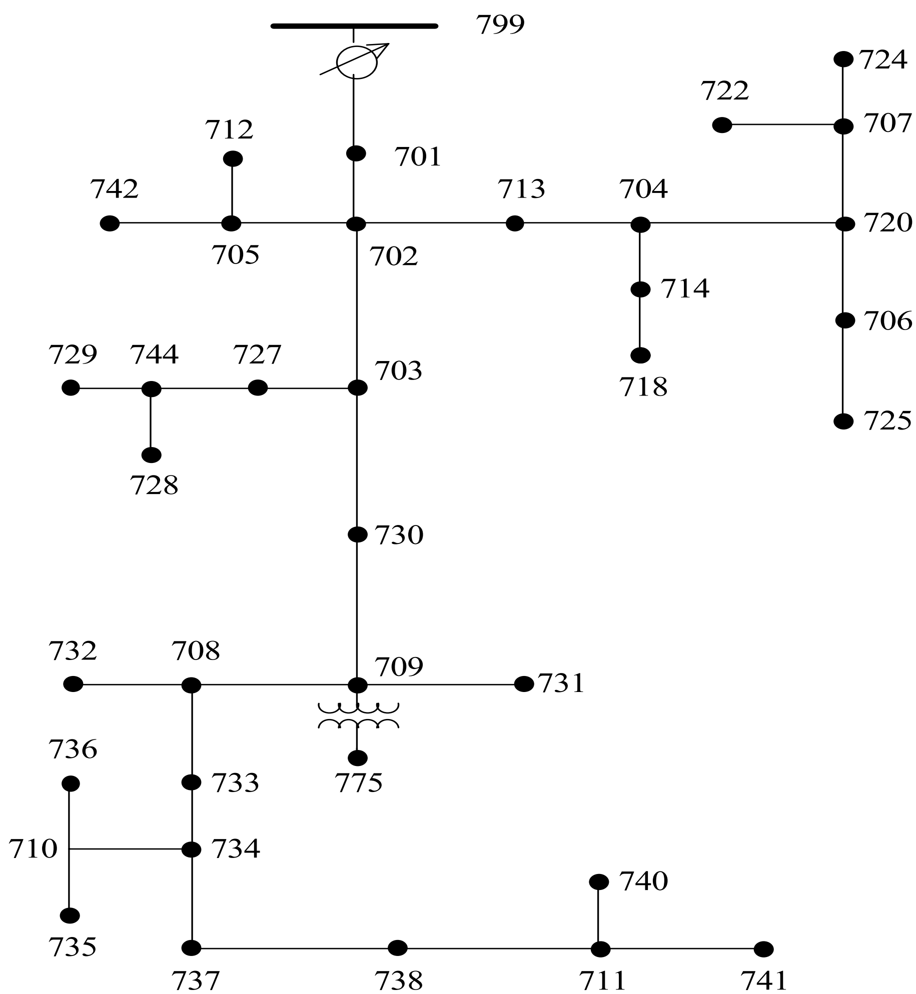

Figure 2.2 IEEE 37 node feeder

IEEE 37 node feeder is the actual feeder in California and the data of the feeder can be obtained from the distribution feeder archive.

The features of the feeders are:

- It has spot loads, distributed loads, single phase and three phase unbalanced loads, wye and delta connected, constant kW, kVAR, constant Z and constant I type loads.
- Overhead and underground lines that are three phase with different spacing.
- A substation transformer and an inline transformer that are delta-delta connected.
- Shunt capacitor banks.

2.7 Software tools used

In this research work LINGO and three phase unbalanced power flow software are used and the details of these software packages are given in the following sections.

2.7.1 LINGO

The LINGO commercial optimization software package from LINDO Systems Inc. solves the constrained optimization problem [27]. Figure 2.3 shows a snapshot of this optimization software package. LINGO is a tool for solving both linear and non-linear optimization problems. Branch-and-bound type techniques cannot be directly applied unless the problems are convex. LINGO has a direct solver, a linear solver, a non-linear solver and a branch-and-bound manager. If integer restrictions exist in the problem, the software invokes a branch-and-bound manager, which in turn invokes a linear or non-linear solver, depending on the nature of the formulation. LINGO uses the revised simplex method for its linear solver, and successive linear programming, as well as a generalized reduced gradient for its non-linear solver. LINGO can solve problems with several constraints and variables but cannot handle complex numbers; it requires a reformulation of the problem associated with this research work. The formulation is input in the format desired by the software. The direct solver first computes the values for as many unknown variables as possible, and if, at that stage all unknown variables are calculated, and then the solution report is displayed.

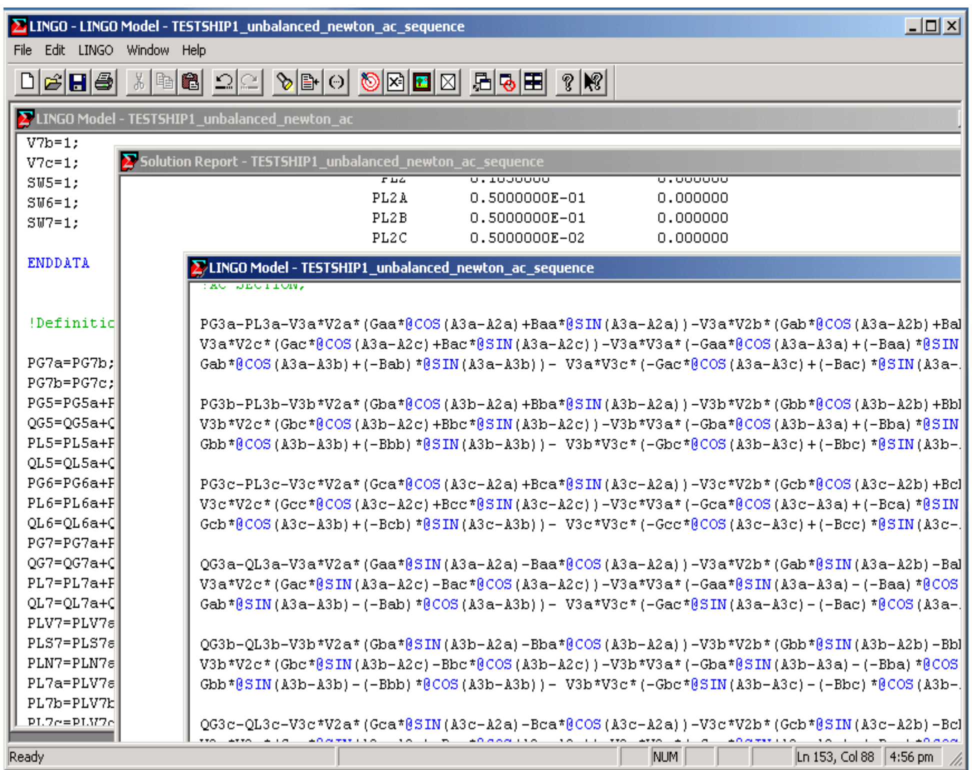

Figure 2.3 Snapshot of LINGO

If unknown variables still exist, then LINGO calls other solvers based on the model equations. If the model is continuous and linear, LINGO calls the linear solver. If the problem involves non-linear constraints, LINGO calls the non-linear solver. In case of integers, the branch-and-bound manager is called. LINGO's solver status window gives a count of the linear and non-linear variables and constraints in a model. If there are any non-linear variables in the model, the non-linear solver runs, which is slower. However, upper and lower bounds on the variables can be provided for an efficient search by using the command:

@BND (Lower bound, Variable, Upperbound).

If the variable takes positive and negative values, it should be specified using

@FREE (Variable).

Conditional statements like "if" can also be defined:

@IF (logical_condition, true_result, false_result).

Table 2.1 displays mathematical functions with functional descriptions and Table 2.2 displays logical operators [28].

Table 2.1 Mathematical function in LINGO

Mathematical Functions	
@LOG(X)-returns natural logarithm	@ABS(X)-returns absolute
@TAN(X)-returns tangent	@COS(X)-returns cosine
@SIGN(X)-returns –1 if X<0 and vice-versa	@EXP(X)-returns e raised to power X
@SIN(X)-returns sine	@FLOOR(X)-rounds to lower integer
@SMAX(X1, X2,..., XN)-returns maximum value	@SQR(X)-returns square of X
@SMIN(X1, X2,..., XN)-returns minimum value	@SQRT(X)-returns square root of X

Table 2.2 Logical operators in LINGO

Logical Operators								
#NOT#	#EQ#	#NE#	#GT#	#GE#	#LT#	#LE#	#AND#	#OR#

LINGO also supports links to any Data Base Management Systems (DBMS) for reading and writing data that has an Open Database Connectivity (ODBC) driver. LINGO can install ODBC drivers for the following DBMSs:

- Access
- dBase
- Excel
- FoxPro
- Oracle
- Paradox
- SQL Server
- Text Files

The constrained optimization problem formulated here uses non-linear and integer solvers of the LINGO software. Branch and bound guarantees an optimal solution.

2.7.2 Three phase unbalanced power flow software

Three phase unbalanced power flow software was developed by Power and Energy Research Lab (PERL), Mississippi State University [28]. The algorithm is based on backward and forward sweep method and makes use of voltages and currents instead of real and reactive powers. DG that has to be connected to the system considered may be set to output power at constant power factor for a small size DG and constant voltage for a large DG. This software was developed MATLAB and it does not involve matrix inversions and is very fast. This speed can help in much distribution system applications. Some of the features of the algorithm are

- The convergence of the algorithm is very fast and it converged even if the R/X ratio is high.
- It has option to model DG either as PV node or PQ node.
- This software has ability to handle multiple DG's with different penetration levels.
- It includes detailed models of lines, switches, loads, transformers, cables and capacitors with updated power flow equations
- The outputs from the power flow software will be three phase line to line, line to ground, sequence voltages and currents.

2.8 Summary

This chapter gives an overview of need of DG's and discusses various issues related to the DG technology, its advantages and disadvantages. It gives a brief idea about the importance of power flow analysis and the change that has to be made to the traditional power flow programs to incorporate DG. This chapter also gives information about the importance of stability analysis and the effect of DG on the stability of the grid and different methods to do the voltage stability analysis. Later, the importance of size and location of DG that has to be connected to the grid is discussed in detail and various optimization approaches that were used to solve this problem were presented and compared with developed optimization work in this thesis.

CHAPTER III

PROBLEM FORMULATION AND SOLUTION ALGORITHM

3.1 Introduction

This chapter presents the problem formulation and the solution algorithm that has been implemented. Power flow analysis was performed on the IEEE distribution test cases to see the impact of the DG on the system and mathematical formulation was developed to find the optimal size and location of the DG to improve the voltage stability of the system. The problem description, mathematical formulation and the solution algorithm are presented in this chapter.

3.2 Problem statement

Typical distribution systems are designed to operate with the main source and power flowing from the source to the end of the feeder. When DG is connected to the distribution systems the reversal of power flow occurs causing bidirectional power flow. The voltage profile of the system changes with DG size and location. Oversize and improper location of the DG may induce overcurrents in the system resulting in undesired voltage profiles. Undesired voltage profiles due to DG may impact power system in terms of voltage stability, system losses and reliability which have to be taken care before installing DG into the system. It is very important to optimize the location of DG and size on a distribution system.

There is always a trade off between the advantages and disadvantages that DG brings into the system. There has been increase in the installing DG units recently and with increase in DG penetration it is very important to study the impacts on the power system accurately in terms of power quality, reliability, stability and security of the system. These system parameters are mostly affected by the size and location of DG hence it is imperative to find the optimal size and location of the DG.

