THE UNIVERSITY OF NAIROBI

SCHOOL OF ENGINEERING

Title: “Controller for Optimising Voltage Profile of Distribution Networks with Distributed Generation”

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A thesis submitted in partial fulfilment for the Degree of Master of Science in Electrical and Electronics Engineering in the Department of Electrical and Information Engineering in the University of Nairobi

Date of Submission: November 2014
Declaration

I, Kigen Christopher Kimosop, hereby declare that this thesis is my original work. To the best of my knowledge, the work presented here has not been presented for a degree in any other Institution of Higher Learning.

Sign: ........................................ Date: ...........................................

Approval:

This thesis has been presented for examination with my approval as university supervisor.

Supervisor: Prof. Nicodemus Abungu Odero

Sign: ........................................ Date: ...........................................
Dedication

This thesis is dedicated to my soul-mate and my family.
Appreciation

I appreciate the assistance of the Gandhi Smarak Nidhi Fund. Without their funding, this work would not have been possible.

I am also indebted to my classmate and colleague, Peter Moses Musau for his help as we worked together towards our Master’s degrees. It has been a full-time course indeed.

Finally, I appreciate the assistance, encouragement, and advice of Dr. Prof. Abungu throughout my Master’s coursework and thesis writing. This work would not have been possible without his infinite patience.
Abstract

The distribution networks to which distributed generators (DG) are connected were not designed for direct connection of generators. DG cause changes to stability, voltage profile and protection systems. Because distribution networks were not designed to accommodate generators, constraints are placed on DG utilization. One such limitation is the level at which DGs supply power to the network. Supply of real power causes voltage to rise around the power source. If the real power supplied is too high, voltage level may rise beyond acceptable limits.

This paper presents a coordinated network controller whose objective is to maintain an optimal voltage profile across radial and meshed distribution networks with distributed generation. Voltage profile is said to be optimal if the voltages at every bus have the minimum possible deviation from the ideal voltage of unity per unit. This is achieved by varying the output of the distributed generators. The controller is modelled as an optimisation problem which is solved using Particle Swarm Optimisation.

The controller makes use of two different load-flow methods, Newton-Raphson load-flow and a modified backward / forward sweep load flow. These load flow techniques are used in turn to optimise meshed and radial distribution networks, respectively. IEEE test networks are then used to verify the effectiveness of the controller. The results obtained show that this controller can effectively improve the voltage profile of distribution networks.
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<td>ANN</td>
<td>Artificial Neural Networks</td>
</tr>
<tr>
<td>AVC</td>
<td>Automatic voltage control</td>
</tr>
<tr>
<td>DE</td>
<td>Differential Evolutionary Algorithm</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation / Distributed Generator</td>
</tr>
<tr>
<td>EPSO</td>
<td>Evolutionary Particle Swarm Optimization</td>
</tr>
<tr>
<td>GA</td>
<td>Genetic Algorithm</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>LV</td>
<td>Low Voltage</td>
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<tr>
<td>MV</td>
<td>Medium Voltage</td>
</tr>
<tr>
<td>OLTC</td>
<td>On-Load Tap Changing transformer</td>
</tr>
<tr>
<td>OPF</td>
<td>Optimal Power Flow</td>
</tr>
<tr>
<td>pf</td>
<td>Power factor</td>
</tr>
<tr>
<td>PSO</td>
<td>Particle Swarm Optimization</td>
</tr>
<tr>
<td>SVC</td>
<td>Static VAR Compensator</td>
</tr>
<tr>
<td>SVR</td>
<td>Step Voltage Regulator</td>
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<tr>
<td>VAR</td>
<td>Volt-Ampere reactive</td>
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CHAPTER 1
INTRODUCTION

In traditional power distribution networks, power has always been generated in bulk at generation plants. The generation plants are located where energy resources are readily available. These include rivers for hydro power, and fossil fuel deposits for thermal power. The generated power is then transmitted long distances through a network of high voltage lines. The power is distributed to consumers through medium and low voltage distribution networks.

In recent years however, there has been a growth in distributed generation alongside the conventional power generation, transmission and distribution network. Distributed generation (DG) is smaller scale generation of power usually connected directly to distribution networks.

As distributed generation becomes more widespread, challenges are being encountered. The distribution networks are connected were not designed for direct connection of generators. They were designed for power flow from a source (substation) to the consumer loads. Introduction of DG may lead to changes in the direction of power flow in distribution networks. In addition to this, DG cause changes to stability, voltage profile and protection systems. Because distribution networks were not designed to accommodate generators, constraints are placed on DG utilization. One such limitation is the level at which DGs supply power to the network. Supply of real power causes voltage to rise around the power source. If the real power supplied is too high, voltage level may rise beyond acceptable limits.

The aim of this research is to investigate a method of increasing the utilization of DG in distribution networks. This is done through coordinated control of DG, On-Line Tap-Changing transformers (OLTC) and network-connected capacitors. Through such control, the DG are able to supply greater levels of power to the network, while still meeting the voltage level constraints.
1.1. Distributed Generation

The Electric Power Research Institute defines distributed generation [1] as the “utilization of small, modular power generation technologies dispersed throughout a utility’s distribution system in order to reduce transmission and distribution loading or load growth and thereby defer the upgrade of facilities, reduce system losses, improve power quality, and reliability.” While this is one definition, the nature of distributed generation varies. Generation can be considered DG if it is located at distribution substations or in subtransmission networks [2].

The advantages of DG include reduced loading on distribution systems, reduction in power losses, and increased use of renewable energy sources [3]. DG plants are comparatively small, less than 100MW. This enables them to vary their output to closely match load. In addition to this, the plants utilize much smaller physical space and land.

DG may be installed and operated by distribution network operators or power customers. Customers may install DG for cogeneration, where electric power is produced at the same time as steam, hot water or other forms of energy. Customers may also install generators as a backup to grid supply. In some cases it may be economical to run such backup generators full-time, and supply the grid when not required locally. Power utility companies can add DGs to their networks to alleviate overloading or boost generation.

If DG are connected to a network, they will alter the active and reactive power and hence change the voltage drop along the lines. DG leads to a significant voltage rise at the end of the long, high impedance lines. A rise in voltage occurs if there is low demand and high generation, which leads to a large amount of power flow along lightly loaded lines with high impedance. This problem is particularly acute in rural areas, where demand tends to be low.
In order to maximise the use of DGs in distribution networks, the problem of voltage rise must be solved [4]. The decentralised voltage control methods in [5], [6] and [7] use dual mode control. This combines fixed power factor and automatic voltage control. However, these localized methods do not produce optimal results across a network.

Centralised methods of control make use of several types of algorithms to control voltage rise due to DG active power output. On-Load Tap Changer (OLTC) tap setting control is used in [8], [9] and [10]. Apart from OLTC control, the output of DGs can be varied in order to control voltage in a distribution network. This is shown in [7] and [11].

The methods proposed in [12] and [13] coordinate OLTC tap settings, reactive power support equipment and DG output simultaneously in order to mitigate the effects of voltage rise. These methods provide optimal solutions for the problem, with the objective of minimising power losses in the network.

In contrast to the problem of voltage rise is that of voltage regulation. In distribution networks, loads are distributed along the transmission lines. In such distribution networks, particularly those with radial configurations, voltage tends to drop along the line. Generally, the farther a load point is from the power source, the lower its voltage.

The increased use of DG in distribution systems has benefits for power consumers as well as owners of DG equipment. However, the uptake and penetration of DG in distribution systems is limited. One reason for this is the voltage rise that is associated with heavy injection at the point of connection of real power. If voltage rise can be minimised, the level of DG penetration can be raised.

A number of methods for voltage control to minimise voltage rise due to DG have been described in literature [14]. DGs with reactive power capabilities can contribute to the voltage control in a system. OLTCs and shunt capacitors have also been used to achieve this objective in other research works.
Alternatively, the reactive power flows in the system can be regulated, which in turn controls voltage. This is achieved using shunt capacitors at substations or feeder capacitors along distribution lines.

An area that has recently been of interest to many researchers is the optimal location and sizing of reactive power and voltage control devices, including OLTCs, shunt capacitors and DGs themselves. Examples of this include [15], [16], [17] and [18]. This involves planning the distribution system and establishing the locations at which reactive power injection can give an optimal system. While exhaustive work has been done on optimal location and sizing during the planning stages, the operations of distribution systems still require study. The control of voltage on a day-to-day basis is of interest here. As loads vary at different times during operation, the reactive power requirements of the system may also vary.

It is noted that the objective of most of the methods in literature is to minimise power losses in the networks. The optimisation of voltage profile is treated as a constraint to the objective function, not as the main objective. In the literature, few examples of the use of voltage profile as an objective function for optimisation were found.

The objective of this research is therefore to design and implement a method to optimise the voltage profile of a given distribution network with DG. The proposed method will control existing DG units, OLTC tap settings and reactive power support devices in order to achieve optimal voltage profile in a distribution network. A controller is developed that uses heuristic methods to perform the allocation of these resources for optimal voltage profile. The problem is treated as an optimisation with multiple objectives.
1.2. Literature Survey: Voltage Control in Distribution Networks with Distributed Generation

1.2.1. Conventional distribution networks

Distribution networks are traditionally designed as passive networks that deliver power from supply points to loads. Distribution system operators are obligated to maintain the voltage level at consumers’ supply points within specified ranges. For example, the American National Standards Institute (ANSI) standard C 84.1 stipulates a range between -13% and +7% of nominal voltage [19]. In order to meet this and other requirements, active network control systems have been developed. These are systems that use communication and control devices to manage the network in real time [10]. Active control systems optimise network parameters during network operations.

In conventional distribution networks without DGs, voltage profile is controlled in two ways: use of On-Load Tap Changing transformers (OLTCs) or management of reactive power flow. The source of power in a distribution network is usually a substation, which may have OLTCs to supply the distribution network. Varying the tap settings on the OLTC is a means by which voltage profile in the network can be controlled.

Automatic voltage control (AVC) is commonly used in 33kV/11kV substations to maintain required voltage profile in distribution feeders. AVC monitors voltage levels on the secondary side of substation transformers. The measured voltage at the secondary is compared to a target voltage by the AVC controller. The transformer tap settings are varied in order to maintain the secondary voltage at the target level. To prevent “hunting”, the target may be a range of voltages called a dead-band.
1.2.2. Decentralised Voltage Control

Raymond O'Gorman, et al. (2008) [20] assert that voltage control with DGs is only possible with DG technologies that allow dispatching, such as combined heat and power and fossil fuel-burning generators. Most renewable energy sources such as photovoltaic (solar) and wind have outputs which are not easily controllable. The authors describe line drop compensation, which uses OLTCs to boost voltage in radial lines with large voltage drops.

A. K. Kiprakis and A. R. Wallace (2004) [5] achieve voltage control through a combination of power factor control and automatic voltage control, known as dual mode control. If DGs in a network operate below a given voltage threshold, they are operated at a constant power factor. If the voltage at the terminals exceeds this threshold, the power factor is varied depending on the voltage level.

Thipnatee Sansawatt, et al. (2010) [6] propose a further improvement to the control scheme in [5]. If dual mode control is not effective, generation curtailment is used as a last resort. During generation curtailment, power output is lowered in order to reduce the associated voltage rise. This combination of dual mode control and generation curtailment prevents excessive voltage rise in a cost-effective manner without significant capital investment.

Panagis N Vovos, et al. (2007) [7] describe two methods of distributed generation management. The first is power factor control. In this control mode, power factor of the generator is kept constant. If power factor is kept constant, the ratio of real to reactive power remains constant. This means that if real power is reduced, there is a corresponding reduction in reactive power output. Now an increase in real power causes an increase in voltage at the generator terminals. In constant pf mode, the generator cannot vary its reactive power output to compensate for voltage rise. This in turn means that the DG in constant pf mode cannot participate in voltage control. Penetration of DG is
increased by varying the power factor at which generators supply power. By absorbing reactive power, DGs can supply real power without increasing voltage levels. To achieve this, the reactive power output of DG is managed.

Andrew Keane, et al. (2011) [4] propose a method of voltage control for distribution networks that does not require additional network infrastructure, but optimises the settings of existing grid equipment. These include DG and the tap settings of OLTCs at bulk supply points in the distribution network. The power factors at which DG operate are set depending on the reactive power sensitivity of the buses to which they are connected. Tap settings of OLTC at bulk supply point are reduced to a level that can accommodate the voltage rise caused by DG.

L. F. Ochoa, et al (2011) [21] describe a method of enhanced passive operation of distribution networks whose objective is to reduce dependence of distribution networks on transmission systems for reactive power supply. The operating power factor of DG is varied in order to achieve the objective in any given time period. At the same time, the voltage settings of OLTCs are varied to ensure that voltage rise due to increase DG power injection does not exceed voltage limits.

Yiyun Guo, et al. (2011) [22] assess the effects of different operational modes of DG when connected to distribution networks. DG operation in constant current, constant voltage and constant power factor modes are assessed. It is found that when DG is introduced to a network, distribution losses are reduced compared to the base case when the DG is operated at constant voltage and also at constant current. When DG is operated at constant power factor, it is noted that the losses are even higher than the base case operation, without DG.

