Analysis of Distribution Systems with DSTATCOM

Thesis submitted in the partial fulfillment of the requirements for the award of the degree of

Master of Engineering
in
Power Systems & Electric Drives

Thapar University, Patiala

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JULY 2010

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CERTIFICATE

I hereby certify that work which is being presented in the Thesis entitled **"Analysis of Distribution System with DSTATCOM"** in partial fulfilment of the requirement for the award of degree of Master of Engineering in ***Power Systems & Electric Drives*** submitted in Electrical & Instrumentation Engineering Department of Thapar University, Patiala, is an authentic record of my own work carried out under supervision of **Dr. Sanjay K. Jain**, Asst. Prof., EIED.

The matter presented in this Thesis has not been submitted for the award of any other degree of this or any other university.

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ACKNOWLEDGEMENT

First of all, I thank the Almighty, who gave me the opportunity and strength to carry out this work.

I would like to thank **Dr. Sanjay K. Jain, Assistant Prof., EIED** for the opportunity to work with him, and also for his encouragement, trust and untiring support. **Dr. Sanjay K. Jain** has been an advisor in the true sense both academically and morally throughout this project work.

I take this opportunity to express my gratitude and sincere thanks to **Mr.Yogesh K. Chauhan** for his valuable advices and suggestions during the thesis work.

Gratitude is accorded to Thapar University, Patiala, for providing all the necessary facilities to complete my M.E. Thesis work.

I am thankful to **Dr. Smarajit Ghosh, Professor & Head, EIED** for his continuous inspiration during this thesis work.

The paucity of words does not compromise for extending my thanks to all the faculty and staff members of EIED, Thapar University and my all family members and friends whose uninterrupted love, inspiration and blessings helped me in completing this research report.

I thank and owe my deepest regards to all who have helped me directly or indirectly.

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ABSTRACT

Distribution system, as the name suggest, is the medium through which power is distributed among the end consumers. Among the distribution systems, Radial Distribution System is popular due to cost and operational issues. In such systems due to high R/X ratio of the cables/lines, the voltage decreases as moved away from the source and results in high losses. Such issues of poor voltage regulation, high loses are related to the reactive power deficiency. This problem of poor voltage or reactive power compensation can be minimized or sometimes overcome by using suitable FACTS devices such as DSTATCOM. The DSTATCOM is also capable of solving various power quality issues such as voltage unbalance etc. DSTATCOMs are voltage source inverter (VSI) based devices, which regulate distribution bus voltage using reactive power compensation.

The work reported in this thesis is carried out with the objective of identifying the optimal location of DSTATCOM, as well as to carry out load flow analysis with a given rating of DSTATCOM. For these purpose two stage methodologies is used. In the first stage pre-compensated load flow of the distribution system is performed. On the basis of load flow solution the voltage drop in each bus is observed. DSTATCOM is applied individually, one by one to those buses which are below the safe limit. After compensation the Rate of Under Voltage Mitigated Nodes (*RUVMN*) of that compensation are computed. This process is carried out for each bus and the optimal location of DSTATCOM is computed upon these two parameters.

Load flow is realized using Backward – Forward sweep algorithm and the effectiveness is tested on 33 and 69 Bus radial distribution system.

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

An electric distribution system is part of an electric system between the bulk power source or sources and the consumers service switches. The bulk power sources are located in or near the load area to be served by the distribution system and may be either generating stations or power substations supplied over transmission lines. Distribution systems can, in general, be divided into six parts, namely, sub transmission circuits, distribution substations, distribution or primary feeders, distribution transformers, secondary circuits or secondary's, and consumer's service connections and meters or consumer's services.

With an increase in load demand, burden on lines and the voltage level is challenged. Now a day's maintaining voltage magnitude at an acceptable range is one of the major system constraints. One of the classical methods to solve this is to place shunt capacitor in line. But the reactive power provided by the shunt capacitor is bus voltage. This may reduce its effectiveness in high and low voltages. Another problem related to shunt capacitor is that they resonate when got tuned with system reactance.

Although the concept of FACTS was developed originally for transmission network; this has been extended since last 10 years for improvement of Power Quality (PQ) in distribution systems operating at low or medium voltages. Apart from all other technical advances, these FACTS devices respond quickly to the changes in network condition unlike to shunt capacitor. Distribution STATCOM (D-STATCOM) is a shunt connected voltage source converter which has been utilized to compensate bus voltages or reactive VARs. However to achieve this goal, size and placement of the device is an important consideration.

1.2 LITERATURE REVIEW

The issues like low voltage, voltage dip, voltage sag etc. have been the major challenge faced by power engineer since two to three decades. Even though transfer of electricity is getting complex and sophisticated day by day, there is no end for the hunt of a regulated voltage profile i.e., better quality. In earlier stages improvement was done by conventional devices such as synchronous condensers, tap-changing transformer, capacitor placement etc. But with improvement of Power Electronic equipments a new dimension has been achieved. Among these devices, DSTATCOM has turned out to be promising tool for such quality improvements. To place the DSTATCOM in distribution system, the load flow analysis of the network is needed to be performed.

Load flow analysis of distribution system differs from transmission system to the fact that, tough distribution systems are generally radial, unbalanced operation and loading conditions, non-linear load models, dispersed generation and have a high R/X ratio, the conventional Newton- Raphson (NR) and fast decoupled load-flow methods find it difficult to generate a conversed result. Numerous efforts have been made to develop power flow algorithms for distribution systems. One of the most typical among these methods is the Forward and backward sweep methods or ladder networks theory [1-5]. These methods take advantage of a natural feature of the radial networks, i.e., there is a unique path from any given bus to the source. The general algorithm consists of two basic steps: forward sweep and backward sweep.

Salama [3] have presented a very simple but robust method – the ladder formula. Essentially, the ladder network method treats the radial system as two basic element types: the network natural elements (impedance) and voltage control current sources (system loads) at each load node. The forward sweep is mainly a voltage drop calculation from the sending end to the far end of a feeder or a lateral; and the backward sweep is primarily a current summation based on the voltage updates from the far end of the feeder to the sending end. Then by using KVL and KCL, the voltage drop can be obtained.

Berg [4] presented a backward method in 1967, which used a backward procedure to update the equivalent impedance at the sending end. The main idea of this method is to treat the load as constant impedance. So if the equivalent impedance is convergent, the whole system convergence will be reached.

Baran [5] presented a forward method in 1989. In this method, the sending end voltage becomes the main concern of the system convergence. Voltage drop and the information on system structure have been considered in the forward sweep. The voltage-sensitive load current can be included in the system model.

There has been a lot of literature on placement of capacitor in distribution system for power quality improvement. Perez [6], proposed a very simple algorithm for optimal capacitor placement. His algorithm is based on the fact that the branch current incremental due to a capacitor placed at a bus, under two different cases where another capacitor is placed at two different buses, is approximately equal. He has taken into consideration loss sensitive factor and size of capacitor for the placement of capacitor.

Apart from normal algorithms many paper deals with advanced search techniques for capacitor placement. Balakumaran [7] has used fuzzy technique for capacitor placement, to have maximum loss reduction in the system. A sequence of nodes for capacitor placement has been identified by repetitive application of loss minimization technique using a single capacitor. After getting the nodes values, size of the capacitor to be placed at that node is determined by minimizing the loss saving equation with respect to capacitor current.

Kyu-Ho Kim [8] has considered unbalanced distribution network for capacitor placement to improve voltage profile using GA (genetic Algorithm). A gradual load variation is also taken into account. Hiroyuki Mori[9] have used parallel tabu search for distribution system capacitor placement. A comparison between different techniques such as Simulated Annealing (SA), Genetic Algorithm (CA), and Tabu Search (TS) has been stressed and an effective algorithm is generated for capacitor placement in tabu search platform.

Due to the advancements in the area of power electronic advances over conventional method of power quality control many has concentrated on the application of these devices known as FACTS devices for power system. In 1995, the first STATCOM was installed at the Sullivan substation of Tennessee Valley Authority (TVA) in northeastern Tennessee. This unit is mainly used to regulate bus voltage during the daily load cycle to reduce the operation of the tap changer. Since then much work has been done on modeling, simulation and installation of a STATCOM in electrical network [10-12]. Now a day's STATCOM is readily installed in Distribution System with a reduced rating and is named as Distribution STAtic COMpensator (DSTATCOM).

Haque [13] considered the effect of DSTATCOM in voltage profile improvement both with and without active power injection. He compares the performance of DVR (Dynamic voltage regulator) with DSTATCOM. His observation were that, amount of apparent power injection required by a D-STATCOM to correct a given voltage sag is much higher than that of a DVR. The advantage of using DSTATCOM to that of a DVR is that, it can correct the voltage sag on both side where as a DVR can correct it only in downstream . It was also observed that DSTATCOM can correct much higher voltage sag without injecting any active power into the system as compared to DVR.

Sensarma[14] considered the problem of voltage compensation at PCC, at the end of a distribution line using a 8 KVA STATCOM. He derived the small-signal model of the system with a distribution line and also considered the compensation of sub-cycle voltage transients**.**

These works were concentrated for small network and for short duration of time. Ramsay [15] considered the application of D-STATCOM for distribution voltage regulation on long, voltage-limited feeders. He successfully compared the superiority of DSTATCOM over conventional methods like capacitor placement and voltage regulators. In his study, two types of distribution lines have been considered, ***each*** serving different types of loads; uniformly distributed and lumped. Low density distribution feeders which are typically found in rural systems has been characterized into one of these line. Husseini et al. [16] has presented the modeling of DSTATCOM suited for radial distribution system load flow.

1.3 OBJECTIVE OF THE WORK

Objective of the present work is to study and implement the DSTATCOM model in the load flow and identify the nodes for DSTATCOM placement. The compensation resulted by operating the DSTATCOM in fixed rating mode and complete compensation mode is also to be investigated.

1.4 ORGANISATION OF THE THESIS

The work carried out in this Thesis has been summarized in five Chapters. The Chapter 1 highlights the brief introduction, summary of work carried out by various researchers, and the outline of the Thesis. The Chapter 2 explains load flow technique using backward and forward sweep, DSTATCOM model suited for load flow and DSTATCOM allocation strategy. Chapter 3 deals with results and discussion pertaining to two test cases, namely 33 bus RDS and 69 bus RDS. The conclusions and the scope of further work are detailed in Chapter 4.

CHAPTER 2

DISTRIBUTION SYSTEM LOAD FLOW AND DSTATCOM PLACEMENT

2.1 INTRODUCTION

The load flow as the name suggest is study of flow of power in a network to meet the load demand at different nods. With the rise in population, demand of load is having a steep rise to that of time. So study of load flow may solve lot of issues such as planning and forecasting, design, operation and control of electrical power. A detail study of the characteristics of load flow will give us bus voltage, branch current, real power flow, reactive power flow for a specific generation and load condition.

To perform load flow analysis, various classical methods have been proposed such as Gauss-Seidel, Newton-Raphson etc. These methods are found to be suitable more for a transmission system rather than a distribution system. The major reason behind it is that, both have a different topology and R/X ratio of the distribution system is much higher than that of the transmission system which makes conventional methods difficult to converse.

Some other inherent characteristics of electric distribution systems are (i) Radial or weakly meshed structure (ii) unbalanced operation and unbalanced distributed loads (iii) large number of buses and branches (iv) It has wide range of resistance and reactance values (v)Distribution system has multiphase operation.