Owing to the importance of the size and location of the DG and the impact of DG on the system stability this research work aims at finding the optimal size and location of the DG that has to be connected to the grid such that the system is most stable. This work is done on two IEEE distribution feeders that are unbalanced and aptly suitable for distribution system analysis. As a first step, unbalanced power flow software was used to do the power flow analysis of the test cases without DG and with DG in the system. Using the voltage profiles obtained technical analysis can be made to study the impact of DG on the system. A proper stability is selected from the literature using which the stability for distribution systems can be calculated. The test cases were analyzed for both power flow and stability using the index selected and it was found that as the size of the system increases this analysis will be difficult and time consuming due to enormous amount of the data.

To automate the process of finding the optimal size and location of the DG, a mathematical formulation is developed in LINGO and the power flow equations are embedded in the formulation. This formulation was tested for both the test cases and optimal size and location was obtained without violating the constraints and maintaining the voltage stability of the system. A multiobjective formulation is also developed to address various issues like voltage support, losses and voltage stability.

3.3 Analysis of IEEE distribution systems for power flow

Power flow analysis gives various information of the system like voltages at all the nodes, line currents and power losses. Using these results different studies related to voltage stability, voltage support, and reconfiguration can be performed. The first step of this research is to analyze small IEEE distribution systems for power flow with DG connected to them. This analysis is done using three phase unbalanced power flow software, which can handle multiple DG's that can be modeled as PQ or PV nodes. When power flow is run with this software the results obtained are the voltages in volts, angle in degrees, current in amps, the positive, negative and zero sequence voltages, total load of the system and power supplied by the DG. A DG modeled as PQ node is placed on the test case considered and by varying the penetration of the DG voltage profiles of the system are obtained by varying the penetration. The results obtained were compared with the base case (case without DG) to see the impact of DG on the voltage profile of the system.

3.4 Selection of suitable voltage stability index

Voltage stability is important factor to be considered in power system operation and planning since voltage instability may lead to the system collapse. DG may improve stability or bring instability in the system depending on the size and location that has been selected. In this research work the best size and location of the DG is found with respect to maximizing the system stability, hence a suitable stability index was selected from the literature that calculates the stability of the distribution systems. Using this stability index the node that is most vulnerable to voltage collapse can be identified based on the power flow results and appropriate actions can be initiated to prevent the system collapse.

The stability index used in this work is selected from [17] and the mathematical formulation for the voltage stability index is derived from power flow equations of two bus network as shown in Figure 3.1

Consider a line connecting bus i to bus j as in figure

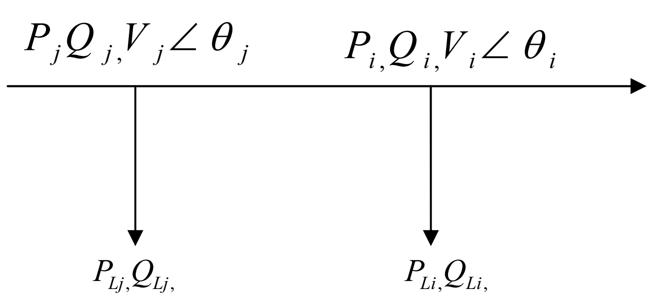

Figure 3.1 Two bus network

Where,

P_i, Q_i are real and reactive powers injected at bus i.

$V_i \angle \theta_i$ are voltage and voltage angles at bus i.

$P_{Li,}Q_{Li,}$ are real and reactive power components of load connected to bus j.

P_j, Q_j are real and reactive powers injected at bus j.

$V_j \angle \theta j$ are voltage and voltage angles at bus j.

$P_{Lj,}Q_{Lj,}$ are real and reactive power components of load connected at bus j.

For this single line network connecting bus j and bus i with impedance $R_i + jX_i$ the voltage derived voltage stability index is

$$L(i) \quad 4\left[\left[V_iV_j\cos(\theta_i-\theta_j)-V_j^2\cos(\theta_i-\theta_j)^2\right]/V_j^2\right] \tag{3.1}$$

$L(i)$ is the value of stability index at node i.

The value of the stability index is used to determine the stability of the system and according to this index

If $L(i)>1$ then the system is unstable and

If $L(i)$ is between 0 and 1 then the system is stable.

If $L(i)$ is negative then the absolute value is taken.

Using this mathematical equation the stability index values at all the nodes can be calculated and the node that is more vulnerable to voltage collapse can be identified. Each node has different stability index and the maximum value indicates the voltage stability margin of the system. This concept can be extended to larger systems and stability analysis can be performed using this index.

3.5 Voltage support index

A voltage support index is the ability of the system to operate normally even when the voltage of distribution system deviates from the rated voltage within limit [29]. Each node has different voltage support index and the maximum value indicates the voltage support level of the system. Voltage support index is calculated as follows

$$V_{si} = \left| V - V_n \right| \tag{3.2}$$

Where,

V is the rated voltage of the particular node and Vn is the expected nodal voltage after contingency.

Normalized voltage support index (V_{sin}) is calculated as

$$V_{sin} = \frac{\left| V - V_n \right|}{K_{vsi}} \tag{3.3}$$

K_{vsi} is the constant that represents the percentage of voltage fluctuation allowed in the system.

K_{vsi}= 0.15 for terrestrial distribution power system and is system dependent.

3.6 Formulation for optimizing the size and location of DG

Optimal allocation and size is the major concern in installing DG units and the solution for this can be obtained by complete study of all feasible combinations of size and location of DG’s. One possible approach for finding optimal size and location is by running power flow for each combination and calculating the stability index values at all the nodes for each case. The combination that gives the minimum stability index values as described in section 3.4 can be considered as optimal size and location. This approach involves handling large amount of data especially for larger systems and it's a time consuming process. In order to automate this idea a mathematical formulation was developed in LINGO which is a commercial optimization tool. This formulation is based on optimal power flow approach with objective function being maximizing the stability or minimizing the stability index. The power flow equations are embedded in the formulation itself and for each size as well as each location of DG power flow is run. The voltage profile obtained through LINGO was used to calculate stability index automatically giving the minimum index values and the best combination. The formulation for optimizing the size is presented in section 3.6.1.

3.6.1 Formulation for optimizing the size of DG

This problem is a mixed integer non linear optimization problem with an objective function, equality and inequality constraints. As discussed in the earlier section the objective function is to minimize the stability index and the constraints enforced are power flow, load current limits, voltage limits and DG power limits. In this formulation DG is modeled as PQ node with negative power injections and the component models like different types of loads are modeled as per [30]. The formulation is as shown below

Objective

$$Min(Max(4\left[\left[V_i V_j \cos(\theta_i - \theta_j) - V_j^2 \cos(\theta_i - \theta_j)^2\right]/V_j^2\right])) \qquad (3.4)$$

Subject to

Equality Constraints

$$V_j^p \quad \left(V_i^p - \sum_{m \;\; a}^{c} Z_{ij}^{mp} I_{ij}^p \right) \qquad (3.5)$$

$$\sum_N I_{ij}^p - \sum_O I_{jr}^p - IL_j^p \quad 0 \qquad (3.6)$$

Inequality Constraints

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad (3.7)$$

$$P_{DG}^{\min} \le P_{DG} \le P_{DG}^{\max} \qquad (3.8)$$

$$IL_i^p \le IL_{i,\max}^p \qquad (3.9)$$

Where,

Z_{ij}^{mp} is the mutually coupled impedance matrix of the branch between nodes i and j.

IL_i^p is the load current flowing in node i and phase p.

IL_j^p is the load current flowing in node j and phase p.

I_{ij}^p is the current flowing from node i to j in phase p.

V_i^p is the voltage at node *i* for phase p.

V_j^p is the voltage at node *j* for phase p.

p belongs to set of phases a, b and c.

N is the set of branches with currents going into the node *j* .

O is the set of branches with currents coming out of the node j.

$P_{DG}^{\min}$ is the minimum size of the DG.

$P_{DG}^{\max}$ is the maximum size of the DG.

$V_i^{\min}$ is the minimum voltage limit at node i.

$V_i^{\max}$ is the maximum voltage limit at node i.

In this above formulation equation 3.4 is the objective function that has to be minimized in order to have the maximum stability. Equations 3.5 and 3.6 are the power flow equations that are based on the forward and backward sweep method which are in terms of voltages and currents and give the voltage profile of the system. Equation 3.7 is the voltage constraint to limit the voltage at all the nodes within the tolerance which is 1±0.05. Equation 3.8 is the constraint on the power supplied by the DG or constraint on the size of the DG and equation 3.9 is the constraint on the load current at each node of the test case considered. Each node of the system has different stability index and the maximum value indicates the voltage stability margin of the system. This formulation finds the optimal size at which the voltage stability margin is minimized. This formulation was developed in a format required by LINGO and it was tested for IEEE 13 node and IEEE 37 node distribution feeders. The results are presented in chapter 5. The size of the DG giving the minimum stability index values with no violations in constraints is considered as the best size of the DG.

3.6.2 Formulation for optimizing the location of DG

The formulation for optimizing the location is similar to that of optimizing the size except that the DG size is kept constant and is placed at all possible locations. For each location of the DG, power flow is run and the voltage profile is used to find the optimal location based on the stability index values. The equations similar to equations (3.4) - (3 .9) were written in the format required by LINGO and they were tested for the IEEE 13 node and IEEE 37 node distribution feeders. The results and discussions of this formulation are presented in chapter 5.

3.6.3 Formulation for optimizing the size and location of DG

In this formulation the best combination of size and location are obtained at the same time. This formulation has two variables DG size and location, which have to be determined from the optimization problem. The combination of variables with which the stability is maximum is considered as the optimal size and location. For example if 10 different penetration levels of DG are considered and they can be connected at 5 possible locations on IEEE 13 node feeder then there would be 50 combinations of size and locations of the DG from which the best has to be selected.

3.6.4 Multiobjective formulation to find optimal size and location

A multi objective formulation to find the best size and location of the DG such that the voltage stability and voltage support of the system will be maximized is developed. The constraints enforced are power flow equations, voltage limits, load current limits and DG power limits. The mathematical formulation is as shown below

Let,

$$L(i) \quad 4\left[\left[V_i V_j \cos(\theta_i - \theta_j) - V_j^2 \cos(\theta_i - \theta_j)^2\right] / V_j^2\right] \tag{3.10}$$

$$V_{\sin} = \frac{|V - V_n|}{K_{vsi}} \tag{3.11}$$

Objective

$$Min\ W_1 Max\ L(i)\ + W_2 Max\ V_{\sin} \tag{3.12}$$

Subject to,

Equality Constraints

$$V_j^p \quad \left(V_i^p - \sum_{m\ a}^{c} Z_{ij}^{mp} I_{ij}^p \right) \tag{3.13}$$

$$\sum_N I_{ij}^p - \sum_O I_{jr}^p - IL_j^p \quad 0 \tag{3.14}$$

Inequality Constraints

$$V_i^{\min} \leq V_i \leq V_i^{\max} \tag{3.15}$$

$$P_{DG}^{\min} \leq P_{DG} \leq P_{DG}^{\max} \tag{3.16}$$

$$IL_i^p \leq IL_{i,\max}^p \tag{3.17}$$

Where,

Z_{ij}^{mp} is the mutually coupled impedance matrix of the branch between nodes i and j.