Takao Tsuji, et al. (2009) [23] note that in the case of high speed voltage control, the operation of tap-changers and shunt capacitors may not be able to operate quickly enough. This is because these equipments require physical adjustments to be made. The authors propose a method in which voltage is
controlled through varying the reactive power generated through the inverters. The DGs monitor voltage at the immediately neighbouring buses. The DGs then adjust their terminal voltages to maintain optimal terminal voltage across this group of neighbouring buses. In this way the authors achieve decentralised voltage control. This research however does not address the possible incorporation of OLTCs and shunt capacitors in voltage control. Only DG reactive power output is varied.

Li Yu, et al (2012) [24] describe a method in which voltage in a distribution network is controlled by breaking the network into smaller subnetworks. The subnetworks are demarcated based on the number of buses over which DGs exert influence. The authors propose a method for voltage regulation in which the voltage profile of each subnetwork is regulated by DGs in that subnetwork. The DGs operate either at constant power factor or at unity power factor. In the former case, the reactive power output of the DG is varied, whereas in the latter mode, the DG active power generation is varied. This research is highly beneficial in extremely large networks. However it does not include voltage regulation equipment such as tap changers and shunt capacitors.

1.2.3. Centralised Voltage Control

Panagis N Vovos, et al, (2007) [7] combine constant power factor control and variable reactive power to provide centralised voltage control. This hybrid method has as its objective the maximisation of DG real power capacity. DGs in a distribution network are dispatched according to an OPF carried out across the network. The objective is modelled as a cost function of active power generated. The constraints of optimisation are thermal capacities of the transformer and transmission lines, voltage limits across all buses, and fault limits at switchgear. This method does not take into account voltage support through capacitors and reactors or OLTC tap settings.

M Fila, et al (2009) [8] describe a method that can be used to control several distribution substations. A state estimation algorithm is proposed that uses data
collected by remote terminal units and sent to a centralised distribution management system to evaluate voltage at all buses. This information is used to calculate parameters that are required to control the network. Signals sent from the distribution management system then alter OLTC tap settings and DG output or reconfigure the network through switching. The centralised Distribution management system offers real-time control of networks with DG, because the network model used to calculate parameters is updated frequently during operation. This method of distribution network control requires a large number of Remote terminal units at key nodes in the network, which has significant cost implications for implementation.

The authors further describe an alternative voltage control scheme that can be used to improve voltage profile in 11kV networks with DG through active control of OLTC. The scheme relies on a network model that may be updated using state estimation of the network under control. A voltage controller with state estimation is used at the point of common connection, with RTUs at various points throughout the network. The number of monitoring equipment in the network will determine the accuracy of the state estimation, and hence the certainty with which the voltage profile can be controlled. In local voltage management, the network model is not updated during normal operation and does not require communication. It is assumed that the network configuration in a local network will not change frequently.

C.M. Hird, et al. (2004) [9] propose a network voltage controller based on variation of voltage at the substation. The controller uses state estimation to model the network. An algorithm is proposed which compares the magnitudes of maximum and minimum node voltages with designed upper and lower voltage limits at each node. If the node voltages during operation are outside the designed limits, the controller raises or lowers the automatic voltage control (AVC) target voltage accordingly. The controller then compares the target voltage with OLTC secondary voltage. The AVC is adjusted so that OLTC secondary voltage matches the target voltage. Simulations show that this
method improved the maximum power that could be injected by DG in a network. It is noted that the method could be improved upon by utilising DG and other reactive power supports for voltage control in addition to transformers.

Tomonobu Senjyu, et al (2008) [10], describe a controller that uses various control devices in a coordinated manner. These control devices are the load ratio transformer at the point of common connection, static var compensator (SVC) in the network, and shunt capacitors and reactors connected at various points in the network. A SVC is located at the point of connection of DG. The operation of this SVC is also regulated by the controller. The simulated controller takes the form of a large-scale optimisation problem solved using GA. The objective function is the minimisation of deviation of node voltages from specified targets while also minimising power losses in the network. The constraints of the problem are transformer tap limits, and point of common connection voltage limits. While the controller is effective in optimising the network, it does not utilise DG for voltage control, which may improve the solution obtained.

M. Z. C. Wanik, et al (2010) [11] aim to minimise active power losses in a distribution network with DG. This is achieved through a predictive technique that manages reactive power generation by the DGs. The tap settings on the OLTC are also controlled in conjunction with the reactive power management. The management method operates the DG within their reactive power generation capacities and OLTC tap setting limits. At the same time, there are constraints on the voltage limits at all buses in the network.

Ferry A Viawan, et al. (2008) [12] propose a coordinated voltage and reactive power control system, similar to that used in transmission networks. The authors use a three-level control system. In the primary level, all DGs control voltage at their own buses by regulating reactive power output. The secondary level incorporates feeder shunt capacitors, substation capacitors and the substation OLTC to regulate voltage and reactive power flows at various
feeders. The tertiary level utilises coordinated control of DGs, OLTC, and substation capacitors. The tertiary controller optimises operations based on a predefined objective function. In the case study described, the objective function is to minimize the total feeder and transformer losses and maximise capacitor utilization. The reason for the latter objective is that reactive power from capacitors is less costly than that supplied by DG. The optimisation is constrained by OLTC power limit, voltage limits at all buses and transmission line thermal limits.

**Olivier Richardot, et al, (2006)** [25] also propose a coordinated distribution network voltage control system based on the primary, secondary and tertiary transmission system controls. By modifying secondary voltage control, coordinated voltage control is achieved. The DGs throughout the network are controlled in order to maintain optimal voltage profile. This allows the DG to reduce the distribution network’s dependence on reactive power support from the transmission grid.

**Madureira and Lopes, (2008)** [13] propose a method that coordinates OLTC tap settings, reactive power support equipment and DG output simultaneously in order to mitigate the effects of voltage rise. These methods provide optimal solutions for the problem, with the objective of minimising power losses in the network.

**Ochoa and Harrison, (2010)** [26] aim to minimise energy losses while maximising DG penetration in distribution networks. This is done by controlling network parameters over several different periods in the day with different load levels. OLTC tap settings are varied within the statutory range, allowing DG to be operated at maximum power supply levels. The method used also incorporates the variation of the power factor at which DG operate.

**A. A. Abou El Ela, et al. (2010)** [27] solve the reactive power dispatch problem using the differential evolution algorithm. Three separate cases are examined, one of which is voltage profile improvement. The constraints of the
problem consist of the power flow equations, voltage limits at each generator bus, reactive power generation limits of the DGs, OLTC tap setting limits, and shunt VAR constraints. The optimal reactive power dispatch is obtained using the differential evolution algorithm.

C. L. Su, (2009) [28] presents a comparison of local (decentralised) and coordinated voltage control of distribution networks with DG. The author investigates three case studies. The first is the case of voltage control by supplying reactive power into the distribution network through the substation transformer. The second case study investigates voltage control using devices available in the distribution network, such as shunt capacitors. In this case study, each device maintains the voltage constant at its point of connection. The third case investigated is that of a coordinated distribution management system. This system controls voltages across the network by coordinating both DG and voltage control devices.

Albert Y.S. Lam, et al, (2012) [29] address the problem of voltage regulation in distribution networks with distributed generation. In particular, the case of networks with heavy penetration of distributed energy resources is considered. The problem is solved by treating it as an optimization problem. The network is modelled as having power injection sources at all buses. The variables used in the solution are real and reactive power injections at each bus. The constraints are line and generated power limits and the objective is to minimise distribution losses.

Sarmin et al., (2013), [30] propose a coordinated voltage control method that incorporates both voltage control and reactive power control. Variables controlled are OLTC tap settings, feeder capacitors, substation capacitors, DG reactive power generation levels and DG power factor. The objective is to minimise distribution losses.

Shivarudraswamy and Gaonkar (2012), [31] present a coordinated voltage control method for distribution networks. The network voltage profile is
regulated by varying settings of OLTCs, load ratio control transformers, shunt capacitors, and static var compensators. The control is carried out as an optimisation of the network using Genetic Algorithm. The objective of the optimisation is to minimise the deviation of the voltage at each bus from a specified reference voltage.

**Van Cutsem and Valverde (2013),** [32] propose another coordinated voltage control method for distribution networks with DG. The objective is to maintain voltages at selected buses in the network within a specified reference band. The method adjusts reactive power outputs of all DG units in the network. This is accomplished through model predictive control that adjusts the automatic voltage controller of each DG. The method imposes a penalty for each control action, encouraging faster convergence of the voltage profile towards its optimum. It is noted that this method focuses purely on reactive power control of DGs to achieve the objective. Other voltage regulation equipment such as shunt capacitors or OLTCs are not taken into account.

**Hiscock, et al, (2007) [33] and O’Gorman (2005) [20],** analyse the effect of line drop compensation in distribution networks with DG. Line drop compensation is the method of adjusting substation OLTC secondary in order to boost voltage and prevent low voltage at the distant end of the feeder. Current drawn from the OLTC secondary is measured and used to calculate the amount of line drop compensation to apply. A target voltage is set by the controller, which takes the ratio of actual load to full load that the line can carry. This target voltage is used to vary the OLTC tap settings. However, when DG is incorporated in the distribution network, line drop compensation is inaccurate. This is because current measured at the OLTC terminals does not include the current supplied by the DG. The proposed method in their research tackles voltage rise due to DG. However, the method does not utilise any voltage regulation equipment other than OLTCs.

**Wang and Zhong (2011) [19]** choose as their objective to maximize the magnitude of the lowest bus voltage in the system. The constraints of this
optimisation problem are as follows. Power flow equations must be satisfied, the voltage at each bus must be within specified limits, and the power supplied by each DG must not exceed its limits. Modified optimal power flow is used to solve the problem of optimal DG location. In the paper, only one DG is located in the system per case.

1.2.4. Voltage Control in Radial Networks

Le, et al. (2005) [34] developed a technique to optimize voltage by effectively placing DG based on voltage sensitivity of the power lines. The authors created a location index for DG placement. The index indicates proximity of each bus to voltage collapse. The DGs are placed at buses closest to collapse (least stable).

Musa and Sanusi (2012) [35] describe a method called Ranked Evolutionary particle swarm optimization which is a hybrid of Evolutionary Programming and PSO. The method uses a ranking process to find the best particle in a population. The method improves voltage profile in the radial network by optimal DG sizing and placement.

Rao and Raju (2010) [36] describe a voltage regulator placement method that uses Plant Growth Simulation Algorithm. Together with a candidate location technique, the method places voltage regulators at optimal locations in the radial network. In this way, optimal voltage profile is achieved.

Shivarudraswamy and Gaonkar (2011) [37] perform a voltage sensitivity analysis of radial networks. This analysis can be used to determine the outputs of multiple DGs in radial networks for the best voltage profile. This output data is used for coordinated voltage control of the network.

Lantharthong and Rugthaicharoenceep (2012) [38] propose a method of reconfiguring radial networks for optimal operation. Tabu search is used to allocate DGs and place capacitors in the radial networks.
Sharma and Vittal (2010) [39] propose a Network Performance Enhancement Index and heuristic rules for location and sizing of DG. This method gives an overall improvement in radial network performance is achieved. Voltage profile is measured using a voltage profile improvement index.

Naik, et al. (2012) [40] propose a method of network optimization based on optimal location of DG through voltage sensitivity index analysis. The method uses the forward-backward sweep method for power flow analysis. This method is effective in load flow of radial networks. The results obtained show an improvement in the voltage profile of the test network compared to the base case.

Kumar and Navuri (2012) [41] demonstrate a method of optimal placement and sizing of DG in a radial distribution network. The optimal position of DG is found through the use of loss sensitivity factors. These factors help to reduce the search space within which the optimal buses are located. A search method known as simulated annealing is used to determine size of DG at the optimal location.

Abu-Mouti and El-Hawary (2012) [42] propose a radial network optimization method, that performs placement and sizing of DG in the network. This is done through the use of the artificial bee colony algorithm. The algorithm is shown to produce results comparable to other optimal placement and sizing methods, while proving itself to be a robust and efficient method.

Chenning and Xuequin (2012) [43] presents an improved backward/forward sweep network load flow method. The method calculates load flow, without reactive flow update. Examples of various sizes and locations of DG within test networks are presented with results.
1.2.5. Summary of Literature Review

From the literature, it is seen that there are three parameters used to control voltage in distribution systems with DG. These are transformers, reactive power devices and DG plants.

Transformers are used to vary the voltage directly. OLTCs at substations can raise or lower the voltage level across the distribution network.

Reactive power devices include shunt capacitors, shunt reactors and power electronics-based devices such as static var compensators. They control voltage by injecting varying levels of leading or lagging reactive power at various buses throughout the network.

Finally, DGs themselves can be used to control voltage in distribution networks. This is achieved by varying the quantity of real and reactive power generated. DGs can also vary the power factor at which they generate power.

