DISSERTATION

Multi-Agent System Based Control of Distributed Energy Resources

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Univ.-Prof. Dr.-Ing. Wolfgang GAWLIK
Institut für Energiesysteme und Elektrische Antriebe

by

Ishtiaque Ahmad
Matr.Nr. 1229645
Staargasse 8/27, 1140 Wien

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Abstract

Today's energy systems are undergoing remarkable changes in the way electrical energy is produced, transmitted and consumed. The operation of traditional electric power systems which is based on production of electric energy in large centralized power plants, usually located away from load centers is facing many challenges due to this transition. Main factors for this transition are use of renewable energy resources, integration of distributed generation into the grid, environmental considerations, increased customer participation and technological development. Further, demand for more and more services to be provided by these energy systems has resulted in complex energy systems. As time passes there will be more and more renewable and distributed energy resources at the lower level of the system. This distributed generation mainly comprising renewable is transforming the power grid from vertical structure to a horizontal one. In order to guarantee continuity of electricity supply to the customers, this transformation is required to be smooth. New methods and paradigms need to be investigated to fulfill the requirements of future grid. This increased use of distributed energy sources at distribution level is contributing in complexity of its operation and control and decentralization, autonomy and active distribution management have become the most important features for the smooth modernization of the present distribution grid. Multi-Agent System(MAS) having features like distributed intelligence, autonomy etc provide an alternative approach for smooth transition of the present grid to the smart grid. Motivated with the above mentioned considerations, the research objective of this dissertation was to develop and study different control architectures for distributed energy resources in the power distribution network using the agent based paradigm. Centralized, decentralized and distributed voltage control schemes developed and suitability of these structures was investigated. As the study involves three domains i.e. the power system, communication and the MAS system, co-simulation framework was developed including tools from these three domains. Proposed control algorithms based on MAS were simulated using this co-simulation framework. A voltage sensitivity based centralized voltage control algorithm was developed and a contract-net-protocol based plan for agent coordination was formulated. Comparisons between agent based decentralized and centralized schemes were made using the Key Performance Indices (KPI). An agent based distributed iterative algorithm for consensus between agents using neighboring communication was presented. Further, a zone based algorithm was developed and system performance was investigated by gradually increasing number of zones in a given network. This gives insight into system performance if we move from centralization towards decentralization. This study investigates the operation of future power distribution network including ICT infrastructure which can increase the flexibility and controllability. It presents different agent based control techniques which constitutes a step forward in determining the best control and management structure including physical and logical structure. It enables us to look into the trade-off between decentralized, distributed and centralized control. Application of such techniques will contribute in smooth modernization of the power grid and explore the design space for alternatives that are insensitive to changes in the system and can maintain their stability and performance in the presence of partial system faults.

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Table of Contents

List of Figures

List of Tables

Abbreviations

MAS	Multi-Agent System
CNP	Contract-Net-Protocol
FIPA	Foundation for Intelligent Physical Agents
DER	Distributed Energy Resources
DG	Distributed Generator
LTC	Load Tap Changers
RFP	Request For Proposal
JADE	Java Agent DEvelopment
DSM	Demand Side Management
ACL	Agent Communication Language
MTS	Message Transport Protocol
AMS	Agent Management Services
V2G	Vehicle-to-Grid
BDI	Belief Desire Intention

1 Introduction

Currently the power system is in transition, as instead of having only large centralized power stations mainly thermal which provide electricity one way down to the distribution systems and to the consumer, electricity is also being generated at distribution level near its consumption. It was designed to provide predictable electricity demand with reliable supply from central generators. However, this paradigm is changing rapidly in US, Europe and around the world. This chapter briefly presents the drivers for change, challenges and objective of the thesis.

1.1 Transition towards smarter power grids

Electrical transmission and distribution system design and operation will need to evolve in future to accommodate the expected variability and diversity of supply and participation. The scale and scope of the change needed is unprecedented for both transmission and distribution infrastructure. A modern grid involves a shift in the operating paradigm on four dimensions:

- Increased variability
- Shorter time cycles
- Resource diversity
- Resource dispersion

Main factors responsible for transition in power grid are given below;

- **Increasing energy demand:** It is expected that energy demand will globally rise in future due to population and economic growths and use of new technologies i.e. electric vehicles. Figure 1.1 shows significant growth in overall energy demand over the 28 year period from 2012 to 2040 [172].
- **Environmental concerns:** Burning coal, oil and gas produces carbon dioxide and nitrous oxide which is one of the reason for global warming and climate change. European Commission low-carbon economy road map suggests to cut emissions to 80% by 2050 below the level of 1990. Power sector has the biggest potential in reducing the emission through the use of renewable sources like wind, solar and biomass.

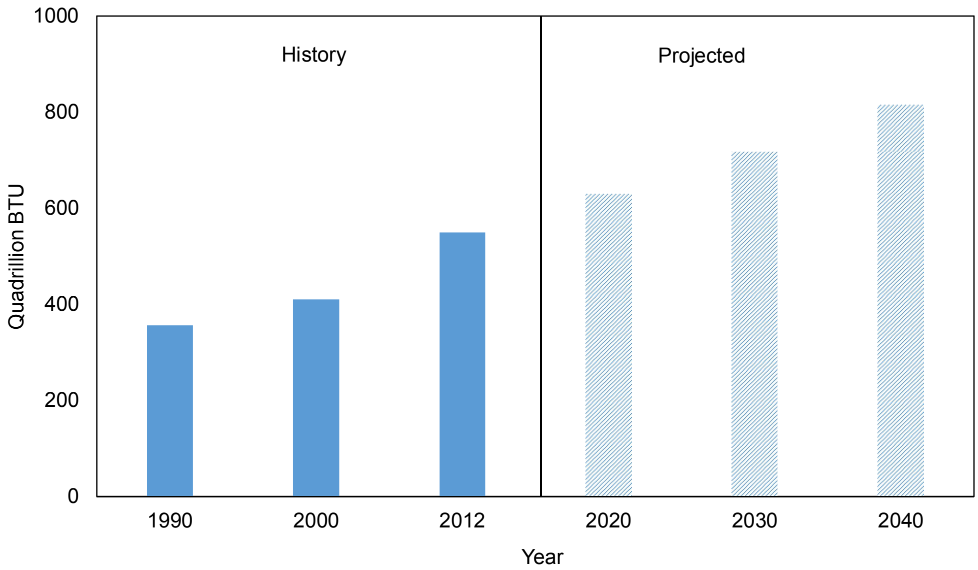

Figure 1.1: World energy consumption (quadrillion Btu), 1990-2040. Source U.S. Energy Information Administration.

- **Increasing share of intermittent renewable generation:** Environmental concerns are the major reason for increased use of renewable sources. However, the presence of intermittent and variable generation sources in energy mix bring issues and challenges in maintaining continuous match between supply and demand. Intermittent generation sources bring short term generation peaks and some period with out generation in a day, however, demand changes rather slowly throughout the day.
- **Increasing share of distributed generation:** Instead of large generating units in which few sources serve the large area, distributed generation consists of small units which serve customers in a small portion of the grid. This transformation requires new control techniques which will be able to operate on small scale.
- **Technological Developments:** Technological developments provide a mean to use the new methods and tools for control of power grid. ICT is an important component for smooth transition of the power grid.

Thus large and small scale intermittent generation, like wind and solar, as well as responsive demand from EVs and smart appliances, necessitates a change from traditional deterministic to stochastic methods for planning and controls. The variability of these resources also requires faster response times for operational systems to maintain grid stability and reliability. Current electrical grid is becoming immensely complex due to the rapid technological changes, political jurisdictions, human values and societal needs. It can be said that future energy systems will be complex energy system and its management and control will be a big challenge.

1.2 Distributed Energy Resources

The concern for reliability and security of the electric power system and for the environment with deregulation has contributed to the development and growth of distributed energy resources. The electrical power system grid is composed of the generation system, the transmission system, and the distribution system. Conventionally, electrical power is generated centrally and transported over a long distance to the end users. However, since the last decade, there has been increasing interest in distributed energy resources (DER). Contrary to the conventional power plants, DER systems are small-scale electric power sources, typically ranging from 1kW to 10MW, located at or near the end users, usually in distribution systems. Typically, DER includes distributed generation (DG) and distributed energy storage. These are reforming power system. Renewable energy technologies contribute to the development of DER. Some distributed generations are powered by renewable fuel, such as wind energy, solar energy, and biomass. Besides the technological innovations, the environment of power systems deregulation, energy security, and environmental concerns all boost the development of DER.

DER provides participants in the electricity market more flexibility in the changing market conditions. First, because many distributed generation technologies are flexible in operation, size, and expandability, they can provide standby capacity and peak shaving; and thus help to reduce the price volatility in market. Secondly, DER can enhance the system reliability by picking up part or all of the lost outputs from the failed generators. Third, because DER supply electrical power locally, they can reduce transmission and distribution congestions, thus saving the investment on expanding transmission and distribution capacity. Fourth, DER can also provide ancillary services for the grid support both in real power related services, such as load following, and reactive power related services, such as voltage regulation. DER technologies generally use local renewable energy. Also, certain technologies, such as energy storage, combined heat and power systems (CHP), and demand-control devices, help to improve energy conversion efficiency. Renewable energy and high efficiency technologies save the consumption of non-renewable natural resources and reduce greenhouse gas emissions.

1.3 Thesis Objectives and Scope

Increase use of DERs in power system result in many technical and scientific challenges for planning, operation and management of distribution network. This also makes traditional approaches for operation and management no longer sufficient for efficient and reliable supply of electricity to the customer. One way to cater for such challenges is to use the enabling technologies i.e. power electronics, communication, distributed control, which provide opportunities to overcome issues with the increase use of DERs.

Main objective of this dissertation is to develop and investigate a distributed control framework to help for efficient and flexible execution of distribution management system tasks. The proposed structure should cope with current issues in the distribution network related to the use of distributed generation i.e. voltage problems. The new techniques should be feasible to upgrade from the current network infrastructure. These objectives are in-line with the smooth transition from the current passive distribution network to an active distribution network by fulfilling the requirements of the future power system.

1.3.1 Key drivers to the Study

Following are the key drivers for this study;

1. **Use of intermittent generation sources.** Currently generation sources include the classical units which can be dispatched accordingly, however it is expected that there will be a shift from such classical dispatch-able units to intermittent generation sources. Main factor for this is environmental concerns and policies, in future more focus will be to generate electricity through the renewables which include intermittent generation sources like wind and solar.

2. **Many small units instead of few large generation units.** Increase use of renewable will result in having many small units serving the local customers instead of relying on a large generating unit.

3. **Transition from centralized transmission to decentralized distribution system.** As more and more distributed generation will be installed, power grid will transform from a centralized system towards decentralized system.

4. **Electricity consumption will increase significantly.** Global energy demand will increase due to growth in population and economics. Also use of new technologies i.e. electric vehicles will also contribute in increasing energy demand.

5. **Increase use of ICT will make power system more observable.** More use of information and communication technologies in power system which will make the grid more observable and more sophisticated controls can be applied.

6. **Distributed resources can offer ancillary services.** With the use of proper control and communication, distributed energy sources will be used to provide ancillary services.

1.3.2 Research Questions

On the basis of thesis objective following research questions are addressed;

- ***What should be suitable agent based control architecture for control of distributed energy resources?***
- ***How MAS based control can be designed and demonstrated in various control architecture scenarios?***
- ***How to design & evaluate the schemes involving multi-domain systems (MAS, Power System, Communication)?***
- ***How to choose appropriate size of a MAS system and degree of autonomy for agents within the power system?***

1.4 Thesis organization

The thesis is organized as follows;

1. **Chapter 1: Introduction**
   Chapter 1 presents the brief introduction of the problem and describes the objective of this thesis. It also includes the assumptions for the study and research questions.

2. **Chapter 2: Power System Evolution and Multi-Agent Systems**
   Chapter 2 presents details about the transition of power system and components of future grid(smart gird). It also describes the functions desired from the future grid along-with the enabling technologies. Further, it presents introduction to multi-agent system, its features and characteristics of an agent. It also describes the tools for development of multi-agent system application.

3. **Chapter 3: State of the Art**
   Chapter 3 presents literature review. It describes the application of MAS in key areas of power system. It also gives details about voltage control schemes in the power distribution network.

4. **Chapter 4: Methodology**
   Chapter 4 presents the general methodology used for investigation in the thesis. It explains the modeling, simulation and results comparison aspects.

5. **Chapter 5: MAS based Decentralized and Centralized Control**
   Chapter 5 investigates MAS based voltage control schemes. It involves purely decentralized and centralized control schemes. The centralized control scheme is based on Contract-Net-Protocol. Simulation results for both the control schemes are presented in the end.

6. **Chapter 6: MAS based Distributed control using Iterative Algorithm**
   Chapter 6 presents distributed iterative algorithm based voltage control using MAS. Participating agents were defined and algorithms for each agent are presented. Simulations were performed to show the effectiveness of the algorithm. This chapter also presents effects of communication delay on performance of the algorithm.

7. **Chapter 7: Zone based Control using Multi-Agent System**
   Chapter 7 presents zone based voltage control scheme. It gives detailed investigation of performance of the system, if we go from centralization towards decentralization. Power system was divided into various zones by using a zoning algorithm based on K-mean clustering method. Results of different zone schemes were presented. Information exchange in term of messages between agents of each zone was calculated and message efficiency was calculated. Relation between information exchange and voltage violation was established.

8. **Chapter 8: Results & Discussion**
   Chapter 8 presents discussion on results obtained in chapter 5, 6 and 7. Results of decentralized, centralized and distributed control approaches were discussed. Further performance of zone based control with information exchange was discussed.

9. **Chapter 9: Conclusion & Future Direction**
   Chapter 9 summarizes the work and presents conclusions drawn from the study. It also describes future direction to further strengthen the idea presented in this thesis.

2 Power System Evolution and Multi-Agent Systems

2.1 Power System Evolution

An electric grid is an interconnected network comprising many hardware and software components to distribute electricity from generation sources to the customers, thus power delivery and communication infrastructure represent main layers of electric grid. Traditional power system was designed to supply predictable electricity with reliable supply from central generation sources. Figure 2.1 shows the architecture and components of electric gird and transition from present grid to the future grid. From figure, it is clear that presently electricity produced by a central power plant, flows one way to the customers through substations which lower the voltage for supply to industrial, commercial and residential customers. However, there are many transitions going on, such as customers not only consume but also produce electricity.

2.2 Current Grid Architecture

In traditional power system, energy is produced in large power plants located away from load centers and distributed to the end customers through transmission lines. Supervisory Control and Data Acquisition (SCADA) systems are used for operation and control of current power system, which utilizes various software applications, electronic devices and communication infrastructure to control and monitor the grid. This control center is the central nerve of power system which

- Monitors the power system
- Adjusts its conditions
- Coordinates its actions
- Provides defense against exogenous events

Control center needs to be highly reliable and yearly availability requirements for control center is 99.95% i.e. operation of control center can not be out of service by more than 230 min or 3.83 hours in a year. The building of control center needs to be resilient against earthquake and a backup control center along-with disaster recovery plan is required. SCADA system at the control center

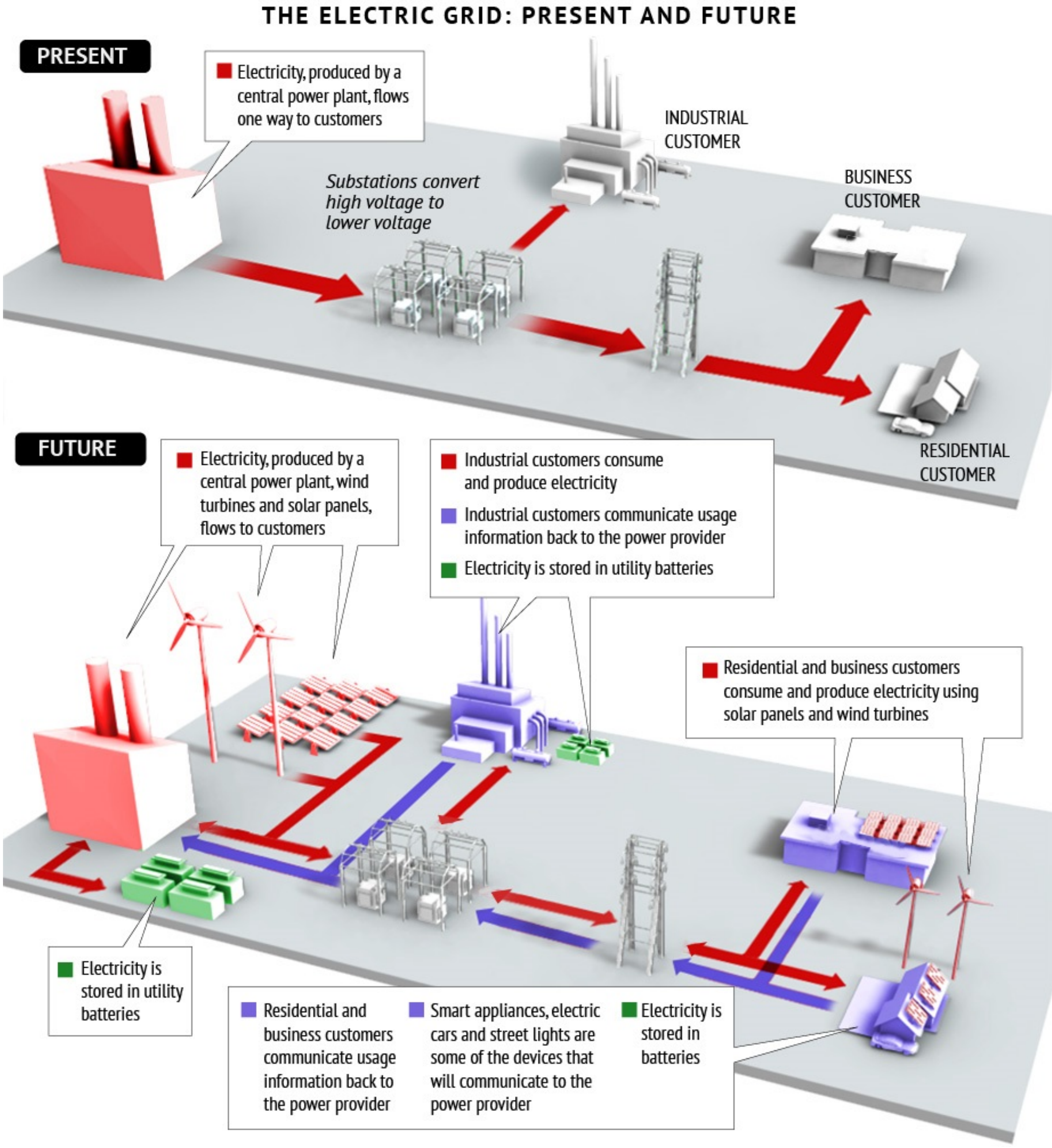

Figure 2.1: The architecture and components of electric gird and transition from present grid to future grid. Republished with the permission of Stratfor, a geopolitical intelligence platform [170].

allows the grid operators to monitor the network equipments and control the processes for smooth operation of the network. SCADA system control center process data obtained from Remote Terminal Units (RTUs) which interface electrical equipments in the field to control center by transmitting data to SCADA system. These RTUs use messages from the control center to control connected equipments[BJN04].Load and generation balance is carried out by the slow control actions. Synchronous Phasor Measurement Units (PMUs) collects data at various time instants to obtain dynamics of system using different communication modes including dedicated and point to point communication between substations [WXK11]. In traditional load management schemes customers are not involved and generally load balancing is focused on electricity generation by the power plants.

2.3 Innovative Concepts for Future Power Grid: "Smart grid"

Conventional power-grid is evolving due to the new requirements and technological advancements. Many innovative concepts has been presented and realized for the future power grid. Smart grid is a term mainly used to represent the future power grid. This term was first used in [Bur03] which published in 2003 after Northeast blackout in which power outage occurred in parts of the Northeastern and Midwestern US and the Canadian province of Ontario and the author emphasized on grid reliability enhancement. According to IEEE Smart grid is a concept for future power grid. IEEE defines smart grid [169] as:

> *"A revolutionary undertaking – entailing new communications-and-control capabilities, energy sources, generation models and adherence to cross-jurisdictional regulatory structures. Successful roll out will demand objective collaboration, integration, and interoperability among a phenomenal array of disciplines, including computational and communications control systems for generation, transmission, distribution, customer, operations, markets and service provider"*

Thus traditional electric grid is evolving into the smart grid which is composed of a spatially distributed complex, intelligent and autonomous power and communication networks. Renewable energy sources, electric vehicles, distributed storage system, microgrids will contribute in reliability enhancement, supply security and increase in stability of the electric grid. Moreover, smart grid enables innovative solutions for operation of electric grid and power markets [MB12]. Concepts introduced in smart grid framework are presented next. Table 2.1 shows smart grid components and technologies with description.

2.3.1 Renewable Energy Sources

Renewable energies and energy efficiency was considered to be the most important factor to meet the challenge of global climate change during Paris Climate Summit in which 188 countries participated [171]. EU countries have already planned to increase share of electricity production from renewable energy sources (RES) up-to 27% by 2030 of its final energy consumption[EU214]. It is predicted that by 2025, installed RES wind and photo-voltaic (PV) generation capacity in Germany will increase by 187% as compared to the capacity in 2013 while prediction of 236% increase as compared to the capacity in 2013 is made[LWT+15] [167]. Smart grid concepts are

Table 2.1: Smart grid components and technologies with description.

Smart grid components & Technologies	
Intelligent appliances loads	Capable of changing power consumption on the basis of pre-set customer preferences.
Advanced Metering Infrastructure (AMI)	Two-way communication between consumers and power providers about consumption and billing data.
Smart substations	Monitoring and control of electrical equipments such as breakers, transformers, batteries etc.
Distribution automation	Capable of self-healing and self-organizing and having automated monitoring and analysis tools which can detect or even predict failures based on real-time data about environment and history.
Smart generation	Able to learn about behavior of power generation sources for energy production optimization and automatically maintain voltage, frequency on the basis of feedback from the system.
ICT	Enabling control and monitoring of electronic devices in an integrated system comprising communication and information infrastructure.
Intelligent control	Intelligent devices and algorithms which can analyze and predict grid conditions and can act autonomously to take appropriate measures for smooth working of the grid.
Interfaces and decision support system	Apply data analytic techniques to process complex power system data for decision making.

proving to be enabler for integration of renewable energy sources into present grid and also provide enhancement in efficiency of these resources. Many studies are carried out to increase the efficiency of power grid having renewable energy resources. Smart algorithms for prediction of solar irradiation and wind speed have been developed to cater for uncertainties associated with the variable and intermittent nature sources i.e. PVs and wind. [XHZ+15], [CDP+14]. These resources not only provide cost benefits but also help in reducing carbon emission. Further, smart grid have capability of incorporation of following characteristics: **Variability:** Some renewable generation sources, mainly wind and solar, are dependent on variable and intermittent resource (the sun and the wind). As, generation and demand must be balanced for continuity of electricity supply, smart grid enables efforts to ensure that enough electricity sources or demand is available to absorb this variability. **Distributed Generation:** Distributed renewable generation are usually small scale systems and privately owned operated with a new and different business model for electricity. Traditional distribution system operator have often concerns over safety and security of grid stability and operation.

2.3.2 Virtual Power Plants

Virtual power plant (VPP) represents the aggregation of distributed energy resources (DERs) comprising renewable and distributed generation to visualize them as a single larger power plant. VPP incorporating storage and demand response capabilities makes variable renewable energy sources, such as PV and wind, a large dispatch-able power plant. This concept of VPP increases the visibility/observability and control of DERs to system operators and other market actors through an appropriate interface between system components [PRS07]. Flexibility provided by VPP helps in reducing the congestion in distribution grid. VPPs are often categorized into Commercial Virtual Power Plant (CVVP) and Technical Virtual Power Plant (TVVP). CVVP refers to a portfolio of distributed energy resources which can participate in energy markets in the same way as a large power plant connected to transmission network. TVVP provides visibility of system operator and enable DERs to contribute in system management activities [EVB16]. This integration of DER through the commercial and technical VPP activities will result in increasing the complexity in system management activities which demand new smart energy management application. Through intelligent control, smart grid technologies are able to address these challenges of renewable electricity generation and facilitate in the use of renewables.

2.3.3 Microgrid

The microgrid concept was introduced to address the increased use of distributed energy resources, particularly the renewables, in distribution systems. U.S. Department of Energy defines microgrid as [160]:

> *"A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode"*

Research on microgrid is currently growing across the globe which aims to address various associated technological and scientific challenges.The Consortium for Electric Reliability Technology

Solutions (CERTS) in United States is prominent in the field of microgrid research and has presented guiding principles. According to CERTS, essential components for microgrid realization are;

- Power electronics,
- Intelligent control, and
- Communication capabilities

Above mentioned features allow a microgrid to function as an autonomous power system and in grid connected mode [CER03]. Microgrid helps in reducing several problems of the current electric grid. For example in case of any outage in utility grid, microgrid has capability of separating itself from the utility grid and continues its operation in island mode for supply of electricity to the customers. Hospitals, telecommunication companies, data centers can be prioritized and thus reliability and supply security can be ensured. Communication based advanced control schemes for operation and management of microgrid have been presented by various researchers. Authors in [THL+16] [DL16] [MQLD14] presented different control schemes for voltage and frequency and major objectives were to develop stable and sustainable solutions which permit integration and operation of distributed, conventional and intermittent variable generation resources.

2.3.4 Plug-in Electric Vehicles

Increased awareness and consideration of environmental issues are driving towards more sustainable alternatives means of transport. In this regard electric vehicles are gaining attention of policy makers and electric cars can become cars of future. Further Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) technology allow the use of plug-in electric vehicles (PHEV), which can not only charge their batteries, but also be able to inject power to the grid when required. This indicates that EV penetration will affect current power system performance [VNSLG+09]. However, using controls and communication infrastructure, co-operation of electric vehicles with distributed energy resources can provide renewable energy storage and backup making power grid more secure and reliable. Thus, EVs can be used to provide peak power, spinning reserves or regulation services to the power grid [YCLL11]. Increased penetration of EVs in power grid is focus of many smart grid projects and is an important feature of smart grid. Presently, EVs do not have V2G capability, however, EVs can offer batteries as a smart load. Authors in [HYS+13] proposed a method to calculate the Electric Energy Storage System (EESS) capacity needed for prevention of voltage rise and drop in distribution grids having PVs and EVs and showed that EVs penetration can decrease the required capacity of EESS.

2.3.5 Demand Response

Demand response (DR) refers to the techniques for reducing electric system loads in peak hours or when renewable output decreases. DR is also used under the term Demand Side Management (DSM). The U.S. Department of Energy defines DSM as:

> *"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized"*

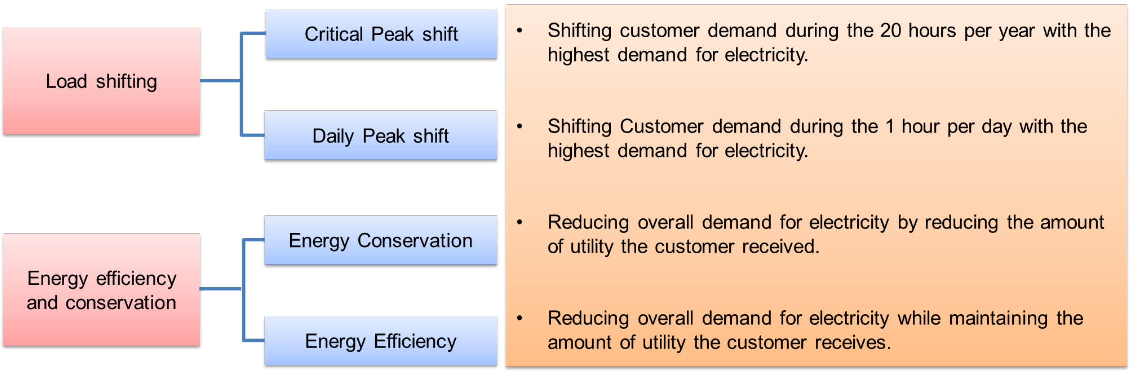

Figure 2.2: Demand response impact area and description. [Bra10]

Figure 2.2 shows major impact areas of demand side management. DR can facilitate the integration of renewable by allowing electricity demand to be controllable, in the same way as a dispatch-able power plant can be controlled. There are three general categories of DR:

- Direct load control (DLC)
- Voluntary load reduction(VLR)
- Dynamic demand

DLC gives utilities limited control of pre-decided customer loads under contracts that provide some compensation/reward to the customers. Large commercial and industrial customers provide in DLC options to the utilities.
VLR scheme requires customers to reduce their consumption voluntarily upon some signals from utility and involves incentives. There are many schemes for VLR, financial compensation for reducing load in a certain time period and a time-linked electricity price signal where high prices are used to motivate people to reduce the use of electricity, are some of them.
Dynamic demand is another way of DSM, however it is a less common scheme. In this technique loads automatically adjusts their power consumption or start-stop time according to some parameters i.e. grid frequency. [RPA13].
The benefits of DR include deferring grid infrastructure enhancement reducing cost, avoiding congestions in distribution networks, facilitation of integration of renewable and distributed generation, enhancing energy efficiency. DR can be managed by the utility or it can be available as a service from third party which works as aggregator for customers and sells the load reduction services to the utility.

