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VOLTAGE REGULATION OF POWER DISTRIBUTION SYSTEM WITH INTERCONNECTED DISTRIBUTED GENERATORS

Thesis

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

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APRIL, 2013

DECLARATION

by the Ph.D. Research Scholar

I hereby *declare* that the Research Thesis entitled **VOLTAGE REGULATION OF POWER DISTRIBUTION SYSTEM WITH INTERCONNECTED DISTRIBUTED GENERATORS**, Which is being submitted to the **National Institute of Technology Karnataka, Surathkal** in partial fulfillment of the requirements for the award of the Degree of **Doctor of Philosophy** in Electrical and Electronics Engineering Department is a *bonafide report of the research work carried out by me*.The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

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Place:NITK- Surathkal

Date: 14-03-2013

CERTIFICATE

This is to *certify* that the Research Thesis entitled " **VOLTAGE REGULATION OF POWER DISTRIBUTION SYSTEM WITH INTERCONNECTED DISTRIBUTED GENERATORS** " submitted by R. Shivarudraswamy, (Registration Number: 081023EE08 F02) as the record of the research work carried out by him, *is accepted as the Research Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy**.

Research Guide.
(Name and Signature with Date and Seal)

Chairman - DRPC.
(Signature with Date and Seal)

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DEDICATED TO MY
FATHER

ABSTRACT

In the recent years the electrical power utilities are undergoing rapid restructuring process worldwide. Indeed, with deregulation, advancement in technologies and concern about the environmental impacts, competition is particularly fostered in the generation side thus allowing increased interconnection of generating units to the utility networks. These generating sources are called as distributed generators (DG) and defined as the plant which is directly connected to distribution network and is not centrally planned and dispatched. Various new types of distributed generator systems, such as microturbines and fuel cells in addition to the more traditional solar and wind power are creating significant new opportunities for the integration of diverse DG systems to the utility. Inter connection of these generators will offer a number of benefits such as improved reliability, power quality, efficiency, alleviation of system constraints along with the environmental benefits. In order to achieve these benefits with large penetration of DG source in existing utility networks several technical problems are to be fronted such as voltage regulation, islanding of DG, degradation of system reliability, power quality problems, protection and stability of the network. These issues need to be resolved, to pave the way for a sustainable energy future based on a large share of DG and hence a lot of research effort is required.

Among the above issues the voltage rise problems have been reported as the foremost concern against the connection of large amounts of distributed generators to medium-voltage and low-voltage distribution networks. The distribution systems have been planned and designed for unidirectional power flow and operated at constant voltage levels. The connection of the large amount of DG systems to the utility may reverse the power flow resulting in voltage rise above the statutory limits. Present network design practice is to limit the generator capacity to the level at which the upper voltage limit is not exceeded with maximum generation and minimum load. This can lead to a reduction in connectable generation capacity, under utilization of appropriate generation sites. The conventional voltage

regulation methods of distribution system are designed with unidirectional power flow in mind and are not going to be effective in presence of a significant number of DG systems. Thus there is a need to redesign these methods to take care of bidirectional power flow or new methods have to be developed to accommodate the large number of DG systems. Thus, development of new voltage control devices/schemes have the potential to revolutionize the control of distribution network.

In this thesis steady state voltage rise problem in a distribution networks interconnected with DG is examined. Case studies are presented using simulation results to study the impact of location, magnitude and operating condition of the integrated DG. The impact of other factors such as voltage at the primary substation, distance from the primary substation, demand on the system, type of loads and loading conditions on voltage level of distribution system are also analyzed. A comprehensive study on voltage control in a distribution system by taking in to account a number of DG systems and capacitors under various conditions is also presented in this work.

In order to prepare the distribution networks for larger penetration of DG systems, effective voltage regulation methods are required so as to keep the voltage levels within the limits. In this work sensitivity analysis and participation factor based approaches for voltage regulation of typical distribution system are presented. The formulation for determination of voltage sensitivity index for voltage control is also given. The effectiveness of the developed approaches for voltage regulation of typical IEEE 69 bus distribution is analyzed using case studies. The OLTC, switched capacitors and DG systems are considered to regulate the voltage level in the distribution system in this study. Both methods can be used to handle all types of radial distribution system structures regardless of the system size proficiently.

Individual control of various voltage regulating device such as OLTC, shunt capacitor including DG in a distribution system may cause unnecessary operations, and consequently wear, energy consumption as well as voltage disturbances. Thus coordination among these devices for effective voltage regulation can lead increase in number of DG interconnection to utility network. In this work a coordinated regulation method using genetic algorithm is developed. Genetic algorithm is utilized to determine the optimal amount of operation for individual voltage regulating device for given distribution network. The performance of the developed method is analyzed using simulation results through two case studies. The sample load conditions using time varying load profile is considered. The multiple voltage regulating devices such as OLTC, LRT, SC, SVC including DG system is considered in this study.

The input load data is very critical for distribution system load flow studies. In most cases time varying load data is required for accurate load flow analysis such as hourly load day for a day or a month. The use of this large data for load flow analysis can complicate the solution approaches. Thus in most of the cases, for validation of voltage regulation methods few samples of data are considered instead of considering the entire load profile. This approach may not accurately represent the load variation of entire profile for load follow analysis. In this work a fuzzy clustering technique for load profile generations is presented. Load profile generation using fuzzy clustering can be more realistic case rather than considering sample load conditions from set of time varying data. Fuzzy clustering is used to find 3 prototypes of hourly load data for a day (24 vectors) instead of considering sample load conditions directly from profile. Load profile generation using fuzzy clustering can be more realistic case as it considers the similarity of variation for entire set of load data. The performance of coordinated voltage control method is analyzed using the load profile generated using fuzzy cluster in this work.

Distribution systems are usually unbalanced due to unbalanced loading of the different phases. Besides industrial or domestic customers some distributed generators can also impose an unbalanced operation of electrical networks. Load flow analysis of balanced radial distribution systems will be inefficient to solve the unbalanced cases and the distribution

systems need to be analyzed on a three phase basis. In this thesis load flow solution for a unbalanced system using forward and back sweep method has been presented. The detailed modeling of various components of the distribution system for the unbalanced load flow solution is also given. The performance of the coordinated voltage regulation method using two Case studies using IEEE 13 and 25 bus unbalanced distribution is analyzed through simulation. The simulation results are reported to evaluate the effectiveness of the developed method in voltage regulation of unbalanced distribution system.

Keywords:Distributed generation, distribution network, voltage control, on-load tap changer, shunt capacitor, sensitive analysis, participation factor, fuzzy cluster, genetic algorithm, unbalanced radial system.

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Nomenclatures

AC	:	Alternating Current
AI	:	Artificial Intelligent
AM	:	Ampere Meridian
ANN	:	Artificial Neural Network
AVC	:	Automatic Voltage Controller
CBAN	:	Cell Based Active Network
CHP	:	Combined Heat and Power
CVC	:	Coordinated Voltage Control
DC	:	Direct Current
DER	:	Distributed Energy Resource
DG	:	Distributed Generation
DNO	:	Distribution Network Operator
FL	:	Fuzzy Logic
GA	:	Genetic Algorithm
GW	:	Giga Watt
HV	:	High Voltage
Hz	:	Hertz
ICE	:	Internal Combustion Engine
IEEE	:	International Electrical and Electronics Engineering
IGBT	:	Insulated Gate Bipolar Transistor
KCL	:	Kirchhoff's Current Low
kV	:	Kilo Volt
kVA	:	Kilo Volt Ampere
kVAR	:	Kilo Volt Ampere Reactive
kW	:	Kilo Watt
LDC	:	Line Drop Compensator
LRT	:	Load Ratio Transformer

LTC	:	Load Tap Changer
LV	:	Low Voltage
MPPT	:	Maximum Power Point Tracking
MTG	:	Microturbine Generator
MV	:	Medium Voltage
MVAR	:	Mega Volt-Ampere Reactive
MW	:	Mega Watt
NOX	:	Nitric Oxide
OLTC	:	On Load Tap Changer
PAFC	:	Phosphoric Acid Fuel Cell
PCC	:	Point of Common Coupling
PM	:	Post Meridian
POC	:	Point of Connection
PV	:	Photovoltaic
SC	:	Shunt Capacitor
SCR	:	Silicon Controlled Rectifier
SL	:	Supervised Learning
SOFC	:	Solid Oxide Fuel Cell
SVC	:	Static Var Compensator
SVR	:	Step Voltage Regulator
T & D	:	Transmission and Distribution
UL	:	Un- supervised Learning
UPFC	:	Unified Power Flow Controller
VCA	:	Voltage Control Area
VSC	:	Voltage Source Converter
VSDG	:	Voltage Support Distributed Generation
WECS	:	Wind Energy Conversion System

Chapter 1

INTRODUCTION

1.1 OVERVIEW

The need for energy is never ending. This is certainly true for electrical energy, which is a large part of total global energy consumption. But growing in tandem with energy needs are the concerns about sustainable development and environmental issues, such as the movement to reduce greenhouse gas emissions. The result of fulfilling energy needs and meeting environmental, social concerns are the growing interest in reliable distributed energy sources. It is believed that the future will bring us more and more small distributed power generation units connected to the grid. These generating sources are called as distributed generators (DG) and defined as the plant which is directly connected to distribution network and is not centrally planned and dispatched. These are also called as embedded or dispersed generation units. The rating of the DG systems can vary between few kW to as high as 100 MW. Various new types of distributed generator systems, such as microturbines and fuel cells in addition to the more traditional solar and wind power are creating significant new opportunities for the integration of diverse DG systems to the utility [Ackermann *et al.* (2001)].

1.2 DRIVERS FOR DISTRIBUTED GENERATION

The drivers for distributed generations are multiple and symbiotic, however all have their basis in the common concerns to use primary energy as efficiently as possible, with the least possible environmental impact whilst ensuring that energy supply is secure, safe and supplied at an agreed quality universally and at a competitive cost. Important drivers for DG system are given below.

- **The liberalization of electricity markets**
  There is an increased interest by electricity suppliers in distributed generation because they see it as a tool that can help them to fill in niches in a liberalized market. In such a market, customers will look for the electricity service best suited for them. Different customers attach different weights to features of electricity supply, and distributed generation technologies can help electricity suppliers to supply to the electricity customers the type of electricity service they prefer. In short, distributed generation allows players in the electricity sector to respond in a flexible way to changing market conditions. In liberalized markets, it is important to adapt to the changing economic environment in the most flexible way. Distributed generation technologies generally provide this flexibility because of their small sizes and the short construction lead times compared to most types of larger central power plants.

- **Environmental performance**
  Environmental policies or concerns are probably the major driving force for the demand for distributed generation in worldwide. Environmental regulations force players in the electricity market to look for cleaner energy- and cost-efficient solutions. Distributed resource technologies generally have lower or no environmental impacts than conventional fossil-fueled generation. Combined Heat and Power (CHP) technology, allowing for portfolio optimization of companies needing both heat and electrical energy, is one of the examples. Compared to separate fossil-fired generation of heat and electricity, CHP generation may result in a primary energy conservation,

varying from 10% to 30%, depending on the size (and efficiency) of the cogeneration units. Further more, as renewable energy sources are by nature small-scale and dispersed over the grid and have least impacts on environment.

- **Power quality and reliability**

  To date, the primary driver of emerging applications has been the desire for enhanced power quality and reliability. The earliest applications of distributed generation have been in commercial and industrial settings where high quality, very reliable power is valued. As the demand for more and better quality electric power increases, DG can provide alternatives for reliable, cost-effective, premium power for homes and business.DG can provide customers with continuity and reliability of supply, when a power outage occurs at home or in the neighborhood, restoring power in a short time.

- **Transmission and distribution support**

  Strategically placed distributed resources can be used to defer or eliminate the need for T & D additions and upgrades that otherwise would be required to serve new load. Deferring or eliminating T&D infrastructure can provide substantial value to utilities and their customers. DG helps to bypass congestion in existing transmission grids. On site production minimizes the transmission and distribution losses as well as the transmission and distribution costs, a significant part (above 30%) of the total electricity cost.

- **Energy price risk management**

  DG can also stimulate competition in supply; adjusting price via market forces. A DG operator can respond to price incentives reflecting fuel and electricity prices. In a free market environment DG operator can buy or sell power to the electricity grid - exporting only at peak demand and purchasing power at off-peak prices. DG can act as a physical hedge against volatile electricity prices.

- **Localized economic benefits**

  Certain distributed generation technologies placed on customer's premises can be operated in a cogeneration mode. Cogeneration can result in lower overall energy bills for the customer as well as provide some of the broader benefits discussed above. Also, distributed resources, by their nature, create investments in the local community. Such investments provide enhanced local economic benefits when compared to investments made in larger, more remote generation resources.

1.3 DG TECHNOLOGIES

Distributed generation encompasses a wide range of prime mover technologies. These technologies can be categorized as renewable and nonrenewable. Renewable technologies include wind, photovoltaic, solar thermal, geothermal. Non renewable technologies include internal combustion engine, microturbines and fuel cell. Knowledge of the characteristics of each of this technology is very important as that defines how they have to be interconnected and their interaction with the grid. The potential, challenges, typical sizes and ability to control power output of these DG units are described briefly in the following sections.

1.3.1 Photovoltaic

The photovoltaic (PV) technology uses semiconductor cells (wafers), each of which is a large area p-n diode with the junction positioned closed to the top surface. The PV effects results in the generation of direct voltage and current from the light falling on the cell. Multiple cells are assembled in modules to generate sufficient voltage and current. Figure 1.1 shows the PV module unit interconnected to grid. As the PV module is an unregulated DC power source, it requires a power conditioning unit to convert the generated DC voltage to suitable AC power for utility purpose. The power conditioning unit in PV system consists of two stages; a DC-DC converter which boost the PV array voltage and tracks the maximum solar power; followed by an inverter which converts this DC power to high quality AC power [Eltawuil and Zhao (2010)].

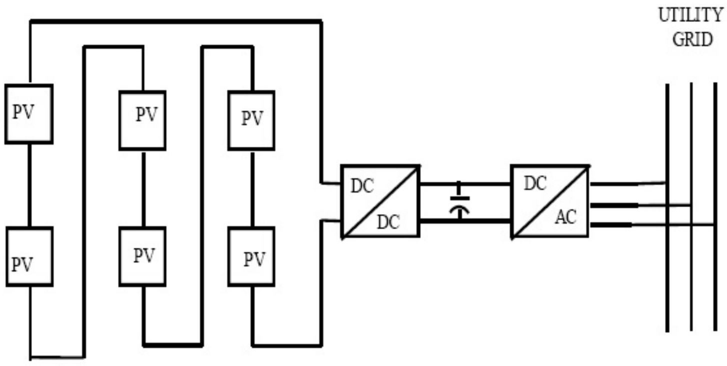

Figure 1.1: Photovoltaic modules interconnection to grid

A battery storage system may be present at the DC bus, mainly in autonomous and small installations. Maximum power point tracking (MPPT) is an essential attribute to extract the maximum power from the PV module during the day. The MPPT device attempt to match, the impedance of the PV module with that of the load or battery to ensure maximum power transfer. The normal efficiency of a PV system is 5-15%, but with the help of such a device, 20-30% more energy can be generated.

PV systems are more attractive for remote and isolated areas where utility power is not available and grid connection cost is higher. Although the majority of the installed PV capacity is still off-grid, the percentage of grid connected PV installations is rapidly increasing, either in the form of solar power stations or as building integrated PV systems. Due to the fact that the PV power output matches well with the peak load demand, this tendency is gaining momentum and it is expected to contribute to the decrease in the cost of photovoltaic technologies. The installed capacity has exceeded 500 MW worldwide and is fast approaching the 1 GW milestone [Blaabjerg *et al.* (2008)].

Most of the present PV technology utilizes the crystalline semiconductor material similar to that used in integrated circuits. Hence, the cost of PV cells has been quite high. Considerable research effort has been devoted during the last two decades in reducing the cost of the cells, without sacrificing their efficiency excessively. But the cost of PV cell is still higher compared to that of other renewable sources. The recent challenges in the research of PV systems are lowering the overall cost/watt, using concentrators to converge the solar energy over a large area into solar cells, increasing the concentrator efficiency and improving solar cells technology to increase the overall efficiency with minimal cost rise [Thomas *et al.* (2001)].

1.3.2 Wind Power

Wind energy is now firmly established as a matured technology for electricity generation and has over 239 GW of installed capacity, worldwide [World wind energy report (2012)]. It is one of fastest growing electricity generation technologies and features in energy plans across all five continents, both in the industrialized and developing world. Wind energy conversion systems (WECS) transform the energy present in the blowing wind to electrical energy. Wind is highly variable resources that cannot be stored and wind energy conversion systems must be operated accordingly. Wind energy is transformed in to mechanical energy by means of a wind turbine that has one or several blades (three blades are more common).The turbine coupled to the generator by means of a mechanical drive train, usually includes a gearbox.

Wind turbines can be of variable speed or of fixed speed types. In fixed speed machines, the generator is directly connected to the main supply grid. The wind turbine can be divided into three categories: the system without power electronics, the system with partially rated power electronics and the systems with full scale power electronic interfacing wind turbines which are shown in Figure 1.2 [Blaabjerg *et al.* (2004)]. The development in wind turbine systems has been steady for the last 25 years and four to five generations of wind turbines exist. Wind power generators can be interconnected to low voltage (up to 11 kV), medium voltage (11 kV to 66 kV) and high voltage (110 kV and above) utility networks either individually or as group to form what is known as wind farm.

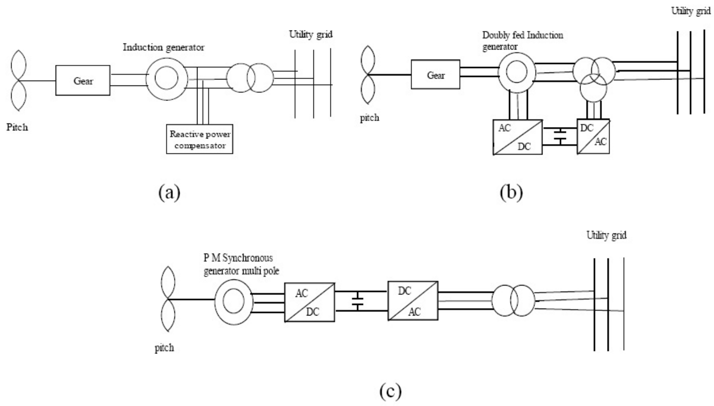

Figure 1.2: Wind generation topologies with (a) induction generator (b) doubly-fed induction generator (c) multi pole permanent magnet synchronous generator

1.3.3 Fuel Cells

A fuel cell (FC) is an electrochemical energy conversion system, where chemical energy is converted directly in to electrical energy and heat. Resulting advantages of this technology are high efficiency (almost at partial load), low emission and noiselessness (due to non existence of moving parts). A fuel cell produces approximately 0.6 to 0.75 V and a current in the range of 1500-3000 Amp/m^2 of cell area depending on operating temperature and pressure. This is equivalent to 900-1800 W/m^2 of cell area in the stack. Groups of stacks may be connected in series/parallel combinations to provide the desired output. The power and voltage levels can range from 2 kW to 50 MW and a few volts to 10,000 V respectively. [Farooque and Maru (2001)]. The power electronic interface system, including inverters and DC/DC converters, are often required in order to supply normal customer load demand or supply electricity to the grid. Figure 1.3 shows the interconnection of a fuel cell module to the grid. The operation of a FC is closely alike to that of a battery system, except that it consumes fuel. The energy savings result from the high conversion efficiency, typically 40% or higher depending on the type of fuel cell. When utilized in a cogeneration applications, energy efficiency can be in the order of 85% or more.

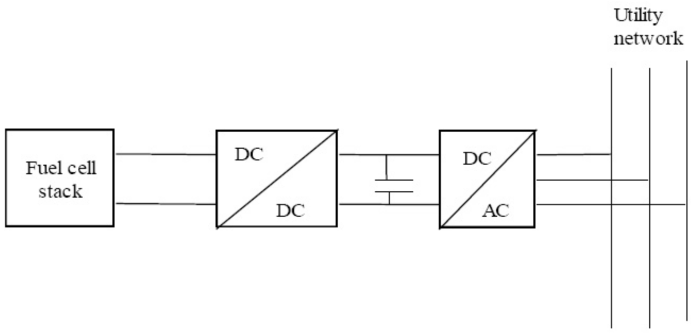

Figure 1.3: Fuel cell module with grid interconnection

Development efforts are currently focused on five FC technologies: phosphoric acid fuel cell (PAFC), solid oxide fuel cell (SOFC) and alkaline fuel cell (AFC). The main challenge in making fuel cells widely used in the DG market is to make them more economically competitive with the current technologies [Ellis *et al.* (2001)].

1.3.4 Small Hydropower

Hydro electric power is the generation of electric power from the movement of water. A hydroelectric facility requires a dependable flow of water and a reasonable height of fall of water, called the head. In a typical installation, water is fed from a reservoir through a channel or pipe into a turbine. The pressure of the flowing water on the turbine blades causes the shaft to rotate. The rotating shaft is connected to an electrical generator which converts the motion of the shaft into electrical energy. Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 MW is generally accepted as the upper limit of what can be termed small hydro. Small hydro can be further subdivided into mini hydro, usually defined as less than 1,000 kW, and micro hydro which is less than 100 kW [Borges and Pinto (2008)]. Micro hydro is usually the application of hydroelectric power sized for smaller communities, single families or small enterprise.

Small hydro plants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydro projects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electrical distribution network. Since small hydro projects usually have minimal reservoirs and civil construction work, they are seen as having a relatively low environmental impact compared to large hydro. This decreased environmental impact depends strongly on the balance between stream flow and power production from the electrical point of view the generators can either be synchronous or asynchronous machines. While synchronous generators capable of isolated plant operation are often used, small hydro plants connected to an electrical grid system can use economical induction generators to further reduce installation cost and simplify control and operation.

1.3.5 Microturbines

Microturbines are essentially very small combustion turbines, individually of the size of a refrigerator. They are often packaged in multiunit systems and can produce power in the range of 25 and 300 kW [Ellis *et al.* (2001)]. Generation system based on microturbine are clean (ultra low emission), reliable, energy efficient and providing to be a supplement to traditional forms of power generation. Microturbine can be operated in the grid connected as well as in the stand alone mode. The main elements of microturbine include a compressor, combustion chamber, turbine generator and a recuperator.

Figure 1.4 [Gaonkar *et al.* (2008)] shows a high speed single shaft designed with the compressor and turbine mounted on the same shaft along with the permanent magnet synchronous generator. The generator generates the power at very high frequency from 1500 to 4000 Hz. The high frequency voltage is first rectified and then inverted to a normal AC power at 50 or 60 Hz. The various power electronic topologies can be used to interface single shaft microturbine generation (MTG) systems, such as matrix converter, back to back inverters and cyclo-converters.

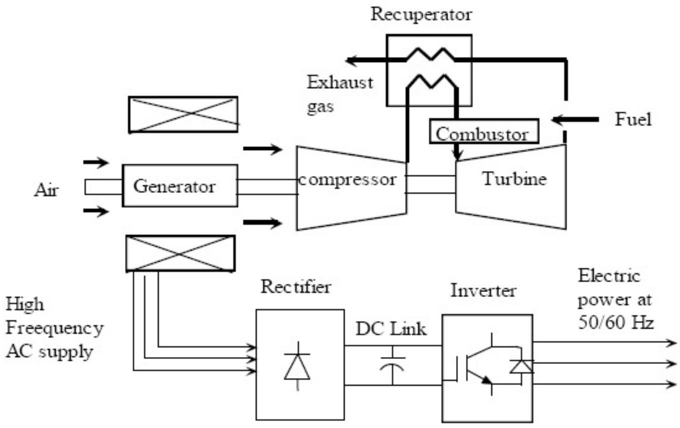

Figure 1.4: Microturbine generation systems with single shaft design

1.3.6 Geothermal

Geothermal is energy available as heat emitted from within the earth, usually in the form of hot water or steam. Geothermal as a recoverable energy resource is very site specific. Geothermal power plant can range from hundreds kW to hundreds MW. [Bloomquist (2002)]. A schematic diagram of geothermal power plant is shown in the Figure1.5. After hydropower and biomass, geothermal energy is the third most exploited energy source worldwide, with a projected installed capacity of 13.5 GW by 2012 [California distributed energy resources guide]. Geothermal power can play a fairly significant role in the energy balance of some area of the world. Geothermal power plants use natural hot water and steam from below the earths surface to rotate turbine generators to produce electricity. Unlike fossil fuel power plants, no fuel is burned in these plants. Hence, geothermal power plants emit water vapors but produce no emissions. Geothermal electricity can be used for the base load power as well as the peak load power demand. There are three basic designs of geothermal power plants, all of which extricate hot water and steam from earths crust, utilize the heat content and return the warm water to the heat source to extend its life [Barun and Mc-Cluer (1993)].

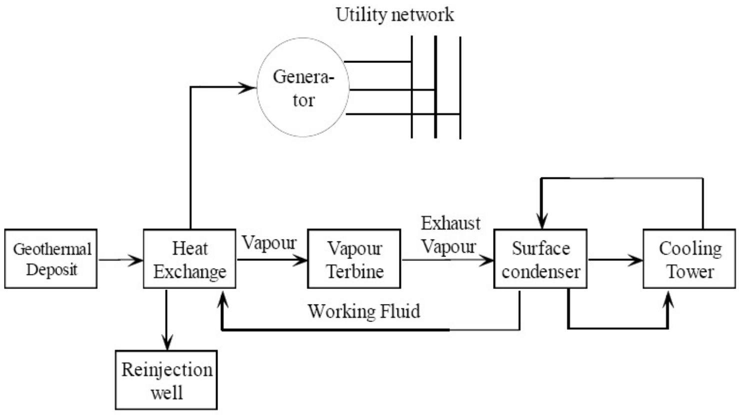

Figure 1.5: Schematic diagram of geothermal power plant

In the simplest design, the steam goes directly to the turbine and then to condenser where it is condensed into water. In the second approach, the steam and hot water are separated as they exit the well, and while steam is used to drive the turbine, the water is sent back to underground. In the third approach known as Binary system, the hot water and steam is passed through a heat exchanger where the heat is extracted to heat up a second liquid (organic fluids like Iso-butane) in a closed loop and then is used to drive the turbine. The choice of the approach to be used to generate electricity is determined solely by the type of the resource, and the availability of steam or water from it.

1.3.7 Internal Combustion Engine

Reciprocating internal combustion engines (ICEs) convert heat resulting from combustion of a fuel in to rotary motion which in turn drives a generator in a distributed generation (DG) system. ICEs are most common technology used for DG [Pandiraj and Fox (2000)]. These engines can be of either spark ignition type using natural gas, propane, or gasoline, or compression types that use diesel fuel or heavy oil. They provide advantages such as low capital cost, large size range, from a few kW to MW, good efficiency, possible thermal or electrical cogeneration in buildings and good operating reliability. These characteristics combined with the engine ability to start-up fast during a power outage, make them the main choice for emergency or standby power supplies. The electrical generator is usually synchronous or induction type. It is connected directly to the electrical power system without any additional interconnection device .The key barriers to ICE usage are high maintenance cost, which is highest among the DG technologies , high NOX (nitric oxide) emissions, which are also highest among the DG technologies, and a high noise level.

1.3.8 Other Sources

Biomass: Biomass is energy derived from any organic or plant matter and, under this term, there is a huge variety of different sources. These include especially the energy stored in trees, grass crops, forestry, vegetal coal, urban wastes, agricultural wastes and forestry wastes. Municipal waste may also be used in many of the new processes developed In terms of resource; biomass is very large, providing about 15% of the worlds primary energy. Biomass has a dominant position for the poor people in the world, who are dependent on wood fuel for cooking and heating. In fact, it plays an important role in developing countries that have large poorest regions. But it is also important in a number of industrialized countries, e.g. the United States, which obtains 4% of its energy from biomass, and Sweden with 14% [Hatziargyriou *et al.* (2000)].

Solar thermal : Solar thermal power plants make use of the thermal energy from the sun to heat a working fluid, which drives an engine or steam-turbine generator [Jianfeng *et al.* (2009)]. Concentrating mirrors or other reflective materials are used to focus the sunlight on a central vessel containing the working fluid. The three most prevalent types of solar thermal plants are the central receiver, parabolic dish, and parabolic trough systems. Like concentrating PV systems, solar thermal plants track the direct sunlight and are limited in application to arid, sunny climates.

Table 1.1: Distributed generators with available size [California distributed energy resources guide]

Technology	**Typical available size module**	**Applications**
Internal combustion engines	5 kW- 10 MW	Peak load shaving and back up operation not for continuous operation
Microturbines	35 kW-1 MW	Peak load shaving,Co-generation and as a base load
Solid oxide fuel cell	250 kW-5 MW	Suitable for providing CHP for air-conditioning, cooling and heating purposes, large stations are suitable for base load application
Wind turbine	200 W -3 MW	Supplementing mains supply. Power for low-to medium electric power needs. Occasionally mechanical power for agriculture purposes.
Photovoltaic arrays	20 W-100 kW	Stand alone and base load in some rural applications if combined with batteries.
Fossil fuels	100kW -20 MW	Main electricity generation as the main base load, used for peak load shaving and boiler operations

1.4 DG INTERFACING TECHNIQUES

The DG interface components are responsible for the converting the energy output of the prime movers into suitable 50/60 Hz electric power. Three basic energy converters are available for DG units.They are : synchronous generator , induction generator and power electronic converters interface.

1.4.1 Synchronous Generator

Synchronous generators are rotating electric machines that convert mechanical power to electrical power. Synchronous generators are typically utilized by the following DG technologies: Internal combustion engines, gas turbines, solar thermal , biomass and geo- thermal. Synchronous generators have the advantage , that they can be controlled to provide reactive power by adjusting their excitation. During short circuits a synchronous generator contributes large fault currents for a relatively long time.Fault currents four to five times of the rated current. [Krause *et al.* (1995)]

1.4.2 Induction Generator

Like synchronous generators, an induction generator is a rotating electrical machine that converts mechanical power into electrical power. Induction generators are extensively used in wind farms and small hydro electric plants. Induction generator combined with a converter interface is currently becoming common in wind power DG. They are cheap in investment and need relatively little maintenance work. The drawback is that they cannot control voltage level in the grid to which they are connected. They also need reactive power from the grid or from shunt capacitances or power electronic based reactive power generators for magnetisation.

1.4.3 Power Electronic Converter

Power electronics plays an essential part in the integration of the distributed generation units for good efficiency and high performance of the power systems. In conventional generation stations, the generators operate at a fixed speed and thereby with a fixed grid frequency. However, the distributed generation presents a quite different and challenging picture. For example, the voltage generated by variable speed wind power generators, PV generators and fuel cells cannot be directly connected to the grid. The power electronic technology plays a vital role to match the characteristics of these distributed generation units with the requirements of the grid connections; including frequency, voltage, control of active and reactive power, harmonic minimization etc. Different power electronic converters topologies can be used to interface the DG system to grid such as, (a) combination of passive rectifier and inverter (DC to AC) (b) DC to DC converter and inverters (c) back to back converters(AC to DC to AC) (d) matrix converter (AC to AC) (e) cycloconverter (AC to AC). Innovations and improvements in semiconductor switch designs have been the driving force for the advancements and implementation of power electronic interfaces [Blaabjerg *et al.* (2004)]. The majority of higher power, PE systems today rely on the insulated gate bi-polar transistor (IGBT) as the switching device.

1.5 ISSUES OF DG INTERCONNECTION

Unlike centralized power plants, the distributed generation units are directly connected to the distribution system; most often at the customer end. The existing distribution networks are designed and operated in radial configuration with unidirectional power flow from centralized generating station to customers. The increase in interconnection of DG to utility networks can lead to reverse power flow violating fundamental assumption in their design. This creates complexity in operation and control of existing distribution networks. Some of the technical issues are steady state voltage regulation, increased system fault level, islanding operation, degradation of power quality and reliability, protection and stability of the network.

1.5.1 Steady State Voltage Regulation

The voltage will drop as the distance from the distribution transformer increases when DG is not connected to the LV network. When a DG plant is connected to the LV network, the voltage at the point of connection (POC) of the DG to the network can increase because the DG plant supplies power demands local to the POC, effectively reducing voltage drop between the distribution substation and POC. During periods of maximum load demand, the voltage at the POC will decrease and may not exceed statutory limits. However, during periods of minimum load demand and maximum DG output, the voltage at the POC will increase due to the greater export of real power and there will be a local voltage rise at the POC. Real power will flow from the POC into the LV network thus reversing the direction of power flow for which the LV network was designed. In [Ackermann and Knyazkin (2002)] an overview of the impact of DG system on the operation of distribution network has been presented. Issues like impact of DG on losses, voltage control, power quality are discussed. Over voltages due to reverse power flows, when the down stream DG output exceeds the down stream feeder load can present a host of problems. Also, with the presence of DGs in the line, setting of the load tap changing transformers and static voltage regulator controls to obtain a good voltage profile may be difficult as the regulators may get confused and set a lower voltage level than required. Large DG power injections can disrupt the voltage regulation in a distribution system, potentially causing voltage violation issues. Voltage violation is a big concern for utilities as it can result in inefficient system operation, invalidation of equipment warranties and a number of other major problems. This can be corrected by coordinated voltage control with various voltage control devices.

1.5.2 Islanding

One of the major concerns in operating DG in grid connecting mode is the possibility of islanding of DG due to grid disturbances such as, network faults. Islanding occurs when a portion of the distribution system becomes electrically isolated from the remaining part of the power system. Yet continues to be energized by the distributed generators connected to the isolated sub systems. The present practice is to disconnect DG whenever islanding takes place for safety and security reasons. But, there is an increasing trend to operate DG in intentional islanding mode, to provide continuous and reliable power to customers during grid outages. As a result, the [IEEE Std.1547(2003)] states, one of its tasks for future consideration is to implement the intentional islanding of DG systems. Thus, there is a need for seamless switching of DG operation between grids connected and islanding modes without down time, during the outages of the utility. This is necessary mainly for power electronic based converter DG systems.

1.5.3 Protection Issues

Power system protection is a technical issue that is sufficiently important to deserve separate discussion. The objective of power system protection is to detect a fault condition (perhaps due to a lightning strike or equipment failure) and isolate the faulted section of the system as rapidly as possible while restoring normal operation to the rest of the system. Connecting DG to a distribution network introduces a source of energy at a point where there may not have been a source before. This may increase the fault level in the network (that is, the fault current that may flow when a fault occurs) and may complicate fault detection and isolation. In a typical urban network, DG may be connected at voltage levels ranging from 240V single phase to 132 kV (line-line). Connections at 132 kV are complex but well understood, whereas connections at 240/415V and 11 kV can be more difficult, particularly if they involve net injections into the network. [Pecas *et al.* (2007)].

The goal of protection design in the presence of DG is to maintain the pre-existing standard of network reliability, security and quality, coordinate with existing network protection and provide reasonable backup. Protection engineers recommend the use of dedicated, utility quality protection devices rather than rely on DG control equipment that is used in normal operation. Because each DG installation involves a unique combination of generation and system factors, protection must be designed for each project, and should be undertaken as early in project design as possible.

1.5.4 Network Fault Level

On any electrical network there is a possibility of an electrical fault on a section of line or cable. The disturbance may be caused by short circuit faults, lighting strikes, earth faults, or mechanical and electrical equipment failures. To prevent fault disturbances from damaging circuits and equipment, switchgear (circuit breakers) is used to isolate faulty components. Fault level is known as the prospective short circuit current at a point in an electricity network. When new generation is connected to the network, including DG, fault levels close to the POC will most likely increase. This additional fault level is referred to as the fault contribution of the generator and can cause the overall fault level to exceed the existing switchgear ratings [Zayandehrodi *et al.* (2011)]. General methods for dealing with increased fault levels on distribution networks include:

- Upgrade existing switchgear
- Reconfigure or re-inforce the network
- Incorporate a fault limiting reactor into the generator connection
- If the connection scheme uses step up transformers then high impedance transformers could be used

For DG connected to low voltage (LV) networks, it would be impractical to use equipment like fault limiting reactors and no step-up transformers are used for LV connections. Reconfiguring the network would not be effective for large numbers of DG and may be difficult and costly. Upgrading the existing switchgear, which may be on customer premises, could be costly and would require a study of the impact of DG, which at present is not normally carried out. A local control system that can detect fault currents and disconnect the DG is a practical and cost effective method. The embedded controller would provide this control functionality.

1.5.5 Power Quality

Different DGs have different characteristics and thus create different power quality issue. The effect of increasing the network fault level by adding generation often leads to improved power quality. A notable exception is that a single large DG, e.g. a wind turbine, on a weak network may lead to power quality problems particularly during starting and stopping, [Tande (2002)]. Excessive use of power electronics devices and modern controls introduces the power quality problems and moreover, these devices are very prone to power quality problems.

The harmonic distortion created due to DGs normally depends on the power converter technology and interconnecting configurations, when DG is connected to the grid. Distortion arises due to the presence of inverters and rotating generators such as alternators [Barker and de Mello (2000)]. Use of IGBTs in inverters instead of line commuted SCRs, while paying close attention to the pitch of the coil, degree of core linearity and grounding of the synchronous machine can reduce harmonic distortion considerably. The grounding arrangement of the step up transformer plays a major role in limiting the feeder penetration of harmonics, and with third harmonic being the most prevalent; arrangement can be made to block it from entering the utility network, so that the harmonics remains confined to the DG site itself. The output should satisfy the harmonic current injection requirements for distributed generation as per the [IEEE Std. 1547 (2003)], and in certain cases, to meet these standards, equipment at the DG site may need to be de-rated due to the added heating by the harmonics.

The issues of voltage flicker can be simple or a complex issue, as far its analysis and mitigation is concerned. In its simplest form, it can be caused by the starting of a machine like an induction generator or step changes in the DG output. Low flickers below the threshold can be ignored, but if the flickers cause considerable problems then corrective measures must be undertaken, which include reduced voltage starts on the induction

Generators, speed matching, tight synchronization and voltage matching of synchronous generators and proper control of inverters to limit the inrush currents. The other forms of flicker, which may be caused by the dynamic behavior of machines and their interactions with the upstream voltage regulators and generators, are difficult to correct. In grid connected DG system, even if the DG flicker is very small, the DG can cause hunting of an upstream voltage regulator. This may include visible flicker in the system, bringing down the system reliability, it is a challenge to take action against such disturbances, and a it requires considerable investigations to resolve.

1.5.6 Stability

Traditionally, distribution network design did not need to consider issues of stability as the network was passive and radial, and remained stable under most circumstances provided the transmission network was itself stable. However, these schemes is likely to change as the penetration of DGs increases and their contribution to network becomes greater. The areas that need to be considered include transient (first swing stability) as well as longterm dynamic stability and voltage collapse [Ledesma *et al.* (2003), Costa and Motos (2006), Akhmatov *et al.* (2003)]. It was concluded that the analysis of the system performance with regard to voltage stability shows that DG can support and improve the voltage profiles at load terminals. This can extend the stability margin of dynamic loads, i.e., induction motors, which can lose their stable operating point with large voltage [Ahmed *et al.* (2005)].

1.6 LITERATURE REVIEW

Steady state voltage rise problem is reported as one of the main obstacles for interconnection of large amounts of distributed generation units to the existing radial networks. [Barker, (2000), Masters (2002), and Jenkins *et al.* (2000)]. In [Masters (2002), the results of some generic studies explaining the voltage rise issue and how it may be overcome are presented. Several methods like reducing primary substation voltage and constraining the generator operation are discussed. Distribution networks are designed to keep the customer voltage constant within tolerance limit as dictated by statute and has always been a top priority. The range of voltage which must be met under a number of different standards does not exceed $\pm 10\%$, with some standards being even tighter than this. [Masters (2002)]. If the connection of a DG to distribution network causes an excessive voltage rise; there are a number of methods that can be employed to alleviate the situation. The system presented in Figure1.6 [Mogos and Guillaud (2004)] illustrates the facilities that can be used to compensate voltage rise effect.

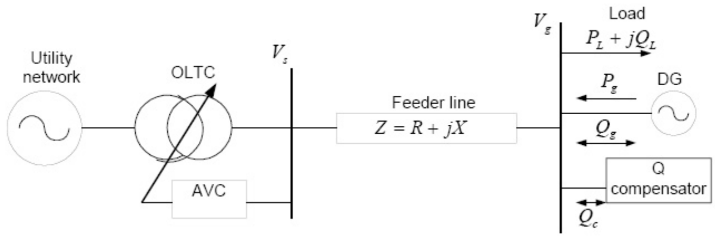

Figure 1.6: A simple system illustrating the options for voltage regulation

A distributed generator, DG (Pg, Qg) together with a local load (P_L, Q_L) and a reactive compensator Q_C are connected to the distribution system through a distribution feeder with impedance Z and an on-load tap changer (OLTC) transformer. In Figure 1.6, the rotating machine based DG system is shown. Similarly in case of power electronic interfaced DG systems, the interfacing circuit can be used as a facility to control.

- **OLTC, LDC based voltage control**

  A new approach using the associative memory system implemented on computational platform of neural-nets has been proposed in [Saric *et al.* (1997)] for the operation planning and real-time volt/var control in radial distribution systems. To provide minimum active power losses and suitable voltage profile, this approach integrates unsupervised learning/supervised learning (UL/SL) and interactive decoupled procedure (IDPC) for coordinated volt/var, control. The complex mappings between input patterns (load profile and source voltage) and output patterns (under load tap changing (ULTC) transformer tap positions and capacitor settings) are efficiently learned by neural-nets which are able to suggest the control action after an appropriate training.

Artificial neural network (ANN) may be applied to systems in which the analytical treatment is either intractable or time consuming [Ramakrishna and Rao (1999)]. The impact of DGs on the conventional load drop compensation (LDC) voltage regulation method for the power distribution systems with unbalanced load diversity on different feeders is analyzed in [Choi and Kim (2001)]. In addition, the multiple line drop compensation (MLDC) voltage regulation method that considers unbalanced load diversity, operation of DGs, and hysterical tap changing mechanism of ULTC transformers has been proposed in [Choi and Kim (2001)].

Three algorithms have been evolved for use in a controller for the target voltage of automatic voltage controller (AVC) relays at 11 kV primary substations in [Hird *et al.* (2004)]. The purpose of the voltage controller is to enable an increase in the distributed generator capacity that can be connected to the network. A statistical state estimation algorithm proposed estimates the voltage magnitude at each network node supplied by the substation. The introduction of DG in the distribution network can be a source of over voltage problems for the electric power system if care is not exercised in the design, control and interface of the DG equipment. To overcome the voltage problems at the point of common coupling (PCC), several solutions for the DG reactive power control have been proposed in [Mogos and Guillaud (2004)].

A knowledge based system for supervision and control of regional voltage profile and security using fuzzy logic is presented in [Marques *et al.* (2005)]. The control strategies are defined by system operators based on their experience and on off-line studies, which are translated into rules of a hierarchical fuzzy inference system (FIS).

Two hierarchical levels, namely, task oriented control level (high level) and set-point control level (low level) compose the control structure. An algorithm for the selection of corrective control actions for bus voltage and generator reactive power in a power system is presented in [Malachi and Singer (2006)]. A genetic algorithm using linear approximation of load flow equations and a heuristic selection of participating controls were combined in a search method for the minimum number of control actions. The use of fuzzy logic (FL) controller in calculating the voltage of AVC relay has been investigated in [Salman and Wan (2007)]. It has been found that the proposed FL controller based AVC relay has the ability to control voltage magnitude of distribution network as load changes. It has been concluded that the performance of the relay is not affected by the connection of distributed generation and its setting does not require re-adjustment as DGs are connected to the network.

Voltage regulation on medium voltage feeders with distributed generation using OLTC and LDC is discussed in [Viawan *et al.* (2007)]. The analysis showed that OLTC is robust against DG, whereas DG can affect the effectiveness of the voltage regulation provided by LDC. With proper coordination between DG and LDC, it is possible to ensure voltage regulation without unnecessarily restricting the integration of distributed generation. Power system state estimator is used to apply adaptive settings to network voltage control systems that can also operate in stand alone mode to provide a robust level of voltage stability. The issues concerning the use of distributed generation are discussed with respect to voltage levels and state estimation is described in [Hiscock *et al.* (2008)].

In [Kim *et al.* (2009)] authors propose a method for designing feasible LDC parameters which guarantee the satisfaction of voltage constraints for all possible variations in DG output. Also presents a method for estimating maximum installable DG capacity. The validity of the proposed design and estimation methods is ascertained through case studies based on IEEE 13 bus system and a model network. In [Gao and Redfern (2012)] author propose an advanced voltage control strategy for OLTC transformers with DG connection. OLTC voltage control strategy provides an automatic voltage setting point change for existing OLTC transformers with AVC relays to maintain the feeder voltage and maximize the power from the connected DG according to the direction of the power flow.