These main controllable network devices can be utilised in different ways, broadly categorised as either centralised or decentralised. In decentralised methods of voltage control, network devices act in reaction to the localised conditions surrounding them. The centralised methods of control involve a network management system, usually located at the substation. The management system processes network data obtained either from state estimation or network monitoring equipment at various points throughout the network. The management system processes this data and generates optimal operating levels for the network devices.

1.3. Problem Statement

In order to maximise the use of DGs in distribution networks, the problem of voltage rise must be solved. Various methods of voltage control have been described in section 1.2 above. In contrast to the problem of voltage rise is that of voltage regulation. In distribution networks, loads are distributed along the
transmission lines. In such distribution networks, particularly those with radial configurations, voltage tends to drop along the line.

It is noted that the objective of most of the methods in literature is to minimise power losses in the networks. The optimisation of voltage profile is treated as a constraint to the objective function, not as the main objective. Voltage profile is said to be optimal if the voltages at every bus have the minimum possible deviation from the ideal voltage of unity per unit. In the literature, few examples of the use of voltage profile as an objective function for optimisation were found.

The objective of this research is therefore to design a method to optimise the voltage profile of a given distribution network with DG. The proposed method controls existing DG units, OLTC tap settings and reactive power support devices in order to achieve optimal voltage profile in a distribution network. A controller is developed that uses heuristic methods to perform the allocation of these resources for optimal voltage profile. The controller is able to manage both meshed and radial distribution networks with DG. The problem is treated as one of optimisation, solved using meta-heuristic optimisation techniques.

1.4. Objectives

It has been seen that a number of options for voltage and reactive power control exist. The aim of this research is to investigate the combination of device parameters and settings that will provide optimal voltage profile in a distribution system with DG. Voltage profile is said to be optimal if the voltages at every bus have the minimum possible deviation from the ideal voltage of unity per unit. The objective of this research is to control network parameters in order to optimise the network’s voltage profile. Similar studies have been carried out in literature. The results of these studies are compared to the results obtained during this research. This is in order to assess the effectiveness of the controller designed in this research.
The objective of this research will therefore be the following.

- Design a method to optimise the voltage profile of a meshed or radial distribution network with DG.
- Control existing DG units, OLTC tap settings and reactive power support devices in a coordinated manner.
- Establish the optimal voltage profile in distribution networks with DG.

### 1.5. Research Questions

To improve voltage profile in systems with DG, this research will aim to answer the following questions.

- How can existing OLTC, DG and network capacitors be utilised in a coordinated manner?
- Can such coordinated control be used to optimise voltage profile in a distribution network?
- Of the different methods of voltage and reactive power control, which combination achieves optimal results?
- What differences are there between optimal voltage control in meshed and radial networks?
- Can a single controller be used to control different topologies of distribution networks?
- What is the most effective balance of utilisation of the different control devices?
- Which is the best optimisation technique for obtaining optimal voltage profile?
- Which is the most efficient load flow method for optimising different topologies of distribution networks?
1.6. Organisation of the Thesis

This thesis has five chapters. Chapter 1 gives an introduction to distributed generation and voltage control in distribution networks including a literature survey. The problem statement and objectives are also presented in this chapter. In Chapter 2, a more detailed theoretical description of voltage control is presented. The effects of voltage rise due to distributed generation are described. In Chapter 3, the details of the design, implementation and simulation of the voltage controller are given. This includes descriptions of the optimisation method used as the controller’s algorithm. Chapter 4 gives the results obtained from the simulation of the controller with meshed networks. Chapter 5 presents the results obtained from simulation with radial networks. In Chapter 6, analysis and discussion of the results is presented. Areas of further research are also identified for future work and conclusions made. The research papers written while carrying out this research are listed. An appendix is provided at the end of this thesis, containing test network data and the controller program code.
CHAPTER 2
VOLTAGE CONTROL IN DISTRIBUTION NETWORKS

2.1. Introduction

The objective of voltage control in distribution networks is to minimize peak power and energy losses while keeping the voltage within the specified limits [44]. In conventional distribution networks, voltage profile is controlled through the use of On-Load Tap Changing transformers (OLTCs) or voltage regulators at substations and along feeder lines. Another common means of voltage control is through the use of shunt capacitors.

2.2. Voltage control using On-Load Tap Changing Transformers

The source of power in a distribution network is usually a substation, which may have OLTCs to supply the distribution network. Most distribution transformers are equipped with a tap changer for regulation of the secondary side voltage. An OLTC is capable of changing the number of active turns on one winding of each phase, and thereby adjusting the transformer ratio [45]. Varying the tap settings on the OLTC is a means by which voltage profile in the network can be controlled. Voltage drops along a power line may cause buses far from the power sources to have lower voltage levels. In this case, OLTC tap setting may be raised to boost voltage.

2.3. Voltage control using capacitors

Shunt capacitors are added to distribution networks to boost voltage levels. These capacitors supply reactive power that counteracts the effects of inductive loads [46]. A transmission line in a distribution network has the following voltage drop.
where $I_R$ is the real component of current, $I_X$ is the reactive component of current, and $R$ and $X_L$ are line resistance and inductive reactance, respectively.

A capacitor located at the load end of a transmission line has the effect of changing the voltage drop on the line as follows.

$$ V_D = I_R R + j I_X X_L $$

(1)

where $I_c$ is the current due to shunt capacitor.

Therefore, comparing equations (1) and (2), we find that the effect of the shunt capacitor is to create a voltage rise at the load end. This voltage rise is given by

$$ V_R = I_c X_L $$

(3)

In this way, the addition of shunt capacitors can boost the voltage levels in a distribution network. By controlling the magnitude of reactive power injected by such capacitors, it is possible to optimise the voltage profile.

**2.4. Voltage Rise Due to Distributed Generation**

When generators operate at leading power factor they inject reactive power into the network. This leads to voltage rise at the connected bus [31], [47]. Consider the simple two-bus network shown below.

![Figure 1: Simplified two-bus network with DG](image)
This figure shows a generator, DG, supplying a local load and supported by a local reactive power compensator [28]. $V_{DG}$ is DG bus voltage, $V_i$ is the voltage at bus “i”, $P_{DG}$ and $Q_{DG}$ represent real and reactive generated power, respectively, $P_R$ and $Q_R$ represent injected real and reactive power, respectively, $P_L$ and $Q_L$ represent real and reactive load power, respectively, $S_R$ represents apparent injected power, $R$ and $X$ represent resistance and reactance of the transmission line, respectively. $I_R$ represents injected current, flowing through line impedance $Z=R+jX$.

The total injected power can be represented as follows

\[ S_R = P_R + jQ_R \quad (4) \]
\[ S_R = P_{DG} + jQ_{DG} + jQ_C - (P_L + jQ_L) \quad (5) \]
\[ S_R = P_{DG} + P_L + j(Q_{DG} + Q_C - Q_L) \quad (6) \]

Also,

\[ S_R = V_{DG}I^*_R \quad (7) \]
\[ S_R^* = V_{DG}^*I_R \quad (8) \]
\[ I_R = S_R^*/V_{DG}^* \quad (9) \]

Substituting equation (1) above into (6),

\[ I_R = (P_R - jQ_R)/V_{DG}^* \quad (10) \]

Now

\[ V_{DG} = V_i + I_RZ \quad (11) \]

Substituting (7) into (8),

\[ V_{DG} = V_i + (P_R - jQ_R)Z/V_{DG}^* \quad (12) \]
\[ V_{DG} = V_i + (P_R - jQ_R)(R + jX)/V_{DG}^* \quad (13) \]
\[ V_{DG} = V_i + \frac{RP_R + XQ_R}{V_{DG}^*} + j \frac{XP_R - RQ_R}{V_{DG}^*} \quad (14) \]

The phase angle $\delta$ between $V_{DG}$ and $V_S$ in a distribution network is small. This means that $\sin \delta$ is also small and negligible. Thus the imaginary part of equation (11) above is negligible as well.
\[ V_{DG} \cong V_i + \frac{R P_R + X Q_R}{V_{DG}^*} \]  
(15)

Assuming reactive power from the compensator is such that \( Q_R = Q_{DG} - Q_L + Q_C = 0 \), then \( V_{DG} \) can be expressed as

\[ V_{DG} \cong V_i + \frac{R P_R}{V_{DG}^*} = V_i + \frac{(P_{DG} - P_L)R}{V_{DG}^*} \]  
(16)

This shows that if load \( P_L \) remains constant, voltage \( V_{DG} \) will increase with increase in generated real power \( P_{DG} \). In other words, increased DG penetration without reactive power compensation leads to voltage rise. This equation also shows that when load \( P_L \) is at its minimum, the voltage rise due to DG is at maximum.

The voltage rise caused by DG has in the past meant that level of DG penetration within a given network is limited. The usual approach taken by distribution system operators is to limit DG rating to the point where voltage rise does not exceed a specified level. This limit is taken when load is at a minimum, and power output from distributed generation is at maximum.
3.1. Introduction

The voltage controller uses a PSO algorithm to optimise the network variables indicated in order to maintain optimal voltage profile across the network.

3.1. Meta-Heuristic Optimisation Methods

Power system optimisation problems have multiple dimensions because of their numerous variables and constraints. This type of problem is best solved by meta-heuristic methods [13]. These techniques take into consideration all the equality and inequality constraints [48], [49], and [50]. The improvement in system performance is based on reduction in cost of power generation and active power loss.

3.1.1. Genetic Algorithm

GA is an optimisation method that models evolutionary adaptation found in nature. The genetic algorithm makes use of a population of solutions. These solutions are in the form of binary numbers. The binary numbers are transformed by three genetic operators. These operators form new generations of the population. Selection or reproduction is the process by which a set of binary numbers are selected to reproduce a set of new strings in a random manner. Crossover is then carried out. This is a process of randomly interchanging digits within a binary number. Mutation is the random changing of the value of digits in a binary number. The suitability of solutions is determined by a fitness function, which is a mathematical representation of the objective.
In [48], the binary numbers that form a population are the degree to which reactive power is added to a bus. Genetic algorithm is used for optimal placement of DG in [3]. The objective is loss reduction and voltage profile improvement. In large networks, GA reduces computation time in the optimisation problem. The algorithm is implemented using MATLAB.

GA is resistant to getting trapped in local optima. In addition, it is versatile and can be used in a wide variety of optimisation problems.

### 3.1.2. Artificial Neural Networks

ANNs are used where there is a need to perform repetitive calculations with low computational time or even in real time. When used in power systems, ANN can be used where real time operations are taking place, such as in network management systems.

These are used in [11] in conjunction with PSO to predict the VAR requirements of the distribution network, and dispatch reactive power from DGs accordingly. The PSO is first used to generate a database of values of variables. These variables produce optimal solutions to the objective function given various load conditions. In this case, the inputs are load conditions in a distribution network. The variables are OLTC tap settings and DG reactive power generation levels. The database generated by repeated PSO optimisations is used to train the ANN. The ANN can then produce suitable outputs when given previously unknown inputs. The ANN is used to manage the reactive power supply in the network by predicting load requirements and controlling the OLTC and DGs accordingly.

ANN is used to emulate microgrids in [13]. The problem involves managing voltage support in an MV/LV distribution network. The MV network connects several LV microgrids. The optimisation of voltage support in the MV network relies on the results of microgrid control, loading and generation from DGs. Instead of running a full optimisation algorithm for each power flow iteration of the MV network, an ANN is used to emulate the behaviour of the LV
microgrids. Load flows are carried out for the microgrid using various values of load and voltage and DG generation. These load flows form a training set and test set of data, which are used to train the ANN.

### 3.1.3. Particle swarm optimization

Power system optimization problems have multiple dimensions because of their numerous variables and constraints. This type of problem is best solved by meta-heuristic methods [13]. These techniques take into consideration all the equality and inequality constraints [48], [49], and [50]. The improvement in system performance is based on reduction in cost of power generation and active power loss.

Particle swarm optimization (PSO) was introduced as an alternative to Genetic Algorithms. This method is inspired by the social behaviour of bird flocks and fish schools. The PSO technique consists of a population refining its knowledge of the given search space. Possible solutions are modelled as particles. The total number of particles is defined as the swarm [51]. The dimensions of the search space are determined by the number of decision variables and the particle population. The coordinates of each particle represent a possible solution. Each particle moves with adaptable velocity through the search space. The velocity of a particle depends on the particle’s historical best position, the best position of other particles in the swarm, and a pre-determined fitness function. This means that the values of the decision variables represented by a particle change during each iteration. Each particle retains a memory of the best position it has encountered. The best position encountered by all of the particles is also remembered. This is known as the global best position.

To implement a PSO solution, a swarm of particles representing possible solutions is first initialized. Initialization may be random. The particles are distributed randomly through the search space in this case. Alternatively,
particles may be evenly distributed across the search space during initialization.