2.3.6 Distributed Storage

Effects of variability and unpredictability of renewable generation can be neutralized by using electricity storage. This storage not only add flexibility in the grid but also extremely helpful for increasing share of renewable generation. Electricity storage can be bulk storage (large power for longer period of time) or distributed storage (small amount of energy for short time period). Main technologies for storage are lithium-ion batteries, lead acid batteries, thermal storage, flywheels, super capacitors.[IR212] Distributed storage is still in a research phase and many pilot projects has been initiated. Although technologies are available but high cost of distributed storage is a hurdle in large scale commercial use in electricity grid. Distributed storage can provide many benefits and some of them are;

- Frequency and voltage regulation services to the grid for grid stability and power quality.
- Minimization of the effects of variability of renewable power generation i.e. ramp rate control.
- Short term peak shaving for loads and renewable generation.
- Backup power and smooth transfer between grid connection to islanding mode for microgrid.

The benefits of any storage system depend upon the used storage technology. For example supper capacitors can only store energy for a short period of time but response time is very quick and can participate in short term frequency control. Integration of control schemes for distributed storage in distribution automation system, demand response programs is necessary to get maximum benefit. Further, there is a need of regulatory support which should provide comprehensive methods for calculating and compensating the benefits of storage to the electric gird for all the stake holders, which is currently lacking [KKLV11] [BCH+13] [ULv+15].

2.3.7 Advanced Metering Infrastructure

Advanced metering infrastructure (AMI) refers to the smart electricity meters, communication networks and data management system capable of two way communication between customer and utility. AMI is integrated system comprising multiple technologies (i.e. smart metering, home area networks, communications networks, data management systems, software applications) which provides an essential link between the grid operator and customer [NET08].

The smart devices in AMI have many functionalities such as measurements, control and calibration, communication, power management, synchronization, display. These functionalities enable various smart grid tasks and net metering, time based pricing, failure or outage notification, remote commands, load change for demand response application, power quality monitoring are some of them. For communication, different topologies and architectures can be used according to the requirements and examples are power line carrier, cellular, wimax, bluetooth, satellite zigbee etc. Data management system can have modules like meter data management system, consumer information system, billing system, load forecasting system. Other than strict cyber security requirements for AMI, it should also have features i.e. confidentiality, integrity, availability etc [MFMR14]. AMI feature of smart grid enable various applications for renewable generation i.e. renewable out put can be measured and used for real time control and compensation. It can be used to integrate distributed resources into data acquisition system through communication infrastructure. [Lee09].

2.4 Key benefits of smart grid

The U.S. Department of Energy's (DOE's) National Energy Technology Laboratory (NETL) describes benefits of smart grid in the area of reliability, security and safety, economics and environment and are enlisted below[NET07];

Self Healing: Smart grid will be able to perform self-assessment to detect, analyze and respond to undesired events and can autonomously restore grid components or parts of the network.
Consumer Participation: Smart grid technologies encourage consumer interaction with the grid for smooth delivery of electricity which is beneficial for the both.
Resilience: The grid will be more resilient to external attacks (physical/cyber) thus improving grid and public safety.
Power Quality: Smart grid features focus on delivering power quality according to the 21 century needs.
Integration of all types of energy resources: Integration of distributed energy resources including renewable with pug-in-play feature will help in use of more efficient, clean power production.
Enable Market: Smart grid enable new market designs with increased consumer participation and helps in reduced transmission congestion for efficient electricity markets.

2.5 Modeling, Control and Simulation based on Agents

2.5.1 An Agent

There is no exact definition of agent available in literature. There are many definitions from simple to detailed description [Mae95] [RNC+03] [WJ95]. All these definitions are impressed by the background field of the researcher (computer science, software engineering, economics and generally engineering). One of the widely used definition is [Woo09]:

> *"An agent is an encapsulated computer system that is situated in some environment and can act flexibly and autonomously in the environment to meet its design objectives."*

This definition is almost same as given in [Mae95]. A more simple definition in [RNC+03] is given below;

> *"An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through effectors."*

According to above definition agent can be anything, physical (hardware/equipment) or virtual(software program) entity that has sensors (to perceive environment) and actuators (to act on the environment). Autonomy means that agents can operate independently and has some kind of control over its actions. Figure 2.3 shows concept of an agent. According to the above definition many existing equipments can be visualized as agents. For example a protection relay is situated in an environment (power system) and reacts to changes in its environment (changes in voltage or current). Authors in [JW98] differentiate an agent with an intelligent agent as an agent having flexible autonomy can be named as an intelligent agent. Other than inputs through sensors, actuators and goals, an agent may also has some domain knowledge (the knowledge about the problem domain). This knowledge can be of any form like algorithm, artificial intelligence (AI) based method (machine learning, specific rule-based, fuzzy or neural network), heuristics, etc. This AI provides flexible autonomy to agents and in this case an agent is termed as intelligent agent. Classification of agents is generally carried out on the basis of the properties of an agent and Table 2.2 enlists properties with their meaning used in literature. Thus an intelligent agent has three basic characteristics:

1. **Reactivity:** Agents are capable of reacting to a certain changes in the environment after some period of time and undertake some action in response to those changes according to the designed objective. Such agents are also called reflex agent.

2. **Pro-activity:** Pro-activeness indicates that an agent exhibits goal oriented behavior. It means agent can change its action and behavior in order to achieve certain goal. An agent can maintain its internal states and able to predict the effect of its actions on the environment. A term deliberative agents is also used for such agents.

3. **Social ability:** Agents can not only communicate with the other agents but can also determine its actions on the basis of information received from other agents. Agents have the property of cooperation, negotiation and coordination.

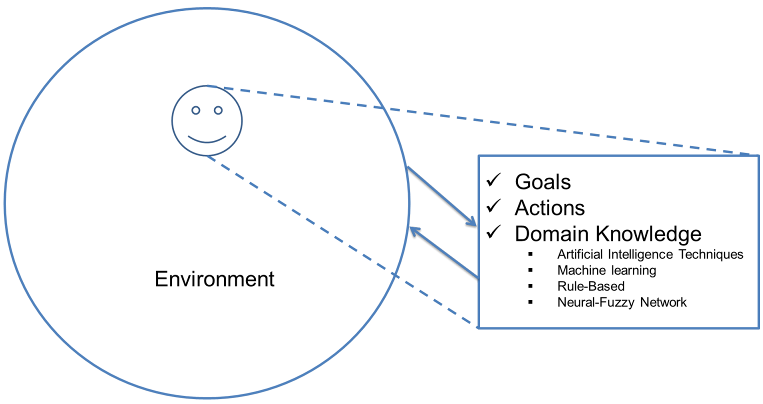

Figure 2.3: An agent situated in an environment having goals, actions and knowledge.

2.5.2 Multi-Agent System

A multi-agent system consists of two or more agents working in coordination and cooperation with each other through communication in order to achieve the desired individual goal. In [SV00], definition of multi-agent system is given as;

> *"A multi-agent system is a loosely coupled network of problem-solving entities (agents) that work together to find answers to problems that are beyond the individual capabilities or knowledge of each entity (agent)."*

Above definition shows some key features of multi-agent system which are communication, cooperation, coordination between different agents. This communication is not just information sharing, but agents can negotiate, cooperate and coordinate through agent communication language to fulfill their designed objective. Generally there is no overall goal of the multi-agent system, but individual agents work in collaboration with each other to achieve their local goals.

Table 2.2: Some properties of agents.

Property	Alternative Names	Description
Reactive	Reflex, sensing and acting	Responds in a timely fashion to changes in the environment.
Autonomous		Exercise control over its own actions.
Goal-oriented	Pro-active, purposeful	Does not simply act in response to the environment.
Temporally continuous		Continuously running process.
Communicative	Socially able	Communicates with other agents.
Learning	Adaptive	Changes its behavior based on its previous experience.
Mobile		Able to transport itself from one machine to another (this is associated manly with software agents).
Flexible		Actions are not scripted.

2.5.3 Classification of Multi-Agent Systems on the basis of Cooperation

On the basis of coordination and cooperation agents can be classified and are given in Figure 2.4 [DFJN97].

Multi-agent system will be an independent system if each agent works to achieve its objective independent of other agents present in the multi-agent system. In discrete multi-agent system, agents goal have no relation with each other, thus there is not any cooperation between agents. However, independent agents can learn and change their behavior at some point of time and involve cooperation only to achieve its own goal. This is called emergent cooperation. One way of cooperation in multi-agent system can be carried out by designing such an agent, which can cooperate with other agents. Thus cooperation between agents is explicitly designed. However, agents can also learn to cooperate to fulfill their goals and adopt cooperation through communication.

2.5.4 Homogeneous and Heterogeneous Multi-Agent systems

Multi-Agent systems can be characterized on the basis of heterogeneity and are called homogeneous and heterogeneous multi-agent systems.

- **Homogeneous Multi-Agent Systems:** In such type of MAS, all the agents have same structure with similar goals/objectives, domain knowledge and actions, if any. All the agents

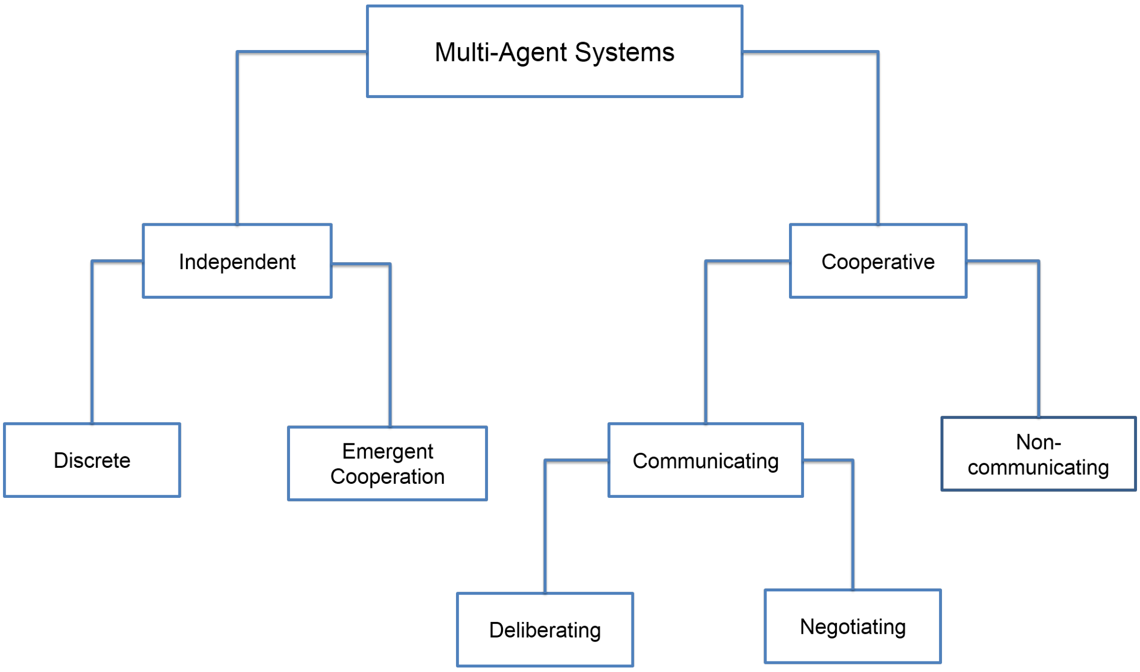

Figure 2.4: Classification of multi-agent systems on the basis of cooperation.

have same procedure/algorithm to fulfill their objectives/goals through actions. The only difference is input and this different input results in different output through the actions. We can also say that the only difference is that these agents are spatially scattered in the environment. For example, a multi-agent system, comprising only distributed generator agents can be considered as a homogeneous multi-agent system.

- **Heterogeneous Multi-Agent Systems:** Individual agents in a MAS can be different in many ways and can have different goals, domain knowledge and actions. All this makes MAS as a heterogeneous system with added complexity. For example, a MAS system comprising distributed generator agents, bus agents, relay agents can be considered as a heterogeneous MAS.

2.5.5 Standards for Agents

In engineering and science for any system importance of standards is increasing and systems must conform to some industry standards. The Foundation for Intelligent Physical Agents (FIPA) have developed a set of standards for agent communication. IEEE officially accepted PIFA as its standard organization for agents and multi-agent systems in 2005. FIPA provides standard specifications for inter-operation of heterogeneous agents and MAS. As agents interact through messaging, these specification largely cover standards for inter-agent communication[162].

2.5.6 Agent communication languages

One of the major aspect of Multi-agent system designing is to formalize specification for agent interaction i.e. how agents will cooperate and coordinate for decision making. Thus agents must have some common language to communicate with other agents. FIPA has defined specifications and standards for agent communications. Two main languages for agent interaction are Agent communication Language(ACL) and Knowledge Query and Manipulation Language (KQML). ACL conforms to the FIPA specification is widely used. Figure 2.5 shows format of an ACL message. More details can be found at [163].

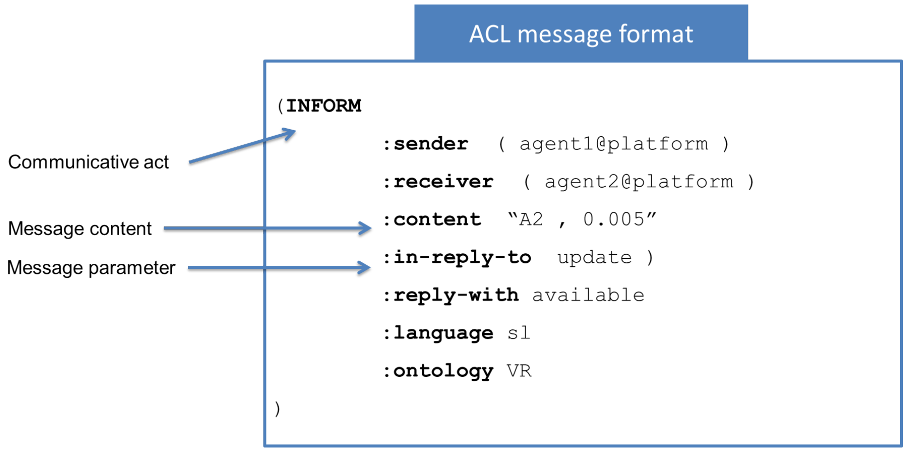

Figure 2.5: ACL message format.

2.5.7 Agent Management

FIPA agent management specifications defines agent management services, agent management ontology and agent platform message transport. These specifications are mainly concerned with defining an agent management reference model. Figure 2.6 shows the entities in this reference model. These are the essential services which enable multi-agent system operation in a distributed and flexible manner. Each platform consists of agents placed in different physical locations while it implements the agent reference model including the following entities [164] ;

- **Agent:** Agent represents a computational process which implements all the agent features, autonomousity, communication etc. Agent uses ACL for communication and is a fundamental actor in agent platform.

- **Directory facilitator (DF):** This is a yellow-pages service to agents. It can have a list of all the agents with their capabilities or services.An Agent can register itself in DF and can look for other agents with a specific services. This is optional entity.

- **Agent Management System (AMS):** This is mandatory component of the agent platform, which supervises it and maintains a list of agents and their addresses within the platform. It acts as a white-pages service(a list of agents with names and addresses). Each agent must register with an AMS.

- **Message Transport System (MTS):** Using MTS agents can send messages from one agent to the other. A message transport protocol is used for exchanging messages between agents.

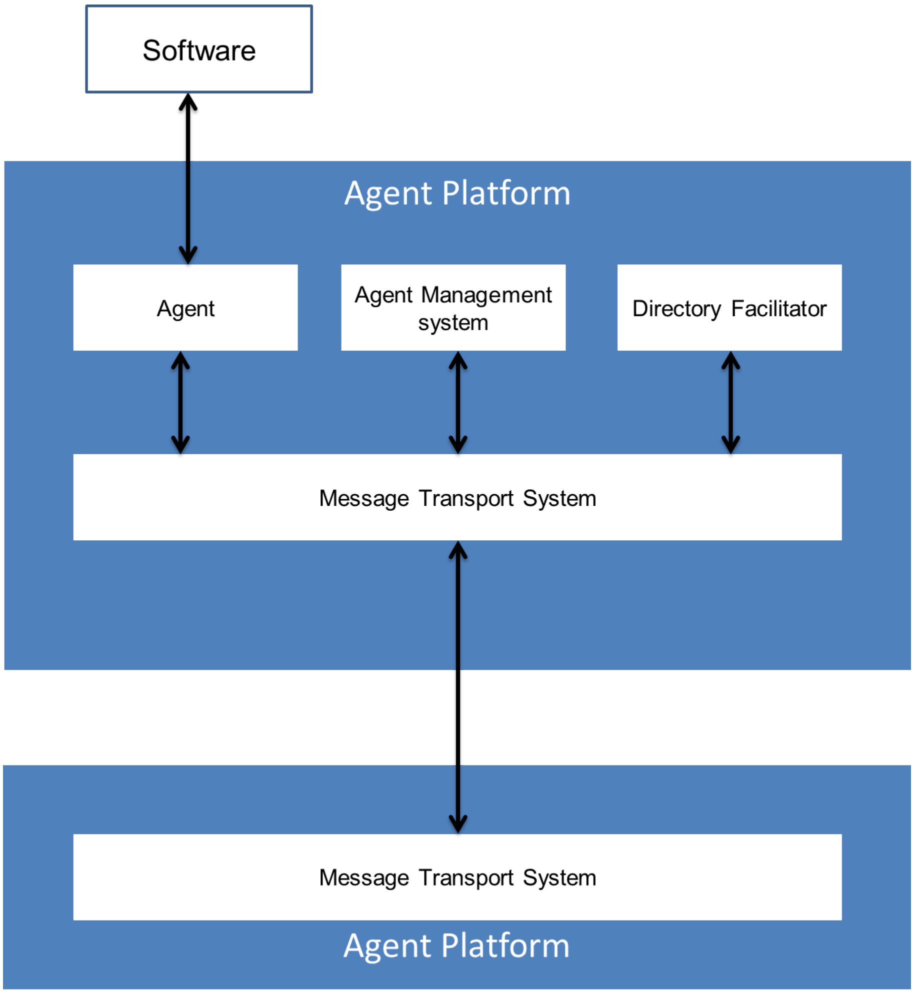

Figure 2.6: Agent management reference model.

- **Agent Platform:** Agent can be deployed on agent platform. It consists of machine, operating system, software, agent management components.
- **Software:** Software is basically all the other applications that can be accessed through agents. Agents can use different software programs and tools for different purposes i.e. changing communication protocol, addition of new services etc.

2.5.8 Multi-Agent System Development Tools

There are many different tools available for multi-agent system development which allow for agent based modeling and simulation [173]. These tools range from general purpose agent based modeling and simulation to some specific domain oriented nature. Authors in [NM09] presented a comprehensive survey of multi-agent system tools (agent based tools) on the basis of programming language requirement for modeling and simulation, operating system requirements to run the tool, license type, primary domain addressed by the tools etc. Some of the tools include AgentBuilder, JADE (Java Agent DEvelopment Framework), ZEUS. NetLogo is another agent based tools with basic small scale applications mainly for beginners. Some of the Tools conform to the FIPA standards mainly for agent communication and agent management and are available in [166]. Almost all the main languages have been used by the agent based tools, however most of the tools are written in JAVA.

2.5.9 The JADE Platform

JADE is a Java based open source multi-agent modeling and simulation environment and has been used by many researchers in the field of power system. JADE was originally developed under TILab, formerly CSELT in Italy. This framework facilitates the development of agent based simulations through basic functionalities like agent and behavior classes, inter-agent communication methods. It also provides graphical tool for monitoring, agent execution and communication with debugging function. It is FIPA (Foundation for Intelligent Physical Agents) compliant and supports standards such as FIPA-ACL. Each instance of runtime environment is called a container and many containers make a platform. First container is called main container which hosts Agent Management Services (AMS) and a Directory Facilitator (DF). Container contains various agents and a typical agent consist of a setup() method, one or more behaviors and a takedown() method. Details can be found in [BCG07]. Figure 2.7 shows distributed architecture of JADE platform [BPR10]. Figure 2.8 shows an agent execution model while source code for an example agent is given in code listing 2.1.

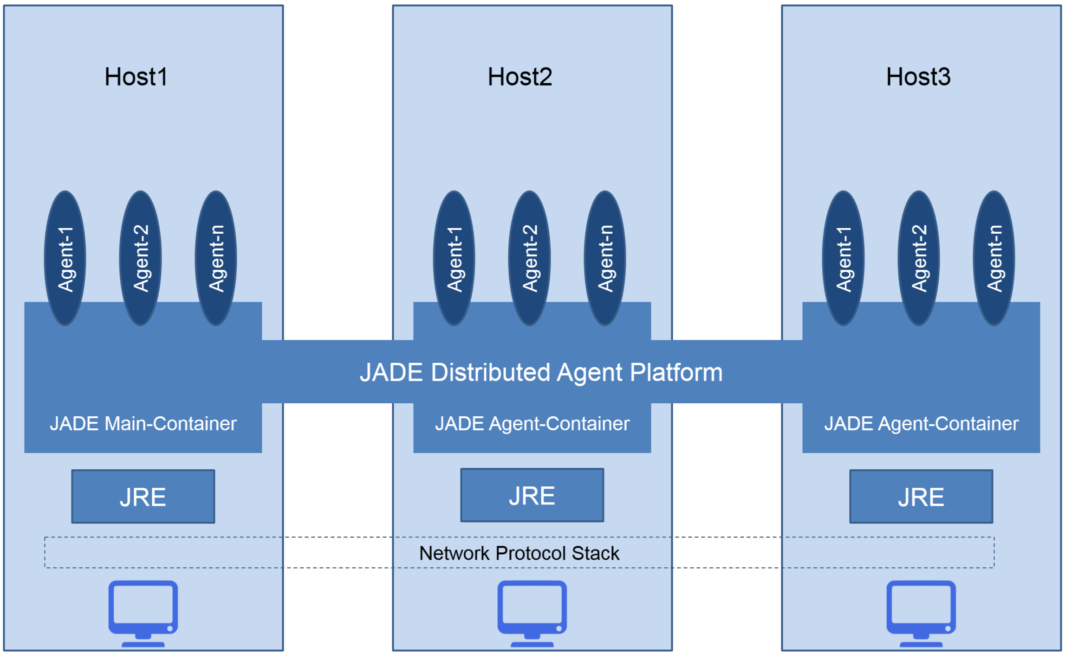

Figure 2.7: Distributed architecture of a JADE platform.

2.5.10 Framework for Power System and Multi-Agent system Co-Simulation

Current simulation tools do not have the ability to simulate multi-domain system as a whole and it is already established that co-simulation framework of domain specific software is a good option

```java
package javafiles;
import jade.core.Agent;
import jade.lang.acl.*;
import jade.core.behaviours.*;
// This example shows an agent that receives and replies a message.
public class DGAgent extends Agent {
        protected void setup() {
                // --------- adding anonymous SimpleBehaviour
                addBehaviour(new SimpleBehaviour(this) {
                        private boolean finished = false;
                        public void action() {
                          ACLMessage msg = receive();
                          if (msg!=null) {
                                //Printing message
                                System.out.println( "-" +
                                  myAgent.getLocalName() + "Received:" + msg.
                                      getContent() );
                                //Creating Reply
                                ACLMessage reply = msg.createReply();
                                reply.setPerformative( ACLMessage.INFORM );
                                reply.setContent("Received");
                                send(reply);
                                finished=true;
                                }
                        }
                        public boolean done() {
                                return finished;
                        }
                });
        } //  --- setup ---
} // ---- End Class ----
```

Listing 2.1: Example source code of an agent with simple behavior. It listens for message. If there is any message it prints out its name and content and reply with inform message containing text "Received".

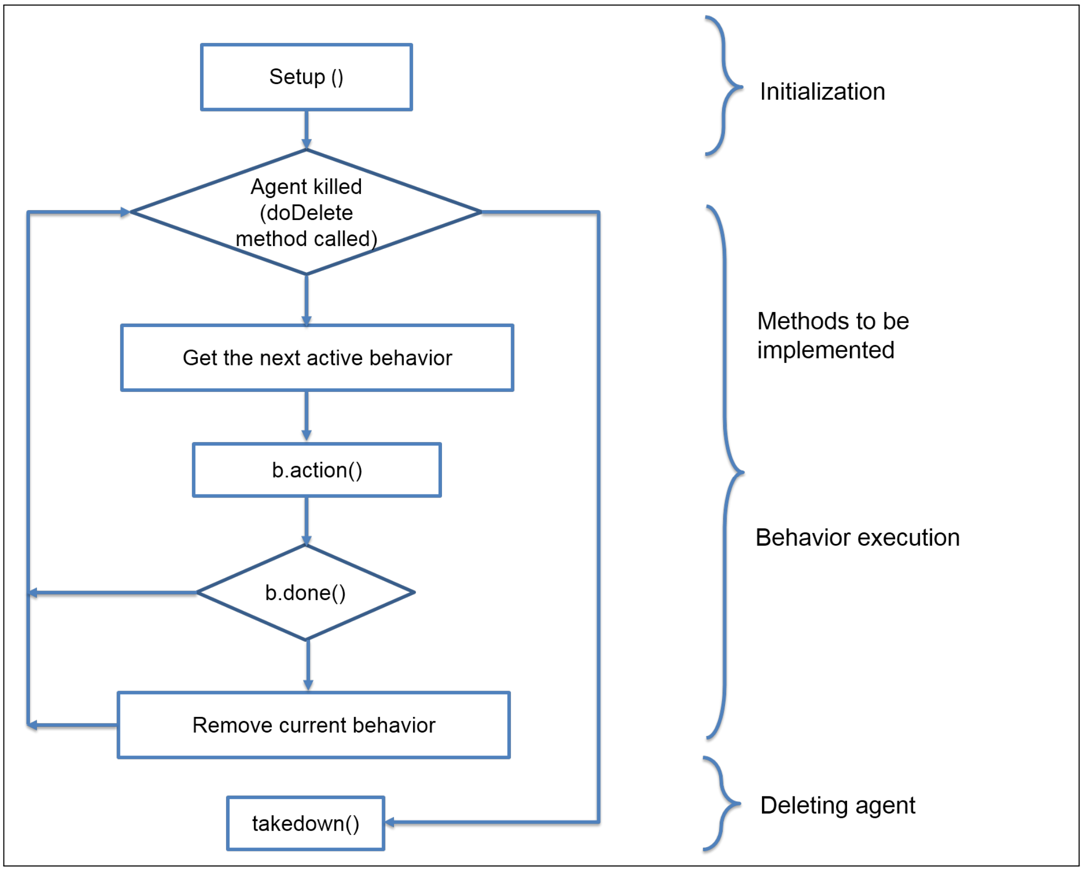

Figure 2.8: An agent execution model in JADE.

for simulating and experimenting cyber-physical systems to have insight into the system behavior and thorough analysis [PWE14] [RNBS12]. Thus a co-simulation framework was developed to test MAS application in electric distribution network. Java Agent Development framework (JADE) was used for developing agent application and electric grid simulations were carried out using DIgSILENT PowerFactory. More detail of the framework is given in methodology chapter.

3 State of the Art

3.1 Overview

This chapter provides status and review of the studies regarding use of multi-agent system in power system applications. It further presents methods, techniques and solutions available for control in power system including multi-agent based control. As main focus of the thesis is on control schemes of distributed energy resources in power distribution network at medium voltage level for voltage control, various approaches for voltage control along with their merits and de-merits are presented. This chapter is organized in two parts. In first part application of multi-agent system in power system are presented while second part gives detail of control schemes for distributed energy resources for voltage regulation. At the end status of voltage control using multi-agent system is presented.

3.2 Multi-Agent System Applications in Power System

From power engineering literature, four main application areas for agents exist. They are, broadly, monitoring and diagnostics, distributed control, protection systems, and modeling and simulation.Figure 3.1 shows MAS phenomena desirable by different power system applications.

3.3 MAS based Modeling Approaches

The main driver for the use of multi-agent application in power system is the growing complexity in operations of power system. Traditionally there are two design approaches, called, top-down and bottom-up, have been used for building complex systems [CGL08].Figure 3.2 shows the two approaches.

3.3.1 Bottom-Up approach

While designing and building the overall system from the top-down may present a highly complex challenge, the behavior of individual agents/actors within the system may be much simpler to model and build. In such situations, a bottom up approach makes building the system far easier. In a bottom-up approach the individual elements of the system are specified in detail. Such approach may result in failure to achieve global objective of the system. With this approach

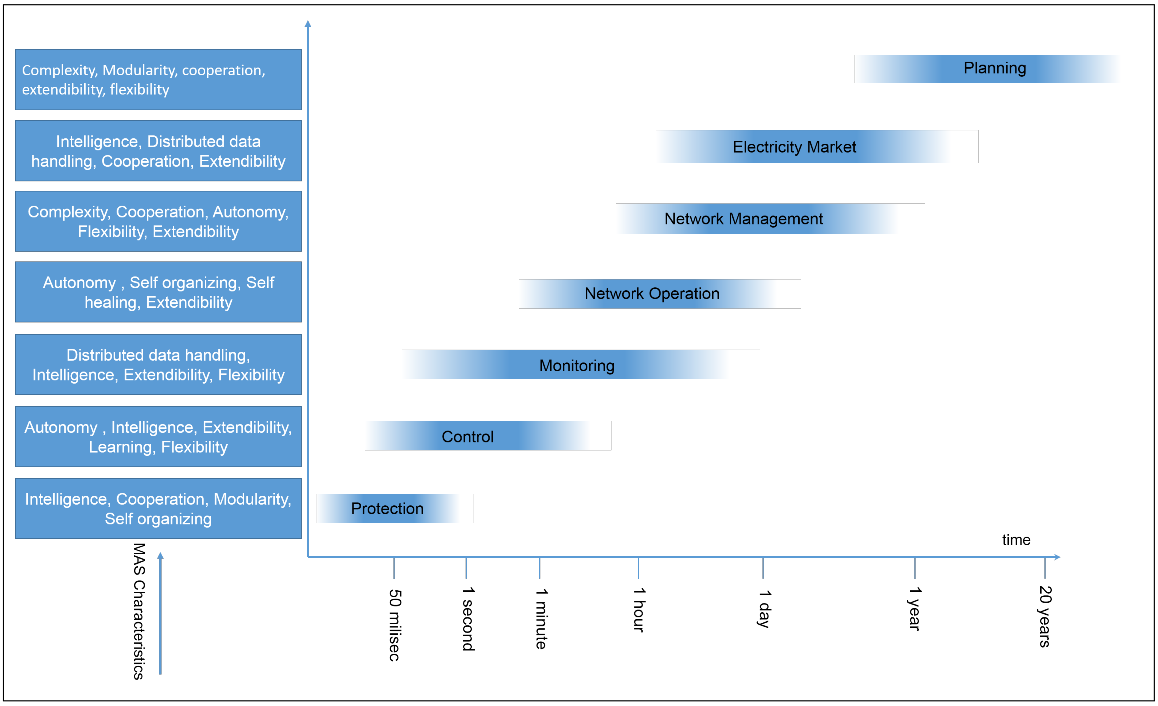

Figure 3.1: MAS phenomena desirable in power system applications at different time scale.