- **Active and reactive power control of DG**
  An automatic voltage control is proposed in [Nobile and Bose (2002)], dividing the system in voltage control area (VCA) and managing the reactive power in each VCA through automatic adjustment of the voltage reference at some controlling units, using participation factor, help to handle the reactive power market as a localized problem. In [Kojovic (2002)] the interaction of DG with voltage regulators and capacitors using simulated computer models is discussed. When a DG is sized to closely match the local load and is located near the local load, it can provide a significant reduction in line losses. If a DG can control reactive power generation, it can control voltages by reducing (or absorbing, if necessary) reactive power output. If voltages increase by increasing the active power, decreasing the reactive power will cause line voltages to drop. DG output voltage regulation can be achieved using the reactive power setting.

Volt/Var control is one of the important control schemes at a distribution substation, which conventionally involves regulation of voltage, and reactive power at substation bus [Niknam *et al.* (2003)]. The control is in distribution substaion achieved by load tap changer (LTC), Voltage regulators and capacitors. Some Volt/Var control algorithms have already been developed by researchers. DG can cause over voltages as well as under voltages, depending on several factors like DG size and location, method of voltage regulation. An under voltage scenario is caused by a DG unit installed on a feeder and the voltage regulation is controlled by the substation LTC transformer that is equipped with LDC controls. In such a case, the DG introduced may allow the regulator to set a lower substation transformer secondary voltage than necessary and thus causing excessively low voltages towards the feeder end [Dai and Baghzouz (2003)].

Voltage control is possible from voltage-source converter (VSC) interfaces. But most distributed energy resources (DER) units are operated at zero reactive power or at constant power factor [Bollen and Sannino (2005)]. They are viewed to be too small to control the voltage; there is a risk of several small machines fighting with each other for control of the voltage; the control by the DER units may interfere with the control by the network operator; and DER with voltage control carries an increased risk of unintentional islanding. A simple distributed reactive control approach for voltage rise mitigation in distribution networks has been proposed in [Pedro *et al.* (2008)]. The purpose is not to control bus voltage but rather to guarantee that active power generation does not cause voltage rise. An automatic voltage reference setting technique, acting on the tap change control of the transformer supplying the network, can be used to control the voltage rise problem after DG is connected to feeder [Li and Leite (2008)]. By measuring essential voltage points along the distribution network, an automatic voltage reference setting technique is applied to the automatic voltage control (AVC) relay. The AVC relay then controls an on load tap changing transformer in order to maximize distributed generation while maintaining the feeder voltage within limits.

A control method for voltage regulation using the DG and power electronics controller is presented in [Li *et al.* (2008)], the voltage regulation of a distribution system with one DG and two DGs are tested, respectively. The factors affecting the gain parameters of the power electronic controller are investigated. The simulation results show that the parameters of the controller determine its dynamic response for voltage regulation and the factors associated with the network characteristics, such as locations of DGs and the amount of load. The above work has been potentially used for the control system design of smart grid or utility of the future. In [Muneender and Kumar (2009)] the method of selection of generators from the most sensitive cluster zone to re-dispatch the real and reactive powers simultaneously using two distribution factors has been utilized, viz. real and reactive power transmission congestion distribution factors. The proposed method has been tested on a practical 75 bus Indian system for single and multi line congestion cases. The results are compared with the conventional particle swarm optimization, real coded genetic algorithm and binary coded genetic algorithm based OPFs.

In [Wang *et al.* (2009)] proposes generalized and independent active and reactive power control strategies based on symmetric sequence components and shows explicitly the contributions of symmetrical sequences to instantaneous power under unbalanced voltage dips. The proposed strategy enables DG inverters to be optimally designed. In [Conti and Greco (2008)] author proposed optimization procedure aims at minimizing an objective function given by the sum of the costs that distribution network operators incur to perform voltage regulation. The control variables are the HV/MV transformer OLTC position and the power output of the reactive power sources connected to the network.

In [Mogos and Guillaud (2004)] deals with a voltage regulation algorithm for a grid connected DG, based on active and reactive power control. When the reactive power control is not sufficient to keep the voltage on the appropriate range, an action on the active power has been considered. Two DG operating modes are identified and two switching methods between those modes are compared in respect with DG dynamics. In [Triggianese *et al.*(2007)] DG capability in PCC voltage regulation is investigated. Power electronic converters are connected to wind turbines which is interconnected to the grid. Besides converting the energy produced by the generators, the power electronic converters that connect wind turbines to the grid also contribute to voltage regulation.

A comparision of centralized and distributed approaches for controlling distribution network voltages in terms of the capacity of DG that could be accommodated within existing networks as well as contrasting them with the current power factor control approach has been presented In [Vovos *et al.* (2007)]. An optimization approach for determining optimal location of distributed generators in deregulated electricity market based on fuel cost minimization has been presented in [Kumar *et al.* (2008)]. The fuel cost has been obtained connecting distributed generator at each bus iteratively and pattern of fuel cost have been obtained. The distributed generator has been located at a load bus with minimum fuel cost. The patterns of real and reactive nodal price, losses, and line flows have been obtained without and with the presence of distributed generator for pool electricity market model. The proposed optimization approach has been applied for IEEE 24 bus reliability test system.

- **Optimal capacitor placement**
  Capacitors have been commonly used to provide reactive power compensation in distribution systems. They are provided to minimize power and energy losses, maintain best voltage regulations for load buses has been presented in [Hooshmand and Joorabian (2002), Ellithy *et al.* (2008)] . The amount of compensation provided is very much linked to the placement of capacitors in the distribution system which is essentially determination of the location, size, number and type of capacitors to be placed in the system. A method for solving the capacitor placement problem in distribution system using genetic algorithm is presented in [Hooshmand (2002)]. The objective is to reduce the system losses and overall annual costs. In this respects, capacitors with sizes easily found in the market have been used as fixed and switched capacitors for placing on the distribution feeders.

The attention to revise the switched capacitor control settings before installing distributed generation units on distribution feeders. Ignoring such a study may lead to the potential problem of over voltages that occur after switched capacitors come on line. The over voltage depends on numerous factors including DG size, type of capacitor controls and feeder load characteristics [Brady *et al.* (2003)]. The optimal shunt capacitor allocation problem is the determination of the location and sizes of the capacitor to be placed in distribution networks in an optimal manner to reduce the energy losses and peak power losses of the networks. In [Ellithy *et al.* (2008)] author presented the capability oF GA for optimization problems. It is capable of determining near global solution with lesser computational burden. In this respect, it is very suitable to solve the capacitor placement problem.

A study on GA based fuzzy multi-objective approach for optimal capacitor placement while improving voltage profile and maximizing net savings in a radial distribution system is presented in [Das (2008)]. The objectives considered attempt to maximize the fuzzy satisfaction of maximization of net savings and minimization of nodes voltage deviations. A new algorithm based on a combination of fuzzy, forward update (FWD) and genetic algorithm approaches for capacitor allocation in distribution feeders are presented in [Seifi and Hesamzadeh (2009)]. The problem formulation considers three distinct objectives related to total cost of energy loss and total cost of capacitors including the purchase and installation costs and one term related to total cost of produced power under peak load condition. The installation of DG at optimum location boosts the performance of distribution system as well as presents a cost effective solution thus giving a new dimension to distribution system planning. The positive impacts of optimal distributed generator placement are reflected in terms of improved distribution system reliability, reduced customer interruption costs, reduction in losses and improvement in voltage profile as well as power quality at the consumer terminal. In [Paliwal (2012)] author aims at providing an overview of several methodologies which have been adopted for finding out optimal location of distributed generator in distribution system in order to maximize benefits.

- **Coordinated Methods**

  A proposal of a decentralized coordinative voltage control framework using ANN is outlined in [Gubina *et al.* (2001)]. The voltage profile during normal operation without outages is governed sub-optimally using only ANN coordinated voltage controller (CVC). A new cooperative control method using both step voltage regulator (SVR) and unified power flow controller (UPFC) considering interconnection of distributed generators as been presented in [Naka *et al.* (2001)]. The proposed method can regulate the line voltage within the prescribed voltage ranges against steep voltage fluctuations. The method requires little capacity and low cost of the voltage compensating equipment and can be effective to regulate the line voltage with existing SVRs.

A new voltage regulation coordination method of DGs is proposed in [Kim and Kim (2001)], design of a traditional power distribution system controlled by LTC & LDC. In the design, internal setting coefficients like resistance, reactance and the voltage of LDC, the tap interval of LTC, and the bandwidth of the VRR (voltage regulating relay) are adopted as each proper value suitable for satisfactory voltage regulation. And also the requirements and coordination algorithm of DGs for proper voltage regulation are analyzed and proposed.

Coordination of DG and step voltage regulator operations for improved distribution system voltage regulation is presented in [Kojovic (2006)]. The analysis includes DG with induction and synchronous generators and SVRs with control modes such as normal bi-directional; reactive bi-directional, and cogeneration. SVRs hold system voltages within predetermined limits and assure consumer voltage magnitudes are kept within standards. Coordinated voltage control system is well adapted to obtain a stable voltage profile and precise reactive power management in addition to pilot bus voltage regulation has been done in [Richardot *et al.* (2006)]. But the main interest of CVC used in distribution level is that it enables mutualized DG to support transmission network secondary voltage control like a classical production unit connected to high voltage(HV) grid, and that several DG units mutualized in a virtual power plant may replace, with a sufficient penetration rate, conventional medium voltage(MV) level voltage regulation devices.

In [Senjyu *et al.* (2008)] author proposed the optimal control of distribution voltage with coordination of distributed installations, such as the load ratio control transformer, step voltage regulator, shunt capacitor, shunt reactor, and static var compensator. In this work, SVR is assumed to be a model with tap changing where the signal is received from a central control unit. Moreover, the communication infrastructure in the supply of a distribution system is assumed to be widespread. The genetic algorithm is used to determine the operation of this control. In order to confirm the validity of the proposed method, simulations are carried out for a distribution network model with photovoltaic generation. A particular development of an active management control which coordinates the OLTC action in primary substation with the reactive production of distributed generation plants is illustrated in [Bignucolo *et al.* (2008)].

In [Toma et al (2008)] author proposed a methodology for voltage control using tap changing transformers in distribution system and inverters interfaced with distributed generator. Information about voltage and power is gathered via a network, based on the information, the optimal reference values are calculated at control center, and sent to transformers and inverters. The method accomplishes coordinated operation among control equipments and improvement against voltage profile in [Le *et al.* (2007)], presented the method for voltage control coordination is developed based on the priority level of each regulating device and implemented through communication. A sensitivity based technique for determining the control zones of the regulating devices has been developed. A practical system with tap changers and distributed generator has been chosen to test the developed control method. In [Gaonkar *et al.* (2010)] proposes a coordinated voltage control scheme using fuzzy logic based power factor controller, for distribution network with multiple distributed generation systems. In the proposed scheme individual generators participate in voltage regulation of the distribution system, based on their participation factor determined using sensitivity analysis.

In [Nguyen *et al.* (2008)] gives an introduction on the cell based active network (CBAN), a potential system concept for future distribution networks. One of its functions, to deal with limiting the network voltage changes, is focused on with a proposed control scheme, based on an appropriate dispatch of DGs active and reactive power which is implemented autonomously within cells (feeders) of the CBAN. The test results show that the voltage regulation in the CBAN can help to control and mitigate voltage deviations effectively. In [Kashem and Ledwich (2005)] author presented an optimal use of distributed generation to support voltage in distribution feeders is analyzed through in terms of voltage response and voltage sensitivity of lines. A mathematical model is developed to analyze the dynamics of multiple DGs, which can be used to formulate design criteria of multiple DG installation in the network.

The coordinated voltage control presented in [Viawan and Karlsson (2008)] based on automatic remote adjustment to the local operation of the voltage and reactive power equipment in the distribution system. The adjusted equipments are the on load tap changer (OLTC), capacitors in the substation, and DG. The automatic adjustment is based on wide area coordination, in order to obtain an optimum voltage profile and reactive power flow for a one day ahead load forecast and DG output planing.

1.7 MOTIVATION

DG has much potential to improve distribution system performance and it should be considered strongly for future power supply. However, distribution system designs and operating practices are normally based on radial power flows and this creates a special challenge to the successful introduction of distributed generation. The existing voltage control mechanism, which has been developed well before distributed generation era and based on using automatic voltage control relay, is designed to control voltage magnitudes of a distribution network which either has very little generation or no generation at all. To allow greater penetration of distributed generation, a suitable active distribution network would comprise the capability for bidirectional power flows, intelligent voltage control methods and data recording/monitoring systems. Thus, development of new voltage control devices/schemes has the potential to revolutionize the control of distribution network. Intelligent control methods can be developed for voltage control using artificial intelligent (AI) techniques mainly fuzzy logic and genetic algorithms and particle swarm optimization tools can be used. Control over active and reactive power flow, real time monitoring of network loading conditions, redesigning the AVC relays and its associated control for reverse power flow and use of software agent based distribution network control are the other factors which require further research. Optimal coordination of distributed generators and multiple voltage regulating devices such as LTCs, fixed and controllable shunt capacitors in a distribution system can be considered for effective steady state voltage regulation.

1.8 AUTHORS CONTRIBUTIONS IN THE THESIS

The authors contributions in the area of research are summarized as follows

- In this thesis a comprehensive analysis on impact of distributed generators on voltage profile of radial distributed network considering 11 bus and IEEE 69 bus test system are presented. The load flow solution for above test cases are obtained using forward and backward sweep method. The effect of various parameters of DG and distribution system on the voltage profiles are also analyzed through simulation results.

- A method for voltage regulation of distribution system with DG is developed using sensitivity analysis and participation factors of the generators. Two case studies are reported to study the performance of the developed methods using IEEE 69 bus radial system in multi DG environment. In the first case study sensitivity analysis is done for the DG systems to determine the sensitivity index under various load conditions. In the second case study participation factor for individual DG systems are obtained for determining their participation in the voltage regulation. The simulation results are reported to analyze the voltage regulation using above methods.

- The coordinated method for voltage regulation of distribution system with DG and multiple regulators is developed using genetic algorithm. The genetic algorithm is used to determine the optimal setting for the multiple voltage control devices including the DG for a given load condition of the distribution system. The effectiveness of the developed method is studied through simulation results using two case studies considering standard radial distribution systems.

- The fuzzy data clustering method for effective generation of load pattern instead of considering sample load data directly from the hourly load profile for the day is presented. The performance of the developed coordinated voltage regulation method is studied using two case studies considering load pattern generated using fuzzy clustering and the sample load data obtained directly from load profile.

- The load flow algorithm has been applied for unbalanced radial distribution system using forward and backward sweep method. The performance of the coordinated voltage regulation method considering DG, shunt capacitor, static var compensator and load ratio transformer is evaluated for IEEE 13 and 25 bus unbalanced system using case studies. The simulation results to analyze the effectiveness of the applied method to regulate the voltage under various load conditions are also reported.

1.9 ORGANIZATION OF THE THESIS

This thesis is organized into seven chapters and brief overview of each chapter is given below

In **Chapter 1**, an overview of different DG technology, the technical benefits and the various technical issues of DG systems when it is interconnected to utility network are given. The detailed Literature reviews on different voltage regulation methods are presented. The contribution of the author in the thesis is also stated in this chapter.

In **Chapter 2**, an introduction to load flow analysis in the distribution system and the mathematical formulation for voltage rise when DG connected to the distribution system is presented. The applied load flow solution using forward and backward sweep method is given in this chapter. Case studies to determine the effect of various parameters of DG and system on the distribution network voltage levels is also given in the chapter.

Chapter 3, presents the various possible methods for voltage regulation of distribution system. The determination of voltage sensitivity index and participation factors of the generator is presented. Two case studies to analyze the performance of the voltage regulation method using sensitivity and participation factor are also reported in this chapter.

In **Chapter 4**, the modeling of various voltage control devices are given in this chapter. The introduction to genetic algorithm along with the flow chart is reported in this chapter. The applied coordinated voltage control method using multiple voltage regulators including

DG is presented. The simulation results to evaluate the performance of developed method considering two case studies are also given in this chapter.

Chapter 5, presented the application of fuzzy logic in power system. The fuzzy clustering Technique for generating the load profile is reported in this chapter. Two case studies are presented in this chapter to evaluate the coordinated voltage regulation method using load pattern obtained from fuzzy clustering.

In **Chapter 6**, the load flow algorithm for 3 phase unbalanced distribution system is presented. The case studies considering IEEE 13 and IEEE 25 bus unbalanced distribution system is also given. The simulation results of the performance of coordinated voltage regulation method in both cases are analyzed and reported in this chapter.

In **Chapter 7**, the overall conclusions of the thesis and scope for further work are given .

Chapter 2

DISTRIBUTION SYSTEM PERFORMANCE WITH DG

2.1 INTRODUCTION

The introduction of generation sources in the distribution system can significantly impact the power flow and hence the voltage conditions at customer end. These impacts may manifest themselves either positively or negatively depending on the operating conditions of distribution system and DG characteristics. To determine if the DG will cause a significant impact on the feeder voltage, the size and location of the DG, the voltage regulator settings and impedance characteristics of the line must be considered. If line drop compensation is used by the regulator then DG units interconnected within the regulator's zone and downstream of the constant voltage point will support (increase) the feeder voltage [Barker and de Mello (2000)].

The voltage rise is more onerous when there is no demand on the system, as all the generation is exported back to the primary substation [Master (2002)]. The voltage rise during periods of no or minimum demand limits how much generation can be connected to the utility. When connecting a generator to the distribution system, a DNO must consider whether the power may be exported back through the primary substation and must ensure that the transformer's tap changers are capable of operating with a reverse power flow. In [Gorman *et al.* (2005)] author discuss the contribution to both voltage control and increasing the loading on radial distribution feeders that can be achieved by allowing distributed generation to participate in voltage control. The IEEE 14 bus system has been used for the simulation to control the voltage with varying power factor. In [Kiprakis and Wallace (2003)] author discuss the implications of the increasing capacity of synchronous generators at the remote ends of rural distribution networks where the line resistances are high and the X/R ratios are low. Local voltage variation is specifically examined and two methods of compensation are proposed in the same.

The effect the operating strategies of a remotely connected generator can have on the voltage profile of a long 11 kV feeder has been investigated in [Salman *et al.* (1996)]. Two operating strategies have been considered. These are constant power factor mode and constant voltage mode of operations. This investigation has shown: (a) the generator generally increases local voltage magnitudes when it is operated at lagging power factor conditions, (b) local voltage magnitude can be reduced by operating the generator with leading power factor conditions. In [Pecas *et al.* (2007)] author analyzed the repercussions in transmission system operation and expansion that result from the connection of large amounts of DG of different energy conversion systems. In this it is focused on issues related with impacts in steady state operation, contingency analysis, protection coordination as well as dynamic behavior analysis. Some results from studies performed in the interconnected transmission system are presented and discussed. In [Dai and Baghzouz (2004)] author addresses the possible under voltages when installing a DG on a feeder whose voltage is regulated by a LTC transformer with LDC (line drop compensator). The numerical example has been used to illustrate and validate the accuracy of the analytical expressions.

This chapter presented the details about distribution system types and power flow solution. The algorithm for forward and back word sweep method is also given. The investiga-

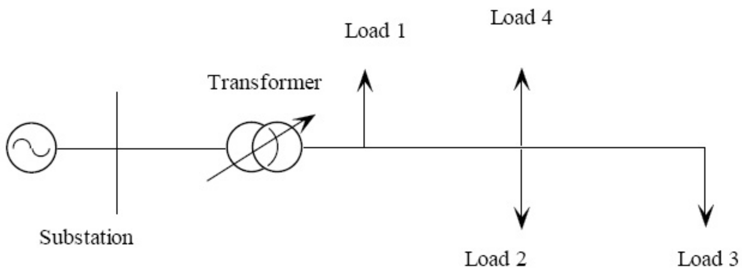

Figure 2.1: A Radial power distribution system

tion on the steady state voltage profile under various conditions of the distribution system is presented. A comprehensive study for voltage profile of distribution system by taking in to account of integrated DG systems and capacitors, considering different locations and capacity is reported in this chapter.

2.2 TYPES OF DISTRIBUTION SYSTEM

The electrical power distribution system can be classified into three types. They are the radial, ring and network systems as shown in Figures 2.1, 2.2 and 2.3 respectively. Radial distribution systems are the simplest type, since power comes from one power source. A generating system supplies power from the substation through radial lines that are extended to the various community. Radial distribtuion systems are the least reliable in terms of continuous service, since there is no back up distribution system connected to the single power source. If any power line opens, one or more loads are interrupted. There is more likelihood of power outages. However, the radial system is least expensive .The radial system is used in remote areas where other distribution systems are not economically feasible.

Ring distribution systems shown in Figure 2.2 are used in heavily populated areas. The distribution lines encircle the service area. Power is delivered from one or more power sources in to substations near the service area and is then distributed from the substations through the radial power lines [Gonen (1986)]. When any power line opens no interruption

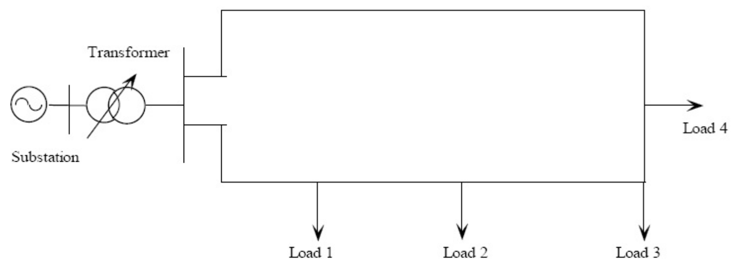

Figure 2.2: Ring power distribution system

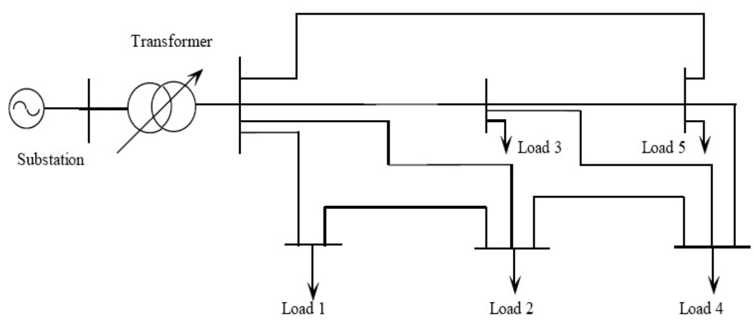

Figure 2.3: Network power distribution system

to other loads will occur. The ring system provides a more continuous service than the radial system. Additional power lines and a greater circuit complexity make the ring system more expensive.

Network distribution systems shown in Figure 2.3 are a combination of the radial and ring systems. They usually result when one of the other systems is expanded. Most of the distribution systems in the United States are network systems. This system is more complex, but it provides very reliable service to consumers. In network power distribution system, each load is fed by two or more circuits.

2.3 POWER FLOW SOLUTION FOR DISTRIBUTION SYSTEMS

One of the most fundamental calculations related to any system is the determination of the steady state behavior. In power systems, this calculation is the steady state power flow problem, also called load flow. It essentially involves finding the steady state voltages at each node, given a certain set of generation and loading conditions. The Newton-Raphson method are very widely used in industry today which has been developed specifically for transmission systems with meshed structure and with many redundant paths from the generation points to the load points. The Newton-Raphson method itself is computationally expensive for large systems, primarily due to the size of the Jacobian and the resulting system of linear equations which must be solved to find the Newton step.

Unlike a transmission system, a distribution system typically has a radial structure. Unfortunately, this radial structure, along with the higher resistance/reactance (R/X) ratio of the lines, makes the fast decoupled Newton method unsuitable for most distribution power flow problems. Since power flow is such a fundamental calculation for a power system, it is used in many applications in planning and operation [Luo and Semlyen (1990)]. Some of the optimization problems related to distribution automation, such as network reconfiguration, service restoration, and capacitor placement, require the solution of hundreds or even thousands of power flow problems. These applications place two primary requirements on a distribution power flow program. First, the modeling must reflect the actual behavior of the system components. Second, the solution algorithm must be robust and efficient. Various efficient distribution power flow algorithms which exploit the radial structure have been proposed in the literature. The most famous methods include: ladder network methods, Gauss-Seidel, Newton- Raphson and Decoupled Newton-Raphson method.

Most of the above methods developed without considering the energy source in distribution system. As distributed generation is becoming an attractive solution to meet the fast load increase in the deregulation era. [Slavickas *et al.* (1999)] utilities have to analyze the operation conditions of the radial systems with distributed resources. Newton-Raphson like methods are not suitable for this purpose because of the high R/X ratio; while traditional ladder network methods also face a great challenge because of the multiple source conditions. In this work load flow solution algorithm is applied using forward and back sweep method and is described in the next section.

2.3.1 Forward and Backward Sweep Method

The forward and backward sweep power flow algorithm for radial system consists of two basic steps, backward sweep and forward sweep, which are repeated until convergence is achieved. The backward sweep is primarily a current or power flow summation with possible voltage updates. The forward sweep is primarily a voltage drop calculation with possible current or power flow updates [Zimmerman (1995)]. Using the boundary condition of zero current and power flow out of the end of each lateral, the backward sweep computes the currents or power flows injected into the beginning of each lateral as a function of the end voltages. The forward sweep is a function of these currents or power flows injected into each lateral and computes the end voltages using the specified source voltage as a boundary condition. The method presented in this section is based on current (as opposed to power flow), and updates both current and voltage in each of the backward and forward sweeps respectively. In [Balamurugan and Dipti (2011)] author presents a review and summery of research developments in the field of distribution network power flow which is an essential part of development of effective smart distribution system analysis tools. Different solution strategies including the modeling of distributed generation sources involved in the distribution network power flow are presented.

The Figure 2.4 shows a single feeder system with notation that will be useful for describing the backward and forward sweeps. This notation will also be used for a general lateral i, where bus zero is not the source in a strict sense but rather the bus where lateral i

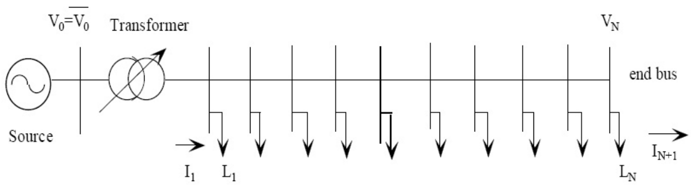

Figure 2.4: Radial feeder of distribution system

branches of lateral *i*-1. The subscripts only refer to the bus index $\overline{V}_o$and refer to the voltage as calculated from lateral *i*-1.

- **Forward Sweep**

  The second half of each iteration of the load flow algorithm in radial distribution system is the forward sweep which starts at the source and moves toward the end buses. During the forward sweep, the laterals are processed in the order. Each lateral is traversed from the supplying connection toward the end bus. Once again, a voltage and current update are performed at each bus. The corresponding update formula for forward calculation is

$$w_k = f_k(w_{k-1}) \tag{2.3.1}$$

Where
w$_k$ is the parameter of (V, I) at kth bus,
W$_{k-1}$ is the parameter of (V, I) at (k-1) bus,

The first two steps are to compute the voltage V_k and current $I_k^{'}$ at the current bus from the voltage and current at the previous bus,V_{k-1} and I_k respectively. The third step is to update the current $\tilde{I}_{LK}$ injected by a load, These injected current is updated from the bus voltage V_k . The last step is to apply KCL to update the current I_{k+1}

on the branch going out to the next bus on the lateral. The KCL has been applied to solved for branch current.

$$I_{k+1} = \widetilde{I}_{LK} - \left(\sum_{j \epsilon A_k} I_j \right) - I_k^{'} \tag{2.3.2}$$

Where

$I_k^{'}$ is the current injected by the bus k in to it's incoming branch,

I_j is the current injected in to sub lateral,

$\widetilde{I}_{LK}$ is the current injected by load,

I_{k+1} is the out going branch current to the next bus on the lateral,

For each lateral, the forward sweep updates the end voltages as a function of the currents injected into the beginning of each lateral. In the notation of the single feeder example of Figure 2.4, V_N is updated as a function of I_1. Given the boundary condition $V_0 = \overline{V}_0$ and a value for I_1, the update equation (2.3.1) is applied recursively starting at the lateral's supplying bus and terminating at the end bus with W_N as shown in equation (2.3.3) .

$$w_1 = f_1(w_0) = f_1 \left(\begin{bmatrix} \overline{V}_0 \\ I_1 \end{bmatrix} \right)$$

$$w_2 = f_2(w_1) = f_2 \times f_1 \left(\begin{bmatrix} \overline{V}_0 \\ I_1 \end{bmatrix} \right)$$

$$f_N(w_{N-1}) = f_N \times \cdots f_2 \times f_1 \left(\begin{bmatrix} \overline{V}_0 \\ I_1 \end{bmatrix} \right) \tag{2.3.3}$$

Where w_1 and w_2 are the parameters of ($\overline{V}_0$, I_1) at bus 1 and 2 respectively,

$\overline{V}_0$ and I_1 are the voltage at source and current at branch 1 respectively.

The upper half of the composite function $f_N \times \cdots f_2 \times f_1$, which yields w_N, is the desired end voltage as a function of the current injected into the lateral and will be denoted as

$$V_N = \tilde{V}_N(I_1) \tag{2.3.4}$$

V_N is the voltage at the end bus,
$\overline{V}_N$ is the function of I_1,

The voltage at the end bus from the equation (2.3.4) is stored for use during the next backward sweep. The lower half of the function $\tilde{I}_{N+1}(I_1)$, is used only as a mismatch. At the solution, this current must be zero. The main feeder is processed first. Then, since the voltages at the supplying buses for all level 2 laterals are known, the level 2 laterals can be processed, followed by level 3, etc. Each lateral is processed in this manner until all the level L laterals have been updated, completing the forward sweep. In the process, all voltages and currents in the network are updated. In particular, all of the end voltages are updated as a function of the currents injected into each lateral.

- **Backward Sweep**

Once the bus voltages are initialized, the algorithm begins with a backward sweep, processing the laterals. Each lateral is traversed from the end bus toward the source and the currents and voltages are updated at each bus. The voltage and current at the previous bus is

$$w_{k-1} = g_k(w_k) \tag{2.3.5}$$

Where w_k is the parameter at k^{th} bus,
w_{k-1} s the parameter at previous bus (k-1)
g_k is the function parameter at k^{th} bus,
The current $\tilde{I}_{LK}$ injected by a load, is computed from the value of the bus voltage V_k at the current iteration. The next step is to apply KCL at bus k to find the current $I_K^{'}$ injected by bus k into its incoming branch. The application of KCL at bus k is

$$I_k^{'} = \widetilde{I}_{lk} - \left(\sum_{j \epsilon A_k} I_j \right) - I_{K+1} \tag{2.3.6}$$

Where the currents I_j are the currents injected into sub-laterals branching off from bus *k*, and I_{k+1} is the current injected into the outgoing branch leading to the next bus on the same lateral. The third and fourth steps compute the V_{k-1} voltage and current I_k at the previous bus. For each lateral, the backward sweep updates the current injected into the lateral as a function of the end voltage. Using the notation from the single feeder example in Figure 2.4 I_1 is updated as a function of V_N . Given the boundary condition $I_{N+1} = 0$ and a value V_N for, the update equation (2.3.1) is applied recursively, starting at the end bus and ending at the lateral's supplying bus with w_0, as shown in equation (2.3.7).

$$w_{N-1} = g_N(w_N) = g_N \left(\begin{bmatrix} \overline{V}_N \\ 0 \end{bmatrix} \right)$$

$$w_{N-2} = g_{n-1}(w_{N-1}) = g_{N-1} = g_{N-1} \times g_N \left(\begin{bmatrix} \overline{V}_N \\ 0 \end{bmatrix} \right)$$

$$w_0 = \begin{bmatrix} V_N \\ I_1 \end{bmatrix} = g_1(w_1) = g_1 \times \cdots \times g_{N-1} \times g_N \left(\begin{bmatrix} \overline{V}_0 \\ 0 \end{bmatrix} \right) \tag{2.3.7}$$

Where

w_0 is the parameter of V_0 and I_1

w_{N-1} and w_{N-2} are the parameters of V_N at previous bus N-1 and N-2 respectively

The lower half of the composite function $g_1 \times \cdots \times g_{N-1} \times g_N$, which yields W_0, is the desired current as a function of the end voltage and will be denoted.

$$I_1 = \widetilde{I}_1(V_N) \tag{2.3.8}$$

This value of the current is stored for use during the KCL calculation at this lateral's supplying bus during the current backward sweep and the succeeding forward sweep.

The upper half, which is the voltage part $\widetilde{V}_0(V_N)$, is used only for mismatch calculation. At the solution, the mismatched $\widetilde{V}_0(V_N) - \overline{V}_0$ between the computed voltage $\widetilde{V}_0(V_N)$ and the specified voltage $\overline{V}_0$ must be zero. To evaluate equation (2.3.8) for a given lateral, the currents injected into all of its sub-laterals must be known, since they are needed for the application of KCL in equation (2.3.6). This means the laterals must be processed in a specific order. Since the level *L* laterals have no sub-laterals, they are processed first. Next, the currents injected into the sub-laterals of all level *L-1* laterals are known, so the level *L-1* laterals can be processed. Each lateral is processed in this manner, starting with level *L* , and then moving to level *L-1* and *L-2*, etc. Finally, the main feeder is processed, completing the backward sweep. In the process, all voltages and currents in the network are updated. In particular, the currents injected into each lateral are updated as a function of the end voltages.

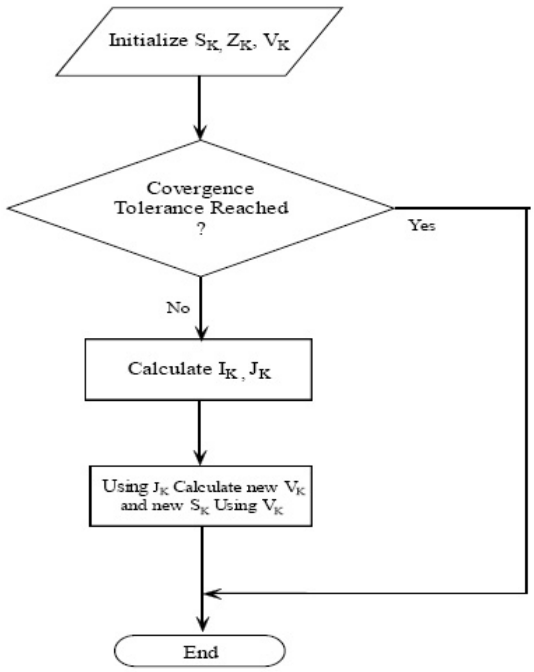

Figure 2.5: General flow chart for the load flow solution

- **Algorithm for forward and backward sweep**

Step1: Initialize the iteration counter, i=1; initialize the voltage values of all feeder buses, i.e.V_2= . . . V_n=1 p.u. V_1=1.03 p.u.

Step2: Calculate the load current:

$$I_k = \left(\frac{S_k}{V_k}\right)^* \qquad \text{with the node voltage profile} V_k$$

Step3: Obtain a new voltage profile V_k^{New}

$$V_k^{New} = V_k - Z_k \times J_k \quad \text{where} \quad J_k \quad \text{is branch current}$$

Step4: Re-calculate S_k^{New}, the adjusted load profile from Equation $V_k^{New} \times I_k$

Step5: Repeat step 2 to step 4 until the convergence tolerance is reached.

2.3.2 Modeling of Load

Load models usually can be classified into two main categories: static and dynamic. Since power flow analysis is mainly performed for static states of power systems, only static load is considered here. Normally, static load can be described using one of the following models: (a) Constant impedance model (b) Constant current model (c) Constant power model (d) Exponential load model. Where as in constant impedance model load power varies with the square of the voltage magnitude and in constant current model load power varies with voltage magnitude only. In costant power model load power does not vary with the voltage magnitude and in exponential load model the load power varies with the voltage magnitude with an exponential relationship [Salaman and Chikhani (1993)].

2.3.3 Consideration of DG System for Load Flow Analysis

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

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

A DG can be modeled as a PV or a PQ bus, the DG can also be modeled as a negative load, which injects real and reactive powers into the system, independent of the system voltage. When the DG is modeled as a PV node the power flow solution determines the machines terminal voltages, and the currents injected by the machines will be a function of the terminal voltage. The DG can be seen as a voltage dependent current source in this mode of operation.

2.4 DISTRIBUTION SYSTEM WITH DG

When the generator is connected to the radial feeder, its active power export reduces the power flow from the primary substation. This causes reduction in the voltage drop along the feeder. If the generator's power export is larger than the feeder load, power flows from the generator to the primary substation and this causes a voltage rise along the feeder. Typically, worst case scenarios are: a) no generation and maximum system demand, b) maximum generation and maximum system demand, c) maximum generation and minimum system demand. In the context of voltage rise effect, minimum load and maximum generation conditions are usually critical for the amount of generation that can be connected [Kojovic (2002)]. However, it may also be necessary to consider maximum load and maximum generation conditions for studying voltage rise problem [Thomson (2000)].

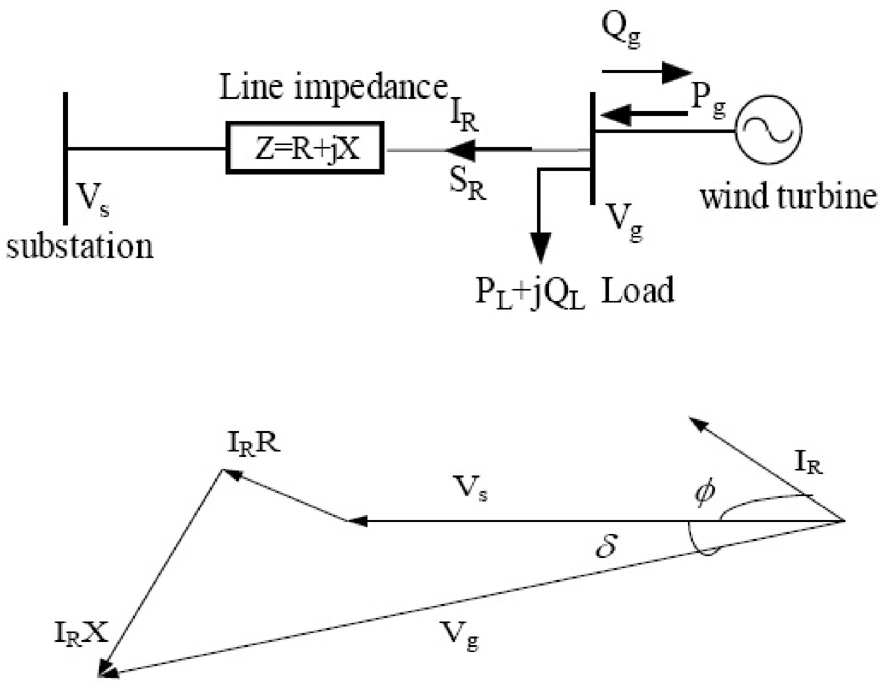

Figure 2.6: Utility network with wind DG system and phasor diagram

The Figure 2.6 Illustrates the connection of distributed generator to the distribution network [Scott *et al.* (2002)]. The active and reactive powers of the generator are P_g and Q_g respectively. P_L and Q_L represent the active and reactive power of the load connected to the distribution system. I_R is the net current through the line impedance, $Z = R + jX$ and S_R is the net power injected to network. The substation voltage and connection point voltage are V_s and V_g and respectively.

$$S_R = P_R + jQ_R = P_g - jQ_g - P_L - jQ_L \tag{2.4.1}$$

And since $$S_R = V_g I_R^*, I_R = (P_R - jQ_R)/V_g^* \tag{2.4.2}$$

$$V_g = V_s + I_R Z$$

$$= V_s + (R + jX)(P_R - jQ_R)/V_g^* \tag{2.4.3}$$

$$= V_s + (P_R + XQ_R)/V_g^* + j(P_R X - Q_R R)/V_g^*$$

Considering the phasor diagram in Figure 2.6

$$V_g \sin\delta = (P_R X - Q_R R)/V_s \tag{2.4.4}$$

Since the voltage angle δ is very small, the term

$$(P_R X - Q_R R)/V_s$$

is also very small and can be neglected. Magnitude of voltage rise ΔV is approximately given by

$$(P_R R + XQ_R)/V_g^*$$

$$\Delta V = (P_g - P_L)R - X(Q_g + Q_L)/V_g^* \tag{2.4.5}$$

The active power produced by embedded generators increase the voltage, whereas the reactive power can further increase or reduce it depending on the type of DG technology. The synchronous generator can generate or absorb reactive power, but the induction generator only consumes reactive power. These outcomes, in combination with the system's R/X ratio or distribution network characteristics and load profiles, determine whether the voltage level at the connection point is increasing by increasing the power production of DG or not. In general for a radial system the voltage level decreases along the feeder, from supply end to the end of the feeder. If the connection of a DG to distribution network causes an excessive voltage rise; there are a number of methods that can be employed to alleviate the situation. In [Xu and Tylor (2008), Tengku *et al.* (2012)] explianed some of the methods of voltage control in steady state voltage of distribution network. The methods for regulating the steady state voltage of distribution network can be given as follows:

- Reduction in line impedance
- Reduction in substation voltage
- Voltage control by AVC using regulating transformers
- Reactive power management
- DG reactive and active power control

Reduction in line impedance is usually achieved by upgrading the distribution feeder through reinforcement. Study presented in [Master (2002)] shows that it is an effective method. However replacing the conductors will be expensive and makes the scheme uneconomical. The DNO can reduce the set point voltage at the primary substation, thus reducing voltage further down the feeder. However, owing to the variability of the renewable energy sources and non dispatchable nature of some DG systems, there may be a loss in generation. When this occurs, the voltages would be further reduced, sometimes below the statutory limits. The technique, which is generally followed to alleviate the voltage rise problem, is constraining the distributed generator operation. But this method reduces the DG efficiency. In general for a radial system the voltage level decreases along the feeder, from supply end to the end of the feeder.

$$\overline{V_{N+1}} = \overline{V}_1 - \sum_{k=1}^{n} \frac{(R_K + jX_k)(P_{k+1} - jQ_{k+1})}{\overline{V_{k+1}^*}} \tag{2.4.6}$$

2.5 RESULTS AND DISCUSSION

There are two case studies that have been considered in this chapter to study the performance of distribution system with distributed generators. In case study-1, the 11 bus system is considered with uniform and concentrated loads and case study-2 a IEEE 69 bus system is considered. In both the case studies voltage profile of distribution system are analyzed considering the DG parameters such as rating of the DG, location and power factor. The various load condition and the effects of capacitor connection to the distribution system are also considered in the study.

2.5.1 Case Study 1: Performance Study with 11 Bus System

The Figure 2.7 shows the 11 bus radial system considered for study. The transformer is rated at 138/12.47 kV. The LTC for the substation transformer is used to adjust the secondary voltage to 1.05 p.u. at all the time. The 4 mile long distribution feeder has resistance and inductive reactance as 0.28 ohm/mi and 0.64 ohm/mi respectively. The total active and reactive peak load of the radial network is 10 MW and 5 MVAR respectively. Load data are given in [Dai and Baghzouz (2003)]. Each node is connected by a load having active and reactive powers as given in the Table 2.1. The voltage profiles from Figures 2.13 to 2.21 show that the variation of voltage level with DG and capacitors connected at different conditions.

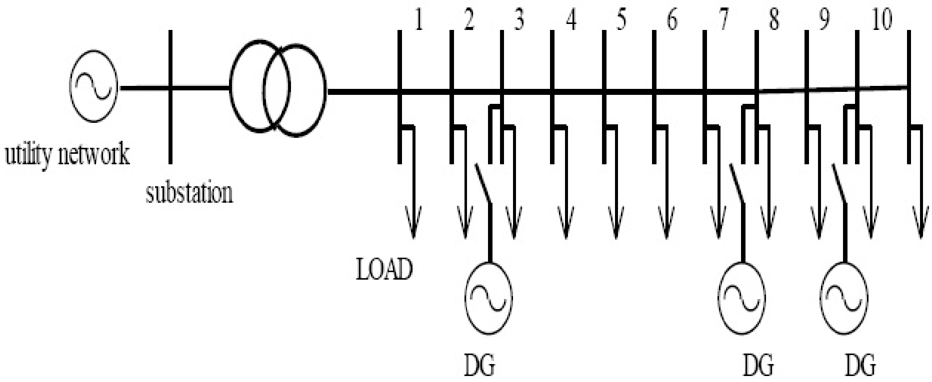

Figure 2.7: 11 Bus radial distribution system

Table 2.1: Feeder and load data of 11 bus radial system

Bus no	Distance in miles	P(MW)	Q(MVAR)
1	0.80	2.1	1.3
2	0.45	1.4	0.8
3	0.30	1.0	0.6
4	0.25	0.5	0.1
5	0.20	0.8	0.2
6	0.25	0.6	0.3
7	0.55	0.9	0.5
8	0.25	1.3	0.6
9	0.30	0.3	0.1
10	0.40	0.5	0.2
11	0.25	0.6	0.3

The Figure 2.8 shows the resulting voltage profile when the load is varied from 100% to 25% prior to the DG installation. When the load is 100%, voltage at the end of the feeder is 0.97 p.u. The Figures 2.9 and 2.10 are the voltage profiles of study distribution system with uniformly distributed and concentrated load respectively with 8 MW DG operating with different power factors. It can be observed that the voltage level increases more at the connection point of DG. The concentrated load method is expected to be more accurate than the uniformly distributed load method for the system under study.