The load flow technique forms the foundation for implementation of any improvising tool in a distribution system. Tough load flow solution runs iteratively, it’s a time consuming process. Hence fastness is the major concern. A very simple and fundamental method of load flow analysis which is based on two basic laws in electrical engineering, the Kirchhoff’s current and voltage law is used. Since specially formulated for the power flow of a distribution system, which is usually, radial in configuration, it is fast and very effective tool for simulation where speed is a factor.

2.2 LOAD FLOW OF RADIAL DISTRIBUTION SYSTEM

In the forgoing Load flow methodology, the major features to be considered are as follows:

- Formation of the node and branch matrix M
- Identification of the end nodes and back propagation paths
- Identifying downstream nodes of the desired node
- Forward and Backward sweep
- Solution Methodology

The very first step to perform in load flow is to generate a matrix M (with *n* columns as nodes and *n*-1 rows equal to number of branches). It is understood that each branch has a sending end node and a receiving end node. So this matrix is so formulated that, for a particular branch (row), the sending end node of a branch is assigned -1 and that of receiving end as +1. Rest elements in that row are assigned 0.

2.2.1 IDENTIFICATION OF THE END NODES AND THE BACK PROPAGATION PATHS

Form the obtained M matrix, it is observed that, the column which represent the end nodes don’t have -1, because the end nodes can only be the receiving node of a branch. After identification of end node (identifying position of 1 in that column), corresponding row gives the branch attached to it and in this row, -1 value is identified. The corresponding column gives the sending end node to the studied branch. This searching process continues until the algorithm reaches a column which has no element equal to 1. This column represents the source node.

2.2.2 IDENTIFYING DOWNSTREAM NODES OF THE DESIRED NODE

After obtaining the end nodes and back propagation paths (nodes connected in between the end node and the source node), all the downstream nodes for a desired node are found out easily.

2.2.3 FORWARD AND BACKWARD SWEEP

Forward/backward sweep-based power flow algorithms generally take advantage of the Radial network topology and consist of forward and/or backward sweep processes. In these types of algorithms, developed, the forward sweep is mainly the node Voltage calculation from the sending end to the far end of the feeder and laterals, and the backward sweep is primarily the branch current and/or power summation from the Far end to the sending end of the feeder and laterals.

Most of the distribution system power flow algorithms employ KVL and Kirchhoff's Current Law (KCL) to calculate the node voltages in the forward and backward processes. The radial part is solved by a straightforward two-step procedure in which the branch currents are first computed (backward sweep) and then the bus voltages are updated (forward sweep) by using Eqn. 2.1 for each branch.

2.2.4 SOLUTION METHODOLOGY

After obtaining the downstream nodes of all nodes and with an assumption that three-phase radial distribution system is balanced, load flow solution is initiated. Voltage of node i can be expressed as:

$$V(i) = V(i-1) - I(i)Z(i) \qquad 2.1$$

where $V(i)$ and $V(i-1)$ are the voltage of nodes i and $i-1$ respectively, $Z(i)$ is the impedance of line i, $I(i)$ is the current flow in line i. Since the voltage of source node is known (1 pu.), Eqn.2.can be used in the forward sweeps to determine the voltage of other nodes in the distribution systems. The load current of node i, $I_L(i)$, can be written as:

$$I_L\,(i) = \frac{P_L\,(i) - Q_L(i)}{V^*(i)} \qquad 2.2$$

where $P_L(i)$ and $Q_L(i)$ are active and reactive power of load connected to node i, respectively. The current through a branch i, i.e. $I(i)$, equals $I_L(i)$ plus the sum of the branch currents connected to this line:

$$I(i) = I_L(i) + \sum_{j \in \beta_i} I(j) \qquad 2.3$$

where β_i is the set consisting of all branches downstream to node i. Thus, β_i is empty for each end node. As a result, $I(i)$ connected to the end nod i can be expressed as:

$$I(i) = I_L(i) \qquad 2.4$$

2.3 ALGORITHM FOR DISTRIBUTION SYSTEM LOAD FLOW

The flow chart of the algorithm is shown in Fig. 2.1. The algorithm steps for load flow solutions of distribution system are given as :

Step1: Read the distribution system line data and load data.

Step 2: Form the node and branch matrix M by steps given in 2.2.1.

Step 3: Get end nodes and the back propagation paths by following steps given in 2.2.2.

Step 4: Obtain the value of β_i of Eqn. 2.3 by calculating the downstream nodes of every node.

Step 5: Make a flat start by assuming the voltage profile of all bus to be 1 pu.

Step 6: Iteration k = k + 1.

Step 7: Calculate the load current $I_L(i)$ of each bus using Eqn. 2.2

Step 8: Summation of all the load currents corresponding to the nodes which are downstream to the desired node, as well as its own node; gives the current injected I(*i*) at that node.

Step 9: After calculating the current injected to each bus, calculate the voltage of each bus using Eqn.2.1

Step 10: compare the difference between each consecutive voltage values of every node. This will give DV (deviation).

Step 11: If DV is not less than equal to the given tolerance limit then, update the new voltage values and Go to Step 7. Else display the Absolute vale of Voltage and the phase angle.

Step 12: STOP

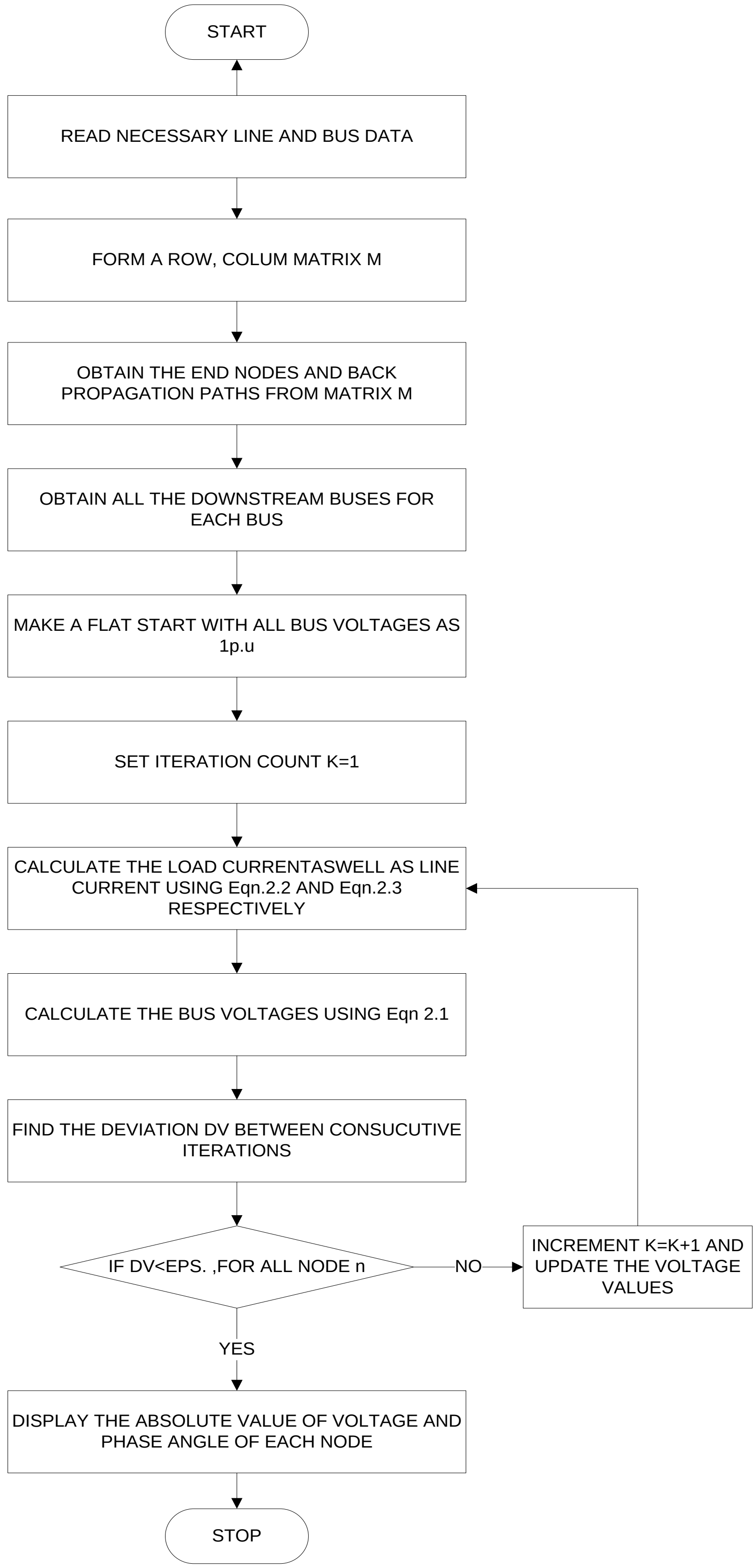

Fig. 2.1 Flow chart for load flow solution of radial distribution system

2.4 MATHEMATICAL MODELING OF DSTATCOM

DSTATCOM is a shunt device which hast the capability to inject or absorb both active and reactive current. The reactive power output of a D-STATCOM is proportional to the system voltage rather than the square of the system voltage, as in a capacitor. This makes DSTATCOM more suitable rather than using capacitors. Though storing energy is a problem for long term basis, considering real power compensation for voltage control is not an ideal case. So most of the operations considered is steady stat only and the power exchange in such a condition is reactive. To realize such a model, it can be said that a DSTATCOM consists of a small DC capacitor and a voltage source converter

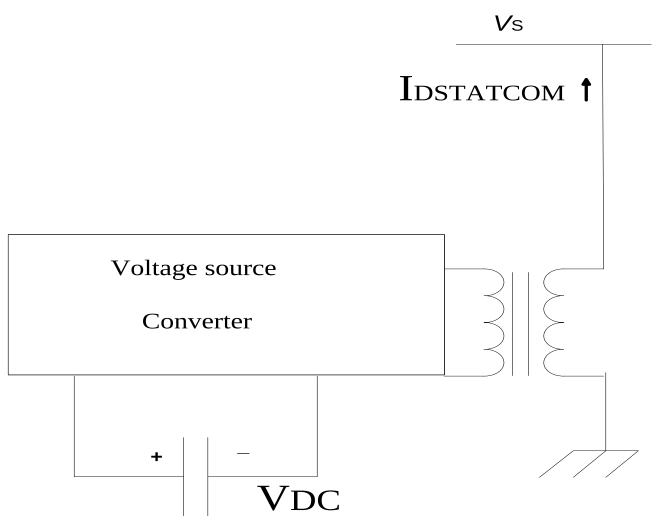

Fig. 2.2 A typical model of DSTATCOM for compensation of reactive power

To model a DSTATCOM in distribution system, a simple single line diagram of two bus distribution line is shown in figure 3.3.

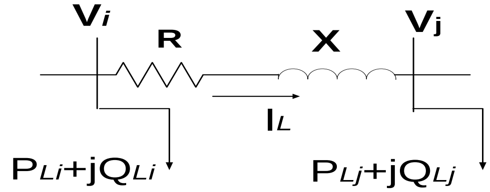

Fig . 2.3 Single line diagram of two buses of a distribution system.