IL_i^p is the load current flowing in node i and phase p.

IL_j^p is the load current flowing in node j and phase p.

I_{ij}^{p} is the current flowing from node i to j in phase p.

V_i^p is the voltage at node i for phase p.

V_j^p is the voltage at node j for phase p.

p belongs to set of phases a, b and c.

N is the set of branches with currents going into the node j

O is the set of branches with currents coming out of the node j .

$P_{DG}^{\min}$ is the minimum size of the DG.

$P_{DG}^{\max}$ is the maximum size of the DG.

$V_i^{\min}$ is the minimum voltage limit at node i.

$V_i^{\max}$ is the maximum voltage limit at node i.

W_1 is the weighting factor for voltage stability index

W_2 is the weighting factor for voltage support index.

In this above formulation equations 3.10 and 3.11 are the voltage stability index and voltage support index. Equation 3.12 is the objective function that has to be minimized in order to have the maximum stability and voltage support. Equations 3.13 and 3.14 are the power flow equations that are based on the forward and backward sweep method which are in terms of voltages and currents and give the voltage profile of the system. Equation 3.15 is the voltage constraint to limit the voltage at all the nodes within the tolerance which is 1±0.05. Equation 3.16 is the constraint on the power supplied by the DG or constraint on the size of the DG and equation 3.17 is the constraint on the load current at each node of the test case considered. The formulation was developed in a format required by LINGO and tested for IEEE 13 node feeder to find the optimal size and location such that the constraints on the system are not violated and the voltage stability and voltage support of the system are maximized.

3.7 Summary

This chapter presents the problem statement and the developed solution algorithm. It gives a brief description about the power flow analysis done on the test cases to study the impacts of DG on the distribution network. Voltage stability index and the voltage support index that are used in this work are explained in detail. The mathematical formulations for optimizing the size, location and a combined mathematical formulation are derived in this chapter. The next chapter includes the results obtained from the power flow analysis, stability analysis and the optimization of size and location.

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the results and discussions related to the power flow analysis comparing the voltage profiles for different sizes of DG for IEEE 13 node and 37 node distribution feeders. Power flow analysis is integrated with stability analysis and the results are shown here. The optimization formulations for sizing and siting of DG that were developed in Chapter 4 are simulated in LINGO and the results will be discussed.

4.2 Power flow analysis

Power flow analysis is an important tool to study different issues of the power system. IEEE 13 node and 37 node distribution feeders are modeled in three phase unbalanced power flow software. Base case (system without DG) is simulated first to get the voltage profile of the system. In [5] power flow analysis was done with single DG and UTPFLOW has the ability to handle to multiple DG's. In this research multiple DG's are placed on the system at some random locations and power flow analysis is done for different sizes of the DG and compared with the base case. The results of the power flow are presented and discussed in detail.

4.2.1 Comparison of voltage profiles for 13 node feeder

IEEE 13 node feeder is highly balanced feeder with total load being 3.466MW. Two DG's modeled as PV nodes are placed at nodes 632 and 671 as shown in figure 4.1. The regulator was removed in the original analysis to clearly see the impacts of the DG on voltage profile

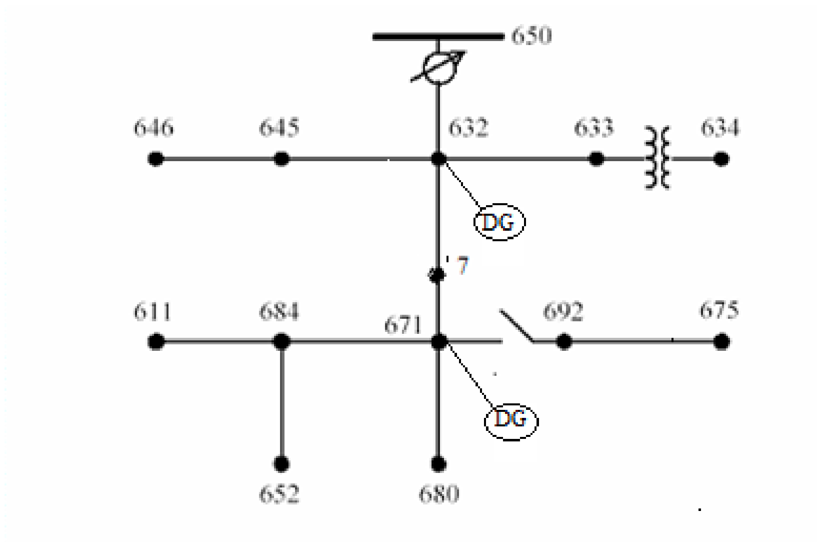

Figure 4.1 IEEE 13 node feeder with DG

Total penetration (Size) of the DG is varied from 10% to 60% of the total load with each DG sharing equally and the voltage profile obtained at each case is compared with that of the base case. Table 4.1 gives the total power injected by the DG with respect to % penetration.

Table 4.1 DG penetration with respect to total load

% DG	Total P_{DG}
10%	346.6 kW
20%	693.2 kW
30%	1.0398 MW
40%	1.3864 MW
50%	1.7333 MW
60%	2.0796 MW

Unbalanced voltage profiles are compared for each phases and Figures 4.2, 4.3 and 4.4 give the comparison of voltages.

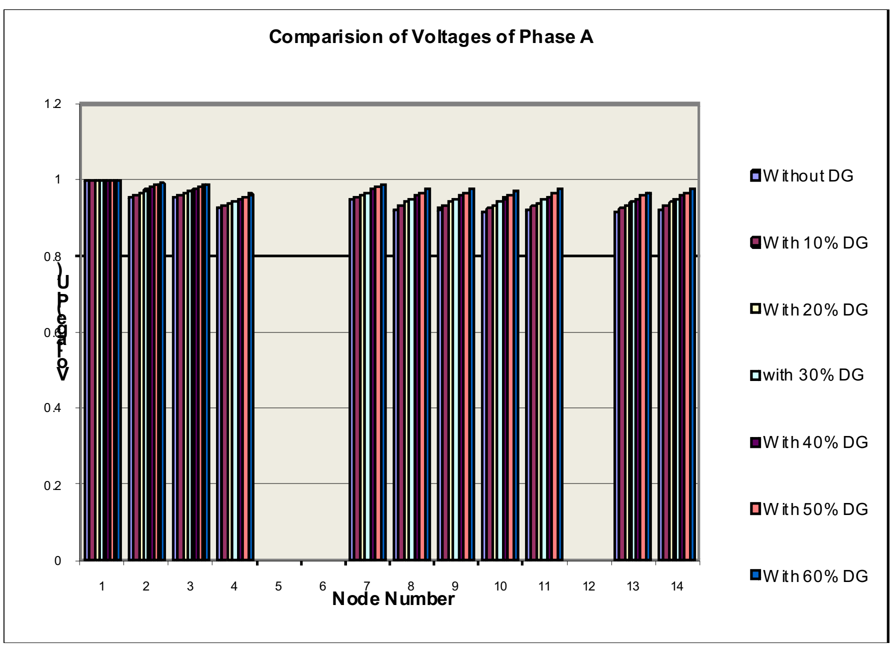

Figure 4.2 Comparison of voltages for phase A for IEEE 13 node feeder

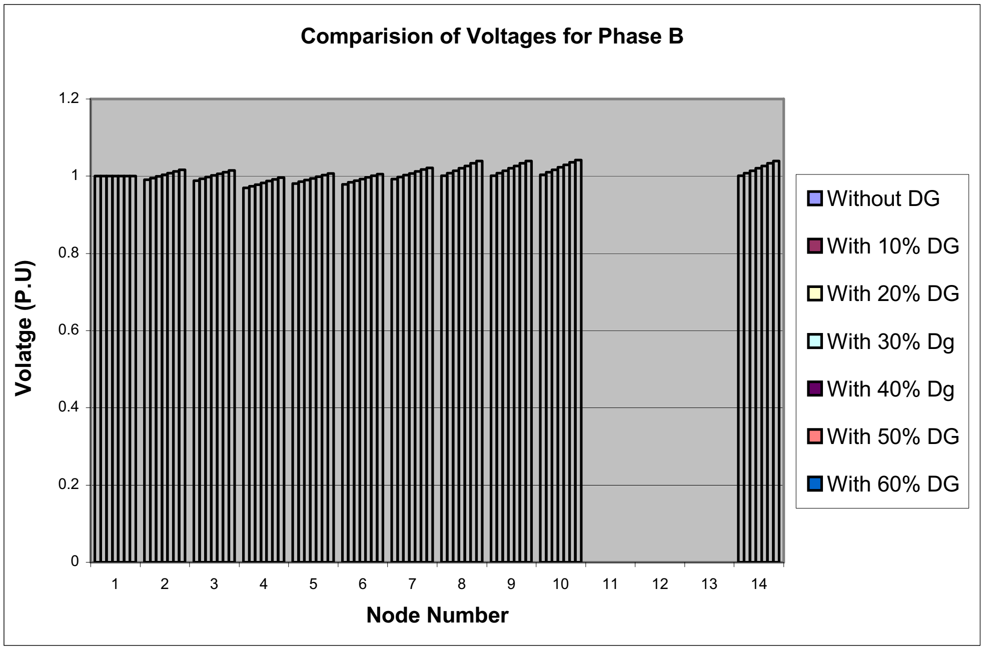

Figure 4.3 Comparison of voltages for phase B for IEEE 13 node feeder

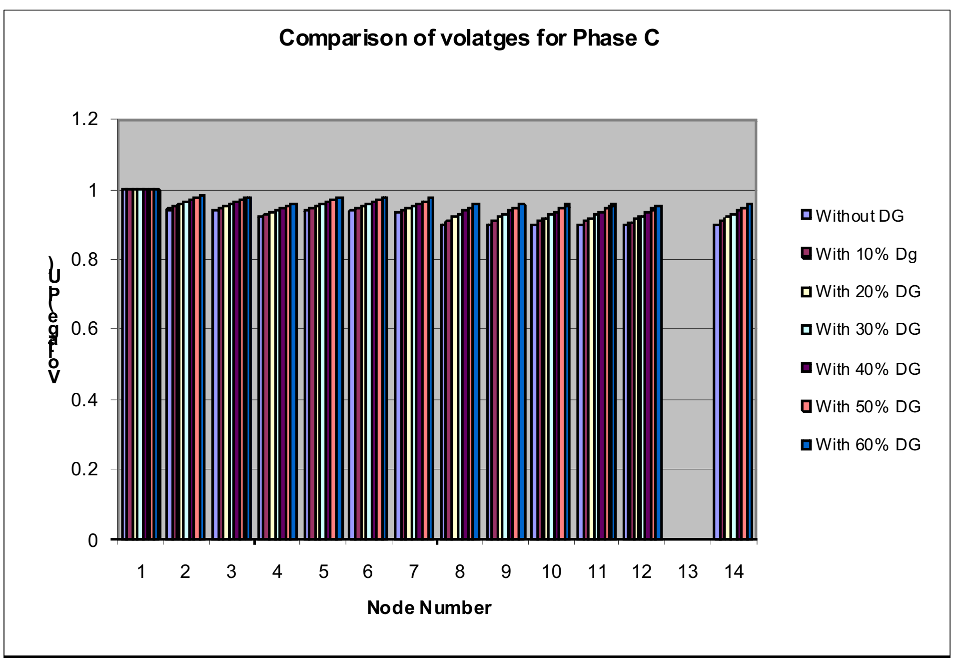

Figure 4.4 Comparison of voltages for phase C for IEEE 13 node feeder

It can be seen from the above figures as the penetration level of the DG is increased from 10% to 60% of the total load the voltage profile of the system is improved. For the system without the DG, the voltages of the downstream nodes was close to lower tolerance level i.e. 0.95pu and for stable operation of power system the voltages at all nodes should be 1±0.05pu. In the distribution system the load changes very frequently and if the load on the downstream nodes increases, the voltages at those nodes may further go beyond the lower tolerance level. It can be seen from the Figures 4.2, 4.3 and 4.4 that with the presence of DG at junction nodes 631 and 671 the voltage of the downstream nodes has increased, thus improving the margin of stability for the system during peak load conditions.