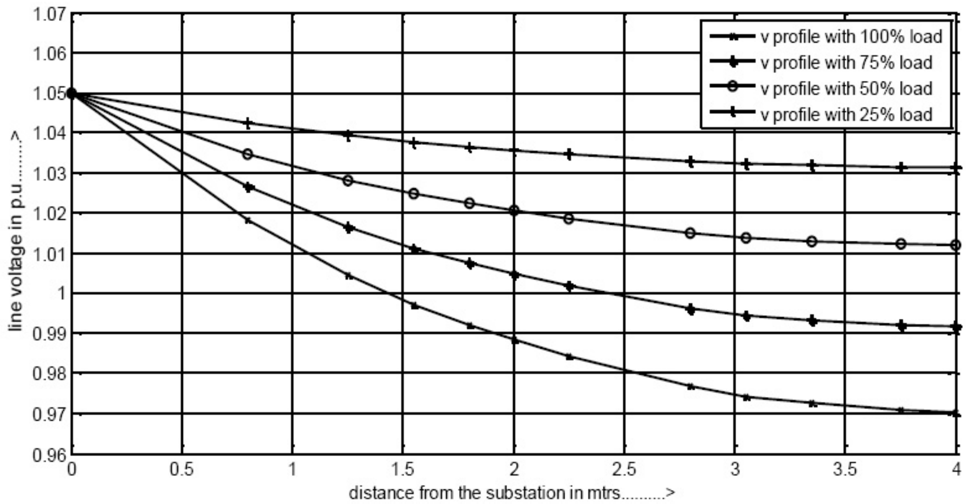

Figure 2.8: Voltage profile with different load levels prior to DG Installation

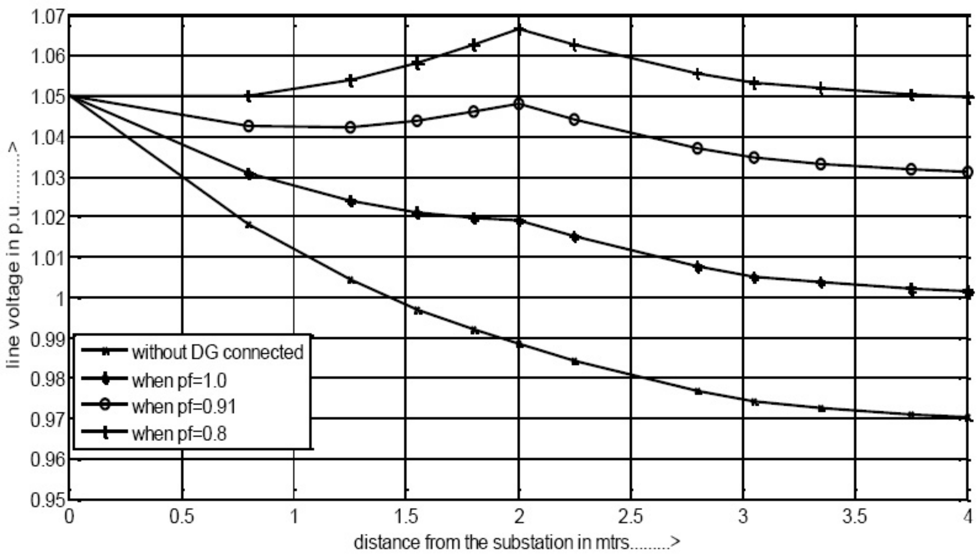

Figure 2.9: Voltage profile with DG at different power factor (with uniform load)

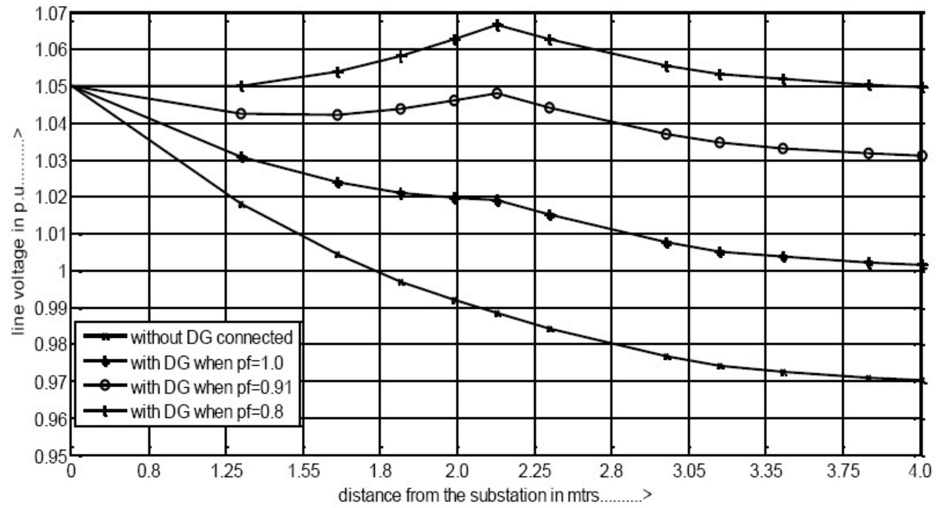

Figure 2.10: Voltage profile with DG at different power factor (concentrated load)

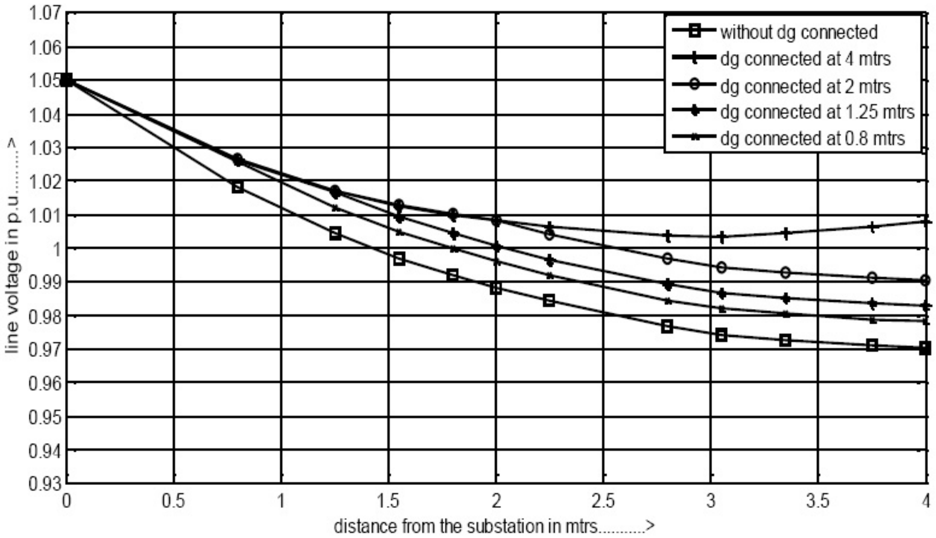

Figure 2.11: Voltage profile with DG installed at different locations

Figure 2.11 shows the voltage profile after installing a 5 MW distributed generator at different location along the feeder during peak load. When this particular DG is installed at the end of the feeder (4^{th} mile), it tends to raise the voltage from 0.97 p.u. (prior to DG installation) to 0.98 p.u, thus providing voltage support. On the other hand, when it is moved close to the substation, it causes the last mile of the feeder to operate at a voltage below 0.95 p.u. hence it confuses the LTC by setting voltage lower than required to maintain adequate service. Figure 2.12 shows the resulting voltage profile when the different sizes of DGs are connected at a fixed point located at 1.25 miles from the substation during peak load. The maximum DG size at this particular location that will not result in an under voltage at the feeder end is estimated to be 3.2 MW (64%). The corresponding voltage profile verifies that such a limit is sufficiently accurate.

Figure 2.13 shows the resulting voltage profile by assuming a uniformly distributed load with 3 capacitors of size 1200 kVAr, each connected at bus no's 4, 8 and10. Also a DG with capacity of 4 MW is connected at bus no 5. If voltage profiles of Figures 2.9 and 2.10 are compared with Figures 2.13 and 2.14 , then the voltage profiles of Figures 2.13 and 2.14 are more steadier throughout the feeder. Thus it can be observed that a constant voltage can be maintained by connecting lower capacity DG (4 MW) and 3 fixed capacitors instead of a higher capacity DG (8 MW) at bus no.5 as in Figures 2.9 and 2.10.

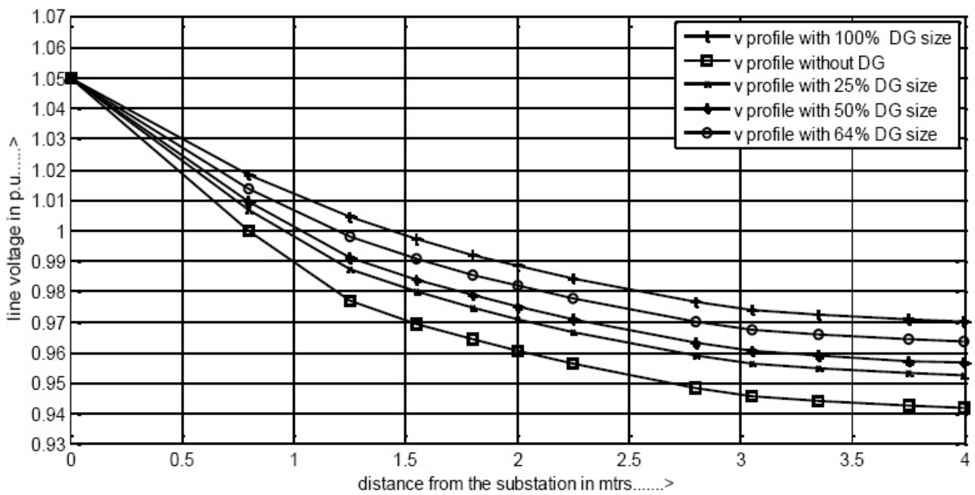

Figure 2.12: Voltage profile with different DG sizes installed at 1.25 miles from substation

Figure 2.14 show the resulting voltage profile by assuming a concentrated load with 3 capacitors of size 1200 kVAr each connected at bus 4^{th}, 8^{th} and 10^{th} and a DG of capacity 4MW connected at bus no.5. The voltage profile without DG connected can be seen in the same Figure 2.14. DG's with the size 4.7 MW, 2.5 MW and 2 MW are connected to the bus 3^{rd}, 8^{th}, and 10^{th} respectively.

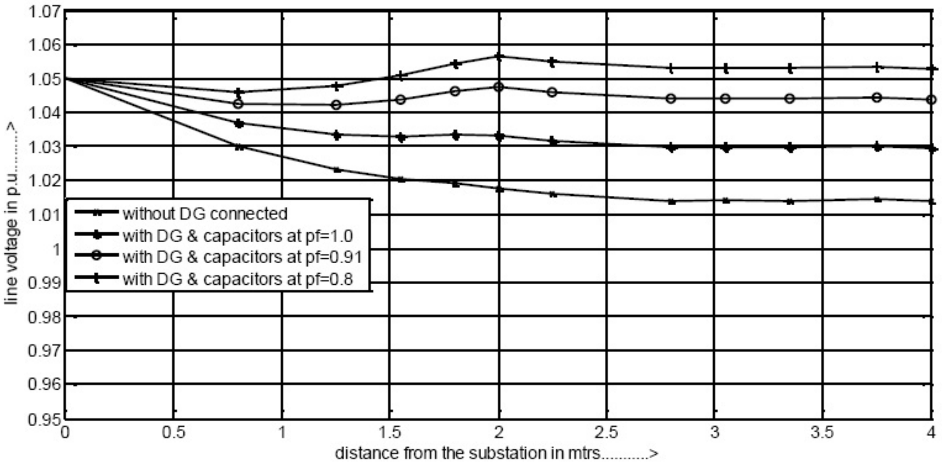

Figure 2.13: Voltage profile with DG and capacitors connected (with uniform loads)

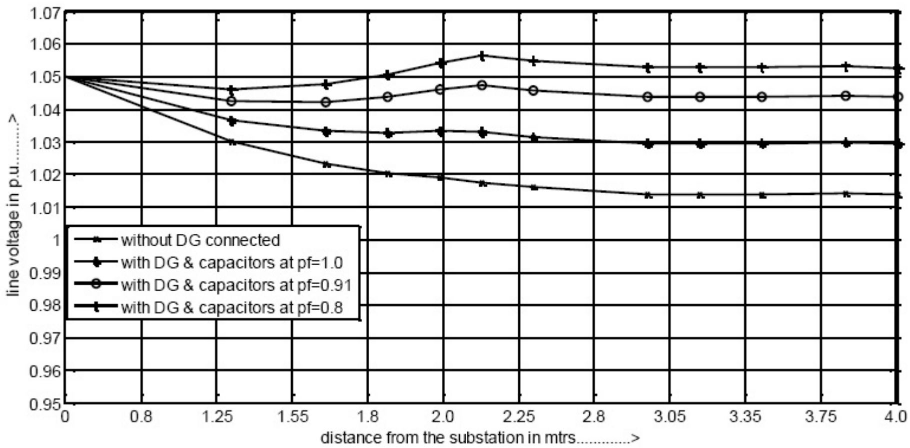

Figure 2.14: Voltage profile with DG and capacitors connected (concentrated loads)

Figures 2.15 and 2.16 show the voltage profile for the system with uniform and concentrated loads with multiple DG's connected at different location. It can be observed that the voltage at each node is approximately the same throughout the feeder without exceeding the voltage limit.

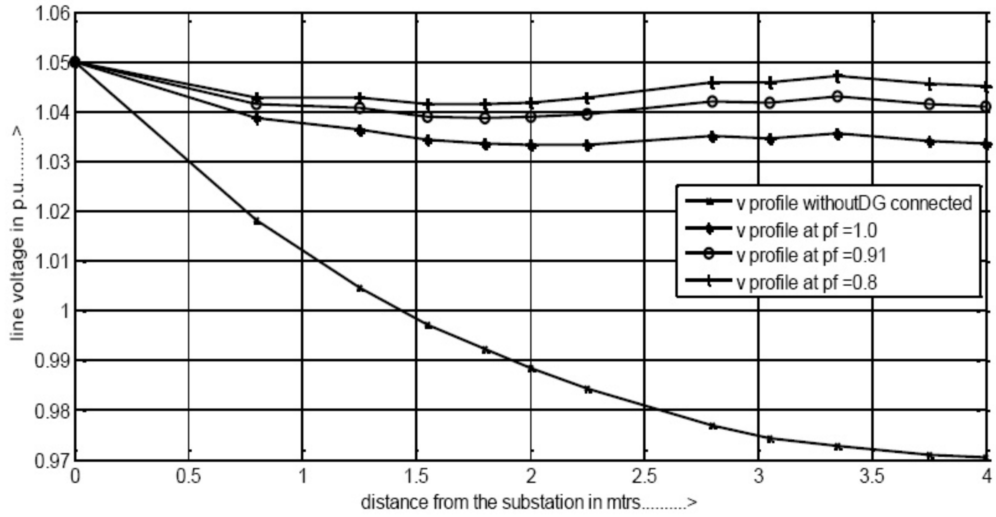

Figure 2.15: Voltage profile with DGs at different power factors (with uniform load)

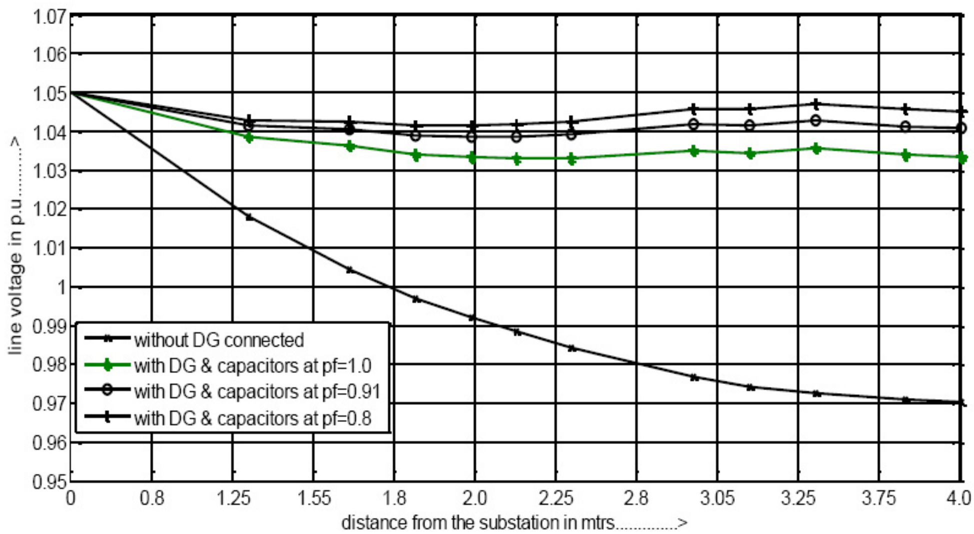

Figure 2.16: Voltage profile with DGs at different power factors (concentrated load)

2.5.2 Case Study 2: Performance Study with IEEE 69 Bus System

The Figure 2.17 shows the IEEE 69 bus radial system considered for the study. In this the substation voltage is 12.66 kV. The LTC for the substation transformer is adjusted with a secondary voltage of 1.0 p.u. at all time. The total active and reactive power load of the radial network is 3.8 MW and 2.69 MVAR respectively. Load data and system data are given in [Das (2008)].

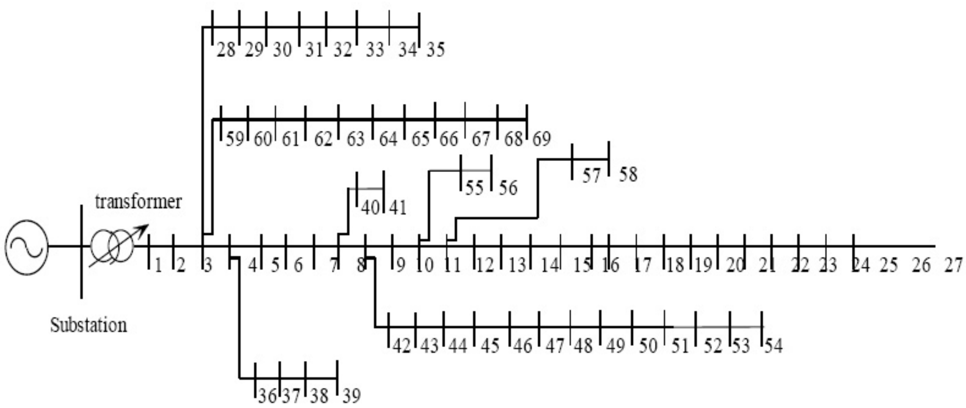

Figure 2.17: IEEE 69 bus radial distribution system

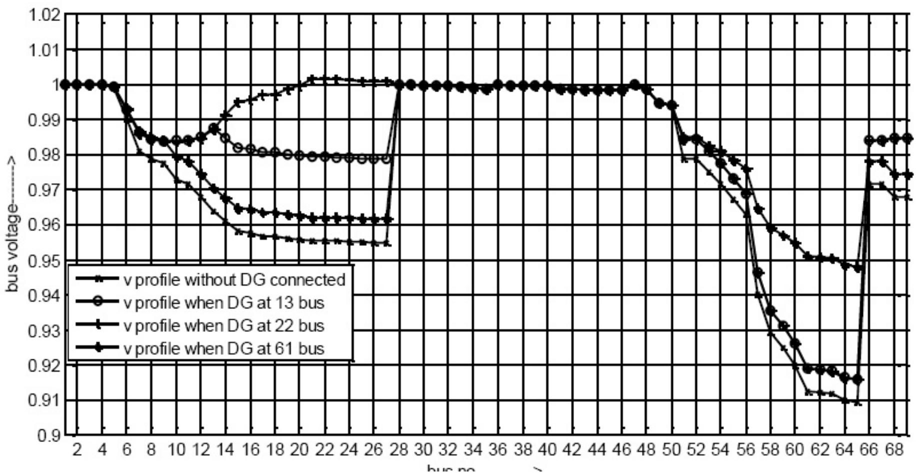

Figure 2.18: Voltage profile with DG (1000 kW) connected at different location of the system

The Figure 2.18 shows the voltage profile of IEEE 69 bus system, with and without DG. In this case DG with 1000 kW capacity is connected at bus 13^{th}, 22^{nd} and 61^{st}. It can be observed that the voltage level of the system is increased more when DG is connected at bus 22^{nd} compared to DG connected at bus no's 13^{th} and 61^{st}. Therefore the DG location plays a vital role in improving the system voltage.

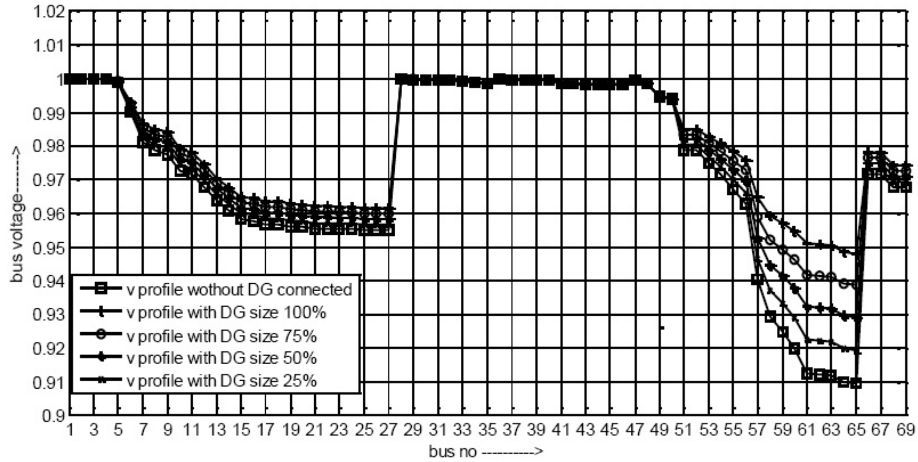

Figure 2.19: Voltage profile with different sizes of the DG connected at bus no 61

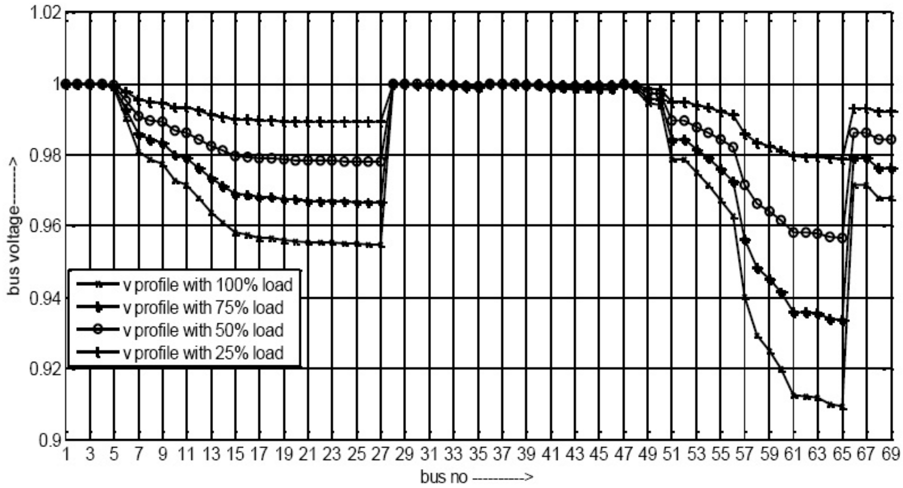

Figure 2.20: Voltage profile with different load level

The voltage profile of the system with a varying capacity DG connected at bus no 61 is depicted in the Figure 2.19. It can be observed from the Figure 2.19 that the voltage level of the system is directly proportional to the size of the DG. The voltage profile of the system with different load level can be seen from the Figure 2.20 .It can be seen that voltage level increases with decrease in load connected to the system.

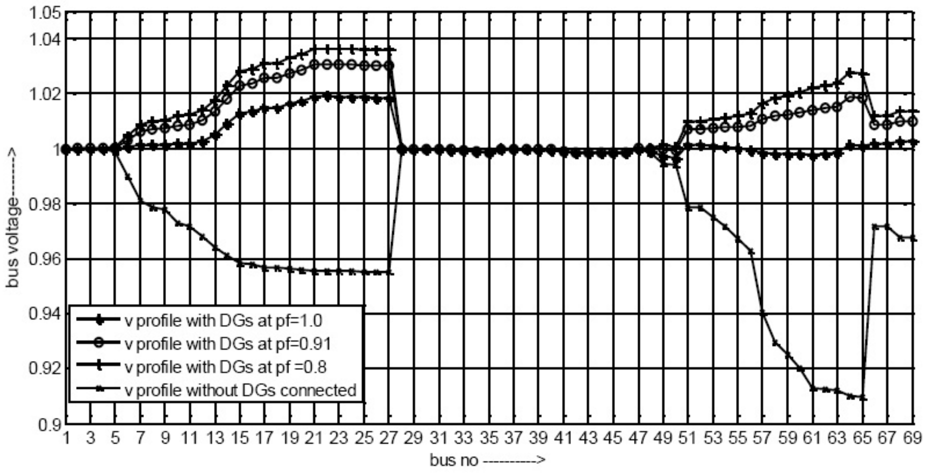

Figure 2.21: Voltage profile with DGs connected at 49^{th}, 62^{nd} and 64^{th} buses.

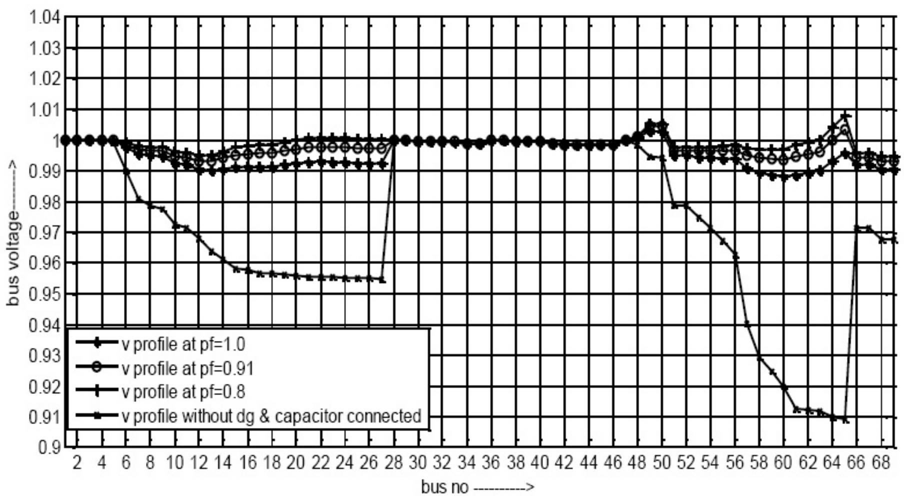

Figure 2.22: Voltage profile with DG at bus 22^{nd}, 50^{th}, 61^{th}, 65^{th}

The Figure 2.21 shows the voltage profile of the 69 bus system without and with DGs with 1000kW capacity connected at bus 9^{th}, 22^{nd}, 49^{th} and 61^{st}. It is observed that the voltage level of the system is increased with decrease in power factor. The voltage profile of the 69 bus system without and with DGs of capacity 500 kW each is connected at bus 22^{nd}, 50^{th}, 61^{st} and 65^{th} and shunt capacitors connected at bus 49^{th}, 62^{nd} and 64^{th} with 1200 kVAr capacity each is depicted in the Figure 2.22. The voltage profile is steadier with reduced DG size and also the shunt capacitor connected to the system.

2.6 CONCLUSION

This chapter presented an overview of the various voltage profile without and with the connection of distribution generation to the distribution system. The study has been done based on the simulation carried out with 11 and IEEE 69 bus radial distribution system with the different DG size, location and fixed capacitor connection to the feeder. The simulation results showed effect of the DG on the voltage level of the system. The DG connection enables the system to withstand higher loading condition thus improving the voltage profile. From the simulation results it has been observed that apart from the varying DG capacity the location of the DG also has an impact on the voltage support ability. The other observation is that the voltage profile of the feeder can be improved much better by using a varied number of DGs with small capacity than connecting a higher size DG. It can be concluded that with a DG connection, a system is immunized against a higher loading condition enabling voltage profile improvement.

Chapter 3

VOLTAGE REGULATION OF UTILITY NETWORK WITH DISTRIBUTED GENERATORS

3.1 INTRODUCTION

Increasing penetration of distributed generation in distribution networks significantly changes both the real and reactive power flows in the network and can create serious voltage control problems. The distribution network operators are obliged by statutory regulation to maintain the voltage levels at the customer within the limits. Furthermore, traditional automatic voltage control schemes that can normally deal with the reverse power flows are unable to cope with the voltage problems associated with the presence of DG under certain conditions. Due to unacceptably high voltage levels new applications of DG are often suspended or the generation capacity limited. The voltage rise is more onerous when there is no demand on the system, as all the generation is exported back to the primary substation.

If the connection of a generator to distribution network causes an excessive voltage rise, there are several techniques that can be employed to alleviate the situation [Master (2002)].

The most common devices and techniques used are network reinforcement, transformer equipped by on load tap changer, OLTC with a line drop compensator [Kim and Kim (2001)], supplementary line regulators installed on distribution feeders [Mogos and Guillaud (2004)], shunt capacitor switched on distribution feeders [Borozan *et al.* (2001)]. The other recent methods are reactive power management and DG reactive and active power control. The reactive power management is a dynamic solution whereby the VAr consumption of the generation is increased to offset the voltage rise from the real power injection. This can be achieved via static var compensators or using Dynamic voltage regulator [Ghosh and Ledwich(2002)], switched capacitor banks [Karla *et al.* (1991)], or via existing inverter in the case of power electronic based DG system. Absorbing reactive power can be very beneficial in controlling the voltage rise effect, especially in weak overhead networks with DG. Furthermore, an increase of the DG injected active power can be realized in this way. Modern wind generations are using mainly double fed induction machines and variable speed synchronous units connected to the grid through electronic interfaces. In [Arief *et al.* (2009)] a new method based on modal analysis for placement of DG units is presented. The results of execution of this method on the modified IEEE 30 bus test system clarify the robustness of this method in optimal placement of DG units. The results show efficiency of modal bus participation factor in determining the optimal allocation for DG installation for improvement of voltage profile, maximum reduction of system active and reactive power losses and also an increase in system eigenvalue.

In this chapter there are two approaches in the selection of generators to control the reactive power of the generators are considered, when more than two generators connected to distribution system. The voltage sensitivity analysis and generator participation factors are developed and analyzed using simulation results. Two case studies are presented in the voltage regulation using OLTC, switched capacitors and DG systems to regulate the voltage rise in the distribution system.

3.2 VOLTAGE SENSITIVITY ANALYSIS

In general, sensitivity analysis measures the impact of changes in the system parameters on the system performance. In connection with power system engineering, sensitivity analysis is used to predict the changes in losses, bus voltages, and branch flows due to changes in load and generation. There are numerous examples in power systems in which sensitivity analysis has been used. In [Khatod *et al.* (2006)] real power loss sensitivity with respect to reactive power injection has been used to identify the candidate locations for the capacitor placement. Sensitivity is defined as the ratio Δ_x/Δ_y relating to small changes of Δ_x some dependent variable to small changes Δ_y of some independent or controllable variable y. Consider a 4 bus system given in Figure 3.1, two generators are connected at nodes 1 and 2 with two loads (S_{L1}, S_{L2})

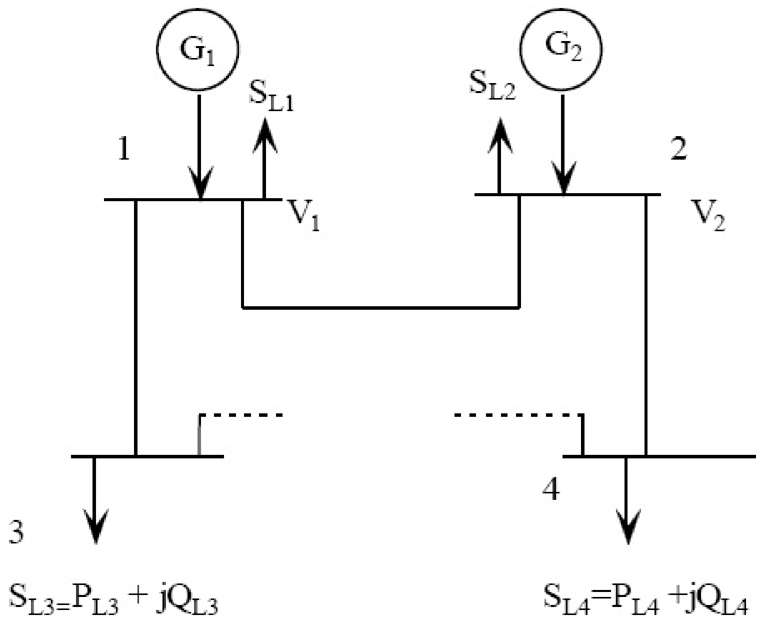

Figure 3.1: Single line diagram for four bus system

Two more loads S_{L3} and S_{L4} are connected at bus no's 3 and 4 as shown. Total power injected in to the network is S_i

$$S_i = P_i + jQ_i = (P_{Gi} - P_{Li}) + j(Q_{Gi} - Q_{Li}) \tag{3.2.1}$$

Where P_i and Q_i are active and reactive powers injected at i^{th} bus and P_{Gi} and Q_{Gi} are active and reactive power generated at i^{th} bus. P_{Li} and Q_{Li} are power demand by the load connected at i^{th} bus

$$[I_{Bus}]_{n\times1} = [Y_{Bus}]_{n\times n}\,[V_{Bus}]_{n\times1} \tag{3.2.2}$$

Y_{Bus} is the bus admittance matrix, *I* is the current and *V* is the voltage at the bus

$$V_{Bus} = Z_{Bus} I_{Bus} \tag{3.2.3}$$

Z_{Bus} (Bus impedance matrix) =Y_{Bus}^{-1}

$$S_i = P_i + JQ_i = V_i I_i^* \tag{3.2.4}$$

Where *i*= 1,2,3 . . . n.
I_i = Source current injected at the i^{th} bus
equation (3.2.4) can be rewritten as

$$P_i - JQ_i = V_i^* I_i \tag{3.2.5}$$

Where *i* $= 1, 2, 3 \ldots n$

$$I_i = \sum_{J=1}^{n} Y_{ij} V_j \tag{3.2.6}$$

Where I_i is the current at i^{th} bus

Substitute equation (3.2.6) in equation (3.2.5) and separate the real and imaginary part, and we get

$$P_i - JQ_i = V_i^* \sum_{J=1}^{n} Y_{ij} V_j \tag{3.2.7}$$

$$P_i = Re\left\{ V_i^* \sum_{J=1}^{n} Y_{ij} V_j \right\} \tag{3.2.8}$$

$$Q_i = -Im\left\{ V_i^* \sum_{J=1}^{n} Y_{ij} V_j \right\} \tag{3.2.9}$$

The voltage and admittance can be written in different forms

$$V_i = |V_i|\, e^{j\delta_i} = |V_i|\, \angle\delta_i = |V_i|(\cos\delta_i + j\sin\delta_i) \tag{3.2.10}$$

$$Y_{ij} = |Y_{ij}| e^{j\theta_{ij}} \tag{3.2.11}$$

Substitute the equations (3.2.10) and (3.2.11) in equations (3.2.8) and (3.2.9), and we get

$$P_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{3.2.12}$$

And the expression of the reactive power is

$$Q_i = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \tag{3.2.13}$$

The partial derivative of the reactive power with respect to the voltage is:

$$\frac{\partial Q_i}{\partial V_{i(j \neq i)}} = |V_i||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) \tag{3.2.14}$$

And

$$\frac{\partial Q_i}{\partial V_i} = \sum_{j=1, j\neq i}^{N} |V_i||Y_{ij}| \sin(\delta_i - \delta_j - \theta_{ij}) + 2|V_i||Y_{ii}| \sin(-\theta_{ii}) \tag{3.2.15}$$

The standard system nodal equation in a decoupled load flow can be written in a matrix form as

$$[\Delta Q] = \left[\frac{\partial Q}{\partial V}\right][\Delta V] \tag{3.2.16}$$

The equation (3.2.16) can be rewritten as

$$[\Delta V] = \left[\frac{\partial V}{\partial Q}\right][\Delta Q] \tag{3.2.17}$$

The sensitivity analysis is done as below:

Step1: Calculate the voltages V_i at all the buses using the load flow program. Check for the voltage limit violation at all buses i.e. $V_{min} < V_i < V_{max}$

Step 2: Consider each connected DG_i varying the reactive power Q_i in steps to Q_{min} , find out the bus for which maximum voltage to reactive power variation occurs by using the following equation

$$\left[\frac{\Delta V}{\Delta Q}\right] = \frac{V_i - V_{new}}{Q_i - Q_{new}}$$

Where ΔV is the change in voltage at the peak value of the voltage profile corresponding to change in reactive power of the generator (ΔQ)

V_i is the voltage at i^{th} bus before change in the reactive power of the generator

V_{new} is the voltage at peak value of the voltage profile after change in the reactive power of the generators

Q_{new} is the reactive power of the generator after increased or decreased to the new value

Step 3: Identify the bus at which $\left[\frac{\Delta V}{\Delta Q}\right]$ maximum occurs. And this gives the sensitivity index.

Step 4: The DG's are given the priority in descending order based on the sensitivity index factor.

Step 5: Set the reactive power of the DG in the DG priority list(generated in step 4) to its Q_{min}

Step 6: Calculate the voltages V_i at all the buses through the load flow program. Check for the voltage limit violation at all buses i.e. $V_{min} < V_i < V_{max}$. Iterate through step 5 until the voltage violation occurs or all the DG's in the priority list are considered.

3.3 PARTICIPATION FACTOR

Participation factor indicates the participation of the generator in voltage control in the distribution system. The generator reactive power influences the voltage profile of each bus of the system. Therefore by decreasing or increasing the reactive power of the generator the voltage level of each bus can be controlled [Arief *et al.* (2009)].

- **Algorithm for generator reactive power calculation**

The algorithm for determination of new reactive power (Q_{new}) which is used to control the rise in voltage at i^{th} bus after connecting the generator to the given radial system is as follows:

Step 1: Calculate the voltages at all the buses (V_i) through the load flow program. Check for the voltage limit violation at all buses $V_{min} < V_i < V_{max}$

Step 2: Find out the bus for which maximum voltage violation exists among all violations. max (*abs(*$V_i - V_{max}$*)*), Where V_{limit} can be V_{max} or V_{min}

Step 3: Suppose that the largest voltage violation happened at i^{th} bus, and then calculate participation factor for different generators connected to the system

Step 4: Calculate the amount of reactive power of the generator. It can decrease or increase the reactive power of generators depending upon voltage level decreased or increased in the voltage profile. Q_{new} is the amount of reactive power of the generator to be increased or decreased. It is calculated using Q_{new} = Q_i + $k\times$ $(Q_{max} - Q_{min})$

Where

Q_i is the reactive power generating at i^{th} bus

Q_{max} is the maximum reactive power limit of the generator

Q_{min} is the minimum reactive power limit of the generator

where k is participation factor of the generator.

If the voltage level crosses the upper limit equation (3.3.1) is used and if the voltage level in the bus crosses the lower limit equation (3.3.2) is used for the calculation of participation of each generator.

$$k^+ = \frac{Q_{imax} - Q_i}{\sum_{j=1}^{n}(Q_{jmax} - Q_j)} \tag{3.3.1}$$

Where Q_{imax} is the maximum reactive power capacity of the generator connected at i^{th} bus.

Q_i is the actual reactive power generated connected at i^{th} bus

Q_{jmax} is the maximum reactive power capacity of the generator connected at j^{th} bus.

Q_j is the actual reactive power generated connected at j^{th} bus

$$k^- = \frac{Q_i - Q_{imin}}{\sum_{j=1}^{n}(Q_j - Q_{jmin})} \tag{3.3.2}$$

Where Q_{jmin} is minimum value of reactive power connected at j^{th} bus

Step 5: Calculate the new voltage profile through load flow program.

Step 6: Repeat Step 1 to 5, to check for voltage limit violations.

3.4 RESULTS AND DISCUSSION

The voltage control methods proposed are studied using two case studies. In case study 1, voltage control method uses an on load tap changing transformer, capacitor and DGs reactive power. Voltage sensitivity analysis is considered for only DGs connected to the system. The voltage sensitivity analysis is based on the voltage sensitivity index of the DGs connected. In case study 2, voltage control for the system with only generators connected to the system is considered. In this participation factor of the generators connected to the system is calculated to find the amount of reactive power to be decreased or increased to enable voltage control. In both the case study IEEE 69 bus system is used for the simulation.

3.4.1 Case Study 1: Voltage Regulation with Sensitivity Analysis

The system used for the simulation is shown in Figure 3.2, the transformer is rated at 138/12.66 kV. The LTC for the substation transformer is assumed to adjust the secondary voltage to 1.0 p.u. at all timeS. The total peak load of the radial network is 3.8 MW, 2.69 MVAR. The load and feeder data is given in [Das (2008)]. The tap settings of the OLTC should not cross $\pm 10\%$ and the voltage profile of the system should not cross the $\pm 6\%$ [Master (2002)].

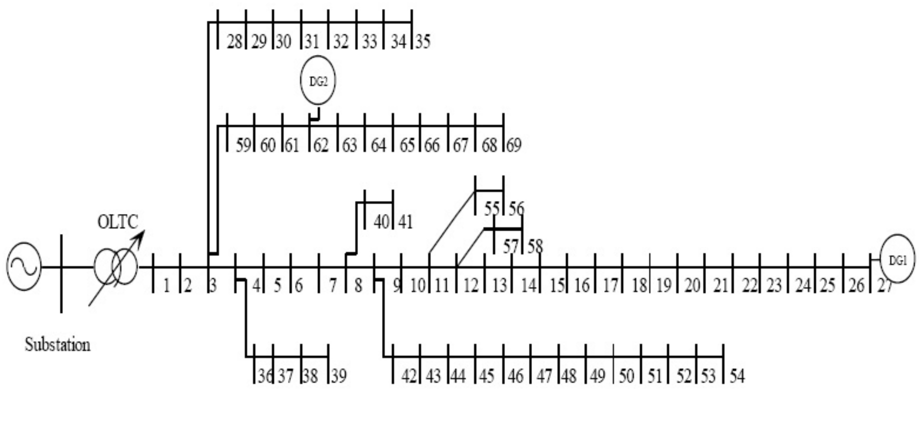

Figure 3.2: IEEE 69 bus radial distribution system

a .Voltage control with DGs reactive powers and OLTC

The two DGs with the capacity of 1.5 MW and 0.730 MVAR are connected at 27^{th} and 62^{nd} bus as shown in Figure 3.2. Figure 3.3 shows the voltage profile of the system without and with DGs connected. The system voltage level from bus no 57^{th} to 64^{th} is low and crossing the lower voltage limit (0.95 p.u.) without DGs connected. It can also be seen that the voltage level exceeds the upper limit 1.05.p.u.at the bus no 27^{th}.