To analyze it, it is assumed that one of the bus is a reference bus and the other has a lower voltage profile than that of the reference bus. Here V_i is the reference bus and V_j is the desired bus for compensation. Now it is desired to compensate the bus voltage of V_j to 1 p.u. by using DSTATCOM. The phasor diagram of the shown single line diagram is expressed as:

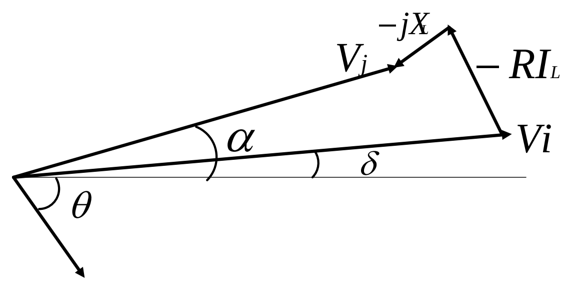

Fig.2.4 Phasor diagram of voltages and current of the system shown in Fig 2.2

From this phasor diagram it is drawn that

$$V_j\angle\alpha = V_i\angle\delta - ZI_L\angle\theta \qquad 2.5$$

where $V_j\angle\alpha$ and $V_i\angle\delta$ are the voltage of buses j and i before compensation respectively, Z=R+ j X is the impedance between buses i and j, $I_L\angle\theta$ is the current flow in line. Voltage $V_i\angle\delta$ and current $I_L\angle\theta$ are the values which are derived from the load flow calculations. Figure shown below gives a better idea of operation of DSTATCOM in steady state analysis.

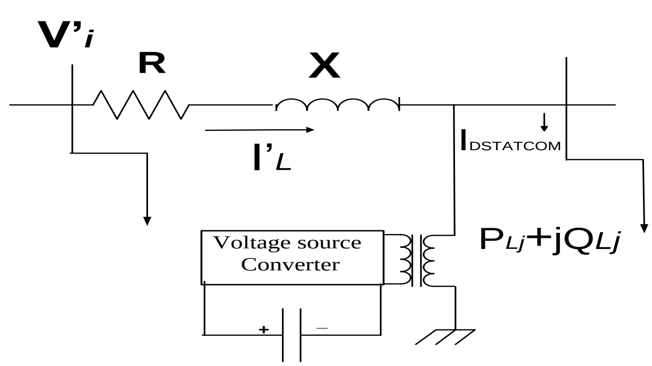

Fig.2.5 Single line diagram of two buses of a distribution system with D-STATCOM consideration.

Here DSATACOM is used to regulate the voltage of bus j. As it is mentioned that only reactive power compensation is considered, so the current drawn by the DSTATCOM ($I_{D-STATCOM}$) is in quadrature with the system voltage. To visualize the impact of DSTATCOM over the system phasor diagram of the complete system is drawn.

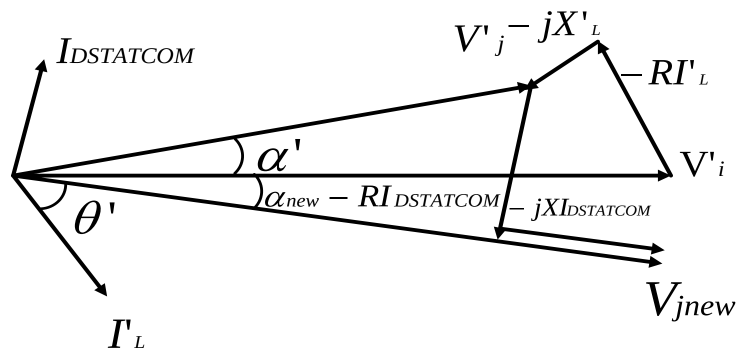

Fig.2.6 Phasor diagram of voltages and currents of the system shown in Fig.2.4

Mathematical analysis of the phasor diagram shown in Fig. 2.6 implies that

$$\angle I_{DSTATCOM} = \frac{\pi}{2} + \alpha_{new} \text{ , } \alpha_{new} < 0 \qquad 2.6$$

$$V_{jnew} \angle \alpha_{new} = V_i' \angle \delta' - (R + jX) I_L' \angle \theta' - (R + jX) I_{DSTATCOM} \angle \left(\alpha_{new} + \frac{\pi}{2}\right). \qquad 2.7$$

Where $I_{D-STATCOM} \angle(\alpha_{new} + \frac{\pi}{2})$ is the injected current by DSTATCOM , $V_{j\ new} \angle \alpha_{new}$ is the voltage of bus j after compensation by DSTATCOM. $V'_i \angle \delta'$ is the voltage of bus i after compensation. $I'_L \angle \theta'$ is derived from load flow calculations. Separating the real and imaginary parts of Eqn.2.7 yields:

$$V_{j\,new}\ \cos\alpha_{new} = \mathrm{Re}\,(V'_i\angle\delta) + X\mathrm{I}_{D-STATCOM}\ \sin(\alpha_{new} + \tfrac{\pi}{2})$$
$$-Re(\,ZI'_L\,\angle\theta')\ - R\mathrm{I}_{D-STATCOM}\ \cos(\alpha_{new} + \tfrac{\pi}{2}). \qquad 2.8$$

$$V_{j\,new}\ \sin\alpha_{new} = Im(V'_i\angle\delta'\,) - X\mathrm{I}_{D-STATCOM}\ \cos(\alpha_{new} + \tfrac{\pi}{2})$$
$$-\,Im\,(\,ZI'_L\,\angle\theta') - \ R\mathrm{I}_{D-STATCOM}\ \sin(\alpha_{new} + \tfrac{\pi}{2}). \qquad 2.9$$

Furthermore these two equations can be modified using the following notations:

$$a_1 = Re(V'_i\angle\delta') - \ \mathrm{Re}(\,ZI'_L\,\angle\theta').$$
$$a_2 = Im(V'_i\angle\delta') - \ \mathrm{Im}(\,ZI'_L\,\angle\theta').$$
$$b = V_{j\,new}$$
$$c_1 = \ -R$$
$$c_2 = \ -X$$
$$x_1 = \mathrm{I}_{D-STATCOM}$$
$$x_2 = \alpha_{new}$$

Eqn. 2.10 and 2.11 are obtained from Eqn. 2.8 and 2.9 as follows:

$$b\ \cos x_2 = \ a_1 - \ c_1 x_1 \sin x_2 - \ c_2 x_1 \cos x_2 \qquad 2.10$$
$$b\ \sin x_2 = a_2 - \ \ c_2 x_1 \sin x_2 + \ c_1 x_1 \cos x_2 \qquad 2.11$$

where $a_1, a_2, c_1 and\ c_2$ are constants, b is the magnitude of compensated voltage (1 p.u.) and x_1, x_2 are variables to be determined. From the above two equations it can be shown that

$$x_1 = \frac{b\ \cos x_2 - a_1}{-\ c_1 \sin\ x_2 - c_2 \cos\ x_2} \qquad 2.12$$

and

$$x_1 = \frac{b\ \sin\ x_2 - a_2}{-\ c_2 \sin\ x_2 + c_1 \cos\ x_2} \qquad 2.13$$

Now by equating Eqn.2.12 and Eqn.2.13 and eliminating x_1 , we get

$$(a_1\, c_2 - a_2 c_1) \sin x_2 + (-a_1\, c_1 - a_2 c_2) \cos x_2 + bc_1 = 0 \qquad 3.14$$

Considering$x = \sin x_2$, following equations is derived

$$(k_1^2 + k_2^2)x^2 + (2k_1 bc_1)x + (b^2 c_1^2 - k_2^2) = 0 \qquad 2.15$$

where,

$$k_1 = a_1\, c_2 - a_2 c_1,$$

$$k_2 = \ a_1\, c_1 + a_2 c_2,$$

Therefore,

$$x = \frac{-B \pm \sqrt{\Delta}}{2A}.$$

Where

$$\Delta = B^2 - 4AC$$

$$A = k_1^2 + k_2^2,$$

$$B = 2k_1 bc_1,$$

$$C = b^2 c_1^2 - k_2^2,$$

From the roots of x, α_{new} value is obtained as $x_2 = arc\ \sin x$ and $x_2 =, \alpha_{new}$. From these values $x_1 = \mathrm{I}_{D-STATCOM}$ is found out. Hence injected reactive power by DSTATCOM is given by

$$jQ_{D-STATCOM} = V_{j\ new}\, I_{D-STATCOM}^{*} \qquad 2.16$$

Where

$$\boldsymbol{V}_{j\ new} = V_{j\ new}\ \angle \alpha_{new} \qquad 2.17$$

$$\mathbf{I}_{D-STATCOM} = \mathrm{I}_{D-STATCOM} \angle (\alpha_{new} + \frac{\pi}{2}) \qquad 2.18$$

Now this reactive power is compensated from the reactive power drawn at the desired bus. This compensation improves the voltage profile of the desired bus to 1 p.u and improves the voltage profile of neighboring buses (mostly the downstream buses).

2.5 LOAD FLOW USING DSTATCOM

To incorporate DSTATCOM in distribution system, first load flow analysis is done without compensation. Now the constraint which is implemented is that, voltage profile below 0.95 p.u or above 1.05 p.u is considered as under voltage or over voltage buses respectively. These buses are needed to be compensated. From the load flow results, buses with under voltage or over voltage profile are selected. DSTATCOM is attached on one of those buses and again load flow analysis is performed. Like this all the under voltage and over voltage buses are compensated individually and results were obtained.

There are two modes of incorporating a DSTATCOM in load flow analysis. One with complete compensation (compensating the desired bus voltage to 1 p.u) and compensation with a set rating of DSTATCOM.

It is first assumed that the voltage magnitude in the node where DSTATCOM is located be 1 p.u. then the phase angle of the voltage and the reactive power injection is calculated from Eqn. 2.17 and Eqn. 2.16 respectively. Then, the new magnitude and phase angle of the compensated node are utilized to determine the voltage of DSTATCOM located downstream nodes in the forward sweep of load flow. If the reactive power calculated from Eqn. 2.16 is greater than the maximum reactive power rating of DSTATACOM, the injected reactive power of DSTATCOM is set to its maximum rating and is considered as a negative constant value in load model in node j, and the load flow program is solved in a normal way as if there is no D-STATCOM.

2.6 Rate Of Under Voltage Mitigated Nodes(RUVMN)

Once the load flow is performed using DSTATCOM in a particular bus, the number of buses whose under or over voltage problems got mitigated is found out. The percentage of improvement gives *RUVMN* (Rate of Under Voltage Mitigated Nodes). The suggested locations for DSTATCOM are ordered in terms of *RUVMN* as well as the required reactive power for compensation. Buses with highest percentage of *RUVMN* are found to be suitable for DSTATCOM allocation

2.7 ALGORITHM FOR DSTATCOM ALLOCATION

Step 1: Read the distribution system branch impedance values and the bus real and reactive power data.

Step 2: Run the Load Flow of Distribution System by using steps given in section 2.3, to find out voltage magnitudes at the buses.

Step 3: Select the candidate bus by method given in section 2.6

Step 4: Assume the voltage profile of the candidate bus to be 1 p.u.

Step 5: Obtain the reactive power of the DSTATCOM and phase angle of the compensated bus using section 2.4

Step 6: Update the reactive power and voltage phase angle at candidate bus.

Step 7: Run the Load Flow of Distribution System with updated reactive power at the candidate bus.

Step 8: Calculate the *RUVMN* and *RPR* using section 2.6, for that bus.

Step 9: Similarly attach DSTATCOM in all the buses one by one and perform Step1 to Step 8 in each case.