The position of the particles changes from one iteration to the next, determined by the following variables. The position of a particle, \( X_i(t) \), is a vector of the value of decision variables in a particle during iteration ‘i’. The best previous position of particle ‘i’ is given by \( P_i \). This variable represents the level of attraction of the particle towards its best solution so far. The best previous position of all particles (global best) is denoted by \( P_{gb} \). This represents the attraction of the particle towards the best solution found by other particles in the swarm. The velocity of a particle during iteration ‘t’ is given by \( V_i(t) \). This represents the rate at which the particle moves in a particular direction. This is a vector whose members are determined by evaluating a velocity update equation. For a general PSO, the vector update equation is given by

\[
V_{i}^{t+1} = wV_{i}^{t} + C_1 \times r_1 \times (P_i - X_{i}^{t}) + C_2 \times r_2 \times (P_{gb} - X_{i}^{t})
\]  

(17)

where \( C_1 \) and \( C_2 \) are acceleration coefficients and \( r_1 \) and \( r_2 \) are random numbers introduced to add stochasticity to the model. \( w \) represents an inertia coefficient. Once the velocity is determined, the position vector is updated using the following equation.

\[
X_{i}^{t+1} = X_{i}^{t} + V_{i}^{t+1}
\]  

(18)

Optimisation problems vary widely in their nature. To improve the implementation of PSO, and adapt the method to suit a particular problem, various adjustments to the algorithm can be made. The particle is influenced by all particles in the swarm, the best solution of all particles is included in the velocity update equation. This is known as \( g_{best} \).

The acceleration coefficients indicated above control the rate at which particles move towards the local, personal or global best. To prevent divergence of the swarm, constriction factors or inertia constants are added to the velocity update equation. During initial search (exploratory phase), the particles are allowed to move freely across the search space, at a higher velocity. As the particles
converge towards the optimal solution (exploitation phase), their velocity is reduced in order to more accurately find a solution without oscillating around the solution.

3.2. Optimisation Method

Voltage regulation devices used in power systems, such as OLTCs and shunt capacitors, are non-linear. Tap changing transformers change voltage at the secondary terminal in discrete steps. This is also the case with shunt capacitors, which are switched on or off as required. Mathematical models of such systems are therefore non-linear. Non-linear systems are not easily optimised by analytical methods. Dynamic programming may be used to solve non-linear optimization problems. However in systems with many parameters, dimensionality becomes an issue. The number of parameters means that dynamic programming methods have long computation times. Thus heuristic search methods are used to solve problems in power systems [52].

The most commonly used heuristic search methods in power systems-related research are PSO and GA. The main disadvantage of GA is that it requires a well-defined fitness function in order to produce optimal results. If the fitness function is not adequate, the GA may converge at a local optimum, giving a wrong solution. PSO is easier to implement than GA because there are fewer parameters to adjust in the model. Additionally, each particle retains a memory of previous best solutions. This memory tends to direct the solution of the problem towards convergence on an optimal solution. Also, in GA, poor solutions are discarded and the population evolves around the best individuals. In PSO the swarm tends to maintain its diversity since all particles remain in the swarm.

PSO has been applied in literature to solve reactive power and voltage control, economic dispatch, power system reliability and security, state estimation in distribution systems [53] and to improve load flow and optimal load flow [54].
A comparison of optimisation methods is found in [55]. The authors compare Genetic Algorithm, differential evolution, Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and tabu search. They conclude that PSO provides the most accurate and efficient means of solving the operation of distribution systems.

It is seen from the literature that PSO offers the most precise solution to the problem when tested on distribution networks with DG. PSO will therefore be used to solve the optimisation problem.

### 3.3. Voltage Controller Design

The objective of the controller is to optimise the voltage profile of a given distribution network subject to load flow and power capacity constraints. This is represented by the mathematical model described below.

The objective function minimises the deviation of voltage at all load buses from the ideal of 1 per unit.

\[
\min f = \sum_{i \in N_L} |V_i - 1.0|
\]  

where \( f \) is the objective function, \( V_i \) is the voltage at bus ‘i’, and \( N_L \) is the number of load buses.

The load flow equations form equality constraints, as follows.

\[
P_{G_i} - P_{D_i} = V_i \sum_{j=1}^{NB} V_j [G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)]
\]  

\[
Q_{G_i} - Q_{D_i} = -V_i \sum_{j=1}^{NB} V_j [G_{ij} \sin(\delta_i - \delta_j) - B_{ij} \cos(\delta_i - \delta_j)]
\]  

\( P_{G_i} \) and \( Q_{G_i} \) are the active and reactive power, respectively, generated at bus ‘i’. \( P_{D_i} \) and \( Q_{D_i} \) are the real and reactive power load, respectively, at bus ‘i’. \( G_{ij} \) is the conductance of the transmission line connecting bus ‘i’ and ‘j’, and \( B_{ij} \) is
the susceptance of the transmission line connecting bus ‘i’ and ‘j’. \( \delta_i \) is the power angle at bus ‘i’.

The DG is limited in its power generation capacity and voltage at its terminals. These are represented by the following inequality constraints.

\[
\begin{align*}
P_{Gi}^{\text{min}} & \leq P_{Gi} \leq P_{Gi}^{\text{max}} \\
Q_{Gi}^{\text{min}} & \leq Q_{Gi} \leq Q_{Gi}^{\text{max}} \\
V_{Gi}^{\text{min}} & \leq V_{Gi} \leq V_{Gi}^{\text{max}}
\end{align*}
\]

OLTC tap settings are limited between maximum and minimum.

\[
T_{i}^{\text{min}} \leq T_i \leq T_{i}^{\text{max}}
\]

Ti is the tap setting of transformer ‘i’.

The reactive power injected by support devices is limited by their capacity.

\[
Q_{ci} \leq Q_{ci}^{\text{max}}
\]

Q_{ci} is the reactive power injected by reactive device ‘i’.
3.4. Controller

Figure 2: Controller Flowchart
All parameters, constraints and limits listed in the previous section are used to create a mathematical model of the controller described. The controller is implemented as a MATLAB program. A flowchart of the controller algorithm is displayed above. A more detailed flow diagram is presented in the Appendices. The controller program consists of three main blocks. These are the “start” program, the particle swarm optimiser and the load flow.

3.4.1. **Controller Pseudocode**

1. Input test network data:
   - Network layout,
   - location and specified values of generators,
   - P and Q values of loads,
   - location and specified values transformers,
   - location and specified values shunt capacitors,
   - line impedances.
2. Load PSO optimisation parameters:
   - number of variables,
   - population size,
   - maximum iterations,
   - acceleration constants,
   - inertia weights,
   - stopping criteria,
   - variable limits,
   - maximum velocity
3. Generate seed values for PSO and initialize gbest and pbest.
4. Create first iteration of particles
5. Generate initial random positions of particles
6. Create a memory store of the gbest and pbests
7. Pass position of the particles to the load flow program.
8. Replace network-specified variables with corresponding PSO-generated variables.
9. Create y-bus from line impedance data
10. Calculate P and Q at each bus using (20) and (21).
11. Using the Newton Raphson method for meshed networks or Backward-forward sweep for radial networks, obtain the load flow solution for the network with the PSO-generated variables.
12. Evaluate the objective function (19) for each particle.
13. The value of the objective function for each particle is returned to the PSO module.
14. Compare the values evaluated by the objective function for each particle with \( p_{\text{best}} \). If the value for any particle is better than its \( p_{\text{best}} \), update the value of the \( p_{\text{best}} \) to current value.
15. The position of the particle at its \( p_{\text{best}} \) is stored.
16. Compare the values evaluated by the objective function for each particle with \( g_{\text{best}} \). If the value for any particle is better than \( g_{\text{best}} \), update the value of the \( g_{\text{best}} \) to that value.
17. The position of the particle with the \( g_{\text{best}} \) is stored.
18. Update the velocity of all particles using (17).
19. The new velocity is used to update the positions of the particles, using (18).
20. Update the inertia weight. The weight varies in order to bias the particle’s movement towards exploration in the initial stage of the search. In the final part of search, inertia weight is such that the particle is in exploitation mode.
21. Check stopping criteria:
22. If the number of iterations has exceeded the maximum
23. If a maximum number of iterations has been reached without a change in the \( g_{\text{best}} \).
24. If stopping criteria have not been met, go to step 7. Otherwise, output the voltage profile for \( g_{\text{best}} \).
3.4.2. Controller Starter

Firstly, the “start” subroutine initiates the controller. This subroutine is used to details of the test network are specified at this stage. These include network topology, line impedances and bus types. The controller operates by varying the tap settings of OLTCs, the voltage at P-V buses and the reactive power injected at P-V buses. P-V buses are defined as those buses at which generators or reactive power sources are connected. Thus the variables that the PSO will adjust are the tap settings of OLTCs, the voltage at P-V buses and the reactive power injected at P-V buses.
The start subroutine identifies positions of the P-V buses. It also identifies the lines on which OLTCs are placed. In order to initialize the variables, the nominal voltages, reactive powers and tap settings are loaded by the start subroutine.

Once the variables have been identified, the dimensions of the problem are identified. The PSO uses as its inputs the following matrix.

Figure 3: Controller Flowchart (A)
matrix size = n \times D \quad (27)

‘D’ is the total number of variables identified above (tap settings, voltages and reactive powers). ‘n’ is the number of particles that move through the search space. Each particle is a vector of dimension 1 x D. That is, each particle has values for each variable.

The start subroutine also defines the search space. In computational terms, this means setting the limits within which the variables can be adjusted.

In order to simulate the operation of the controller, the inequality constraints are given the following per-unit values.

\[ 0.9 \leq P_{Gi} \leq 1.1 \quad (28) \]
\[ Q_{Gi}^{\text{min(specified)}} \leq Q_{Gi} \leq Q_{Gi}^{\text{max(specified)}} \quad (29) \]
\[ 0.9 \leq V_{Gi} \leq 1.1 \quad (30) \]
\[ 0.9 \leq T_i \leq 1.1 \quad (31) \]

where \( Q_{Gi}^{\text{min(specified)}} \) and \( Q_{Gi}^{\text{max(specified)}} \) represent the lower and upper limits of reactive power generation of respective condensers as given in network data.

Once all the parameters and variables have been defined and initialized by the start subroutine, the subroutine passes them to the PSO function

### 3.4.3. PSO Module

The second block of the controller is the PSO function. The PSO is the core of the controller, evaluating the optimal settings for the various network variables. It is the PSO that provides the optimal solution to the problem of optimal voltage profile.

The PSO establishes initial values for \( g_{\text{best}} \) and \( p_{\text{best}} \). The optimisation is seeded with the nominal values provided in the network data. That is, the voltages, reactive powers and tap settings provided in the test network base case are assigned to the values of the positions of all the particles during initialization.
The implementation of the controller in MATLAB is a customised version of a particle swarm optimiser [56]. The PSO program accepts inputs from the start subroutine in the form of an n x d matrix, as described above.

3.4.3.1. PSO Parameters

PSO requires a number of parameters to be selected before optimisation. Some parameters are well established from previous research, while others are tailored to the problem at hand. The parameters used during the testing of the voltage controller in this research are listed below.
3.4.3.1.1. Particle Parameters

The characteristics of particles must also be clearly defined. The number of particles in the swarm is called the population size. It is designated ‘n’. In this
controller, the population size is 35. This population size is large enough that it provides a sufficient number of particles to quickly cover the search space. It is also small enough that computation is not slowed down by requiring a large amount of memory.

Each particle represents a vector of variables. The voltage of each P-V bus is listed followed by the tap setting of each OLTC in the network. The size of this vector is designated ‘\( D \)’. The value of \( D \) depends on the number of generators and OLTCs in the test network. It therefore is not a constant parameter and varies from network to network.

### 3.4.3.1.2. Search Space Parameters

The scope of the optimisation problem must be clearly defined. The power flow problem has limits of acceptable values. This is an advantage when performing optimisation, because the search space can be narrowed down. In this controller, the variables represented in each particle are limited as in equations (26) and (27).

Another advantage of power flow problems is that we know the ideal value is usually a good estimate of the optimal value. Therefore the initial particle values can be defined. For voltages, a value of unity is used as the starting point. For OLTC tap-settings, a value of 1 is used. These values represent the optimal value to which we strive. The ideal voltage is unity p.u. Similarly, we strive to keep OLTCs at the home tapping, represented by 1.

### 3.4.3.1.3. Termination Parameters

The PSO will search for an optimal solution iteratively. After the initial exploration phase, the PSO will carry out exploitation within a localised search space. The aim of this is to find the optimum within a local area. The PSO will continue searching for this optimum indefinitely unless termination parameters are specified. Thus termination parameters are set which define the point at which the PSO will stop the search and give final outputs.
The PSO may end its search if a pre-defined number of iterations has been carried out. This parameter is the maximum iterations, designated ‘\( mi \)’. In this controller, \( mi \) is 3000. During the course of this research, it was found that convergence of the PSO generally occurs within 3000 iterations. If more iterations are required, then other parameters need to be adjusted to obtain a faster convergence of the optimisation.

The PSO may also stop its search if it carries out a certain number of iterations without any change to the optimal solution more than a specified minimum. The minimum change is defined as minimum global error gradient, designated ‘\( ergrd \)’ In this controller, the minimum error gradient is taken as \( 10^{-10} \). This value allows the controller to run for a sufficiently long time that the search space is extensively covered. The limit of iterations without a change above the minimum error gradient is designated ‘\( ergrdep \)’. In this controller, \( ergrdep \) is 250. That is, without an error gradient above the minimum, the PSO will count 250 iterations before stopping.