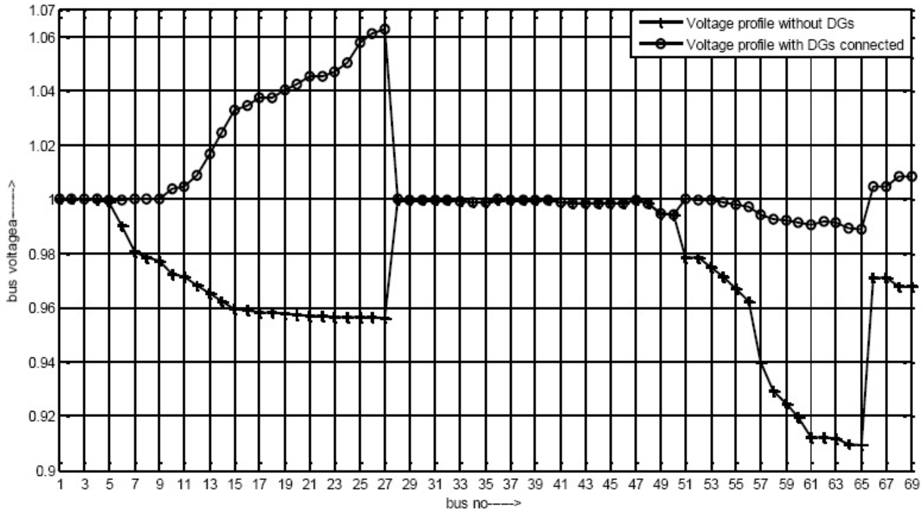

Figure 3.3: Voltage profile with and without DGs at 100% load

To bring the voltage level within limits, the reactive powers of the DGs has to be changed from maximum to minimum value. The voltage sensitivity analysis has been done to find out the voltage sensitivity index of each of the generators connected to the system. Depending on the generator sensitivity index value, priority is given to bring their reactive power from maximum to minimum. The generator having highest sensitivity index can have its reactive power reduced to its minimum value; similarly the generator having the second highest sensitivity index is considered to decrease its reactive power to minimum value. The sensitivity analysis has been done for the different load connected to the system; The sensitivity index of the generators is indicated in the Table3.1. The Table 3.1 indicates the voltage sensitivity index of two generators with the same capacity connected at bus no 27^{th} and 62^{nd} bus at different load conditions. It can be observed that the generator connected at 27^{th} bus has a higher sensitivity index value compared to the generator connected at 62^{nd} bus at all load considered.

Table 3.1: Voltage sensitivity index analysis at different load

Different Load	**Voltage sensitivity index**	
	27^{th} bus generator	62^{nd} bus generator
100%	1.785×10^{-5}	3.24×10^{-6}
75%	1.769×10^{-5}	3.08×10^{-6}
50%	1.737×10^{-5} .	2.92×10^{-6}

Voltage profiles for 100% load:

Figure 3.4 shows that the voltage profile of the 69 bus system after decreasing the reactive powers of two DGs connected at 27^{th} and 62^{nd} bus to Q_{min} . It can be seen from the voltage profile that the voltage level of the system is still above the upper limit even after reducing both DGs reactive powers.

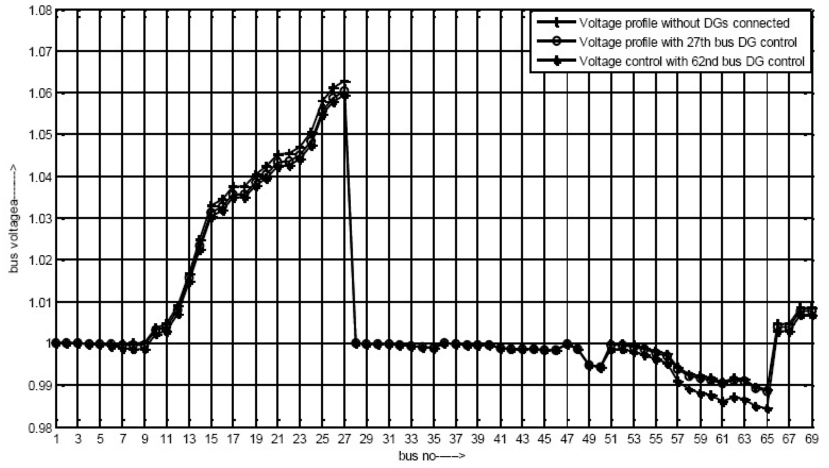

Figure 3.4: Voltage profile with DGs reactive power control

Figure 3.5 shows the voltage profile of the system with DGs reactive power and OLTC control, and it can be observed that the voltage regulation has been achieved.

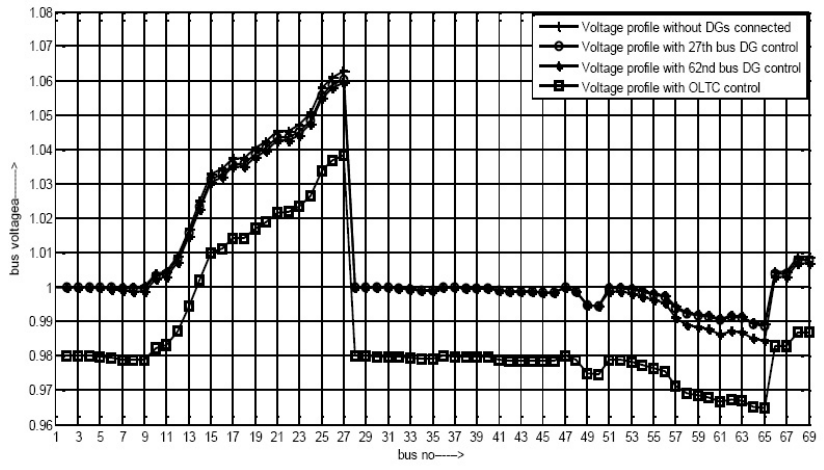

Figure 3.5: Voltage profile with both DGs and OLTC control

Voltage profiles for 75% loads:

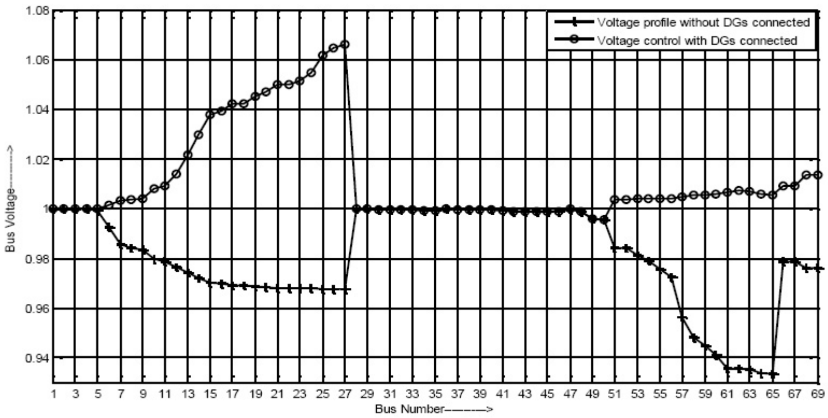

Figure 3.6: Voltage profile with and without DGs connected

Figure 3.6 shows the voltage profile for system with and without connecting DGs at 75% load. It can be seen that the voltage levels at 57^{th} to 64^{th} bus is below the voltage limit 0.95 p.u. when DGs are not connected. In the voltage profile (Figure 3.6), the upper voltage limit has been violated at bus no 27. To bring the voltage within the limit, the DGs reactive power is decreased to their Q_{min} based on the priority decided by their voltage sensitivity index.

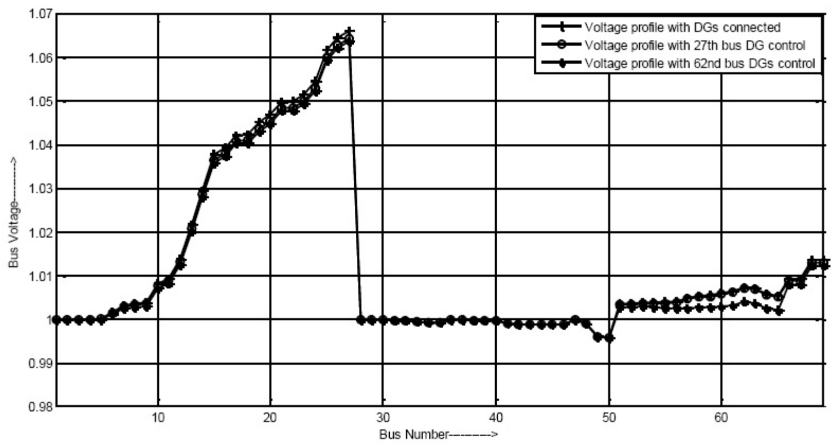

Figure 3.7: Voltage profile with DGs reactive power control

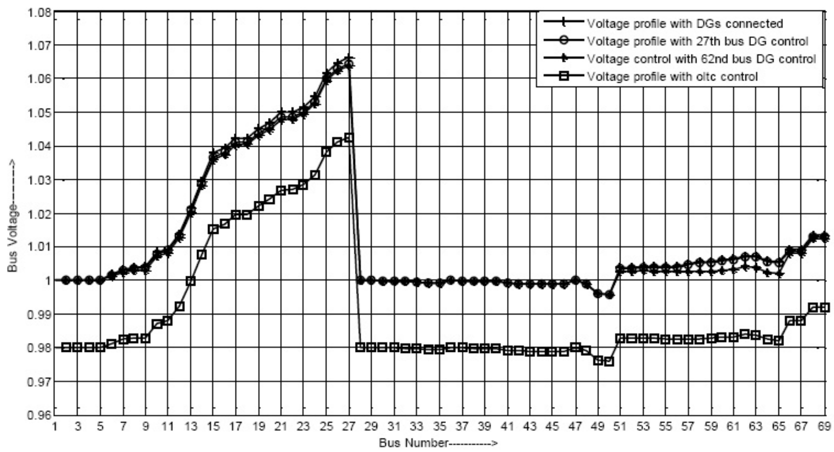

Figure 3.8: Voltage profile with DGs and OLTC control

It can be seen from Figure 3.7, that the voltage level of the system at 27^{th} bus still exceeds the upper limits even with the reactive powers of DGs reduced to Q_{min}. From Figure3.8, it can be observed that the voltage control is achieved by OLTC tap adjustment.

Voltage profile for 50% load:

Figure 3.9 shows that, the voltage profile of the system with 50% of the full load with and without connecting the DGs. It can be seen that when DGs are not connected to the system voltage level at all the buses are within the voltage limits. When the DGs connected at 27^{th} and 62^{nd} bus (1.5 MW and 0.730 MVAR each) the voltage level at 27^{th} bus crosses the upper limit.

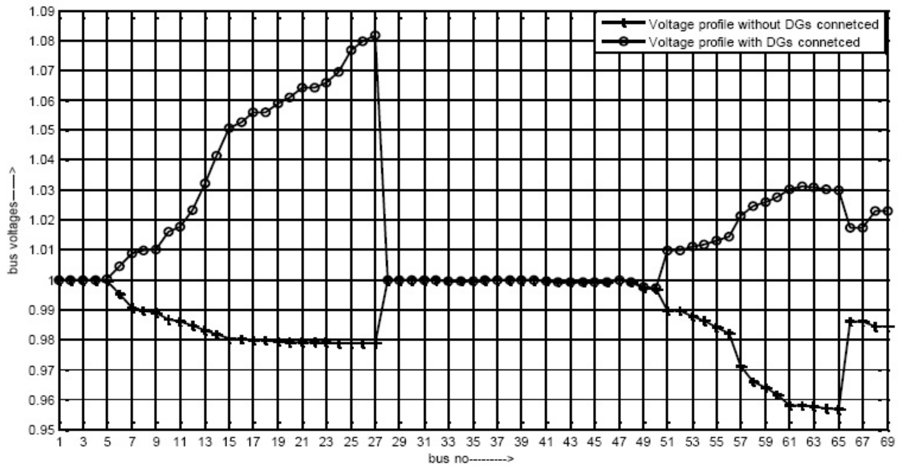

Figure 3.9: Voltage profile with and without DGs connected

Figure 3.10 shows the voltage profile of the system with DGs reactive power and OLTC control. It can be observed that the voltage level of the system cannot be controlled only by the reactive powers of DGs.The voltage has been regulated with both DGs reactive power reduction and OLTC tap setting adjustment. The OLTC tap setting values and maximum and minimum voltage levels of the system with and without DGs at different loading conditions is indicated in the Table 3.2

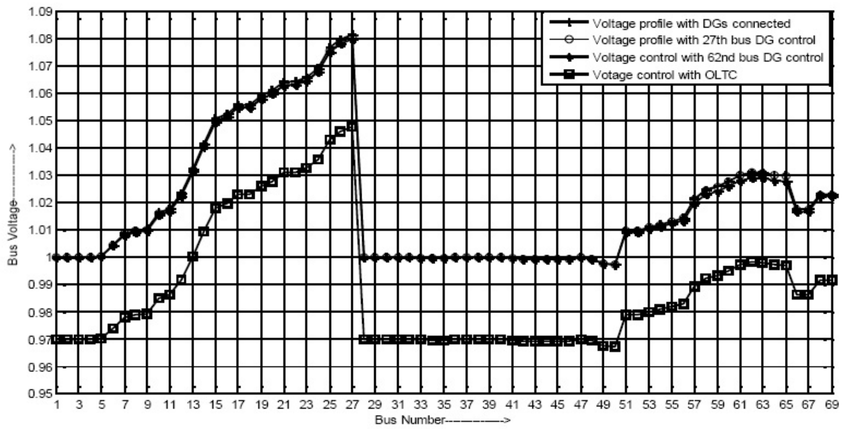

Figure 3.10: Voltage profile with both DGs and OLTC control

Table 3.2: Maximum and minimum voltage level in p.u with and without voltage control

Voltage control devices	Voltage level	100% load	75%load	50%load
w/o DG control	max	1.0912	1.09946	1.1095
	min	1.0193	1.0258	1.0273
with 1 DG control	max	1.889	1.0928	1.1083
	min	1.0189	1.0258	1.0273
with 2 DG control	max	1.0880	1.0922	1.1080
	min	1.0146	1.0258	1.0273
with OLTC control	max	1.0499	1.0458	1.0470
	min	0.9791	0.9848	0.9708
OLTC Tap Setting		0.965	0.960	0.940

b .Voltage control with DGs reactive powers, switched capacitor and OLTC

Voltage profiles at 100% load:

When DGs with a capacity 2.0 MW and 0.970 MVAR are connected at 49^{th}, 50^{th}, 61^{st}, and 64^{th} buses of the IEEE 69 radial system as shown in Figure 3.2 voltage profile has increased. The capacitor with 1000 kVAr is connected at 59^{th} bus. The voltage profiles of the system with and without DGs connected at full load can be seen in Figure 3.11. It can be seen that, the voltage level at 64^{th} bus exceeds the upper limit, but it can be observed that the bus no 6^{th} to 26^{th} voltage level is improved in comparison to the voltage level before DGs are connected.

The voltage sensitivity analysis has been done to obtain the DG priority to reduce the generators reactive powers among 4 DGs connected to the system. The voltage sensitivity analysis helps us to identify which among the DGs influences more on peak voltage level at 64^{th} bus. From the voltage sensitivity analysis, the generator connected at 64^{th} bus is found to have the highest voltage sensitivity index. Therefore the reactive power of the generator connected at 64^{th} bus is decreased to Q_{min}. It is more effective in achieving voltage control compared to other bus generators. The next priority should be given to the generators connected at 61, but generators connected at 49^{th} and 50^{th} bus have no influence on the peak voltage at 64^{th} bus. The voltage sensitivity index of the generators can be seen in Table 3.3.

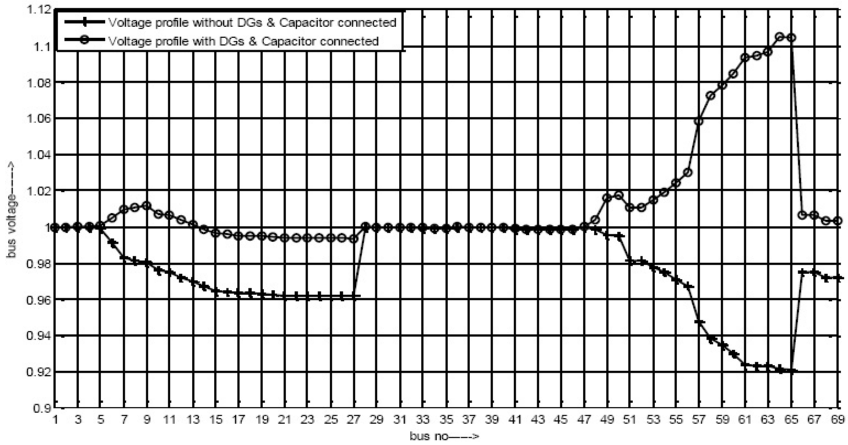

Figure 3.11: Voltage profile with and without DGs and capacitor connected

Table 3.3: Voltage sensitivity index of generator at different load

Different Load	**Voltage sensitivity index**			
	$49^{th} bus$	$50\ ^{th} bus$	$61^{st} bus$	$64^{th} bus$
100%	No influence	No influence	1.173x10^{-5}	1.442x10^{-5}
90%	No influence	No influence	1.161x10^{-5}	1.430x10^{-5}
75%	No influence	No influence	8.19x10^{-6}	1.075x10^{-5}

Figure 3.12 shows the voltage profile of the system with all DGs reactive power control. It can be observed that, the voltage levels are still above the upper voltage

limit even after decreasing the DGs reactive powers to Q_{min}. The voltage profile of the system with the DGs reactive power and capacitors control is shown in Figure 3.13. The capacitor connected to the system at 59^{th} bus has been switched off after the DGs reactive power control. It can be observed that the voltage still crosses the upper limit.

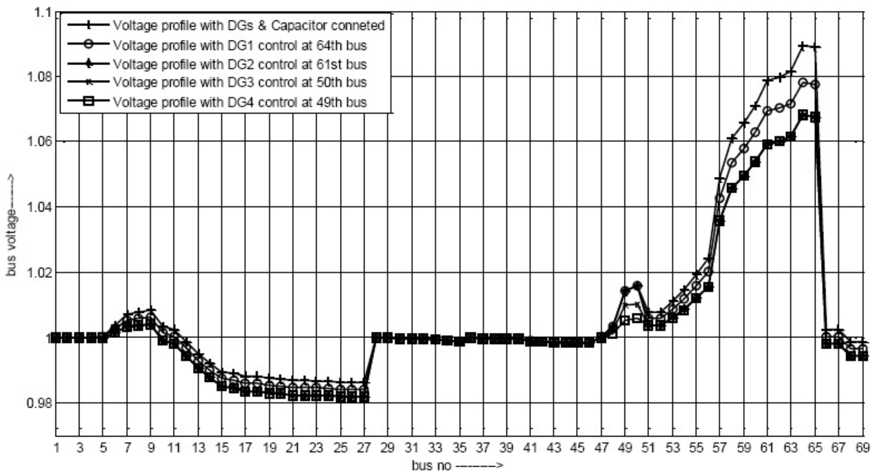

Figure 3.12: Voltage profile with DGs reactive power control

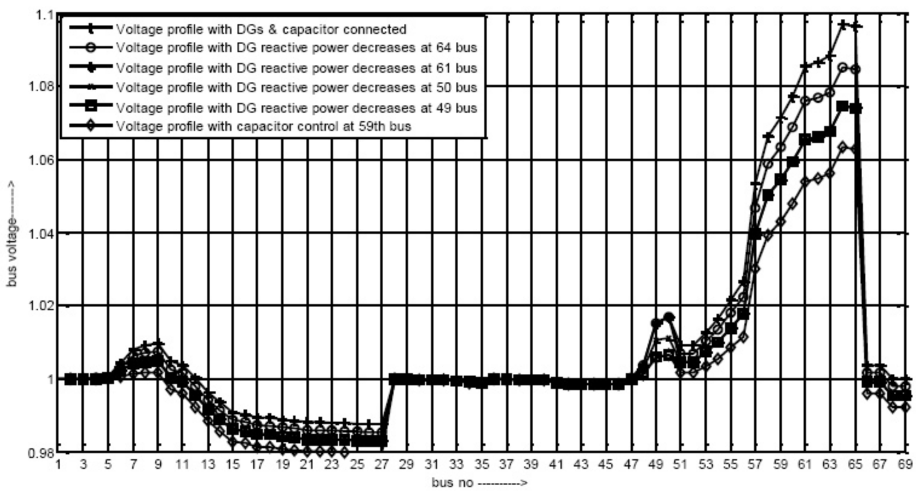

Figure 3.13: Voltage profile with DGs and capacitor control

Figure 3.14 shows the voltage profile of the 69 bus system with voltage control using DGs reactive powers, capacitor control and OLTC tap setting adjusted at the substation. The voltage has been successfully regulated.

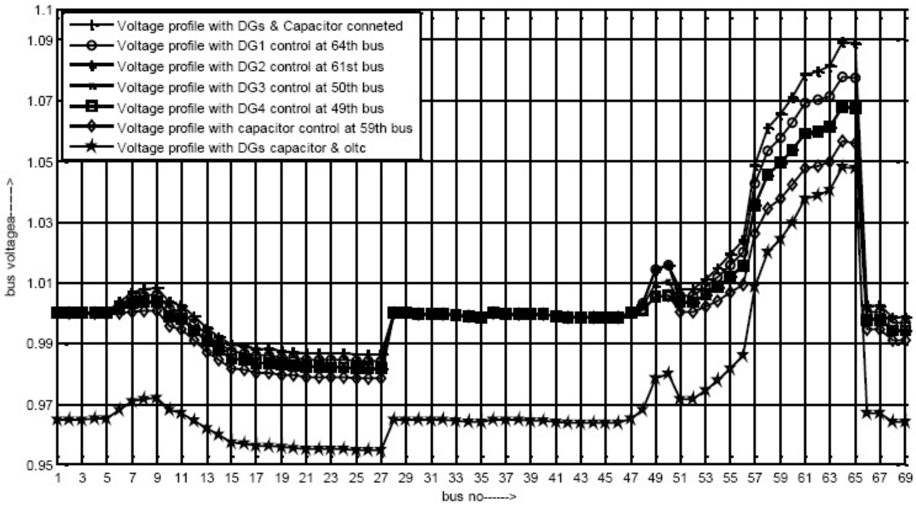

Figure 3.14: Voltage profile with DGs, capacitors and OLTC control

Voltage profiles with 90% load:

Figure 3.15 shows the voltage profile of the system at 90% load with and without DGs connected. It can be seen that the voltage has increased after connecting the DGs at 49^{th}, 50^{th}, 61^{st} and 64^{th} bus and a capacitor at 59^{th} bus. The voltage rise can be seen at 64^{th} bus. Even after reducing the reactive powers of all 4 generators to Q_{min} according to their priority decided based on their voltage sensitivity index, voltage of the system still crosses the upper limit even with the capacitor at 59^{th} bus switched off.

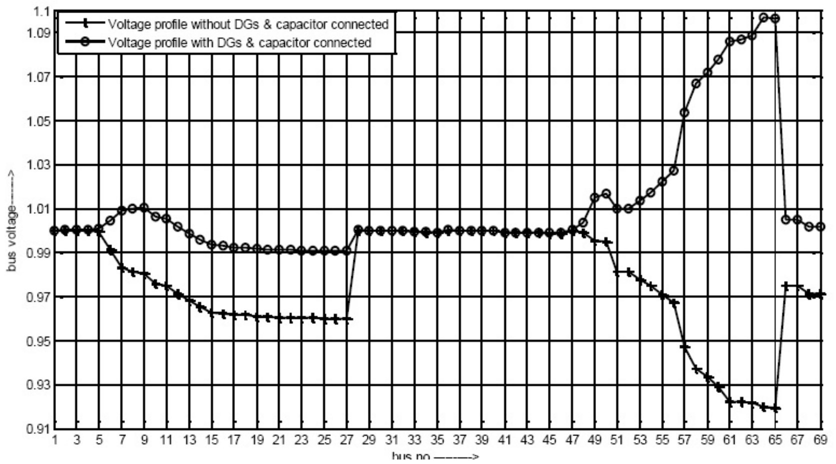

Figure 3.15: Voltage profile with and without DGs connected

Figure 3.17 shows the voltage profile of the system with and without voltage control using reactive power of the DGs, switching off the capacitor and by OLTC tap changing. It can be observed that the voltage control happens only after changing tap positions of OLTC.

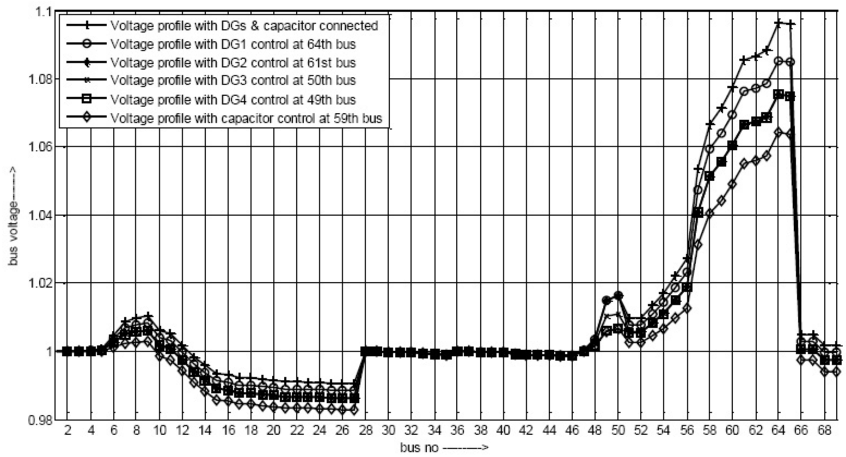

Figure 3.16: Voltage profile with DGs and capacitor control

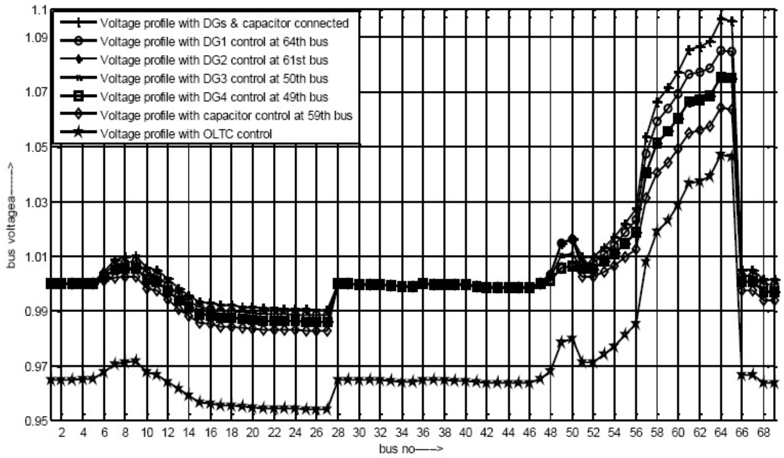

Figure 3.17: Voltage profile with DGs, capacitor and OLTC control

Voltage profile with 75% load:

The voltage profile for the system at 75% load condition with and without DGs connected can be seen in Figure 3.18 .The system behaves similar to the previous scenarios considered. It can be seen from Figure 3.19, the peak voltage level of the system still remains above the limit even after DGs reactive power is reduced to minimum and capacitor is switched off. The voltage profile of the system with voltage control using DGs reactive power, capacitor and OLTC control can be seen in Figure 3.20. It can be observed that, the voltage has been controlled after the OLTC tap setting, with all DGs reactive power and capacitor control.

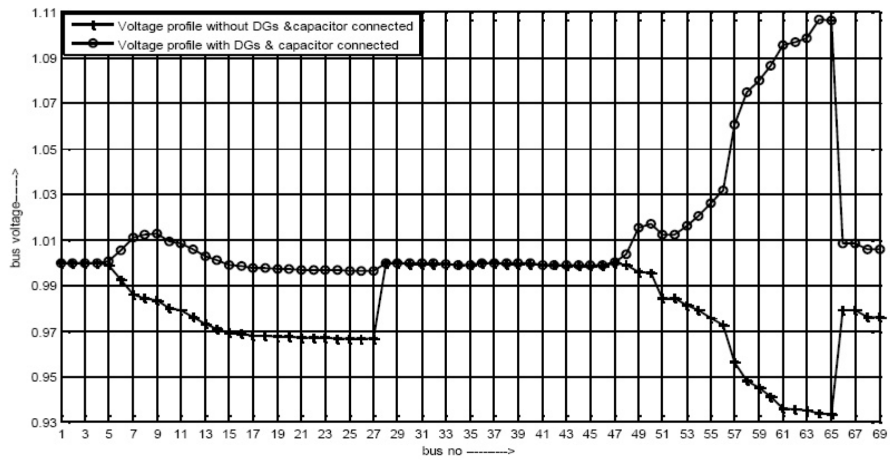

Figure 3.18: Voltage profile with and without DGs connected

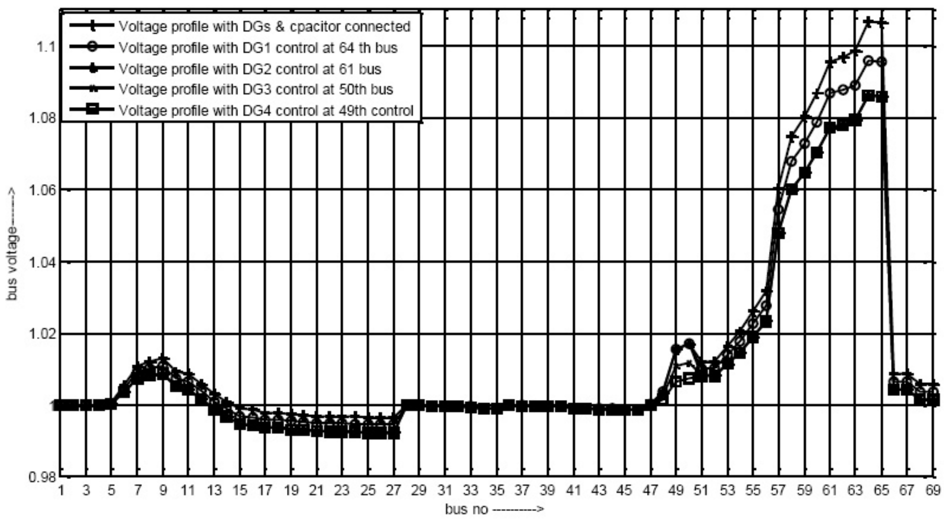

Figure 3.19: Voltage profile with DGs reactive power and capacitor control

The OLTC tap setting values is indicated in the Table 3.4, with maximum and minimum voltage level at all the voltage profiles after the voltage control at different loading conditions.

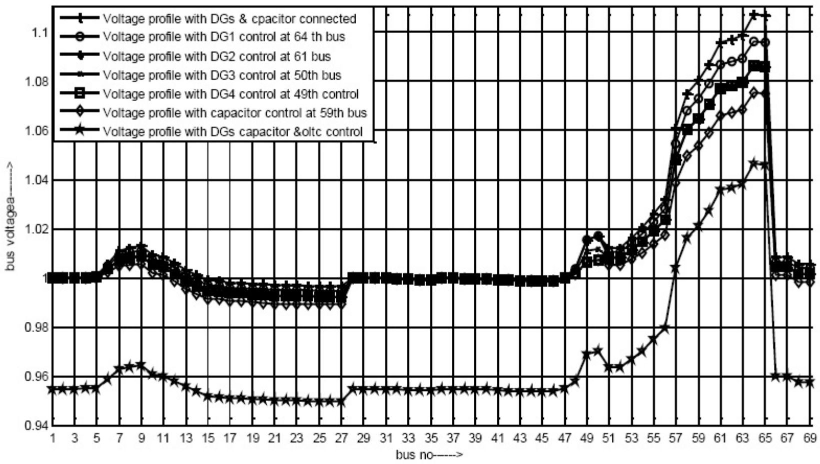

Figure 3.20: Voltage profile with DGs, capacitor and OLTC control

Table 3.4: Maximum and minimum voltage level of the system in p.u with and without voltage control

Voltage control devices	**Voltage level**	**100% load**	**90%load**	**75%load**
W/O DG and capacitor control	Max	1.0965	1.1035	1.1137
	Min	0.9889	0.9929	0.9989
With all DGs control	Max	1.0946	1.1016	1.1119
	Min	0.9885	0.9925	0.9985
With capacitor control	Max	1.0854	1.0922	1.1029
	Min	0.9859	1.0258	0.9959
With OLTC control	Max	1.0474	1.0487	1.0478
	Min	0.9514	0.9503	0.9500
OLTC Tap Setting		0.9650	0.9600	0.9500

3.4.2 Case Study 2: Voltage Regulation with Participation Factor

The 12.66 kV, IEEE 69 bus radial distribution systems shown in Figure 3.21 is used to study the performance of the proposed voltage regulation. This network has 7 lateral feeders along with the main feeder and its load and system data are given in [Das (2008)]. The three generators are connected at 27^{th}, 61^{st} and 62^{nd} bus with the capacity of 1200 kW and 580 kVAr each.

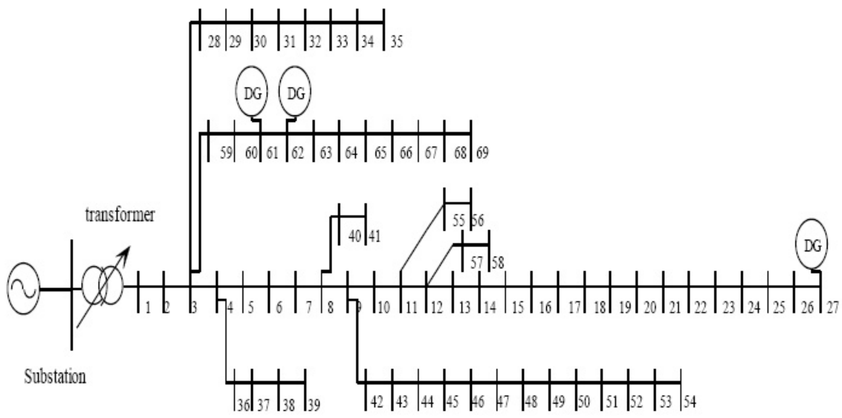

Figure 3.21: IEEE 69 bus distribution system

The voltage profile of the study system with three synchronous generators with and without voltage control can be seen from the Figures. 3.22 to 3.26. It can be observed that the voltage limit at 27^{th} bus is above the upper voltage limit (1.06 p.u.). This may cause damage to the customer loads connected to these buses. Thus chances of customers getting disconnected due to voltage limit violation are more in this case. In the proposed method, individual DG systems co-ordinate the voltage regulation of distribution network through their participation factor. The participation factor for each DG system is determined to decide the amount of reactive powers to be decreased to mitigate the voltage rise. The participation factor of each DG is indicated in Table 3.5

Table 3.5: Participation factor of DGs connected to the system at different loads

Bus no. at DGs connected	**100% load**	**90% load**	**85% load**	**82%load**	**80%load**
27	1.0353	0.9342	0.8908	0.8667	0.8513
61	0.0096	0.0423	0.0681	0.0836	0.0939
62	1.004	0.91	0.8695	0.8469	0.8325

Figures 3.22 to 3.26 shows the voltage profile for IEEE 69 bus radial distribution system for different load conditions with and without DGs connected to the system and with voltage control by reducing reactive powers of DGs.

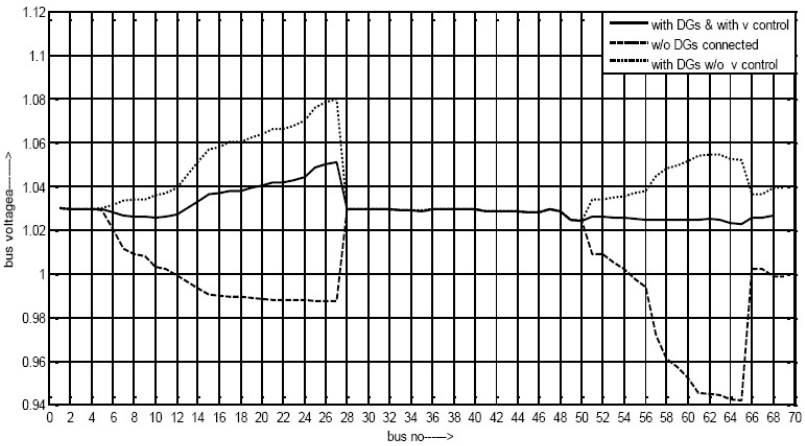

Figure 3.22: Voltage profile with 100% load

The Figures 3.22 to 3.26, shows the voltage profile of the 69 bus distribution network with proposed voltage control using participation factor of generator reactive power with 100% ,90%, 85%,82% and 80% load connected. Voltage has been regulated by controlling the reactive powers of the generators according to their participation factor. Q_{new} is calculated for each generator to decide the amount of reduction in the reactive power to mitigate the voltage rise.

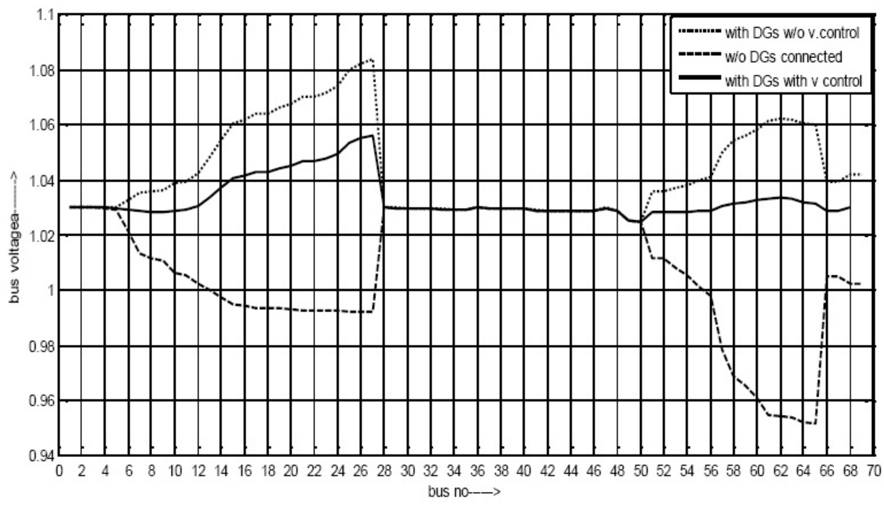

Figure 3.23: Voltage profile with 90% load

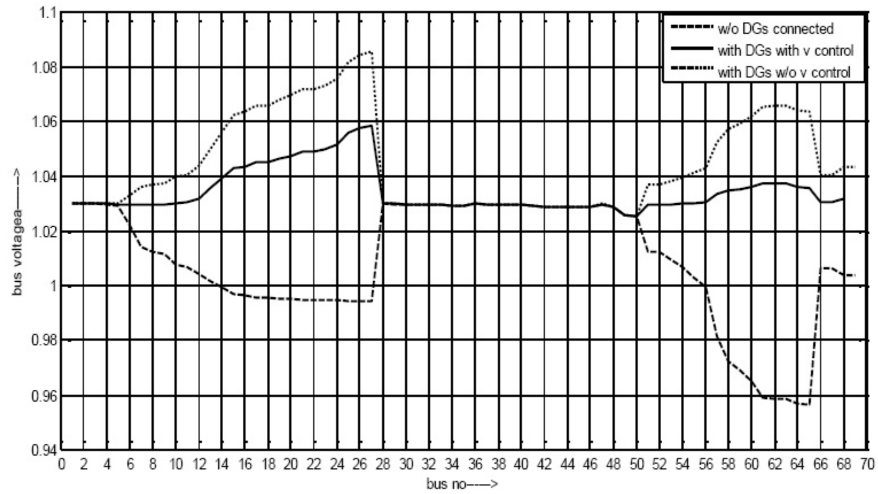

Figure 3.24: Voltage profile with 85% load

The voltage profile of the 69 bus system with 82% load, for the system considered for study is the minimum load for which voltage control can be achieved as shown in Figure 3.25.

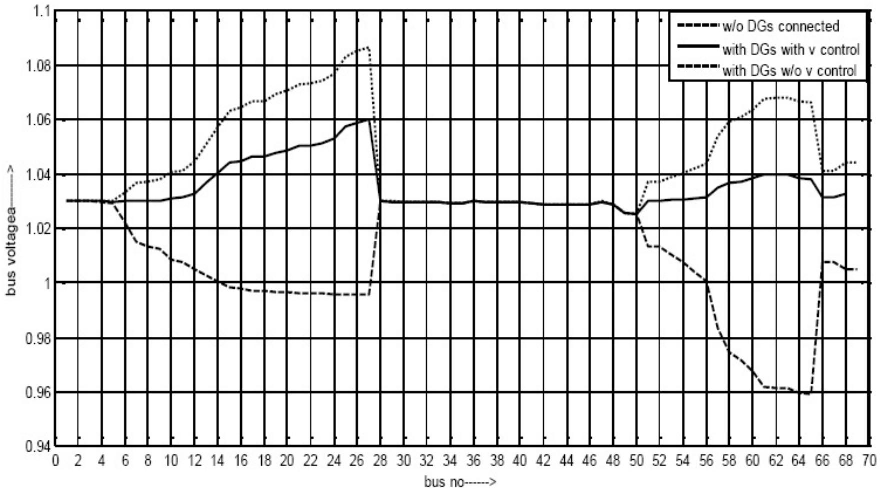

Figure 3.25: Voltage profile with 82% load

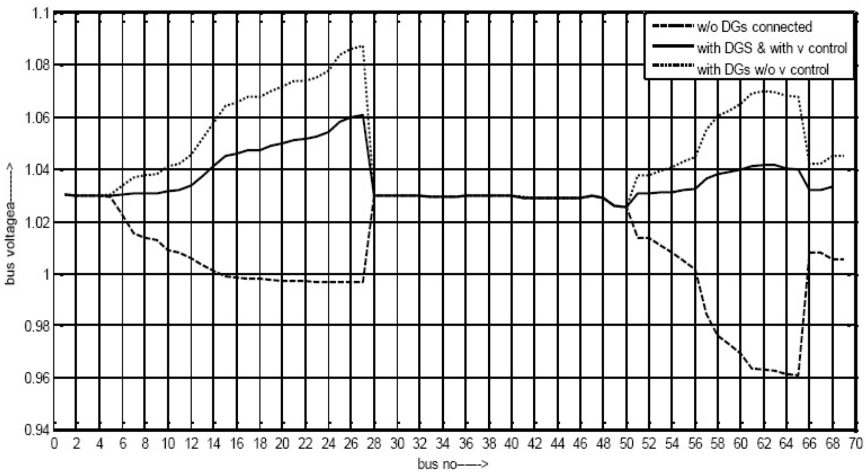

Figure 3.26: Voltage profile with 80% load

From the voltage profile of the system with 80% load shown in Figure3.26, it can be seen that even after the reduction in the reactive power (Q_{new}) of the DGs the voltage level violates the upper limit for the considered system with application of the proposed method. The simulation results for all the loads below 80% showed that the voltage rise could not be controlled within the voltage limits. The amount of reactive power reduction from the generators connected at different nodes to control the voltage at different loading conditions is indicated in Table 3.6. The voltage level at different loading conditions, with and without voltage control is indicated in the Table 3.7.

Table 3.6: Amount of reactive power reduction from the generators connected at different nodes

Bus no	100% load	90% load	85% load	82%load
27	-433.16	-456.37	-454.63	-462.52
61	-4.68	-68.10	-99.85	-118.90
62	-428.48	-443.23	-451.76	-456.50

Table 3.7: Voltage levels in p.u. of the system at different loading conditions

Load level	Without control		With control	
	Maximum	Minimum	Maximum	Minimum
100%	1.0802	1.0244	1.0507	1.0222
90%	1.0833	1.0250	1.0558	1.0250
85%	1.0856	1.0253	1.0582	1.0252
82%	1.0867	1.0255	1.0596	1.0254
80%	1.0874	1.0256	1.0605	1.0255

3.5 CONCLUSION

In this chapter the voltage control has been done using OLTC, shunt capacitor and DGs reactive power variation with different loading conditions. Two case studies have been presented, in case study 1 voltage sensitivity analysis is used to find the voltage sensitivity index for each generator. The priority has been given to the DGs connected to the system according to sensitivity index value, to vary the reactive power of the generators to regulate the voltage. The OLTC tap settings is adjusted with shunt capacitors operation, and the voltage of the system has been regulated. In case study 2 the voltage control simulation has been presented based on participation of the generators. In both the case studies simulation is carried out with the IEEE 69 bus system. Both methods can be proficiently used to handle all types of radial distribution system structures regardless of the system size. Utilization of these developed methods can make potential DG projects more attractive by effective utilization of the generator capacity.

Chapter 4

COORDINATED VOLTAGE REGULATION METHOD

4.1 INTRODUCTION

There has been increasing interest in coordinated voltage control for distribution system in recent years. Traditional voltage control strategies are often based on system analysis which is generally carried out in a steady-state setting. However, the complexity and non-linearity of a real power system demands simplifying assumptions and militate against the use of multi-objectives in the analysis. Load requirements and power factor variations, load distribution, and network topology, all influence the voltage regulation along with the DG in a distribution networks. The majority of the existing control strategies deals with only a single control class, such as generator terminal voltage setting, transformer tap control, capacitor switching, and load shedding separately, and very few of these methods take account of the discrete nature of controls.