4.2.2 Comparison of voltage profiles for 37 node feeder

The IEEE 37 node feeder is an original feeder in California and the total load of the system is 2.44MW. To compare the voltage profiles power flow is run by placing two DG's that are modeled as PV nodes at nodes 703 and 734 as shown in Figure 4.5. Voltage regulator was removed in the analysis to clearly see the effects of DG on voltage profile of the system.

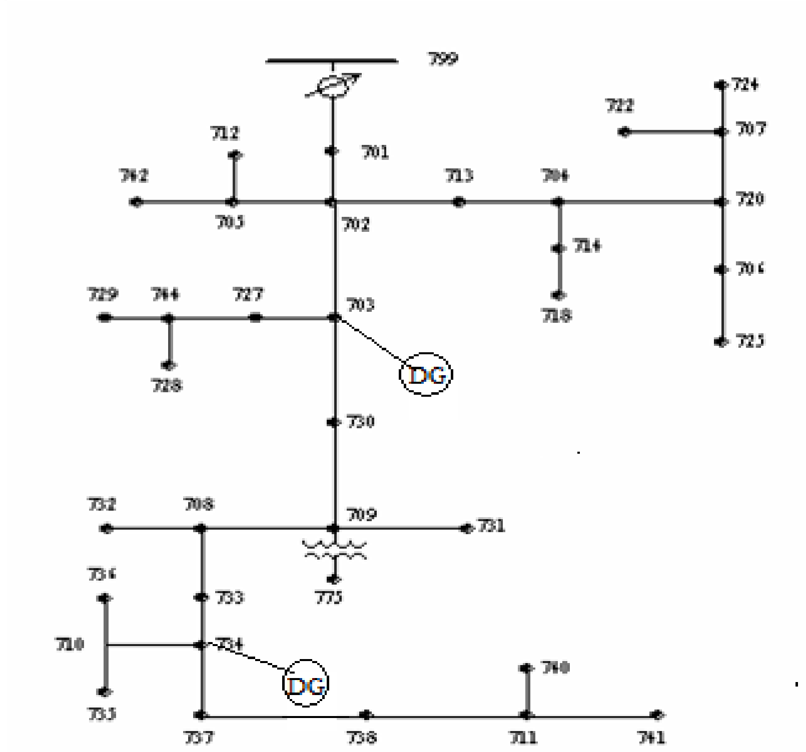

Figure 4.5 IEEE 37 node feeder with DG

The total penetration level of DG (size) is varied from 10% to 70% of the total load with each DG sharing equally and the voltage profile of each case is compared with that of the base case. IEEE 37 node feeder is relatively large feeder compared to IEEE 13 node feeder with distributed loads. Table 4.2 gives the % penetration levels of DG and respective real power of the DG.

Table 4.2 DG penetration with respect to total DG power

% DG	Total P_{DG}
10%	244kW
20%	288kW
30%	732kW
40%	976kW
50%	1220kW
60%	1464kW
70%	1708kW

The comparison of voltages for each phase is shown in Figures 4.7, 4.8 and 4.9.

Figure 4.6 gives the comparison of voltages at all the nodes and to see the effect of DG clearly the voltages were compared at few selected nodes in figures 4.7 and 4.8. It can be seen that as the size of the DG is increased the voltage profile of the system improves. IEEE 37 node feeder is relatively large and if loads are supplied by single source, the voltages at the downstream nodes were very low due to losses. With the presence of DG's in the system the voltage profile of the downstream nodes has improved. It is also observed from the power flow analysis that, there were over voltages at some nodes as seen in Figure 4.8. If DG penetration is too low there was not much impact on the voltage profile of the DG. Hence it is important that we consider proper size and location of DG.

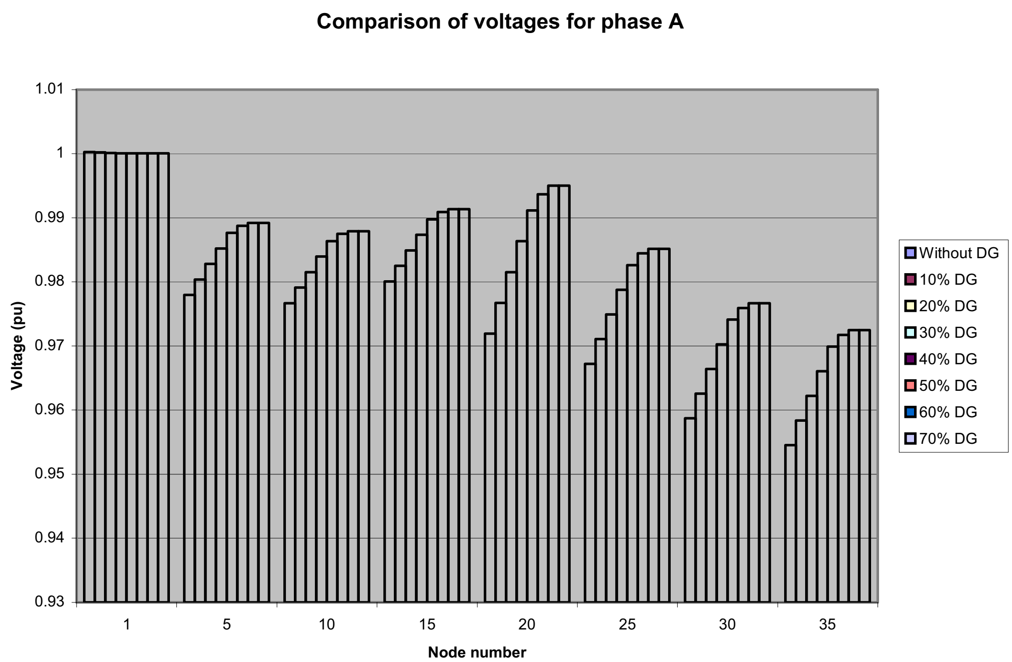

Figure 4.6 Comparison of voltages for phase A of IEEE 37 node feeder

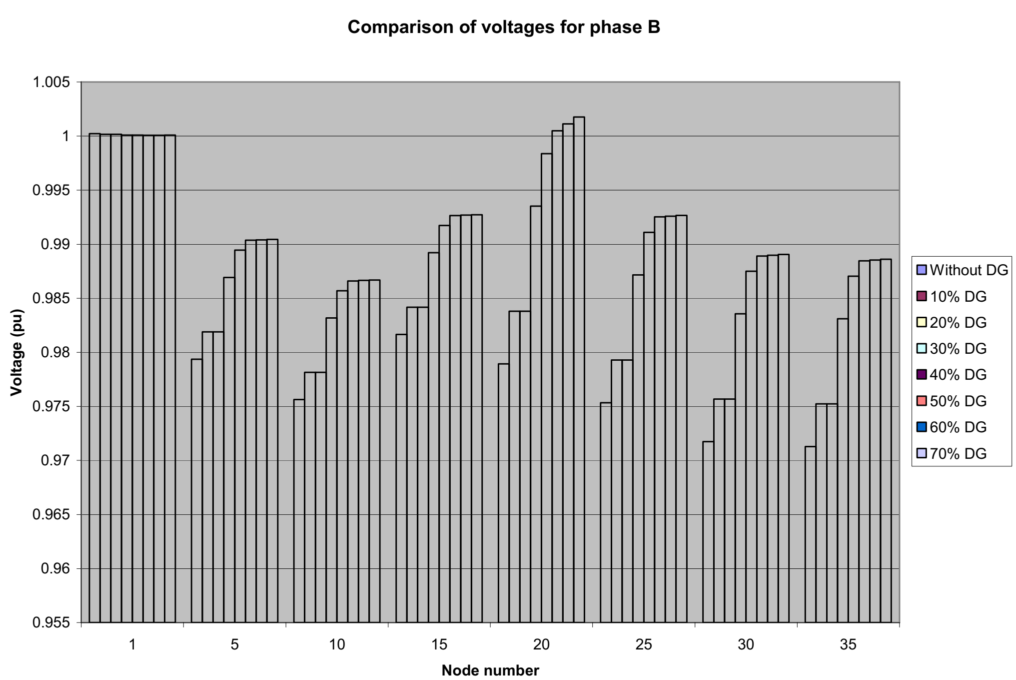

Figure 4.7 Comparison of voltages for phase B for IEEE 37 node feeder

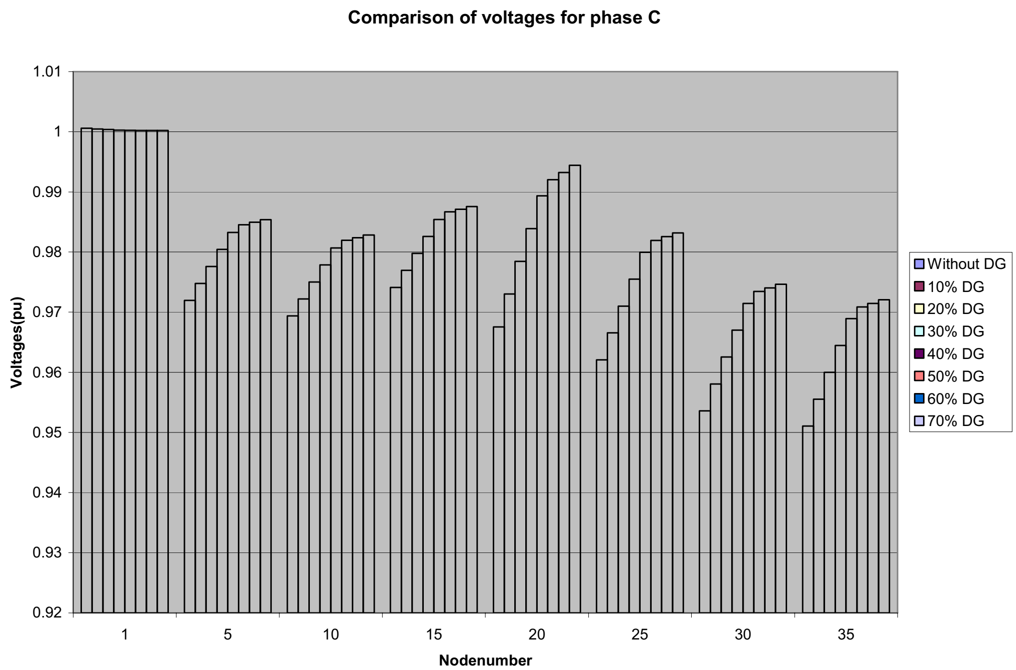

Figure 4.8 Comparison of voltages for phase C for IEEE 37 node feeder

4.3 Voltage stability analysis

The voltage profiles obtained from the power flow analysis can be used to study the voltage stability of the system using the stability index selected and details were explained in section 3.5. Stability index can be used to find the nodes that are close to voltage collapse and brings instability in the system. The stability index selected makes use of voltages and voltage angles at all the nodes obtained from power flow to calculate the stability index values at all the nodes. The following sections give the stability index values at all the node for base case and the system with DG. This analysis was done on IEEE 13 node feeder and the results are presented.