- Fundamental element (Agent) is designed with complete knowledge of the system.
- It involves additional development efforts which might not need for the current use case.

PowerMatcher [Kok13] is a well-known application which uses hierarchical bottom up control design approach. It is a MAS based application which intends for demand and supply matches in a power distribution network and takes into account all the network constraints. Supply and demand match is carried out by utilizing the potential of electricity generation and consumption devices which can change their operation to decrease the over-all mismatch between electricity production and consumption. It works on market based control concept using agent structure in which the different devices are represented by agents that work as actors of demand and/or supply in market. [KWK05].

3.3.2 Top-Down approach

This approach requires complete concept and high level abstraction of the whole system. It is assumed that all the resources are available globally for each subsystem. Specifications are defined as global and assumed that each individual subsystem is able to receive or estimate the information. Thus with these assumptions, the global specifications are considered to result in acceptable performance also in decentralized environment. Further top down prospective

- can provide required functionality of the current use case (voltage control, reconfiguration, protection etc)

- However, this approach has limited extensibility as this approach may cover the functionality of current use case under study but will not be able to cater for any future/other scenario.

Autonomous Regional Active Distribution Management System (AuRA-NMS) [DDAM10] uses design approach on the basis of functionality. Instead of defining each agent as a device in the system, it defines agents on the basis of different tasks i.e. for voltage control or power flow computation. In power system most of the applications of MAS are to perform specific task of power system and details are given in the next section.

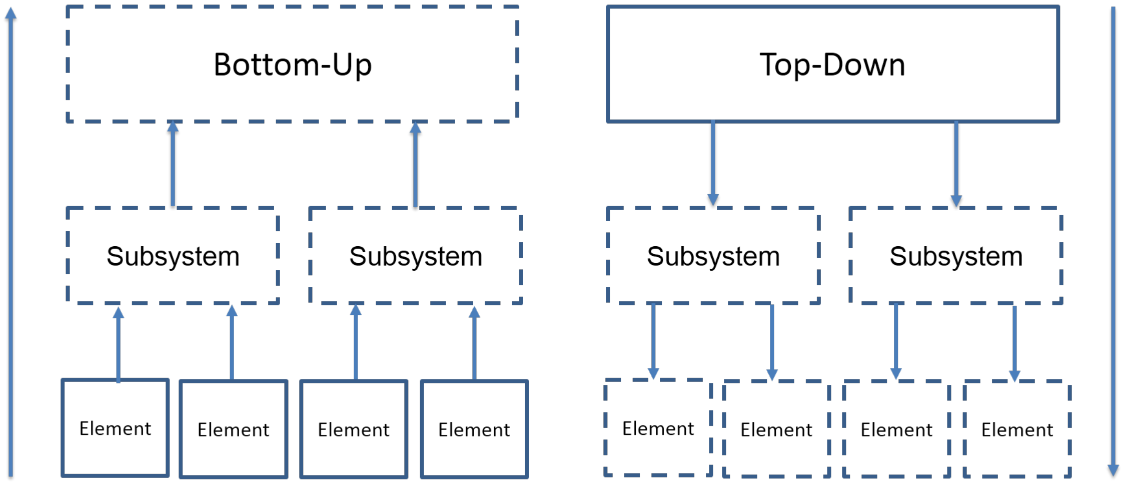

Figure 3.2: MAS based modeling approaches.

3.3.3 Management and Control in Microgrid

Multi-agent system has been used by various researchers for microgrid management and control. Major motivation is to bring intelligence, autonomy and modularity in the system with increased reliability [KGHP11]. One major requirement of microgrid is capability of transfer between grid connected mode to islanded and vice versa. Further, the transition between two modes must be in a stable and secure way. In [EGC15], authors presented MAS based distributed management of microgrid operation. Focus of this study was on solving the issues related to the market operation of microgrid. Agents were defined representing the devices and actors in market operation which include generation agents, load agents, market clearing engine agents, coordination agents, grid agents etc. A hierarchical control architecture was used for the microgrid operation and authors claimed that the proposed technique is capable of handling economical and technical requirements. However, it does not have coordination capability with other microgrids. Authors in [XTX12] presented coordination control scheme for microgrid in grid connected and islanded mode. Control objective was to balance supply and demand using generation sources and loads through active power control. Microgrid control agent (MGC), load agent, Point of common coupling (PCC) agent, gas turbine agent were defined. Results showed that, in grid connected mode MGC agent can coordinate with PCC agent for power exchange between microgrid and power distribution network, while in islanded mode, it can maintain balance of generation and demand.

A MAS based two-level architecture for distributed-energy-resource management for multiple microgrids is presented in [ND13]. Focus of this control architecture was market and resource management in microgrids. Various agents which can participate in market were defined and include generation agents,load agents, auction agents, storage agents etc. Multiple microgrid participation in the market was simulated and results showed that MAS based resource management was quite effective. Similar study was carried out in [HCZS14]. MAS based control system for active energy management for a multiple microgrid system comprising different microgrids was developed. Effectiveness of the proposed modeling approach and the active power management algorithm was demonstrated through simulations.

A three level intelligent control architecture for microgrid operation was proposed by the authors in [LNW+15]. This control was designed for both islanded and grid connected mode using MAS. Local droop control, optimal power balance and electricity market were handled in the three control levels. Agents interact locally and exchange information for decision making to ensure power quality, voltage and frequency regulation for secure and optimal operation of microgrid. A similar study was carried out in [DLZ+15] and, however, the authors used two level hierarchical decentralized control strategy based on MAS. Objective was to improve security and stability of microgrid. A coordinated switching control scheme comprising lower level droop control for unit stability and an upper level control for optimal operation was proposed. Effectiveness of MAS based decentralized control was demonstrated with the help of simulations.

Authors in [LZZ+16] addressed the problem of automatic generation control of intermittent inverter interfaced generation sources in microgrid. MAS based distributed algorithm to acquire global information was used in order to deal with the draw backs associated with conventional droop control. A market based control of microgrid was proposed by [MMS+14]. MAS system was developed to manage the energy sources on the basis of demand and market price. MAS operation was demonstrated using co-simulation framework in different scenarios.

MAS was used for real time autonomous decision making for reliable and robust operation of microgrid by the authors in [CN13]. A decentralized control architecture was presented for grid connected and islanded mode operation of microgrid. Simulation scenarios demonstrated the capability and potential of decentralized agent based control for microgrid. Similarly in [MJHC14] authors proposed hybrid energy management system (HEMS) for microgrid operation. A MAS based centralized and decentralized control architecture was proposed. This HEMS coordinated framework consists of local level autonomous control and a coordinated energy system control at the central level. Effectiveness of the proposed scheme was showed with simulations.

A decentralized control on the basis of MAS for multiple microgrids was presented in [DS14]. Microgrid was modeled as combination of renewable based local generation sources wind/solar, storage and loads. Optimization problem (minimization of cost of power exchange between multiple grids) was addressed through cooperating agents. A convex optimization approach was used for this purpose. Table 3.1 highlights summery of the studies with intended functionalities of MAS.

3.3.4 Electricity Market

Power system transition has resulted in restructuring the electricity markets and privatization, deregulation are some of the examples[SBT14]. Such liberalized electricity markets are considered as a complex system where participants have not enough information about the market, and

Table 3.1: Microgrid studies with desired functionalities using MAS.

Study	Intended functionalities by MAS
[XTX12]	Grid connected and islanded mode operation, power balance, stability, coordination
[EGC15]	Market based control, coordination, stability, cooperation
[ND13]	Multiple microgrids, two level architecture, market, resource management, cooperation
[HCZS14]	Multiple microgrids, islanded and grid connected mode operation, power management, coordination, autonomous
[LNW+15]	Island and grid connected, three level control, droop control, power balance, intelligent, optimal operation, market
[MMS+14]	market,Balance
[DLZ+15]	Two level hierarchical control, lower level droop control, unit stability, upper level, optimal operation, security, stability, Coordination, switching
[CN13]	Grid connected and islanded, self organizing, robustness, smartness, intelligent, Independent decision making, power management, autonomousity
[MJHC14]	Energy management, three level hierarchical, local control of DERs, coordinated at central, stable economic, optimal, autonomous, Optimize
[DS14]	Multigrids power exchange, optimal, power balance, cooperation

further the market outcome is influenced by the local decision making actors [GSW+05]. In such environment, information is distributed over the entire system and local actors require cooperation and coordination for profit and also fulfillment of required generation and constraints i.e. transmission capacity etc [YYC+00]. As MAS are characterized by the distributed, autonomous and cooperative and have intelligent properties, it has a good potential for application in electricity markets. MAS in electricity market are being used in two ways i.e. MAS as a tool for simulation studies and MAS as modeling and control in electricity market.

- **MAS as a tool for simulation studies:** MAS are well suited to study the behavior of electricity markets having complex adaptive nature [YL08]. Thus major application of MAS in electricity market are simulation studies to analyze behavior of different actors in the market. An ontology was developed in[SPM+15] which incorporates various concepts in order to infer from available information of electricity market. A case study was carried out on a multi-agent system platform using scenarios on real data. European electricity market environment was simulated and performance on different complex market mechanisms were studied. A distributed simulation system for power system market was proposed by the authors in [QGW+08] using JADE, a MAS based tool. Market actors were modeled as agents which use learning methods and participate in bidding strategy. This distributed approach using intelligent agents proved to be better than centralized approach in term of benefit. In [LR11], the authors developed MAS based application for the analysis of generator bidding behavior in electricity market. The market characteristics like generator, structure, operating rules can be modeled as agents. Real data for modeling was obtained from the market operator. Profit-based unit commitment (PBUC) problem was solved in [YZW+04] using MAS. Rule based and dynamic programming methods were utilized by the MAS. It was claimed that this approach can help generation companies to make intelligent decisions on scheduling generators, selling etc to maximize their profit.

  A MAS based electricity market simulator for the study of electricity markets operation MASCEM (Multi-Agent Simulator of Competitive Electricity Markets) was presented in [PSV+14]. Realistic simulation scenarios can be developed using real data. A scenario based on real data was simulated and compared with the real electricity market results.

- **MAS as modeling and control in electricity markets:** Market-based control can be considered as an example of competitive model of MAS in which many agents compete and negotiate with each other for trading on an electronic market with objective of optimally achieving their local control action goals [KWK05] [ZM10]. Authors in [ZY06] used MAS for intelligent decision making for supplier in electricity market. A layered architecture was proposed and focus was on data collection, analysis and decision making. On the basis of this layered architecture optimal bidding strategy was proposed. Another study of smart home trading features was carried out in [KRSA13] using MAS. Each home was modeled as an autonomous agent which can sell or buy or store electricity based on the information about present and future load, generation or storage taking into account of benefit associated with each decision. Case studies were presented and showed that MAS based smart home modeling offer benefits to both utility and home. Another study in [CMM15] presents real time implementation of auction algorithm based on MAS in microgrid market operation including distributed energy resources. Monitoring, control and auction process of DERs was carried out using a MAS based platform. Similarly authors in [BHA15] proposed a MAS based framework which implements combinatorial auction algorithm for smart grid energy market using demand side management. Another market based control using MAS was presented in [FM16]. It proposed electricity management at house hold level. In market-based MAS, heat and electricity price negotiation can be carried out with the objective of economically balancing supply and demand of heat and electricity at a house level. Simulation results showed that proposed approach is quite economical as compared to conventional heat driven approach without compromising the user comfort. Authors in [CGY04] proposed MAS based approach for determining the optimal wholesale electricity trade schedule. Power exchange agents along-with other coordinating agents were defined and simulation results showed the effectiveness of the approach.

3.3.5 Power System Protection

Power system protection schemes can be designed using MAS which brings intelligence cooperation, autonomousity, reactivity for secure and safe operation. Protection equipment can easily be modeled into agents and can be operated with coordination and cooperation with other devices. Further use of distribution generation in power distribution networks has complicated the protection schemes and an intelligent solution is required [QWHL11] [YXZ+02] [HWW+15].

A study was carried out in [MR12] regarding effects of distributed generation in power distribution system and MAS based protection scheme was proposed. Agents representing over-current relays were defined and coordination mechanisms between agents was devised to find a timely solution for action through communication. Results showed reduction in protection operating time and better selection of relays.

Authors in [LCSH13] proposed MAS based wide area protection scheme and objective was to avoid unexpected operation of relays and it also takes into account for the post fault transient period. A similar study was done in [LCSH15] and main focus was to cope with voltage instability due to cascading trips. Two layers architecture was proposed in which emergency control parameters were re-adjusted by the agent based process control which monitor states of the distributed controllers. A hybrid simulation platform was used to demonstrate the effectiveness of the proposed method. Authors in [GA15] proposed a solution to mitigate the negative impacts of variable distributed generation on the power system protection schemes. Distributed generation causes variation in fault current characteristics which results in malfunction of relays. MAS based adaptive relaying was proposed in which relays have decision making capability in the changing environment which makes the relays intelligent. The proposed strategy was demonstrated on a real electrical network.

A comprehensive agent based decentralized wide area protection scheme was proposed by the authors in [TWW+13]. Agents used peer-to-peer communication for negotiation and information sharing. Line decision agents for local fault detection and regional decision making agents as a supervision layer was defined. Results showed the higher fault-tolerance capabilities of MAS based protection system under protection, communication failures. Authors in [MKES14] presented self evolving intelligent MAS based architecture for control and protection of power system. Different agents were defined with communication parameters and ontology were defined for inter-agent communication. Through mutation process agents can evolve during malicious attacks and thus capable of monitoring and performing the protection operation.

3.3.6 Demand Response

Flexibility in load consumption, increase or decrease, according to the variation in power supply and real time market provides a good opportunity for generation and load balance. This change in load consumption automatically within the constraints in response to the signal from market actors offer customers to save electricity cost. MAS having attractive features like reactivity, intelligence and autonomousity is receiving more and more attention of scientific community for demand response applications in smart distribution network. MAS based demand response application can be embedded in energy management system for smart home office or building [LN15].

Authors in [ANH13] presented Load management scheme based on MAS in distribution network. Self decision making feature of MAS was utilized for optimal capacity commitment of distributed generation and load management. Load management, feeder, demand response and distribution generation agents were defined. Proposed method was claimed to be fast and scalable with minimum error. In order to bring intelligence in building energy management system, the authors in [PKK+15] proposed an agent based platform capable of interactive management of Internet of Things (IoT) devices. The main goal was to improve energy efficiency, reduction in consumption and use of demand response applications.

In another similar study an agent based demand side management framework was proposed for responsive loads[NDS13]. Focus was on demand response application in microgrid. Demonstration was made using co-simulation framework comprising JADE and Open DSS software and two microgrids. This work was further enhanced in [NSS+16] and novel incentive mechanism for participants was presented. Proposed market model was simulated using the co-simulation framework.

A MAS based demand response program for residential consumers was proposed in [KTT+15] to mitigate the effects of intermittency and uncontrollability of renewable generation i.e. wind or solar, which result in frequency fluctuation and voltage imbalances. Demonstrations show reduction in negative impacts of distributed energy resources without compromising consumer comfort.

3.3.7 Power System Monitoring

With the increase use of ICT in power system, network is becoming more observable and a huge amount of data is obtained. In this situation, dealing with data scattered over the whole system for monitoring purpose has become a big challenge [MD04]. The process of diagnostics becomes complex due to presence of large amount of data which need to be analyzed centrally using different algorithms [ZM07]. MAS has been used for handling of data in various tasks related to the power system which involves:

- **Diagnostics:** Authors in [DPM+05] used MAS for diagnostics and monitoring of power system. Instead of a centralized system, a peer to peer system was used for monitoring and objective was to re-define the control action on the basis of changing network conditions.
- **Restoration and Reconfiguration:** Restoration of power is carried out after detecting fault and isolation of faulted area in power system to serve maximum number of loads. The process needs to be quick and intelligent. The authors in [GCF14] used MAS based approach for restoration process in order to make the process quick and intelligent through learning of agents. Proposed framework was applied on a test case and results showed that learning feature improved the performance of agents for power restoration. Further, in another study [SSG05], reconfiguration process was carried out using MAS. Main motivation was to overcome single point failure draw back of centralized approach and introduction of

autonomy feature of decentralization approach. Virtual Test Bed and MATLAB was used to develop the MAS based framework. Authors in [BL07] presented some design concepts for MAS in power distribution network restoration. A prototype for restoration based on MAS was presented and MAS features i.e. autonomousity and intelligence were evaluated and proved that MAS has a good potential for application in restoration process.

3.3.8 Distributed Control

Power system is growing in size and operation is becoming complex due to many reasons, some are increased use of distributed generation, technological advance and consumer participation. In such scenario traditional centralized control schemes are more likely to have problems associated with centralized control structure i.e. single point failure. MAS has a good potential for application in such situations, as individual agents have local decision capability, along-with information exchange, thus distributing the control action. All the above mentioned applications has been studied in distributed environment in order to avoid reliance on a single centralized control unit.

3.3.9 Other Areas

Other than above mentioned areas MAS has also been used in cyber security, load forecasting etc. A concept for improving the cyber security of SCADA system based on MAS was presented in [KKK07]. A flexible key distribution concept involves agents like local security state analysis agent, intrusion detection agent, key distribution agent etc. The authors suggested to use artificial neural network, genetic algorithm and game theory to bring intelligence in agents operation. In [Par13], the authors discussed agent based modeling of power system infrastructure cyber security. It was suggested that the effects of various forms of cyber attacks i.e. denial of service, delay, failure of components, should be considered and developed strategies can be tested using software agent model.

Table 3.2 shows MAS features in power system application areas on the basis of literature studies.

Table 3.2: Power system application areas and MAS features:
R=Required
D=Desired
A=Additional

Application Area	**MAS Feature**						
	Distributed	Intelligence	Autonomy	Modularity	Learning	Cooperation	Negotiation
Microgrid	A	R	R	D	D	D	A
Market	R	R	A	D	R	R	R
Demand Response	A	D	R	D	D	R	R
Protection	D	R	R	D	A	D	A
Monitoring	R	A	A	D	R	A	A
Restoration & Configuration	D	R	D	D	D	R	A
Control	D	R	R	R	D	D	A

3.4 Voltage Control in Distribution Network

This section presents literature review of various voltage control schemes using specialized voltage control equipments to distributed energy resources. Voltage regulation is an important task of power distribution management system. With the increase use of distributed generation traditional voltage regulation techniques are no longer sufficient and limit the integration of distributed generation and thus major hurdle in efficient use of renewable energy resources. Next section provides power distribution network management and operation areas.

3.4.1 Distribution Network Management & Operation Areas

Distribution management involves applications which are designed to monitor and control the distribution network to ensure network efficiency and reliability. Some of the applications are given below;

- **Load Flow Applications:** The objective of load flow study is to obtain the complete information of voltage magnitude and angle for each node/bus in the network for a specific load and generator power. As a result of this study real and reactive power flow on each point of the network can be determined. It is very important for the best operation of the network.
- **Volt-VAR Control and Optimization:** The objective of volt-var control is to manage voltage levels and reactive power throughout the power distribution network. Traditionally, volt-var control application uses three main equipments for voltage level management and these are : on load tap changers, voltage regulators and capacitor banks.
- **Fault Management & System Restoration:** An important task of utility is to supply electricity continuously and ensure reliability. In case of some outage, fault management and system restore application helps to resume supply of electricity and thus increases the reliability. This application uses intelligent switching management for restoration.
- **Feeder Reconfiguration:** Reconfiguration application is used for various purposes by the utility where, there are multiple feeders serving to the loads. For example in case of restoration process, feeders might be reconfigured using the switches in order to isolate the faulty areas. Further, load balancing can be carried out in load congested areas using feeder reconfiguration.
- **Load Shedding Application:** In emergency operation of power network, load shedding and restoration becomes important. In case of fault/instable condition, this application can be used to shed some part of the non critical loads to maintain system stability i.e. in case of frequency violation (under frequency load shedding) etc.
- Some other useful applications are
  - **Outage Management**
  - **Crew Management System**
  - **Customer Information System**

3.4.2 Volt-VAR Control and Optimization in Distribution Network

Volt-var control is an important task of distribution network operator. Conventionally distribution network operator, carries out volt-var control with the help of equipments installed throughout the network. Next sections provide details of volt-var control techniques and equipments used in literature.

3.4.2.1 Volt-VAR control Techniques

There are various methods proposed in literature for volt-var control. Research on volt-var control is increased a lot with the growing use of distributed generation in power distribution network. This increased use is causing voltage regulation task complicated and required intelligent solutions which should facilitate the integration of distributed generation. These methods are given below;

- **Reactive Power Compensation:**
  Voltage violations (upper or lower limits) in distribution network can be decreased by using the devices which are capable of absorbing/induction of reactive power and are dispersed through out the network. As, it is costly to transmit reactive power over the long distances, these dispersed devices are used for voltage regulation by controlling the production, absorption and flow of reactive power. This reactive power compensation is divided into active or passive compensation depending upon the operation of the equipment. This compensation is carried out by the equipments which belong to the Flexible AC Transmission System and can be classified as;

  - Shunt capacitors, shunt reactors
  - Series capacitors
  - Synchronous condensers
  - Static var compensator
  - Static synchronous compensator (STATCOM)

  Authors in [GPC10] used STATCOM for voltage control through reactive power compensation. Genetic Algorithm was used to optimize and tune the DC link capacitor and battery source parameters. Similarly authors in [Tit15] used PI based control for STATCOM for reactive power compensation for different load conditions. In another study, [HRE06], the authors used fuzzy logic controller for STATCOM to compensate reactive power in distribution network. Results showed that performance of the fuzzy controller is better than PI controller. Authors in [AS16] used STATCOM for regulating the voltage at point of common coupling between the wind farm and the grid and results showed that the STATCOM have capability of regulating fast variation in voltage at the point of common coupling.

  Distributed generations capable of reactive power absorption/induction are also being used for reactive power compensation. The authors in [SC15] used coordinated control of OLTC and reactive power compensation by the wind power generators. Mitigation of over-voltage at the remote bus was carried out through reactive power compensation by the local wind generator when the remote wind generator reaches its reactive power limits. Effectiveness of the proposed voltage regulation was demonstrated using a case study.

- **Power Factor Control:**
  Generally, distributed generator connected to the distribution network are required to be operated in power factor control mode and particularly, distributed generators are not allowed to perform automatic voltage regulation as it may result in destabilization of automatic OLTCs of distribution transformers [VKWH07]. Also when small generators running in terminal bus voltage regulation mode connected to a strong/stiff bus, system voltage will not change much. However, in case of system voltage significantly changes the generator will try to maintain the voltage set point. This may result in over or under excitation of the generator and consequently can have adverse effect on the operation of generator i.e.

excessive heating etc [ES02]. Power factor control mode is less disruptive to the network devices i.e. OLTCs. In power factor control mode real power and reactive power ratio, p/q is kept constant. Any change in real power is followed by the reactive power. Both the methods, power factor control and automatic voltage control can be combined for smooth and stable operation.

- **On load tap changers:**
Voltage regulation in distribution network can be carried out using OLTCs which regulate the substation secondary bus voltage according to the allowable limits through changing its tap position. These are generally motorized mechanical switching arrangements which changes the transformer turns ratio in steps of 1.25% or 1.43% [Tho00]. Each OLTC transformer is connected to an automatic voltage controller (AVC) relay to raise or lower the voltage by changing the tap position. This AVC relay monitor the voltage at the secondary side of the transformer and compare with the desired voltage set point thus determining whether to change top position or not [SRP03]. Authors in [HBP14] studied different control schemes for tap change transformers under high share of distributed generation. Tap change operation was studied on a clear day and a day with clouds in a network having variable generation sources (PVs). It was observed that there is always a trade-off between reducing the number of tap operations and minimization of voltage violations.

- **Active Power Curtailment**
Due to increased use of distributed generation especially PVs in distribution network, there are increased voltage violations. These voltage violations are generally due to excess injection of active power into the network which leads to voltage rise problem. Such voltage rise problems are more in weakly connected low voltage networks. There are two possible solutions;

  - **Disconnection of Generating Unit:** One solution adopted by the many distribution network operators are to disconnect the distributed generation from the network to overcome the problem [RPH13] [TLEF11]. However, this method involves inherently unfairness. As mostly violations occur at the end of the feeder and generating units at the end of the feeder are disconnected frequently [XT08].
  - **Limiting/curtailing the output of Generating Unit:** Instead of disconnection of the generating unit from the network at the point of voltage rise, active power of all the generating units can be curtailed so that net effect results in removal of voltage violation. However this method required coordination mechanisms and fairness. In this case net active power curtailment is usually more then the single generating unit disconnection at the point of voltage rise. So, there is a trade-off between fairness and energy loss. Authors in [TLEF11] proposed droop-based active power curtailment method for over voltage prevention in a radial distribution network. Objective was to increase the hosting capacity of the network. Total desired active power curtailment was shared among PVs by using different droop coefficients. However it was noted that, active power curtailment sharing among all the generating units results in higher required active power curtailment. Authors in [CAV15] proposed priority based algorithm for voltage control in distribution network including distributed generation. Priorities of the three proposed methods; power factor control, on load tap change control, generation curtailment, were defined. Effectiveness of the proposed methods were shown by using simulations. Authors in [LGP16] proposed voltage control in low voltage network and main focus were on mitigation of unfairness in active power curtailment. Active

power curtailment schemes were presented and key performance indices were used to measure the unfairness in the algorithm. Results indicate that active power fairness can be brought in active power curtailment algorithms, however at the expense of increased curtailment.

- **Energy Storage:**
  Energy storage is considered to be a possible solution for addressing the issues related to variable and intermittent generation. Other than facilitating the increased use of generation in distribution systems, it can also be used to improve network operation [WTLJ10]. Voltage control is one of the major area where energy storage has a potential application and can be used for power factor correction, minimize tap operation and mitigate voltage flickers. Authors in [WTLS09] used energy storage for power flow management and voltage control in a medium voltage distribution network. Objective was to minimize the steady-state voltage variations at the point of common coupling along-with reduction of reverse power flow when distributed generator is producing more power as compared to the load demand. Authors in [MPG15] developed two voltage controllers using energy storage to regulate the voltage at the point of connection of distributed generation. Charging of battery storage was controlled using an over-voltage controller which can charge the battery in case there is over-voltage at the point of common connection. The other controller was used to set up the battery in schedule mode. A similar study was carried out in [WLY+14], in which the authors used energy storage in voltage control schemes. It was concluded that coordinated voltage control schemes by using energy storage can provide cost-optimized voltage control solutions for the distribution networks with increased distributed generation. Authors in [MFBB12], proposed energy storage based voltage support methods in distribution network to ensure the fulfillment of voltage requirements in a low voltage network with high penetration of PV sources. The proposed method can be used in cooperation with reactive power control schemes to avoid active power curtailments.

- **Network Reconfiguration:**
  In a typical distribution network generally there are alternative paths/lines for supply in order to serve the load without any interruption.Thus network can be connected in various ways and offers reconfiguration, if necessary or desired. Main purpose of reconfiguration is improvement of quality of service, loss reduction and to ensure the reliability of the network. There are some studies to find a suitable reconfiguration of the network to change and redistribute the power flow which may result in improvement of voltage profiles so that there are no voltage rise or low problem. Authors in [KGJ00], used network reconfiguration for voltage stability in distribution network. An algorithm was developed which search for the best switching combination which maximize the voltage stability. A similar study was carried out in [SVSR05], in which the authors presented an algorithm to increase voltage stability by network reconfiguration. This algorithm determines the switching options of the distribution system for loss reduction and with out compromising voltage stability of the system.

  A fuzzy based genetic approach was used in [SP06] for reconfiguration to increase voltage stability of radial distribution systems. The network reconfiguration process involves opening/closing of switches in such a way that the new configuration of the network fulfill the desired performance characteristics. A combination of reactive power control and reconfiguration process was used in [ZLLZ09], in order to improve voltage profile. An optimization algorithm consist of reactive power control of wind farm and network reconfiguration was proposed and evaluated. The results showed the effectiveness of the algorithm. In the presence of distributed generation, reconfiguration process becomes complicated and there are several open questions such as cooperation with the existing network restoration schemes, cooperation with other voltage control devices and priority of different control actions for voltage control.