A problem that arises in this kind of voltage control system is the possibility of excessive operations of the regulating devices such as OLTC and/ or the DG. This might happen due to insufficient voltage control method or a lack of proper coordination between the two devices in their simultaneous operation [Madureira and Lopes (2009)]. The voltage control coordination is therefore necessary in the distribution network and has been a subject of interest in many research papers.

In [Le *et al.* (2007)] the method for voltage control coordination is developed based on the priority level of each regulating device. A sensitivity-based technique for determining the control zones of the regulating devices has been developed in the same. In [Kejovic (2006)], the coordination method for the DG and step voltage regulator operations for improved distribution system voltage regulations has been presented. In [Senjyu *et al.* (2008)] autors proposed an optimal control of distribution voltage with coordination of distributed installations, such as load ratio control transformer, step voltage regulator, shunt capacitor, shunt reactor, and static var compensator. In this, SVR is assumed to be a model with tap changing where the signal is received from a central control unit. In [Reid *et al.* (2009)] authors presented a range of active voltage management schemes based on coordinated voltage control. These schemes can be used to improve the voltage profile in 11kV distribution networks and increase their ability to accommodate distributed generation. Technical limitations and commercial barriers are discussed.

In this chapter an optimal coordinated voltage control method is presented with the coordination of distribution installations such as OLTCs, SCs, and SVCs including the generators reactive power. The genetic algorithm is considered for the voltage control simulation, the 21 and 33 bus distribution systems are used to study the coordinated voltage regulation. The modeling of various voltage regulating devices are also given.

4.2 VOLTAGE REGULATING DEVICES IN DISTRIBUTION SYSTEM

The system presented in Figure 4.1 illustrates the facilities to control the voltage rise effect. The regulating devices shown in Figure 4.1 includes the shunt capacitors, DG system, tap changing transformers, load ratio transformer and static var-compensators. These devices regulate the voltage by controlling the production, absorption and flow of reactive power at all levels of the system. In these, shunt capacitors, reactors and series compensators provide passive compensation. They are either permanently connected to the transmission and distribution system or switched. They contribute to voltage control by modifying the network characteristics.

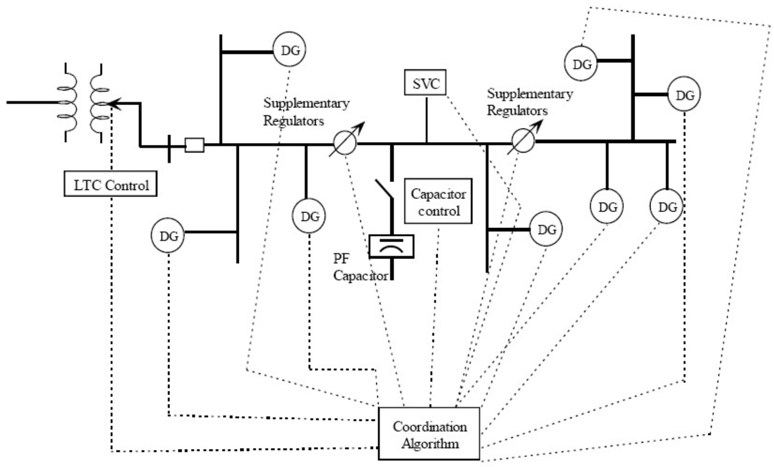

Figure 4.1: Facilities for voltage regulation

In a local or uncoordinated voltage control methods these equipment operate without considering its effect on other parts of the system. It doesnt provide any provision to minimize the overall system losses. Where as coordinated operation of all these devices can optimize losses and increase the penetration of DG along with the voltage control. In this work the facilities shown in the Figure 4.1 is optimally coordinated for voltage regulation using genetic algorithm.

4.3 GENETIC ALGORITHM

Genetic algorithms belong to the larger class of evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as inheritance, mutation, selection, and crossover. In a genetic algorithm, a population of strings (called chromosomes or the genotype of the genome), which encode candidate solutions (called individuals, creatures, or phenotypes) to an optimization problem, evolves towards better solutions. Traditionally, solutions are represented in binary as strings of 0s and 1s, but other encodings are also possible. The evolution usually starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness of every individual in the population is evaluated, multiple individuals are stochastically selected from the current population (based on their fitness), and modified (recombined and possibly randomly mutated) to form a new population [Goldberg (1989)]. The new population is then used in the next iteration of the algorithm. Commonly, the algorithm terminates when either a maximum number of generations have been produced, or a satisfactory fitness level has been reached for the population. If the algorithm has terminated due to a maximum number of generations, a satisfactory solution may or may not have been reached. Genetic algorithms find application in bioinformatics, phylogenetics, computational science, engineering, economics, chemistry, manufacturing, mathematics, physics and other fields.

A typical genetic algorithm requires a genetic representation of the solution domain and fitness function to evaluate the solution domain. A standard representation of the solution is as an array of bits. Arrays of other types and structures can be used in essentially the same way. The fitness function is defined over the genetic representation and measures the quality of the represented solution. The fitness function is always problem dependent. Once the genetic representation and the fitness function are defined, a GA proceeds to initialize a population of solutions (usually randomly) and then to improve it through repetitive application of the mutation, crossover, inversion and selection operators. The some of the basic operation of GA is given below.

- **Initialization:** Individuals with random chromosomes are generated that set up the initial population N.

- **Reproduction:** The degree of conformity of each object is calculated and an individual is reproduced under a fixed rule depending on the degree of conformity. Here, some individuals with a low degree of conformity will be screened, while individuals with a high degree of conformity will increase.

- **Crossover:** New individuals are generated by the method of intersection that has been set up.

- **Mutation:** This is performed by an operation determined by the installed mutation probability or mutation, and a new individual is generated.

- **Termination:** If end conditions are fulfilled, the best individual thus obtained is the semi-optimal solution in question.

- **Scattered cross over:** Combines two individuals, or parents, to form a new individuals, or child, for the next generation. It then selects the genes where the vector is a 1 from the first parent, and the genes where the vector is a 0 from the second parent, and combines the genes to form the child [Goldberg (1989)].

  For example,
  P_1=[a b c d e f g h]
  P_2= [1 2 3 4 5 6 7 8]
  Random crossover vector =[1 1 0 0 1 0 0 0]
  Child=[a b 3 4 e 6 7 8]

- **Stochastic selection:** Chooses the parents for the next generation based on their scaled values from the fitness scaling function. It lays out a line in which each parent corresponds to a section of the line of length proportional to its expectation. The algorithm moves along the line in steps of equal size, one step for each parent. At each step, the algorithm allocates parents from the solution it lands on. The first step is uniform random number less than the step size.

- **Adaptive feasible mutation:** An adaptive mutation operator for a genetic algorithm that programmatically mutates individuals in a constrained optimization for a modeled system. The mutation operator takes into account linear and bound constraints in generating new mutated individuals. The mutation operator generates random mutation direction vectors and random initial step sizes. A mutated individual is generated and moved along a randomly chosen mutation direction vector a distance equal to the initial step size. The generated mutated individual is compared to the linear and bound constraints. In the event the generated mutated individual is located in an infeasible region, the illustrative embodiment of the present invention automatically adjusts the step size to a smaller value and generates another mutated individual along the chosen mutation direction vector. The process iterates until the generated individual is within the feasible region. The number of available valid mutation directions increases as the step size decreases.

Genetic algorithms do not require linearity, continuity, or differentiability of the objective function, nor do they need continuous variables. These two features make GAs particularly effective in dealing with discrete control devices such as tap changing transformers and with objectives such as minimal number of control actions. A considerable disadvantage of GAs is the amount of calculation time involved that increases exponentially with the number of independent variables. Several GA applications on the voltage-reactive power problem are known. Applications exist for planning and optimal allocation of reactive power sources [Malachi and Singer (2006)], as well as for voltage security enhancement by preventive control. The optimal power flow (OPF) problem has also been addressed in several publications [Osman *et al.* (2004)].

In this work GA is used to determine the amount of operation of each regulating device is determined by solving the objective function. The determined optimal values of the individual devices are used to regulate the voltage. The objective function is set up so that a voltage margin can be fully secured to a steep voltage variation and power loss is minimum. Algorithm for the determination optimal setting of voltage control devices is shown in Figure 4.2. To control the voltage within the limits used in this work is described below.

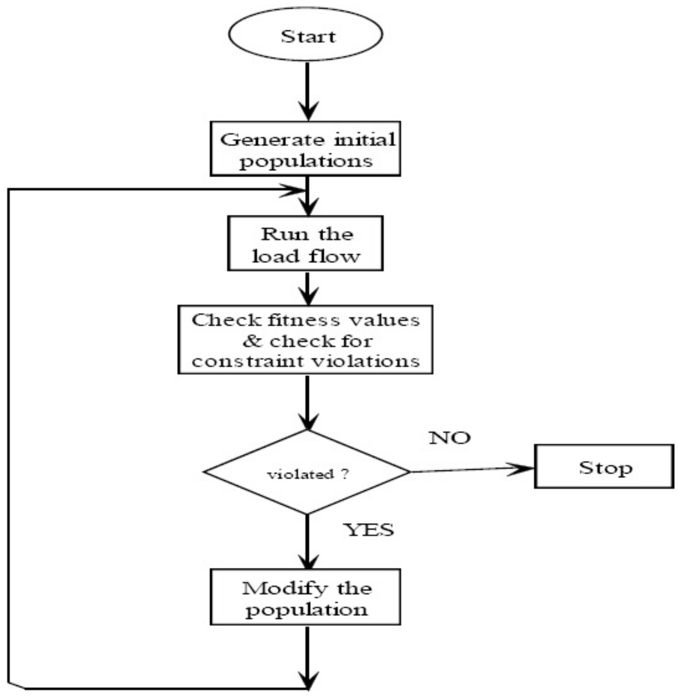

Figure 4.2: Flow chart for Genetic Algorithm

The objective function for GA implementation in this work is given as follows.

$$F(Q,T) = \sum_{i=1}^{n} |V_0 - V_i| \tag{4.3.1}$$

where V_0 is the initial voltage in p.u.

n is the total number of nodes in the distribution network

V_i is the voltage at the node i

T is the tap position of LRT, OLTC

Q is the reactive power at node i

Constraint conditions: Node voltage:$V_{min} < V_i < V_{max}$, Reactive power of DG: $Q_{min} < Q_i < Q_{max}$, Tap position: $T_{min} < T_i < T_{max}$

Genetic algorithm parameters used in this work is given in table 4.1

Table 4.1: Parameters for genetic algorithm

Generation	100
Population	20
Selection	Stochastic
Crossover	Scattered
Mutation	Adaptive feasible

4.4 MODELING OF THE VOLTAGE REGULATING DEVICES

There are many voltage regulating devices to control the voltage in the distribution system. Some of the voltage control devices are explained in this section.

4.4.1 Tap Changing Transformers

A tap changer can change the number of turns in the transformer and thereby adjust the transformer ratio. The transformers with tap changers can shift reactive power between the primary and secondary sides and thus regulate the voltage of the secondary side. Those movements are performed by mechanical switches. The possible tap ratio change is ±10-15% in steps of 0.6-2.5%. Each tap operation takes 0.1-0.2 seconds. The conventional control for the OLTC is an integrator control with a time delay and a dead band. The dead band sets the tolerance or long term voltage deviations and the time delay is intended for noise-rejection.The basic arrangement of voltage control with LTC regulation is shown in Figure 4.3 [Gao (2010)]. The LTC will keep the local bus bar voltage, i.e., the sending end voltage U_0, constant within the range:

$$U_{LB} < U_o < U_{UB}$$

Where U_{LB}=U_{set} -0.5 bandwidth is the lower boundary voltage U_{LB}=U_{set}+0.5 bandwidth is the upper boundary voltage and U_{set} is the set point voltage. Where U_{LB} is the lower band and U_{UB} is the upper band voltage limit.

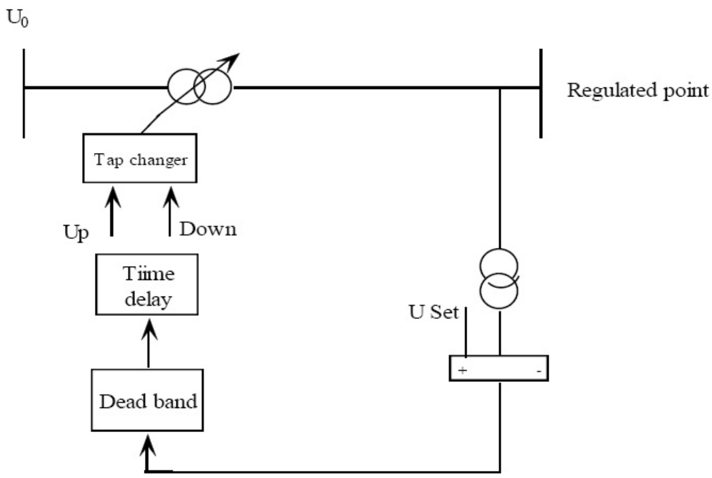

Figure 4.3: On load tap changing transformer

The voltage on a conventional MV feeder decreases towards the end. The LTC shall then be set to ensure that the voltage at the feeder end is higher than the minimum allowed voltage U_{min}, and the sending-end voltage is lower than the maximum allowed voltage U_{max}. Since the LTC keeps the sending-end voltage U_0 constant, it is possible to operate the feeder with minimum losses at any load condition.

4.4.2 Load Ratio Transformer

Transformers with tap changing facilities constitute an important means of controlling voltage throughout the system at all voltage levels. Autotransformers are used to change voltage from one subsystem to another are and often furnished with tap changing facilities. These can be controlled either automatically or manually. The taps on the system transformer provide a convenient means of controlling reactive power flow between subsystems. These are mainly used for improving voltage profiles and, and minimize active and reactive power losses. The control of single transformer will cause changes in voltages at its terminals. In addition, it influences the reactive power flow through the transformer. The resulting effect on the voltages at other buses will depend on the network configuration and load/generation distribution. Coordinated control of tap changing tap changers of all the transformers interconnecting the subsystems is required if the general level of voltage is to be changed.

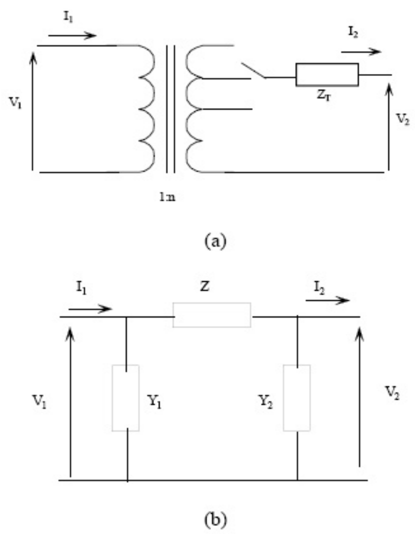

Figure 4.4: (a) Equivalent model of load ratio transformer (b) Four terminal network

The equivalent circuit of LRT is shown in Figure 4.4(a). This is changed into an equivalent 4 terminal circuit and is shown in Figure 4.4(b) [Senjyu *et al.* (2008)]. Suppose that the number of turns ratio of the winding of a transformer has now changed times from a standard transformation ratio. Then, the relationship between the primary voltage displayed by the unit method with current, and secondary voltage V_2 with current I_2, is expressed in the formula below.

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} n & (\frac{1}{n})Z_T \\ 0 & \frac{1}{n} \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} \tag{4.4.1}$$

The input/output voltage and current expression of relations of the equivalent 4 terminal circuit of Figure 4.4(b) is given by the following formula

$$\begin{bmatrix} V_2 \\ I_2 \end{bmatrix} = \begin{bmatrix} 1 + Zy_1 & -Z \\ -(y_1 + y_2 + y_1 y_2 Z) & 1 + Zy_2 \end{bmatrix} \begin{bmatrix} V_1 \\ I_1 \end{bmatrix} \tag{4.4.2}$$

Where , Z is impedance, y is admittance, V_1 and V_2 are the primary and secondary voltages respectively, I_1 and I_2 are the primary and secondary currents respectively. When each element of the coefficient procession of equations (4.4.1) and (4.4.2) is set to be mutually equal, the following relations apply:

$$Z = \frac{Z_T}{n} \qquad Y_1 = \frac{n(n-1)}{Z_T} \qquad Y_2 = \frac{(n-1)}{Z_T} \tag{4.4.3}$$

Where n=turns ratio

Therefore, the impedance of LRT is expressed in the equivalent 4 terminal circuit of Figure 4.4b and the value of each element is calculated from equation (4.4.3).

4.4.3 Shunt Reactors

Shunt reactors are used to compensate for the effects of line capacitance, particularly to limit voltage raise on open circuit on light load. These absorb reactive power. These characteristics helps for their usage in distribution system with distributed generation, in which there is a chance of reverse power flow [Trar Soe (2008)]. These reactors also serve to limit energization over voltages (switching transients). The reactive power absorbed by the inductor (Q_L) is given by

$$Q_L = -\frac{V_L^2}{X_L} \quad \text{in VAr} \tag{4.4.4}$$

X_L= Shunt inductor reactance in ohm.

V_L = Voltage across inductor in volt.

4.4.4 Shunt Capacitors

Shunt capacitors supply reactive power and boost over voltages. They are used throughout the system and are applied in a wide range of sizes. These were first used in for power factor correction. They are very a economical means of supplying reactive power. The principal advantages of shunt capacitors are their low cost and their flexibility of installation and operation [Safigianni and Salis (2001)]. They are readily applied at various points of the system, there by contributing to efficiency of transmission and distribution. The main disadvantage of shunt capacitors is that their reactive power output is proportional to square of the voltage. Consequently, the reactive power output is reduced at low voltages when it is likely to be needed most. Heavy use of shunt capacitor could lead to reduction in small signal (steady state stability) and poor voltage regulation.

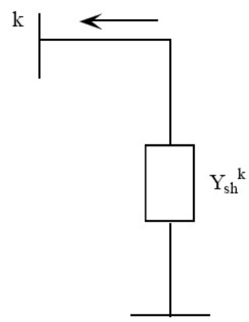

Figure 4.5: Shunt capacitor connected to a node

The reactive power supplied by the capacitors (Q_c) is given by

$$Q_c = -\frac{V_c^2}{X_c} \quad inVAr \tag{4.4.5}$$

X_c= Shunt capacitive reactance in ohm..

V_c= Voltage across capacitor in volt.

Shunt capacitors are also expressed in VAr. In this work, these are represented as negative reactive load, capacitors are considered are switched capacitors.

4.4.5 Static Var Compensator

Static var compensator is built up with reactors and capacitors, controlled by thyristor valves which are parallel to a fixed capacitor bank. It is connected in shunt with the transmission line through a shunt transformer and thus, represented in Figure 4.6 [Cai (2004)]. Figure 4.7 shows the equivalent circuit at which SVC is modeled [Acha *et al.* (2000), Agelidis (2002)].

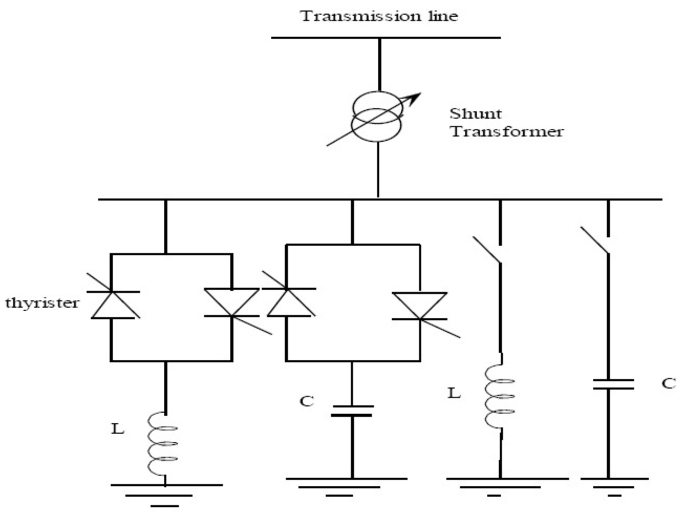

Figure 4.6: Functional diagram of SVC

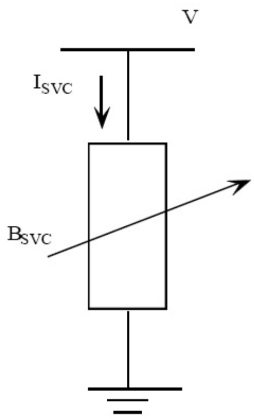

Figure 4.7: Equivalent circuit of SVC

The model of SVC can be considered as shunt connected variable susceptance, BSVC which is adapted automatically to achieve the voltage control. The equivalent susceptance, equivalent susceptance (B_{eq}) is determined by the firing angle α of the thyristors that is defined as the delay angle measured from the peak of the capacitor voltage to the firing instant. The fundamental frequency equivalent neglecting harmonics of the current results in [Hingorani and Gyugyi (2000)].

$$B_{eq} = B_L(\alpha) + B_c \tag{4.4.6}$$

Where

$$B_L(\alpha) = -\frac{1}{wL}\left(1 - \frac{2\alpha}{\pi} - \frac{\sin(2\alpha)}{\pi}\right)$$

,

Where B_L and B_c are the Inductive and capacitive succeptance respectively

B_c=wC and $0^0 < \alpha < 90^0$

If the real power consumed by the SVC is assumed to be zero, then:

$$P_{SVC} = 0, \qquad Q_{SVC} = -V^2 B_{SVC} \tag{4.4.7}$$

Where, V is the bus voltage magnitude.

As the reactive power demand at the bus varies, the susceptance is varied subject to the limits. However, the reactive power is a function of the square of the bus voltage. Hence the reactive power generated decreases as the voltage decreases.

4.5 RESULTS AND DISCUSSION

The optimal coordinated voltage control using genetic algorithm is tested on two distribution systems. Case study 1 uses a 21 bus system and case study2 uses a IEEE 33 bus system. The connections of the systems are made through HV/MV transformer, with on load tap changing for voltage regulation. The multiple voltage regulating devices like OLTC, LRT, shunt capacitors and static var compensator are used to control the voltage. The OLTC and LRT provide a regulation range $\pm 10\%$. The steady state voltage magnitude for the network should keep with a tolerance of $\pm 6\%$ of the nominal voltage [Barker and de Mello (2000)]. The genetic algorithm parameters and flow chart used for the voltage control simulation is indicated in the Table 4.1 and Figure 4.2 respectively.

4.5.1 Case Study 1:Voltage Regulation with 21 Bus System

A residential area power distribution system model with 21 buses is used for the simulation. The system capacity is 2500 kVA, the line and load data is given in [Senjyu *et al.* (2008)] The distribution system has two distributed generators, on load tap changer, load ratio transformer, shunt capacitors, static var compensator are connected as shown in the Figure 4.8. The active and reactive power of DGs is 0.3 p.u. and 0.14 p.u. respectively, the Shunt capacitors connected are of 0.05 p.u. and static var compensator is of 0.1 p.u. The LRT is connected between 7^{th} and 8^{th} node, and it can be used to adjust the voltage of the power distribution system. The daily load profile of a residential area power distribution system is as shown in Figure 4.9.

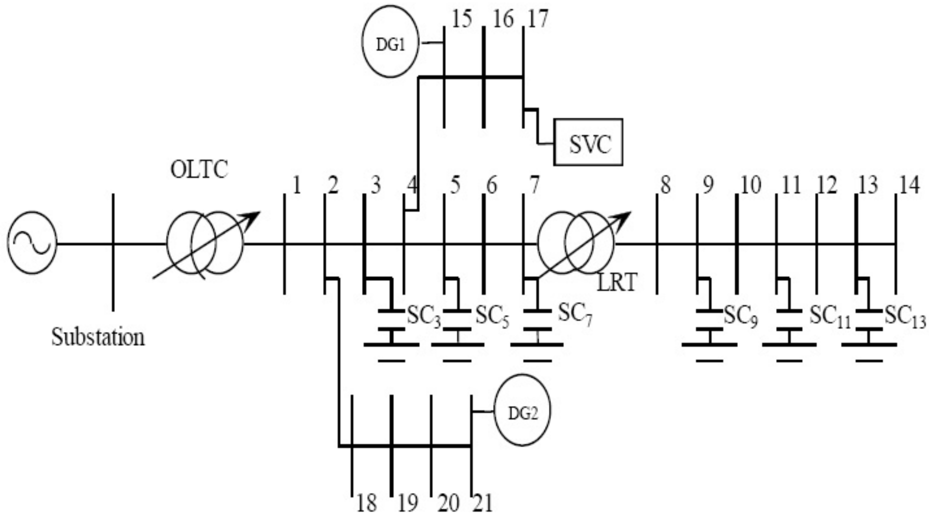

Figure 4.8: 21 bus radial distribution system

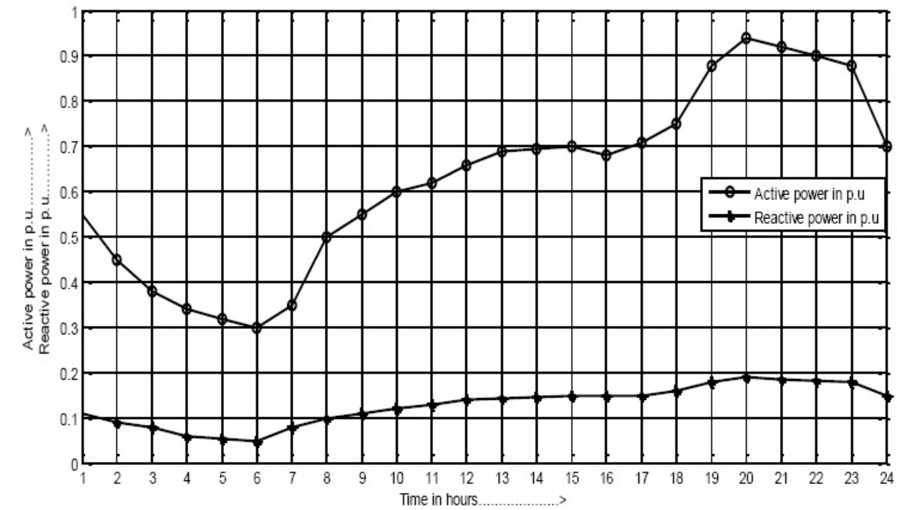

Figure 4.9: Time varying load profile for 21 bus system

Three types of the loads from the load profile are considered for the simulation.

i. Light load condition at 6.00 AM, P=0.3 p.u. and Q=0.05 p.u.

ii. Medium load condition at 12 Noon, P=0.66 p.u. and Q=0.14 p.u.

iii. Heavy load condition at 8.00 PM, P=0.93 p.u. and Q=0.18 p.u.

The assumption is that active and reactive power at each node is equally divided at above load conditions. The three sets of voltage control devices used for the simulation are given below.

a. With OLTC, LRT are available with DGs reactive power

b. With OLTC, LRT, SCs with DGs reactive power

c. With OLTC, LRT , SCs & SVC with DGs reactive power

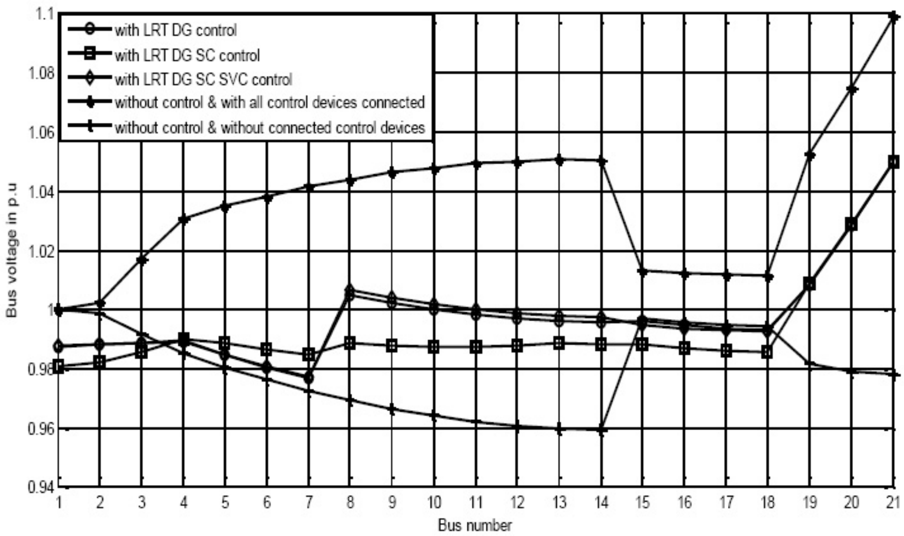

Figure 4.10: Voltage profile with light load for 21 bus system

Figures 4.10 to 4.12 show the voltage profile for 21 bus system with and without voltage control at light load, medium load and heavy load conditions. Figure 4.10 shows, the voltage profile with light load condition using three sets of control devices. It can be observed that without voltage control the voltage profile crosses the upper limit (1.05 p.u.), the peak value of the voltage profile is 1.1 p.u. at 21^{st} bus It can be seen in Figure 4.10, the voltage has been effectively controlled with the selected set of controlling devices. Figure 4.11 shows that, the voltage profile with and without voltage control for the load at 12 noon from the load profile. It is seen that the without control voltage is crossing the upper limit and its peak value is 1.08 p.u. The rise in voltage is mitigated by using voltage control devices with optimal setting of reactive power of the DGs can be seen in Figure 4.11.

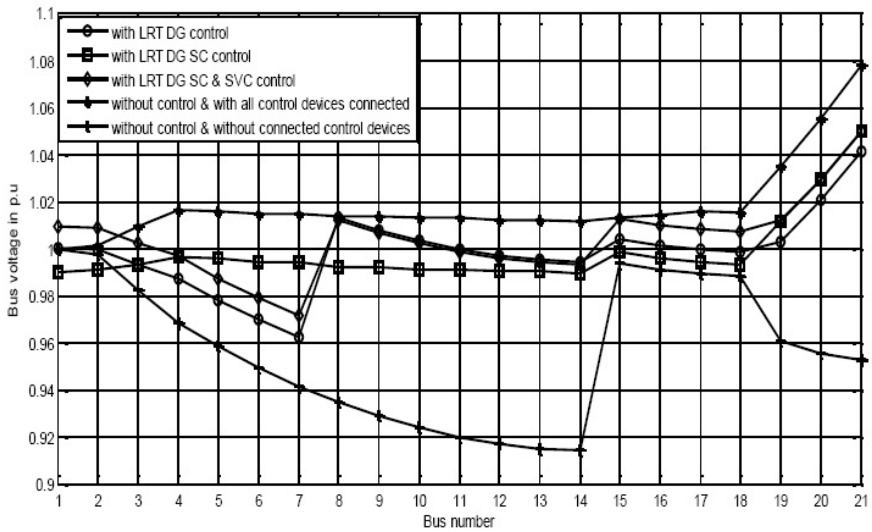

Figure 4.11: Voltage profile with medium load for 21 bus system

A peak value of 1.06 p.u. is obtained without voltage control for heavy load condition as seen in Figure 4.12. The optimal setting values of the voltage control devices and position of the shunt capacitors are given indicated Table 4.2 and 4.3 respectively.

The operation of shunt capacitors for different load conditions is indicated in Table 4.2, it can be observed that the shunt capacitors participation is more in light load condition compared to other loads and also on the number of participation of voltage control devices. In the first set voltage control shunt capacitors are not considered for voltage control.Table 4.3 shows that the optimal values of the voltage control devices for the voltage control at different load conditions. It can be observed that the setting values of OLTC and LRT control devices increases with the load and others control devices participation varies with the load variation and participation of number of devices. The voltage has been controlled with the coordination of all control devices.

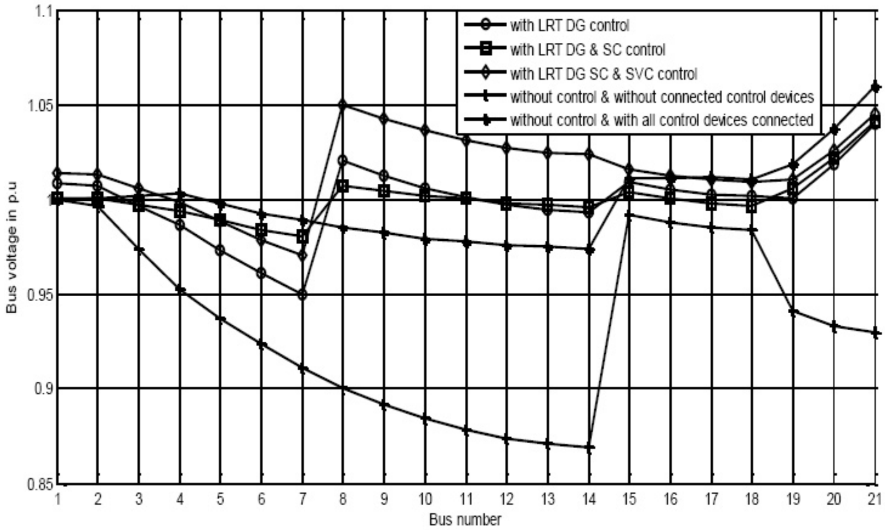

Figure 4.12: Voltage profile with heavy load for 21 bus system

Table 4.2: Operation of shunt capacitors in 21 bus system

Types of load from the load profile	**Different set of control**	**SC**$_3$	**SC**$_5$	**SC**$_7$	**SC**$_9$	**SC**$_{11}$	**SC**$_{13}$
Light load	2^{nd} set	off	off	off	off	off	on
	3^{nd} set	off	off	off	off	off	off
Medium load	2^{nd} set	on	on	on	on	on	on
	3^{nd} set	off	off	off	off	off	off
Heavy load	2^{nd} set	on	on	on	on	on	on
	3^{nd} set	on	on	on	off	off	off

Table 4.4 indicated the power loss in the 21 bus system before and after the voltage

control at low medium and heavy load conditions.It can be observed that the total power loss is more with increase in load and power loss can be reduced drastically with the voltage control.

Table 4.3: Optimal setting value of the voltage control devices in 21 bus system

Different set of control	**Controlling devices**		**Different load conditions**		
			Light load	**Medium load**	**Heavy load**
1^{st} set of control	**LRT** tap setting in p.u		1.03	1.05	1.08
	OLTC tap setting in p.u		0.98	1.0	1.0
	DGReactive power in p.u	**DG**$_1$	0.14	0.038	0.022
		DG$_2$	0.02	0.044	0.085
2^{nd} set of control	**LRT** tap setting in p.u		1.01	1.0	1.03
	OLTC tap setting in p.u		0.98	0.99	1.0
	DGReactive power in p.u	**DG**$_1$	0.10	0.072	0.043
		DG$_2$	0.025	0.022	0.022
	Shunt Capacitors position		6SCs off	6SCs on	6SCs on
3^{rd} set of control	**LRT** tap setting in p.u		1.02	1.05	1.09
	OLTC tap setting in p.u		0.98	1.0	1.01
	DGReactive power in p.u	**DG**$_1$	0.03	0.022	0.022
		DG$_2$	0.026	0.025	0.025
	Shunt Capacitors position		6SCs off	6SCs off	3SCson 3SCsoff
	SVC setting value		-0.02	-0.01	0.01

Table 4.4: Power loss in the 21 bus system

Load conditions	Power loss before voltage control		Power loss after voltage control	
	P_{loss} in p.u	Q_{loss} in p.u	P_{loss} in p.u	Q_{loss} in p.u
Low load	0.00445	0.0069	0.0044	0.0065
Medium load	0.0045	0.0072	0.0044	0.0071
Heavy load	0.0046	0.0073	0.0045	0.0072

4.5.2 Case Study 2: Voltage Regulation with IEEE 33 Bus System

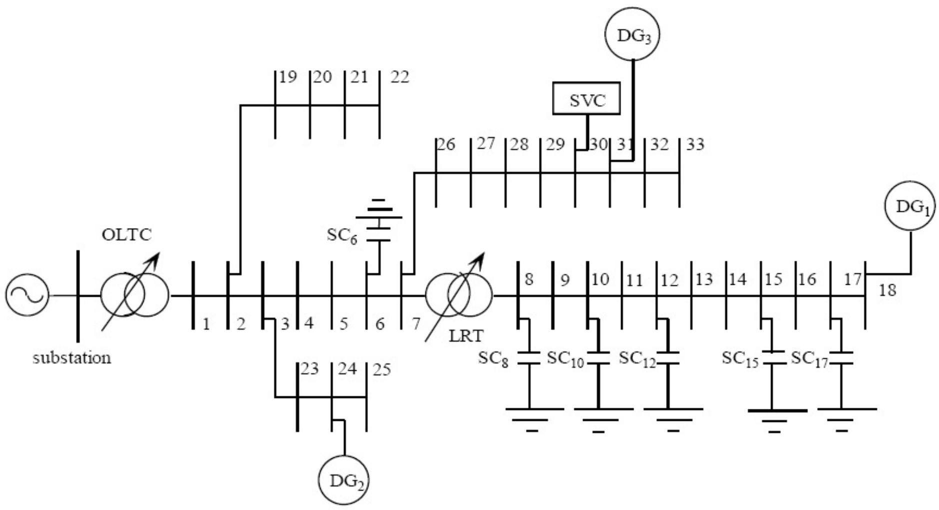

Figure 4.13: IEEE 33 bus system

A residential area power distribution system model with IEEE 33 buses is used for the simulation. The total installed peak loads on the system are 3715 kW, 2290 kVAr, the line and load data is given in [Zhang *et al.* (2009)]. Figure 4.13 shows the 33 bus system considered for voltage control with time varying load connected with 3 DGs of active power=0.24 p.u. and reactive power=0.11 p.u. each. A 6 shunt capacitors and one static var compensator are also connected as shown in Figure 4.13. The LRT is connected between 7^{th} and 8^{th} bus,and OLTC is connected near substation.

a. With LRT,OLTC and DGs reactive powers

b. With LRT,OLTC,SC and DGs reactive powers

c. With LRT,OLTC,SC,SVC and DGs reactive powers

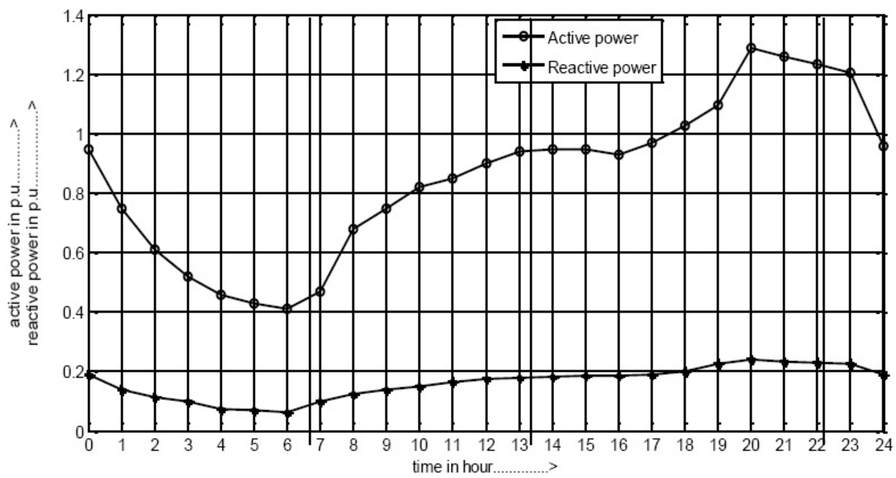

Figure 4.14: Time varying load profile for IEEE 33 bus system

Time varying load profile of the system is as shown in the Figure 4.14. Three loads are considered from the load profile for the simulation. The low load at 6 A.M, medium load at 12 noon and heavy load at 8 P.M. The total value of active and reactive powers at 6 A.M is P=0.41 p.u. and Q=0.063 p.u. at 12 Noon P=0.91 p.u. Q=0.176 p.u.at 8 P.M P=1.289 p.u. and Q=0.24 p.u. The mean values of the active and reactive powers are considered for the simulation in each case. Figure 4.15 shows the voltage profile for the system at light load condition, it can be seen that the voltage level at 18^{th} bus crosses the upper limit 1.05 p.u. and reaches 1.32 p.u. Using the control mechanism which involves all the three sets of voltage control devices voltage rise is mitigated. The voltage profile of the system with and without voltage control at medium load condition is as shown in the Figure 4.16

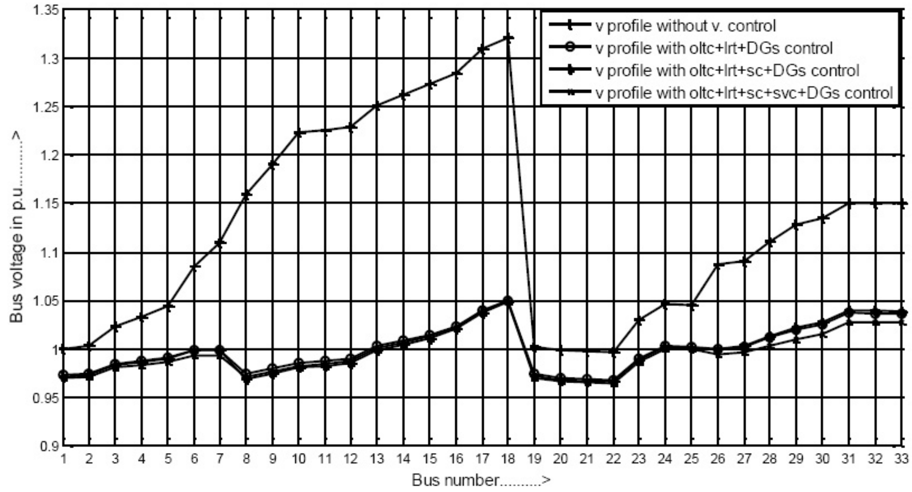

Figure 4.15: Voltage profile with light load for IEEE 33 bus system

At 18^{th} bus the voltage crosses the upper limit after the DGs are connected achieving a peak voltage of 1.15 p.u. With voltage control the level is within the voltage limits (0.95 p.u-1.05 p.u). The simulation done for a system with heavy load condition also can be seen in the Figure 4.17. The peak voltage level achieved with the DG connection is 1.06 p.u. and has been controlled successfully.

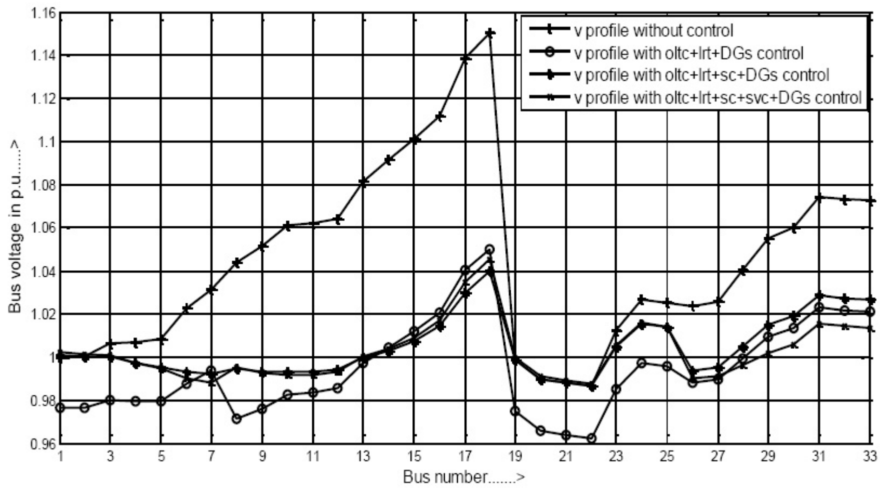

Figure 4.16: Voltage profile with medium load for IEEE 33 bus system

The voltage control is successfully accomplished using all the 3 sets of voltage control devices, and is as shown in the Figures. 4.15 to 4.17. Table 4.5 indicates the optimal setting values of voltage control devices and Table 4.6 indicates the operation of shunt capacitors after the voltage control. Figures 4.16 and 4.17 depicts the voltage profile for with and without voltage control at medium and heavy load conditions.