### 3.4.3.1.4. Inertia Constants

The initial phase of the PSO is its exploration phase. During this phase, the particles move randomly through the search space. As the iterations continue, the \( g_{\text{best}} \) and \( p_{\text{best}} \) values begin to converge around certain areas of the search space. The PSO then enters the exploitation phase, during which the search is narrowed. In order to enable the transition between these phases as time goes by, inertia weight constants are used.

The inertia at the start of the optimisation process is designated ‘\( iw1 \)’. In this controller, it is given a value of 0.9. The final inertia is designated ‘\( iw2 \)’. Its value in this controller is 0.4. These two values were selected from [57]. The iteration at which the inertia should have reached its final value is designated ‘\( iwe \)’. Its value here is 1500. This means that the exploration phase is limited to the first 1500 iterations.

The process of changing the inertia value is defined in the equation below.
\[ iwt(i) = \frac{i - 1}{iwe - 1} \times (iw2 - iw1) + iw1 \]  

(32)

where \( i \) is the current iteration and \( iwt(i) \) is the value of the inertia constant at iteration \( i \). As the value of \( i \) tends towards \( iwe \), the first term in equation (28) tends to unity. \( iwt(i) \) then tends to \( iw2 \).

3.4.3.1.5. Acceleration Constants

The PSO changes the velocity of the particle while taking into consideration the \( g_{\text{best}} \) and \( p_{\text{best}} \) values. As shown in equation (17), the constants increase the velocity of the particle if the value of \( P_l - X_l^f \) is high. This has the effect of slowing the velocity as the particle approaches its \( g_{\text{best}} \) and \( p_{\text{best}} \) values. The acceleration constant associated with \( p_{\text{best}} \) is designated ‘\( ac1 \)’ and that associated with \( g_{\text{best}} \) is designated ‘\( ac2 \)’. Initially, the value of 2.0 was used, based on [57]. However, by means of trial and error during initial testing of the controller algorithm, \( ac1 \) value of 0.1 and \( ac2 \) value of 0.1 were found to give a faster convergence rate.

3.4.3.1.6. Inertia Weight Update

The inertia weight constant decreases linearly from 0.9 to 0.4 [57]. The acceleration constants are both set at 0.1. The latter constant was arrived at after running a number of simulations with different values.

3.4.3.2. PSO Search

The vector update equation is given by (17), where \( X_l^f \) represents the matrix of values of the network variables. These are generator P and Q values, OLTC tap settings and shunt capacitor Q value. The objective function is evaluated using the load flow methods described in section 3.4.4 below.

3.4.4. Load Flow

Meshed networks and radial networks are optimised using different load flow methods. The respective methods are suited for the characteristics of each network topology.
Meshed networks have nodes that are densely interconnected. This means that they produce a large number of simultaneous equations that need to be solved. This type of system is solved with traditional power system load flow methods such as Gauss-Siedel or Newton-Raphson.

Radial networks have nodes with very little interconnection. Most nodes connect to only 2 other nodes. This leads to a sparse set of equations. These are solved with specialised methods such as the ladder method and backward / forward sweep methods.

3.4.4.1. Newton-Raphson Load Flow

In order to optimise the voltage profile, the PSO must evaluate the objective function. This function is a mathematical representation of the voltage profile of the test network. The objective function is the summation of all the per-unit voltage levels of all buses in the test network. To obtain these voltage levels, the third block of the controller, Load Flow, is used.
The third block of the controller is a Newton-Raphson load flow. It is implemented using a modified version of a program written in MATLAB [57]. The Newton-Raphson load flow takes the input of each particle position in turn. These inputs come from the PSO. Using the inputs, the load flow of the network is carried out. This calculates the voltages at each network bus as well as real and reactive power flow across the network. The voltages obtained from
the Newton-Raphson load flow are then evaluated for their fitness. The objective function given by equation (16) above is used to evaluate the fitness of the PSO-generated values for each particle.

The value of the objective function after carrying out the Newton Raphson load flow is compared to previous values for the particle, as well as all previous values for all particles. In this way, the PSO obtains $p_{best}$ and $g_{best}$ respectively.

The PSO generates positions and velocities for each particle in the population. The particles continue moving through the search space, using the Newton-Raphson load flow and objective function to evaluate the suitability of each position in the search space. After thousands of generations, the PSO will converge towards an optimal position.

The optimal position represents the best voltage profile of the network that can be achieved within the constraints given. The values of the variable quantities (power, voltage and tap settings) that produce this optimal position are therefore the solution to the problem.

3.4.4.2. Modified Backward / Forward Sweep Load Flow

In the case of radial networks, the third block of the controller is a backward/forward sweep load flow. This is because the Newton-Raphson method is inefficient in analysis of radial networks. This is because radial network data produces sparse matrices, which are time-consuming to process. Accordingly, there are a number of reported studies in the literature specially designed for solution of power flow problem in radial distribution networks.

The backward / forward Sweep algorithms use the Kirchhoff laws. Different formulations can be found in literature. Using these methods, power flow solution for a distribution network can be obtained without solving any set of simultaneous equations.

The backward forward sweep method used in this research is based on Alsaadi, and Gholami (2009) [58]. The special topological characteristics of distribution
networks have been fully utilized to make the direct solution possible. Two matrices are used to obtain power flow solutions. These are the bus-injection to branch-current (BIBC) matrix and the branch-current to bus-voltage (BCBV) matrix.

The BIBC presents the relationships between branch currents flowing through the radial network and node currents injected at each bus.

![Sample Radial Network](image)

In the figure above, the branch currents are denoted by the symbol ‘B’ and injected currents by symbol ‘I’. Taking current $B_5$,

$$B_4 = I_5$$  

(33)

Also,

$$B_3 = I_4 + B_4$$  

(34)

Substituting (36) into (37),

$$B_3 = I_4 + I_5$$  

(35)

Similarly,

$$B_2 = I_3 + I_4 + I_5 + I_6$$  

(36)

By taking all the equations for branch currents simultaneously, we form the matrix equation,
\[
\begin{bmatrix}
B_1 \\
B_2 \\
B_3 \\
B_4 \\
B_5
\end{bmatrix} =
\begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
0 & 1 & 1 & 1 & 1 \\
0 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
I_4 \\
I_5
\end{bmatrix}
\]  
(37)

This is generalized to,

\[
[B] = [BIBC][I]
\]  
(38)

Similarly, the BCBV is formulated as the relationship between branch currents and node voltages. Taking the same radial network illustrated above, the voltage at bus 4 can be represented as,

\[
V_4 = V_3 - B_3 Z_{34}
\]  
(39)

Where \(Z_{34}\) is the impedance of the branch between buses 3 and 4.

By using a process similar to that used to form the BIBC, we get the BCBV of the illustrated network as follows.

\[
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
V_4 \\
V_5
\end{bmatrix} -
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
V_4 \\
V_5
\end{bmatrix} =
\begin{bmatrix}
Z_{12} & 0 & 0 & 0 & 0 \\
Z_{12} & Z_{23} & 0 & 0 & 0 \\
Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\
Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\
Z_{12} & Z_{23} & 0 & 0 & Z_{56}
\end{bmatrix}
\begin{bmatrix}
B_1 \\
B_2 \\
B_3 \\
B_4 \\
B_5
\end{bmatrix}
\]  
(40)

This is generalized to,

\[
[\Delta V] = [BCBV][B]
\]  
(41)

Substituting (41) into (44), we get the relationship between bus voltages and bus injection currents as,

\[
[\Delta V] = [BCBV][BIBC][I]
\]  
(42)

The injected current at a bus ‘\(i\)’ is given by

\[
I_t = \frac{(R_i - jQ_i)^*}{V_i}
\]  
(43)
In order to incorporate DGs into the radial load flow, they are considered as current sources. In a bus with a DG, the injected power is given as follows.

\[ S_i = S_{Di} - S_{Gi} \]  

(44)

Where \( S_i \) is injected power at bus \( 'i' \), and \( S_{Di} \) and \( S_{Gi} \) represent load power and generator power at bus \( 'i' \), respectively. Thus, injected current at a bus with DG is given by

\[ I_i = \frac{[(P_{Di} - P_{Gi}) - j(Q_{Di} - Q_{Gi})]^*}{V_i} \]  

(45)

The radial network loadflow can be carried out by solving the following equations iteratively.

\[
\begin{bmatrix}
\Delta V^{k+1}
\end{bmatrix} = \begin{bmatrix} BCBV \end{bmatrix} \begin{bmatrix} BIBC \end{bmatrix} \begin{bmatrix} I^k \end{bmatrix}  
\]  

(46)

\[
\begin{bmatrix}
V^{k+1}
\end{bmatrix} = \begin{bmatrix} V^0 \end{bmatrix} - \begin{bmatrix} \Delta V^{k+1} \end{bmatrix}  
\]  

(47)
CHAPTER 4
VOLTAGE CONTROL IN MESHED NETWORKS

4.1. Test Case 1: IEEE 30-Bus Network

The proposed controller was tested on the IEEE 30 bus network. Generator, load and line data for this network are given in [59]. The topology of the network is illustrated in [60].

The IEEE 30-bus system has 2 generators, 4 shunt capacitors, 21 loads, and 41 branches. Bus 1 is taken as the point of common coupling (substation) and bus 2 is the location of the DG. The shunt capacitors are located at buses 5, 8, 11, and 13. This network is used extensively in literature for testing and simulation purposes.
The 30-bus network has been used to demonstrate several optimal power flow solutions. In [61], a single-objective optimal power flow solution is presented, in which PSO is used to minimize reactive power transmission losses. Volt / var control is the objective in [62], and several system variables are controlled. The voltage profile is improved through the use of PSO. In [54], [63], and [64] the system is used as a test case for PSO-based optimal power flow solutions. The voltage profile of the 30-bus system is optimized in [65], in addition to a main objective of fuel cost optimisation.

Apart from optimal power flow, the IEEE 30-bus network has been used as a test case for optimal load dispatch in [66]. It has also been used to test reactive power dispatch algorithms in [67], [68], [69] and [70]. In addition to this the 30-bus network has been used to test optimal DG location methods. Examples of this include [15], [16], [17] and [18].

The voltage profile of the 30-bus network is optimised in [17], [61], [62], [64], and [70] as described above. The controller designed in this research is compared to the methods used in these works. This is done by analysing the results of simulation of the controller and comparing them to the data obtained from the listed works.

4.1.1. Test Case 1a: Voltage Control with DG

The controller was applied to the test network to regulate the voltage in the presence of DG. In this network, there is one DG at Bus 2. The voltage profiles as defined by the objective function are given below.

Table 1: Test Case 1a

<table>
<thead>
<tr>
<th>Voltage profile</th>
<th>Base case without controller</th>
<th>Optimised case with this method</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.3825</td>
<td>2.0519</td>
</tr>
</tbody>
</table>

These voltage profiles for the networks are illustrated below.
**Figure 8: Test Case 1a**

### 4.1.2. Test Case 1b: Voltage Control with Shunt Capacitors

In this test case, the controller was applied to the test network to regulate the voltage in the presence of shunt capacitors. In this network, there are 4 shunt capacitors. The voltage profiles as defined by the objective function are given below.

**Table 2: Test Case 1b**

<table>
<thead>
<tr>
<th>Voltage profile</th>
<th>Base case without controller</th>
<th>Optimised case with this method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>0.4327</td>
<td>0.3059</td>
</tr>
</tbody>
</table>

These voltage profiles for the networks are illustrated below.
4.1.3. Test Case 1c: Voltage Control with DG and Shunt Capacitors

In this test case, the controller was applied to the test network to regulate the voltage in the presence of DG and shunt capacitors. The voltage profiles as defined by the objective function are given below.

<table>
<thead>
<tr>
<th>Voltage profile</th>
<th>Base case without controller</th>
<th>Optimised case with this method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>0.5215</td>
<td>0.2617</td>
</tr>
</tbody>
</table>

These voltage profiles for the networks are illustrated below.
It is observed that the Controller produces the best voltage profile when applied with both DG and shunt capacitors. The controller maximises the use of network equipment to regulate voltage.

### 4.2. Test Case 2: IEEE 14-Bus Network

The proposed controller was also tested on the IEEE 14-bus network. The IEEE 14-bus network comprises five P-V buses. There are two generator buses and three buses injecting reactive power. The latter three buses are shunt capacitors, located on buses 3, 6 and 8. Bus 1 is the substation, and Bus 2 is where the DG is located. The bulk of the load buses are concentrated in one region of the network.

The network is shown below:
The 14-bus network is used to study optimal reactive power dispatch in [71], [72], [73] and [74]. It is also used to investigate under-voltage load shedding in [75]. Optimal electricity market settlements are investigated with this network as a case study in [76]. The network is used to optimise voltage profile in [77].

4.2.1. Test Case 2a: Voltage Control with DG

Similarly to test case 1, in this test case, the controller was applied to the test network to regulate the voltage in the presence of DG only. The voltage profiles as defined by the objective function are given below.