- **Demand side management:**
Increased customer participation has encouraged network operators to use demand side management techniques to improve network operation. Other than generation demand balance, peak load reduction, demand side management can also be used for secure and reliable operation of the network. Authors in [MBYH15] proposed dynamic operation of voltage regulator along-with demand side management for voltage control in distribution network having a large number of PV generation sources. The results indicated that by using load control, number of tap operations of voltage regulator were reduced while maintaining the desired voltage profile. It was suggested that demand side action should be considered as a second option for voltage profile improvement. A similar study was carried out in [YWT+12] [Chr16], however it also includes combine operation of energy storage and demand side management technique for voltage control in distribution network.

3.4.2.2 Equipments for volt/var control in Distribution Network

Following are the equipments which can be used for voltage regulation services in power distribution network;

- **Onload Tap Changers OLTC**
- **Capacitor Banks**
- **Static Synchronous Compensator**
- **Automatic Voltage Regulator**
- **Distributed Generation**

Figure 3.3 shows voltage control techniques and equipments with description.

3.4.3 Voltage Control using Distributed Energy Resources

Distributed energy resources (DER) is the term often used and includes distributed generation, distributed storage and distributed loads [Bra07]. Distributed generations are small energy generating units (as compared to the large centralized power plants) which provide electricity near the loads. Major criteria used for classification as distributed energy resource are size, location, voltage level, type etc. These DERs include such technologies as solar photo-voltaic (PV),combined heat and power (CHP), wind turbines, micro turbines, back-up generators and energy storage etc [DNV14]. Power distribution networks which were not initially designed to include distributed generation faces many challenges and issues due to integration of these DERs [MKS08], [CT07], [KESEH15], [GMK09], [BSR12]. Figure 3.4 shows impact of DERs integration in distribution network which involves capacity and quality issues.

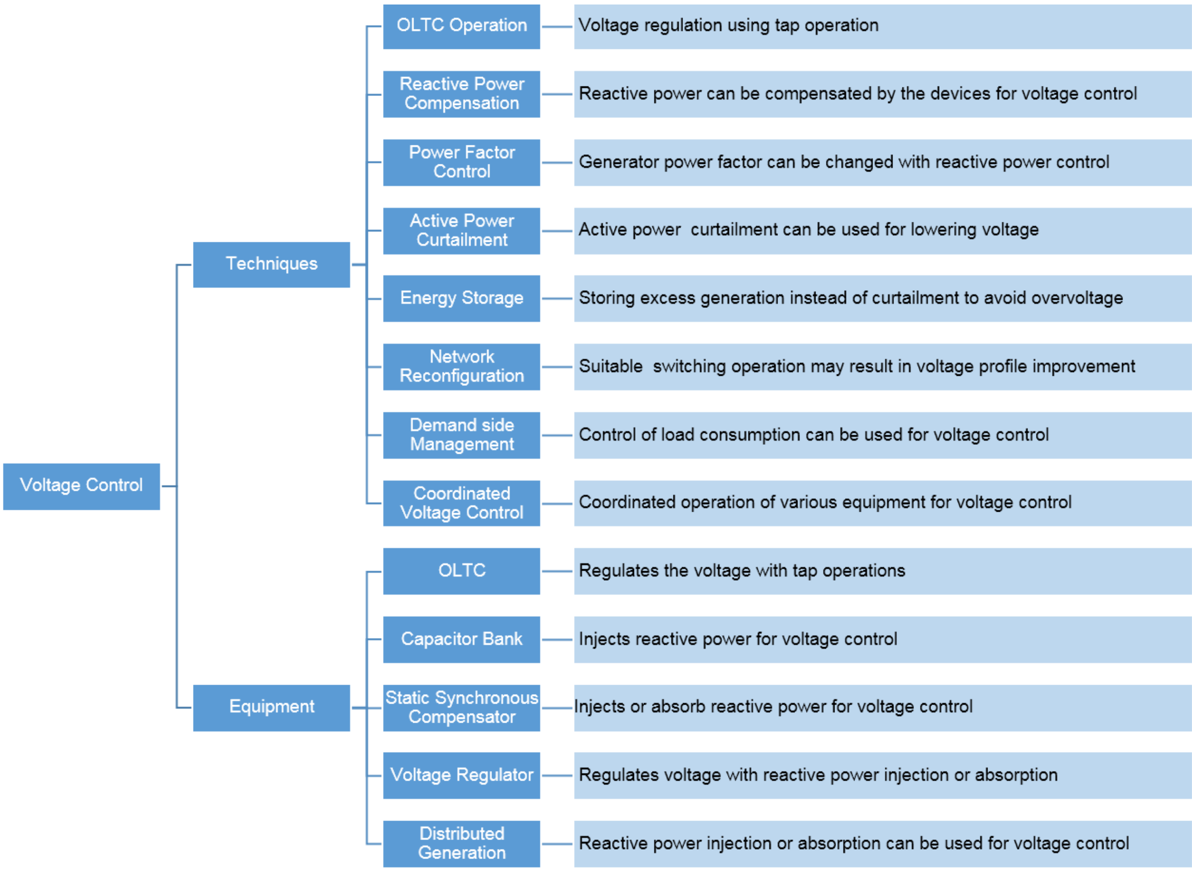

Figure 3.3: Various voltage control techniques and equipments.

However, with proper control and coordination, these DERs can participate in network operation and enhance the network reliability. Thus these DERs can provide the ancillary services i.e. voltage control. This provision of voltage control support during voltage violations will not only improve the power quality but also enhance the reliability of electricity supply. Table 3.3 shows voltage control capabilities of different grid integration technologies. In order to get benefit of the control capabilities, coordinated control of DERs is required to guarantee secure and safe operation of distribution network. Next section provides control architectures for coordination between DERs.

3.4.4 Voltage Control Architecture

Conventionally, in passive distribution networks voltage control with the help of OLTC is accomplished. Distribution networks with the integration of DERs and more controls and communication have made these networks active systems. Current active network management and control schemes may be categorized as centralized or coordinated control, semi-coordinated (distributed) and decentralized control strategies. On the other hand, the semi-coordinated and decentralized or distributed control strategies must be able to control the DG unit locally in an active manner while coordinating it with a limited number of other network devices. These approaches are able to improve the overall network performance with limited cost incurring due to lower need of

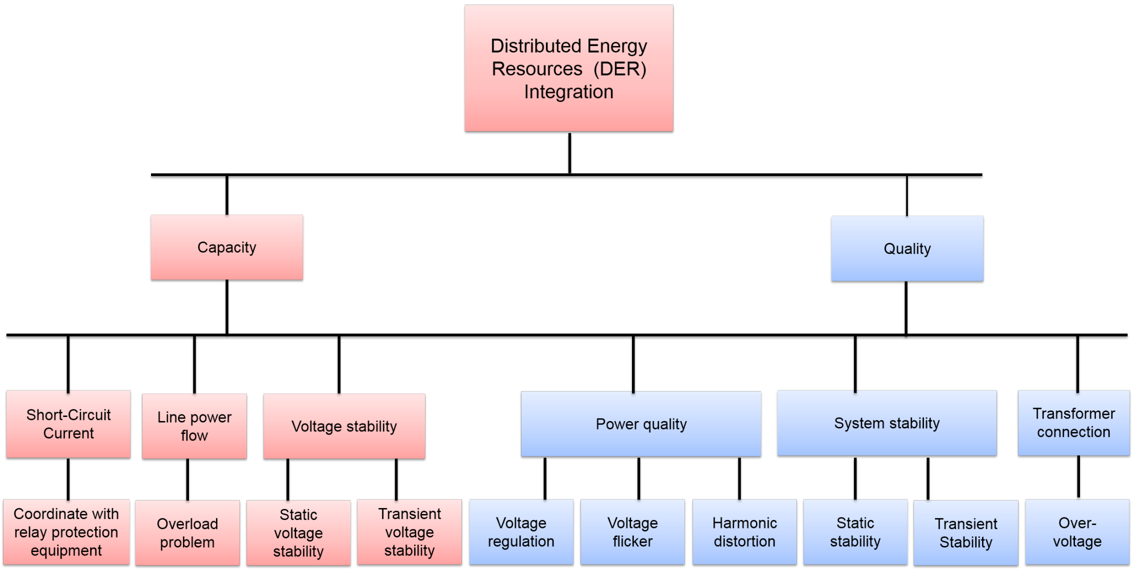

Figure 3.4: Impact of distributed energy resources in power distribution network.

Table 3.3: Control capabilities of different grid integration technologies. [Bra07]

Coupling Technology	**Reactive Power Control**	**Direct Voltage Control**	**Voltage Quality Improvement**
Induction Generator	No	No	No
Doubly Fed Induction Generator	Limited	Yes	Yes
Synchronous Generator	Yes	Yes	No
Inverter	Yes	Yes	Yes

communication systems.

It requires new control architecture for controlling OLTC and other controllable devices i.e. DERs installed at various locations in distribution network. This control architecture can be purely decentralized to centralized system. It can be classified into three main categories and are described in the next section.

3.4.4.1 Centralized

Centralize control has simple conceptual framework. In this scheme the whole system is being controlled with a single controller. It has been studied from decades and many controller design procedures are available for linear and nonlinear systems. Further, transmission of system measurements to a unique and central controller might be challenging, if system is deployed over a wide area. Centralize control might also be unappealing for economic, political or societal reasons. [Bak08]. Voltage control of the distribution network can be achieved centrally, in a similar manner to the transmission system through dispatch of active and reactive power from distributed generators and other network elements. Such an active management scheme would consist of a distribution management system controller accepting voltage, power flow and equipment status measurements at selected locations in the distribution network. The controller would then use state estimation to estimate network power flow and voltage profiles before dispatching plant according to economic dispatch. The downsides to this approach include necessary investment in sensors, communications and dedicated controllers as well as the balance required to ensure adequate accuracy of the state estimator.

3.4.4.2 Decentralized

Decentralized control scheme refers to the local control of a device. In such cases there is no communication between other devices present in the network. Such control schemes does not require communication infrastructure and knowledge of the whole system.

3.4.4.3 Distributed

In decentralize control, there is no communication between controllers which limits the desired performance. In order to overcome this problem distributed control can be used in which controllers can communicate with each other. Thus distributed control is a middle ground between centralized and decentralized schemes. In distributed control communication network might be part of the design problem.

Table 3.4 shows the pros and cons of the three control schemes.

Table 3.4: Pros and cons of the three control schemes.

Decentralized control	Centralized control	Distributed Control
All the DERs are operating using decentralized control mode	Information from all the DERs is collected through a common bus (high bandwidth communication channel) at a central point	Only neighboring DERs communicate with each other using low cost low bandwidth communication channel.
No coordination,	decision making is done centrally then commands are communicated to all the DERs	Decision making is done locally with neighboring information
Cost saving	Wide coordination, requires communication	—

3.4.4.4 Selection of Control Architecture

All the three control philosophies can be used for voltage control and have been used in voltage control studies in the past. However, there some important factors which are crucial in deciding the best suitable control architecture [HGDC11]. The main factors are ;

- **Speed:** It is related to the maximum allowable delay between an event occurred in distribution network and control action. This maximum allowable delay depends upon the application and ranges from few milliseconds to several minutes.
- **Complexity:** It refers to the degree of flexibility that must be built into control system application. Thus the control rule or logic must be changed to accommodate any change in the system without effecting the performance. Operation of OLTC with the introduction of DER in the network can be considered as complex.
- **Cost:** It is very important factor for deployment of any control architecture. Distribution network operator want to operate the network in a regulated environment with cost effective solutions. Choice of control architecture can influence the budget of the network operator i.e. for centralized system more communication infrastructure is required.
- **Safety:**It refers to the minimum safety and security conditions required for people and devices during operation and control of the electrical network. Control architecture must fulfill the rules imposed by the distribution network operator.

3.5 MAS based Voltage Control

MAS has been used in literature for voltage control applications in different architectures from centralized to decentralized architecture [LCM13] [FES11]. Authors in [KCM15] and [JKCM15] used MAS for voltage regulation and proposed a centralized moderator based structure, in which moderator decides for reactive power contribution of each distributed generator agent. Different types of agents were defined which include distributed generator agent for distributed generator control, monitoring agent for bus voltage monitoring, moderator agent for coordination and decision making. Moderator agent uses the reactive power sensitivities of distributed generators and fuzzy inference system for decision making.

Authors in [IMS15] used MAS for voltage control during emergency and catastrophic disturbance in power system. The control algorithm used decentralized architecture with different zones and agents in each zone coordinate with each other for corrective measure during emergency operation. Two types of agents; load agent and generator agent, were defined. There were no coordinator or central agent and each agent coordinates with other agents in its zone. Load shedding scheme in case of contingency was also presented. Quick remedial measure using MAS was main advantage of the proposed algorithm. MAS based holarchy structure was proposed in [AS14], [NS16] for wide area voltage control. Bus agents for monitoring and reactive agents (capacitors and tap changers) were defined. This structure was compared with the team and conventional (without agents) and found better. Multi-agent based secondary voltage control was proposed in [GXY05]. Coordinator agents as secondary voltage control and execution agent as primary voltage control were defined and coordination schemes among voltage controllers in normal operating condition and system contingencies were investigated.

The authors in [BCP16] presented decentralized voltage control in active distribution networks having distributed energy storages. In order to minimize information exchange, voltage control areas on the basis of voltage sensitivities were defined. Decentralized algorithms based on MAS were presented. Effectiveness of the proposed algorithms were demonstrated through simulations of test cases based on IEEE 13 node and 123 node test system. Most of the MAS based voltage control studies used hierarchical structure. Authors in [SJ13] used three level control architecture on basis of MAS for voltage control using distributed generation. Further, network zones were defined in order to decentralize the voltage control process. Authors in [RFB+14] also used agent based framework for voltage control and peer-to-peer structure for agent communication was considered.

In another study MAS based distributed voltage control schemes was presented [AL16]. Objective was to use minimum information for voltage control action and minimize losses in the network. Various types of agents were defined and each agent in the network communicate with the other agents and can exchange tokens which contains information about the control action. Proposed scheme was tested on a network with varying level of distributed generation penetration. Authors in [ZFN16] proposed distributed power flow computation for volt-var control using MAS framework. The voltage regulator agent and shunt capacitor agents coordinate with each other to determine the optimal setting for the whole network system. The goal of optimization was voltage profile maintenance, minimizing system losses and reducing operation of shunt capacitors. IEEE 34 node network was used to validate the proposed distributed power flow and voltage control algorithm. Authors [BB14] in used a co-simulation framework for volt-var control in distribution network using MAS. Agents coordinate with each other to decide reactive power outputs of compensator through a shared communication network. Effects of communication delay and loss on the performance of algorithm were studied. Agent based hierarchical structure for voltage support in power system was proposed in [ALKO11]. In this control scheme, each action follows a chain of command from Control Center to the distribution network and loads. Effectiveness of the proposed algorithm was tested on ten bus and thirty four bus systems in a co-simulation environment. In another study [SFBES12] fuzzy MAS based control for voltage regulation in distribution network was proposed. Agent framework comprising on-load tap changer agent, distributed generator agents and load agents was developed.

4 Methodology

4.1 Overview

This chapter presents brief methodological steps and implementation of the proposed methods. First component is modeling. As systems from three domains are involved in the test cases, and it necessary to have tools in which all the three systems can be modeled in detail. Three domains involved are;

- **Power System**
- **Multi-Agent System**
- **Communication System**

A co-simulation approach was used to simulate the system involving the systems from above three domains. In order to analyze the performance Key Performance Indices (KPIs) were formulated for the three systems. Figure 4.1 shows the general diagram for the methodology.

4.2 Modeling

4.2.1 Power System Modeling

Power system for investigation of proposed algorithm were taken from IEEE bench mark test systems. These test systems belong to the medium voltage distribution feeder category. Network from small, medium to large were chosen for investigation and are given below.

1. IEEE 13 node test feeder
2. IEEE 37 node test feeder
3. IEEE 123 node test feeder

These networks were modified and distributed generations were included in the network.

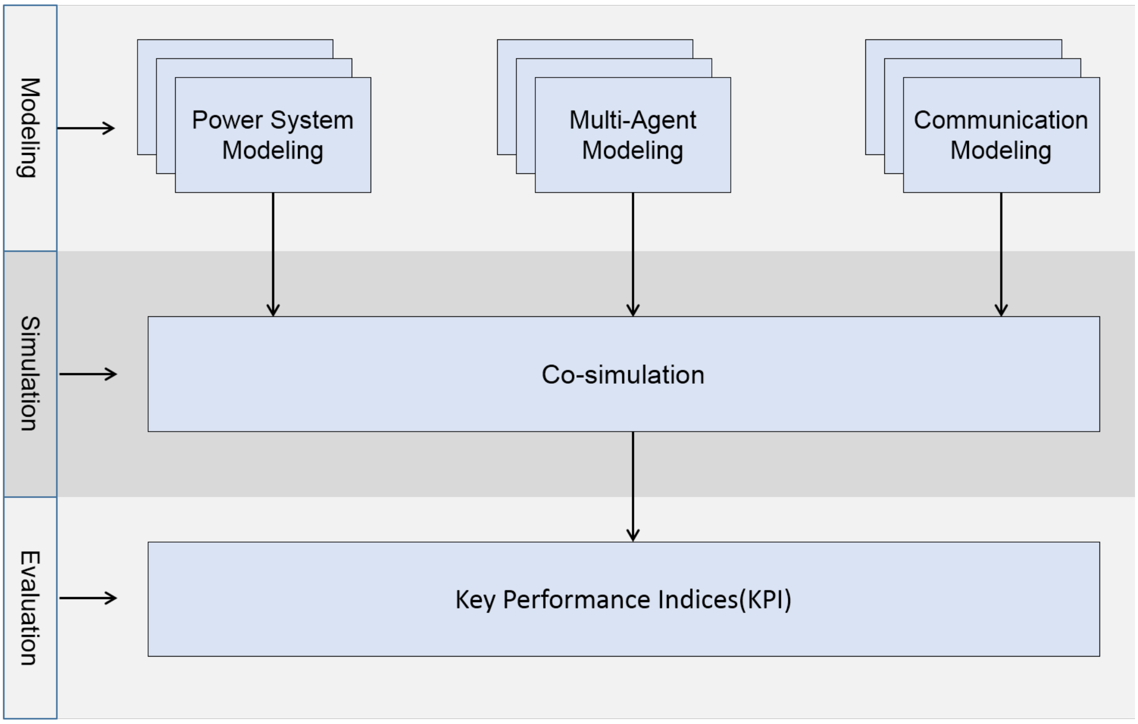

Figure 4.1: General methodology.

4.2.2 Multi-Agent System Modeling

Three MAS based algorithms were developed and analyzed. These algorithms are;

1. Contract-Net-Protocol based Centralized Algorithm
2. Distributed Iterative Algorithm
3. MAS based control for zones

4.2.3 Communication Modeling

Communication modeling was carried out in OMNeT++ - a discrete event simulator. Different network traffic scenarios were generated. Effect of communication and its parameter changes on the algorithm performance was investigated.

4.3 Simulation

Before deployment of a solution extensive simulations are required for analyzing the expected results. This highlights the importance of simulation and methods/tools used for simulation because application of these solutions heavily depend upon the results obtained after simulation. Currently many computer tools are available for power system simulations and one can model power system in detail for the analysis purpose. However, these specialized software tools lack modeling capability of other features of smart grid applications like intelligent control and communication which put the question mark on validation of results, as in case of smart grid applications there is tight coupling between power system, communication and intelligent control. In such cases co-simulation approach seems to be good choice.

4.3.1 Co-simulation

It is already established that co-simulation of domain specific software is a good option for simulating and experimenting cyber-physical systems to have insight into the system behavior and thorough analysis [PWE14] [RNBS12]. Thus a Co-simulation framework was developed to test the proposed MAS based voltage control schemes. Detail of the tools for power system, MAS simulation and communication network simulation are given next.

4.3.2 Power System Tool

DigSILENT PowerFactory was used as a power system simulator. It is a powerful simulator capable of modeling analysis and simulation of complex power system models and scenarios. It provides many methods for coupling with other tools and are discussed in detail in [SSAS13] and [SAST14]. In this work, Python API was used to integrate PowerFactory with other tools as it gives full access and control of all the objects, features and functionalities of PowerFactory.

4.3.3 MAS Environment Tool

Java Agent DEvelopment Framework (JADE) was used as Multi-Agent System modeling and simulation which is free open source JAVA based platform independent software and is distributed by Telecom Italia [BBCP05].It provides a run-time environment to execute agent programs as well as a development framework which aids developers to create agents. JADE has a nice Graphical User Interface (GUI) that support the debugging and deployment phases. It provides agent abstraction along with agent task execution and composition model, peer to peer agent communication based on the asynchronous message passing paradigm. Java sockets were used for coupling of JADE with other tools (power system and communication) for data transfer and sharing. JADE contained *SocketProxyAgent* which can be used to send/receive data/message on multiple sockets in FIPA standard Agent Communication Language (ACL) format. However, it can connect to 50 clients at a time. A custom $interfaceAgent$ class was developed for coupling.

4.3.4 Communication Modeling Tool

OMNeT++ (Objective Modular Network Testbed in C++) is an open-source, modular, extendable and component-based discrete event simulation environment for modeling the communication systems. In the co-simulation framework, the modeling of the communication system is carried out in OMNeT++. Its a widely used simulation tool for the modeling of the communication network and the protocols. A custom OMNeT++ scheduler developed in[SKAS14] was used for interfacing OMNeT++ and running it in real-time.

Figure 4.2 shows the developed co-simulation setup.

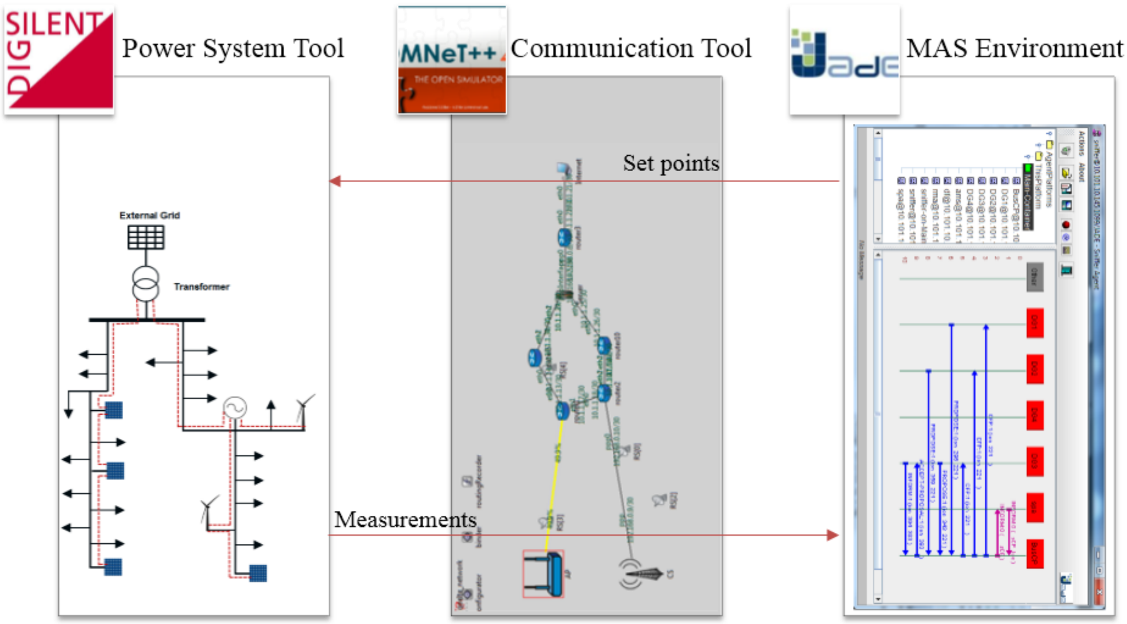

Figure 4.2: Co-simulation framework setup.

4.4 Performance Matrices

Key Performance Indices (KPI) was used in this study for validation of proposed algorithms and & comparison. Three categories of KPIs related to, 1) the power system performance 2) the information exchange and 3) communication network were formulated.

4.4.1 Power System KPI

As main focus of the work is on voltage control, KPIs related to the voltage quality were considered. These KPIs were adopted from the IGREENGrid project co-founded by the European Commission under 7th framework program [161]. [IGr14]. These KPIs have been formulated according to the standard EN 50160 [A+04]. According to this standard, under normal operating conditions;

> *"During each period of one week 95% of the 10 minutes mean RMS values of the supply voltage shall be with in the range of +/-10% of the nominal voltage value for low voltage and medium voltage distribution networks"*

Three aspects of the voltage quality;

1. voltage limits fulfillment
2. voltage variability
3. voltage violations

were considered and respective KPIs are given next.

4.4.1.1 Voltage limit fulfillment

It refers to fulfillment of the limit condition laid down in the standard EN50160. Let
Nominal voltage : V_n
Voltage profile along the time $t := V(t)$
Normalized voltage : $V^*(t) = \frac{V_t}{V_n}$
Change in voltage can be written as

$$\triangle V_n = \mid V^*(t) - V_0 \mid \tag{4.1}$$

Considering $V_0 = 1$, we get

$$\triangle V_n = \mid V^*(t) - 1 \mid \tag{4.2}$$

In order to have assessment of the whole power system performance, node having worst KPI was selected as representative performance indicator.Thus for n node system

$$KPI\ of\ the\ system = min\{KPI_{node-1}, KPI_{node-2}, KPI_{node-3} .... KPI_{node-n}\} \tag{4.3}$$

Further to obtain a single value as an representative quantity 95^{th} percentile of $\triangle V_n$ was used. Normalizing for the assumed voltage limits $\pm 10\%$ we get

$$KPI = 1 - \frac{\triangle V_{n(95per)}}{0.1} \tag{4.4}$$

while

$$KPI \begin{cases} = 1 & \text{voltage equal to the nominal value constantly} \\ \geq 0 & \text{with in the limits} \\ < 0 & \text{out of the limits} \end{cases} \tag{4.5}$$

4.4.1.2 Voltage Variability

It refers to the variation in voltage profile on a particular node/bus during a certain period of time. Further, this variation can also be along the feeder. As voltage profile is effected by the intermittent and variable nature of the DERs, it is important to evaluate and investigate the variability of voltage profile.

- **Variability on a single node along the time** Voltage variation on a single node along the time shows, how much vulnerable is this node to the variability of DERs or load and near to the limits set by the standard EN50160.

- **Variability along the feeder** Variability along the feeder refers to the difference in voltage at a certain time between two consecutive nodes. It indicates the uniformity of the load and generators distribution along the feeder under investigation.

The evaluation of above mentioned variability along the feeder and on the node can be formulated as under; Let Voltage at a node at step n : $V(n)$
Voltage at a node at step $n+1$: $V(n+1)$
difference in voltage : $dV(n)$ then $dV(n) = V(n+1) - V(n)$

This can give the voltage variation speed and non-uniformity of the load and generation along the feeder. RMS value of voltage differential is given below ;

$$dV_{RMS} = \frac{\sqrt{\frac{1}{N-1}\sum_{n=1}^{N-1} dV(n)}}{V_n} \tag{4.6}$$

where
N is the total number of measurements
V_n is the nominal voltage

KPI for voltage variation can be written $KPI = 1 - dV_{RMS}$ while

$$KPI = \begin{cases} 1 & \text{Constant Voltage profile} \\ < 1 & \text{lower value, higer voltage variations} \end{cases} \tag{4.7}$$

4.4.1.3 Voltage Violations

This KPI gives indication about the violations of the voltage limits. These violations can be based on two factors and given below;

- **The duration of abnormal situations**
- **The number of abnormal occurrences**

Let T_v is the total time during which node voltage remains out of the standard limit
N_v is the total number of violations

Both the values can be calculated over some time period. KPI for voltage violation can be obtained by using the base case (reference case) and is given below and equation 4.8 shows time based voltage violation KPI, while 4.9 shows amount based voltage violation KPI.

$$KPI = \frac{T_{v(base)} - T_{v(proposedsolution)}}{T_{v(base)}} \tag{4.8}$$

$$KPI = \frac{N_{v(base)} - N_{v(proposedsolution)}}{N_{v(base)}} \tag{4.9}$$

4.4.2 Information Exchange

One of the objective of using the distributed and decentralized control is to minimize the information exchange and flow in the network. For this purpose two types of KPI were formulated and given below.

4.4.2.1 Message Efficiency

It refers to the effectiveness of the information exchange during control action. Higher value of message efficiency means, higher information is related to the computation and lower information for other purpose i.e. synchronization, agent discovery etc. This KPI basically evaluates the information exchange in centralized and distributed algorithms. Let, total number of messages exchanged by agents to compute the algorithm are T_{msg} and number of messages exchanged for synchronization, agent discovery, unused (means message which does not have any effect on algorithm computation) etc. are $T_{msg-extra}$ then message efficiency can be written as given below;

$$M_{efficiency} = \frac{T_{msg} - T_{msg-overhead}}{T_{msg}} \tag{4.10}$$

4.4.2.2 Amount of Information

This is simple measure of information exchange between agents and represents the total number of messages exchanged in an algorithm. Let, total number of messages exchanged in case A are $T_{msg}(A)$ while total number of messages exchanged in case B are $T_{msg}(B)$ Then Information KPI can be written as;

$$KPI = \frac{T_{msg}(A) - T_{msg}(B)}{T_{msg}(A)} \tag{4.11}$$

4.4.3 Communication

In order to evaluate the effect of change in communication network and parameters on performance of algorithm different network scenarios were evaluated. If we consider voltage KPI considering ideal communication as $V_{KPI}(ideal)$ and voltage KPI considering communication scenario as $V_{KPI}(comm)$ then KPI can be written as given below;

$$KPI = \frac{V_{KPI}(ideal) - V_{KPI}(comm)}{V_{KPI}(ideal)} \tag{4.12}$$

5 MAS based Decentralized and Centralized Control

This chapter presents MAS based control of distributed generation for voltage support in power distribution network. In conventional distribution feeder LTC or VR placed at the substation is used to control the voltage. The objective of voltage regulation is to maintain voltage at all the buses in the system within "normal" limits, which is $+/-5\%$ of the rated voltage. In conventional feeder, voltage drop on the feeder mainly depends on the load level and by measuring the total load current at the substation enables the voltage regulator to estimate and compensate the voltage drop by adjusting the voltage at the substation end.