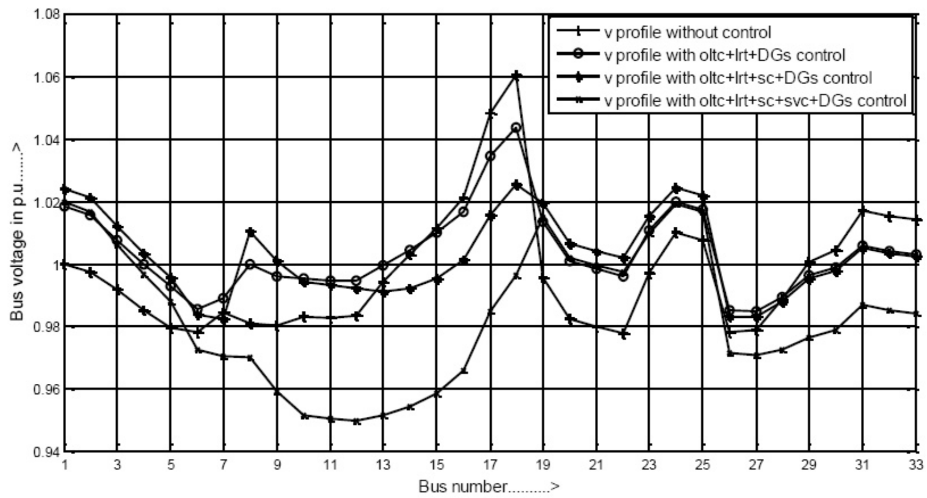

Figure 4.17: Voltage profile with heavy load for IEEE 33 bus system

The operation of the shunt capacitors after the voltage control at different load condition for a 33 bus system is indicated in the Table 4.6. It can be observed that most of the shunt capacitors are switched off at light and medium load condition. Participation of SCs in heavy load condition in voltage control is comparatively less than other load. It also depends upon the other voltage control devices. Table 4.7 indicates the power loss of the 33 bus system before and after the voltage control. It can be observed that there is a drastic reduction of active and reactive power loss after the voltage control. The optimal setting values of voltage control devices are indicates in Table 4.5. In this system also, the participation of LRT and OLTC in the voltage control is more in light load compared to heavy load condition. The shunt capacitor participation in voltage control in light load is more than the other load as seen from the Table 4.5.

Table 4.5: Optimal setting values of voltage control devices in IEEE 33 bus system

Different set of control	**Controlling devices**		**Different load conditions**		
			Light load	**Medium load**	**Heavy load**
1^{st} set of control	**LRT** tap setting in p.u.		0.97	0.97	1.01
	OLTC tap setting in p.u.		0.97	0.97	1.01
	DGReactive power in p.u.	**DG**$_1$	0.0169	0.0169	0.0170
		DG$_2$	0.0169	0.0531	0.0198
		DG$_3$	0.0169	0.0169	0.0169
2^{nd} set of control	**LRT** tap setting in p.u.		0.98	1.0	1.03
	OLTC tap setting in p.u.		0.97	1.0	1.02
	DGReactive power in p.u.	**DG**$_1$	0.0188	0.0244	0.034
		DG$_2$	0.0220	0.0226	0.018
		DG$_3$	0.0459	0.0169	0.023
	Shunt Capacitors position		6SCs off	5SCsoff 1SCs on	3SCs0n 3SCsoff
3^{rd} set of control	**LRT** tap setting in p.u.		0.97	1.01	1.02
	OLTC tap setting in p.u.		0.97	1.0	1.02
	DGReactive power in p.u.	**DG**$_1$	0.0169	0.0316	0.070
		DG$_2$	0.0239	0.0173	0.027
		DG$_3$	0.0255	0.0172	0.030
	Shunt Capacitors position		6SCs off	5SCsoff 1SCs on	2SCson 4SCsoff
	SVC setting value		-0.05	0.01	0.03

Table 4.6: Operation of shunt capacitors after voltage control in IEEE 33 bus system

Different types of load load profile	**Different Set of control**	**SC6**	**SC8**	**SC10**	**SC12**	**SC15**	**SC17**
Light load	2^{nd} set	off	off	off	off	off	off
	3^{rd} set	off	off	off	off	off	off
Medium load	2^{nd} set	off	off	on	off	off	off
	3^{rd} set	on	OFF	off	off	off	off
Heavy load	2^{nd} set	on	on	on	off	off	off
	3^{rd} set	on	on	off	off	off	off

Table 4.7: Power loss in the IEEE 33 bus system

	Power loss before voltage control		**Power loss after voltage control**	
Load conditions	**P_{loss} in p.u.**	**Q_{loss} in p.u.**	**P_{loss} in p.u.**	**Q_{loss} in p.u.**
Low load	0.00252	0.00197	0.00145	0.00133
Medium load	0.00421	0.00302	0.00243	0.00204
Heavy load	0.00630	0.00421	0.00365	0.00285

4.6 CONCLUSION

The coordinated voltage regulation of distribution system with distributed generators using genetic algorithm has been presented with the two case studies. In this study multiple voltage regulators such as OLTC, LRT, SCs and SVC are considered along with the reactive powers of the DGs. The simulation results report the performance of the developed method using time varying load. In this work voltage regulation of both 21 and 33 bus distribution system are analyzed through simulation using case study 1 and 2 respectively. The results presented through case studies show that by optimally setting the values various voltage control devices through genetic algorithm. The distribution system voltage can be regulated well within the statute limits and also power loss can be reduced. The presented method of coordinating various voltage control devices in distribution system helps in effective integration of large number of DG system to the utility network.

Chapter 5

LOAD PROFILE GENERATION USING FUZZY CLUSTERING FOR VOLTAGE CONTROL

5.1 INTRODUCTION

The load flow study is an important tool involving numerical analysis applied to a power system. The load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line. All the voltage regulation methods require load flow analysis of the system and it is assumed that the real power and reactive power at each load bus (load data) are known. Thus load profile data becomes critical for voltage regulation methods. In most cases time varying load data is required for accurate load flow analysis such hourly load day for a day or a month. The use of this large data for load flow analysis can complicate the solution approaches [Miranda and Patrica (2002)]. Thus in most of the cases, for validation of voltage regulation methods few samples of data are considered instead of considering the entire load profile. This approach may not accurately represent the load variation for load follow analysis. Thus in this chapter a fuzzy clustering based method is used to generate the load profile data for effective analysis of voltage regulation methods.

This chapter presents the introduction to fuzzy clustering techniques. Algorithm for fuzzy C-means clustering methods for load profile generation is given. Case studies are also presented in this chapter to analyse the effectiveness of the developed coordinated voltage regulation method using fuzzy clustered load profiles.

5.2 FUZZY CLUSTERING

Clustering techniques are mostly unsupervised methods that can be used to organize data into groups based on similarities among the individual data items. Most clustering algorithms do not rely on assumptions common to conventional statistical methods, such as the underlying statistical distribution of data, and therefore they are useful in situations where little prior knowledge exists. The potential of clustering algorithms to reveal the underlying structures in data can be exploited in a wide variety of applications, including classification, image processing, pattern recognition, modeling and identification. Various definitions of a cluster can be formulated, depending on the objective of clustering.

Generally, one may accept the view that a cluster is a group of objects that are more similar to one another than to members of other clusters [Bezdek (1981), Jain and Dubes (1988)]. The term 'similarity' should be understood as mathematical similarity, measured in some well-defined sense. In metric spaces, similarity is often defined by means of a distance norm. Distance can be measured among the data vectors themselves, or as a distance from a data vector to some prototypical object (prototype) of the cluster. Many clustering algorithms have been introduced in the literature. Since clusters can formally be seen as subsets of the data set, one possible classification of clustering methods can be according to whether the subsets are fuzzy or crisp (hard). [Chicco (2012)] presents an overview of the clustering techniques used to establish suitable customer grouping, included in a general scheme for analyzing electrical load pattern data. The characteristics of the various stages of the customer grouping procedure are illustrated and discussed.

Hard clustering methods are based on classical set theory, and require that an object either does or does not belong to a cluster. Hard clustering means partitioning the data into a specified number of mutually exclusive subsets. Fuzzy clustering methods, however, allow the objects to belong to several clusters simultaneously, with different degrees of membership. In many situations, fuzzy clustering is more natural than hard clustering. Objects on the boundaries between several classes are not forced to fully belong to one of the classes, but rather are assigned membership degrees between 0 and 1 indicating their partial membership. The discrete nature of the hard partitioning also causes difficulties with algorithms based on analytic functional, since these functional are not differentiable.

5.2.1 Fuzzy C-Means Clustering

Most analytical fuzzy clustering algorithms are based on optimization of the basic c-means objective function, or some modification of it. Hence we start our discussion with presenting the fuzzy c means functional. The following parameters must be specified: the number of clusters,c, the 'fuzziness' exponent, m, the termination tolerance,$\in$, and the norm-inducing matrix A. Moreover, the fuzzy partition matrix U, must be initialized. The choices for these parameters are now described one by one.

5.2.2 The Fuzzy C-Means Functional

A large family of fuzzy clustering algorithms is based on minimization of the fuzzy C-means functional formulated as [Dunn (1973) and Bezdek (1981)].

$$J(Z;U,V) = \sum_{i=1}^{c}\sum_{k=1}^{N}(\mu_{ik})^{m}\left\|Z_k - V_i\right\|_A^2 \qquad (5.2.1)$$

Where N is the number of data points.

m is the fuzziness index.

c represents the number cluster center.

$\mu_i k$ represents the membership of i^{th} data to k^{th} cluster center.

$\|Z_k - V_i\|_A^2$ is the Euclidean distance between k^{th} data and i^{th} cluster center.

$$U = [\mu_{ik}] \in M_{fc} \tag{5.2.2}$$

is a fuzzy partition matrix of Z

$$V = [V_1, V_2......V_c], V_i \in R^n \tag{5.2.3}$$

is a vector of cluster prototypes (centers), which have to be determined,

$$D_{ikA}^2 = \|Z_k - V_i\|_A^2 = (Z_k - V_i)^T A(Z_k - V_i) \tag{5.2.4}$$

is a squared inner product distance norm, and

$$m \in (1, \infty) \tag{5.2.5}$$

is a parameter which determines the fuzziness of the resulting clusters. The value of the cost function from the equation (5.2.1) can be seen as a measure of the total variance of Z_k from V_i.

5.2.3 The Fuzzy Clustering Algorithm

The Fuzzy clustering algorithm starts with an initial guess for the cluster center. Each data point is allotted a membership function. By iteratively updating the cluster centers and the membership grades for each data point, cluster center is moved to the right location within a data set. The iteration is based on minimizing an objective function that represents the distance from any given data point to a cluster center weighted by that data point's membership grade, [Nascimento *et al.* (2000)]. Fuzzy C-means (FCM) is a method of clustering which allows one piece of data to belong to two or more clusters. It is based on minimization of the following objective function. The minimization of the C-means functional in the equation (5.2.1) represents a nonlinear optimization problem that can be solved by using a variety of methods, including iterative minimization, simulated annealing or genetic algorithms. The most popular method is a simple Picard iteration through the first-order conditions for stationary points of equation (5.2.1), known as the fuzzy C-means (FCM) algorithm. The stationary points of the objective function in the equation (5.2.1) can be found by adjoining the constraint to J by means of Lagrange multipliers.

$$\bar{J}(Z;U,V,\lambda) = \sum_{i=1}^{c}\sum_{k=1}^{N}(\mu_{ik})^m D_{ikA}^2 + \sum_{k=1}^{N}\lambda_k\left[\sum_{i=1}^{c}\mu_{ik} - 1\right] \tag{5.2.6}$$

and by setting the gradients of $\bar{J}$ with respect to U,V and λ to zero. It can be shown that if

$D_{ikA}^2 > 0$,$\forall_i$, k and $m > 1$ then $(U,V) \in M_{fc} \times R^{n\times c}$ may minimize in equation (5.2.1) only if

$$\mu_{ik} = \frac{1}{\sum_{j=1}^{c}(D_{ilkA}/D_{jKA})^{2/(m-1)}} \tag{5.2.7}$$

$1 \le j \le c, 1 \le K \le N$

$$V_i = \frac{\sum_{k=1}^{N}(\mu_{ik})^m Z_k}{\sum_{k=1}^{N}(\mu_{ik})^m} \tag{5.2.8}$$

$1 \le j \le c$

equation (5.2.3) are first order necessary conditions for stationary points of the functional in equation (5.2.1). The FCM iterates through equations (5.2.7) and (5.2.8). Sufficiency of equation (5.2.7) and the convergence of the FCM algorithm is proven in [Bezdek

(1981)]. Note that equation (5.2.8) gives V_i as the weighted mean of the data items that belong to a cluster, where the weights are the membership degrees. That is why the algorithm is called C-means.

Given the data set Z, choose the number of clusters $1 < c < N$,the weighting exponent $m > 1$,the termination tolerance $\in > 0$and the norm-inducing matrix A. Initialize the partition matrix randomly, such that $U^0 \in M_{fc}$

Repeat for $l = 1, 2, ...$

Step 1: Compute the cluster prototypes (means):

$$V_i^l = \frac{\sum_{k=1}^{n} (\mu_{ik}^{(l-1)})^m Z_k}{\sum_{k=1}^{N} (\mu_{ik}^{(l-1)})^m}, \quad 1 \leq i \leq c$$

Step 2: Compute the distances:

$$D_{ikA}^2 = (Z_k - V_i^l)^T A (Z_k - V_i^{(l)})$$

$1 \leq i \leq c, 1 \leq k \leq N$

Step 3: Update the partition matrix:

$1 \leq k \leq N$

if $D_{ikA} > 0$ for all $i = 1, 2...c$

$$\mu_{ik}^{(l)} = \frac{1}{\sum_{j=1}^{c} (D_{ikA}/D_{jKA})^{2/(m-1)}}$$

otherwise

$\mu_{ij}^l = 0$, if $D_{ikA} > 0$ and $\mu_{ik}^{(l)} \in [0, 1]$ with $\sum_{ik}^{(l)} \mu_{ik}^{(l)}$ =1

$until \| U^l - V^{l-1} \| < \in$

For which D$_{ikA}$>0 and the memberships are distributed arbitrarily among the clusters fro which D$_{ikA}$=0. The flow chart for the given algorithm is given below

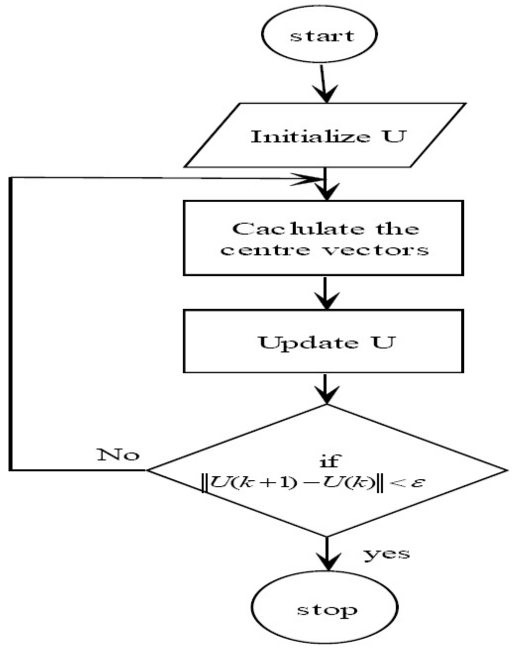

Figure 5.1: Flow chart for fuzzy clustering method

5.2.4 Load Profile Generation Using Fuzzy Clustering

In this work Fuzzy clustering is used to find 3 prototypes of 24 load profiles. The prototypes are nothing but the cluster centers obtained by the fuzzy clustering algorithm. Since we have 24 load profiles (vectors), fuzzy clustering helps to find a meta-structure in this set of vectors, [Miranda and Patrica (2002)]. It gives us three load profiles (vectors) from the set of 24 vectors. In this work Fuzzy C-means clustering is selected as a clustering technique to extract prototypes from the set of available load profiles. The main reasons are (a)the method allows us to identify the centroids or prototypes of the clusters defined (b) the method associates to each load profile a membership value to each cluster, represented to each centroid. This makes fuzzy clustering more natural than hard clustering. The Load profiles along n number of buses can be treated as n dimensional vector. Our objective is to find 3 cluster centers from 24 data points (each data point is n dimensional vector).

5.3 RESULTS AND DISCUSSION

The optimal coordinated voltage control using genetic algorithm is tested on two distribution system. The multiple voltage regulating devices like OLTC, LRT, shunt capacitors and static var compensator are used to control the voltage. The OLTC and LRT provide a regulation range is $\pm 10\%$. The steady state voltage magnitude for the network should keep with a tolerance of $\pm 6\%$ of the nominal voltage. For the voltage control simulation, two case studies 21 and 33 bus systems are considered. The objective function of GA used for the study and constraints are given in section 4.3 of chapter 4.The flow chart for genetic algorithm used for the study given in Figure 4.2 of chapter 4.

5.3.1 Case Study 1: Voltage Regulation with 21 Bus System

A residential area power distribution system model with 21 buses is used for the simulation, the system capacity is 2500 kVA, the line and load data are taken from [Senjyu *et al.* (2008)]. The distribution system is connected by two distributed generators [DG], on load tap changer, load ratio transformer, shunt capacitors and static var compensator are connected as shown in the Figure 4.8 in chapter 4. The active and reactive power of DGs is 0.3 p.u. and 0.14 p.u. respectively, the shunt capacitors connected are of 0.05 p.u. and static var compensator is of 0.1 p.u. The LRT is connected between 7^{th} and 8^{th} node, it can be used to adjust the voltage of the power distribution system. The daily load profile of a residential area power distribution is as shown in the Figure 5.2. The system reaches peak load at 8 pm. The three types of the loads from the load profile are considered for the simulation.

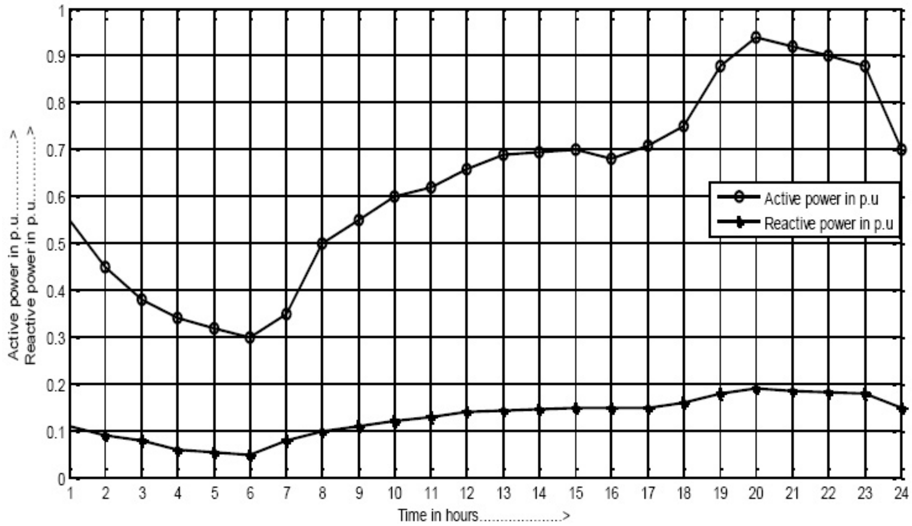

Figure 5.2: Time varying load profile for the 21 bus system

The three sets of voltage control devices are used for the simulation is given below.

a. With OLTC, LRT are available with DGs reactive power

b. With OLTC, LRT, SCs with DGs reactive power

c. With OLTC, LRT , SCs and SVC with DGs reactive power

Considering the 24 hours load from the load profile shown in Figure 5.2, three sets of fuzzy load pattern is generated using fuzzy clustering as discussed in section 5.2.4 for the 21 bus system. Here each node has different value of active and reactive power in each fuzzy load pattern. In this case study these three sets of loads are used for the simulation. The 3 sets of fuzzy load pattern generated by fuzzy cluster is indicated in Table 5.1.

Table 5.1: Fuzzy load patterns for 21 bus system from fuzzy clustering

Bus no	Fuzzy Load Pattern 1		Fuzzy Load Pattern 2		Fuzzy Load Pattern 3	
	P in p.u.	**Q in p.u.**	**P in p.u.**	**Q in p.u**	**P in p.u.**	**Q in p.u.**
1	0.03845	0.002471	0.03571	0.00201	0.02136	0.00202
2	0.04473	0.001229	0.02196	0.00330	0.03464	0.00257
3	0.03801	0.004653	0.03468	0.00370	0.01901	0.00242
4	0.03687	0.003465	0.03970	0.00264	0.03995	0.00198
5	0.02198	0.002602	0.03893	0.00196	0.05032	0.00372
6	0 .05971	0.002346	0.02694	0.00224	0.02069	0.00124
7	0.01261	0.005620	0.09091	0.00145	0.01042	0.00312
8	0.03772	0.003293	0.01805	0.00202	0.02684	0.00167
9	0.02495	0.006720	0.04603	0.00268	0.03767	0.00491
10	0.04429	0.009500	0.03903	0.00266	0.04295	0.00302
11	0.03152	0.002803	0.04234	0.00284	0.01321	0.00270
12	0.03984	0.001131	0.03099	0.00393	0.05238	0.00390
13	0.02659	0.003744	0.04951	0.00166	0.01262	0.00208
14	0.06961	.003945	0.08211	0.00336	0.01696	0.00166
15	0.02820	0.003917	0.02793	0.00346	0.02171	0.00282
16	0.02803	0.001164	0.05244	0.00283	0.01010	0.00343
17	0.02594	0.003316	0.04552	0.00324	0.02069	0.00124
18	0.03151	0.002641	0.07286	0.02289	0.03088	0.00044
19	0.03877	0.004392	0.04054	0.00199	0.00351	0.00110
20	0.03384	0.003397	0.04262	0.00402	0.01996	0.00083
21	0.02972	0.003832	0.04268	0.00226	0.02142	0.00302

- **Voltage profiles for the 21 bus distribution system**

Figures 5.3 to 5.5 show the voltage profile for the 21 bus system with and without voltage control. Figure 5.3 show the voltage profile for the system with and without voltage control for fuzzy load pattern1. It can be seen that voltage profile without control crosses the upper voltage limit with the observed peak voltage value being 1.062 p.u. It has been mitigated by each set of controls mentioned earlier and the results are as shown in the Figure 5.3.

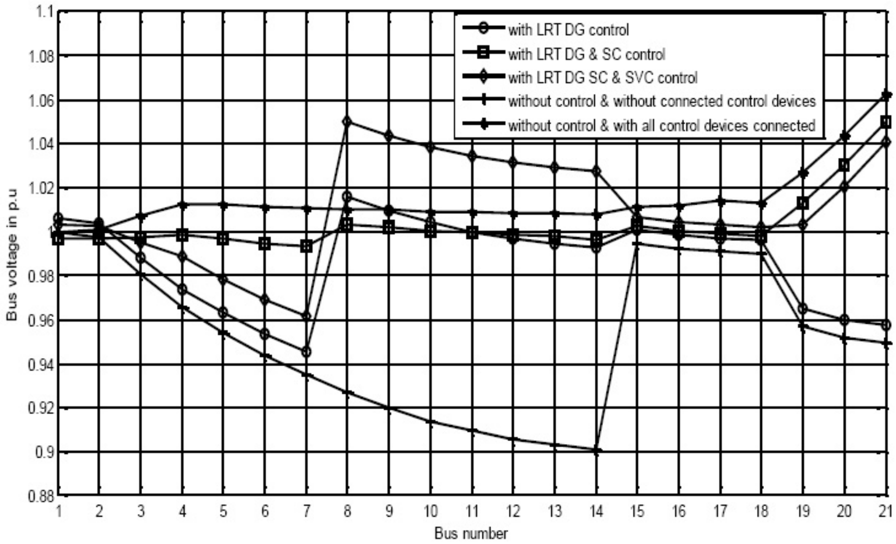

Figure 5.3: Voltage profile for 21 bus system with fuzzy load pattern 1

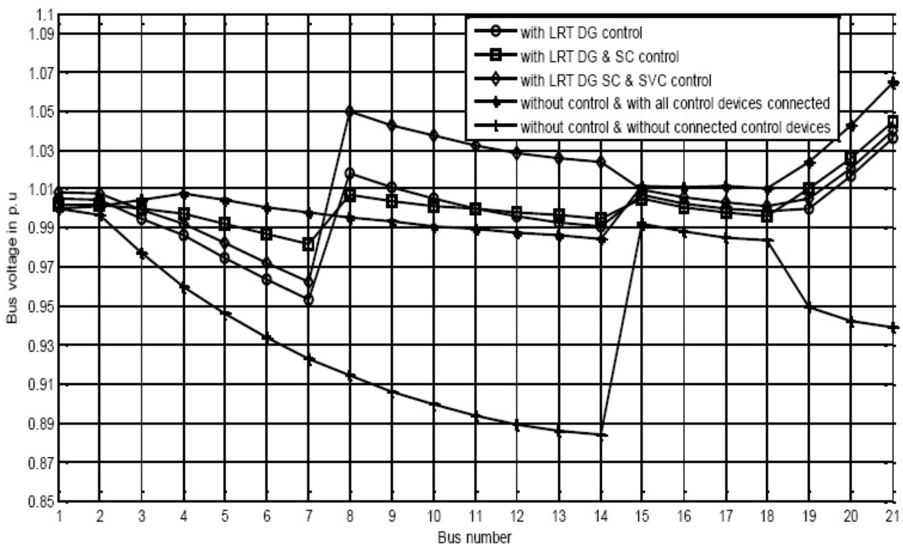

Figure 5.4: Voltage profile for 21 bus system with fuzzy load pattern 2

The voltage profile for the system with fuzzy load pattern 2 with and without control is shown in the Figure 5.4. The peak voltage level achieved in the fuzzy load pattern 2 without control is 1.068 p.u., the voltage has been controlled using multiple controlling devices.

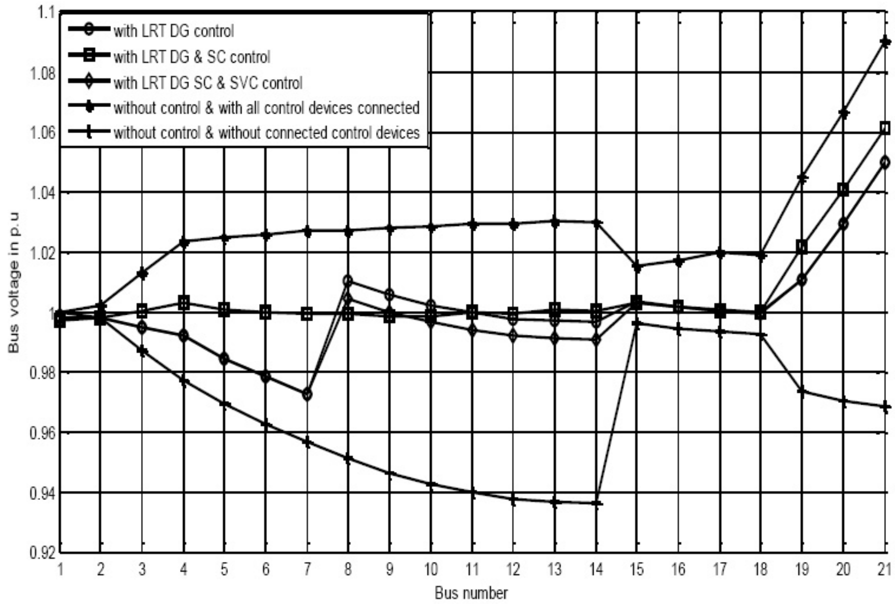

Figure 5.5: Voltage profile for 21 bus system with fuzzy load pattern 3

Figure 5.5 show the voltage profile for fuzzy load pattern 3. The peak value of the uncontrolled voltage is 1.09 p.u. It can be seen in Figure 5.5 that the voltage has been controlled effectively.

Table 5.2 indicates the optimal setting values of voltage control devices considering the fuzzy load pattern for the simulation. Here the load values are different from the load profile shown in Figure 5.1 and are generated by fuzzy clustering such that each load pattern has different load values. The setting values of OLTC and LRT depends on the load patterns and also the switching ON and OFF operation of shunt capacitors also depends on loads and other voltage control devices participation. The operation of the shunt capacitors is indicated in the Table 5.3, it can be seen that the participation of shunt capacitor is almost the same at all the three sets of load patterns.

Table 5.2: Optimal setting values of voltage control devicesin 21 bus systems

Different set of control	**Controlling devices**		**Fuzzy cluster load 1**	**Fuzzy cluster load 2**	**Fuzzy cluster load 3**
1^{st} set of control	**LRT** tap setting in p.u		1.07	1.07	1.04
	OLTC tap setting in p.u		1.01	1.0	0.99
	DGReactive power in p.u	**DG**$_1$	0.14	0.023	0.022
		DG$_2$	0.025	0.043	0.022
2^{nd} set of control	**LRT** tap setting in p.u		1.03	1.03	1.01
	OLTC tap setting in p.u		0.99	1.0	0.99
	DGReactive power in p.u	**DG**$_1$	0.025	0.047	0.102
		DG$_2$	0.033	0.022	0.023
	Shunt Capacitors position		4SCs on 2SCsoff	5SCs on 1SCs off	2SCs on 4SCsoff
3^{rd} set of control	**LRT** tap setting in p.u		1.08	1.09	1.04
	OLTC tap setting in p.u		1.01	1.0	0.99
	DGReactive power in p.u	**DG**$_1$	0.022	0.022	0.022
		DG$_2$	0.026	0.023	0.023
	Shunt Capacitors position		1SC on 5SCs off	1SC on 5SCsoff	1SCon 5SCsoff
	SVC setting value		-0.06	-0.004	0.003

The power loss of the 21 bus system before and after the voltage control is indicated in Table 5.4. It can be observed that, the power loss is more in fuzzy load 1 compared to other set of load patterns. Power loss has been reduced after the voltage control for all the load pattern generated by fuzzy clustering.

Table 5.3: Operation of shunt capacitors in 21 bus system

Different load from fuzzy cluster	**Different set of control**	**SC_3**	**SC_5**	**SC_7**	**SC_9**	**SC_{11}**	**SC_{13}**
Fuzzy load pattern 1	2^{nd} set	on	on	off	off	on	on
	3^{rd}set	off	off	on	off	off	off
Fuzzy load pattern 2	2^{nd}ser	on	on	on	off	on	on
	3^{rd}set	off	on	off	off	off	off
Fuzzy load pattern 3	2^{nd}set	off	off	off	off	on	on
	3^{rd}set	on	off	off	off	off	off

Table 5.4: Power loss in 21 bus system

Load pattern	**Power loss before voltage control**		**Power loss after voltage control**	
	P_{loss} p.u	**Q_{loss} p.u**	**P_{loss} p.u**	**Q_{loss} p.u**
Fuzzy load 1	0.00821	0.0071	0.0079	0.0068
Fuzzy load 2	0.00445	0.0067	0.00439	0.0056
Fuzzy load 3	0.00446	0.0056	0.00445	0.0054

5.3.2 Case Study 2: Voltage Regulation with IEEE 33 Bus Radial System

The study is based on a IEEE 33 bus distribution system with 3 DGs (active power=0.24 p.u. and reactive power=0.11 p.u. each). The load and system data are taken from [Zhang *et al.* (2009)]. The other voltage control devices used are shunt capacitors(6 nos) with 0.05 p.u., one static var compensator with 0.1 p.u. capacity and a LRT connected between 7^{th} and 8^{th} bus. The OLTC is connected near to substation as shown in the Figure 4.13 of chapter 4. Three sets of load profiles are generated using fuzzy clustering as discussed in the section 5.2. The three set of load is given in Table 5.5 is generated considering 24 hours load data indicated in the load profile of Figure 5.6. Three sets of voltage control devices given below are considered for the voltage control simulation using fuzzy load patterns.

a. With LRT,OLTC and DGs reactive powers

b. With LRT,OLTC,SC and DGs reactive powers

c. With LRT,OLTC,SC,SVC and DGs reactive powers

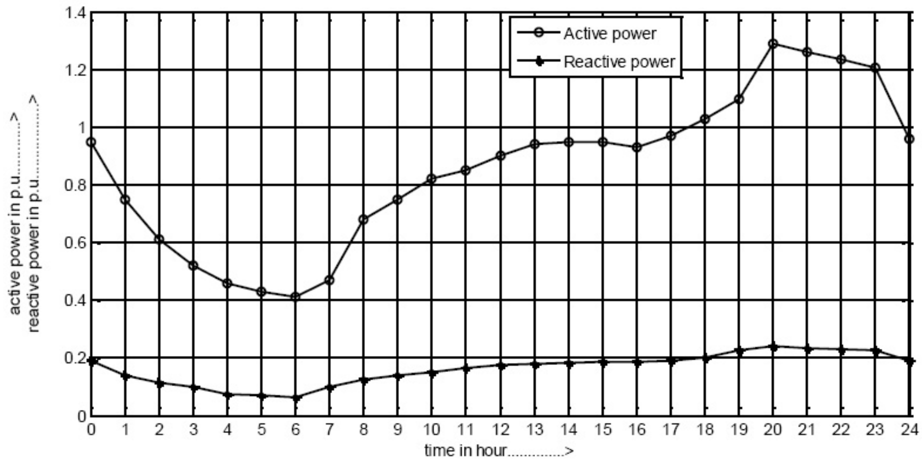

Figure 5.6: Time varying profile load for IEEE 33 bus system

Table 5.5: Fuzzy load patterns for IEEE 33 bus system from fuzzy clustering

Bus no	Fuzzy Load Pattern 1		Fuzzy Load Pattern 2		Fuzzy Load Pattern 3	
	P in p.u.	**Q in p.u.**	**P in p.u.**	**Q in p.u.**	**P in p.u.**	**Q in p.u.**
1	0.03888	0.00156	0.02899	0.00392	0.01132	0.002028
2	0.02829	0.001025	0.03591	0.003672	0.01578	0.005750
3	0.04010	0.00680	0.03828	0.001954	0.01876	0.001509
4	0.03349	0.03323	0.03380	0.001602	0.02492	0.001429
5	0.00259	0.002857	0.02380	0.003600	0.01477	0.001637
6	0 .01420	0.04056	0.00117	0.001795	0.02672	0.003866
7	0.03022	0.02214	0.00914	0.003410	0.02705	0.001927
8	0.07880	0.03486	0.00104	0.035270	0.02632	0.002780
9	0.02857	0.02654	0.00750	0.001056	0.02754	0.003883
10	0.03162	0.002237	0.03243	0.003073	0.02896	0.002028
11	0.03210	0.02664	0.01997	0.023880	0.01091	0.002923
12	0.04191	0.002755	0.02386	0.001466	0.02467	0.003095
13	0.04420	0.01232	0.01810	0.008580	0.03478	0.001942
14	0.03561	0.02176	0.07560	0.033730	0.08813	0.05367
15	0.02867	0.02513	0.02461	0.01190	0.05252	0.03585
16	0.06015	0.02869	0.08865	0.01228	0.06645	0.09938
17	0.05122	0.03570	0.07595	0.03151	0.03563	0.03681
18	0.06910	0.02216	0.06739	0.004141	0.02911	0.003946
19	0.01033	0.01730	0.03655	0.013920	0.02247	0.03026
20	0.03934	0.001939	0.02491	0.003124	0.02086	0.002483
21	0.02699	0.003087	0.02953	0.001098	0.04058	0.003180

Bus no	Fuzzy Load Pattern 1		Fuzzy Load Pattern 2		Fuzzy Load Pattern 3	
	P in p.u.	**Q in p.u.**	**P in p.u.**	**Q in p.u.**	**P in p.u.**	**Q in p.u.**
22	0.03741	0.002199	0.01641	0.004327	0.01494	0.002442
23	0.01289	0.002848	0.02144	0.025170	0.01373	0.01498
24	0.02588	0.003094	0.03223	0.003143	0.01194	0.01016
25	0.03135	0.002803	0.01845	0.008030	0.02251	0.002824
26	0.006564	0.002144	0.03868	0.026670	0.002366	0.02541
27	0.002686	0.002132	0.01348	0.003399	0.01670	0.002456
28	0.002036	0.002203	0.04317	0.001001	0.001948	0.002745
29	0.008520	0.002337	0.002949	0.002496	0.003230	0.001025
30	0.02315	0.001590	0.02788	0.001862	0.02345	0.001820
31	0.001672	0.002452	0.004522	0.002518	0.01850	0.003087
32	0.00838	0.001270	0.001529	0.002131	0.001140	0.003311
33	0.01189	0.00100	0.01996	0.001107	0.03076	0.001168

- **Voltage profile for IEEE 33 bus distribution system**

The Figures 5.7 to 5.9 show the voltage profile for the three fuzzy load patterns with and without voltage control. It can be observed that from the Figure 5.7, the voltage profile of the system with fuzzy load pattern1 crosses the upper limit after the DGs connected. The voltage level at 31^{st} bus is 1.1 p.u. The figure also shows that the voltage control devices effectively mitigate the voltage rise.

Figure 5.8 shows that the voltage profile for the system with fuzzy load pattern 2, voltage level at buses 18^{th} and 29^{th} to 33^{rd} crosses the upper limit. It has been mitigated successfully with all control devices. Figure 5.9 shows the voltage profile for the system with fuzzy load pattern 3. The peak voltage level after DGs connected is 1.092 p.u. It can be observed that the violated bus voltages have been controlled.

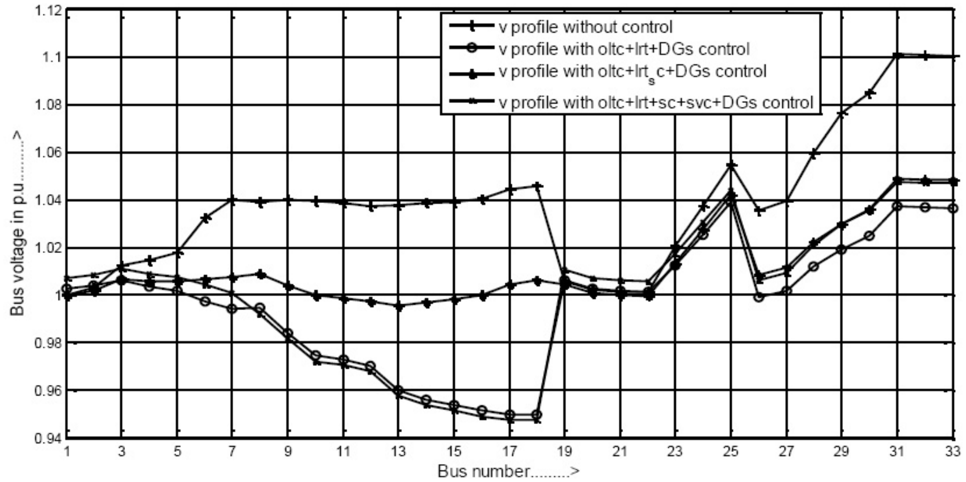

Figure 5.7: Voltage profile for IEEE 33 bus system with fuzzy load patter 1

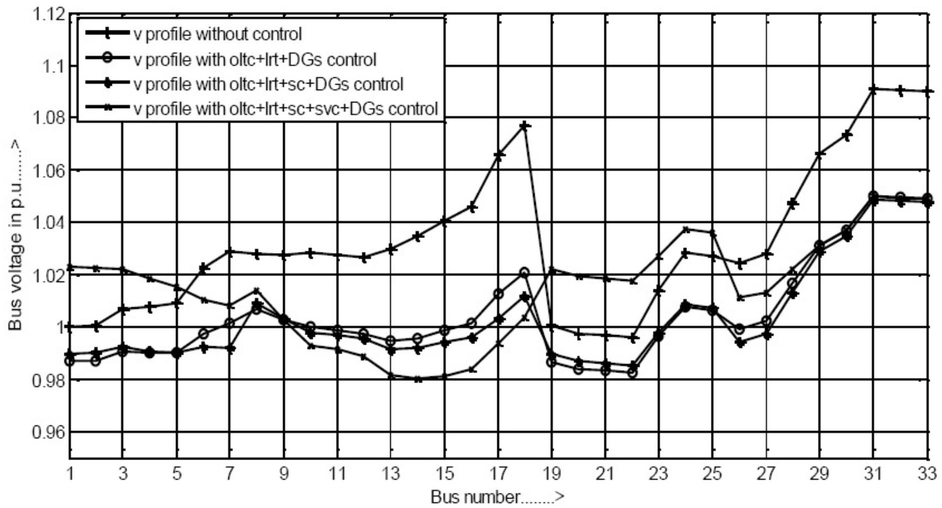

Figure 5.8: Voltage profile for IEEE 33 bus system with fuzzy load pattern 2

Table 5.6 indicates the operation of shunt capacitors after the voltage control, equally participation in the voltage control at all the load patterns has been observed. Table 5.7 indicates the optimal setting values of the control devices. It can be observed that the setting values of LRT and OLTC are changed depending on other devices setting values and the load value. Table 5.8 indicates the power loss in the IEEE 33 bus system at different load, it has been observed that the power loss is more in fuzzy load pattern 3 compared to other load patterns. And power loss has been reduced after the voltage control at all the load condition.

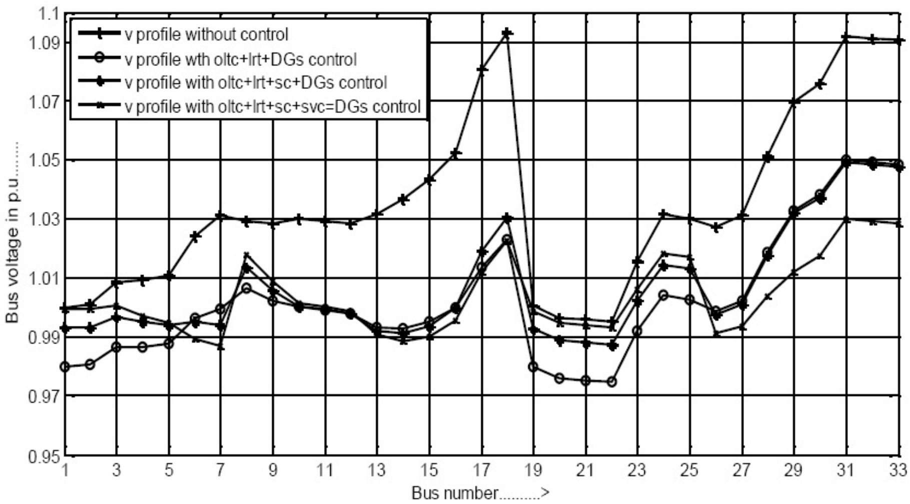

Figure 5.9: Voltage profile for IEEE 33 bus system with fuzzy load pattern 3

Table 5.6: Operation of shunt capacitors in IEEE 33 bus system

Different load from fuzzy cluster	**Different set of control**	**SC_6**	**SC_8**	**SC_{10}**	**SC_{12}**	**SC_{15}**	**SC_{17}**
Fuzzy load pattern 1	2^{nd} set	off	off	off	off	on	on
	3^{rd}set	off	off	off	off	off	off
Fuzzy load pattern 2	2^{nd}ser	off	off	off	on	on	off
	3^{rd}set	off	on	off	off	off	off
Fuzzy load pattern 3	2^{nd}set	off	off	off	off	on	off
	3^{rd}set	off	off	off	off	on	off

Table 5.7: Optimal setting value of voltage control devices in IEEE 33 bus system

Different set of control	**Controlling devices**		**Fuzzy cluster load 1**	**Fuzzy cluster load 2**	**Fuzzy cluster load 3**
1^{st} set of control	**LRT** tap setting in p.u.		1.01	1.01	1.01
	OLTC tap setting in p.u.		1.0	0.98	0.97
	DGReactive power in p.u.	**DG**$_1$	0.033	0.0169	0.0169
		DG$_2$	0.0169	0.027	0.017
		DG$_3$	0.021	0.0169	0.0169
2^{nd} set of control	**LRT** tap setting in p.u.		0.01	1.03	1.03
	OLTC tap setting in p.u.		1.0	0.99	0.99
	DGReactive power in p.u.	**DG**$_1$	0.055	0.034	0.058
		DG$_2$	0.025	0.019	0.0169
		DG$_3$	0.0169	0.023	0.0169
	Shunt Capacitors position		4SCs off 2SCs on	2SCson 4SCs off	1SCson 5SCsoff
3^{rd} set of control	**LRT** tap setting in p.u.		1.0	1.02	1.05
	OLTC tap setting in p.u.		1.0	1.01	0.99
	DGReactive power in p.u.	**DG**$_1$	0.022	0.050	0.030
		DG$_2$	0.019	0.0178	0.0176
		DG$_3$	0.016	0.0172	0.0171
	Shunt Capacitors position		6SCs off	1SCson 5SCsoff	3SCson 3SCsoff
	SVC setting value		0.03	0.0009	-0.009

Table 5.8: Power loss before and after voltage control in IEEE 33 bus system

Different load	**Before voltage control**		**After voltage control**	
	P_{loss} p.u.	**Q_{loss} p.u.**	**P_{loss} p.u.**	**Q_{loss} p.u.**
Fuzzy load 1	0.00595	0.00409	0.00344	0.00276
Fuzzy load 2	0.00485	0.00379	0.00280	0.00256
Fuzzy load 3	0.00601	0.00425	0.00348	0.00287

5.4 CONCLUSION

In this chapter a fuzzy clustering technique for load profile generations has been presented instead of considering sample data directly from time varying load profile. The generated fuzzy load patterns are used to study the performance of coordinated voltage regulation method. The voltage regulators like OLTC, SC, SVC are used with DGs reactive powers for the voltage control. In this work two case studies has been considered for the simulation with 21 and 33 bus system. The results indicate that by optimally setting the values of various voltage control devices through genetic algorithm, the distribution system voltage can be regulated well within the statute limits and also power loss can be reduced. It has been observed that obtaining the load profile through fuzzy clustering can represent a more realistic case compared to considering the sample load conditions from the load profile.