4.3.1 Stability index values for 13 node feeder without DG

Power flow was run on IEEE 13 node feeder with no DG connected and the voltages and voltage angles obtained at the nodes were used to calculate the stability values using

$$L(i) \quad 4\left[\left[V_i V_j \cos(\theta_i - \theta_j) - V_j^2 \cos(\theta_i - \theta_j)^2\right] / V_j^2\right] \tag{4.1}$$

Table 4.3 gives the stability index values for the base case

Table 4.3 Stability index values without DG

Node no	Phase A	Phase B	Phase C
650	F	F	F
632	0.0571	0.3097	0.1898
633	0.1415	0.2450	0.2870
634	0.6730	0.6730	0.778
645	-	0.4320	0.4194
646	-	0.2911	0.0561
7	0.5506	0.2184	0.2366
671	0.6674	0.0457	0.3570
692	0.0113	-	-
675	0.8719	0.2458	0.5027
684	0.7882	-	0.6350
611	-	-	0.6190
652	0.5240	-	-
680	0.6480	-	-

Where,

"-" represents that index does not exist at this place as nodes might be single phase or two phase for example node 652 is single phase node and lines does not exist for phase B and phase C

"F" Feeder node

It can be seen from Table 4.3 that the stability index values of phase A of node 684 and phase A of node 675 are close to 1 indicating that they are prone to collapse if the load on the system is increased during peak load conditions and necessary preventive actions may need to taken. Presence of DG at some location on the system may improve the stability of the system hence the same analysis is done with DG at different locations to see the impact of DG on the voltage stability of the system.

4.3.2 Stability index values of 13 node feeder with DG

To see the impact of DG on voltage stability two DG's were placed at node 632 and 671 as shown in Figure 4.1 with the total power supplied by the DG is selected randomly as P_{DG}=2.0796MW. From the power flow results obtained the stability index values were calculated at all the nodes using equation 4.1 and are shown in table 4.4.

Table 4.4 Stability index values with P_{DG} =2.0796MW

Node no	Phase A	Phase B	Phase C
650	F	F	F
632	G	G	G
633	0.0216	0.0124	0.0108
634	0.3250	0.4372	0.4540
645	-	0.1770	0.2713
646	-	0.0164	0.0131
7	0.3915	0.0113	0.1825
671	G	G	G
692	0.0003	-	-
675	0.3470	0.1042	0.2735
684	0.3880	-	0.0082
611	-	-	0.0550
652	0.0350	-	-
680	0.0001	-	-

Where,

"-"represents that index does not exist at this place as nodes might be single phase or two phase.

"G" Generator node

"F" Feeder node

The results from this analysis show that with DG in the system the voltage profiles are improved and thus the system was more stable. With DG in the system, the margin of stability limit was improved for the nodes that were close to collapse without DG. The stability index value of node 675 was 0.8719 for the base case and with DG at node 671 the stability index value has moved down to 0.3470 proving that the voltage stability margin of the system has improved. In the similar way stability index values can be calculated for all the possible combinations of DG size and locations and the best combination can be selected based on the minimum stability index values. But this process involves a large amount of data and to automate this process an optimization approach was developed in LINGO to find the best location and size and the results of this analysis are presented in the following sections.

4.4 Optimizing the size of DG for IEEE 13 node and 37 node feeders

The formulation for optimizing the size of the DG was developed in section 3.6. The objective function of the formulation was to maximize the grid stability i.e. minimizing the stability index selected with constraints being voltage limits, load limits and source limits. The formulation was implemented in LINGO which is commercial optimization tool that solves the linear and non linear problems precisely and it can handle unlimited variables. This formulation was tested for IEEE 13 node and IEEE 37 node feeders and the results are presented here.

4.4.1 Results for IEEE 13 node feeder

IEEE 13 node feeder is considered first and a DG modeled as PQ node is placed at node 671 which being a junction node and close to downstream nodes mostly experience the low voltage problems. The power factor is fixed at 0.95 lagging, P and Q values are calculated as follows

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

Since,

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

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

The size of the DG is varied from 10% to 70% of the total load in steps of 5% and for each size of the DG power flow is run simultaneously and the objective function is minimized without violating the system constraints. The following assumptions were made before modeling the system components in LINGO

- The regulator was removed from the system to see the impact of DG on the voltage profile.
- Capacitor banks were not modeled, hence removed from the system.
- All loads were modeled as constant current loads.

The formulation was simulated in LINGO and the steady state solution obtained gives the optimal size where the stability index values are minimum and without violating the constraints. It is found from the simulation that the optimal size for IEEE 13 node feeder is "P_{DG}=2.0796MW" i.e. when the total penetration was 60% of the total load. The stability index values obtained from the simulation are shown in Table 4.5.

Table 4.5 Stability index values with 60% DG for IEEE 13 node feeder

Node no	Phase A	Phase B	Phase C
650	F	F	F
632	0.0116	0.0224	0.0508
633	0.0516	0.3097	0.0801
634	0.1830	0.4063	0.4954
645	-	0.2684	0.4194
646	-	0.0164	0.0131
7	0.2431	0.0184	0.2366
671	G	G	G
692	0.2046	-	-
675	**0.6461**	0.1973	0.3061
684	0.1493	-	0.0082
611	-	-	0.1151
652	0.4235	-	-
680	0.3924	-	-

Where,

"-" represents that index does not exist at this place as nodes might be single phase or two phase.

"G" Generator node.

"F" Feeder node.

The total variables in this formulation are

Non linear variables = 338

Integer variables = 16

Linear variables = 59

Total variables = 413

It can be seen from the Table 4.9 that the minimized stability index value is 0.6461 which is at phase A of node 675. This value gives the margin of stability which is obtained by minimizing the maximum values of all the cases. The system is more stable when DG is at node "671" with all values closer to "0". In order to validate the results the power flow results obtained from LINGO are compared with three phase unbalanced power flow software and the comparison of voltages is shown in Table 4.6.

Table 4.6 Comparison of voltages from LINGO and MATLAB with 60% DG

Node ID	LINGO		MATLAB		LINGO		MATLAB		LINGO		MATLAB	
	Van	∠Van	Van	∠Van	Vbn	∠Vbn	Vbn	∠Vbn	Vcn	∠Vcn	Vcn	∠Vcn
1	1.0003	0.00	1.000	0.0	0.9999	-120.00	1	-120	1.0001	120.00	1	120.00
2	0.9912	-0.31	0.995	-0.4	1.0166	-120.87	0.998	-120.84	0.9815	119.51	0.992	119.61
3	0.9881	-0.39	0.981	-0.5	1.0146	-120.91	0.989	-120.88	0.9985	119.54	0.991	119.65
4	0.9631	-0.44	0.979	-0.5	0.9951	-120.93	0.989	-120.9	0.9933	119.57	0.993	119.68
5	-	-	-	-	1.0073	-120.96	0.982	-120.93	0.9964	119.46	0.994	119.56
6	-	-	-		1.0055	-121.75	0.983	-120.97	0.9761	119.44	0.994	119.54
7	0.9876	-0.42	0.984	-0.5	1.0217	-120.87	0.992	-120.83	0.9986	119.43	0.989	119.52
8	0.9763	-0.79	0.981	-0.9	1.0396	-120.81	0.992	-120.77	0.9898	119.27	0.982	119.37
9	0.9764	-0.81	0.982	-0.9	1.0396	-120.79	0.992	-120.75	0.9577	119.26	0.982	119.35
10	0.9697	-0.81	0.983	-0.9	1.0422	-120.79	0.992	-120.75	0.9568	119.26	0.982	119.35
11	0.9743	-0.84	0.978	-0.9	-	-	-	-	0.9864	119.28	0.981	119.37
12	-	-	-		-	-	-	-	0.9725	119.25	0.979	119.34
13	0.9682	-0.76	0.96	-0.8	-	-	-	-	-	-	-	-
14	0.9763	-0.80	0.98	-0.9	-	-	-	-	-	-	-	-

From Table 4.6 it is seen that the voltage profile obtained from LINGO and Unbalanced power flow software are almost same. The differences are caused by relaxed solution in MATLAB while constrained Optimal Power Flow (OPF) in LINGO. It is found from the literature that if the DG size is small it should be modeled as PQ node and for larger DG size it should be modeled as PV node [12]. In this analysis DG is modeled as PQ node irrespective of the size to minimize the complexity of problem, which may result in differences in the voltage profiles.

4.4.2 Results for IEEE 37 node feeder

IEEE 37 node feeder is considered and DG modeled as PQ node is placed at node 703 being the junction node. P and Q values of the DG are calculated as shown in section 4.4.1. The size of the DG is increased from 10% to 70% in steps of 5% and for each size of DG, power flow is run simultaneously and the objective function is minimized without violating the constraints. The following assumptions were made before modeling the test case in LINGO.

- Regulator was removed to clearly see the impacts of DG on voltage profile of the system.
- Capacitors were not modeled.
- All loads are considered as constant current loads.

The formulation was simulated in LINGO and the steady state solution obtained gives the optimal size where the stability index values are minimum without violating the constraints. It is found from the simulation that the optimal size for IEEE 37 node feeder is "P_{DG}=1.22MW" i.e. when the total penetration was 50% of the total load. The stability index values obtained from the simulation are shown in Table 4.7. The total variable in this formulation are

Non Linear – 1004

Linear - 287

Integer – 42

Total variables – 1333

In Table 4.7,

"F" Feeder node and

"G" Generator node.

It can be seen from the Table 4.7 that the minimized stability index value is "0.7191" which is at phase A of node 733. Among all the cases, the system is more stable with 50% DG penetration with all values closer to "0" and the margin of stability is given by the minimum of all maximum values for each case. In order to validate the results the power flow results obtained from LINGO are compared with three phase unbalanced power flow software and the comparison of voltages is shown in Table 4.8.

Table 4.7 Stability index values with 50% DG for IEEE 37 node system

Node No	Phase A	Phase B	Phase C
799	F	F	F
701	0.0116	0.0224	0.0508
702	0.0516	0.3097	0.0801
713	0.1730	0.4063	0.4954
704	0.3813	0.2684	0.4194
720	0.0453	0.0164	0.0131
707	0.5874	0.0184	0.2366
724	0.1780	0.3834	0.2836
722	0.2046	0.5824	0.3719
706	0.4932	0.0921	0.0082
725	0.1884	0.2723	0.0280
714	0.6931	0.5813	0.1150
718	0.4235	0.0178	0.3489
705	0.3924	0.1380	0.0153
742	0.0043	0.0133	0.0035
712	0.0028	0.1827	0.0047
703	G	G	G
727	0.0285	0.0072	0.0172
744	0.0216	0.0124	0.0108
729	0.5928	0.4372	0.4940
728	0.0566	0.1770	0.4194
730	0.0457	0.0164	0.0131
709	0.5506	0.0184	0.2366
775	0.0831	0.3827	0.2894
731	0.0731	0.0178	0.3489
708	0.1474	0.1931	0.1721
732	0.0881	0.0015	0.0280
733	**0.7191**	0.7031	0.0501
734	0.4930	0.0921	0.0052
710	0.1880	0.2723	0.0281
736	0.6931	0.5813	0.1150
735	0.4235	0.0178	0.3489
737	0.3924	0.1380	0.0153
738	0.3813	0.2684	0.4194
711	0.0453	0.0164	0.0131
740	0.6461	0.0184	0.2366
741	0.7131	0.4321	0.3980

Table 4.8 Comparison of voltage profiles from LINGO and MATLAB with 50% DG for IEEE 37 node feeder.