<table>
<thead>
<tr>
<th>Table 4: Test Case 2a</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Base case without controller</strong></td>
</tr>
<tr>
<td>Voltage profile</td>
</tr>
</tbody>
</table>

These voltage profiles for the networks are illustrated below.
4.2.2. Test Case 2b: Voltage Control with Shunt Capacitors

Similarly to test case 1, in this test case, the controller was applied to the test network to regulate the voltage in the presence of DG only. The voltage profiles as defined by the objective function are given below.

Table 5: Test Case 2b

<table>
<thead>
<tr>
<th>Voltage profile</th>
<th>Base case without controller</th>
<th>Optimised case with this method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>0.3553</td>
<td>0.2077</td>
</tr>
</tbody>
</table>

These voltage profiles for the networks are illustrated below.
4.2.3. Test Case 2c: Voltage Control with DG and Shunt Capacitors

Similarly to test case 1, in this test case, the controller was applied to the test network to regulate the voltage in the presence of DG only. The voltage profiles as defined by the objective function are given below.

Table 6: Test Case 2c

<table>
<thead>
<tr>
<th>Voltage profile</th>
<th>Base case without controller</th>
<th>Optimised case with this method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>0.5662</td>
<td>0.1633</td>
</tr>
</tbody>
</table>

These voltage profiles for the networks are illustrated below.
4.3. Simulation Results

The best simulation results obtained are as listed below.

Table 7: Simulation Results for Mesh Networks

<table>
<thead>
<tr>
<th>TEST NETWORK</th>
<th>BASE CASE</th>
<th>USING THIS METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DG ONLY</td>
<td>SHUNT CAPS ONLY</td>
</tr>
<tr>
<td>30-BUS</td>
<td>1.3825</td>
<td>0.4237</td>
</tr>
<tr>
<td>14-BUS</td>
<td>0.9543</td>
<td>0.3553</td>
</tr>
</tbody>
</table>

The optimal value is the best value obtained by the controller for the objective function. A comparison with the original values of the network without controller operation is included. As can be seen, the voltage controller gives better optimal results with shunt capacitors included in the network.
Figure above shows the optimal voltage profile attained by the controller with 30-bus network during simulation. For comparison, the voltage profile of the network without a controller (in its original configuration) is shown. The results of Smita, et al. (2012) [61] and Ben Attous, et al. (2009) [65] are also included for comparison.
Figure 16: IEEE 14-Bus Network Voltage Profile

Figure above shows the optimal voltage profile attained by the controller during simulation with the 14-bus network. For comparison, the voltage profile of the network without a controller (in its original configuration) is shown.
The figure above shows the convergence plot of the PSO. Each line represents the progression of optimisation during one run of controller simulation. The plot displays the exploration phase as well as the exploitation phase. The figure shows that during exploration, the PSO quickly converges towards the optimal solution.

4.4. Observations

The proposed controller gives a near-ideal voltage profile. All controllable voltages are within ±0.02 p.u. of unity. The objective function, given by (5), and denoted by $f$, is minimised to an optimal value of 0.2371 for the test network. This is a considerable improvement compared to the value for the network operating without a controller.
CHAPTER 5
VOLTAGE CONTROL IN RADIAL NETWORKS

5.1. Test Case 3: IEEE 33-Bus Network

The proposed controller was tested on the IEEE 33 bus network. Load and line data for this network are given in [78]. The total installed peak loads on the system are 3715 kW and 2290 kVAR. Base voltage is 12.66 kv. The topology of the network is illustrated below.

![IEEE 33-bus Network](image)

Figure 18: IEEE 33-bus Network

The IEEE 33-bus radial distribution system has 32 branches. Bus 1 is taken as the point of common coupling (substation). This network is used extensively in literature for testing and simulation purposes.
5.1.1. Test Case 3a: IEEE 33-Bus Network

A comparison was made with [39]. In this case, there is one DG in the network. The DG is placed on bus 30 and has a real power output of 1470kW and reactive power of 500kVAr. The controller was fed with this information and a simulation was run. The voltage profile of the network with these parameters is shown below.

![Graph showing voltage profile](image)

Figure 19: Test Case 3a

The results of the objective function are given below.

Table 8: Test Case 3a

<table>
<thead>
<tr>
<th>Voltage profile</th>
<th>Base Case</th>
<th>Sharma, Vittal [39]</th>
<th>This Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>1.8406</td>
<td>0.762</td>
<td>0.698</td>
</tr>
</tbody>
</table>

This illustrates that the controller gives a better optimal profile compared to the literature.
5.1.2. Test Case 3b: IEEE 33-Bus Network

A further comparison is made with [39]. In this case, there are three DG in the network. The first DG is placed on bus 15, and has a real power output of 50kW. The second and third DG are placed on bus 25 and 31 respectively, and have real power outputs of 250kW and 750kW, respectively. The voltage profile of the network with these parameters is shown below.

The results of the objective function are given below.

Table 9: Test Case 3b

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Sharma, Vittal [39]</th>
<th>This Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>1.8406</td>
<td>0.708</td>
<td>0.504</td>
</tr>
</tbody>
</table>

This illustrates that the controller gives a better optimal profile compared to the literature.
5.1.3. Test Case 3c: IEEE 33-Bus Network

A further comparison is made with [40]. In this case, there is one DG in the network. The DG is placed on bus 16, and has a real power output of 1350kW as well as reactive power of 654kVAr. The voltage profile of the network with these parameters is shown below.

![Figure 21: Test Case 3c](image)

The results of the simulation are given below.

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Naik, Khatod [40]</th>
<th>This Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>1.8406</td>
<td>0.7027</td>
<td>0.698</td>
</tr>
</tbody>
</table>

This illustrates that the controller gives a better optimal profile compared to the literature [40].
5.1.4. Test Case 3d: IEEE 33-Bus Network

A further comparison is made with [43]. In this case, there are two DG in the network. The DG are placed on bus 16 and 32, and have real power output of 400kW and 200kW, respectively. The voltage profile of the network with these parameters is shown below.

![Voltage profile graph](image)

Figure 22: Test Case 3d

The results of the simulation are given below.

<table>
<thead>
<tr>
<th>Voltage profile</th>
<th>Base Case</th>
<th>Wu, Lu [43]</th>
<th>This Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.8406</td>
<td>1.3834</td>
<td>0.698</td>
</tr>
</tbody>
</table>

This illustrates that the controller gives a better optimal profile compared to the literature.

5.1.5. Test Case 3e: IEEE 33-Bus Network

A further comparison is made with [41]. In this case, there are three DG in the network. The DG are placed on bus 17, 18 and 33, and have real power output
of 719kW, 113kW and 1043kW, respectively. The reactive power outputs of the DG’s are 415kVAr, 65kVAr and 6kVAr, respectively. The voltage profile of the network with these parameters is shown below.

![Voltage profile graph](image)

**Figure 23: Test Case 3e**

The results of the simulation are given below.

**Table 12: Test Case 3e**

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Kumar, Navuri [41]</th>
<th>This Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>1.8406</td>
<td>0.304</td>
<td>0.3021</td>
</tr>
</tbody>
</table>

This illustrates that the controller gives a better optimal profile compared to the literature.

**5.2. Test Case 4: IEEE 69-Bus Network**

The proposed controller was tested on the IEEE 69 bus radial network. Load and line data for this network are given in [41]. The topology of the network is illustrated below.
The IEEE 69-bus radial distribution system has 70 branches and 7 laterals. Bus 1 is taken as the point of common coupling (substation). The test system is a 12.66 kV radial distribution system. The total loads for this test system are 3,801.89 kW and 2,694.10 kVar. This network is used extensively in literature for testing and simulation of radial distribution feeder networks.

5.2.1. Test Case 4a: IEEE 69-Bus Network

A comparison is made with [41]. In this case, there are two DG in the network. The DG are placed on bus 26 and 65, and have real power output of 656kW and 1606kW, respectively. The reactive power outputs of the DG’s are 378kVAR and 927kVAR, respectively. The voltage profile of the network with these parameters is shown below.
The results of the objective function are given below.

### Table 13: Test Case 4a

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Kumar, Navuri [41]</th>
<th>This Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>1.8368</td>
<td>0.3821</td>
<td>0.2473</td>
</tr>
</tbody>
</table>

This illustrates that the controller gives a better optimal profile compared to the literature.

#### 5.2.2. Test Case 4b: IEEE 69-Bus Network

A comparison is made with [42]. In this case, there is one DG in the network. The DG are placed on bus 61, and has real power output of 1870kW and reactive power output of 1159kVAr. The voltage profile of the network with these parameters is shown below.
Figure 26: Test Case 4b

The results of the objective function are given below.

Table 14: Test Case 4b

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>Abu-Moutti, el-Hawary [42]</th>
<th>This Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage profile</td>
<td>1.8368</td>
<td>0.608</td>
<td>0.598</td>
</tr>
</tbody>
</table>

This illustrates that the controller gives a better optimal profile compared to the literature.
5.3. Simulation Results

The results above are summarized in the table below.

Table 15: Simulation results for radial networks

<table>
<thead>
<tr>
<th>Test Case</th>
<th>Reference Article</th>
<th>Optimum Voltage Profile in Reference</th>
<th>Optimum Voltage Profile in This Research</th>
</tr>
</thead>
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<td>0.762</td>
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<tr>
<td>3b</td>
<td>Sharma and Vittal (2010) [39]</td>
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<tr>
<td>3c</td>
<td>Naik, et al. (2012) [40]</td>
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<td>Chenning and Xueqin (2012) [43]</td>
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<td>Kumar and Navuri (2012) [41]</td>
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<td>Kumar and Navuri (2012) [41]</td>
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<td>0.2473</td>
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<td>Abu-Mouti and El-Hawary (2011) [42]</td>
<td>0.608</td>
<td>0.598</td>
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</tbody>
</table>

The figures given represent the results of the objective function of the controller algorithm.

This function is a measure of the extent to which bus voltages – represented by $V_i$ – deviate from unity. The lower the value of ‘$f$’, the better the voltage profile of the network. A lower value is a better result.

5.4. Observations

These results indicate that the controller consistently outperforms existing research in literature when used in radial networks. By adjusting the output of DGs, a better voltage profile can be achieved.
CHAPTER 6
ANALYSIS, DISCUSSION AND CONCLUSIONS

6.1. Formulation

This research work has presented an optimisation-based controller for power networks with distributed generation. The controller was first presented as a mathematical model of the test network. The optimisation problem is formulated to include an objective function that is minimised. Equality constraints were added, in the form of power balance equations. Inequality constraints are the parameters of the controller, which are the independent variables of the model. A PSO-based optimisation algorithm was developed. A Newton-Raphson load flow and modified backward / forward load flow were developed to carry out load flow in meshed and radial networks respectively. The algorithm was implemented in MATLAB and tested on the 4 different IEEE test networks.

6.2. Computer Program

The controller was implemented using MATLAB 2012. A starter module initialised all variables and parameters. These were then passed to the Particle Swarm Optimisation module. The PSO evaluated an objective function by performing a load flow iteratively. For each test network and PSO variation, the program was run to obtain the best result.

6.3. Contributions

In previous literature, researchers have focused on various aspects of the problem of increasing penetration of distributed generation. The aspects of voltage rise, reactive power control and dispatch, and optimal generation have
been addressed. However, few research papers have included network transformers, capacitors and DGs simultaneously.

In carrying out this research, a voltage controller for distribution systems with distributed generation has been designed. The controller in this research has take into account these three equipments found in distribution networks. This research has demonstrated the advantages of combining the three types of equipments together for optimising voltage profile. This has been achieved using software that can be easily adapted to any distribution network. The tools required are also extremely low-cost, comprising entirely of the controller software and the hardware on which it runs.

### 6.4. Beneficiaries of this work

The beneficiaries of this work include all organisations involved in the operations of distribution networks and distributed generation. These include distribution system operators, owners and operators of distributed generation equipment and regulating bodies in the power sector. In addition to this, the voltage controller introduced in this work will ultimately benefit the final consumer of power, be it residential, commercial or industrial. This is because of the benefit of better voltage profile introduced by the voltage controller as described in the research work.

### 6.5. Conclusion

From the results obtained, it is seen that with minimal changes to the network equipment, it is possible to greatly improve the voltage profile. This has been achieved by adjusting the tap settings of transformers and real and reactive power injection of generation equipment. Such an approach could be a cost-effective way of improving voltage profile.
In addition, the controller can be modified to include multiple objectives. These could include marginal cost of generation or power losses in the network.

**6.6. Recommendations for Future Work**

The controller in this research work has been tested on small, theoretical, meshed networks. This was done to demonstrate feasibility. In order to extend this work further, the controller code needs to be modified in order to optimise larger practical networks with thousands of buses. The controller in its current form would take an impractically long time to carry out large-scale optimisations. Therefore, the controller could be adjusted to accept only critical buses as a representation of the entire network.