However, introduction of Distributed Generation in a distribution feeder affects the voltage profile. This impact mainly depends on the type of DG, amount of power DG supply back to the system and its location in the feeder. Thus when multiple DGs are present in a distribution feeder and supply a considerable part of the load, it becomes difficult for the voltage regulator to use the local current measurements to estimate the accurate voltage drop. Also, sudden disconnection of a DG can result in low voltage limit violation and this voltage condition may cause other DGs to be disconnected by their under-voltage relays. It is mainly because a voltage regulator is a slow acting device (can take more than 5s to move one tap position and corresponds to about 5/8% voltage change). On the other side the DGs use under-voltage/over voltage protection schemes and are quite sensitive to voltage sags. These protection schemes are usually fast and if voltage level is more than $+/-10\%$, can trip the DG with in 2 sec. Thus voltage regulator alone cannot provide quick voltage support to restore voltage after a sudden disconnection of DG.

Therefore voltage regulation provided by the LTC needs to be improved for the facilitation of DG integration in distribution network. For this purpose we need a communication link between voltage regulator and DGs, which will enable voltage regulator to collect data from the DGs to estimate voltage across the feeder and allow DGs to provide voltage support. DGs, through proper control of power electronics can be used to provide reactive power support during emergency conditions. The DGs are usually equipped with their own control (local control) to control active and reactive power output. By using these capabilities, a distributed control scheme for voltage regulation using Multi-agent system is proposed in this paper. MAS become a good choice for such kind of problem as local controllers on the regulators and DGs can be improved by the agents that can act as supervisory controllers.

5.1 Decentralized Control

5.1.1 Voltage Variation in Conventional Distribution Network

Mostly conventional distribution networks are modeled as a passive networks having radial configuration. The flow of real power P and reactive power Q is unidirectional and from higher voltage to the lower voltage levels. This voltage variation (drop) can be analyzed as given in figure 5.1 a.

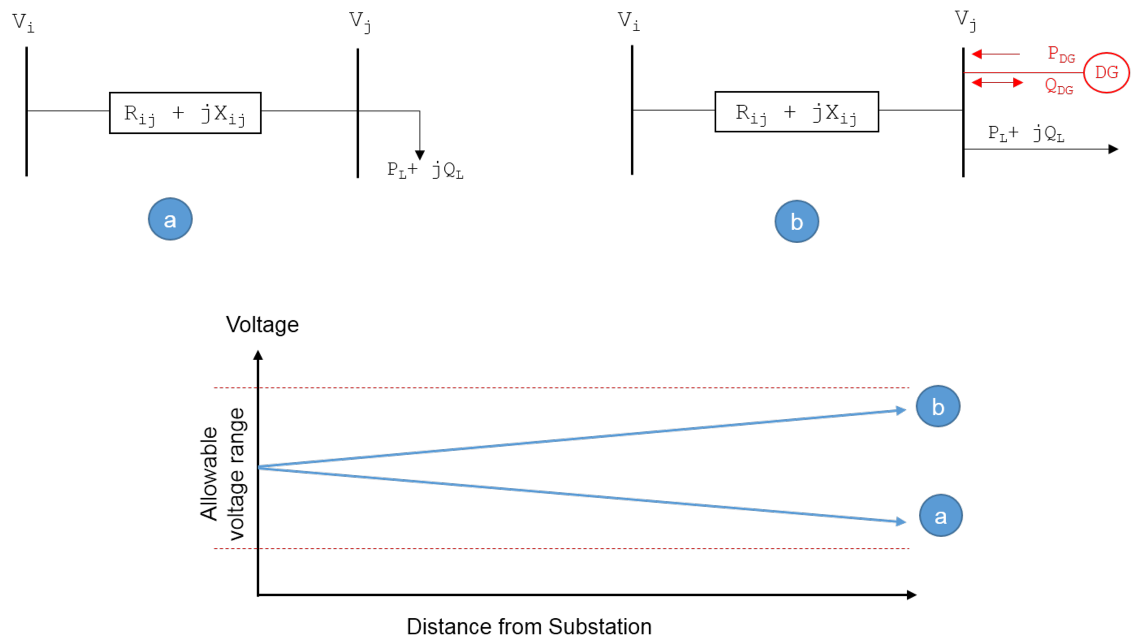

Figure 5.1: Change in voltage with and without DG in a network. a) Shows with out DG, only low voltage is possible in the down stream bus b) Shows, with the presence of DG, voltage can be high in the downstream bus.

In figure 5.1 a, V_i is the voltage at bus i, which is at higher level, while V_j is the voltage at the bus j, which is at lower voltage level. Further, V_i can be considered as the sending voltage and V_j as receiving voltage. P_{ij} and Q_{ij} are the real and reactive powers flowing from bus i to bus j. P_L and Q_L are the real and reactive power loads. The voltage at the bus i is given as

$$V_i = V_j + I(R + jX) \tag{5.1}$$

where I is the current flowing through the line. The power flowing through the line can be written as

$$P_{ij} + jQ_{ij} = V_i I \tag{5.2}$$

Hence, current through the line can be written as

$$I = \frac{P_{ij} - jQ_{ij}}{V_i} \tag{5.3}$$

Using value of I, voltage at the bus i, which is sending end voltage can be written as;

$$V_i = V_j + \frac{P_{ij} - jQ_{ij}}{V_i}(R_{ij} + jX_{ij}) \tag{5.4}$$

$$V_i = V_j + \frac{P_{ij}R_{ij} + P_{ij}jX_{ij} - jQ_{ij}R_{ij} - jQ_{ij}jX_{ij}}{V_i} \tag{5.5}$$

$$V_i = V_j + \frac{P_{ij}R_{ij} + Q_{ij}X_{ij}}{V_i} + j\frac{P_{ij}X_{ij} - Q_{ij}R_{ij}}{V_i} \tag{5.6}$$

Now, change in voltage between bus i,sending point, and bus j, receiving end, can be written as;

$$\Delta V_{ij} = V_i - V_j = \frac{P_{ij}R_{ij} + Q_{ij}X_{ij}}{V_i} + j\frac{P_{ij}X_{ij} - Q_{ij}R_{ij}}{V_i} \tag{5.7}$$

If the angle between bus i and bus j is very small, imaginary part of the Equation 5.7 can be neglected. Further, taking bus i as reference bus with angle =0, the equation 5.7 can be approximated as;

$$\Delta V_{ij} \approx \frac{P_{ij}R_{ij} + Q_{ij}X_{ij}}{V_i} \tag{5.8}$$

Thus Equation 5.8 gives change in voltage (V_{ij}) between i^{th} and j^{th} bus. Where, X_{ij} is the reactance between bus i and j, V_i voltage at bus i.

5.1.2 Voltage change in distribution network with Distributed Generation

When distributed generations are connected to the distribution network, power flow and voltage profiles are affected and the system does not remain passive and becomes active. In active distribution networks due to distributed generation power flow can be bidirectional, which means reverse power flow can happen. When a DG is connected in distribution network and injects active power at a certain bus, the voltage of that bus can be raised. Further, in order to inject power in the grid distributed generator is likely to operate at a higher voltage as compared to the other buses where it supply power. This can be represented by the two bus model as shown in figure 5.1 b. Because power flow direction is reversed, according to equation 5.8, we can write voltage at bus j as under;

$$V_j = V_i + \frac{P_{ij}R_{ij} + Q_{ij}X_{ij}}{V_j} \tag{5.9}$$

Thus, in case of distributed generation connected in the bus j, it will raise the voltage at bus j, which is clarified in figure 5.1 b. A distributed generator is connected at bus j with P_{DG} generator active power and Q_{DG} generator reactive power. While P_L and Q_L are active power and reactive power demands, respectively. Voltage rise in this case can be written as;

$$\Delta V = V_j - V_i \approx \frac{P_{ij}R_{ij} + Q_{ij}X_{ij}}{V_j} \tag{5.10}$$

where
$P_{ij} = P_G - P_L$

$Q_{ij} = \pm Q_G - Q_L$
substituting the values of P_{ij} and Q_{ij} in equation 5.10, we get

$$\Delta V = V_j - V_i \approx \frac{R_{ij}(P_G - P_L) + X_{ij}(\pm Q_G - Q_L)}{V_j} \tag{5.11}$$

If active power of the DG unit increases the term $P_G - P_L$ increases and voltage variation will be increased which means V_j is greater than V_i. Thus active power injection of DG can result in voltage rise problem and this is more likely to happen when the x/r ratio is low. Further, it is obvious that voltage variation depends upon active and reactive power injection of DG unit, demand of loads and line impedances. As DG active and reactive power injection (especially wind and PV) and load both vary through out the day, voltage rise and voltage drop problems can be occurred. Further, if there is any shunt compensator connected at point of DG connection having reactive power Q_C, the equation 5.11 can be written as;

$$\Delta V = V_j - V_i \approx \frac{R_{ij}(P_G - P_L) + X_{ij}(\pm Q_C \pm Q_G - Q_L)}{V_j} \tag{5.12}$$

5.1.3 Voltage variation scenarios with distributed generation

As discussed earlier, presence of distributed generation in distribution network have effect on voltage profile of distribution network. Re-arranging the equation 5.12 and expressing V_j in terms of per unit to observe the effects of distributed generation, we get;

$$P_G \approx \frac{V_j - V_i + R_{ij}P_L - X_{ij}(\pm Q_C \pm Q_G - Q_L)}{R_{ij}} \tag{5.13}$$

From equation 5.13, we can observe that amount of distributed generation that can be connected to the distribution network depends upon the following factors;

- Voltage at the primary bus (sending end, V_i)
- Voltage at end bus (receiving end, V_j)
- conductor size and distance from the primary bus (R and X)
- load demand and other generation in the system (P_L)

Worst case operation scenario can be demonstrated to analyze the effect of distributed generation on voltage variation so that customers will not be effected. These general scenarios are;

- minimum load maximum generation (P_{L-min}, P_{Gmax})
- maximum load minimum generation (P_{L-max}, P_{Gmin})
- maximum load maximum generation (P_{L-max}, P_{Gmax})

By using equation 5.13, we can describe the worst case scenario. For maximum generation and minimum load we can have; $P_L = P_{Lmin}0$, $Q_{Lmin} = 0$ and $P_G = P_{Gmax}$ and in case of unity power factor $\pm Q_G = 0$ and $\pm Q_C = 0$. Substituting these values in equation 5.13, we get;

$$\Delta V_{ji-worst} = V_{jmax} - V_i \approx R_{ij}P_{Gmax} \tag{5.14}$$

If the system is not operating on unity power factor, then $\pm Q_G \neq 0$ and $\pm Q_C \neq 0$, substituting these values in equation 5.14, we get;

$$\Delta V_{ji-worst} \approx R_{ij}P_{Gmax} + X_{ij}(\pm Q_{Gmax} \pm Q_C) \tag{5.15}$$

From equation 5.15, it can be observed that change in voltage can be decreased if second term on the right hand side has some smaller value or negative value. This generally happens when reactive power is injected or absorbed from the network. Thus, voltage in a distribution network can be controlled using reactive power compensation by the distributed generation or other reactive power sources.

5.1.4 Voltage Control Using Reactive Power Compensation

As explained in previous section reactive power compensation can be used for voltage control of distribution network. Traditionally, capacitor banks are used to compensate voltage drop in distribution network. However, in distribution network having DGs, both the voltage drop and voltage rise problem can occur and must be addressed. One way of voltage control is to use reactive power capability of DG. DG can be used to absorb or inject reactive power into the system for voltage regulation.

5.1.5 Problem formulation

The standard EN 50160 gives requirements for many voltage parameters with allowable variation at the customer's connection in low voltage and medium voltage electricity distribution network in normal operating conditions. According to this standard, voltage magnitude variations can be up to ±10% for 95% time of the week. Thus in order to ensure the desired voltage profile in distribution network, reactive power can be used to control the voltage. Distribution networks having distributed generators capable of providing reactive power support can be used for reactive power dispatch. Thus, if voltage at a certain bus goes out of permissible limit, voltage control problem can be translated into optimal reactive power dispatch by the distributed generators. Thus we can write;

- **Objective Function:**

  $$Minf(Q) = Q_1 + Q_2 + Q_3 + ...Q_n = \sum_{i=1}^{m}(Q_i) \tag{5.16}$$

  where Q is the reactive power for distributed generator $i = 1...n$

- **Constraints:**

- **Line flow constraints:** Thermal limits of lines
$$S_{Li} \leq S_{Li}^{max}$$
where $i = 1, 2, 3, ...,$ total number of lines
- **Bus Voltage Magnitude:** Limits on the bus voltage according to the standard EN-50160.
$$V_i^{min} \leq V_i \leq V_i^{max}$$
where $i = 1, 2, 3, ...,$ total number of buses
- **Generation Reactive Power Constraints:** Generator reactive power out put constraints (lower and upper limits of Q)
$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max}$$
where $i = 1, 2, 3, ...,$ total number of generators
- **Generator Power factor constraints:** Upper and lower limits of power factor limits for a generator
$$pf_{Gi}^{min} \leq pf_{Gi} \leq pf_{Gi}^{max}$$
where $i = 1, 2, 3, ...,$ total number of generators

The objective function can be modified to include additional objectives i.e. power loss minimization. However, it was not included in the used formulation since objective of the study is to improve voltage profile fulfilling all the network technical and regulation constraints using distributed generation and exhibit cooperation and coordination between these generators (agents). Further, Other reactive power sources i.e. shunt capacitors in the network can also be included in the objective function and priority can be given to the desired equipment, distributed generator, shunt capacitor, etc. In case of tap change transformers, minimization of tap operations can also be included in objective function with constraints on the maximum and minimum number of taps. Active power generation curtailment is also a way to control voltage for voltage raise problems. These additional constraints are given below ;

- **Limits on number of transformer tap:**
$$TAP_{min} \leq Tap^t \leq TAP_{max}$$
where t is any time instant

- **Limit on capacitors steps:**
$$C_{i-step}^{min} \leq C_{i-step} \leq C_{i-step}^{max}$$

- **Maximum number of permissible tap operations in a fixed time period:** (i.e. daily or weekly)
$$\sum_{t=1}^{Nt-1} \left|TAP^{t+1} - TAP^t\right| \leq N_{TAP-Operation}^{max}$$
where Nt is total time

- **Maximum number of permissible capacitor switching in a fixed time period:** (i.e. daily or weekly)
$$\sum_{t=1}^{Nt-1} \left|C_{i-step}^{t+1} - C_{i-step}^{t}\right| \leq N_{C-Operation}^{max}$$

5.1.6 Voltage Sensitivity based approach for reactive power dispatch

In the above section cost of dispatch in objective function is the total amount of reactive power required from all distributed generators. As mentioned earlier the other equipment is not included in the objective function as support by distributed generators is much faster than the voltage regulator response to an emergency situation and it is assumed that voltage regulator setting remains unchanged. The decision on value of Q, reactive power, can be made on the basis of voltage sensitivity of the bus with respect to the change in reactive power. These voltage sensitivities can be calculated using load flow Jacobian matrix and given next.

5.1.6.1 Voltage Sensitivity calculation

Let us consider a distribution network comprising $n+1$ buses. At a certain time instant t, the magnitude of voltage and angle at bus i can be denoted as $V_i[t]$ and $\vartheta_i[t]$, respectively. Considering, bus $i=0$ as a slack bus which is infinite source then we can say that voltage and angle at bus $i=0$ will remain the same for all the time $t = 0, 1, 2, 3.....$ All the other buses are taken as PQ buses. We can write vector for buses voltage magnitude and angle:

$$V[t] = \begin{bmatrix} V_1[t] \\ V_2[t] \\ V_3[t] \\ . \\ . \\ . \\ V_n[t] \end{bmatrix}, \ \vartheta[t] = \begin{bmatrix} \vartheta_1[t] \\ \vartheta_2[t] \\ \vartheta_3[t] \\ . \\ . \\ . \\ \vartheta_n[t] \end{bmatrix}$$

where i is bus number and bus $i=0$ is excluded from the vector as voltage at this bus will remain same for all the time.

Consider $P_i[t]$ and $Q_i[t]$ are the injections of active and reactive power at the bus i. Corresponding vector at all the PQ buses can be written as;

$$P[t] = \begin{bmatrix} P_1[t] \\ P_2[t] \\ P_3[t] \\ . \\ . \\ . \\ P_n[t] \end{bmatrix}, \ Q[t] = \begin{bmatrix} Q_1[t] \\ Q_2[t] \\ Q_3[t] \\ . \\ . \\ . \\ Q_n[t] \end{bmatrix}$$

Change in voltage magnitude and angle over a small period of time t to $t+1$ can be defined as;

$$\Delta V[t] = V[t+1] - V[t], \ \Delta\vartheta[t] = \vartheta[t+1] - \vartheta[t]$$

And similarly variations in active and reactive power injections over a small period of time t to $t+1$ can be written as;

$$\Delta P[t] = P[t+1] - P[t], \ \Delta Q[t] = Q[t+1] - Q[t]$$

Now the matrix of partial derivatives can be written as under

$$\begin{bmatrix} \Delta P_1[t] \\ \vdots \\ \Delta P_n[t] \\ - \\ \Delta Q_1[t] \\ \vdots \\ \Delta Q_n[t] \end{bmatrix} = \begin{bmatrix} \frac{\delta P_1[t]}{\delta \vartheta_1} & \cdots & \frac{\delta P_1[t]}{\delta \vartheta_n} & | & \frac{\delta P_1[t]}{\delta |V_1|} & \cdots & \frac{\delta P_1[t]}{\delta |V_n|} \\ \vdots & \ddots & \vdots & | & \vdots & \ddots & \vdots \\ \frac{\delta P_n[t]}{\delta \vartheta_1} & \cdots & \frac{\delta P_n[t]}{\delta \vartheta_n} & | & \frac{\delta P_n[t]}{\delta |V_1|} & \cdots & \frac{\delta P_n[t]}{\delta |V_n|} \\ - & - & - & - & - & - & - \\ \frac{\delta Q_1[t]}{\delta \vartheta_1} & \cdots & \frac{\delta Q_1[t]}{\delta \vartheta_n} & | & \frac{\delta Q_1[t]}{\delta |V_1|} & \cdots & \frac{\delta Q_n[t]}{\delta |V_n|} \\ \vdots & \ddots & \vdots & | & \vdots & \ddots & \vdots \\ \frac{\delta Q_n[t]}{\delta \vartheta_1} & \cdots & \frac{\delta Q_n[t]}{\delta \vartheta_n} & | & \frac{\delta Q_n[t]}{\delta |V_1|} & \cdots & \frac{\delta Q_n[t]}{\delta |V_n|} \end{bmatrix} = \begin{bmatrix} \Delta \vartheta_1[t] \\ \vdots \\ \Delta \vartheta_n[t] \\ - \\ \Delta V_1[t] \\ \vdots \\ \Delta V_n[t] \end{bmatrix}$$

By substituting

$$H = \begin{bmatrix} \frac{\delta P_1[t]}{\delta \vartheta_1} & \cdots & \frac{\delta P_1[t]}{\delta \vartheta_n} \\ \vdots & \ddots & \vdots \\ \frac{\delta P_n[t]}{\delta \vartheta_1} & \cdots & \frac{\delta P_n[t]}{\delta \vartheta_n} \end{bmatrix}, N = \begin{bmatrix} \frac{\delta P_1[t]}{\delta |V_1|} & \cdots & \frac{\delta P_1[t]}{\delta |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\delta P_n[t]}{\delta |V_1|} & \cdots & \frac{\delta P_n[t]}{\delta |V_n|} \end{bmatrix}, K = \begin{bmatrix} \frac{\delta Q_1[t]}{\delta \vartheta_1} & \cdots & \frac{\delta Q_1[t]}{\delta \vartheta_n} \\ \vdots & \ddots & \vdots \\ \frac{\delta Q_n[t]}{\delta \vartheta_1} & \cdots & \frac{\delta Q_n[t]}{\delta \vartheta_n} \end{bmatrix}, L = \begin{bmatrix} \frac{\delta Q_1[t]}{\delta |V_1|} & \cdots & \frac{\delta Q_n[t]}{\delta |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\delta Q_n[t]}{\delta |V_1|} & \cdots & \frac{\delta Q_n[t]}{\delta |V_n|} \end{bmatrix}$$

we get

$$\begin{bmatrix} \Delta P[t] \\ \Delta Q[t] \end{bmatrix} = \begin{bmatrix} H & N \\ K & L \end{bmatrix} \begin{bmatrix} \Delta \vartheta[t] \\ \Delta V[t] \end{bmatrix} \tag{5.17}$$

For decoupling voltage and angle, there is a standard assumption that values H,L are much greater than the values of N,K. This assumption holds true transmission systems. This is due to the fact that ratio of reactance to the resistance of lines in transmission system is large ($x >> r$), which is commonly described as "x/r" ratio. From this assumption we can say that bus voltage angle is effected by the variation in active power injection, while changes in reactive power have direct effect on bus voltage magnitude. However, in distribution network, this assumption is not true since x/r ratio is lower in distribution network. While in low voltage network this ratio is much lower. Thus bus voltages in distribution network is much sensitive to the injection of active power. In the above formulation ΔP is considered changes in active power injection due to the variable distributed generation i.e. wind and PV, and this also affects the bus voltage magnitude. This voltage variation can be minimized by controlling Q injection in the network, thus Q is considered to be the control variable. In order to find the effect of changes in reactive power on bus voltage magnitude, from equation 5.17 we can write;

$$\begin{bmatrix} \Delta \vartheta[t] \\ \Delta V[t] \end{bmatrix} = \begin{bmatrix} H & N \\ K & L \end{bmatrix}^{-1} \begin{bmatrix} \Delta P[t] \\ \Delta Q[t] \end{bmatrix} \tag{5.18}$$

$$\begin{bmatrix} \Delta \vartheta[t] \\ \Delta V[t] \end{bmatrix} = \frac{1}{(HL - KN)} \begin{bmatrix} L & -N \\ -K & H \end{bmatrix} \begin{bmatrix} \Delta P[t] \\ \Delta Q[t] \end{bmatrix} \tag{5.19}$$

As we are interested to find voltage variation with respect to change in reactive power, separating ΔV, from equation 5.19, we get

$$\Delta V[t] = \frac{1}{(HL - KN)}(H\Delta Q[t] - K\Delta P[t]) \tag{5.20}$$

$$\Delta V[t](HL - KN) = H\Delta Q[t] - K\Delta P[t]$$

$$HL\Delta V[t] - KN\Delta V[t] = H\Delta Q[t] - K\Delta P[t]$$

Assuming H is invertible, we can write

$$L\Delta V[t] - \frac{KN}{H}\Delta V[t] = \Delta Q[t] - H^{-1}K\Delta P[t]$$
$$(L - \frac{KN}{H})\Delta V[t] = \Delta Q[t] - H^{-1}K\Delta P[t]$$
$$(L - \frac{KN}{H})\Delta V[t] = \Delta Q[t] - H^{-1}K\Delta P[t]$$
$$\Delta V[t] = \frac{1}{(L - H^{-1}KN)}(\Delta Q[t] - H^{-1}K\Delta P[t])$$
$$\Delta V[t] = (L - H^{-1}KN)^{-1}(\Delta Q[t] - H^{-1}K\Delta P[t])$$
$$\Delta V[t] = (L - H^{-1}KN)^{-1}\Delta Q[t] - (L - H^{-1}KN)^{-1}H^{-1}K\Delta P[t] \tag{5.21}$$
$$\Delta V[t] = S\Delta Q[t] - \epsilon[t] \tag{5.22}$$

where $S = (L - H^{-1}KN)^{-1}$ and $\epsilon[t] = (L - H^{-1}KN)^{-1}H^{-1}K\Delta P[t]$ and this $\epsilon[t]$ gives effect of active power injection on voltage magnitude of a bus in a time instant t. By rewriting equation 5.22, we can describe how voltage change in the next time instant and is given below;

$$V[t+1] - V[t] = S\Delta Q[t] - \epsilon[t]$$
$$V[t+1] = V[t] + S\Delta Q[t] - \epsilon[t] \tag{5.23}$$

Equation 5.23 shows voltage at the next time step $t+1$. Generally, for a fixed configuration of the network, value of S with time t for a range of operating conditions are small [BV].

5.2 Multi Agents Modeling and Control

This section provides detail of the MAS modeling and voltage control scheme using reactive power dispatch based on voltage sensitivity approach explained in the previous section.

5.2.1 Agent Based Decentralized Control

As explained in the literature review MAS has great potential for use in power system, which is a step forward towards decentralization and autonomy of electric grid. Agent based technology provides an alternative approach for smooth transition of present distribution grid to the smart distribution grid. Major justifications can be:

- Due to the increase complexity and size of the distribution grid, there is need of distributed intelligence and some local solutions, such problems can be tackled by the agent based approach.
- Agent based modeling and simulation can be used to test the smart grid design concepts which are related to operation and communication.
- Decentralization, autonomy and active distribution management are the most important features for the smooth modernization of present distribution grid. Any system developed under agent-oriented philosophies contains all the three above mentioned properties, making it a best choice. Also properly modeled agent-based systems can result in flexible, scalable and robust systems.

Figure 5.2, shows abstract architecture of an agent based on Belief Desire Intention (BDI).

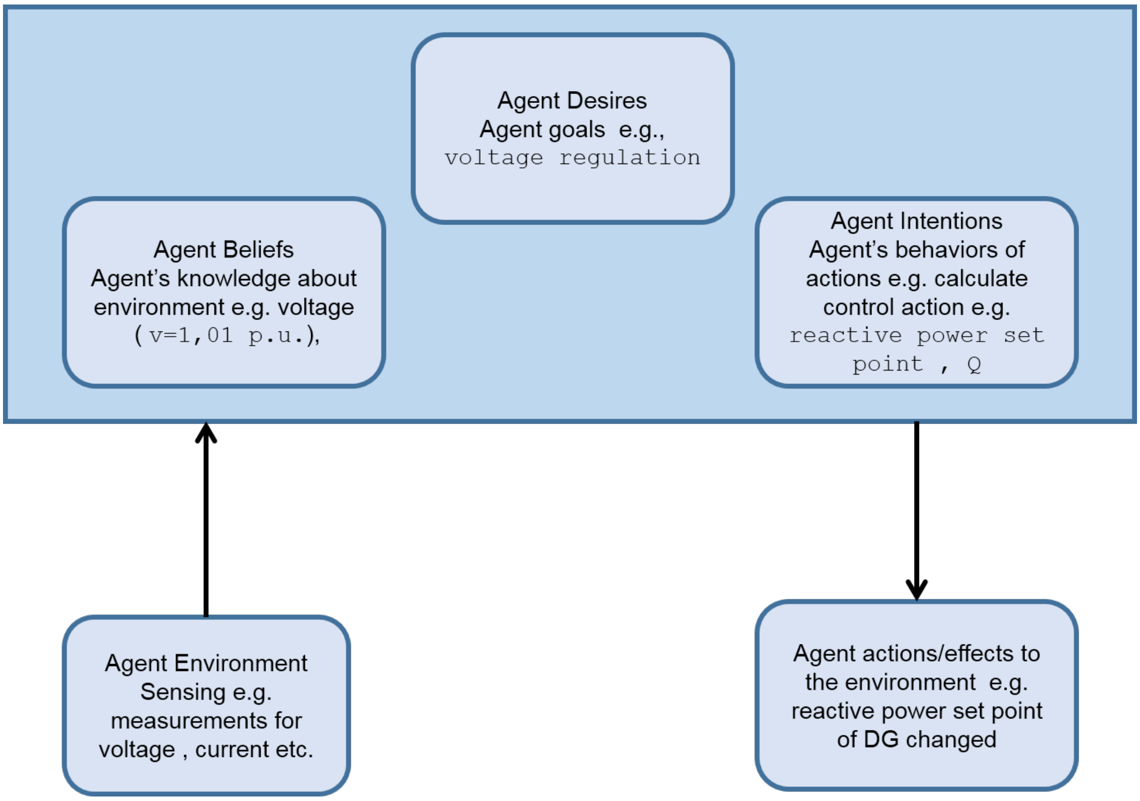

Figure 5.2: Abstract agent architecture based on Belief Desire Intention.

5.2.2 Agent classification and definition

Agents can have various characteristics based on the different classification. Details of agent characteristics and classification are given in chapter 2. In order to investigate decentralized control using agents following agents were defined;

- **DG Agent:** *DGAgent* corresponds to the distributed generator in the power distribution network. Although type for the *DGAgents* can also be defined on the basis of capability of reactive power injection and absorption. However, in this work it is assumed that distributed generator can be any generation source capable of injecting/absorbing reactive power from the network i.e. inverter interfaced wind and PV sources. Characteristics of *DGAgent* are given in table 5.1.

- **Bus Agent:** *BusAgent* corresponds to the buses in the network at which voltage magnitude is required to be under permissible limits. In pure decentralized control there will not be any communication between *BusAgent* and *DGAgent*. *BusAgent* will only act as monitoring agent and will be used in coordinated control approach.

Figure 5.3, shows all the *DGAgent* connected to the network, work independently and try to regulate the voltage at the point of common coupling.