Node No	LINGO		MATLAB		LINGO		MATLAB		LINGO		MATLAB	
	Va	∠Va	Va	∠Va	Vb	∠Vb	Vb	∠Vb	Vc	∠Vc	Vc	∠Vc
799	1.0	0.001	1.0	-0.02	1.0	-119.9	1.0	-120	1.0	119.9	1.0	119.9
701	0.994	0.08	0.993	-0.04	0.995	-120.1	0.995	-120.3	0.991	119.9	0.990	119.7
702	0.993	0.143	0.990	-0.08	0.994	-120.1	0.993	-120.4	0.988	119.8	0.986	119.5
713	0.990	0.136	0.989	-0.09	0.992	-120.2	0.992	-120.4	0.986	119.8	0.985	119.5
704	0.989	0.107	0.987	-0.12	0.990	-120.2	0.989	-120.4	0.984	119.8	0.983	119.6
720	0.988	0.072	0.986	-0.16	0.987	-120.2	0.986	-120.5	0.982	119.9	0.980	119.6
707	0.986	-0.011	0.984	-0.25	0.981	-120.2	0.980	-120.4	0.980	120.0	0.979	119.8
724	0.985	-0.031	0.984	-0.27	0.980	-120.2	0.979	-120.4	0.980	120.1	0.978	119.8
722	0.985	-0.027	0.984	-0.26	0.981	-120.2	0.980	-120.4	0.980	120.1	0.979	119.8
706	0.987	0.062	0.986	-0.17	0.986	-120.2	0.985	-120.5	0.982	119.9	0.980	119.6
725	0.986	0.054	0.986	-0.17	0.986	-120.2	0.985	-120.5	0.982	119.9	0.980	119.6
714	0.988	0.108	0.987	-0.12	0.990	-120.2	0.989	-120.4	0.984	119.8	0.983	119.6
718	0.987	0.119	0.986	-0.11	0.990	-120.1	0.989	-120.4	0.984	119.8	0.982	119.5
705	0.991	0.151	0.990	-0.08	0.993	-120.1	0.992	-120.4	0.987	119.8	0.985	119.6
742	0.991	0.134	0.989	-0.09	0.992	-120.1	0.991	-120.4	0.987	119.9	0.985	119.6
712	0.991	0.168	0.989	-0.06	0.993	-120.2	0.992	-120.4	0.986	119.8	0.984	119.6
703	0.992	0.267	0.989	-0.10	0.995	-120.0	0.995	-120.4	0.989	119.8	0.986	119.3
727	0.996	0.271	0.992	-0.16	1.001	-120.0	0.998	-120.5	0.993	119.8	0.989	119.3
744	0.995	0.270	0.991	-0.18	1.001	-120.0	0.998	-120.5	0.993	119.8	0.989	119.2
729	0.995	0.274	0.991	-0.16	1.001	-120.0	0.998	-120.5	0.993	119.8	0.989	119.2
728	0.994	0.274	0.991	-0.16	1.000	-120.0	0.998	-120.5	0.992	119.8	0.989	119.1
730	0.986	0.325	0.984	-0.04	0.994	-120.1	0.992	-120.5	0.984	119.7	0.981	119.2
709	0.985	0.338	0.982	-0.03	0.993	-120.1	0.991	-120.5	0.982	119.7	0.982	119.2
775	0.985	0.338	0.982	-0.03	0.993	-120.1	0.991	-120.5	0.982	119.7	0.980	119.2
731	0.985	0.318	0.982	-0.02	0.993	-120.1	0.991	-120.5	0.982	119.7	0.979	119.2
708	0.982	0.369	0.980	-0.00	0.992	-120.1	0.990	-120.5	0.980	119.6	0.978	119.2
732	0.982	0.381	0.980	0.08	0.992	-120.1	0.990	-120.5	0.980	119.6	0.977	119.2
733	0.980	0.392	0.978	0.17	0.991	-123.0	0.990	-120.5	0.978	119.5	0.976	119.1
734	0.977	0.440	0.974	0.05	0.990	-120.1	0.981	120.5	0.975	119.5	0.972	119.0
710	0.976	0.464	0.974	0.08	0.988	-120.1	0.987	-120.4	0.974	119.5	0.971	119.0
736	0.976	0.430	0.973	0.05	0.987	-120.1	0.985	-120.3	0.973	119.5	0.971	119.1
735	0.976	0.478	0.974	0.10	0.988	-120.1	0.987	-120.7	0.973	119.5	0.970	119.0
737	0.973	0.470	0.971	0.09	0.989	-120.0	0.987	-120.8	0.973	119.4	0.970	118.9
738	0.975	0.491	0.970	0.11	0.988	-120.0	0.987	-120.2	0.972	119.3	0.969	118.9
711	0.972	0.513	0.969	0.37	0.988	-120.1	0.987	-120.6	0.971	119.3	0.968	118.9
740	0.972	0.528	0.969	0.15	0.983	-120.1	0.986	-120.9	0.970	119.3	0.968	118.9
741	0.972	0.521	0.969	0.14	0.988	-120.1	0.986	-120.5	0.971	119.3	0.968	118.9

The steady state power flow solution obtained from LINGO and MATLAB were almost the same. The differences are caused by relaxed solution in MATLAB while constrained Optimal Power Flow (OPF) in LINGO. It is found from the literature that if the DG size is small it should be modeled as PQ node and for larger DG size it should be modeled as PV node [12]. In this analysis DG is modeled as PQ node irrespective of the size to minimize the complexity of problem, which may result in differences in the voltage profiles.

4.5 Optimizing the location of DG for IEEE 13 node and IEEE 37 node feeders

The formulation for optimizing the location of the DG was developed in section 3.6. The objective function of the formulation was to maximize the grid stability i.e. minimizing the stability index selected with constraints being power flow, voltage limits, load limits and source limits. The formulation was implemented in a format required by LINGO. This formulation was tested for IEEE 13 node and IEEE 37 node feeders and the results are presented in the sections 4.51 and 4.5.2.

4.5.1 Results for IEEE 13 node feeder

IEEE 13 node feeder is considered first and the component models are developed in LINGO. The optimal size obtained form section 4.4, i.e. DG with penetration level of 60% of total load is placed at all possible locations of the system. There are 5 possible locations in IEEE 13 node feeder, which are three phase nodes as DG is modeled as three phase. Using proper switching logic DG is placed at these locations with fixed size and for each location of DG power flow is run simultaneously minimizing the objective function without violating the system constraints.

It is found from the simulations that the optimal location at which the stability of the system is maximum is when DG was at node "671" which is junction node and half way from the main feeder and junction loads. The stability index values obtained in this case from LINGO are shown in Table 4.9.

Table 4.9 Stability index values with DG at node 671

Node no	Phase A	Phase B	Phase C
650	F	F	F
632	0.0116	0.0224	0.0508
633	0.0516	0.3097	0.0801
634	0.1830	0.4063	0.4954
645	-	0.2684	0.4194
646	-	0.0164	0.0131
7	0.2431	0.0184	0.2366
671	G	G	G
692	0.2046	-	-
675	**0.6461**	0.1973	0.3061
684	0.1493	-	0.0282
611	-	-	0.1151
652	0.4235	-	-
680	0.3924	-	-

Where,

"-" index does not exist at this place as nodes might be single phase or two phase.

"G" Generator node.

"F" Feeder node.

The total variables in this formulation are

Non linear variables = 338

Integer variables = 25, Linear variables = 59 and Total variables = 413

It can be seen from the Table 4.9 that the minimized stability index value is 0.6461 which is at phase A of node 675. This value gives the margin of stability which is obtained by minimizing the maximum values of all the cases. The system is more stable when DG is at node "671" with all values closer to "0". In order to validate the results the power flow results obtained from LINGO are compared with three phase unbalanced power flow software and the comparison of voltages is shown in Table 4.10.

Table 4.10 Comparison of voltages from MATLAB and LINGO with DG at node 671

Node ID	LINGO		MATLAB		LINGO		MATLAB		LINGO		MATLAB	
	Van	∠Van	Van	∠Van	Vbn	∠Vbn	Vbn	∠Vbn	Vcn	∠Vcn	Vcn	∠Vcn
1	1.0003	0	1	0	0.9998	-120	1	-120	1.0001	120	1	120
2	0.9912	-0.31	0.995	-0.4	1.0166	-120.87	0.99	-120.84	0.985	119.51	0.992	119.61
3	0.9881	-0.39	0.981	-0.5	1.0146	-120.91	0.989	-120.88	0.998	119.54	0.991	119.65
4	0.9631	-0.44	0.979	-0.5	0.9951	-120.93	0.989	-120.90	0.993	119.57	0.993	119.68
5	-	-	-	-	1.0073	-120.96	0.982	-120.93	0.996	119.46	0.994	119.56
6	-	-	-	-	1.0055	-121.65	0.985	-120.97	0.976	119.44	0.994	119.54
7	0.9876	-0.42	0.984	-0.5	1.0217	-120.87	0.991	-120.83	0.998	119.43	0.989	119.52
8	0.9763	-0.79	0.983	-0.9	1.0396	-120.8	0.992	-120.77	0.989	119.27	0.982	119.37
9	0.9764	-0.83	0.985	-0.9	1.0396	-120.79	0.992	-120.75	0.957	119.26	0.982	119.35
10	0.96974	-0.81	0.982	-0.9	1.0424	-120.79	0.992	-120.75	0.956	119.26	0.982	119.35
11	0.9744	-0.84	0.978	-0.9	-	-	-	-	0.986	119.28	0.981	119.37
12	-	-	-	-	-	-	-	-	0.972	119.25	0.979	119.34
13	0.9682	-0.76	0.960	-0.8	-	-	-	-	-	-	-	-
14	0.973	-0.8	0.980	-0.9	-	-	-	-	-	-	-	-

From the above comparison it is found that the voltage profile obtained from LINGO and unbalanced power flow software were almost same hence validating the results for optimizing the location of DG. The differences are caused by relaxed solution in MATLAB while constrained OPF in LINGO.

4.5.2 Results for IEEE 37 node feeder

Component models for IEEE 37 node feeder are developed in LINGO. The optimal size obtained from section 4.4 for this feeder i.e. DG with penetration level of 50% of total load is placed at all possible locations of the system. All the nodes in this feeder are three phase nodes and possible locations for DG placement. With all the locations considered the formulation in LINGO failed to converge properly due to computation complexity. The possible locations were reduced to 10 which were junction nodes since it was proved in [5] and analysis of IEEE 13 node feeder has shown that the best location was junction node where the system is more stable. Using proper switching logic DG is placed at these locations with fixed size and for each location of DG power flow is run simultaneously minimizing the objective function without violating the system constraints.