Step 10: End

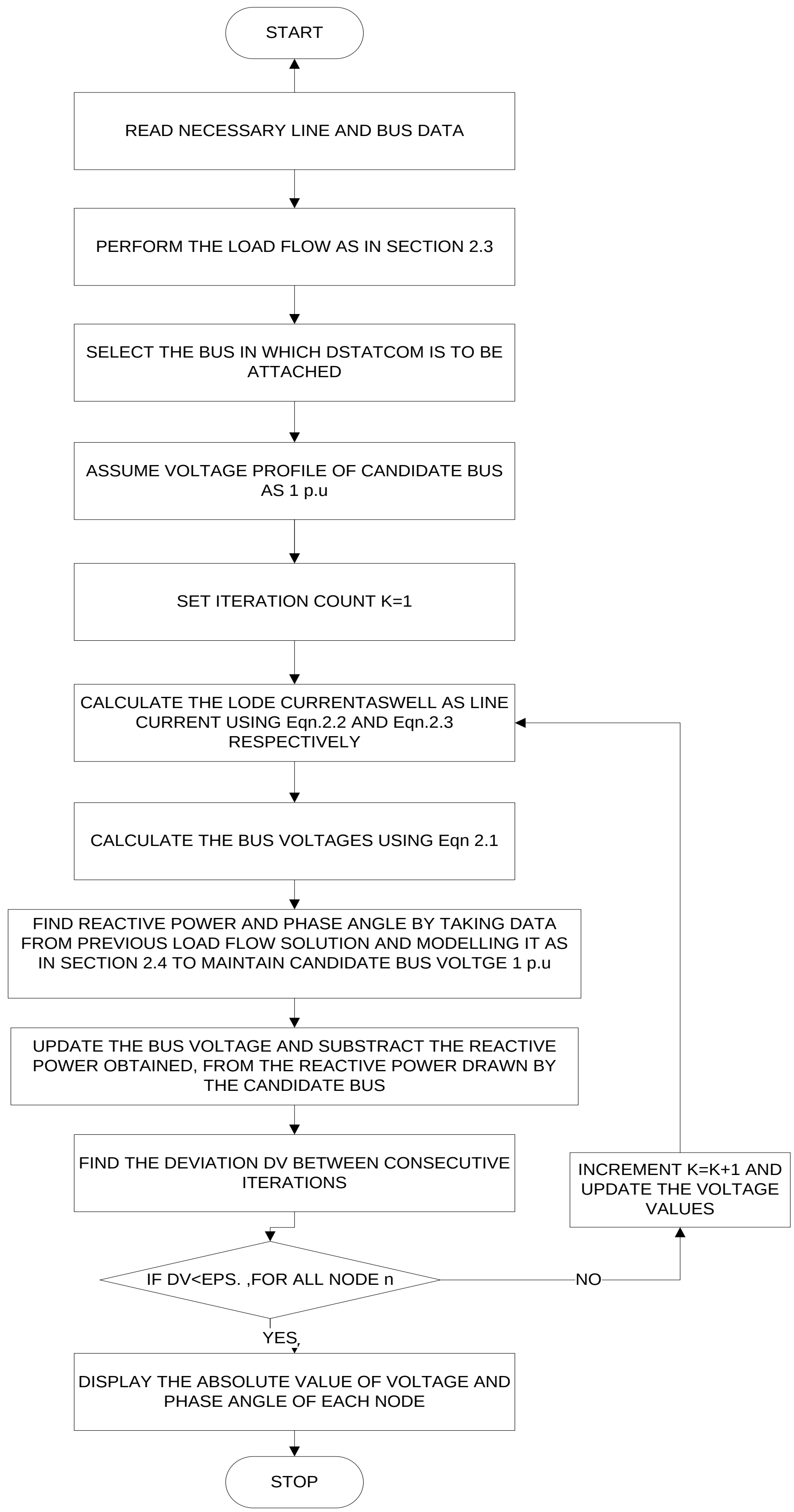

Figure 2.7 Flow chart of radial distribution system with DSTATACOM

2.8 CONCLUSION

In this chapter, forward and backward sweep method for load flow analysis is performed. A mathematical model of DSTATCOM is proposed and is used to improve the performance of the distribution network. *RUVMN* is taken as the selection criteria for placement of DSTATCOM in the network. With these theories, a much needed background for case study of DSATACOM placement in distribution system is achieved.

CHAPTER 3

RESULTS AND DISCUSSION

This chapter contains the results of the implementation of the theoretical content discussed in Chapter 2, for two cases. These Algorithms are developed in MATLAB environment and has been tested on 33 and 69 bus radial distribution system. Bus data and line data of the 33 and 69 bus radial system is given in Appendix-A and Appendix-B respectively.

RUVMN (Rate of Under Voltage Mitigation) has been taken as the criteria for selection of the locations of DSTATCOM in the test module. Results have been divided into two major parts.

CASE I : With fixed voltage (variable rating) DSATACOM

CASE II : With fixed rating DSTATCOM.

3.1 DSTATCOM placement on 33-Bus Radial Distribution System

Following are the characteristics of the 33-bus radial distribution system shown in Fig 3.1

Number of buses = 33
Number of lines = 32
Slack Bus No =1
Base Voltage=12.66 KV
Base MVA=100 MVA

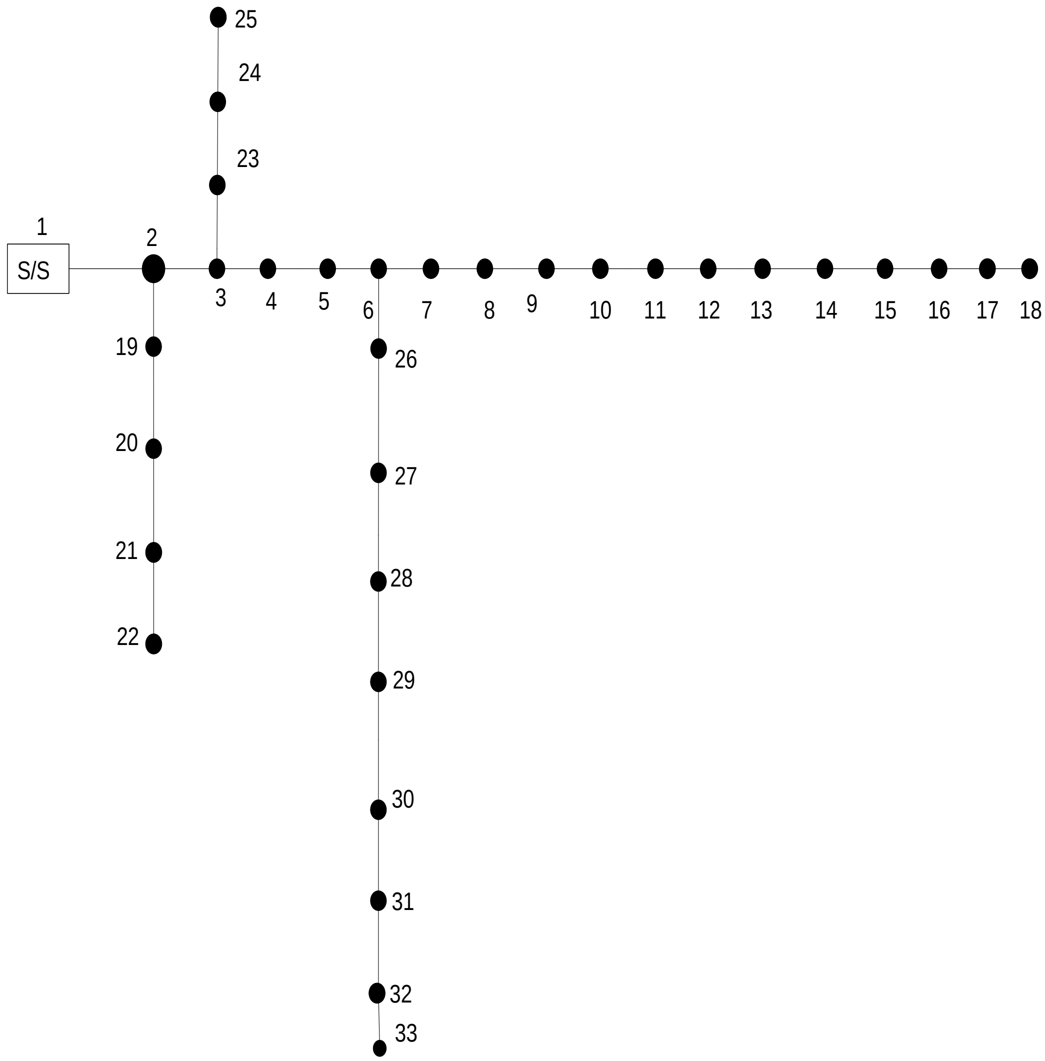

Figure 3.1 33-Bus Radial Distribution System

For the above given network, we have to know the downstream nodes for each node, to perform backward sweep calculations as per the Algorithm. Table 3.1 below shows the downstream nodes behind every node.

Table 3.1 Tabulation of all downstream nodes for a given node.

Branch No.	Sending End Bus.	Receiving End Bus.	Down Stream Node
1	1	2	2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33
2	2	3	3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 23 24 25 26 27 28 29 30 31 32 33
3	3	4	4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 26 27 28 29 30 31 32 33
4	4	5	5 6 7 8 9 10 11 12 13 14 15 16 17 18 26 27 28 29 30 31 32 33
5	5	6	6 7 8 9 10 11 12 13 14 15 16 17 18 26 27 28 29 30 31 32 33
6	6	7	7 8 9 10 11 12 13 14 15 16 17 18
7	7	8	8 9 10 11 12 13 14 15 16 17 18
8	8	9	9 10 11 12 13 14 15 16 17 18
9	9	10	10 11 12 13 14 15 16 17 18
10	10	11	11 12 13 14 15 16 17 18
11	11	12	12 13 14 15 16 17 18
12	12	13	13 14 15 16 17 18
13	13	14	14 15 16 17 18
14	14	15	15 16 17 18
15	15	16	16 17 18
16	16	17	17 18
17	17	18	18
18	2	19	19 20 21 22
19	19	20	20 21 22
20	20	21	21 22
21	21	22	22
22	3	23	23 24 25
23	23	24	24 25
24	24	25	25
25	6	26	26 27 28 29 30 31 32 33
26	26	27	27 28 29 30 31 32 33
27	27	28	28 29 30 31 32 33
28	28	29	29 30 31 32 33
29	29	30	30 31 32 33
30	30	31	31 32 33
31	31	32	32 33
32	32	33	33

The load flow of the distribution system is obtained using the Algorithm discussed in Chapter 2. The load flow result of 33-bus RDS without DSTATCOM compensation are summarizes in Table 3.2

Table 3.2. Voltage magnitude and Phase angle from 33-bus Radial Distribution system Load flow solution

Bus Number	Voltage Magnitude in p.u.	Angles in degree
1	1.0000	0
2	0.9970	0.0002
3	0.9829	0.0017
4	0.9754	0.0028
5	0.9679	0.0040
6	0.9495	0.0024
7	0.9459	-0.0017
8	0.9323	-0.0044
9	0.9260	-0.0057
10	0.9201	-0.0068
11	0.9192	-0.0067
12	0.9177	-0.0065
13	0.9115	-0.0081
14	0.9092	-0.0095
15	0.9078	-0.0102
16	0.9064	-0.0106
17	0.9044	-0.0119
18	0.9038	-0.0121
19	0.9965	0.0000
20	0.9929	-0.0011
21	0.9922	-0.0015
22	0.9916	-0.0018
23	0.9793	0.0011
24	0.9726	-0.0004
25	0.9693	-0.0012
26	0.9475	0.0030
27	0.9450	0.0040
28	0.9335	0.0055
29	0.9253	0.0068
30	0.9218	0.0087
31	0.9176	0.0072
32	0.9167	0.0068
33	0.9164	0.0067