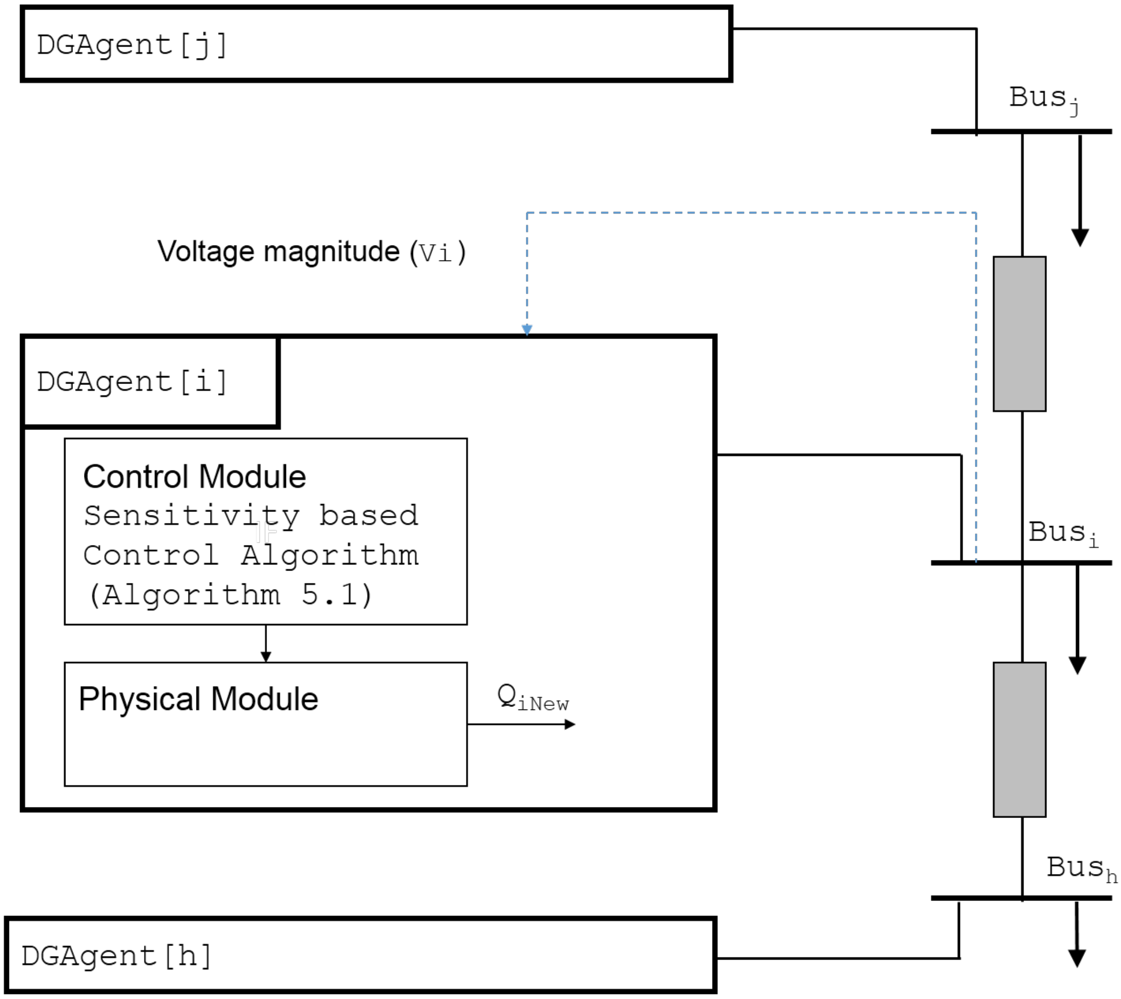

Figure 5.3: Working of *DGAgents* in a network.

Table 5.1: Characteristics of a *DGAgent*.

Property	Description
Reactive	*DGAgent* reacts to any change in voltage V at point of connections with the network
Autonomous	*DGAgent* has control over its own action.
Temporally continuous	*DGAgent* acts as a continuously running process
Non-communicative	*DGAgent* does not communicate with the other agents in the network.

Algorithm 5.1: *DGAgent*$[i]$ algorithm for decision of new reactive power, Q_{DGi}^{New} set-point

Result: Q_{DGi}^{New}
initialization:
DG Reactive power $Q_{DGi} = Q_{DGi}^{Current}$, Bus Voltage Sensitivity S_i, Bus Voltage Limits: upper limit V_i^{Upper}, lower limit V_i^{Upper} Change in voltage: $\Delta V_i = 0$ DG Reactive power limits: Upper limit, Q_{DGi}^{max}, lower limit Q_{DGi}^{min} ;

```
if V_i > V_i^Upper then
    ΔV_i = V_i^Upper − V_i;
    ΔQ = ΔV_i / S_i;
    Q_DGi^New = Q_DGi − ΔQ ;
    if Q_DGi^New < Q_DGi^min then
        Q_DGi^New = Q_DGi^min, return Q_DGi^New
    else
        return Q_DGi^New
    end
end
if V_i < V_i^Lower then
    ΔV_i = V_i^Lower − V_i;
    ΔQ = ΔV_i / S_i;
    Q_DGi^New = Q_DGi + ΔQ ;
    if Q_DGi^New > Q_DGi^max then
        Q_DGi^New = Q_DGi^max, return Q_DGi^New
    else
        return Q_DGi^New
    end
else
    Q_DGi^New = Q_DGi, return Q_DGi^New
end
```

5.2.3 Control Algorithm

DGAgent's decision making is carried out using the algorithm based on voltage sensitivity of the bus with variation of reactive power. This algorithm is based on the rule in which $DGAgent_i$ continuously monitor the voltage V_i at the terminal bus i. If voltage V_i goes out of the limits defined by the regulation standard, *DGAgent* calculates the new value of reactive power, Q_{DGi}. However, if the desired voltage increase or decrease is not possible then reactive power Q is set to the minimum or maximum reactive power (Q_{min} or Q_{max}). Further, these constraints on the reactive power are defined in a way that power factor of the generator remains under allowable limits of leading or lagging power factor. However, if active power of the generator is variable then, it will also effect the minimum and maximum reactive power which is needed to have power factor within limits. In this case Q_{min} and Q_{max} can be updated dynamically. It is pertinent to mention that there will also be a small change in sensitivity S with different operating conditions. However, it is generally small enough to ignore. One way to over come this issue is to update sensitivity dynamically.

5.3 Contract Net Protocol based voltage control

Algorithm presented in previous section does not require any communication infrastructure as no communication between agents required. However, with this approach some time, it might not be possible to bring the bus voltage magnitude within the required band due to the constraints on reactive power. Thus a centralized strategy in which information of the network is gathered and decision making is done centrally becomes a possible solution. For this strategy, communication infrastructure is required so that agents can communicate with a central node/agent.

5.3.1 Agent Classification and Definition

Following agents are defined for centralized control strategy;

- **DG Agent:** *DGAgent* represents distributed generator as in the case of decentralized approach. However this *DGAgent* has some additional and different properties than agents in decentralized strategy.
- **Monitor Agent:** *MonitorAgent* represents bus in the network. It continuously monitor the bus voltage magnitude. If, there is any violation in voltage limits at the bus, it starts process of voltage regulation.
- **Control Agent:** *ControlAgent* is responsible for decision making and coordinating with other agents in the network.

Table 5.2 shows the type of agents and their intended properties.

Table 5.2: Characteristics and types of agents in centralized control strategy.

Agent	Property	Description
DGAgent	Responsive	*DGAgent* responds to any message received from other agents in the network.
	Passive	*DGAgent* takes commands from other agents for action.
	Communicative	*DGAgent* can communicate with the other agents in the network.
MonitoringAgent	Reactive	*MonitoringAgent* reacts to any change in voltage V at point of connections with the network.
	Temporally continuous	*MonitoringAgent* acts as a continuously running process.
ControlAgent	Communicative	*ControlAgent* communicates with other agents in the network.
	Decision Making	Decision making is carried out by the *ControlAgent*.

5.3.2 FIPA Contract Net Protocol for agent Communication

One of the challenging task in designing multi-agent system is to develop a strategy that how agents will communicate and cooperate with each other. Usually a plan is formulated that specifies the actions required by the agents to achieve their goals. FIPA (Foundation for Intelligent Physical Agents) specifies Contract-Net-Protocol (CNP) which is mostly used to make a plan for agent interaction. In this protocol, one agent acts as a manager which initiates the process to accomplish a task and is named as initiator agent. The task is required to be performed by the other agents (participants). This task can be of any nature i.e. optimization of a certain variable, resource allocation, fair distribution etc. In this protocol, for a given task any agent can participate and respond with a proposal or it can refuse. Decision is made by the manager agent through negotiations with the participants and can accept or reject the proposal [165]. Agent interaction is given in figure 5.4.

5.3.3 Contract Net Protocol based reactive power dispatch

A CNP based plan for agent interaction was designed to determine the reactive power dispatch by the each distributed generator. Agent interaction and decision making algorithms for *MonitoringAgent*, *ControlAgent* and *DGAgent* are given in algorithm 5.2, 5.3 and 5.4, respectively. These algorithms are explained below.

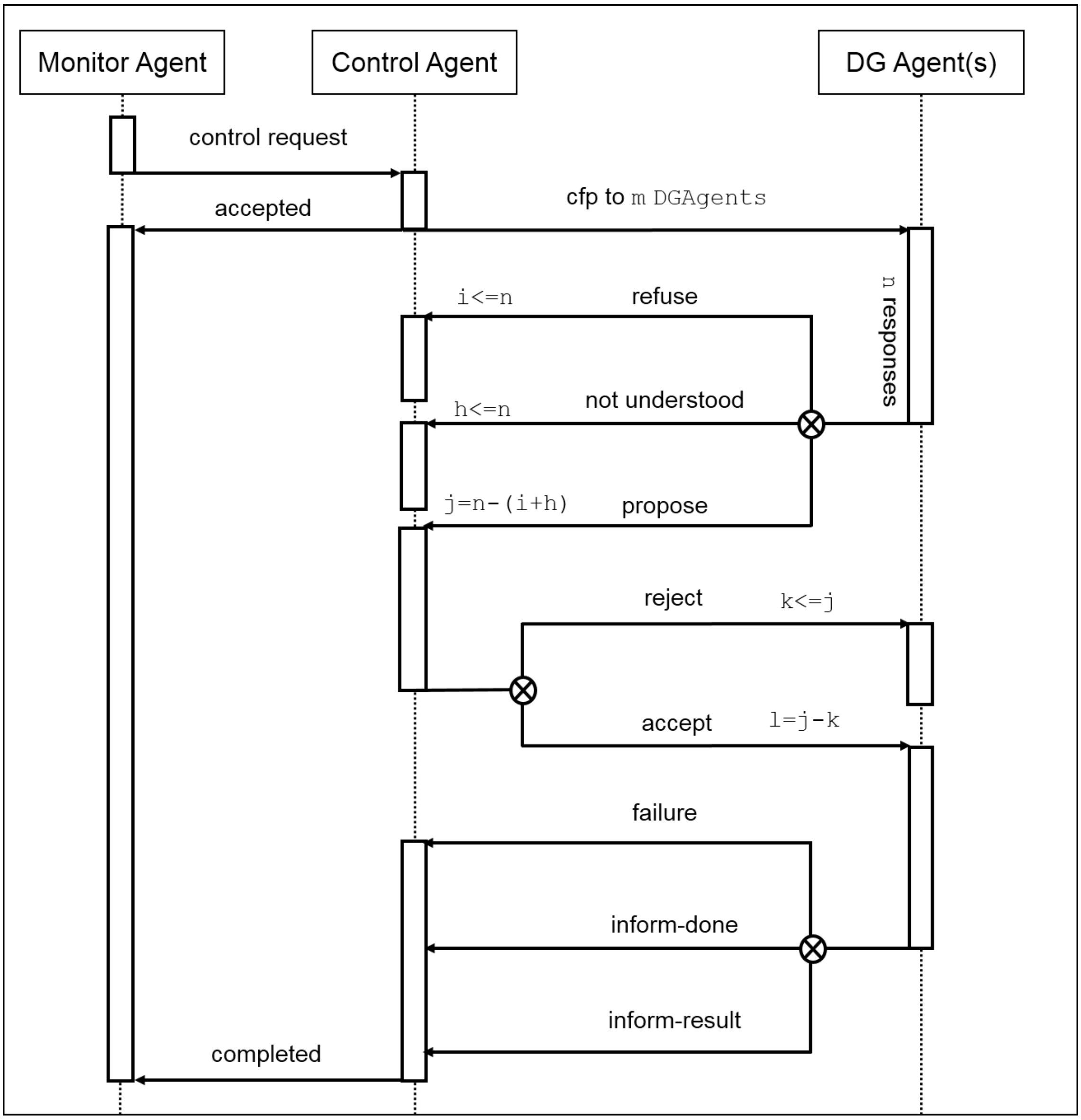

Figure 5.4: Interaction of agents using Contract-Net-Protocol.

- **Monitoring Agent:** Monitoring agents corresponds to each bus in the network. A monitor agent continuously monitor the voltage at the bus and if there is any violation in the bus voltage limits, it initiates the process of voltage control by sending a message to $ControlAgent$. It also calculates the desired voltage boost or drop. It should be noted that in this algorithm difference between the limits and actual voltage is taken as change in voltage. However, we can also take difference of nominal voltage and current voltage in case of violation. Agent status is defined by using modes. In this case, $Mode = 0$ means a request for voltage control action is forwarded to $ControlAgent$ and this request is accepted and control action is under process and no further request will be sent until reception of *done* message from $ControlAgent$. $Mode = 1$ means $MonitoringAgent$ is monitoring the bus voltage and upon violation, it will forward request to the $ControlAgent$.

- **Control Agent:** $ControlAgent$ acts as manager or moderator. It completes the process of voltage control by deciding the reactive power set points for the $DGAgents$. After receiving a request of control action with desired voltage boost or drop ΔV_i at a certain bus i, it sends Call-For-Proposal(CFP) message to all the $DGAgents$ in the network. After receiving responses from all the agents or finishing the dead line for proposals, it makes a list of proposals received from $DGAgents$ in descending order of voltage sensitivity S_j, $Q_j^{available}$. It selects $DGAgents$ and Q from the top of the list until $\Delta Q_1 S_1 + \Delta Q_2 S_2 + ... + \Delta Q_k$ becomes equal to the desired voltage boost or drop ΔV_i. After receiving done message from all the $DGAgents$ which received the order, it sends done message to $MonitoringAgent$ and changes its mode to 1 from 0. It is possible that even with Q proposed by all the $DGAgents$ desired voltage boost or drop can not be obtained. In this case available Q will be ordered and dispatched.

- **DG Agent:** $DGAgent$ corresponds to distributed generator in the network. This send response to control agent upon receiving a CFP message. If it is not operating on the limits of Q_{limits}, then it forwards its proposal containing voltage sensitivity S_i, current reactive power $Q_i^{current}$ and min/max reactive power Q_{limits}. If it is already operating on limits then sends refuse message. If proposal is accepted by the $ControlAgent$, it updates its $Q^{current}$ and sends done message to the $ControlAgent$.

5.4 Simulation and Results

This section provides investigation of the two developed control strategies using simulation studies on IEEE distribution system test case which is described in the next section.

5.4.1 Test case

The detail data of the used IEEE test system is available at [168]. IEEE 13 node test feeder distribution system with some modification was used for the simulation studies. This test system has nominal voltage of $4.16kV$. It also includes shunt capacitors and voltage regulator. This model was modified by including some distributed generation and load profile was used to exhibit

Algorithm 5.2: Algorithm for each $MonitoringAgent$, M_j in the network

initialization: $tolerance = \epsilon$,$\Delta V_i = 0$, time interval $= t_{interval}$ $Mode = 1$;
Step 1: ;
Calculate the, ΔV_i according to the bus voltage limits ;
if $V_i > V_i^{Upper}$ **then**
    $\Delta V_i = V_i^{Upper} - V_i$, upper limit violation;
else
    $\Delta V_i = V_i^{Lower} - V_i$, lower limit violation;
Step 2: ;
while $\Delta V_i > |\epsilon|$ **do**
    Send change in voltage, $(\Delta V_i) \rightarrow ControlAgent$ (for control action to remove the violation) ;
    if *(received* $\leftarrow$ *accepted)* **then**
        set $mode = 0$;
        if *received* $\leftarrow$ *completed* **then**
            set $mode = 1$;
    if *(received* $\leftarrow$ *rejected)* **then**
        set $mode = 1$, wait for $t_{interval}$, goto Step 1
    else
        goto Step 1

Algorithm 5.3: Algorithm for $ControlAgent$ of the network

if $Mode = 1$ **then**
    $\Delta V_i \leftarrow M_i$, receive change in voltage from monitoring agent ;
    set $Mode = 0$;
    Call-For-Proposal($\Delta Q_k \rightarrow DG_j$, $j = 1, 2, ...m$);
    Receive Proposals ($Q_j^{limits}, Q_j^{current}, S_j$) $\leftarrow A_j$, $j = 1, 2, ...m$;
    if *(received all responses)*$||$*(deadline reached)* **then**
        List $\leftarrow$ Descend(S_j, $Q_j^{available}$), $j = 1, 2, ...k$, k =number of proposals received
        Accept$_P$*roposals* ($\Delta Q_j S_j = \Delta V_i$) from A_h $h \in List$;
        $MessageDone \leftarrow A_h$;
        $SendMessage \rightarrow M_j$;
        set $Mode = 1$;

Algorithm 5.4: Algorithm for each *DGAgent* A_j of the network

if *(Mode* $= 1$ && *CFP* $\leftarrow$ *ControlAgent)* **then**
- **if** $Q_j^{min} < Q_j^{current} < Q_j^{max}$ **then**
  - Calculate S_j, update the sensitivity ;
  - SendProposal $(Q_j^{limits}, S_j, Q_j^{current}) \rightarrow ControlAgent$;
  - set $Mode = 2$, waiting for acceptance
- **else**
  - refuse

if $Mode = 2$ **then**
- wait for proposal acceptance/rejection;
- **if** $Acceptance \leftarrow ControlAgent$ **then**
  - $Update\ Q_j,\ Q_j^{current}$;
  - $MessageDone \rightarrow ControlAgent$;
  - set $Mode = 1$
- **else**
  - set $Mode = 1$

the voltage problem. Further system was balanced and shunt capacitor and regulator was omitted. Figure 5.5 shows the one line diagram of the network in which distributed generators were connected at different buses.

5.4.2 Decentralized algorithm for 13 Node Network

Test network included seven *DGAgents* and data of these agents is given in table 5.3. Voltages at all the buses in normal condition is given in figure 5.6. It is clear from the figure that $bus13$ has low voltage as compared to all the other buses and it is more likely that this bus can violate the lower limit voltage. Thus this bus was considered as the target bus or critical point and voltage at this bus was monitored. In decentralize approach *DGAgent* monitors bus voltage at the connection point and as long voltage goes out of limit, it starts process to remove voltage violation. As voltage $bus13$ is out of limit, figure 5.7 shows the voltage profile of $bus13$. At time $t = 405$ minutes voltage at the $bus13$ becomes less than the allowable lower limit i.e. 0.95. Figure 5.8 shows voltage on all the buses in normal and high load conditions. $DGAgent4$ calculates the desired boost as per algorithm 5.1 and given below;

$$\Delta V = V^{lowerlimit} - V_t$$

Thus, $\Delta V = 0.95 - 0.94 = 0.01$ becomes the desired voltage boost. After determining the voltage boost new reactive power set-point, Q_{new} is calculated as $Q^{new} = \Delta V/S + Q^{Current}$ according to the algorithm 5.1. Then $Q^{new} = 0.01/0.0176 + 0.01 = 0.57.DGAgent4$ changes the reactive power as $Q_{current} = Q_{new} = 0.57$. Voltage profile of bus 13 after voltage support by the $DGAgent4$ is given in figure 5.10, while comparison with the base case is presented in figure 5.11.

5.4.3 Contract-Net-Protocol based algorithm for 13 Node test network

As we have seen in the case of purely decentralize control without any communication, it was not possible to remove voltage violation for all the times due to constraints on the DG reactive

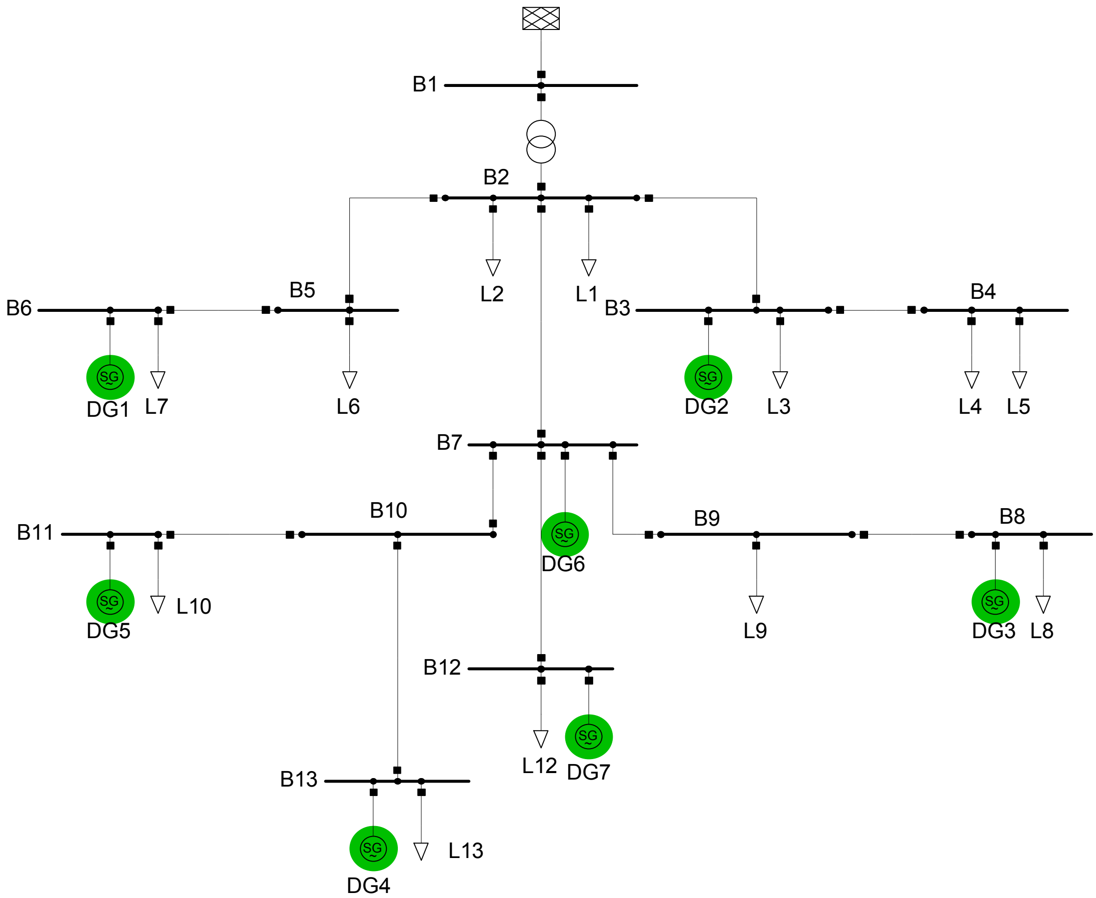

Figure 5.5: Modified IEEE 13 node test feeder with distributed generation.

power output. In order to remove voltage violation for all the times, *DGAgents* can collectively contribute in voltage control process by coordinating with each other. This section presents CNP based control algorithm for the above mentioned test network. The control process is explained below in steps.

- **Step-1** In this control scheme, *BusAgents* are considered as the *MonitoringAgent*. The *MonitoringAgent* at $bus13$ observes the voltage violation and calculates the desired voltage boost as $\Delta V = V^{lower} - V^{current}$ according to the algorithm 5.2 and forwards this value to the *ControlAgent*

- **Step-2** If *ControlAgent* is not already busy in other control action ($mode = 1$), then it starts the control process by sending messages to the *DGAgents* in the network and sets $Mode = 0$ i.e. busy. In this test case desired voltage boost was set as $\Delta V = 0.01$. Here, lower and upper limits were taken as reference value for calculation of voltage change. However, it can be set to any value above lower limit or below upper limit as per requirements of the network. *ControlAgent* sends Request-For-Proposal (RFP) message to the *DGAgents*. In this network total seven *DGAgents* were considered. If any *DGAgent* adds to the network, it registers itself in the directory services. *ControlAgent* looks for available *DGAgents* in the directory services and sends them message.

Table 5.3: Generation data for IEEE 13 node network.

Name	**Location**	**P (MW)**	**Q (MVar)**	Q_{max}	Voltage Sensitivity (dv/dq)
$DGAgent1$	Bus 6	5	0.1	2.8	0.0054
$DGAgent2$	Bus 3	2.4	0.01	1.3	0.0049
$DGAgent3$	Bus 8	2.5	0.7	1.3	0.0153
$DGAgent4$	Bus 13	1	0.01	0.57	0.0176
$DGAgent5$	Bus 11	2	0.01	1.1	0.0168
$DGAgent6$	Bus 7	2.5	0.5	1.4	0.0056
$DGAgent7$	Bus 12	0.5	0.1	0.28	0.0112

- **Step-3** Each $DGAgent$ receives RFP message, respond with a message containing, current reactive power $Q^{Current}$, maximum and minimum reactive power Q^{max}, Q^{min}, voltage sensitivity S. The seven $DGAgents$ reply as per values given in table 5.3. For example reply from $DGAgent1$ is $DGAgent1(0.1, 2.8, 0.0054)$.

- **Step-4** After receiving replies from the $DGAgents$, $ControlAgent$ selects the $DGAgents$ with the higher voltage sensitivity and sends the new set point for the reactive power, Q^{new} to the selected $DGAgents$ as per algorithm 5.3. In this case $DGAgent4$ had the highest sensitivity, and new reactive power for the DG was calculated as $Q^{new} = 0.57$.

- **Step-5** $DGAgent4$ after receiving the new reactive power set-points, changes its current reactive power to 0.57 and sends an acknowledgment message to the $ControlAgent$.

- **Step-6** After acknowledgment from $DGAgent4$, $ControlAgent$ sends completion message to $MonitorAgent$ and sets its mode to free i.e. $Mode = 1$.

In second violation at time $t = 1080$, above mentioned control process repeated, this time only six $DGAgents$ reply for RFP message as $DGAgent4$ was already running on maximum allowable reactive power. This $DGAgent5$ was selected for voltage support as it has the highest voltage sensitivity in the remaining $DGAgents$. The new reactive power for $DGAgents5$ was set as $Q^{new} = \Delta V/S + Q^{current} = 0.1/0.016 + 0.01 = 0.60$. Figure 5.12 shows the voltage profile at $bus13$ with the CNP based control algorithm. Figure 5.13 shows voltage of bus B13 after second violation with base case(no control), decentralize control and CNP based control.

5.4.4 Communication and information exchange

As, there is no exchange of information between agents in decentralized scheme, no communication infrastructure required to implement such type of control scheme. This scheme is similar to the

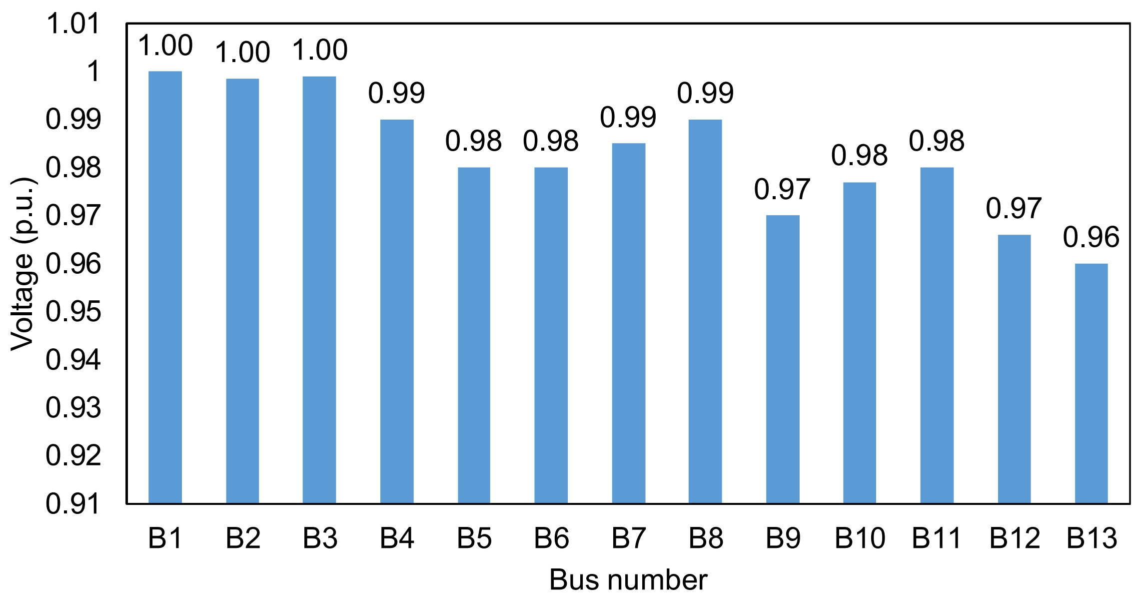

Figure 5.6: Voltage at all the buses during normal condition.