It is found from the simulations that the optimal location at which the stability of the system is maximum, with DG with at node "709" which is junction node and half way from the main feeder and junction loads. The stability index values obtained in this case from LINGO are shown in table 4.11. The total variables in this formulation are

Non Linear – 1004, Linear - 297, Integer – 42 andTotal - 1343

Table 4.11 Stability index values with 50% DG at node 709 for IEEE 37 node feeder

Node No	Phase A	Phase B	Phase C
799	F	F	F
701	0.1061	0.0184	0.2366
702	0.0831	0.3827	0.2894
713	0.0731	0.0178	0.3489
704	0.1472	0.1931	0.1721
720	0.0883	0.0015	0.0288
707	0.3281	**0.7730**	0.0512
724	0.4932	0.0921	0.0082
722	0.1880	0.2723	0.0282
706	0.6931	0.5813	0.1151
725	0.4235	0.0178	0.3489
714	0.3924	0.1381	0.0153
718	0.3813	0.2684	0.4194
705	0.0453	0.0164	0.0131
742	0.2183	0.0184	0.2366
712	0.3617	0.4321	0.3982
703	0.3712	0.1943	0.2891
727	0.0285	0.0072	0.0172
744	0.0216	0.0124	0.0108
729	0.5872	0.4372	0.4941
728	0.0566	0.1772	0.4194
730	0.0457	0.0016	0.0131
709	G	G	G
775	0.0516	0.3097	0.0801
731	0.1730	0.4063	0.4954
708	0.3813	0.2684	0.4194
732	0.0453	0.0164	0.0131
733	0.6461	0.0184	0.2366
734	0.1788	0.3834	0.2836
710	0.2046	0.5824	0.3719
736	0.4939	0.0921	0.0082
735	0.1881	0.2723	0.0280
737	0.6931	0.5813	0.1150
738	0.4235	0.0178	0.3489
711	0.3924	0.1380	0.2630
740	0.6391	0.5287	0.4862
741	0.5145	0.4834	0.3925

Where,

"F" Feeder node and "G" Generator node.

It can be seen from the Table 4.11 that the minimized stability index value is 0.7730 which is at phase B of node 707. This value gives the margin of stability which is obtained by minimizing the maximum values of all the cases. The system is more stable when DG is at node “707” with all values closer to “0”. In order to validate the results, a DG with which supplies 50% of the total load is kept at same location in the unbalanced power flow software and the power flow results obtained is compared with LINGO. The comparison of voltage profiles is shown in Table 4.12.

From the comparison in Table 4.12 it is found that the voltage profile obtained from LINGO and unbalanced power flow software were almost same and the difference is caused by relaxed solution from MATLAB and constrained OPF from LINGO.

Table 4.12 Comparison of voltages from LINGO and MATLAB with DG at node 709

Node No	LINGO		MATLAB		LINGO		MATLAB		LINGO		MATLAB	
	Va	∠Va	Va	∠Va	Vb	∠Vb	Vb	∠Vb	Vc	∠Vc	Vc	∠Vc
799	1.0	-0.003	1.0	-0.007	1.0	-119.9	1.0	-119.9	1.0	120.00	1.0	119.99
701	0.994	0.166	0.994	0.007	0.995	-120.0	0.995	-120.2	0.991	119.97	0.991	119.78
702	0.992	0.281	0.991	0.005	0.994	-120.03	0.994	-120.3	0.989	120.01	0.988	119.68
713	0.991	0.275	0.990	-0.001	0.993	-120.0	0.992	-120.3	0.987	120.02	0.986	119.69
704	0.989	0.245	0.988	-0.031	0.990	-120.0	0.990	-120.3	0.985	120.04	0.984	119.72
720	0.985	0.210	0.987	-0.066	0.987	-120.1	0.987	-120.4	0.982	120.11	0.982	119.78
707	0.986	0.119	0.985	-0.157	0.981	-120.07	0.981	-120.3	0.981	120.26	0.980	119.93
724	0.986	0.099	0.985	-0.177	0.980	-120.06	0.980	-120.3	0.981	120.28	0.980	119.9
722	0.986	0.111	0.986	-0.16	0.981	-120.07	0.981	-120.3	0.981	120.2	0.980	119.94
706	0.988	0.200	0.987	-0.076	0.986	-120.11	0.986	-120.4	0.982	120.12	0.981	119.79
725	0.988	0.193	0.987	-0.083	0.986	-120.11	0.986	-120.4	0.982	120.13	0.982	119.80
714	0.989	0.246	0.989	-0.030	0.990	-120.05	0.990	-120.3	0.985	120.0	0.984	119.71
718	0.988	0.257	0.987	-0.019	0.990	-120.02	0.990	-120.3	0.984	120.01	0.984	119.68
705	0.992	0.289	0.991	0.013	0.993	-120.04	0.993	-120.3	0.987	120.04	0.986	119.71
742	0.991	0.272	0.991	-0.003	0.992	-120.04	0.992	-120.3	0.987	120.06	0.986	119.73
712	0.991	0.305	0.991	0.030	0.993	-120.06	0.993	-120.3	0.987	120.05	0.986	119.7
703	0.992	0.484	0.991	0.048	0.997	-119.84	0.997	-120.3	0.990	120.09	0.988	119.57
727	0.997	0.536	0.994	0.056	1.002	-119.78	1.009	-120.3	0.994	120.13	0.992	119.52
744	0.996	0.535	0.994	0.049	1.001	-119.77	1.005	-120.3	0.995	120.12	0.992	119.50
729	0.996	0.539	0.993	0.084	1.001	-119.76	1.004	-120.3	0.995	120.11	0.990	119.49
728	0.996	0.539	0.993	0.009	1.001	-119.77	1.001	-120.3	0.995	120.12	0.991	119.51
730	0.987	0.545	0.986	0.105	0.994	-119.86	0.994	-120.3	0.985	120.00	0.983	119.47
709	0.986	0.558	0.984	0.180	0.993	-119.86	0.993	-120.3	0.983	119.69	0.982	119.44
775	0.986	0.558	0.985	0.118	0.993	-119.86	0.993	-120.3	0.984	119.97	0.982	119.44
731	0.985	0.538	0.984	0.098	0.992	-119.87	0.992	-120.3	0.981	119.99	0.981	119.46
708	0.983	0.589	0.982	0.148	0.992	-119.86	0.992	-120.3	0.982	119.91	0.980	119.38
732	0.983	0.601	0.982	0.160	0.993	-119.87	0.992	-120.4	0.981	119.91	0.979	119.39
733	0.981	0.614	0.979	0.172	0.991	-119.86	0.991	-120.3	0.979	119.85	0.978	119.32
734	0.977	0.662	0.976	0.217	0.990	-119.86	0.989	-120.2	0.976	119.47	0.974	119.24
710	0.974	0.686	0.975	0.241	0.989	-119.89	0.988	-120.8	0.974	119.80	0.973	119.27
736	0.976	0.652	0.975	0.207	0.987	-119.87	0.987	-120.3	0.974	119.84	0.973	119.34
735	0.977	0.700	0.976	0.256	0.988	-119.90	0.988	-120.1	0.974	119.80	0.972	119.02
737	0.974	0.693	0.973	0.247	0.989	-119.83	0.989	-120.1	0.974	119.68	0.972	119.15
738	0.973	0.713	0.972	0.267	0.988	-119.84	0.988	-120.1	0.972	119.65	0.971	119.12
711	0.973	0.736	0.971	0.290	0.988	-119.86	0.988	-120.4	0.972	119.64	0.970	119.11
740	0.973	0.757	0.972	0.304	0.988	-119.87	0.989	-120.3	0.971	119.66	0.970	119.12
741	0.973	0.743	0.971	0.298	0.988	-119.87	0.988	-120.8	0.971	119.64	0.970	119.11

4.6 Optimizing the size and location of DG for IEEE 13 node and IEEE 37 node feeder

The aim of the formulations developed in sections 3.6.1 and 3.6.2 is to find the optimal size and location of the DG individually. These formulations can be used when the unknown variable is either size of the DG or location of the DG, but there may be situations where size and location of DG has to be found simultaneously and in this scenario there will be many possible combinations form which the best has to be selected without violating the system constraints. In order to find the optimal size and location a mathematical formulation was developed in LINGO which is combination of those developed in LINGO and the unknown variables are two (size and location).

This formulation was written in a format required by LINGO and by switching the DG at the required location and varying the size simultaneously power flow is run for each combination and the objective function is minimized without violating the system constraints. This formulation was tested for IEEE 13 node feeder and IEEE 37 node feeder and the results are discussed in the following sections.

4.6.1 Results for IEEE 13 node feeder

IEEE 13 node feeder is considered and the component models are developed in LINGO. There are 5 possible locations for DG in this test system and the size of the DG is varied from 10% to 70% of the total load in steps of 5%. The optimization problem here is to find the best possible combination from 65 combinations of DG size and location at which the system will be more stable and the system constraints are not violated.

DG is modeled as PQ node and the mathematical formulation is simulated and it is observed that when a DG with "60%" penetration is placed at node "671" the system was more stable. The minimum stability index values and the comparison of voltage profiles from LINGO and that obtained from unbalanced power flow software using the optimal combination are shown in Tables 4.5 and 4.6.With this combination the minimized stability index is "0.6461" and from the Table 4.5 it can be seen that all the values are close to "0" indicating that the system is stable in the presence of DG.

4.6.2 Results for IEEE 37 node feeder

IEEE 37 node feeder is considered and the component models are developed in a format required by LINGO. All the nodes in this feeder are three phase nodes and possible locations for DG, to reduce the computation complexity the possible locations were reduced to 10 which were mainly junction nodes in the system. The size of the DG is varied from 10% to 70% of the total load in steps of 5%. The optimization problem here is to find best the best possible combination from 130 combinations of DG size and locations, at which the system will be more stable without violating the system constraints.

DG is modeled as PQ node and the mathematical formulation is simulated and it is observed that when a DG with "60%" penetration is placed at node "709" the system was more stable. The minimum stability index values and the comparison of voltage profiles from LINGO and that obtained from unbalanced power flow software using the optimal combination are shown in table 4.15

Where,

"F" Feeder node and

"G" Generator node.

It can be seen from the Table 4.13 that the minimized stability index value is 0.6931 which is at phase A of node 706. This value gives the margin of stability which is obtained by minimizing the maximum values of all the cases. The system is more stable with 60% DG penetration at node 706 where the values were closer to "0".

When IEEE 37 node feeder was analyzed individually for size and location the optimal size relates to 50% penetration of DG and the location was at node "709". But when all possible combinations were simulated using the combined formulation the best size was 60% DG and location was at node "709". To validate this DG size was fixed at 60% penetration and the formulation to find the optimal location was simulated again. It is found from this simulation that the best location was still node "709" validating the results.

Table 4.13 Stability index values with 60% DG at node 709 for IEEE 37 node feeder

Node No	Phase A	Phase B	Phase C
799	F	F	F
701	0.0714	0.0254	0.0247
702	0.0921	0.0261	0.2894
713	0.1831	0.0778	0.3489
704	0.1970	0.2931	0.1951
720	0.2088	0.0885	0.0628
707	0.5691	0.4740	0.3050
724	0.4930	0.0221	0.3731
722	0.1880	0.2723	0.0280
706	**0.6931**	0.5813	0.1150
725	0.4235	0.0178	0.3489
714	0.3924	0.1380	0.0153
718	0.3813	0.2684	0.4194
727	0.0285	0.0072	0.0172
744	0.0216	0.0012	0.0108
729	0.0735	0.1721	0.2440
703	0.1820	0.2731	0.0094
705	0.0453	0.0164	0.0131
742	0.0062	0.0184	0.1250
712	0.0073	0.0031	0.0391
728	0.0566	0.1770	0.4194
730	0.0457	0.0164	0.0131
709	G	G	G
775	0.0516	0.3097	0.0801
731	0.1730	0.4063	0.4954
708	0.3813	0.2684	0.4194
732	0.0453	0.0164	0.0131
733	0.6349	0.0184	0.2366
734	0.1780	0.3834	0.2836
710	0.2046	0.5824	0.3719
736	0.4930	0.1921	0.1820
735	0.1880	0.2723	0.0280
737	0.6931	0.5813	0.1150
738	0.4235	0.0178	0.3489
711	0.3924	0.1380	0.0153
740	0.3530	0.4941	0.5892
741	0.2932	0.3272	0.4937

4.6.3 Comparison of results for all formulations

The formulations were successfully tested for both the feeders and the optimal size and location obtained in each scenario are given in Table 4.14 along with the minimized stability index values obtained from the formulation.