OBSERVATION:

1. Total Number of Buses out of constraint limit: 21
2. Bus number out of constraint limit: 6 , 7 , 8 , 9 , 10 , 11 , 12 , 13 , 14 , 15 , 16,17, 18 , 26 , 27 , 28 , 29 , 30 , 31 , 32 , 33
3. Total percentage of Buses out of constraint limit: 63.6364%

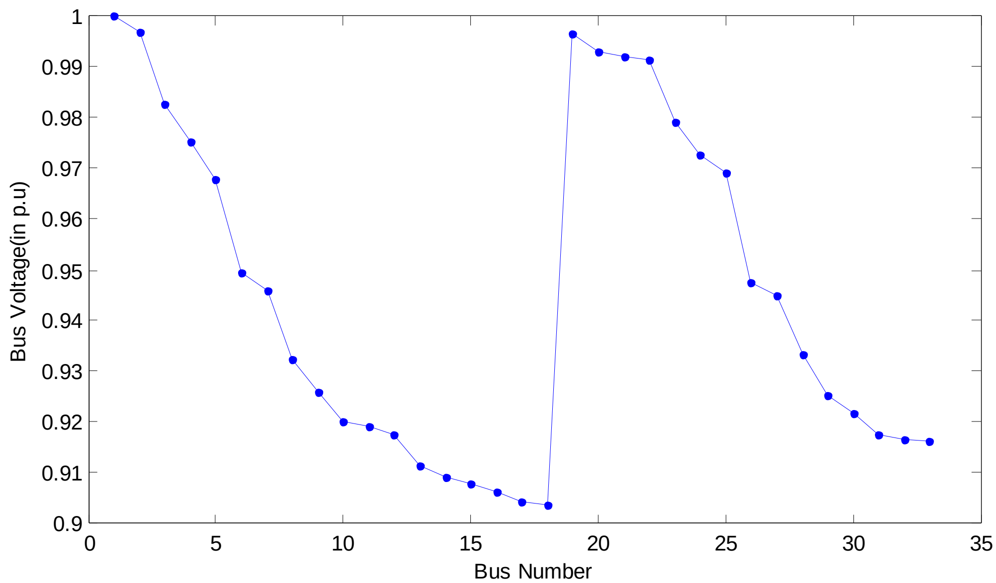

Figure 3.2 Graph between Bus Voltage and Number of Buses for 33-Bus RDS

CASE I : With fixed voltage DSATACOM

Once the load flow data is obtained, modeling of DSTATCOM is done using these data and tested on the given 33-bus radial distribution system. A clear picture of the performance of DSTATCOM is obtained by randomly selecting bus and attaching DSTATCOM to it. Following are the results obtained after placing DSTATCOM on some of the nodes.

Table 3.3 Voltage magnitude Comparison for some test buses after DSTATCOM attachment

Compensated buses → / Bus No.↓	Compensated bus no. 3	Compensated bus no. 6	Compensated bus no. 28	Compensated bus no. 32
1	1.0000	1.0000	1.0000	1.0000
2	0.9971	0.9971	0.9971	0.9970
3	1.0000	0.9835	0.9832	0.9830
4	0.9926	0.9763	0.9759	0.9756
5	0.9854	0.9693	0.9688	0.9682
6	0.9672	1.0000	0.9509	0.9499
7	0.9638	0.9967	0.9474	0.9464
8	0.9504	0.9837	0.9337	0.9328
9	0.9442	0.9778	0.9274	0.9264
10	0.9384	0.9722	0.9216	0.9206
11	0.9376	0.9714	0.9207	0.9197
12	0.9361	0.9700	0.9192	0.9182
13	0.9301	0.9641	0.9130	0.9120
14	0.9278	0.9620	0.9107	0.9097
15	0.9264	0.9606	0.9093	0.9083
16	0.9251	0.9593	0.9079	0.9069
17	0.9231	0.9574	0.9059	0.9049
18	0.9225	0.9568	0.9053	0.9043
19	0.9965	0.9966	0.9965	0.9965
20	0.9930	0.9930	0.9930	0.9929
21	0.9923	0.9923	0.9923	0.9922
22	0.9916	0.9917	0.9916	0.9916
23	0.9965	0.9799	0.9797	0.9794
24	0.9899	0.9732	0.9730	0.9727
25	0.9867	0.9699	0.9697	0.9694
26	0.9653	0.9982	0.9491	0.9480
27	0.9628	0.9957	0.9467	0.9455
28	0.9516	0.9849	1.0000	0.9343
29	0.9436	0.9771	0.9923	0.9263
30	0.9401	0.9738	0.9890	0.9229
31	0.9360	0.9698	0.9852	0.9189
32	0.9351	0.9690	0.9843	1.0000
33	0.9348	0.9687	0.9840	0.9997

From Table 3.3 we can see that placement of DSTATCOM improves the voltage profile of the desired bus to 1 p.u and it also improves the voltage profile of neighboring buses. After placing DSTATCOM on bus no. 6, it is seen that V p.u of bus no.6 is 1 p.u as well as there is 63.63% under voltage mitigation.. Similarly improvement of voltage profile, after compensation on Bus no. 3,28 and 32 can be seen.

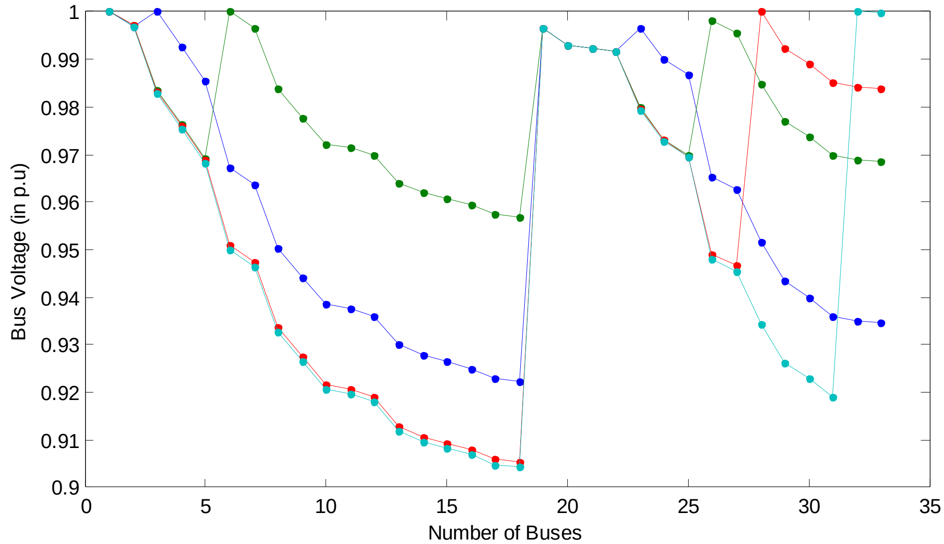

Figure 3.3 A Comparison between voltage profile of Bus 3, 6, 28, 32 after DSTATCOM placement on these nodes.

As per Chapter 2, RUVMN forms the criteria for selection of suitable buses for DSTATCOM Placement. Now our aim is to find out the buses in which, after placing DSTATCOM, there is maximum improvement of voltage profile in the neighboring buses as well as its own voltage profile gets improved. In other words, DSTATCOM is placed on all the buses, and the nodes which are violating the constraint limits after DSTATCOM placement are found out. Hence a observation is made by comparing the constraint violating buses before and after the compensation. These observation shows, how many buses, which were out of constraint limit, managed to make it within the constraint limit after compensation. A ratio of the difference of the number of these buses (before and after compensation) to that of the total number of buses multiplied with hundred gives percentage or Rate of under voltage mitigated nodes(*RUVMN*). Higher the value of *RUVMN* for a particular node, more is the chances of placing a DSTATCOM on that bus.

Table 3.4 Tabulation for RUVMN of 33-Bus Radial Distribution System

Nodes No.	***RUVMN*(in %)**
1	0
2	6.0606
3	18.1818
4	24.2424
5	45.4545
6	63.6364
7	39.3939
8	36.3636
9	33.3333
10	30.3030
11	27.2727
12	24.2424
13	21.2121
14	18.1818
15	12.1212
16	9.0909
17	6.0606
18	3.0303
19	0
20	0
21	0
22	0
23	0
24	0
25	0
26	27.2727
27	24.2424
28	21.2121
29	18.1818
30	15.1515
31	12.1212
32	6.0606
33	3.0303

From the above tabulation we can observe that Bus No. 5,6,7,8 are having high value of *RUVMN*. This makes all these Buses much desirable for DSTATCOM placement.

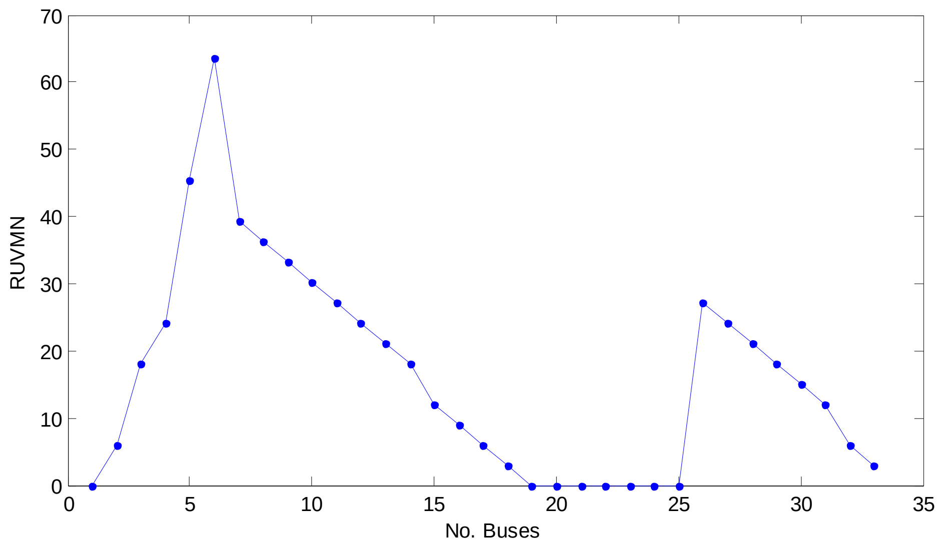

Figure 3.4 Graph comparing the Rate of under voltage mitigation for all 33-Buses

CASE II: With fixed rating DSTATCOM.

In this case a specific rating of DSTATCOM is assumed. If the reactive power calculated from Eq.2.16 is greater than the maximum reactive power rating of D-STATACOM, the injected reactive power of DSTATCOM is set to its maximum rating and is considered as a negative constant value in load model for the compensating node, and the load flow program is solved in a normal way as if there is no DSTATCOM. In other case if calculated rating is less than DSTATCOM rating, then the case switches to variable rating DSTATCOM (CASE I).