Chapter 6

VOLTAGE REGULATION OF 3 PHASE UNBALANCED DISTRIBUTION SYSTEM WITH DG

6.1 INTRODUCTION

Distribution systems are usually unbalanced due to unbalanced loading of the different phases. Besides industrial or domestic customers some distributed generators can also impose an unbalanced operation of electrical networks. Typically, a distribution system originates at a substation and continues to a lower voltage for delivery to the customers. Unlike a transmission system, a distribution system typically has a radial topological structure. The radial structure, along with the higher resistance/reactance (R/X) ratio of the lines, means distribution systems are ill conditioned and hence the Fast-Decoupled Newton method is unsuitable for most distribution power flow problems. Most of the conventional power flow methods consider power demands as specified constant values. This should not be assumed because in distribution system bus voltages are not controlled [Khushalani (2006)].

The techniques for three phase power flow analysis cannot be developed by simply extending the balanced methods to three phases. Thus, load flow analysis of balanced radial distribution systems will be inefficient to solve the unbalanced cases and the distribution systems need to be analyzed on a three phase basis instead of single phase basis. Therefore this requires detail modeling of special features such as multiphase, grounded or ungrounded, multi-mode control distribution equipment, unbalanced distribution loads etc. Once all these features are included in load flow model it is applicable to any three phase practical distribution system.

Recently many researchers have paid attention to obtain the load flow solution of distribution network. In [Vulasala *et al.* (2009)] presented a selection of optimal locations and tap setting for voltage regulators in unbalanced radial distribution system. Genetic algorithm is used for voltage regulator placement in distribution system. An algorithm makes the initial selection, installation and tap setting of the voltage regulators to provide a smooth voltage profile along the network. In [Ramana *et al.* (2010)] presents a simple method for investigating the problem of contemporaneously choosing the best location and capacity of DG in three-phase unbalanced radial distribution systems to improve the voltage profile of the system.

In this chapter the impacts of distributed generators on the voltage profiles of unbalanced distribution systems have been analyzed. SVC, shunt capacitors and LRT with DG reactive power are used in distributed systems for controlling the voltage. In this work genetic algorithm is used for optimal setting of voltage regulators and it is simulated to verify on IEEE 3 phase 13 and 25 bus unbalanced radial distribution feeders.

6.2 MODELING OF UNBALANCED RADIAL DISTRIBUTION SYSTEM

Radial distribution system can be modeled as a network of buses connected by distribution lines, switches or transformers. Each bus may also have a corresponding load, shunt capacitor and or co-generator connected to it. This model can be represented by a radial interconnection of copies of the basic building block shown in Figure 6.1. [Umapathi *et al.* (2012)] Since a given branch may be single-phase, two-phase, or three-phase, each of the quantities is respectively a complex scalar, 2×1, or 3×1 complex vector. The model consist of distribution line with are without voltage regulator or Switch or Transformer.

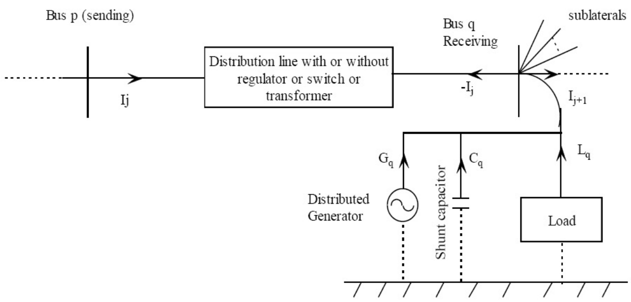

Figure 6.1: Basic building blocks of unbalanced radial distribution system

6.2.1 Distribution System Line Modeling

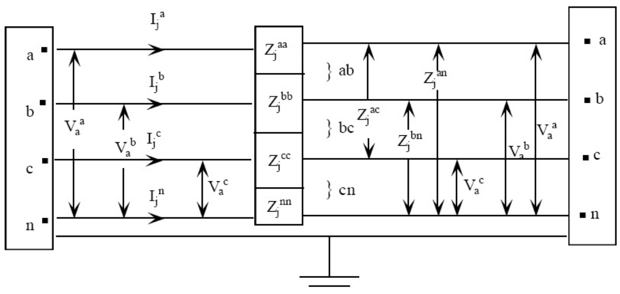

Figure 6.2: Model of the three phase four wire distribution line

For the analysis of power transmission line, two fundamental assumptions are made, namely: Three phase currents are balanced and transposition of the conductors to achieve balanced line parameters. A general representation of a distribution system with N conductors can be formulated by resorting to the Carsons equations, leading to a N× N primitive impedance matrix. The standard method used to form this matrix is the Kron reduction, based on the Kirchhoffs laws [Chen (1991)]. For instance a four-wire grounded star connected overhead distribution line shown in Figure 6.2. results in a 4× 4 impedance matrix. The corresponding equations are

$$\begin{bmatrix} V_p^a \\ V_p^b \\ V_p^c \\ V_p^n \end{bmatrix} = \begin{bmatrix} V_q^a \\ V_q^b \\ V_q^c \\ V_q^n \end{bmatrix} + \begin{bmatrix} Z_j^{aa} & Z_j^{ab} & Z_j^{ac} & Z_j^{an} \\ Z_j^{ba} & Z_j^{bb} & Z_j^{bc} & Z_j^{bn} \\ Z_j^{ca} & Z_j^{cb} & Z_j^{cc} & Z_j^{cn} \\ Z_j^{na} & Z_j^{nb} & Z_j^{nc} & Z_j^{nn} \end{bmatrix} \begin{bmatrix} I_j^a \\ I_j^b \\ I_j^c \\ I_j^n \end{bmatrix} \tag{6.2.1}$$

It can be represented in matrix form as

$$\begin{bmatrix} V_p^{abc} \\ V_p^n \end{bmatrix} = \begin{bmatrix} V_q^{abc} \\ V_q^n \end{bmatrix} + \begin{bmatrix} Z_j^{aa} & Z_j^n \\ Z_j^{nT} & Z_j^{nn} \end{bmatrix} \begin{bmatrix} I_j^{abc} \\ I_j^n \end{bmatrix} \tag{6.2.2}$$

If the neutral is grounded,the voltage nV_p and nV_q can be considered to be equal.From the 1^{st} row of equation (6.2.2) it is possible to obtain

$$I_j^n = -Z_j^{nn-1}(Z_j^n)^T I_j^{abc} \tag{6.2.3}$$

and substituting equation (6.2.3) into equation (6.2.2), the final form corresponding to the Krons reduction becomes

$$V_p^{abc} = V_q^{abc} + Ze_j^{abc} I_j^{abc} \tag{6.2.4}$$

where,

$$Ze_j^{abc} = Z_j^{abc} - Z_j^n Z_j^{n(n-1)}(Z_j^n)^T = \begin{bmatrix} Ze_j^{aa} & Ze_j^{ab} & Ze_j^{ac} \\ Ze_j^{ba} & Ze_j^{bb} & Ze_j^{bc} \\ Ze_j^{ca} & Ze_j^{cb} & Ze_j^{cc} \end{bmatrix} \tag{6.2.5}$$

$I_j^{abc}$is the current vector through line between nodes p and q can be equal to the sum of the load currents of all the nodes beyond line between node p and q plus the sum of the charging currents of all the buses beyond line between node p and q , of each phase. Therefore the bus Q voltage can be computed when we know the bus P voltage, mathematically, by rewriting equation (6.2.4).

$$\begin{bmatrix} V_q^a \\ V_q^b \\ V_q^c \end{bmatrix} = \begin{bmatrix} V_p^a \\ V_p^b \\ V_p^c \end{bmatrix} + \begin{bmatrix} Ze_j^{aa} & Ze_j^{ab} & Ze_j^{ac} \\ Ze_j^{ba} & Ze_j^{bb} & Ze_j^{bc} \\ Ze_j^{ca} & Ze_j^{cb} & Ze_j^{cc} \end{bmatrix} \begin{bmatrix} I_j^a \\ I_p^j \\ I_j^c \end{bmatrix} \tag{6.2.6}$$

6.2.2 Shunt Admittance Modeling

These current injections for representing line charging, which should be added to the respective compensation current injections at nodes p and q, are given by

$$\begin{bmatrix} Ish_q^a \\ Ish_q^b \\ Ish_q^c \end{bmatrix} = 1/2 \begin{bmatrix} -(y_j^{aa} + y_j^{ab} + y_j^{ac}) & y_j^{ab} & y_j^{ac} \\ y_j^{ba} & -(y_j^{ba} + y_j^{bb} + y_j^{bc}) & y_j^{bc} \\ y_j^{ca} & y_j^{cb} & -(y_j^{ca} + y_j^{cb} + y_j^{cc}) \end{bmatrix} \begin{bmatrix} V_q^a \\ V_q^b \\ V_q^c \end{bmatrix} \tag{6.2.7}$$

6.2.3 Distributed Load Modeling

Sometimes the primary feeder supplies loads through distribution transformers tapped at various locations along line section. If every load point is modeled as a node then there are a large number of nodes in the system. So these loads are represented as lumped loads, at one fourth length of line from sending node, where two thirds of the load is connected. For this a dummy node is created. One third loads is connected at the receiving node. In the unbalanced distribution system, loads can be uniformly distributed along a line. When the loads are uniformly distributed it is not necessary to model each and every load in order to determine the voltage drop from the source end to the last loads.

6.2.4 Capacitor Modeling

Shunt capacitor banks are commonly used in distribution systems to help in voltage regulation and to provide reactive power support. The capacitor banks are modeled as constant susceptances connected in either star or delta. Similar to the load model, all capacitor banks

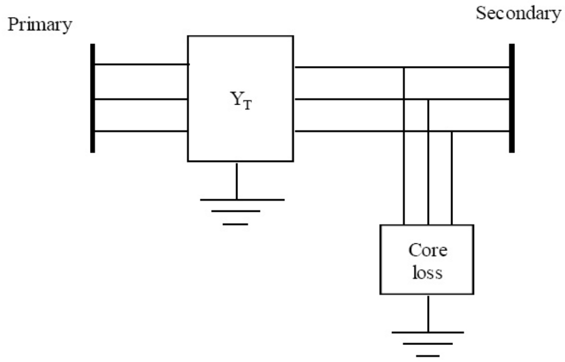

Figure 6.3: General model for three phase transformer

are modeled as three phase banks with the currents of the missing phases set to zero for single phase and two phase banks.

6.2.5 Transformer Modeling

Three phase transformer is represented by two blocks shown in Figure 6.3. One block represents the per unit leakage admittance matrix Y_T^{abc} and the other block models the core loss as a function of voltage on the secondary side [Mahmoud and Akher (2010)].

Now that Y_{sp}^{abc} is not singular, the non- zero sequence components of the voltages on the primary side can be determined by

$$V_P^{abc'} = (Y_{sp}^{abc'})^{-1}(I_s^{abc'} - Y_{ss}^{abc} V_s^{abc}) \tag{6.2.8}$$

Similar results can be obtained for forward sweep calculation

$$V_s^{abc''} = (Y_{ss}^{abc''})^{-1}(I_{sp}^{abc''} - Y_{sp}^{abc''} V_p^{abc}) \tag{6.2.9}$$

Where $V_s^{abc''}$ is the nonzero sequence component of V_s^{abc} , $Y_{ss}^{abc''}$ is same as Y_{ss}^{abc} except that the last row is replaced with [1 1 1], I_s^{abc} and Y_{sp}^{abc} are obtained by setting the elements in the last row of I_s^{abc} and Y_{sp}^{abc} to 0 respectively [Selvan and Swarup (2006)]. Once the nonzero-sequence components of V_p^{abc} or V_s^{abc} are calculated, zero-sequence components are added to them to form the line to neutral voltages so that the forward and backward sweep procedure can continued.

6.3 FORWARD AND BACKWARD SWEEP LOAD FLOW METHOD FOR UNBALANCED SYSTEM

The forward and backward sweep method models the distribution system as a tree network, with the slack bus denoted as the root of the tree and branch networks as the layers that are far away from the root node. Weakly meshed networks are converted to radial networks by breaking the loops and computing injection currents. The backward sweep primarily sums either the line currents or power flows from the extreme feeder (leaf) to the root.

6.3.1 Backward Sweep

The purpose of the backward sweep is to update branch currents in each section, by considering the previous iteration voltages at each node. During backward propagation voltage values are held constant at the values obtained in the forward path and updated branch currents are transmitted backward along the feeder using backward path. Backward sweep starts from extreme end branch and proceeds along the forward path.

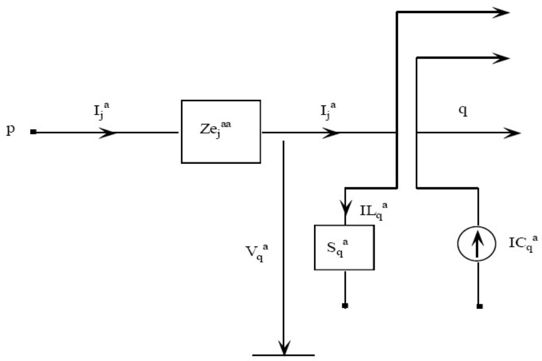

Figure 6.4: Single phase line section with load connected

Figure 6.4 shows phase a of a three-phase system where lines between nodes p and q feed the node q and all the other lines connecting node q draw current from line between node p and q . During this propagation different load currents and capacitor currents (if exist) are calculated using mathematical models of loads and capacitors presented in section 6.2.3. The line charging currents of all the branches are added to the load current. Figure 6.5 shows a branch j of the distribution network, connected between two nodes p and q, and m sub-laterals are connected to it. The parent branch current feeds the load at the qth node and the sub-laterals connected to the parent branch. This current can be calculated using equation (6.3.1).

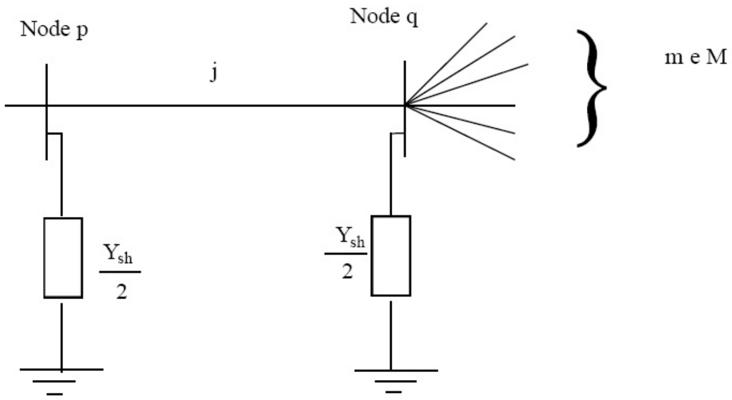

Figure 6.5: m sub-laterals conected to j^{th} node of distribution network

$$(I_j^{abc})^k = (IL_q^{abc})^k + \sum_{m \in M} (I_m^{abc})^k + \sum_{m \in M} (Y_{sh}^{abc})_m^k (V_q^{abc})_m^{k-1} \tag{6.3.1}$$

Where $(Y_{sh}^{abc})_m^k$ is the half line shunt admittance of the branch in k^{th} iteration.
$(I_j^{abc})^k$is the branch current vector in line section j in k^{th} iteration.
$(I_m^{abc})^k$is the current vector in branch m before updating in k^{th} iteration.
$(V_q^{abc})_m^{k-1}$is the voltage vector of the branch m in $(k-1)^{th}$ iteration.
m represents the set of line sections connected to j^{th} branch

If capacitor bank is placed at the receiving end of the branch then capacitor current should also be included. Another advantage of the proposed method is all the data is stored in vector form, thus saving an amount of computer memory [Subramanyam (2009)]. The proposed method finds extensive use in network reconfiguration, capacitor placement and voltage regulator placement studies.

6.3.2 Forward Sweep

The purpose of the forward sweep is to calculate the voltages at each node starting from the source node. The source node voltage is set as 1.0 per unit and other node voltages are calculated as

$$(V_q^{abc})^k = (V_p^{abc})^k + Ze_j^{abc}\left\{(Y_{sh}^{abc})(V_p^{abc})^k(-I_j^{abc})^k\right\} \tag{6.3.2}$$

Where

$(V_q^{abc})^k, (V_p^{abc})^k$ are the voltage vectors of phases for p^{th} and q^{th} nodes respectively in k^{th} iteration.

$$Ze_j^{abc} = \begin{bmatrix} Ze_j^{aa} & Ze_j^{ab} & Ze_j^{ac} \\ Ze_j^{ba} & Ze_j^{bb} & Ze_j^{bc} \\ Ze_j^{ca} & Ze_j^{cb} & Ze_j^{cc} \end{bmatrix}$$

$(I_j^{abc})^k$ is the current vector in j^{th} branch in k^{th} iteration.

These calculations will be carried out till the voltage at each bus is within the specified limits. Therefore the real and reactive power losses in the line between nodes p and q may be written as:

$$S_j^{abc} = (V_p^{abc} - V_q^{abc})(I_j^{abc})^* \tag{6.3.3}$$

where

S_j^{abc} is a vector of power loss with three, two or single phase

V_p^{abc} and V_q^{abc} are voltage vector of three phases at nodes p and q

I_j^{abc} is the branch current vector of three phases for the section connected in between p^{th} and q^{th} node

6.3.3 Algorithm for Forward and Backward Sweep Method for Unbalanced System

Step 1: Read input data regarding the unbalanced radial distribution system.

Step 2: Determine forward backward propagation paths.

Step3: Initialize the voltage magnitude at all nodes as 1.0 p.u. and voltage angles to be 0^0, -120^0, and 120^0 for phase A, phase B and phase C respectively.

Step 4: Determine forward and backward propagation paths.

Step 5: Initialize the voltage magnitude at all nodes as 1.0 p.u and voltage angles to be 0^0, -120^0, and 120^0 for phase A, phase B and phase C respectively.

Step 6: Set iteration count k=1 and ϵ= 0.0001

Step 7: Calculate load currents and capacitor currents (if exist) at all nodes.

Step 8: Calculate the branch currents using equation (6.3.1) in the backward sweep.

Step 9: Calculate node voltages using equation (6.3.2) in the forward sweep.

Step10: Check for the convergence, if the difference between the voltage magnitudes in two consecutive iterations is less than I then go to step 9 else set $k = k + 1$ and go to step 5.

Step11: Calculate real and reactive power loss in each branch.

Step12: Print voltages and power losses at each node.

Step13: Stop.

6.4 RESULTS AND DISCUSSION

There are two case studies which have been considered for the simulation to control the voltage with multiple voltage control devices using genetic algorithm. In case study 1, IEEE 13 bus unbalanced distribution system and in case study 2, 25 bus unbalanced distribution system is used for the simulation.

6.4.1 Case Study 1: Voltage Regulation with IEEE 13 Bus System

In this study the standard 4.16 kV IEEE 13 bus 3 phase unbalanced radial distribution system is used for the simulation, the line and load data is given in [Kersting (2002)].The base voltage and base MVA chosen are 4.16 kV and 100 MVA respectively. Two DGs with the active and reactive power capacity 0.14 p.u. and 0.06 p.u. are connected respectively. The LRT between bus 1 and 2, shunt capacitors and static var compensator with the rating 0.05 p.u. and with 0.1 p.u. respectively are connected as shown in the Figure 6.6. The GA parameters are indicated in the Table 6.1.

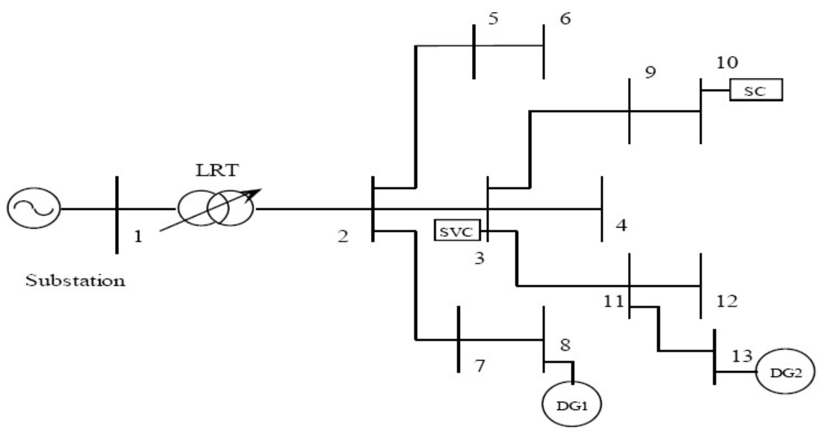

Figure 6.6: IEEE 3 phase 13 bus unbalanced system

Table 6.1: Genetic algorithm parameters

Generation	100
Population	50
Selection	Stochastic
Crossover	Scattered
Mutation	Adaptive feasible

Figures 6.7 and 6.8 show the voltage profiles for the 3 phase 13 bus system without and with voltage control respectively. In the Figure 6.7, it can be seen that the voltage profiles of the phase A and C are within the upper (1.05 p.u.) and lower voltage (0.95 p.u.) limits. The voltage profile of the phase B crosses the upper voltage limit with peak value 1.068 p.u. The rise in voltage has been mitigated by using voltage control devices with their optimal setting can be seen in the Figure 6.8 . The optimal setting values of the controlling devices with DGs reactive power setting values are given in Tables 6.2 and 6.3

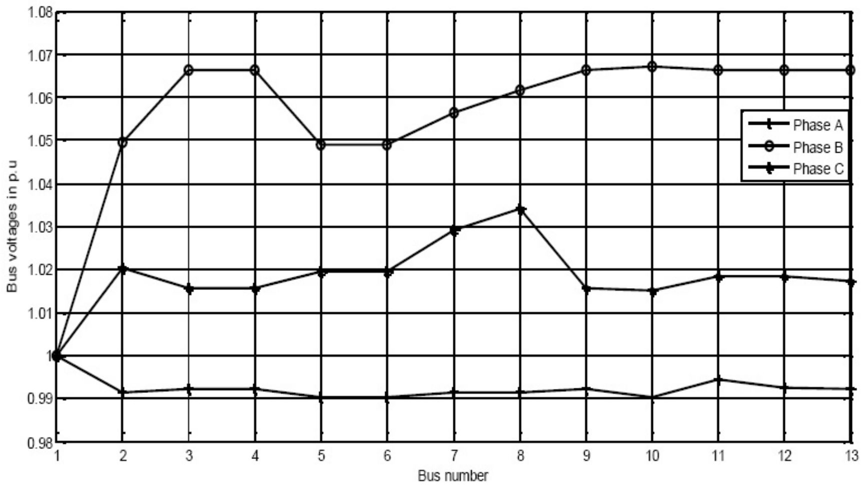

Figure 6.7: Voltage profile with DGs connected for 100% load

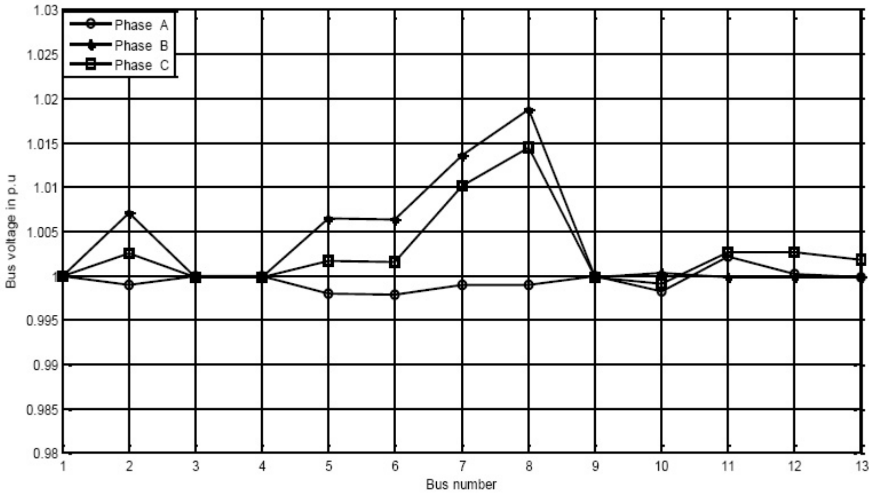

Figure 6.8: Voltage profile with voltage control for 100% load

Voltage profiles for the system with 90% load without connecting the DGs can be seen from the Figure 6.9, phase B voltage profile is below the voltage limit 0.95 p.u. The Figure 6.10 shows that, the phase A and B are crossing the upper limit after connecting the DG and it has been controlled with voltage control devices as shown in the Figure 6.11. All phase voltage profiles are within the limits 1.05 p.u to 0.95 p.u.

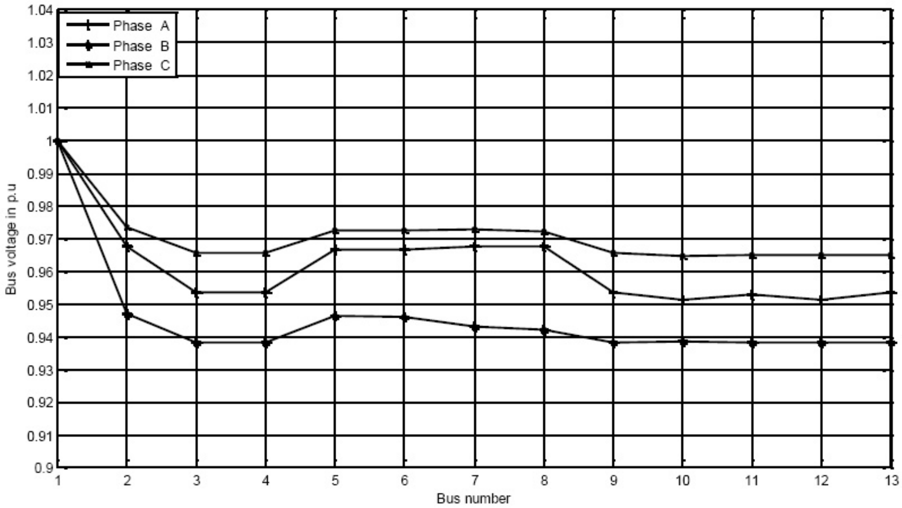

Figure 6.9: Voltage profile without DGs connected for 90% load

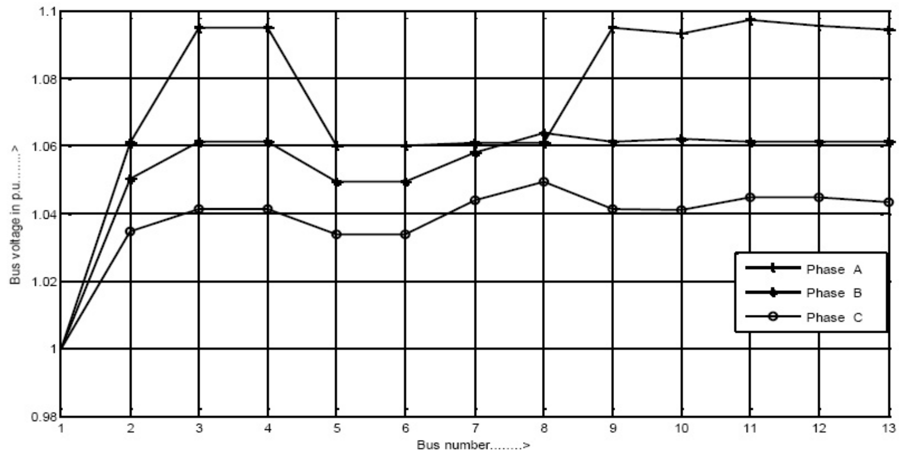

Figure 6.10: Voltage profile with DGs connected for 90% load

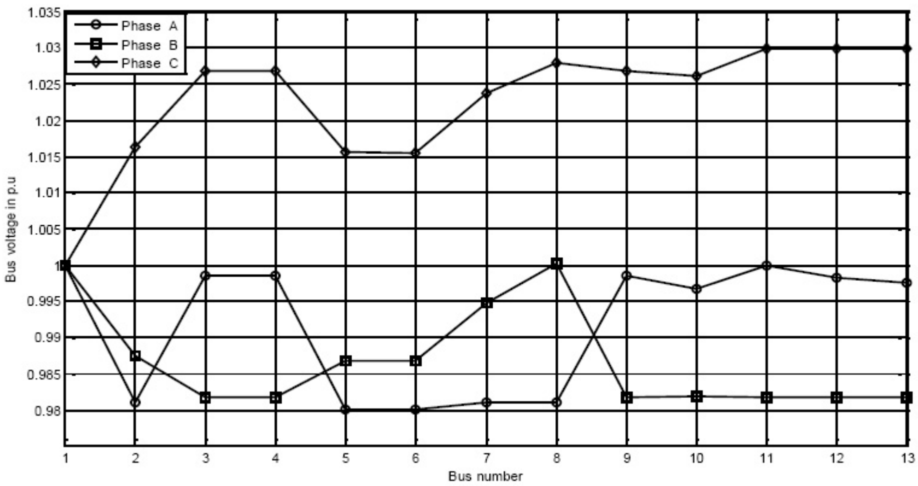

Figure 6.11: Voltage profile with voltage control for 90% load

The voltage profile of the system at 80% load without DGs connected is shown in the Figure 6.12. The Figure 6.13 show the voltage profile with DGs connected, it can be seen that all phase voltage profiles are above upper voltage limit. Voltage has been controlled using voltage control devices. It can be observed from the Figure 6.14, all the voltage profiles are within the limits. The setting values of the voltage control devices are indicated in the Tables 6.2 and 6.3.

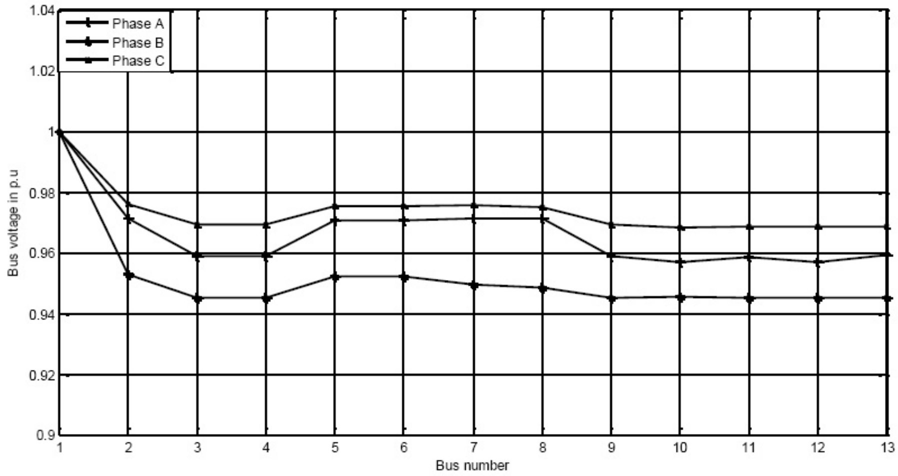

Figure 6.12: Voltage profile without DGs connected for 80% load

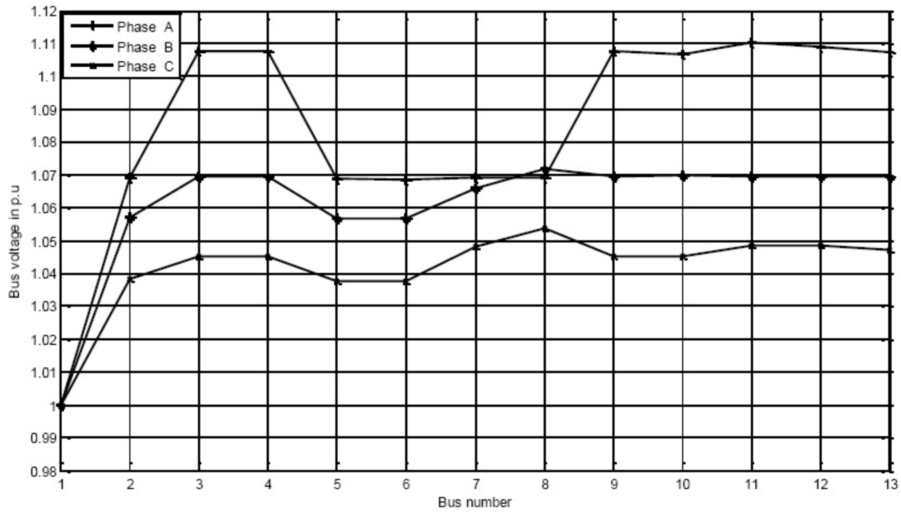

Figure 6.13: Voltage profile with DGs connected for 80% load

Figures 6.15 to 6.17 shows the voltage profile of the system with 70% load without DGs, with DGs and with voltage control. Figure 6.16 shows the voltage profile of the system with DGs connected, it can be seen that all the phase voltages are crossing the upper limit.

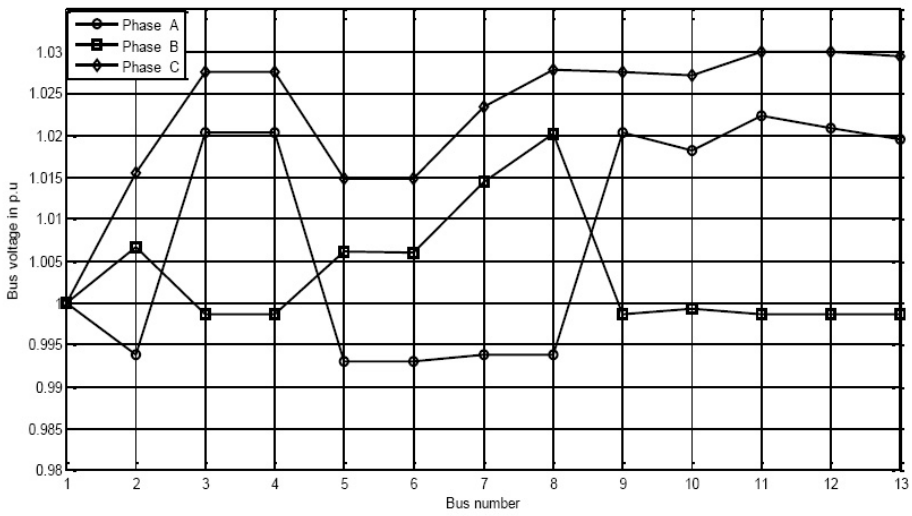

Figure 6.14: Voltage profile with voltage control for 80% load

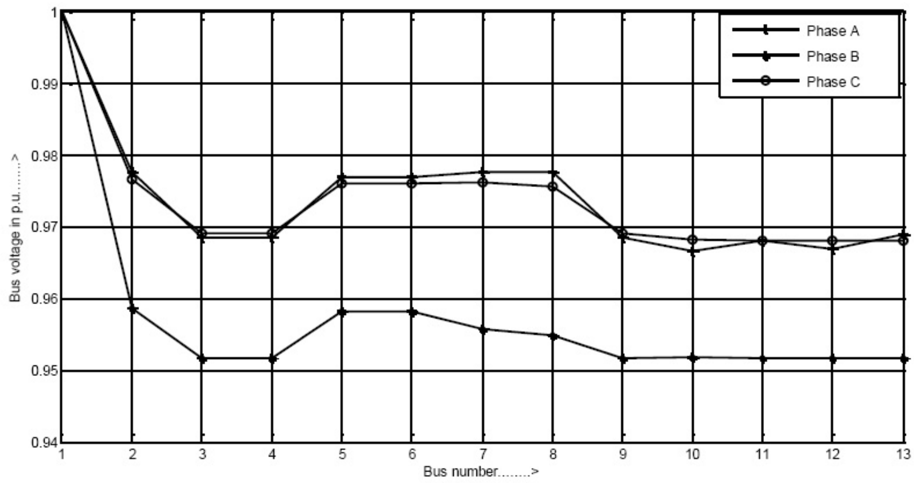

Figure 6.15: Voltage profile without DGs connected for 70% load

The voltage profile of the system with voltage control can be seen in the Figure 6.17, and all the phase voltages are within the voltage limits. The optimal setting values of the voltage regulating devices and power loss in the system before and after the voltage control are indicated in the Tables 6.2, 6.3 and 6.4 respectively.

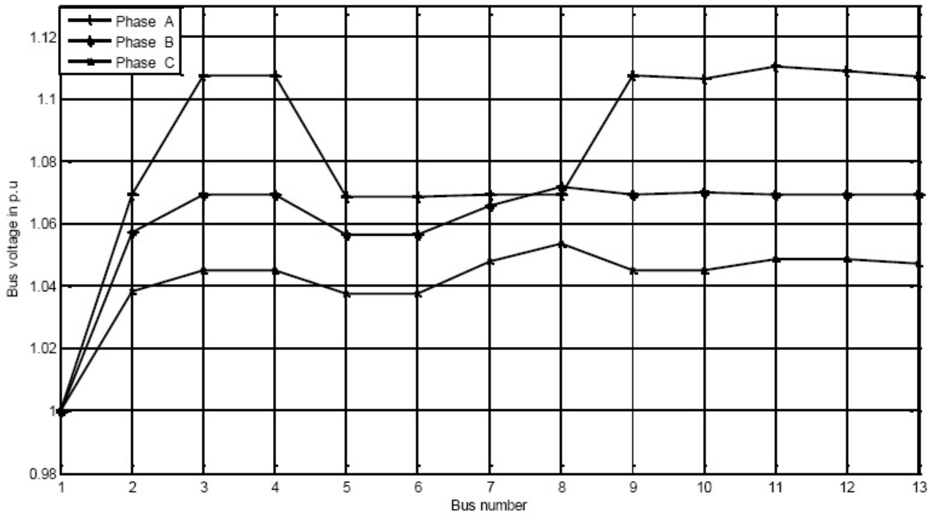

Figure 6.16: Voltage profile with DGs connected for 70% load

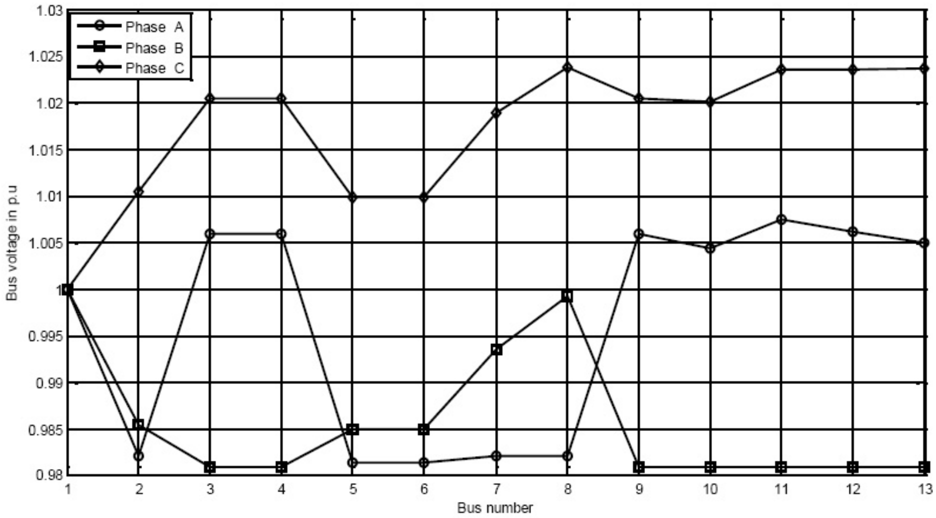

Figure 6.17: Voltage profile with voltage control for 70% load

Table 6.2: Optimal setting values of voltage control devices in IEEE 13 bus system

Different load conditions	**Voltage control devices setting value**								
	LRT			**SVC**			**DG_1 reactive power**		
	Phase A	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
100%	0.96	0.96	0.98	-0.07	0.04	0.05	0.049	0.06	0.04
90%	0.95	0.96	0.99	-0.08	0.04	0.04	0.059	0.06	0.026
80%	0.95	0.97	0.98	-0.04	-0.00	-0.00	0.050	0.06	0.06
70%	0.95	0.95	0.97	-0.03	0.04	0.04	0.041	0.06	0.06

Table 6.3: Optimal setting values of voltage control devices in IEEE 13 bus system

Different load conditions	**Voltage control devices setting value**					
	SVC			**DG_2 reactive power**		
	Phase A	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
100%	off	off	ON	0.017	0.035	0.033
90%	off	off	off	0.017	0.04	0.052
80%	off	off	off	0.017	0.023	0.03
70%	off	off	off	0.017	0.029	0.047

Table 6.4: Power loss in IEEE 13 bus unbalanced system at full load

Phases	**Before voltage control**		**After voltage control**	
	P_{loss} in p.u.	**Q_{loss}in p.u.**	**P_{loss}in p.u.**	**Q_{loss}in p.u.**
Phase A	0.0144	0.0492	0.0132	0.0450
Phase B	0.0176	0.0613	0.0155	0.0538
Phase C	0.0040	0.0143	0.0036	0.0138

6.4.2 Case Study 2: Voltage Regulation with 25 Bus System

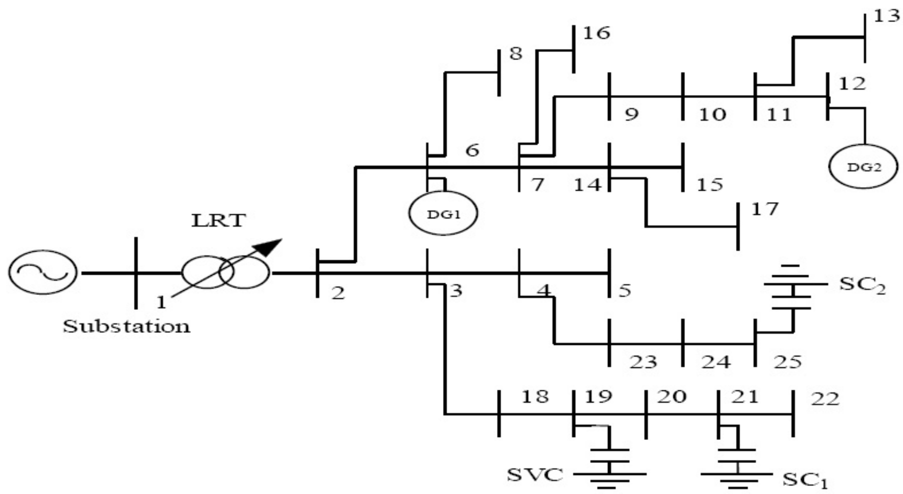

Figure 6.18: 3 Phase 25 bus radial unbalanced distribution system

The 25 bus radial unbalanced distribution system is taken and voltage controlling devices are distributed across the system as shown in the Figure 6.18, the line and load data are given in [Vulasala (2009)]. The voltage control devices LRT, SC and SVC with DG reactive powers are considered in this system for voltage control. DGs capacity with active power of 0.12 p.u. and reactive power of 0.06 p.u. are connected at buses 5^{th} and 12^{th}, shunt capacitors with 0.05 p.u. each connected at buses 15^{th} and 18^{th} ,static var compensator with 0.1 p.u. is connected at bus no 22^{nd}. All the voltage controlling devices are connected to each phase. The base MVA of the system is 30 MVA and base kV is 4.16 kV.

The voltage profile for the 3 phase 25 bus unbalanced system without and with voltage control can been seen from the Figures 6.19 and 6.20 respectively. In the Figure 6.19, it can be seen that voltage profile of all the 3 phases cross the upper limit 1.05 p.u. The voltage profiles after the mitigation using voltage regulators can be seen from the Figure 6.20. All phase voltage profiles are within the limits 1.05 -0.95 p.u.