Table 4.14 Comparison of results for different scenarios

Feeder type	Optimal size	Minimized stability index value	Optimal location	Minimized stability index value	Optimal size and location	Minimized stability index value
IEEE 13 node feeder	60%DG at node 671	0.6461	671 with 60% DG	0.6461	60% DG at node 671	0.6461
IEEE 37 node feeder	50% DG at node 703	0.7191	709 with 50% DG	0.7730	60% DG at node 709	0.6931

From the Table 4.14 it can be seen that the minimized stability index values indicate the margin of voltage stability for each system and the system was very stable in all the cases in the presence of DG.

4.7 Results of multi objective formulation for IEEE 13 node feeder

The multiobjective formulation that was developed in section 3.6.4 was written in a format required by LINGO and it was tested for IEEE 13 node. Assuming the weights has the same contribution for voltage stability index and voltage support index the formulation was simulated in LINGO and it was found that when DG with 60%

penetration was placed at node "671" the multiobjective function has minimized increasing the voltage stability and voltage support of the system. The results are shown in table 4.15. The total variables in this formulation are

Non Linear – 1041

Linear – 288

Integer – 42

Total - 1371

Table 4.15 Results from multi objective formulation

Node no	Phase A	Phase B	Phase C
650	F	F	F
632	0.0249	0.0444	0.0580
633	0.0438	0.1356	0.0737
634	0.1392	0.1447	0.2552
645	-	0.1057	0.1850
646	-	0.0177	0.0843
7	0.1330	0.0545	0.1345
671	G	G	G
692	0.1267	-	-
675	**0.3170**	0.1364	0.2012
684	0.2880	-	0.1079
611	-	-	0.2150
652	0.2152	-	-
680	0.1834	-	-

Where,

"F" feeder node

"G" Generator node

"-" Represents that index does not exist at this place as nodes might be single phase or two phase.

It is seen from the table 4.15 that the minimized value of the multiobjective function is "0.3170" at node 675 and phase A. The multi objective values at all the nodes are closer to "0" indicating that the presence of DG has improved the voltage stability margin and voltage stability margin of the system.

4.8 Summary

This chapter has discussed the results obtained from the power flow analysis with DG for IEEE 13 node and IEEE 37 node feeders. The voltage profiles for different sizes of the DG are compared with that of base case. Voltage stability analysis using the selected index was found for both the feeders. The optimization formulations developed in chapter 3 are simulated in LINGO and tested for both the feeders to find the optimal size and location and the results are validated using the power flow results from MATLAB. The next chapters give the conclusions of this research work and future work.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

5.1 Research work contributions and conclusions

Sizing and siting of DG are important aspects related to distribution network which need to be investigated. The advantages that DG brings to the system can be best utilized if these resources have been properly allocated in the system. DG has significant impacts on the voltage stability of the system as it may improve stability or reduce stability margins in the system. This work uses optimization approach to provide the best configuration for voltage stability considering size, location and both.

In this thesis work, IEEE 13 node feeder and IEEE 37 node feeder are used as the test cases. Power flow analyses are done on these test cases with DG connected and it is observed that as the size of the DG is increased the voltage profile of the system is improved. The voltages at the downstream nodes which are close to lower limit (0.95pu) improve, hence this increases the voltage stability margin of the system. If the DG size is very large then there are voltages in the system giving undesired voltage profiles, which may bring instability in the system. Using the selected stability index simulation studies shows that the presence of DG has improved the stability margins of the system.

To find the optimal size and location of the DG at which the system will be more stable, mathematical formulations are developed in LINGO. Three different formulations for optimizing the size of DG, optimizing the location of DG and optimizing the size and location of DG are developed to find the optimal size, location and both respectively. These formulations have been tested for two test cases considered and the results are validated using the Unbalanced Three Phase Power Flow Software (UTPFLOW). The comparison of voltage profiles from LINGO and UTFLOW showed some differences in the voltages which is due to constrained Optimal Power Flow (OPF) and relaxed solution in UTPFLOW. The differences are also due to modeling of DG since smaller DG's should me modeled as PQ node and larger DG's as PV node. In this optimization work DG was modeled as PQ node to reduce the complexity. The size of the DG is varied from 10% to 70% of the total load for all the formulations and it is observed from these simulations that IEEE 13 node feeder is more stable with the 60% DG penetration and IEEE 37 node feeder is more stable when the DG penetration is 50% of the total load. The junction nodes from which current distributes to two or more other nodes and the nodes that are at the midpoint between main feeder to the down stream nodes have proven to be the best locations for DG in the both the test cases. The optimal size and location varies for different systems, as it is dependent on the load, distribution of load in the system and distance from the main source. The results from this research show that this is one possible approach that can be used to find the optimal size and location of DG for any system.

5.2 Future Work

This research work deals with finding the optimal size and location of the DG and it is tested for small IEEE distribution feeders, which represents realistic distribution systems closely. Future work would be to find the location and size of the DG using real larger and realistic system data. This analysis was done with single DG so future work could be with multiple DG's. The comparison of voltage profiles obtained from UTPFLOW and LINGO showed some differences which could be due to the modeling of DG. Future work could be to consider different models of DG and compare the results. Optimization function can be extended to include other objectives such as losses, cost of generations and this can be tested with different optimization techniques like genetic algorithm, Particle Swarm Optimization (PSO) and other intelligent techniques.

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APPENDIX A

TEST CASES

A.1 Data of IEEE 13-node feeder

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

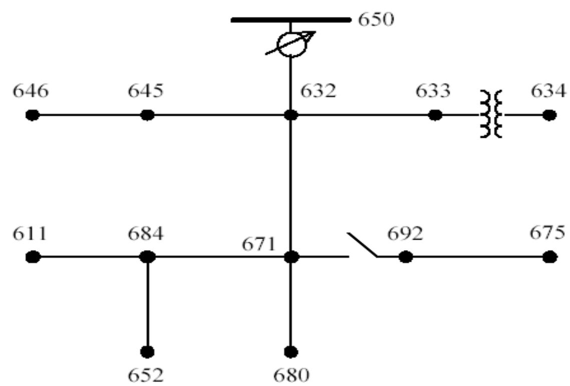

Figure A.1 Layout of IEEE 13-node distribution feeder [26]

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. The table below gives the kind of load and load model.

Table A.1 Load Models and Codes [26]

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 [26]

Node	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
634	D-I	160	110	120	90	120	90
645	D-I	0	0	170	125	0	0
646	D-I	0	0	230	132	0	0
652	D-I	128	86	0	0	0	0
671	D-I	385	220	385	220	385	220
675	D-I	485	190	68	60	290	212
692	D-I	0	0	0	0	170	151
611	D-I	0	0	0	0	170	80
	TOTAL	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 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 [26]

Node A	Node B	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 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 [26]

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

Overhead line spacing data

The overhead line spacing data is given in Table A.5.

Table A.5 Overhead line Spacing [26]

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 [26]

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 [26]

Config.	Phasing	Phase	Neutral	Spacing
		ACSR	ACSR	ID
601	B A C N	556,500 26/7	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

There are two transformers in the system. Transformers can be located at either end node of any segment. 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 [26]

	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

This is a radial system consisting of several segments. 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 Line segment data[26]

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.

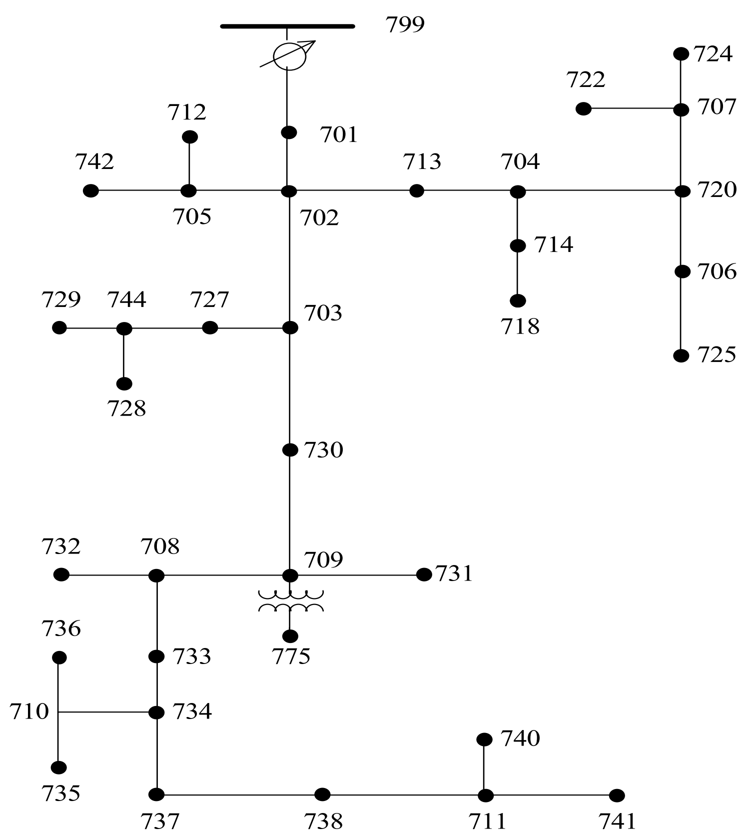

Figure A.2 Layout of the IEEE 37 node feeder test case [26]

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

Underground Cable Configurations

The underground cable configurations for the IEEE 37 node feeder are given in Table A.10.

Table A.10 Underground cable configuration data [26]

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 [26]

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
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
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 [26]

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 [26]

Node	Load Model	Ph-1 KW	Ph-1 Kvar	Ph-2 KW	Ph-2 Kvar	Ph-3 KW	Ph-3 Kvar
701	D-I	140	70	140	70	350	175
712	D-I	0	0	0	0	85	40
713	D-I	0	0	0	0	85	40
714	D-I	17	8	21	10	0	0
718	D-I	85	40	0	0	0	0
720	D-I	0	0	0	0	85	40
722	D-I	0	0	140	70	21	10
724	D-I	0	0	42	21	0	0
725	D-I	0	0	42	21	0	0
727	D-I	0	0	0	0	42	21
728	D-I	42	21	42	21	42	21
729	D-I	42	21	0	0	0	0
730	D-I	0	0	0	0	85	40
731	D-I	0	0	85	40	0	0
732	D-I	0	0	0	0	42	21
733	D-I	85	40	0	0	0	0
734	D-I	0	0	0	0	42	21
735	D-I	0	0	0	0	85	40
736	D-I	0	0	42	21	0	0
737	D-I	140	70	0	0	0	0
738	D-I	126	62	0	0	0	0
740	D-I	0	0	0	0	85	40
741	D-I	0	0	0	0	42	21
742	D-I	8	4	85	40	0	0
744	D-I	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 [26]

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