Table 3.5 Comparison of Compensation Between Bus No. 3 , 6, 28 and 32 with a fixed 2 MVAr rating DSTATCOM

Compensated Buses→ / Bus No. ↓	Compensated bus no. 3	Compensated bus no. 6	Compensated bus no. 28	Compensated bus no. 32
1	1.0000	1.0000	1.0000	1.0000
2	0.9976	0.9976	0.9976	0.9976
3	0.9867	0.9869	0.9868	0.9867
4	0.9792	0.9818	0.9818	0.9815
5	0.9718	0.9770	0.9770	0.9766
6	0.9534	0.9679	0.9679	0.9672
7	0.9499	0.9645	0.9644	0.9637
8	0.9363	0.9511	0.9511	0.9503
9	0.9300	0.9449	0.9449	0.9441
10	0.9242	0.9392	0.9391	0.9384
11	0.9233	0.9384	0.9383	0.9375
12	0.9218	0.9369	0.9368	0.9360
13	0.9156	0.9308	0.9307	0.9300
14	0.9134	0.9286	0.9285	0.9277
15	0.9119	0.9272	0.9271	0.9263
16	0.9106	0.9258	0.9257	0.9250
17	0.9085	0.9238	0.9237	0.9230
18	0.9079	0.9232	0.9231	0.9224
19	0.9971	0.9971	0.9971	0.9971
20	0.9935	0.9935	0.9935	0.9935
21	0.9928	0.9928	0.9928	0.9928
22	0.9922	0.9922	0.9922	0.9922
23	0.9831	0.9833	0.9833	0.9831
24	0.9765	0.9766	0.9766	0.9764
25	0.9732	0.9733	0.9733	0.9731
26	0.9515	0.9660	0.9673	0.9665
27	0.9489	0.9635	0.9667	0.9658
28	0.9375	0.9523	0.9676	0.9663
29	0.9294	0.9443	0.9593	0.9672
30	0.9258	0.9408	0.9559	0.9670
31	0.9217	0.9367	0.9519	0.9752
32	0.9208	0.9358	0.9510	0.9789
33	0.9205	0.9355	0.9507	0.9787

Table 3.6 RUVMN For a given 2 MVAr DSTATCOM In 33-Bus Distribution System

Nodes No.	*RUVMN* (in %)
1	0
2	3.0303
3	6.0606
4	12.1212
5	12.1212
6	18.1818
7	21.2121
8	39.3939
9	48.4848
10	48.4848
11	48.4848
12	48.4848
13	48.4848
14	45.4545
15	45.4545
16	45.4545
17	45.4545
18	45.4545
19	3.0303
20	3.0303
21	3.0303
22	3.0303
23	6.0606
24	6.0606
25	6.0606
26	18.1818
27	18.1818
28	33.3333
29	33.3333
30	33.3333
31	33.3333
32	33.3333
33	33.3333

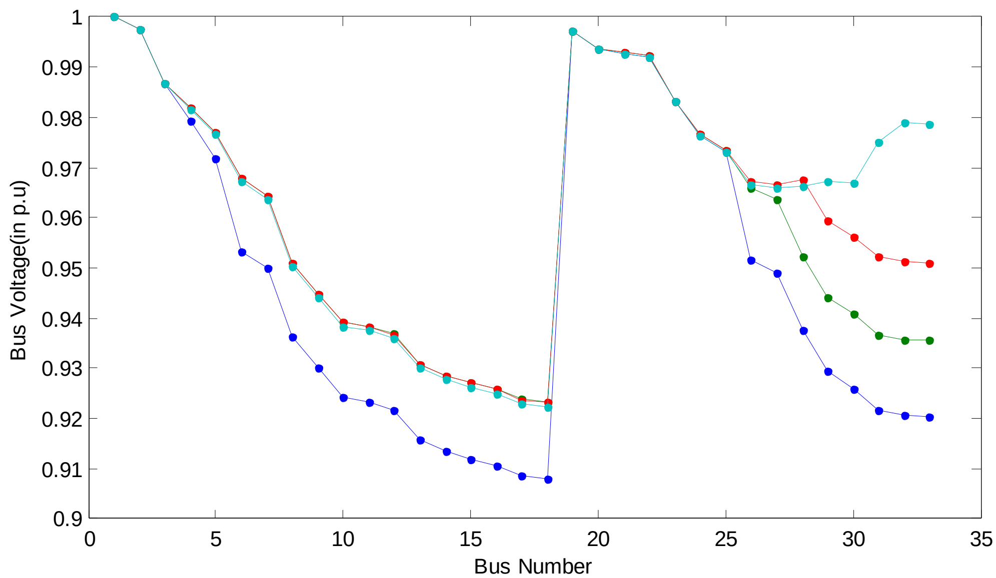

Figure 3.5 Comparison of compensation at buses 3, 6, 28, 32 of 33-Bus Radial Distribution System

By comparing the results obtained between table 3.4 and table 3.6 to that between Table 3.3 and Table 3.5, we can observe that DSTATCOM has less effect when it's rating is specified. Also it becomes less desirable when the difference between the required reactive power and maximum reactive rating of the DSTATCOM becomes greater. It can also be observed that a DSTATCOM not only improves voltage profile of downstream node , but also improves the voltage profile of uphill nodes.

3.2 DSTATCOM Placement on 69-Bus Radial Distribution System

The 69-bus radial distribution system shown in Fig. 3.6 has the following characteristics:

No. of Buses: 69

No. of branches: 68

Slack Bus: 1

Base Voltage: 12.66 KV

Base MVA: 100 MVA

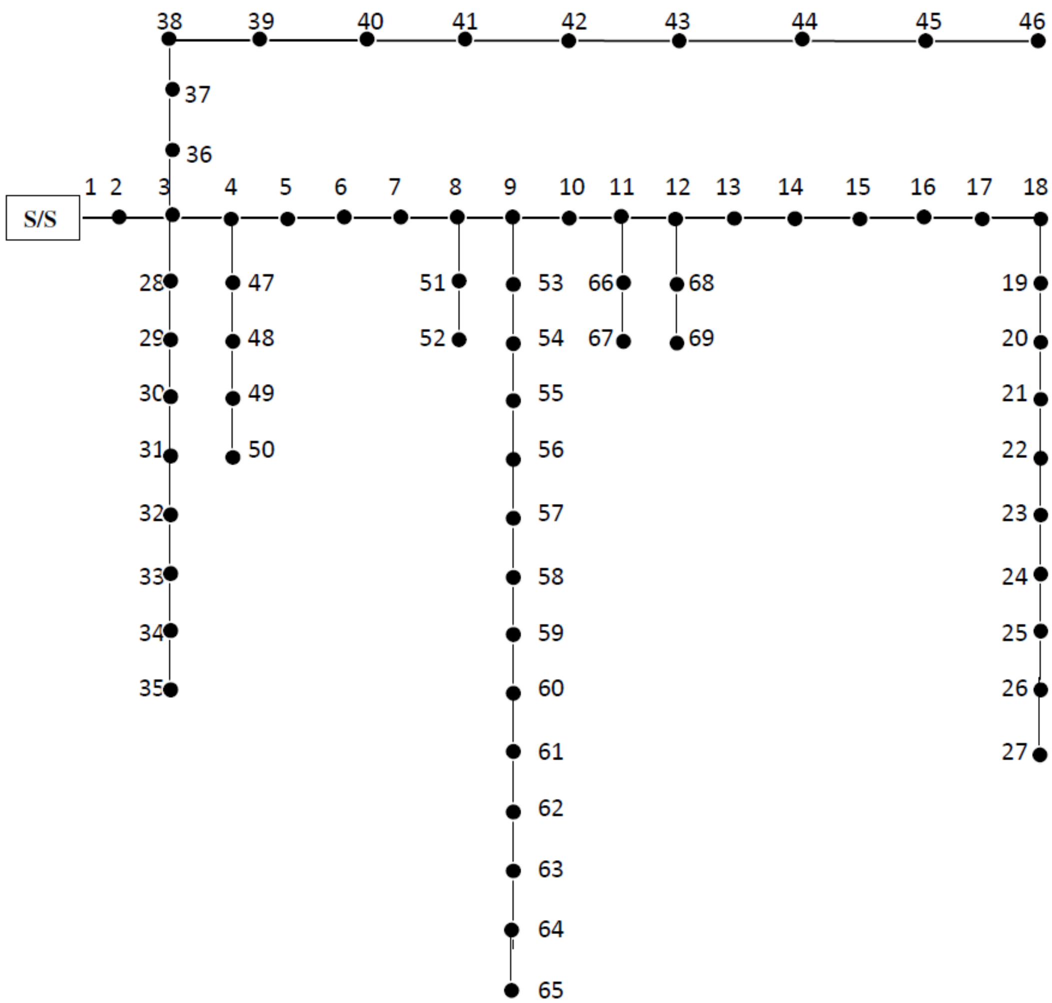

Figure 3.6 69-Bus Radial distribution System.

The down stream nodes from the developed program are obtained and summarized in Table 3.7.

Table 3.7 Down stream nodes for each node in 69-Bus Radial Distribution System

Branch No.	Sending end Bus	Receiving end bus	Total downstream Buses	Bus Numbers
1	1	2	68	2,3,4,5,6,7,8,,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,,63,64,65,66,67,68,69
2	2	3	67	3,4,5,6,7,8,,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,,63,64,65,66,67,68,69
3	3	4	47	4,5,6,7,8,910,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,47,48,49,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69
4	4	5	42	5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69
5	5	6	41	6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69
6	6	7	40	7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69
7	7	8	39	8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69
8	8	9	36	9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,53,54,55,56,57,58,59,60,61,62,63,64,65,66,67,68,69
9	9	10	22	10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,66,67,68,69
10	10	11	21	11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,66,67,68,69
11	11	12	18	12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,68,69
12	12	13	15	13,14,15,16,17,18,19,20,21,22,23,24,25,26,27
13	13	14	14	14,15,16,17,18,19,20,21,22,23,24,25,26,27
14	14	15	13	15,16,17,18,19,20,21,22,23,24,25,26,27
15	15	16	12	16,17,18,19,20,21,22,23,24,25,26,27
16	16	17	11	17,18,19,20,21,22,23,24,25,26,27
17	17	18	10	18,19,20,21,22,23,24,25,26,27
18	18	19	9	19,20,21,22,23,24,25,26,27
19	19	20	8	20,21,22,23,24,25,26,27
20	20	21	7	21,22,23,24,25,26,27
21	21	22	6	22,23,24,25,26,27
22	22	23	5	23,24,25,26,27
23	23	24	4	24,25,26,27
24	24	25	3	25,26,27
25	25	26	2	26,27
26	26	27	1	27

27	3	28	8	28,29,30,31,32,33,34,35
28	28	29	7	29,30,31,32,33,34,35
29	29	30	6	30,31,32,33,34,35
30	30	31	5	31,32,33,34,35
31	31	32	4	32,33,34,35
32	32	33	3	33,34,35
33	33	34	2	34,35
34	34	35	1	35
35	3	36	11	36,37,38,39,40,41,42,43,44,45,46
36	36	37	10	37,38,39,40,41,42,43,44,45,46
37	37	38	9	38,39,40,41,42,43,44,45,46
38	38	39	8	39,40,41,42,43,44,45,46
39	39	40	7	40,41,42,43,44,45,46
40	40	41	6	41,42,43,44,45,46
41	41	42	5	42,43,44,45,46
42	42	43	4	43,44,45,46
43	43	44	3	44,45,46
44	44	45	2	45,46
45	45	46	1	46
46	4	47	4	47,48,49,50
47	47	48	3	48,49,50
48	48	49	2	49,50
49	49	50	1	50
50	8	51	2	51,52
51	51	52	1	52
52	9	53	13	53,54,55,56,57,58,59,60,61,62,63,64,65
53	53	54	12	54,55,56,57,58,59,60,61,62,63,64,65
54	54	55	11	55,56,57,58,59,60,61,62,63,64,65
55	55	56	10	56,57,58,59,60,61,62,63,64,65
56	56	57	9	57,58,59,60,61,62,63,64,65
57	57	58	8	58,59,60,61,62,63,64,65
58	58	59	7	59,60,61,62,63,64,65
59	59	60	6	60,61,62,63,64,65
60	60	61	5	61,62,63,64,65
61	61	62	4	62,63,64,65
62	62	63	3	63,64,65
63	63	64	2	64,65
64	64	65	1	65
65	11	66	2	66,67
66	66	67	1	67
67	12	68	2	68,69
68	68	69	1	69

Load flow solution without compensation for 69 bus RDS obtained from the developed program is summarized in Table 3.8.