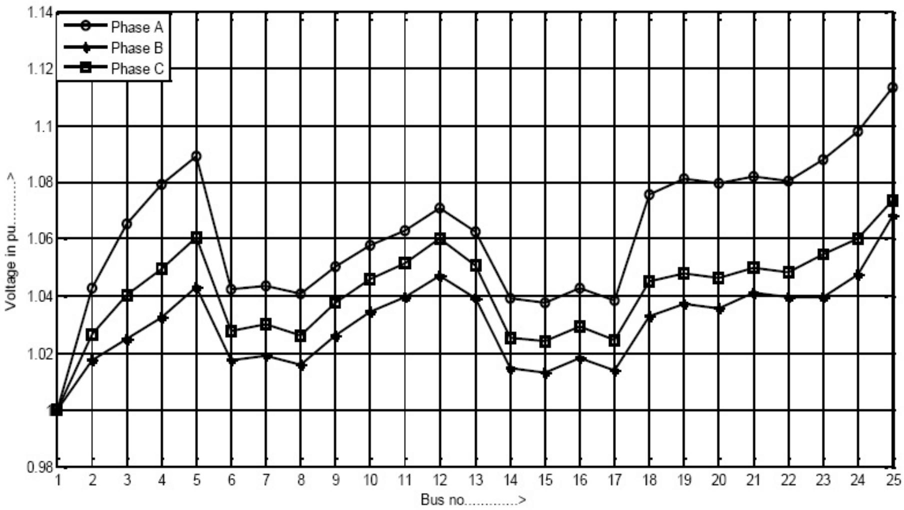

Figure 6.19: Voltage profile without voltage control for 100% load

The voltage profile for the system with 90% load without DGs connected, with DGs connected and with voltage control can be seen from the Figures 6.21 to 6.22. It can be seen that from the Figure 6.23 that all the 3 phase voltage profiles are above the upper limit 1.05 p.u. It has been mitigated with voltage control devices effectively and all phase voltages are within the limits as observed from the Figure 6.22.The optimal setting values of the voltage control devices are indicated in the Table6.5.

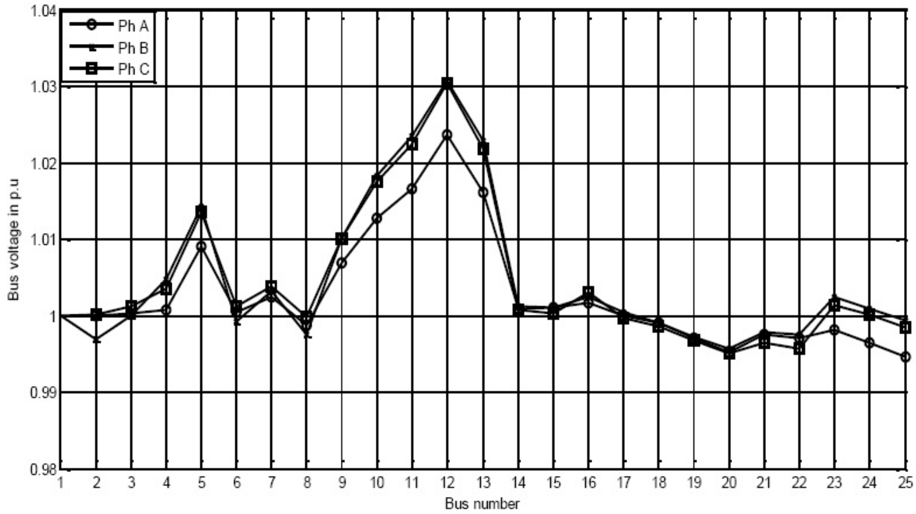

Figure 6.20: Voltage profile with voltage control for 100% load

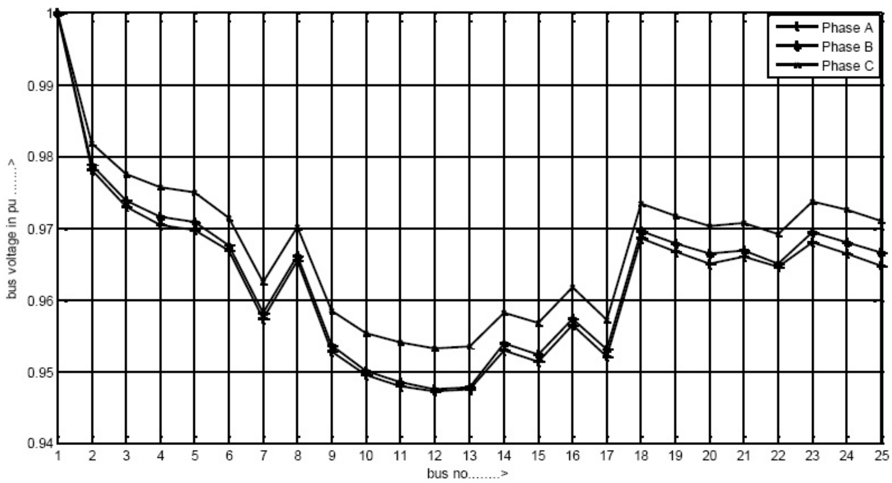

Figure 6.21: Voltage profile without DGs connected for 90% load

Voltage control simulation has been done for the radial distribution system with 80% load with voltage control devices, the simulation results can be seen from the Figures. 6.24 to 6.26. Figure 6.24 shows that the voltage profile of the system with 80% load without connecting distributed generators.

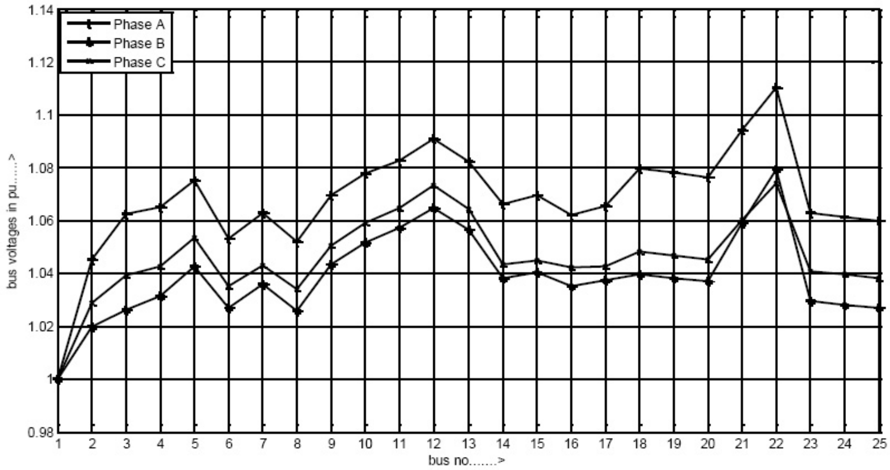

Figure 6.22: Voltage profile with DG connected for 90% load

After DGs are connected to the system to all phases the voltage level increases, as shown in Figure 6.25, all the phase voltages are above the upper limit, the effect of the voltage control devices on voltage rise can be seen in the Figure 6.26.

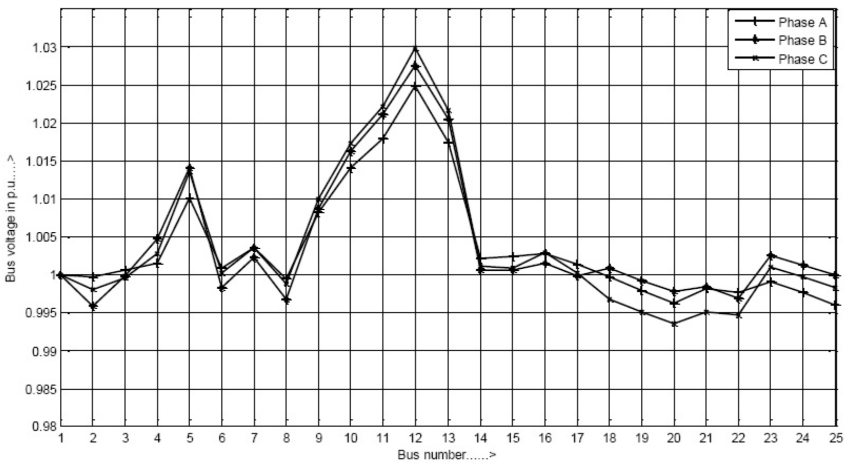

Figure 6.23: Voltage profile with voltage control for 90% load

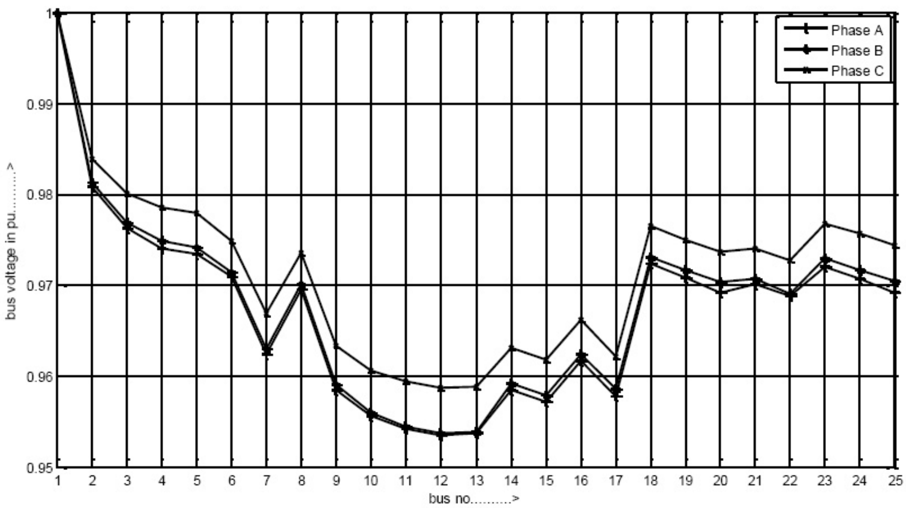

Figure 6.24: Voltage profile without DGs connected for 80% load

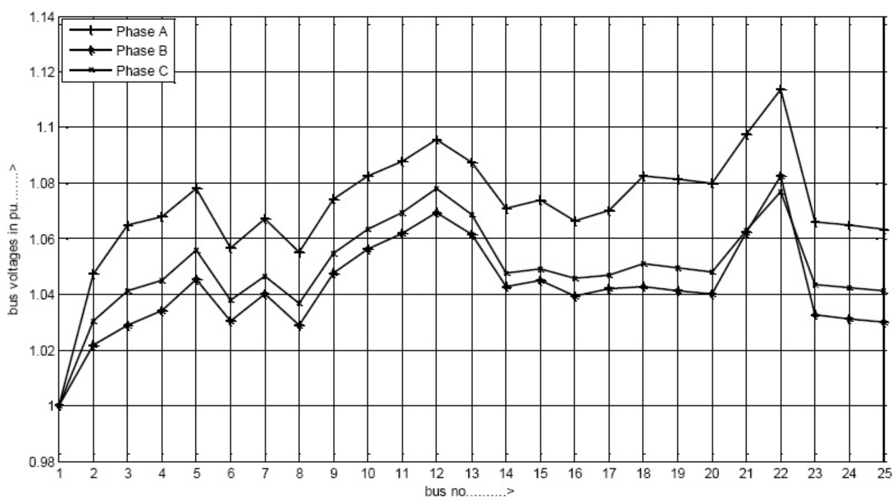

Figure 6.25: Voltage profile with DGs connected for 80% load

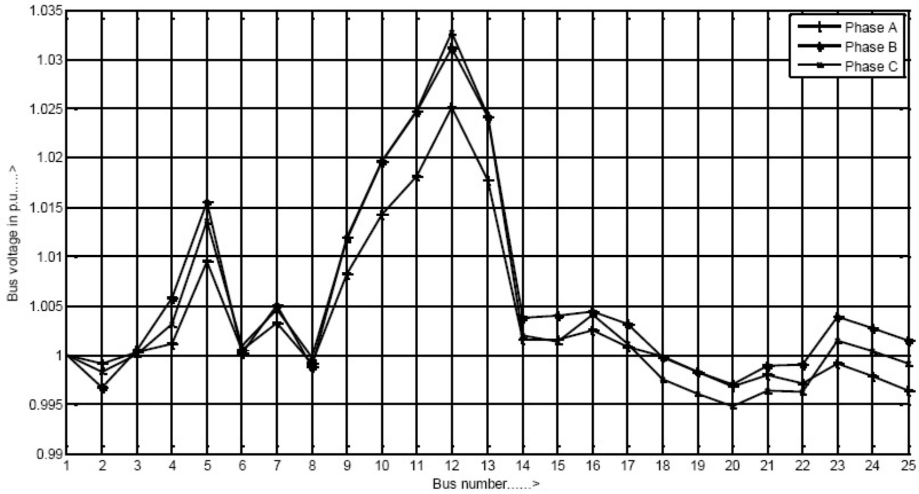

Figure 6.26: Voltage profile with voltage control for 80% load

The voltage profiles of the system with 70% load without DGs connected, with DGs connected; with voltage control can be seen from the Figures 6.22 to 6.29. All the phase voltages are crossing the upper voltage limit after DGs connected to the system is depicted in the Figure 6.28. Figure 6.29 show that, the voltage profile of the system with voltage control, it can be observed that all phase voltages are within the voltage limits. The optimal setting values of the voltage control devices and power loss before and after the voltage control are indicated in Tables 6.5, 6.6 and 6.7 respectively.

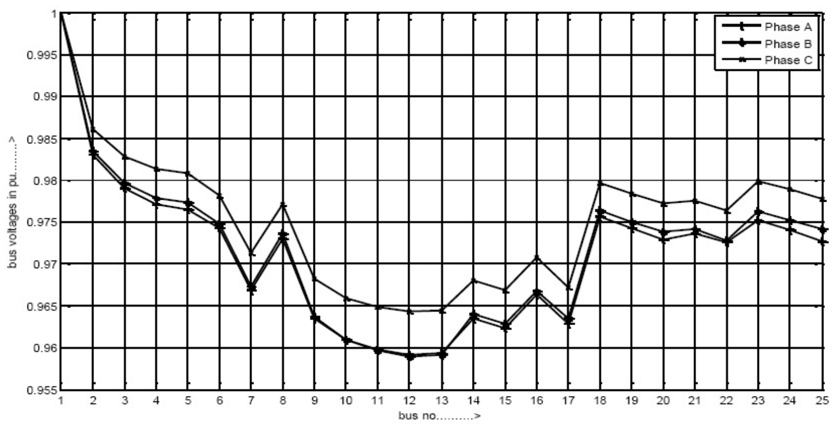

Figure 6.27: Voltage profile without DGs connected for 70% load

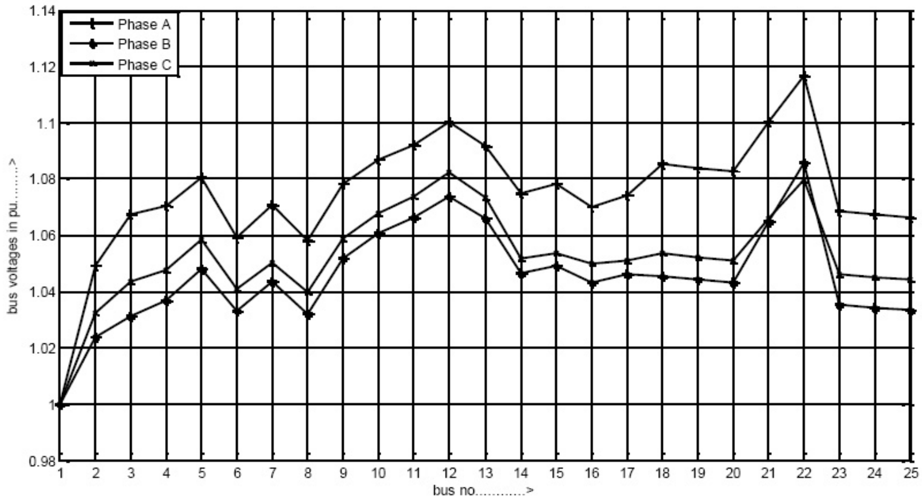

Figure 6.28: Voltage profile with DGs connected for 70% load

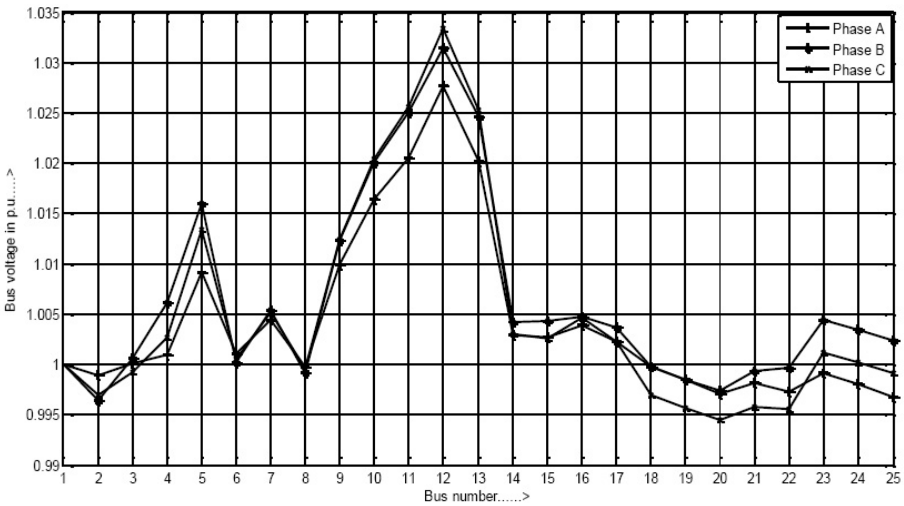

Figure 6.29: Voltage profile with voltage control for 70% load

Table 6.5: Optimal setting values of DGs reactive power in 25 bus system

Different load conditions	**Voltage control devices setting value**								
	LRT			**DG_1 reactive power**			**DG_2 reactive power**		
	Phase A	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
100%	0.99	0.98	0.99	0.0159	0.0175	0.0128	0.0166	0.0101	0.0126
90%	0.99	0.98	0.99	0.0117	0.0131	0.0170	0.0158	0.0101	0.0101
80%	0.99	0.98	0.99	0.0126	0.0101	0.0140	0.0153	0.0091	0.0116
70%	0.99	0.98	0.99	0.0129	0.0086	0.0155	0.0136	0.0102	0.0097

Table 6.6: Optimal setting values of voltage control devices in 25 bus system

Different load conditions	**Voltage control devices setting value**								
	SC_1			**SC_2**			**SVC**		
	Phase A	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**	**Phase A**	**Phase B**	**Phase C**
100%	off	on	0ff	off	off	off	0.02	0.02	0.01
90%	off	off	off	off	off	off	0.001	0.005	0.006
80%	off	off	0ff	off	off	off	0.006	0.001	0.007
70%	off	off	off	off	off	off	0.006	0.001	0.005

Table 6.7: Power loss in 25 bus unbalanced system at full load

	Before voltage control		**After voltage control**	
Phases	**Q_{loss}in p.u**	**Q_{loss}in p.u**	**Q_{loss}in p.u**	**Q_{loss}in p.u**
Phase A	0.0035	0.0022	0.0048	0.0031
Phase B	0.0036	0.0023	0.0049	0.0032
Phase C	0.0034	0.0022	0.0048	0.0031

6.5 CONCLUSION

In this chapter load flow solution for unbalanced system using forward and back sweep method has been presented. The detailed modeling of various components of the distribution system are considered. The two case studies have been considered for the voltage control with 13 and 25 bus unbalanced distribution system. The voltage has been regulated successfully using voltage control devices LRT, SVC, SC and DGs reactive power with the optimal setting values. The voltage control can be done effectively to maintain system voltage within the limits at different loading conditions. Power loss also can be reduced with the voltage control. The simulation results show the effectiveness of the developed method in voltage regulation of unbalanced distribution system considered in this study.

Chapter 7

CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1 CONCLUSIONS

DG has much potential to improve distribution system performance and use of DG strongly contributes to a clean, reliable and cost effective energy for future. However, distribution system designs and operating practices are normally based on radial power flow and this creates a significant challenge for the successful integration of DG system. As the issues are new and are the key for sustainable future power supply, lot of research is required to study their impacts and exploit them to the full extent. This thesis has dealt with steady state voltage rise of distribution system with DG and possible solutions that can be considered to ensure that distribution system voltage limits dictated by statute are not violated. The conclusions drawn from the study reported in thesis are summarized below.

- The introduction of generation sources on the distribution system can significantly impact the flow of power and voltage conditions at customers and utility equipment. This hinders the successful interconnection of large number of DG systems, as maintaining constant voltage in the distribution system is critical for system performance, efficiency, safety and customer satisfaction. In this work impact of distributed generation system on voltage profile of distribution network has been investigated using case studies. It is shown that the voltage rise in a distribution network is dependent on the location, magnitude and operating condition of the integrated DG. It is also observed that the factors such as voltage at the primary substation, distance from the primary substation, demand on the system, type of loads and loading conditions will decide the amount of generation that can be absorbed by the distribution system. A comprehensive approach to voltage control in a distribution system by taking in to account a number of DG systems and capacitors under various conditions is also been presented.

- In order to prepare the distribution network for increasing interconnection of DG system, effective voltage regulation methods are required to keep the voltage levels within the limits. The present practice of limiting generation capacity cannot be a solution as it leads to under utilization of DG sources. In this work two approaches for voltage regulation of distribution system is developed one is using sensitivity analysis and another using the participation factor for generators. The OLTC, switched capacitors and DG systems are considered to regulate the voltage level in the distribution system used in this study. The effectiveness of both the approaches are analyzed through simulation results using IEEE 69 bus system. Both methods can be used to handle all types of radial distribution system structures regardless of the system size proficiently. Utilization of these developed methods can make potential DG projects more attractive by effective utilization of the generator capacity.

- The voltage regulation using individual regulators without optimal coordination among them may cause the possibility of excessive operations of the regulating devices such as, OLTC and/ or the DG. In order to overcome this a optimal coordinated voltage regulation method using genetic algorithm has been presented. The effectiveness of the developed method has been analyzed through simulation case studies. Three loading conditions minimum, medium and heavy loads are used from the time varying load profile for the voltage control using OLTC, LRT, SC, SVC and DG system. The study indicates that, by optimally setting the values various voltage control devices through genetic algorithm, the distribution system voltage can be regulated well within the statute limits and also power loss can be reduced. The study also shows that involving DG systems and shunt capacitors in the coordinated voltage control will result in reduction of the number of OLTC and LRT operations.

- The effectiveness of the voltage regulation methods can be analyzed by using load flow studies. The input load data is very critical for such studies. In this a fuzzy clustering technique for load profile generations has been presented instead of considering sample data directly from time varying load profile. The generated fuzzy load patterns are used to study the performance of coordinated voltage regulation method using case studies. It has been observed in the study that obtaining the load profile through fuzzy clustering can represent the more realistic case compared to considering the sample load conditions from the load profile. In this study multiple voltage regulators such as OLTC, LRT, SCs and SVC are considered along with the reactive power control of DG systems.

- Power distribution systems are inherently unbalanced in nature due to presences of single phase, two phase and three phase loads. Load flow program developed for balanced system are inefficient for unbalanced system applications. In this work load flow solution for unbalanced system using forward and back sweep method has been presented. The detailed modeling various component of the distribution system are considered. The performance of the coordinated voltage regulation method using two Case studies considering using IEEE 13 and 25 bus unbalanced distribution is analyzed through simulation. The simulation results show the effectiveness of the developed method in voltage regulation of unbalanced distribution system considered in this study.

7.2 SCOPE FOR FUTURE WORK

The research work presented in this thesis can be further focused on

- Distributed generations (DGs) are generally modeled as PV or PQ nodes in power flow studies (PFSs) for distribution system. Determining a suitable model for each DG unit requires knowing the DG operation and the type of its connection to the grid (direct or indirect). The work reported in the thesis considers the synchronous generator based DG system and modeled as PQ node. In this regard incorporation of detailed model of other DG sources such as wind power, photovoltaic, microturbine system with or without necessary power electronic interface in the load flow programs can be considered for further research. The developed voltage regulation method can also be extended to above scenarios.

- In this work multiple voltage regulating devices are considered to coordinate the voltage regulation of the system. In this kind of methods, there may be possibilities of conflict among the regulators to decide their contribution in voltage regulation in a multi DG complex distribution system. This can lead problem in determining their amount of operation, which can also be considered for further research.

- The introduction of active elements in distribution networks can provide an efficient, flexible and intelligent approach to overcome problems in future circumstances with large amounts of DG including voltage regulation. A multi agent based voltage regulation technique can be developed using intelligent network controllers. An agent can, not only able to react to change in its environment but is also able to interact with other intelligent agents. This approach can be used to develop the voltage regulation method for distribution system with multi DG and multi regulating devices.

LIST OF PUBLICATIONS

International Journals

1. Shivarudraswamy, R and Gaonkar, D. N. (2012). "Coordinated voltage regulation of distribution network with distributed generators and multiple voltage control devices." *J. Electric Power Components and Systems.* 40(9), 1072-1088.

2. Shivarudraswamy, R and Gaonkar, D. N. (2011). "Voltage control in the distribution system using reactive power participation factor of distributed generators." *J. Distributed Energy Resources,* 7(3), 217-228.

3. Shivarudraswamy, R and Gaonkar, D. N. (2011). "Coordinated voltage control using multiple regulators in distribution system with distributed generators." *J. World Academy of Science, Engineering and Technology,* 74, 574-578.

4. Shivarudraswamy, R and Gaonkar, D. N. (2012). "Coordinated voltage control with reactive powers of the distributed generators using genetic algorithm." *J. Science Engineering and Research.* 3(6),1-5.

Conference Publications:

1. Shivarudraswamy, R and Gaonkar, D. N. (2010). "Steady state voltage control using distributed generation allocation in radial network." *Proc., 1st Int. Conf. on Advances in Energy Conversion Technologies,* Manipal, India, 903-908.

2. Shivarudraswamy, R and Gaonkar, D. N. (2010). "Coordinated voltage control in distribution system with distributed generators." *Proc., of 34th National System Conference,* NITK, Surathkal, India, 1-5.

3. Shivarudraswamy, R and Gaonkar, D. N. (2011). "Coordinated voltage control in 3 phase unbalanced distribution system with multiple regulators using genetic algorithm." *Proc., of 2nd Int. Conf. on Advances in Energy Engineering*, Bangkok, Thailand, 1199-1206.

APPENDIX

IEEE 69 BUS DATA

Branch	Source and Destination		System Data		Load Data	
	Sending End	Receiving End	R in ohm	X in Ohm	P_L in kW	Q_L in kVAR
1	1	2	0.005	0.0012	0.0	0.0
2	2	3	0.005	0.0012	0.0	0.0
3	3	4	0.0015	0.0036	0.0	0.0
4	4	5	0.0251	0.0296	0.0	0.0
5	5	6	0.3660	0.1864	2.6	2.2
6	6	7	0.3810	0.1941	40.40	30.0
7	7	8	0.0922	0.0470	75.0	54.0
8	8	9	0.0493	0.0251	30.0	22.0
9	9	10	0.8190	0.2707	28.0	19.0
10	10	11	0.1872	0.0619	145.0	104.0
11	11	12	0.7114	0.2351	145.0	104.0
12	12	13	1.0300	0.3400	8.0	5.0
13	13	14	1.0440	0.3400	8.0	5.0
14	14	15	1.0580	0.3496	0.0	0.0
15	15	16	0.1966	0.0650	45.0	30.0
16	16	17	0.3744	0.1238	60.0	35.0
17	17	18	0.0047	0.0016	60.0	35.0
18	18	19	0.3276	0.1083	0.0	0.0
19	19	20	0.2106	0.0690	1.0	0.6
20	20	21	0.3416	0.1129	114.0	81.0
21	21	22	0.0140	0.0046	5.0	3.5
22	22	23	0.1591	0.0526	0.0	0.0
23	23	24	0.3463	0.1145	14.0	10.0
24	24	25	0.7488	0.2475	14.0	10.0
25	25	26	0.3089	0.1021	14.0	10.0
26	26	27	0.1732	0.0572	14.0	10.0
27	3	28	0.0044	0.0108	26.0	18.6
28	28	29	0.0640	0.1565	26.0	18.6
29	29	30	0.3978	0.1315	0.0	0.0

Branch	Source and Destination		System Data		Load Data	
	Sending End	Receiving End	R in ohm	X in Ohm	P_L in kW	Q_L in kVAR
30	30	31	0.0702	0.0232	0.0	0.0
31	31	32	0.3510	0.1160	0.0	0.0
32	32	33	0.8390	0.2816	14.0	10.0
33	33	34	1.7080	0.5646	19.5	19.0
34	34	35	1.4740	0.4873	6.0	14.0
35	35	36	0.0044	0.0108	26.0	4.0
36	36	37	0.0640	0.1565	26.0	18.55
37	37	38	0.1053	0.1230	0.0	18.55
38	38	39	0.0304	0.0355	24.0	17.0
39	39	40	0.0018	0.0021	24.0	17.0
40	40	41	0.7283	0.8509	1.2	1.0
41	41	42	0.3100	0.3623	0.0	0.0
42	42	43	0.0410	0.0478	6.0	4.3
43	43	44	0.2106	0.0116	0.0	0.0
44	44	45	0.1089	0.1393	39.22	26.3
45	45	46	0.0009	0.0019	39.22	26.3
46	46	47	0.0034	0.0084	0.0	0.0
47	47	48	0.0851	0.2083	79.0	56.4
48	48	49	0.2898	0.7091	384.7	10.0
49	49	50	0.0822	0.2011	384.7	274.5
50	8	51	0.0928	0.0473	40.50	28.3
51	51	52	0.3319	0.114	3.6	2.7
52	9	53	0.1740	0.0886	4.35	3.5
53	53	54	0.2030	0.1034	26.4	19.0
54	54	55	0.2842	0.1447	24.0	17.2
55	55	56	0.2813	0.1433	0.0	0.0
56	56	57	1.5900	0.5337	0.0	0.0
57	57	58	0.7837	0.2630	0.0	0.0
58	58	59	0.3042	0.1006	100.0	72.0
59	59	60	0.3861	0.1172	0.0	0.0

Branch	Source and Destination		System Data		Load Data	
	Sending End	Receiving End	R in ohm	X in Ohm	P_L in kW	Q_L in kVAR
60	60	61	0.5075	0.2585	1244.0	888.0
61	61	62	0.0974	0.0496	32.0	23.0
62	62	63	0.1450	0.0738	0.0	0.0
63	63	64	0.7105	0.3619	227.0	162.0
64	64	65	1.0410	0.5302	59.0	42.0
65	11	66	0.2012	0.0611	18.0	13.0
66	66	67	0.0047	0.0014	18.0	13.3
67	12	68	0.7394	0.2444	28.0	20.0
68	68	69	0.0047	0.0016	28.0	20.0

IEEE 33 BUS SYATEM DATA

Branch	Source and Destination		System Data		Load Data	
	Sending End	Receiving End	R in ohm	X in ohm	P_L in kW	Q_L in kVAR
1	1	2	.00575	.00297	0	0
2	2	3	.03076	.01566	.01	.006
3	3	4	.02283	.01163	.009	.004
4	4	5	.02377	.01211	.012	.008
5	5	6	.05110	.04410	.006	.003
6	6	7	.01168	.03860	.02	.01
7	7	8	.10670	.07706	.02	.02
8	8	9	.06420	.04617	.06	.002
9	9	10	.06260	.04610	.06	.002
10	10	11	.01226	.00405	.0045	.003
11	11	12	.02336	.00772	.06	.0035
12	12	13	.09150	.07200	.06	.0035
13	13	14	.03379	.04440	.012	.008
14	14	15	.03687	.03281	.06	.001
15	15	16	.04656	.03400	.06	.002
16	16	17	.08042	.10730	.06	.002
17	17	18	.04567	.03580	.09	.004
18	2	19	.01023	.00976	.09	.004
19	19	20	.09385	.08456	.09	.004
20	20	21	.02550	.02980	.09	.004
21	21	22	.04423	.05840	.09	.004
22	3	23	.02815	.01923	.09	.005
23	23	24	.05603	.04420	.042	.02
24	24	25	.05590	.04374	.042	.02
25	6	26	.01266	.00645	.06	.0025

Branch	Source and Destination		System Data		Load Data	
	Sending End	Receiving End	R in ohm	X in ohms	P_L in kW	Q_L in kVAR
26	26	27	.01770	.00902	.006	.0025
27	27	28	.06607	.05825	.006	.002
28	28	29	.05017	.05805	.012	.007
29	29	30	.03166	.01612	.02	.06
30	30	31	.06079	.06000	.015	.007
31	31	32	.01937	.02250	.021	.01
32	32	33	.02127	.03308	.006	.004

21 BUS SYSTEM LINE DATA

Line	Source and Destination		System Data	
	Sending End	Receiving End	R in ohm	X in ohm
1	1	2	0.00270	0.00328
2	2	3	0.02158	0.03686
3	3	4	0.02158	0.03686
4	4	5	0.02158	0.03686
5	5	6	0.02158	0.03686
6	6	7	0.02158	0.03686
7	7	8	0.02158	0.03686
8	8	9	0.02158	0.03686
9	9	10	0.02158	0.03686
10	10	11	0.02158	0.03686
11	11	12	0.02158	0.03686
12	12	13	0.02158	0.03686
13	13	14	0.02158	0.03686
14	2	15	0.02158	0.03686
15	15	16	0.02158	0.03686
16	16	17	0.02158	0.03686
17	17	18	0.02158	0.03686
18	4	19	0.07480	0.02992
19	19	20	0.07480	0.02992
20	20	21	0.07480	0.02992

21 BUS SYSTEM LOAD DATA

Branch	Load Data		Load Data		Load Data	
	P_L	Q_L	P_L	Q_L	P_L	Q_L
1	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
2	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
3	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
4	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
5	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
6	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
7	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
8	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
9	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
10	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
11	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
12	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
13	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
14	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
15	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
16	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
17	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
18	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
19	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
20	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090
21	0.0143	0.0036	0.0319	0.0057	0.0443	0.0090

25 BUS 3-PHASE UNBALANCED SYSTEM LINE DATA PHASE A

Line	Source and Destination		Load Data	
	Sending End	Receiving End	R in ohm	X in ohm
1	1	2	0.1210 + 0.2250i	0.1234 + 0.2205i
2	2	3	0.0605 + 0.1125i	0.0617 + 0.1102i
3	3	4	0.0605 + 0.1125i	0.0617 + 0.1102i
4	4	5	0.1605 + 0.1431i	0.1616 + 0.1421i
5	2	6	0.1605 + 0.1431i	0.1616 + 0.1421i
6	6	7	0.1605 + 0.1431i	0.1616 + 0.1421i
7	6	8	0.3209 + 0.2862i	0.3232 + 0.2841i
8	7	9	0.1605 + 0.1431i	0.1616 + 0.1421i
9	9	10	0.1605 + 0.1431i	0.1616 + 0.1421i
10	10	11	0.0963 + 0.0859i	0.0970 + 0.0852i
11	11	12	0.1266 + 0.0932i	0.1268 + 0.0933i
12	11	13	0.1266 + 0.0932i	0.1268 + 0.0933i
13	7	14	0.1605 + 0.1431i	0.1616 + 0.1421i
14	14	15	0.0963 + 0.0859i	0.0970 + 0.0852i
15	7	16	0.1605 + 0.1431i	0.1616 + 0.1421i
16	14	17	0.1899 + 0.1398i	0.1902 + 0.1400i
17	3	18	0.1605 + 0.1431i	0.1616 + 0.1421i
18	18	19	0.1605 + 0.1431i	0.1616 + 0.1421i
19	19	20	0.2532 + 0.1864i	0.2536 + 0.1867i
20	18	21	0.2532 + 0.1864i	0.2536 + 0.1867i
21	21	22	0.2532 + 0.1864i	0.2536 + 0.1867i
22	4	23	0.1284 + 0.1145i	0.1293 + 0.1137i
23	23	24	0.1284 + 0.1145i	0.1293 + 0.1137i
24	24	25	0.2532 + 0.1864i	0.2536 + 0.1867i

25 BUS 3-PHASE UNBALANCED SYSTEM LINE DATA PHASE B

Line	Source and Destination		Load Data	
	Sending End	Receiving End	R in ohm	X in ohm
1	1	2	0.1222 + 0.2227i	0.0055 + 0.0497i
2	2	3	0.0611 + 0.1113i	0.0028 + 0.0249i
3	3	4	0.0611 + 0.1113i	0.0028 + 0.0249i
4	4	5	0.1610 + 0.1420i	0.0027 + 0.0279i
5	2	6	0.1610 + 0.1420i	0.0027 + 0.0279i
6	6	7	0.1610 + 0.1420i	0.0027 + 0.0279i
7	6	8	0.3221 + 0.2839i	0.0055 + 0.0557i
8	7	9	0.1610 + 0.1420i	0.0027 + 0.0279i
9	9	10	0.1610 + 0.1420i	0.0027 + 0.0279i
10	10	11	0.0966 + 0.0852i	0.0016 + 0.0167i
11	11	12	0.1270 + 0.0935i	0.0011 + 0.0078i
12	11	13	0.1270 + 0.0935i	0.0011 + 0.0078i
13	7	14	0.1610 + 0.1420i	0.0027 + 0.0279i
14	14	15	0.0966 + 0.0852i	0.0016 + 0.0167i
15	7	16	0.1610 + 0.1420i	0.0027 + 0.0279i
16	14	17	0.1905 + 0.1402i	0.0016 + 0.0117i
17	3	18	0.1610 + 0.1420i	0.0027 + 0.0279i
18	18	19	0.1610 + 0.1420i	0.0027 + 0.0279i
19	19	20	0.2540 + 0.1870i	0.0021 + 0.0155i
20	18	21	0.2540 + 0.1870i	0.0021 + 0.0155i
21	21	22	0.2540 + 0.1870i	0.0021 + 0.0155i
22	4	23	0.1288 + 0.1136i	0.0022 + 0.0223i
23	23	24	0.1288 + 0.1136i	0.0022 + 0.0223i
24	24	25	0.2540 + 0.1870i	0.0021 + 0.0155i

25 BUS 3-PHASE UNBALANCED SYSTEM LINE DATA PHASE C

Line	Source and Destination		Load Data	
	Sending End	Receiving End	R in ohm	X in ohm
1	1	2	0.0062 + 0.0680i	0.0051 + 0.0360i
2	2	3	0.0031 + 0.0340i	0.0025 + 0.0180i
3	3	4	0.0031 + 0.0340i	0.0025 + 0.0180i
4	4	5	0.0031 + 0.0373i	0.0025 + 0.0207i
5	2	6	0.0031 + 0.0373i	0.0025 + 0.0207i
6	6	7	0.0031 + 0.0373i	0.0025 + 0.0207i
7	6	8	0.0061 + 0.0747i	0.0050 + 0.0415i
8	7	9	0.0031 + 0.0373i	0.0025 + 0.0207i
9	9	10	0.0031 + 0.0373i	0.0025 + 0.0207i
10	10	11	0.0018 + 0.0224i	0.0015 + 0.0124i
11	11	12	0.0011 + 0.0078i	0.0011 + 0.0078i
12	11	13	0.0011 + 0.0078i	0.0011 + 0.0078i
13	7	14	0.0031 + 0.0373i	0.0025 + 0.0207i
14	14	15	0.0018 + 0.0224i	0.0015 + 0.0124i
15	7	16	0.0031 + 0.0373i	0.0025 + 0.0207i
16	14	17	0.0016 + 0.0117i	0.0016 + 0.0117i
17	3	18	0.0031 + 0.0373i	0.0025 + 0.0207i
18	18	19	0.0031 + 0.0373i	0.0025 + 0.0207i
19	19	20	0.0021 + 0.0155i	0.0021 + 0.0155i
20	18	21	0.0021 + 0.0155i	0.0021 + 0.0155i
21	21	22	0.0021 + 0.0155i	0.0021 + 0.0155i
22	4	23	0.0024 + 0.0299i	0.0020 + 0.0166i
23	23	24	0.0024 + 0.0299i	0.0020 + 0.0166i
24	24	25	0.0021 + 0.0155i	0.0021 + 0.0155i

25 BUS 3-PHASE UNBALANCED SYSTEM LOAD DATA

Line	Phase A		Phase B		Phase C	
	P_A in p.u.	Q_A in p.u.	P_B in p.u.	Q_B in p.u.	P_C in p.u.	Q_C in p.u.
1	0	0	0	0	0	0
2	0	0	0	0	0	0
3	0.0030	0.0032	0.0037	0.0020	0.0025	0.0028
4	0.0042	0.0050	0.0042	0.0032	0.0037	0.0030
5	0.0032	0.0032	0.0032	0.0025	0.0025	0.0025
6	0.0032	0.0037	0.0030	0.0025	0.0028	0.0020
7	0	0	0	0	0	0
8	0.0032	0.0032	0.0032	0.0025	0.0025	0.0025
9	0.0050	0.0042	0.0042	0.0037	0.0032	0.0030
10	0.0030	0.0032	0.0037	0.0020	0.0025	0.0028
11	0.0037	0.0030	0.0032	0.0028	0.0020	0.0025
12	0.0042	0.0050	0.0042	0.0030	0.0037	0.0032
13	0.0030	0.0037	0.0032	0.0020	0.0028	0.0025
14	0.0042	0.0042	0.0050	0.0030	0.0032	0.0037
15	0.0110	0.0110	0.0110	0.0083	0.0083	0.0083
16	0.0032	0.0032	0.0032	0.0025	0.0025	0.0025
17	0.0032	0.0030	0.0037	0.0025	0.0020	0.0028
18	0.0032	0.0032	0.0032	0.0025	0.0025	0.0025
19	0.0030	0.0032	0.0037	0.0020	0.0025	0.0028
20	0.0050	0.0042	0.0042	0.0037	0.0030	0.0032
21	0.0032	0.0030	0.0037	0.0025	0.0020	0.0028
22	0.0042	0.0050	0.0042	0.0030	0.0037	0.0032
23	0.0050	0.0042	0.0042	0.0037	0.0032	0.0030
24	0.0030	0.0037	0.0032	0.0020	0.0028	0.0025
25	0.0050	0.0042	0.0042	0.0037	0.0025	0.0030

IEEE 13 BUS UNBALANCED LOAD DATA

Bus No	Source to Destination		Load Data-1		Load Data-2		Load Data-3	
	Sending End	Receiving End	P_A in p.u.	Q_A in p.u.	P_A in p.u.	Q_A in p.u.	P_A in p.u.	Q_A in p.u.
1	1	0	0	0	0	0	0	0
2	2	11	0.0017	0.001	0.0066	0.0038	0.0117	0.0068
3	3	21	0.077	0.044	0.077	0.044	0.077	0.044
4	4	0	0	0	0	0	0	0
5	5	0	0	0	0	0	0	0
6	6	11	0.032	0.022	0.024	0.018	0.024	0.018
7	7	11	0	0	0.034	0.025	0	0
8	8	23	0	0	0.046	0.0264	0	0
9	9	23	0	0	0	0	0.034	0.0302
10	10	11	0.097	0.038	0.0136	0.012	0.058	0.0424
11	11	0	0	0	0	0	0	0
12	12	13	0.0256	0.0172	0	0	0	0
13	13	13	0	0	0	0	0.034	0.016

LINE DATA 1

Bus No	Source to Destination		Z	
	From End	To End	Z_1	Z_2
1	1	2	0.0479+.09i	0.1369i+ 0.19147i
2	2	3	0.0379 + 0.1114i	0.0369 + 0.1147i
3	3	4	0.0724 + 0.0743i	0
4	2	5	0.0206 + 0.0323i	0.0205 + 0.0328i
5	5	6	0.0011 + 0.0020i	0.0011 + 0.0020i
6	2	7	0	0.0364 + 0.0369i
7	7	8	0	0.0218 + 0.0221i
8	3	9	0	0
9	9	10	0.0218 + 0.0122i	0.0216 + 0.0111i
10	3	11	0.0218 + 0.0223i	0
11	11	12	0.0588 + 0.0224i	0
12	11	13	0	0

LINE DATA 2

Bus No	Source to Destination		Z	
	From End	To End	Z_1 in ohm	Z_2 in ohm
1	1	2	0.0479+ 0.1933i	0.0171+0.0549i
2	2	3	0.0374 + 0.1133i	0.0171 + 0.0549i
3	3	4	0.0727 + 0.0737i	0
4	2	5	0.0203 + 0.0331i	0.0043 + 0.0116i
5	5	6	0.0011 + 0.0020i	0
6	2	7	0.0362 + 0.0371i	0
7	7	8	0.0217 + 0.0223i	0
8	3	9	0	0
9	9	10	0.0218 + 0.0122i	0.0087 + 0.0009i
10	3	11	0.0218 + 0.0221i	0
11	11	12	0	0
12	11	13	0	0

LINE DATA 3

Bus No	Source to Destination		Z	
	From End	To End	Z_1 in ohm	Z_2 in ohm
1	1	2	0.0168 + 0.0421i	0.0173 + 0.0464i
2	2	3	0.0168 + 0.0421i	0.0173 + 0.0464i
3	3	4	0	0.0113 + 0.0251i
4	2	5	0.0042 + 0.0105i	0.0043 + 0.0137i
5	5	6	0	0
6	2	7	0.0057 + 0.0126i	0
7	7	8	0.0034 + 0.0075i	0
8	3	9	0	0
9	9	10	0.0087 + 0.0009i	0.0078 - 0.0004i
10	3	11	0	0.0034 + 0.0075i
11	11	12	0	0
12	11	13	0	0.0218 + 0.0221i

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