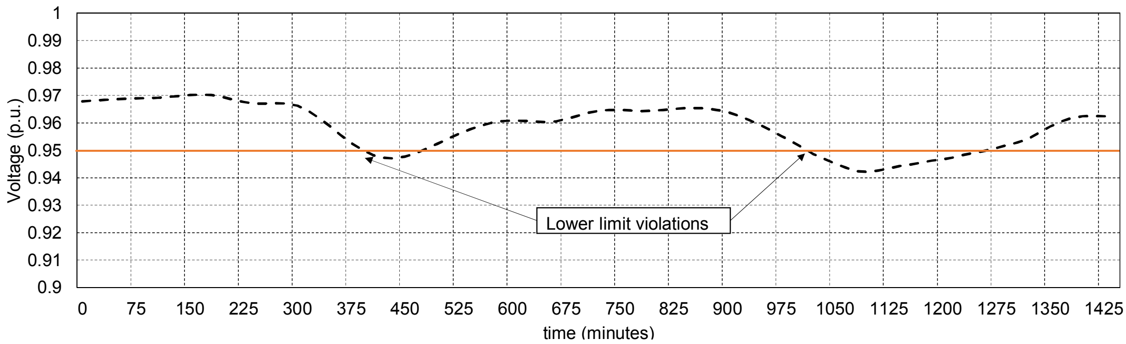

Figure 5.7: Voltage profile at bus B13 without any control action. There are two lower limit voltage violations.

local control of a DG in which control objective is to keep voltage at the point of connection within limits. On the other hand, in CNP based algorithm, information exchange between agents is carried out and communication infrastructure is required to fulfill the control objective. In the test case there were seven *DGAgents* and each bus is considered as the *BusAgent* which acts as monitoring agent. There is one *ControlAgent* which is responsible for computing the control action through coordination of the *DGAgents*. It is necessary to investigate that how much information exchange is required for the control action as if network becomes very large, a lot of information exchange is carried out between agents. Communication infrastructure requirements increase for such network. Table 5.4 shows the number of messages exchange between agents for a control action.

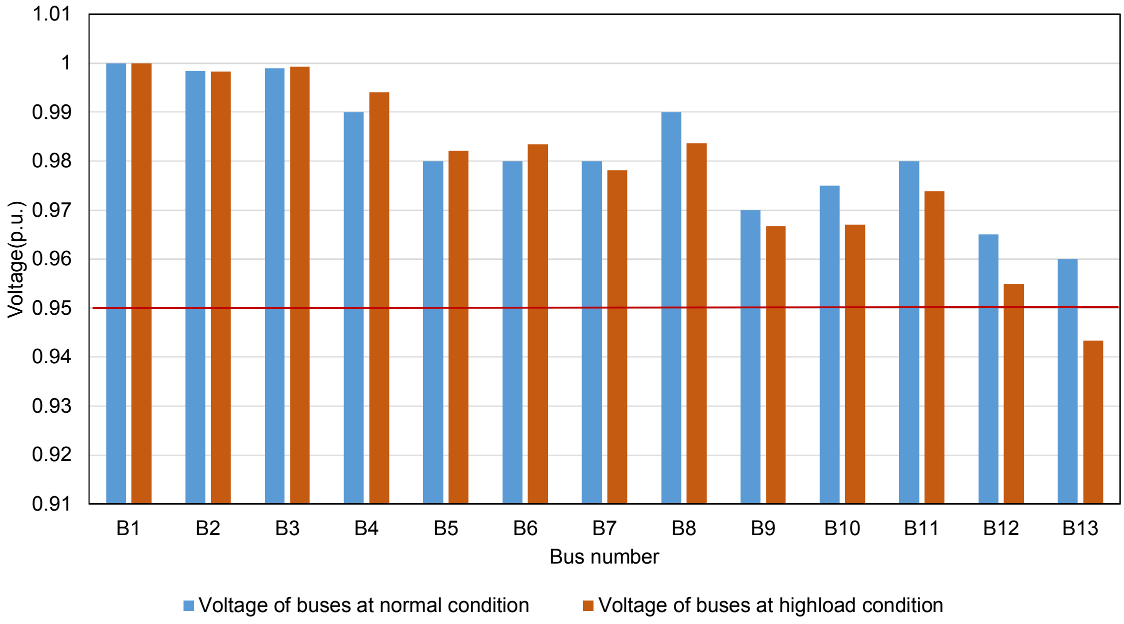

Figure 5.8: Voltage at all the buses in normal and high load conditions.

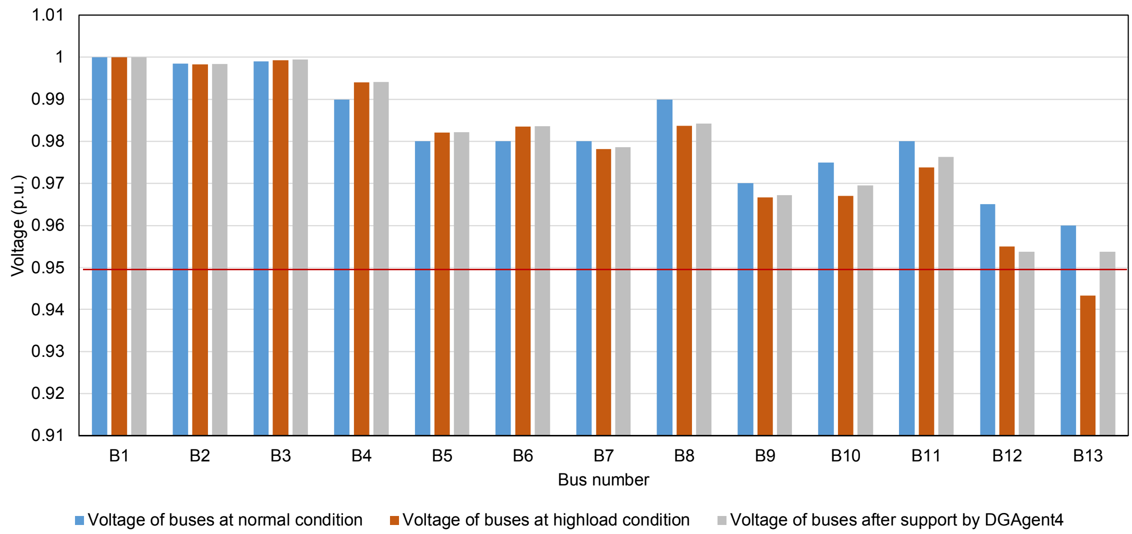

Figure 5.9: Voltage at all the buses 1) normal condition 2) high load condition 3) after voltage support by DGAgent4.

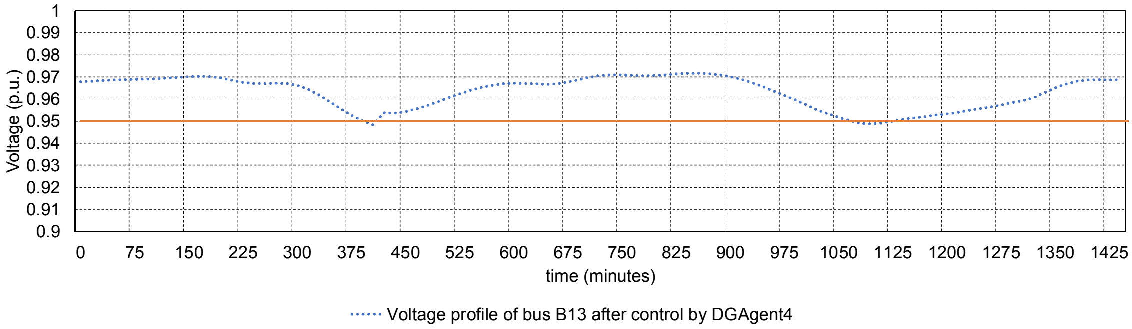

Figure 5.10: Voltage profile at bus B13 after support by *DGAgent4*.

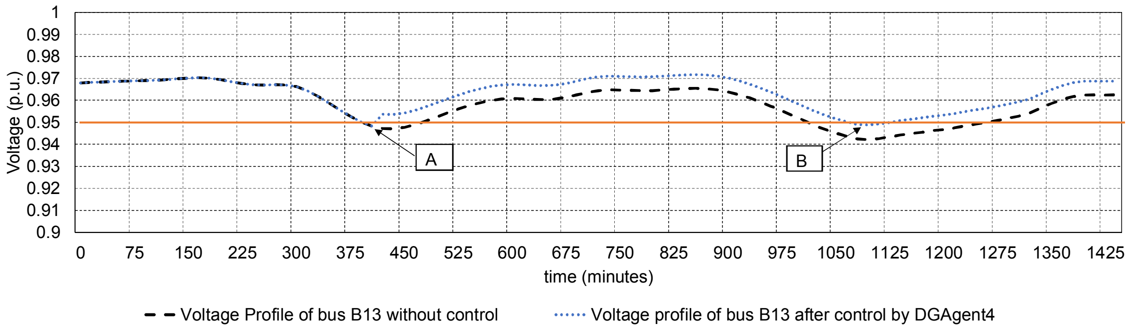

Figure 5.11: Voltage profile at bus B13 before and after control action. **A)** Voltage at $t = 405$ minutes goes down from 0.95 $p.u.$ in case with no control action, however it is clear that after the control action voltage is above the lower limit.**B)** Voltage at this point in base case is below the lower limit, however as *DGAgent4* already running at the maximum reactive power, voltage goes out of lower limit for some time.

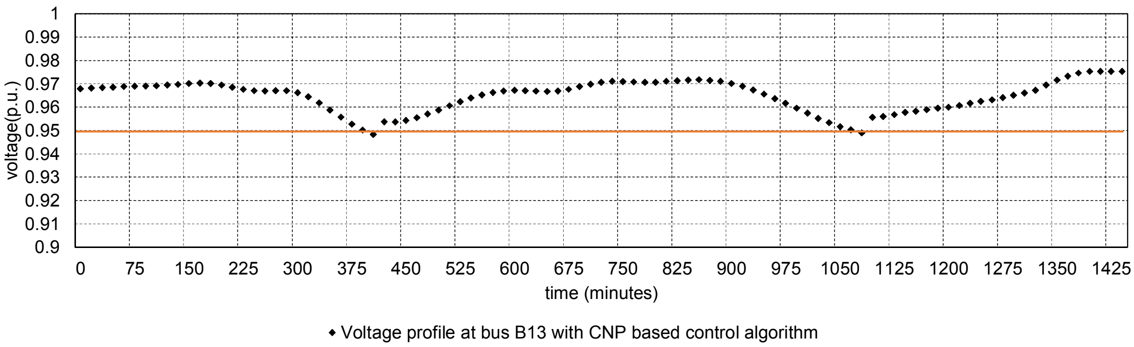

Figure 5.12: Voltage profile at bus B13 after control by CNP based algorithm.

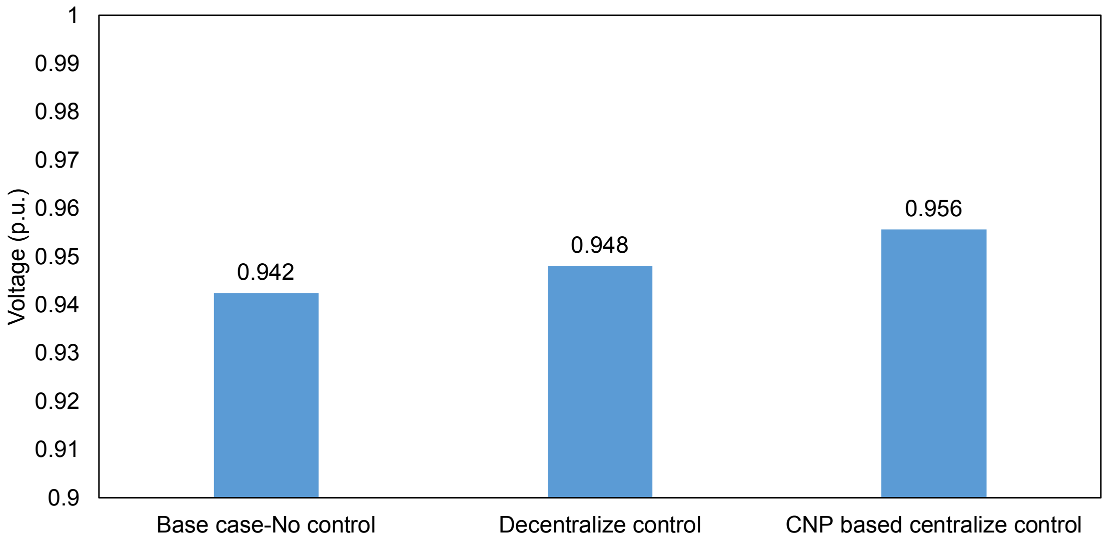

Figure 5.13: Voltage at bus B13 after second violation with 1) Base Case-no control 2) Decentralized control 3) CNP based centralized control.

Table 5.4: Agents and number of messages exchanged between them for voltage control in 13 Node test network.

Agent Name	**No. of Agents**	**No. of Messages**	**Description**
Control Agent	1	9	There is only one *ControlAgent* in the network, it computes the control action through information exchange with all the DGAgent.
Monitor Agent	13	1	Monitor agent only sends message to *ControlAgent* when there is a voltage violation, for one violation there is only one message.
DGAgent	7	8	There are seven *DGAgents*, which reply the *ControlAgent* on RFP.
Total	21	18	Total number of messages exchanged in control action.

6 MAS based Distributed Control using Iterative Algorithm

6.1 Overview

In the previous chapter decentralized and centralized voltage control schemes were developed and investigated. This chapter presents distributed iterative algorithm for voltage control. In this algorithm, agents communicate with the pre-defined neighboring agents and compute the reactive power share of each participating distributed generator for voltage control. For this algorithm no central control agent is required and agents calculate the share of reactive power iteratively. In order to know effects of communication delay on performance of the system, communication scenarios were developed. IEEE 37 node power distribution network was used to test the proposed algorithm. Under various communication scenarios, voltage profile of critical bus was examined.

6.2 Reactive Power Dispatch using Distributed Approach

Purely decentralized approach and centralized approach with CNP based protocol was presented in previous chapter. This chapter presents another algorithm for reactive power dispatch which works in distributed fashion and each agent calculates its reactive power share by exchanging its value with the neighboring agents through the communication network.

6.2.1 Definition of Agents

Following agents are defined to implement this algorithm.

- DG Agent: *DGAgent* represents the distributed generation in the network. Each *DGAgent* can communicate with the predefined neighboring *DGAgents*. *DGAgent* can share its calculation through the communication network.

- Monitoring Agent: *MonitorAgent* monitors the bus voltage and starts control process in case of bus voltage violation.

6.2.2 Algorithm Description

The distributed iterative algorithm is adopted from [OSFM07], in which authors presented various algorithms for the consensus between agents for a specific task in a networked system. In any system that consists of several entities i.e. agents which are networked with each other through a defined communication network, consensus can be defined as reaching an agreement between agents on some value which depends upon initial state of the agent in network. A network of sensors measuring the same variable is a typical example application of consensus. For example, measurement of temperature by the multiple sensors. Another example of coordination is flock of birds which move in a certain direction set by the leader bird in which each bird coordinate its movement with the nearby birds to follow the leader bird.

Distributed generators in a power distribution network can be considered as agents which can send and receive information from the neighboring generators to calculate new set-points of reactive power or active power. Thus the distributed iterative algorithm can be used to calculate the share of reactive power by the each generator through exchange of information with neighboring agents.

Message exchange between *DGAgents* can be described using graph theory. Let $G = \{V, E\}$, where the set $V = \{1, 2, 3, ...n\}$ represents *DGAgents* in the network while E is the set of edges and $E \subseteq V \times V$. If $\{i, j\} \in E$ means agent i can receive information from agent j. Further, if $\{i, j\} \in E$ and also $\{j, i\} \in E$ then agent i can receive information from agent j as well as can send information to agent j, which is the case of directed edge. The neighbors of *DGAgent* i can be represented as $N_i = \{j \in: \{i, j\} \in E\}$. All the agents which can send message to agent i are called neighbors of agent i. Number of neighbors of agent i are called in-degree of agent i and can be denoted as D_i-. Similarly the number of agents that have agent i as a neighbor can be called out-degree of agent i and is denoted as D_i+. This means agent i can send messages to these agents.

Let the monitoring agent observe voltage violation at a certain bus i at time instant t, it estimates the desired total reactive power $\tau[t]$ for voltage boost/decrease, where t is the time instant. If *DGAgent* i at bus i has reactive power $Q_i[t]$ then the estimate of the reactive power required at bus i will become;

$$Q_i[t + 1] = Q_i[t] + \tau[t] \tag{6.1}$$

If $Q_i^{min} \leq Q_i[t + 1] \leq Q_i^{min}$ then *DGAgent* i will be able to provide the whole reactive power and there will be no need for *DGAgents* to communicate with each other. This is basically equal to the purely decentralized control as explained in the previous chapter. However, if $Q_i[t+1] < Q_i^{min}$ or $Q_i[t + 1] > Q_i^{max}$ then *DGAgent* i can not provide the desired amount of reactive power and will start communication with the other agents in the network to calculate the new set-points for reactive power to globally raise or lower the voltage of the network by using the distributed algorithm. In order to account for the constraints on reactive power capacities of the distributed generators, let Q_i^{min} and Q_i^{max} for $i = 1, 2, 3, ...n$ be the minimum and maximum reactive power that can be provided by the agents. Further, as DG might also inject or absorb some reactive power in this case $Q_i^{max} = Q_i^{max} - Q_i^{current}$. Then we can define the following corresponding vectors of minimum and maximum capacities as;

$$Q^{min} = \begin{bmatrix} Q_1^{min} \\ Q_2^{min} \\ Q_3^{min} \\ . \\ . \\ . \\ Q_n^{min} \end{bmatrix}, \; Q^{max} = \begin{bmatrix} Q_1^{max} \\ Q_2^{max} \\ Q_3^{max} \\ . \\ . \\ . \\ Q_n^{max} \end{bmatrix}$$

Further, the total reactive power desired from *DGAgents* can be written as

$$\tau = \sum_{i=1}^{n} Q_i \tag{6.2}$$

It is assumed that all the *DGAgents* can collectivity provide the required total reactive power, such that $Q^{min} \leq \tau \leq Q^{max}$. All the *DGAgents* run the following algorithm;

$$\sigma_i[t+1] = \frac{1}{1+D_i^+}\sigma_i[t] + \sum_{j \in N_i} \frac{1}{1+D_j^+}\sigma_j[t] \tag{6.3}$$

According to the above equation each *DGAgent* i update value of variable σ_i. N_i represents the neighbors of *DGAgent* i. Other than the above mentioned variable, each agent will also update the following two variables to account for the constraints;

$$\nu_i[t+1] = \frac{1}{1+D_i^+}\nu_i[t] + \sum_{j \in N_i} \frac{1}{1+D_j^+}\nu_j[t] \tag{6.4}$$

$$Q_i = Q_i^{min} + \frac{\sigma_i[t+1]}{\nu_i[t+1]}\Delta Q_i \tag{6.5}$$

Initial conditions for algorithm 6.3 and 6.4 are given below ;

$$\sigma_i[0] = \begin{cases} \tau - Q_i^{min} \text{ ; if is first/starting agent} \\ -Q_i^{min} \text{ ; otherwise} \end{cases} \tag{6.6}$$

$$\nu_i[0] = Q_i^{max} - Q_i^{min} = \Delta Q_i \tag{6.7}$$

Thus after some iterations, m, each *DGAgent* i will calculate its reactive power Q_i as per equation 6.5 and sets its new reactive power as;

$$Q_i^{new} = Q_i^{current} + Q_i \tag{6.8}$$

Thus this algorithm ensures that total reactive power demand is met by all the DGs fulfilling their capacity constraints.

6.2.3 Convergence of the algorithm

From equation 6.3, we can see that the number of neighbors of an agent define the weights and thus communication network plays major role in convergence of the algorithm. change in communication network can result in change in convergence speed. If we define the following ;

$$\sigma[t] = \begin{bmatrix} \sigma_1[t] \\ \sigma_2[t] \\ \sigma_3[t] \\ . \\ . \\ . \\ \sigma_n[t] \end{bmatrix}, \sigma[0] = \begin{bmatrix} \sigma_1[0] \\ \sigma_2[0] \\ \sigma_3[0] \\ . \\ . \\ . \\ \sigma_n[0] \end{bmatrix}$$

Now we can write the equation 6.3 in matrix form as below;

$$\begin{bmatrix} \sigma_1[t+1] \\ \sigma_2[t+1] \\ \sigma_3[t+1] \\ . \\ . \\ . \\ \sigma_n[t+1] \end{bmatrix} = \begin{bmatrix} p11 & p12 & p13 & . & . & . & p1n \\ p21 & p22 & p23 & . & . & . & p2n \\ p31 & p32 & p33 & . & . & . & p3n \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ pn1 & pn2 & pn3 & . & . & . & pnn \end{bmatrix} \begin{bmatrix} \sigma_1[t] \\ \sigma_2[t] \\ \sigma_3[t] \\ . \\ . \\ . \\ \sigma_n[t] \end{bmatrix} \tag{6.9}$$

$$\sigma[t+1] = P\sigma[t] \tag{6.10}$$

The entries of matrix P depends upon the connectivity of agents and can be defined as ;

$$P = \begin{cases} P_{ij} = \frac{1}{1+D_i}, \text{ if } i = j \\ P_{ij} = \frac{1}{1+D_j}, \text{ if } i \neq j, (i,j) \in E \\ P_{ij} = 0, \text{ if } i \neq j, (i,j) \notin E \end{cases} \tag{6.11}$$

6.2.4 Coordination between agents

In order to compute the algorithm correctly, agents must be synchronized to perform the iterations. These iterations can be predefined on the basis of experiments or can use error tolerance. A message based synchronization scheme was adopted. Each agent updates its iteration variable after performing calculation and exchange with the neighboring variables. Pseudo code for coordination and computation of reactive power is given below;

Algorithm 6.1: Algorithm for *DGAgents* coordination for finding new reactive power set points Q_{DGi}^{New}

initialization: $tolerance = \epsilon$, constraints, initial conditions for $\sigma[0]$, Iteration counter $k = 0$, Total iterations $ItrNumb$;
Result: Reactive power Q_{DGi}^{New} ;
while $k < ItrNumb$ **do**
  compute $\sigma[k]$, $\nu^{upper}[k]$, $\nu^{lower}[k]$, $\tau[k]$;
  according to equations 6.3, 6.4, 6.5 respectively ;
  send computed value to neighbours ;
  if *value* $\leftarrow$ *from all the neighbors* **then**
    $k = k + 1$
  wait for the specified time
Return $Q_{DGi}^{New} = \tau[k] + Q_{DGi}$

6.2.5 Agent Communication Network Modeling

As mentioned above that communication between agents plays important role in convergence speed of the algorithm. Figure 6.1 shows two example communication topologies between agents with undirected graph. According to this communication network the transition matrix P can be calculated. Transition matrix for communication topology in figure 6.1 a) is given below;

$$P = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & \frac{1}{3} & 0 & 0 & 0 \\ \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 \\ 0 & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} \\ 0 & 0 & 0 & \frac{1}{3} & 0 & \frac{1}{3} & \frac{1}{3} \\ 0 & 0 & 0 & 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix}$$

while for communication topology in figure 6.1 b) is ;

$$P = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 & 0 \\ \frac{1}{3} & \frac{1}{3} & 0 & \frac{1}{3} & 0 & 0 & 0 \\ \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & 0 \\ 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{2} & 0 \\ 0 & 0 & \frac{1}{3} & 0 & \frac{1}{3} & 0 & \frac{1}{2} \\ 0 & 0 & 0 & \frac{1}{3} & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{3} & & \frac{1}{2} \end{bmatrix}$$

One can observe that the matrix P for topology a is doubly stochastic matrix (represents transition matrix also called probability matrix or Markov matrix). In doubly stochastic all the entries are real non negative and sum of each column as well as each row is equal to one. While matrix P for topology b is a left stochastic matrix i.e. sum of entries in each column is equal to one.

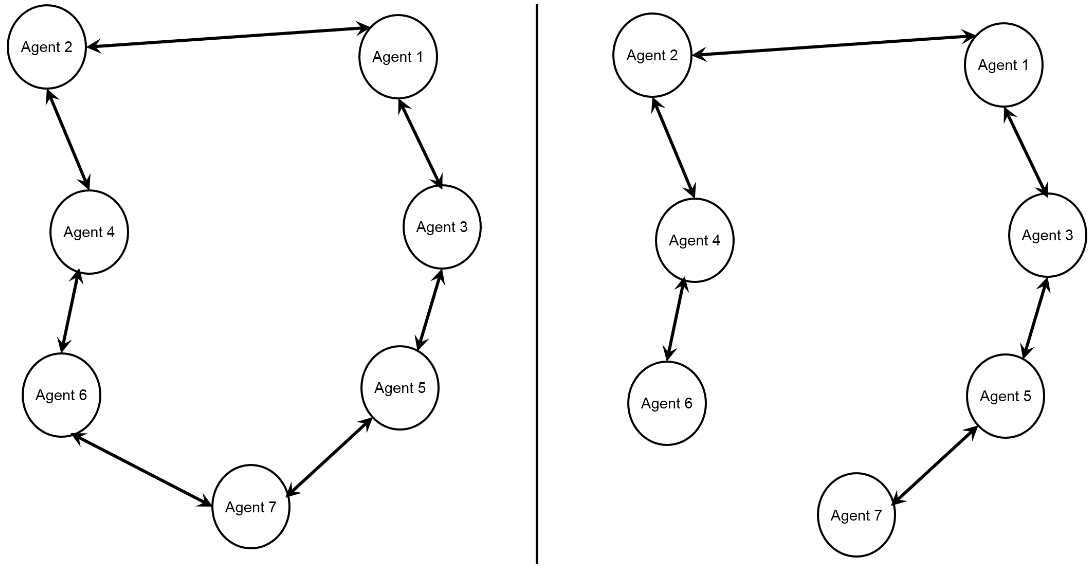

Figure 6.1: Graph representing two different example communication topologies between agents. a) Shows all the agents have two neighbors and can send and receive messages. b) Agent 6 and agent 7 have only one neighbor.

6.3 Test case studies

IEEE 37 node test feeder system was used to test the proposed algorithm. Figure 6.2 shows the network diagram. Six DGs were installed at different buses and communication link between them is also shown. Table 6.1 shows generation data for the network. Effects of communication parameter changes on the network were also investigated. Thus two types of simulations were carried out, one considering ideal communication between agents and the other considering different communication parameters modeled in communication modeling tool OMNeT++. Simulations were carried out in a co-simulation framework described next.

6.3.1 Simulation setup

Test case was simulated using a co-simulation framework. This framework comprises three simulators; DigSILENT Power factory for power system simulation, JADE for MAS simulation and OMNeT++ for communication simulation. Figure 6.3 shows how information exchange is carried out between agent 1 and agent 4. Agent 1 in JADE gets updated information from DG1 (which is in Power system model developed in Power Factory) sends this information to agent 4 through the communication network developed in OMNeT++. IEEE 37 test feeder was used to investigate the effects of real communication between agents on performance of the algorithm.

6.3.2 Simulations considering ideal communication

Test case was simulated considering ideal communication between agents i.e. there is no communication delay between agents. The transition matrix P which depends upon the communication

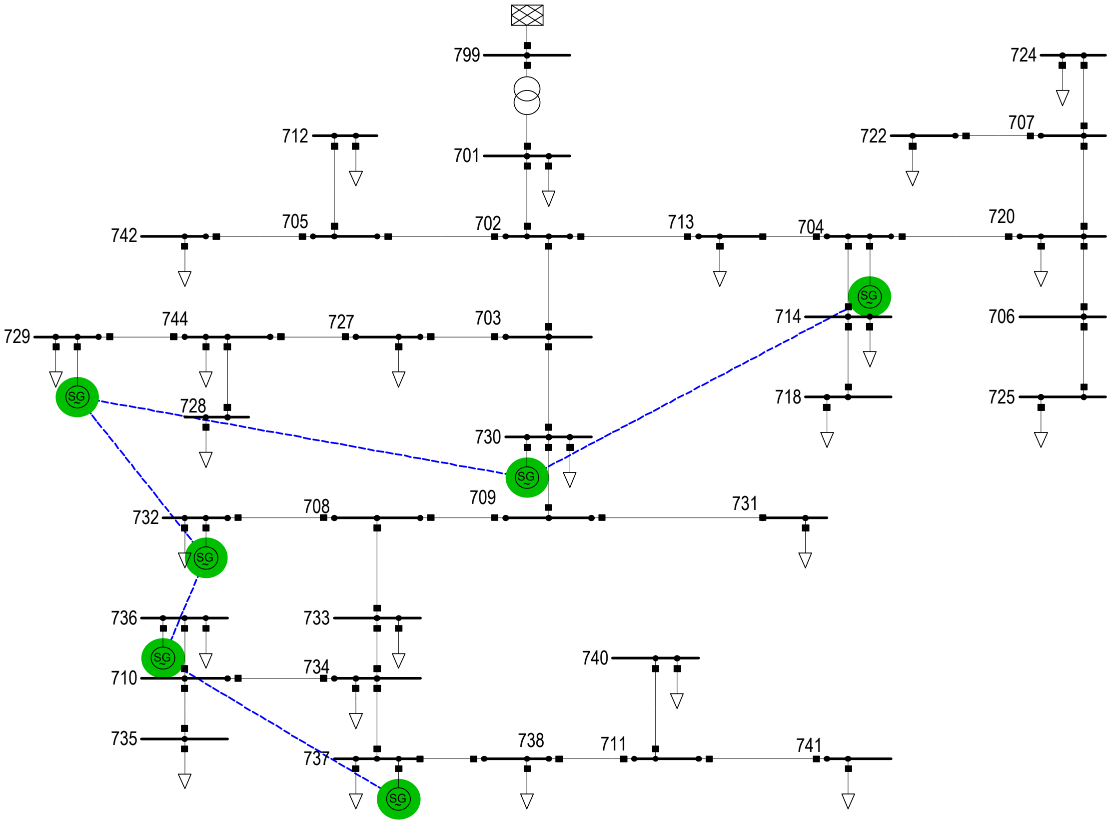

Figure 6.2: IEEE 37 node test system with distributed generation. Dotted line shows the communication link between DGs.