Table 3.8 Base Distribution System Load flow for a 69-Bus Radial Network

Bus Number	Bus Voltage (in p.u)	Phase Angle(in deg.)
1	1.0000	0
2	1.0000	-0.0000
3	0.9999	-0.0000
4	0.9998	-0.0001
5	0.9990	-0.0003
6	0.9901	0.0009
7	0.9808	0.0021
8	0.9786	0.0024
9	0.9774	0.0026
10	0.9724	0.0040
11	0.9713	0.0044
12	0.9682	0.0053
13	0.9653	0.0061
14	0.9624	0.0069
15	0.9595	0.0077
16	0.9590	0.0078
17	0.9581	0.0081
18	0.9581	0.0081
19	0.9576	0.0082
20	0.9573	0.0083
21	0.9568	0.0085
22	0.9568	0.0085
23	0.9568	0.0085
24	0.9566	0.0086
25	0.9564	0.0086
26	0.9564	0.0087
27	0.9563	0.0087
28	0.9999	-0.0000
29	0.9999	-0.0001
30	0.9997	-0.0001
31	0.9997	-0.0000
32	0.9996	-0.0000
33	0.9993	0.0001
34	0.9990	0.0002
35	0.9989	0.0002
36	0.9999	-0.0001
37	0.9997	-0.0002
38	0.9996	-0.0002
39	0.9995	-0.0002
40	0.9995	-0.0002
41	0.9988	-0.0004
42	0.9986	-0.0005
43	0.9985	-0.0005
44	0.9985	-0.0005
45	0.9984	-0.0005
46	0.9984	-0.0005

47	0.9998	-0.0001
48	0.9985	-0.0009
49	0.9947	-0.0033
50	0.9942	-0.0037
51	0.9785	0.0024
52	0.9785	0.0024
53	0.9746	0.0029
54	0.9714	0.0034
55	0.9669	0.0040
56	0.9626	0.0046
57	0.9401	0.0115
58	0.9290	0.0151
59	0.9247	0.0165
60	0.9197	0.0183
61	0.9123	0.0195
62	0.9120	0.0196
63	0.9116	0.0196
64	0.9097	0.0199
65	0.9092	0.0200
66	0.9713	0.0044
67	0.9713	0.0044
68	0.9679	0.0054
69	0.9678	0.0054

The bus voltage profile resulted after the load flow solution is shown in Fig. 3.7.

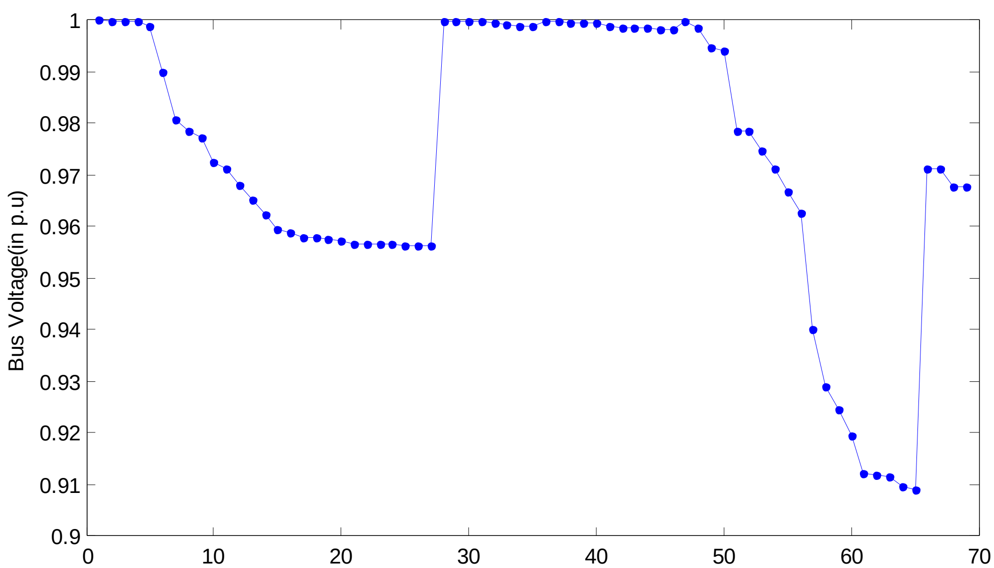

Figure 3.7 Plot for Load Flow Results of 69-Bus Radial Distribution System

Case I With fixed voltage DSTATCOM

The effect of compensation by fixed voltage DSTATCOM applied to buses 8, 57 and 59 one by one is summarized in Table. 3.8 and also shown in Fig. 3.8.

Table 3.9 Comparison of Compensation between Bus No. 8, 59 and 57 with fixed voltage DSTATCOM

Bus No.	Compensation on Bus No.8	Compensation on Bus No.59	Compensation on Bus No.57
1	1.0000	1.0000	1.0000
2	1.0000	1.0000	1.0000
3	0.9999	0.9999	0.9999
4	0.9998	0.9998	0.9998
5	0.9990	0.9991	0.9991
6	0.9903	0.9906	0.9905
7	0.9812	0.9817	0.9816
8	1.0000	0.9796	0.9794
9	0.9989	0.9786	0.9784
10	0.9940	0.9736	0.9734
11	0.9929	0.9725	0.9723
12	0.9898	0.9693	0.9691
13	0.9870	0.9664	0.9662
14	0.9842	0.9635	0.9633
15	0.9814	0.9606	0.9604
16	0.9808	0.9601	0.9599
17	0.9800	0.9592	0.9590
18	0.9800	0.9592	0.9590
19	0.9795	0.9588	0.9586
20	0.9792	0.9585	0.9583
21	0.9788	0.9580	0.9578
22	0.9787	0.9580	0.9578
23	0.9787	0.9579	0.9577
24	0.9785	0.9577	0.9575
25	0.9784	0.9576	0.9574
26	0.9783	0.9575	0.9573
27	0.9783	0.9575	0.9573
28	0.9999	0.9999	0.9999
29	0.9999	0.9999	0.9999
30	0.9997	0.9997	0.9997
31	0.9997	0.9997	0.9997
32	0.9996	0.9996	0.9996
33	0.9993	0.9994	0.9994
34	0.9990	0.9990	0.9990
35	0.9989	0.9989	0.9989
36	0.9999	0.9999	0.9999
37	0.9997	0.9997	0.9997

38	0.9996	0.9996	0.9996
39	0.9995	0.9995	0.9995
40	0.9995	0.9995	0.9995
41	0.9988	0.9988	0.9988
42	0.9986	0.9986	0.9986
43	0.9985	0.9985	0.9985
44	0.9985	0.9985	0.9985
45	0.9984	0.9984	0.9984
46	0.9984	0.9984	0.9984
47	0.9998	0.9998	0.9998
48	0.9985	0.9986	0.9985
49	0.9947	0.9947	0.9947
50	0.9942	0.9942	0.9942
51	1.0000	0.9796	0.9794
52	1.0000	0.9796	0.9794
53	0.9962	0.9760	0.9757
54	0.9930	0.9730	0.9727
55	0.9886	0.9688	0.9685
56	0.9844	0.9648	0.9644
57	0.9625	0.9441	1.0000
58	0.9517	0.9339	0.9896
59	0.9475	1.0000	0.9856
60	0.9426	0.9954	0.9809
61	0.9354	0.9885	0.9740
62	0.9351	0.9883	0.9737
63	0.9347	0.9879	0.9734
64	0.9329	0.9862	0.9716
65	0.9323	0.9856	0.9711
66	0.9929	0.9724	0.9722
67	0.9929	0.9724	0.9722
68	0.9895	0.9690	0.9688
69	0.9895	0.9690	0.9688

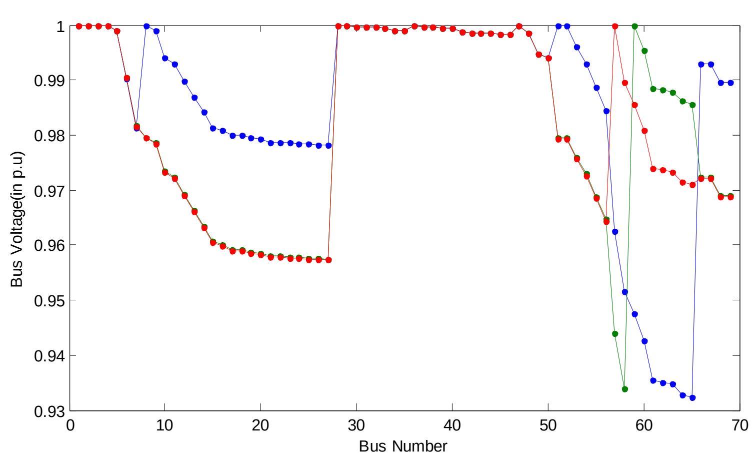

Figure 3.8 Plot Comparing Improvement in Voltage Profile of Buses 8, 59, 57

The RUVMN resulted due to fixed voltage DSTATCOM is summarized in Table 3.10. and also presented in Fig. 3.9. The maximum value is obtained at when DSTATCOM is placed at bus 57.

Table 3.10 RUVMN of variable DSTATCOM Rating for a 69-Bus Radial Distribution System

Bus No.	RUVMN (in %)
1	0
2	0
3	0
4	0
5	0
6	1.4493
7	1.4493
8	2.8986
9	2.8986
10	0
11	0
12	0
13	0
14	0
15	0
16	0
17	0
18	0
19	0
20	0
21	0
22	0
23	0
24	0
25	0
26	0
27	0
28	0
29	0
30	0
31	0
32	0
33	0
34	0
35	0
36	0
37	0
38	0

39	0
40	0
41	0
42	0
43	0
44	0
45	0
46	0
47	0
48	0
49	0
50	0
51	0
52	0
53	4.3478
54	4.3478
55	5.7971
56	10.1449
57	**13.0435**
58	11.5942
59	10.1449
60	8.6957
61	7.2464
62	5.7971
63	4.3478
64	2.8986
65	1.4493
66	0
67	0
68	0
69	0

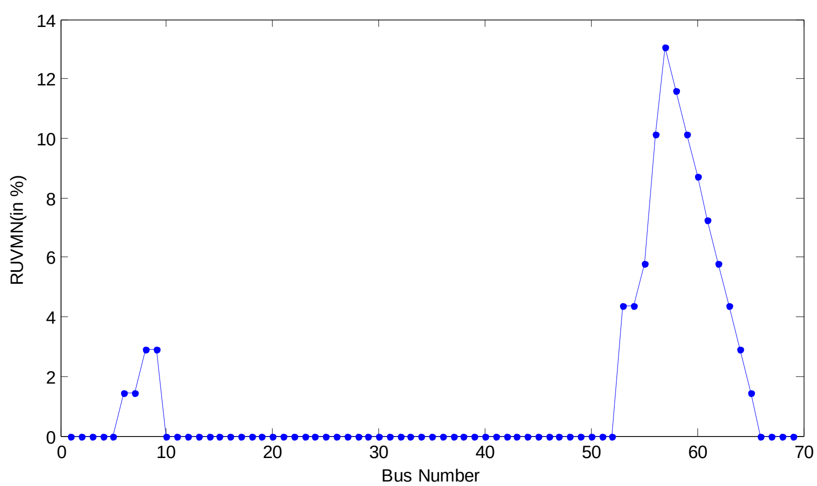

Figure 3.9 RUVMN for 69-Bus Radial Distribution System.