Further, the controller in this research assumes continuous operation of OLTCs and shunt capacitors. In practical systems, this is not the case. OLTC taps are usually changed in steps. Shunt capacitors are generally installed in banks of several units, which are switched in or out of the network as required. Shunt capacitors and OLTC tap settings could therefore be made into discrete step-settings, similar to the practical implementation of these devices.
REFERENCES


pp. 1-8.


[16] L. G. Meegahapola, S. R. Abbott, D. J. Morrow, T. Littler, and D. Flynn, "Optimal allocation of distributed reactive power resources under network


[53] Shigenori Naka, Takamu Genji, Toshiki Yura, and Yoshikazu Fukuyama, "A Hybrid Particle Swarm Optimization for Distribution State


APPENDICES

A.1. Controller Algorithm

START

INPUT INITIAL PV BUS VOLTAGES, Q AT PV BUSES, & OLTC TAP SETTINGS

START PSO PROGRAM

INITIALIZE G BEST AND PBEST FOR PSO USING MATRIX.

INITIALIZE PSO PROGRAM COUNTER, j=1

GENERATE VECTOR ARRAY OF PARTICLES.

START CONTROLLER PROGRAM

INITIALIZE CONTROLLER PROGRAM COUNTER, i=1

RUN CONTROLLER PROGRAM FOR PARTICLE i

REPLACE ORIGINAL VALUES FOR V, Q AND TAP SETTINGS IN NETWORK DATA WITH VALUES OBTAINED FROM PSO
A

EVALUATE NEWTON-RAPHSON LOAD FLOW FOR MODIFIED NETWORK DATA

B

INCREMENT COUNTER: i = i + 1

C

EVALUATE OBJECTIVE FUNCTION FOR CURRENT PARTICLE

RETURN RESULTS OF OBJECTIVE FUNCTION FOR EACH PARTICLE

FOR EACH PARTICLE, \( P_{\text{best}} > \) CURRENT BEST VALUE?

YES

REPLACE \( P_{\text{best}} \) WITH CURRENT BEST VALUE

NO

EVALUATE CURRENT GLOBAL BEST VALUE FOR THIS PSO ITERATION

ALL PARTICLES EVALUATED?

YES

NO

OBTAIN VOLTAGE LEVELS FOR EACH BUS
C

\( G_{best} \neq \) CURRENT BEST VALUE?

YES

UPDATE PARTICLE INERTIA WEIGHTS

REPLACE \( G_{best} \) WITH CURRENT BEST VALUE

NO

UPDATE PARTICLE VELOCITIES

UPDATE PARTICLE POSITIONS, i.e. VALUES OF V, Q AND TAP SETTINGS

MAXIMUM TOTAL PSO ITERATIONS REACHED?

YES

OUTPUT \( G_{best} \) AND PLOT VOLTAGE PROFILE WITH OPTIMAL SETTINGS

NO

MAXIMUM ITERATIONS WITHOUT CHANGE IN \( G_{best} \) REACHED?

YES

END

NO
## A.2. IEEE 30-bus Network Data

### Table 16: IEEE 30-bus Network Line Data

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<tr>
<th>From Bus</th>
<th>To Bus</th>
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<th>X (pu)</th>
<th>B/2 (pu)</th>
<th>Tap set</th>
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### A.3. IEEE 14-bus Network Data

Table 18: IEEE 14-Bus Network Line Data

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A.4. IEEE 33-bus Network Data

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## A.5. IEEE 69-bus Network Data

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### A.6. Network Results

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A.7. MATLAB Listing

A.7.1. Main Controller Program

% Script to start network controller.
% Input various PSO parameters here
clear;
cle;
clf;

% FIND NUMBER OF VARIABLES
nbus = 30;
bud = busdata0808();
BMva = 100;
bustype = bud(:,2);
V = bud(:,3); % Specified Voltage..
del = bud(:,4); % Voltage Angle..
Qg = bud(:,6)/BMva; % QGi..
Qmax=bud(:,10)/BMva;
Qmin=bud(:,9)/BMva;
lined=linedata0808(nbus);
tap=tappedata0808(nbus);

% Generator voltages and power
qvx = find(bustype == 2); % find PV Buses except slack bus..

% Transformer tap settings
tapset = find(taps ~= 1); % find locations of transformers..
ntapset = length(tapset); % No. of transformers..
VariableCount=nqvx+ntapset;
xval=zeros(2*nqvx+ntapset);
yval=zeros(2*nqvx+ntapset);
for i=1:nqvx % x=specified values of variables
    xval(i)=V(qvx(i));
    yval(i)=qvx(i); % location of PV bus
    xval(i+nqvx)=Qg(qvx(i));
    yval(i+nqvx)=qvx(i); % location of PV bus
end
for i=1:ntapset
    xval(i+nqvx*2)=taps(tapset(i));
    yval(i+nqvx*2)=tapset(i); % the index number of line on which transformers are located
end
ckkdmin=2*nqvx+ntapset; % set number of variables (genes) in a particle (individual)
ckkminmax=ones(ckkdmin,2); % set limits for random particle value
ckkminmax(:,1)=0.9; % set upper value
ckkminmax(:,2)=1.1; % set lower value
for i=1:nqvx % set maximum and minimum values of reactive power injected Qgmax, Qgmin
    ckkminmax(nqvx+i,1)=Qmin(qvx(i)); % set lower value
    ckkminmax(nqvx+i,2)=Qmax(qvx(i)); % set upper value
end
ckkpopsiz=24; % set population size

ckkPSOseed=zeros(ckkpopsiz,ckkdmin); % create nXd matrix of particles
xval(:,1);
for bla=1:ckkpopsiz
    for ble=1:ckkdmin

20
% Parameter 6: parameters required by pso program (see PSO m-file)
ckkparams = [1 3000 ckkpopsiz .1 .1 0.9 1500 1e-10 250 NaN 0 1];

% create a variable that passes the following parameters:
% number of pv buses
% indices of pv buses
% number of transformers
% indices of transformers
powersys = {'nqx qvx' 'tapset tapset'};
simulationruns = 10;
displayckk = zeros(nbus+1,1,simulationruns);
VOLTPROF = zeros(1,nbus);
for repeat = 1:simulationruns
% PSO
% function(minmax, plotfcn, PSOparams, PSOseedValue, powersys)
% -------------
% |--------1--------|--------2--------|--------3--------|--------4--------|--------5--------|--------6--------|--------7--------|
% [VarFinalout, VOLTPROF] = pso0808b('controller0808', ckkdim, 2, ckkminmax, ckkparams, ckkPSOseed, powersys);
% tracediag = VarFinalout(ckkdim+3:end);
% PlotpsoCKK(tracediag, nbus)
displayckk(:, repeat) = [VarFinalout(ckkdim+1); VOLTPROF'];
if repeat == simulationruns
    displayckk
end
diary off;
end

A.7.2. PSO Function

% Based on pso_Trelea_vectorized.m, a program by B. Birge [56]
% Usage:
% [optOUT] = PSO(functname, D)
% or:
% [optOUT, tr, te] = ...
% PSO(functname, D, mv, VarRange, minmax, PSOparams, plotfcn, PSOseedValue)
%
% Inputs:
% functname - string of matlab function to optimize
% D - # of inputs to the function (dimension of problem)
%
% Optional Inputs:
% mv - max particle velocity, either a scalar or a vector of length D
% (this allows each component to have it's own max velocity),
% default = 4, set if not input or input as NaN
%
% VarRange - matrix of ranges for each input variable,
% default = -100 to 100, of form:
% [ min1 max1
%   min2 max2
%   minD maxD ]
%
% minmax = 0, funct minimized (default)
% = 1, funct maximized
% = 2, funct is targeted to P(12) (minimizes distance to errgoal)
%
% PSOparams - PSO parameters
% P(1) - Epochs between updating display, default = 100. if 0,
% no display
% P(2) - Maximum number of iterations (epochs) to train, default = 2000.
% P(3) - population size, default = 24
% P(4) - acceleration const 1 (local best influence), default = 2
% P(5) - acceleration const 2 (global best influence), default = 2
% P(6) - Initial inertia weight, default = 0.9
% P(7) - Final inertia weight, default = 0.4
% P(8) - Epoch when inertia weight at final value, default = 1500
% P(9) - minimum global error gradient,
% if abs(Gbest(i+1)-Gbest(i)) < gradient over
% certain length of epochs, terminate run, default = 1e-25
% P(10) - epochs before error gradient criterion terminates run,
% default = 150, if the SSE does not change over 250 epochs
% then exit
% P(11) - error goal, if NaN then unconstrained min or max, default=NaN
% P(12) - type flag (which kind of PSO to use)
% 0 = Common PSO w/intertia (default)
% P(13) - PSOseed, default=0
% = 0 for initial positions all random
% = 1 for initial particles as user input
% plotfcn - optional name of plotting function, default 'goplotpso',
% make your own and put here
% PSOseedValue - initial particle position, depends on P(13), must be
% set if P(13) is 1 or 2, not used for P(13)=0, needs to
% be nXm where n<=ps, and m<=D
% If n<ps and/or m<D then remaining values are set random
% on Varrange
% Outputs:
% optOUT - optimal inputs and associated min/max output of function, of form:
% [ bestin1
% bestin2
% bestinD
% bestOUT ]
%
function [OUT, OptVoltP]=ps0808b(functname,D,mv,VR,P,PSOseedValue,powersys)
rand('state',sum(100*clock));
me      = P(2);
ps      = P(3);
ac1     = P(4);
ac2     = P(5);
iw1     = P(6);
iw2     = P(7);
iwe     = P(8);
ergrd   = P(9);
ergrdep = P(10);
trelea  = P(12);
PSOseed = P(13);

if ( (PSOseed==1) && ~exist('PSOseedValue') )
    error('PSOseed flag set but no PSOseedValue was input');
end
if exist('PSOseedValue')
    tmpsz=size(PSOseedValue);
    if D < tmpsz(2)
        error('PSOseedValue column size must be D or less');
    end
    if ps < tmpsz(1)
        error('PSOseedValue row length must be # of particles or less');
    end
end
tr = ones(1,me)*NaN;

% take care of setting max velocity and position params here
if length(mv)==1
    velmaskmin = -mv*ones(ps,D); % min vel, psXD matrix
    velmax = mv*ones(ps,D); % max vel
elseif length(mv)==D
    velmaskmin = repmat(forcerow(-mv),ps,1); % min vel
    velmaskmax = repmat(forcerow(mv),ps,1); % max vel
else
    error('Max vel must be either a scalar or same length as prob dimension D');
end

posmaskmin  = repmat(VR(1:D,1)',ps,1);  % min pos, psXD matrix
posmaskmax  = repmat(VR(1:D,2)',ps,1);  % max pos

% PLOTTING
% message = sprintf('PSO: %g/%g iterations, GBest = %20.20g. %s',me);

% INITIALIZE INITIALIZE INITIALIZE INITIALIZE INITIALIZE INITIALIZE

% initialize population of particles and their velocities at time zero,
% format of pose (particle#, dimension)
% construct random population positions bounded by VR
pos(1:ps,1:D) = normmat(rand([ps,D]),VR',1);

if PSOseed == 1 % initial positions user input, see comments above
    tmpsz = size(PSOseedValue);
    pos(1:tmpsz(1),1:tmpsz(2)) = PSOseedValue;
end

% construct initial random velocities between -mv,mv
vel(1:ps,1:D) = normmat(rand([ps,D]),
    [forcecol(-mv),forcecol(mv)]',1);

% initial pbest positions vals
pbest = pos;

% VECTORIZE THIS, or at least vectorize cost funct call
out = feval(functname,powersys,pos);  % returns column of cost values (1 for each particle)

pbestval=out; % initially, pbest is same as pos

[gbestval,idx1] = min(pbestval);

% preallocate a variable to keep track of gbest for all iters
bestpos = zeros(me,D+1)*NaN;

gbest = pbest(idx1,:); % this is gbest position CKK:A vector of gbests of all particles
bestpos(1,1:D) = gbest;

% INITIALIZE END INITIALIZE END INITIALIZE END INITIALIZE END

% rstflg = 0; % for dynamic environment checking
% start PSO iterative procedures

cnt2 = 0; % counter used for the stopping subroutine based on error convergence

for i=1:me  % start epoch loop (iterations)
    [out, PSOVoltP] = feval(functname,powersys,[pos;gbest]);
    % outbestval = out(end,:); % returns column of cost values (1 for each particle)
    out = out(1:end-1,:);
    tr(i+1) = gbestval; % keep track of global best val
    te = i % returns epoch number to calling program when done

end
bestpos(1:1:D+1) = [gbest,gbestval];

% chkdyn = 1;
rsflg = 0; % for dynamic environment checking

if rsflg == 0
    [tempi] = find(pbestval>=out); % new min pbestvals
    pbestval(tempi,1) = out(tempi); % update pbestvals
    pbest(tempi,:) = pos(tempi,:); % update pbest positions

    [iterbestval,idx1] = min(pbestval);
    if gbestval >= iterbestval
        gbestval = iterbestval;
        gbest = pbest(idx1,:);
        OptVoltP = PSOVoltP(idx1,:);
    end
end