Case II Fixed rating DSTATCOM

The effect of compensation of 2 MVAR by DSTATCOM on randomly chosen bus numbers 8, 27 and 69 is summarized in Table 3.11.

Table 3.11 Comparison between Bus voltage of Bus No.8,27,69 using fixed rating DSTATCOM

Compensated Buses→ Bus NO. ↓	Compensation on Bus no.8	Compensation on bus No.27	Compensation On Bus No.69
1	1.0000	1.0000	1.0000
2	1.0000	1.0000	1.0000
3	1.0000	1.0000	1.0000
4	0.9999	0.9999	0.9999
5	0.9995	0.9994	0.9995
6	0.9929	0.9925	0.9928
7	0.9862	0.9852	0.9859
8	0.9845	0.9835	0.9843
9	0.9834	0.9826	0.9835
10	0.9784	0.9802	0.9817
11	0.9774	0.9797	0.9814
12	0.9742	0.9789	0.9811
13	0.9713	0.9794	0.9782
14	0.9684	0.9801	0.9754
15	0.9656	0.9811	0.9726
16	0.9651	0.9813	0.9720
17	0.9642	0.9818	0.9712
18	0.9642	0.9818	0.9712
19	0.9637	0.9826	0.9707
20	0.9634	0.9831	0.9704
21	0.9629	0.9840	0.9699
22	0.9629	0.9840	0.9699
23	0.9629	0.9846	0.9699
24	0.9627	0.9858	0.9697
25	0.9625	0.9887	0.9695
26	0.9625	0.9899	0.9695
27	0.9625	0.9906	0.9694
28	1.0000	1.0000	1.0000
29	0.9999	0.9999	0.9999
30	0.9998	0.9998	0.9998
31	0.9997	0.9997	0.9997
32	0.9996	0.9996	0.9996
33	0.9994	0.9994	0.9994

34	0.9990	0.9990	0.9990
35	0.9990	0.9990	0.9990
36	0.9999	0.9999	0.9999
37	0.9998	0.9998	0.9998
38	0.9996	0.9996	0.9996
39	0.9996	0.9996	0.9996
40	0.9996	0.9996	0.9996
41	0.9989	0.9989	0.9989
42	0.9986	0.9986	0.9986
43	0.9985	0.9985	0.9985
44	0.9985	0.9985	0.9985
45	0.9984	0.9984	0.9984
46	0.9984	0.9984	0.9984
47	0.9999	0.9999	0.9999
48	0.9986	0.9986	0.9986
49	0.9948	0.9948	0.9948
50	0.9942	0.9942	0.9942
51	0.9845	0.9835	0.9842
52	0.9845	0.9834	0.9842
53	0.9806	0.9799	0.9807
54	0.9774	0.9766	0.9775
55	0.9730	0.9722	0.9730
56	0.9686	0.9678	0.9687
57	0.9463	0.9455	0.9464
58	0.9353	0.9345	0.9354
59	0.9311	0.9303	0.9311
60	0.9261	0.9253	0.9261
61	0.9188	0.9179	0.9188
62	0.9185	0.9176	0.9185
63	0.9181	0.9172	0.9181
64	0.9162	0.9153	0.9162
65	0.9156	0.9148	0.9157
66	0.9773	0.9796	0.9813
67	0.9773	0.9796	0.9813
68	0.9739	0.9785	0.9839
69	0.9739	0.9785	0.9839

3.3 Concluding Remarks

From the above study it is observed that the developed algorithm works well to model DSTATCOM operation in Fixed voltage mode and Fixed rating VAR compensation mode. The Fixed voltage mode operation of DSTATCOM is more suited for improving the voltage profile of buses than the fixed rating modes.

CHAPTER 4
CONCLUSIONS AND SCOPE FOR FURTHER WORK

4.1 CONCLUSIONS

The work has been carried out with an aim to identify the best suitable node for DSTATCOM placement in a distribution network. Study has been carried out with both fixed rating and variable rating DSTATCOM and a comparison has been made between them. To perform this act initially load flow is performed with backward and forward sweep method and then after modeling the DSTATCOM, again load flow is done with DSTATCOM attachment on the desired bus. Study has been carried out on 33-Bus and 69-Bus radial distribution system taking into account that the system is completely in steady state.

- This compensation yield better voltage profile.
- Method for identifying bus for DSTATCOM placement is easy and effective.
- The compensation by operating the DSTATCOM in fixed voltage mode is effective for improving the voltage profile.

4.2 SCOPE FOR FUTURE WORK

Tough much work as compared to capacitor placement is not there for DSTATCOM placement in Distribution system load flow , this leaves much scope for further work in many related areas. Following are the areas identified for further studies

1. Modeling of DSTATCOM for load flow in dynamic loading condition.
2. Modeling of DSTATCOM for three-phase unbalanced load.
3. Modeling of DSTATCOM for other topologies such as mesh distribution network.

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APPENDIX A

Table (A.1) Line data of 33- Bus Radial Distribution system

Branch No.	Sending-end bus	Receiving-end bus	Branch Resistance(Ω)	Branch reactance(Ω)
1	1	2	0.0922	0.0477
2	2	3	0.4930	0.2511
3	3	4	0.3660	0.1864
4	4	5	0.3811	0.1941
5	5	6	0.8190	0.7070
6	6	7	0.1872	0.6188
7	7	8	1.7114	1.2351
8	8	9	1.0300	0.7400
9	9	10	1.0040	0.7400
10	10	11	0.1966	0.0650
11	11	12	0.3744	0.1238
12	12	13	1.4680	1.1550
13	13	14	0.5416	0.7129
14	14	15	0.5910	0.5260
15	15	16	0.7463	0.5450
16	16	17	1.2890	1.7210
17	17	18	0.7320	0.5740
18	2	19	0.1640	0.1565
19	19	20	1.5042	1.3554
20	20	21	0.4095	0.4784
21	21	22	0.7089	0.9373
22	3	23	0.4512	0.3083
23	23	24	0.8980	0.7091
24	24	25	0.8960	0.7011
25	6	26	0.2030	0.1034
26	26	27	0.2842	0.1447
27	27	28	1.0590	0.9337
28	28	29	0.8042	0.7006
29	29	30	0.5075	0.2585
30	30	31	0.9744	0.9630
31	31	32	0.3105	0.3619
32	32	33	0.3410	0.5302

Table (A.2) Load Data of 33-Bus Radial distribution System

Bus Number	P(KW)	Q(KVAR)
1	0	0
2	100	60
3	90	40
4	120	80
5	60	30
6	60	20
7	200	100
8	200	100
9	60	20
10	60	20
11	45	30
12	60	35
13	60	35
14	120	80
15	60	10
16	60	20
17	60	20
18	90	40
19	90	40
20	90	40
21	90	40
22	90	40
23	420	50
24	420	200
25	60	200
26	60	25
27	60	25
28	120	20
29	200	70
30	150	600
31	210	70
32	60	100
33	60	40

APPENDIX-B

Table (B.1) Line Data of 69-Bus Radial Distribution system

Branch No.	Sending-end Bus	Receiving-end bus	Branch Resistance(Ω)	Branch reactance(Ω)
1	1	2	0.0005	0.0012
2	2	3	0.0005	0.0012
3	3	4	0.0015	0.0036
4	4	5	0.0215	0.0294
5	5	6	0.366	0.1864
6	6	7	0.381	0.1941
7	7	8	0.0922	0.047
8	8	9	0.0493	0.0251
9	9	10	0.819	0.2707
10	10	11	0.1872	0.0619
11	11	12	0.7114	0.2351
12	12	13	1.03	0.34
13	13	14	1.044	0.34
14	14	15	1.058	0.3496
15	15	16	0.1966	0.065
16	16	17	0.3744	0.1238
17	17	18	0.0047	0.0016
18	18	19	0.3276	0.1083
19	19	20	0.2106	0.069
20	20	21	0.3416	0.1129
21	21	22	0.014	0.0046
22	22	23	0.1591	0.0526
23	23	24	0.3463	0.1145
24	24	25	0.7488	0.2475
25	25	26	0.3089	0.1021
26	26	27	0.1732	0.0572
27	3	28	0.0044	0.0108
28	28	29	0.064	0.1565
29	29	30	0.3978	0.1315
30	30	31	0.0702	0.0232
31	31	32	0.351	0.116
32	32	33	0.839	0.2816
33	33	34	1.708	0.5646
34	34	35	1.474	0.4873
35	3	36	0.0044	0.0108
36	36	37	0.064	0.1565
37	37	38	0.1053	0.123
38	38	39	0.0304	0.0355
39	39	40	0.0018	0.0021
40	40	41	0.7283	0.8509
41	41	42	0.31	0.3623
42	42	43	0.041	0.0478

43	43	44	0.0092	0.0116
44	44	45	0.1089	0.1373
45	45	46	0.0009	0.0012
46	4	47	0.0034	0.0084
47	47	48	0.0851	0.2083
48	48	49	0.2898	0.7091
49	49	50	0.0822	0.2011
50	8	51	0.0928	0.0473
51	51	52	0.3319	0.114
52	9	53	0.174	0.0886
53	53	54	0.203	0.1034
54	54	55	0.2842	0.1447
55	55	56	0.2813	0.1433
56	56	57	1.59	0.5337
57	57	58	0.7837	0.263
58	58	59	0.3042	0.1006
59	59	60	0.3861	0.1172
60	60	61	0.5075	0.2585
61	61	62	0.0974	0.0496
62	62	63	0.145	0.0738
63	63	64	0.7105	0.3619
64	64	65	1.041	0.5302
65	65	66	0.2012	0.0611
66	66	67	0.0047	0.0014
67	67	68	0.7394	0.2444
68	68	69	0.0047	0.0016

Table (B.2) Bus Data of 69-bus Radial distribution system

Bus Number	P(KW)	Q(KVAR)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	2.6	2.2
7	40.4	30
8	75	54
9	30	22
10	28	19
11	145	104
12	145	104
13	8	5
14	8	5
15	0	0
16	45	30
17	60	35
18	60	35
19	0	0
20	1	0.6
21	114	81
22	5	3.5
23	0	0
24	28	20
25	0	0
26	14	10
27	14	10
28	26	18.6
29	26	18.6
30	0	0
31	0	0
32	0	0
33	10	10
34	14	14
35	4	4
36	26	18.55
37	26	18.55
38	0	0
39	24	17
40	24	17
41	102	1
42	0	0
43	6	4.3
44	0	0
45	39.22	26.3

46	39.22	26.3
47	0	0
48	79	56.4
49	384.7	274.5
50	384.7	274.5
51	40.5	28.3
52	3.6	2.7
53	4.35	3.5
54	26.4	19
55	24	17.2
56	0	0
57	0	0
58	0	0
59	100	72
60	0	0
61	1244	888
62	32	23
63	0	0
64	227	162
65	59	42
66	18	13
67	18	13
68	28	20
69	28	20