%PSO start

% get new velocities, positions (this is the heart of the PSO algorithm)
% each epoch get new set of random numbers
rannum1 = rand([ps,D]); % for Trelea and Clerc types
rannum2 = rand([ps,D]);
else
% common PSO algo with inertia wt
% get inertia weight, just a linear funct w.r.t. epoch parameter iwe
if i<=iwe
    iwt(i) = ((iw2-iw1)/(iwe-1))*(i-1)+iw1;
else
    iwt(i) = iw2;
end
% random number including acceleration constants
ac11 = rannum1.*ac1; % for common PSO w/inertia
ac22 = rannum2.*ac2;
vel = iwt(i).*vel...
+ac11.*(pbest-
vel...                      % independent
+ac22.*(repmat(gbest,ps,1)
pos);           % social
end
% limit velocities here using masking
vel = ( (vel <= velmaskmin).*velmaskmin ) + ( (vel > velmaskmin).*vel );
vel = ( (vel >= velmaskmax).*velmaskmax ) + ( (vel < velmaskmax).*vel );
% update new position (PSO algo)
pos = pos + vel;
% position masking, limits positions to desired search space
% method: 0) no position limiting, 1) saturation at limit,
% 2) wraparound at limit , 3) bounce off limit
minposmask_throwaway = pos <= posmaskmin; % these are psXD matrices
maxposmask_throwaway = pos >= posmaskmax;
minposmask_keep = pos > posmaskmin;
maxposmask_keep = pos < posmaskmax;
pos = ( minposmask_throwaway.*posmaskmin ) + ( minposmask_keep.*pos );
pos = ( maxposmask_throwaway.*posmaskmax ) + ( maxposmask_keep.*pos );
vel = (vel.*minposmask_keep) + (-vel.*minposmask_throwaway);
vel = (vel.*maxposmask_keep) + (-vel.*maxposmask_throwaway);
%PSO end
% check for stopping criterion based on speed of convergence to desired
A.7.3. Newton—Raphson Load Flow Function

```matlab
% Newton Raphson Load Flow Function based on a program by P. G. Praviraj [57]

function [evaluation, NRVoltP]=controller0808(powersysparams,x)

% split power system parameters
%PV buses
pxxstart=1;
nqx=powersysparams(pxxstart);
pxxend=pxxstart+nqx;
xV=zeros(2,nqx);
xV1,:)=powersysparams(pxxstart+1:pxxend);
xQg=zeros(2,nqx);
xQg1,:)=powersysparams(pxxstart+1:pxxend);
% transformer tap setting
tpxstrt=pxxend+1;
ntaps=powersysparams(tpxstrt);
tapsetend=txpstrt+ntapset;
tapset=zeros(2,ntapset);
tapset1,:)=powersysparams(tpxstrt+1:tapsetend);
x(end,:); % remove terminal semi-colon to display the last row of data in input matrix 'x'
numPSOpart=length(x(:,1)); % read in number of particles in pso population
nbus = 30;
evaluation=zeros(numPSOpart,1);
NRVoltP=zeros(numPSOpart,nbus);
for hol=1:numPSOpart

  % No. of branches in network...
  xV1=1;% index starting point in x matrix
  xVend=xV1+nqx-1; % index of end point in x matrix
  xV2,:)=x(hol,xV1:xVend);
  xQg1=st=txpstrt+1; % index starting point in x matrix
  xQgend=xQg1+nqx; % index of end point in x matrix
  xQg2,:)=x(hol,xQg1:xQgend-1)*100; % multiply by 100 because PSO figures are normalised
  busd = busdata0808(xV,xQg);
  % Calling busdata...
  BMva = 100; % Base MVA...
  bus = busd(:,1); % Bus Number...
```

% error
tmp1 = abs(tr(i) - gbestval);
if tmp1 > ergrd
cnt2 = 0;
elseif tmp1 <= ergrd
cnt2 = cnt2+1;
if cnt2 >= ergrddep
  break
end
end  % end epoch loop

OUT=[gbest';gbestval; tr'];
return
```
bustype = busd(:,2); % Type of Bus 1-Slack, 2-PV, 3-PQ...

V = busd(:,3); % Specified Voltage..
del = busd(:,4); % Voltage Angle..
Pg = busd(:,5)/BMva; % PGi..
Qg = busd(:,6)/BMva; % QGi..
Pl = busd(:,7)/BMva; % PLi..
Ql = busd(:,8)/BMva; %QLi..
Qmin = busd(:,9)/BMva; % Minimum Reactive Power Limit..
Qmax = busd(:,10)/BMva; % Maximum Reactive Power Limit..

% pv = find(bustype == 2 | bustype == 1); % PV Buses..
pq = find(bustype == 3); % PQ Buses..
% npv = length(pv); % No. of PV buses..
npq = length(pq); % No. of PQ buses..

P = Pg - Pl; % Pi = PGi - PLi..
Q = Qg - Ql; % Qi = QGi - QLi..
Psp = P; % P Specified..
Qsp = Q; % Q Specified..

xtapsetstrt=2*npvx+1;%index starting point in x matrix
xtapsetend=xtapsetstrt+ntapset; %index of end point in x matrix
tapset(:,2)=x(hol,(xtapsetstrt:xtapsetend-1));
Y = ybus0808(nbus,tapset); % Calling ybus.m to get Y Bus Matrix..
G = real(Y); % Conductance matrix..
B = imag(Y); % Susceptance matrix..

%start Newton Raphson
Tol = 1;
Iter = 1;
while (Tol > 1e-8) % Iteration start
    P = zeros(nbus,1);
    Q = zeros(nbus,1);
    % Calculate P and Q
    for i = 1:nbus
        for k = 1:nbus
            P(i) = P(i) + V(i)* V(k)*(G(i,k)*cos(del(i)-del(k)) + B(i,k)*sin(del(i)-del(k)));
            Q(i) = Q(i) + V(i)* V(k)*(G(i,k)*sin(del(i)-del(k)) - B(i,k)*cos(del(i)-del(k)));
        end
    end
    % Checking Q-limit violations..
    if Iter <= 7 & & Iter > 2 % Only checked up to 7th iterations..
        for n = 2:nbus
            if bustype(n) == 2
                QG = Q(n)+Ql(n); % if QG < Qmin(n)
                V(n) = V(n) + 0.01;
                else QG > Qmax(n)
                V(n) = V(n) - 0.01;
            end
        end
    end
    % Calculate change from specified value
    dPa = Psp-P;
    dQa = Qsp-Q;
    k = 1;
    dQ = zeros(npq,1);
    for i = 1:nbus
        if bustype(i) == 3
            dQ(k) = dQa(i);
            k = k+1;
        end
end

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\[ dP = dP_a(2:nbus); \]
\[ M = [dP; dQ]; \quad \text{% Mismatch Vector} \]

% Jacobian
% J1 - Derivative of P with Angles \( dP/\Delta \theta \)
\[ J_1 = \text{zeros}(\text{bus}-1, \text{bus}-1); \]
for \( i = 1:(\text{bus}-1) \)
\[ m = i+1; \]
for \( k = 1:(\text{bus}-1) \)
\[ n = k+1; \]
if \( n == m \)
\[ J_1(i,k) = J_1(i,k) + V(m)*V(n)*(G(m,n)*\sin(\Delta \theta(m)-\Delta \theta(n)) + B(m,n)*\cos(\Delta \theta(m)-\Delta \theta(n))); \]
else
\[ J_1(i,k) = V(m)^2*B(m,m); \]
end
end
end

% J2 - Derivative of P with V.
\[ J_2 = \text{zeros}(\text{bus}-1, \text{pq}); \]
for \( i = 1:(\text{bus}-1) \)
\[ m = i+1; \]
for \( k = 1: \text{pq} \)
\[ n = \text{pq}(k); \]
if \( n == m \)
\[ J_2(i,k) = J_2(i,k) + V(n)*(G(m,n)*\cos(\Delta \theta(m)-\Delta \theta(n)) + B(m,n)*\sin(\Delta \theta(m)-\Delta \theta(n))); \]
else
\[ J_2(i,k) = V(m)^2*G(m,m); \]
end
end
end

% J3 - Derivative of Reactive Power Injections with Angles.
\[ J_3 = \text{zeros}(\text{pq}, \text{bus}-1); \]
for \( i = 1: \text{pq} \)
\[ m = \text{pq}(i); \]
for \( k = 1:(\text{bus}-1) \)
\[ n = k+1; \]
if \( n == m \)
\[ J_3(i,k) = J_3(i,k) + V(n)*(G(m,n)*\cos(\Delta \theta(m)-\Delta \theta(n)) + B(m,n)*\sin(\Delta \theta(m)-\Delta \theta(n))); \]
else
\[ J_3(i,k) = V(m)^2*G(m,m); \]
end
end
end

% J4 - Derivative of Reactive Power Injections with V.
\[ J_4 = \text{zeros}(\text{pq}, \text{pq}); \]
for \( i = 1: \text{pq} \)
\[ m = \text{pq}(i); \]
for \( k = 1: \text{pq} \)
\[ n = \text{pq}(k); \]
if \( n == m \)
\[ J_4(i,k) = J_4(i,k) + V(n)*(G(m,n)*\sin(\Delta \theta(m)-\Delta \theta(n)) - B(m,n)*\cos(\Delta \theta(m)-\Delta \theta(n))); \]
else
\[ J_4(i,k) = V(m)^2*B(m,m); \]
end
end
end

end
end
J = [J1 J2; J3 J4];     % Jacobian Matrix

X = JM;           % Correction Vector

dTh = X(1:nbus-1);     % Change in Voltage Angle.
dV = X(nbus:end);     % Change in Voltage Magnitude.

% Updating State Vectors.
del(2:nbus) = dTh + del(2:nbus);      % Change in Voltage Angle.
k = 1;
for i = 2:nbus
    if bustype(i) == 3
        V(i) = dV(k) + V(i);        % Voltage Magnitude.
k = k+1;
    end
end

Iter = Iter + 1;
Tol = max(abs(M));                  % Tolerance.
end

A.7.4. Modified Backward / Forward Sweep Load Flow Function

function [evaluation, RLFVoltP] = CKKbfgen0127(gen_bus,x)
global NBUS LINEDATA BUSDATA;

size_gen=size(gen_bus);% number of generators
num_gen=size_gen(1);%find number of generators

gen_pos=gen_bus(:,1);
x(end,:); %remove terminal semi-colon to display the last row of data in input matrix 'x'

numPSOpart=length(x(:,1));
evaluation=zeros(numPSOpart,1);
RLFVoltP=zeros(numPSOpart,NBUS);
PBASE=100000;
VBASE=1.602756;
bd=BUSDATA;
ld=LINEDATA;
bd(:,2:3)=bd(:,2:3)/PBASE;
ld(:,4:5)=ld(:,4:5)/VBASE;
Z=complex(ld(:,4),ld(:,5));%branch impedance

for hol=1:numPSOpart
    bibc=zeros(size(ld,1),size(bd,1)-1);
    for c=1:size(ld,1) %create bus injection to bus current (bibc) matrix
        if ld(c,2)==1
            bibc(ld(c,3)-1,ld(c,3)-1)=1;
        else
            bibc(ld(c,3)-1,ld(c,3)-1)=bibc(ld(c,2)-1);
            bibc(ld(c,3)-1,ld(c,3)-1)=1;
        end
    end
bcbv=zeros(size(bd,1)-1,size(ld,1));% matrix of Z-values in respective branches
for c=1:size(bd,1)-1 %create branch current to bus voltage (bcbv) matrix
    if ld(c,2)==1; %only for first branch
        bcbv(ld(c,3)-1,ld(c,3)-1)=Z(c);
    else
        bcbv(ld(c,3)-1,:)=bcbv(ld(c,2)-1,:);
        bcbv(ld(c,3)-1,ld(c,3)-1)=Z(c);
    end
end

S_D=complex(bd(:,2),bd(:,3));% complex power load
S_G=zeros(size(bd,1),1);
for c=1:num_gen
    PG=x(hol,c);
    QG=x(hol,c+num_gen);
    S_G(gen_pos(c))=complex(PG/PBASE,QG/PBASE);
end
S=S_D-S_G;
S(1)=[];

Vo=ones(size(bd,1)-1,1);% initial bus voltage% 10 change to specific data value
VB=Vo;
Tol = 1;
while (Tol > 0.00001)
%backward sweep
    I=conj(S./VB);% injected current at each bus
    IB=bibc*I;  %get the cumulative injected current flowing through each branch
%forward sweep
    DLF=bcbv*bibc;% distribution load flow matrix
    Vprev=VB;
    DLFI=DLF*I;%voltage drops along each branch.
    VB=Vo-DLFI;
    polVprev=abs(Vprev);
    polVB=abs(VB);
    Tol = max(abs(polVprev-polVB));
end
evaluation(hol)=objective(abs(VB));
RLFVoltP(hol,:)=[1 abs(VB)'];
end
RLFVoltP;
evaluation;

%1)An Effective Approach for Distribution System Power Flow Solution A. Alsaadi, and B. Gholam [58]
%2)The Standard Backward/Forward Sweep Power Flow Paulo M. De Oliveira-De Jesus, Member, IEEE