Table 6.1: Generation data for IEEE 37 node network

Name	Location	P (MW)	$Q^{current}$ (MVar)	Q^{max}	Voltage Sensitivity (dv/dq)
$DGAgent1$	704	0.1	0.008	0.05	0.01
$DGAgent2$	730	0.5	0.01	0.27	0.02
$DGAgent3$	729	0.1	0.01	0.06	0.05
$DGAgent4$	732	0.7	0.01	0.36	0.02
$DGAgent5$	736	0.6	0.007	0.32	0.04
$DGAgent6$	737	0.13	0.01	0.07	0.03

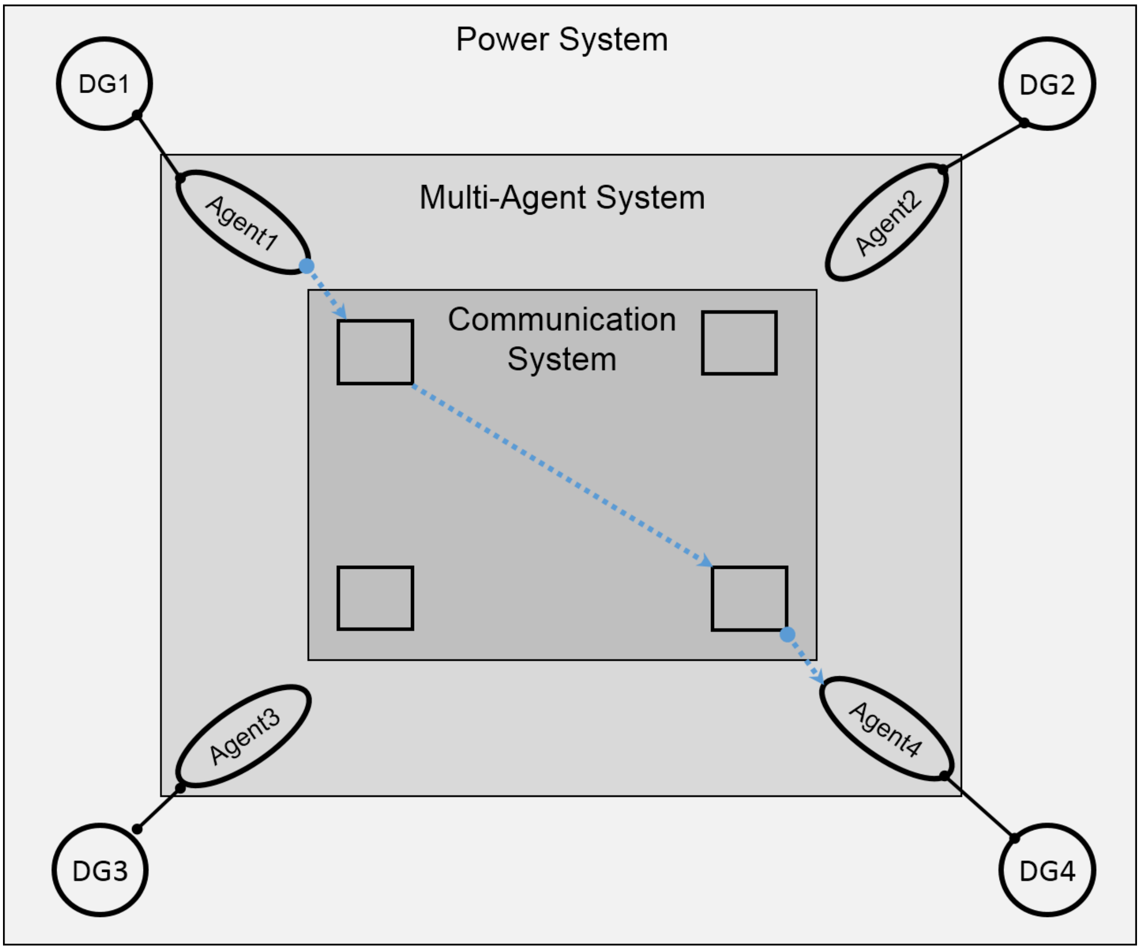

Figure 6.3: Simulation set up for the test case.

link between agents (equation 6.11) is given below;

$$P = \begin{bmatrix} \frac{1}{2} & \frac{1}{3} & 0 & 0 & 0 & 0 \\ \frac{1}{2} & \frac{1}{3} & \frac{1}{3} & 0 & 0 & 0 \\ 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 & 0 \\ 0 & 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & 0 \\ 0 & 0 & 0 & \frac{1}{3} & \frac{1}{3} & \frac{1}{2} \\ 0 & 0 & 0 & 0 & \frac{1}{3} & \frac{1}{2} \end{bmatrix}$$

Bus 735 was chosen to be the critical bus and voltage profile of this bus is given in 6.4, while voltage of all the buses when voltage at $bus735$ goes down is given in figure 6.5.

As the voltage of $bus735$ goes down from 0.95 p.u. Monitor Agent calculates the voltage boost as $\Delta V = 0.95 - 0.94 = 0.01$ and estimate the required reactive power with the help of formula, $\frac{\Delta V}{\Delta Q} = S$ as 0.333. $MonitorAgent$ sends message to the neighboring $DGAgent6$ for providing the reactive power support. This $DGAgents6$ then starts the iterative algorithm as per equation 6.3, 6.4 and 6.5. Figure 6.6 shows JADE environment in which agents are exchanging information through messages. Evolution of Σ, ν and Q are given in figure 6.7, 6.8 and 6.9.

Value of Q converges almost after 31 iterations, so total number of iteration performed was set to

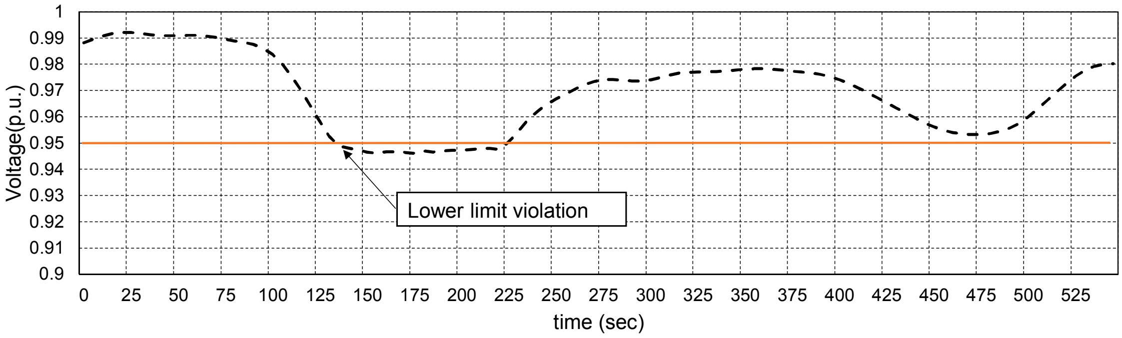

Figure 6.4: Voltage profile of the bus 735 (critical bus) without control.

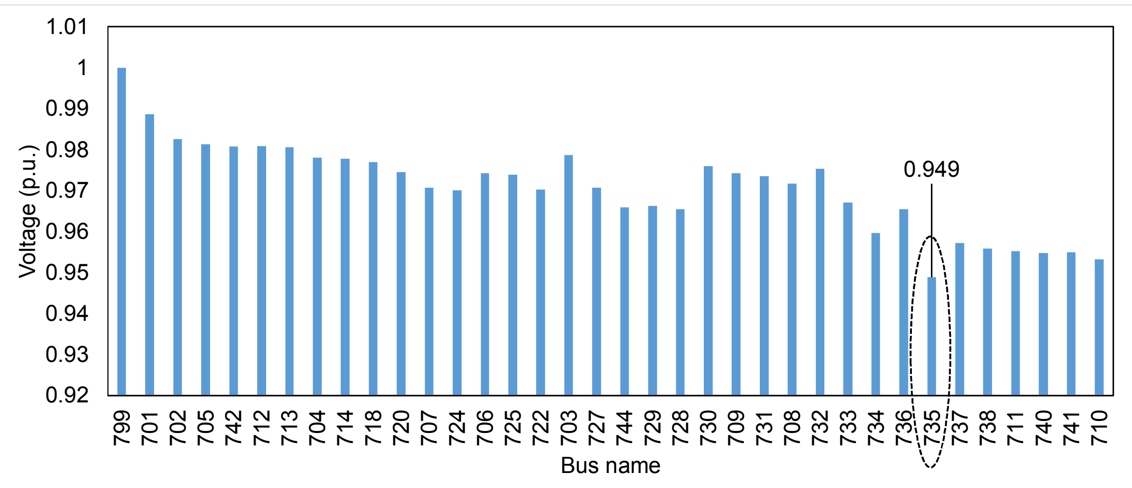

Figure 6.5: Voltage of all the buses at the time when voltage at bus 735 (critical bus) goes down from 0.95 p.u.

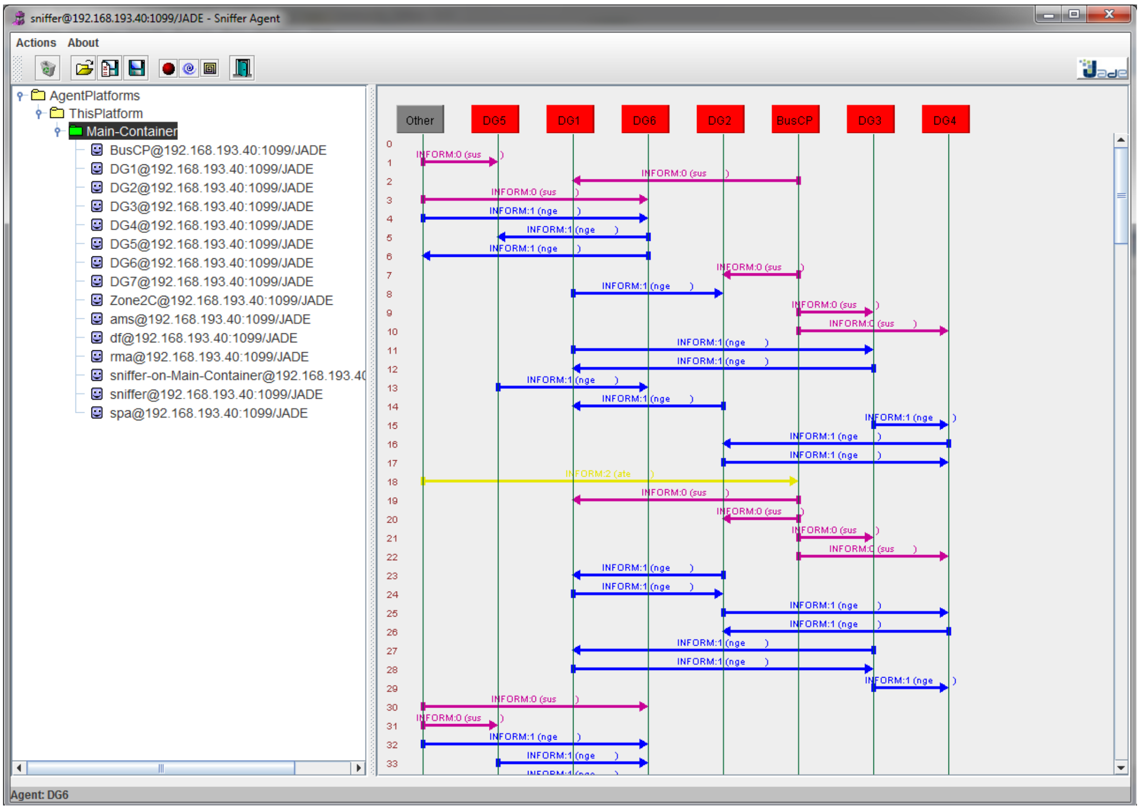

Figure 6.6: An example of messages exchanged between agents in JADE environment.

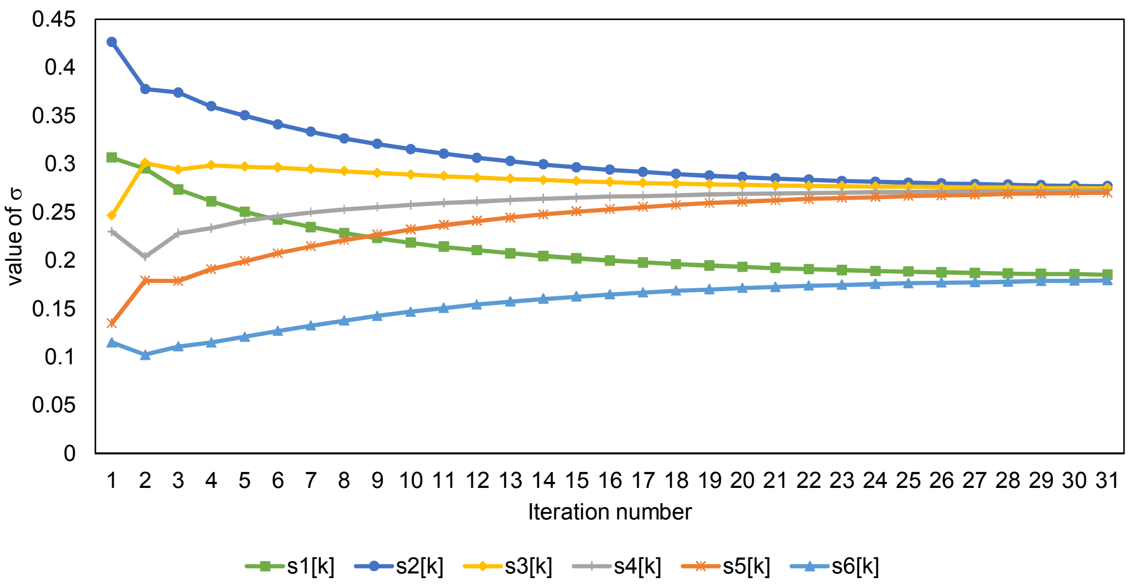

Figure 6.7: Evolution of Σ for each *DGAgent*. The value of Σ converges as number of iterations increase.

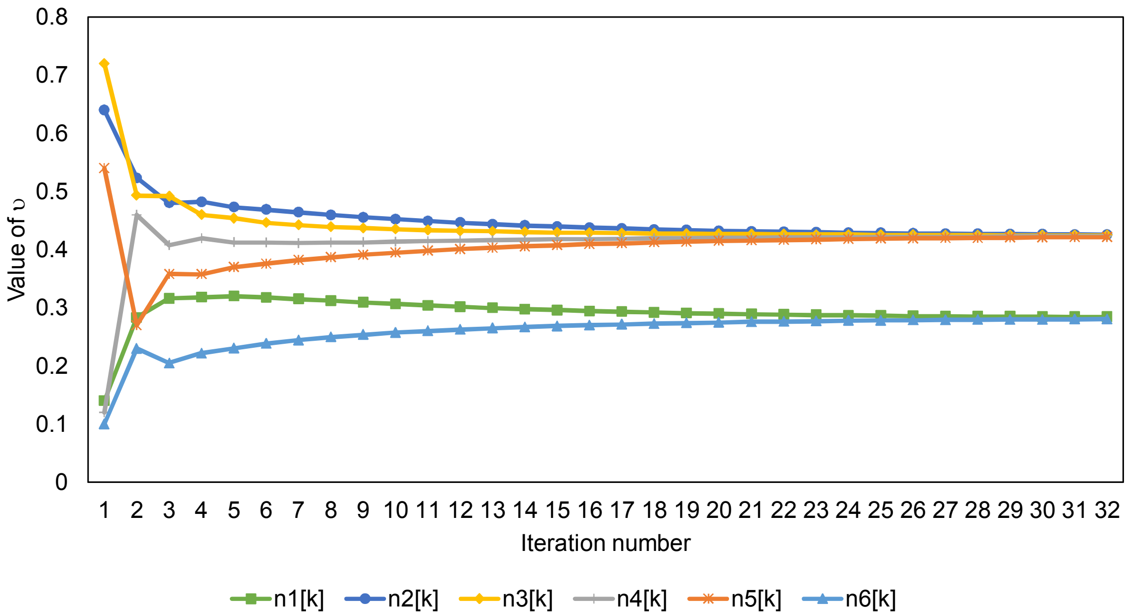

Figure 6.8: Evolution of ν for each *DGAgent*. The value of ν converges as number of iterations increase.

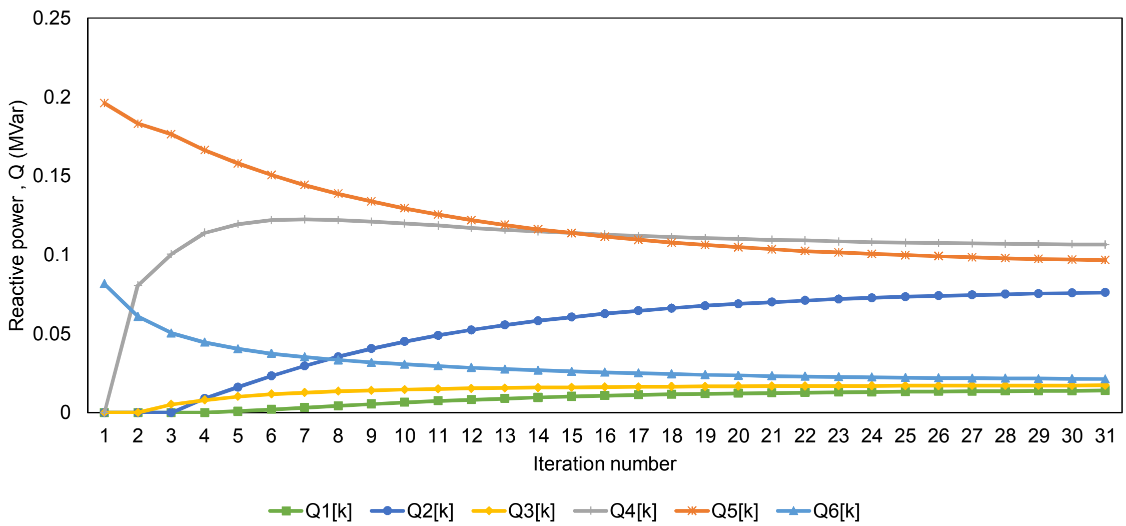

Figure 6.9: Evolution of Q for each *DGAgent*. The value of Q converges as number of iterations increase. Further it can be seen that Q remains in limits for each *DGAgent*.

32. Thus each *DGAgent* computes and exchange the values of the Σ, ν and Q at each step and stops after 32 iterations. Further this depends upon the number of Agents participating in the control process. A good way of stopping criteria is defining the error tolerance. As total required reactive power was $Q = 0.33$ and after performing this algorithm we have;

$$Q = \sum_{i=1}^{6} Q_i = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6$$

$$Q = 0.014 + 0.076 + 0.017 + 0.106 + 0.096 + 0.021 = 0.330$$

Further, this reactive power, Q for each *DGAgent* also satisfy the minimum and maximum constraints. As given below;

$$Q_i = \begin{cases} Q_1^{min} \le Q_1 \le Q_1^{max} : & -0.05 \le 0.014 \le 0.05 \\ Q_2^{min} \le Q_2 \le Q_2^{max} : & -0.27 \le 0.076 \le 0.27 \\ Q_3^{min} \le Q_3 \le Q_3^{max} : & -0.06 \le 0.017 \le 0.06 \\ Q_4^{min} \le Q_4 \le Q_4^{max} : & -0.36 \le 0.106 \le 0.36 \\ Q_5^{min} \le Q_5 \le Q_5^{max} : & -0.32 \le 0.096 \le 0.32 \\ Q_6^{min} \le Q_6 \le Q_6^{max} : & -0.07 \le 0.021 \le 0.07 \end{cases}$$

Figure 6.10 shows the voltage at all the buses after voltage support by the *DGAgents*. From figure, one can see that voltage at the critical bus ($bus735$) is well above the lower limit 0.95. Further, voltage at all the other buses is also with in the allowable limits. Figure 6.11 shows the voltage profile of bus 735 before and after voltage support by the DGs using distributed iterative algorithm.

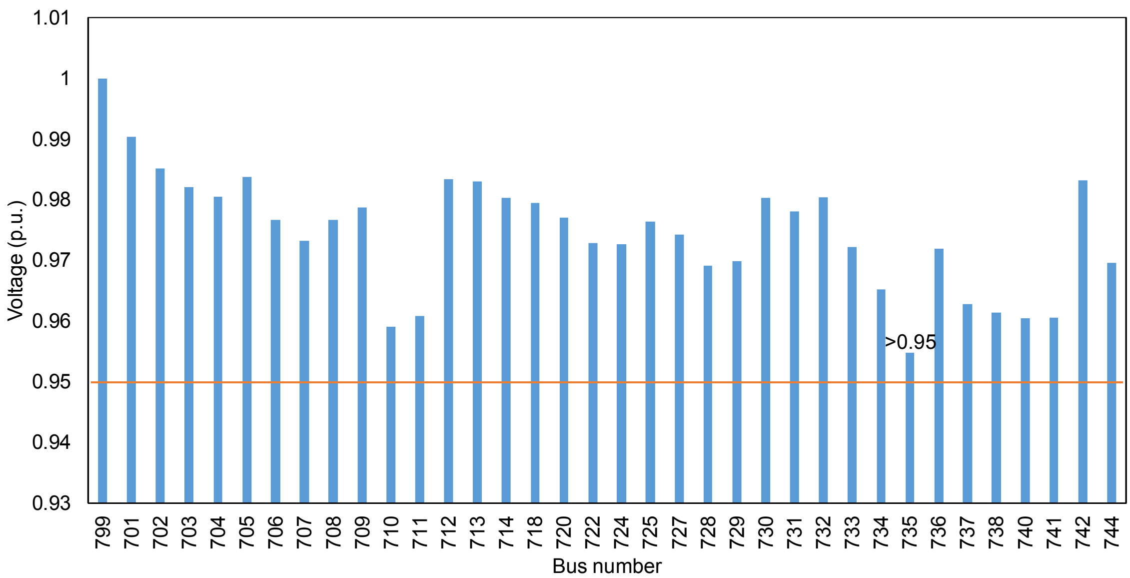

Figure 6.10: Voltage at all the buses after voltage support by the *DGAgents*. Voltage at the critical bus (735) is well above the lower limit.

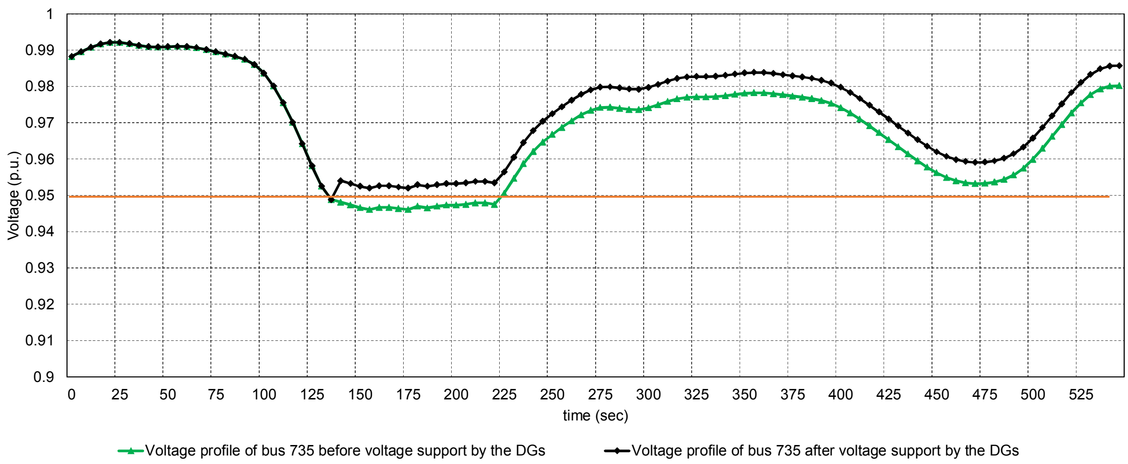

Figure 6.11: Voltage profile of bus 735 before and after voltage support by the DGs using agent based iterative algorithm.

6.3.3 Simulations considering communication network

In order to exhibit real communication, various communication scenarios were considered and communication traffic modeling was carried out and described in the next section.

6.3.4 Network Traffic Modeling

Communication modeling was carried out in OMNeT++ , a discrete event simulator. The whole network was modeled with three small (local area networks) LANs employing the Star topology. Since these LANs are apart, they are connected to each other with a backbone network consisting of two routers. The whole network is based on the Ethernet (IEEE 802.3) with Internet Protocol (IP) and Transmission Control Protocol (TCP) version 4. It is assumed that some amount of (uniformly distributed) background traffic is also going in the network. Multiple scenarios were created by varying the communication parameters and are given below;

- **Scenario-1:** In this scenario backbone bandwidth was considered to be 10Mbps. In order to create background traffic a packet after every 40 seconds was sent on the network.
- **Scenario-2:** This scenario has the same bandwidth as of scenario 1 (10Mbps), however background traffic was increased and a packet was sent over the network after every 2 seconds.
- **Scenario-3:** This scenario has more bandwidth as compared to the scenario 1 and scenario 2, which is 1Gbps. A packet after every 40 seconds was sent over the network to create the background traffic.
- **Scenario-4:** In this scenario, bandwidth was taken as 1Gbps and background traffic was generated by sending a packet after every 2 seconds.

Thus, these scenarios have different backbone bandwidths (10Mbps to 1Gbps) and the intensity (from a packet every 40 seconds to a packet every 2 seconds) of the background traffic. Table 6.2

enlists the four scenarios with communication parameters. The selection was based on the visibility of the effects of the communication and its parameter changes on the algorithm performance. Figure 6.13 shows communication network designed in OMNeT++ with low bandwidth and for scenario 1 and 2, while Figure 6.12 represents high bandwidth for scenario 3 and 4.

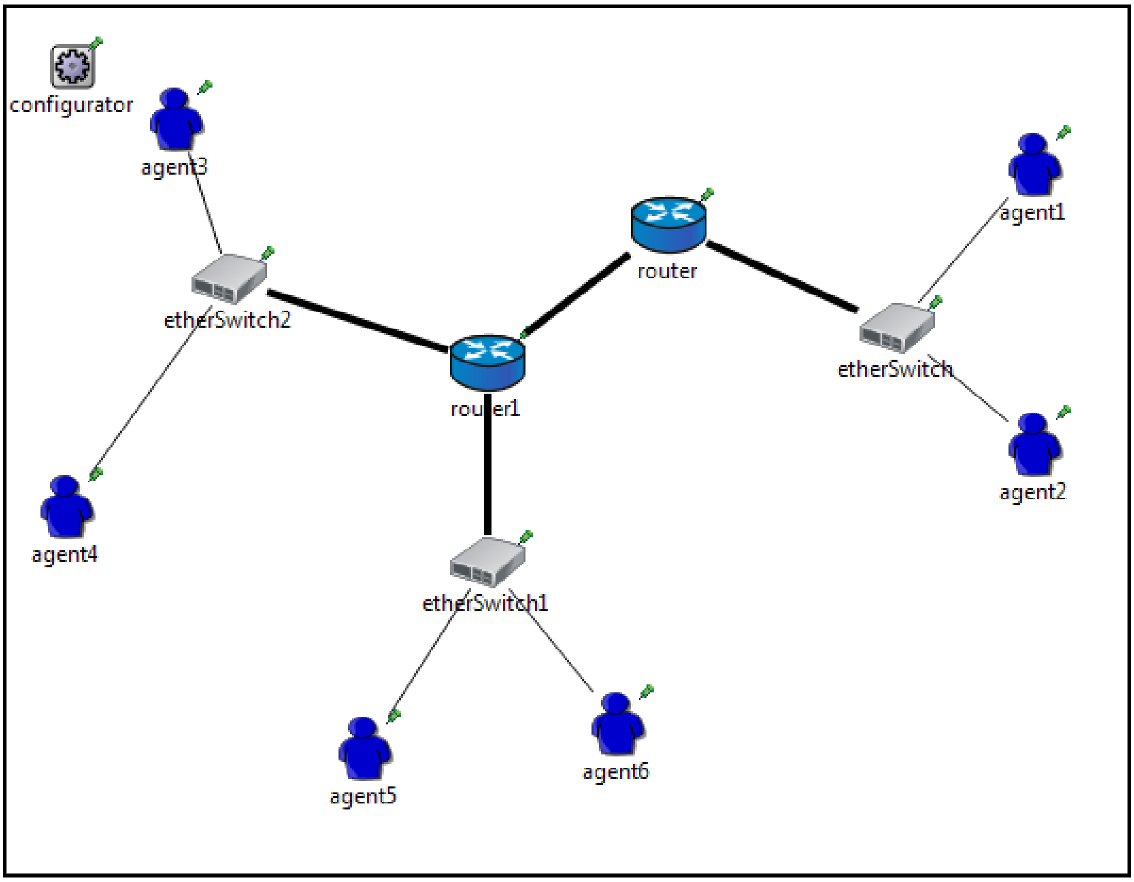

Figure 6.12: Communication network with high bandwidth(1Gbps).

6.3.5 Investigation of communication effects on Power System

In order to investigate the effects of communication changes on the power system, first system was simulated considering the ideal communication and then the same system was simulated considering the above mentioned four communication scenarios. Results of ideal communication case were compared with the communication scenarios. These simulations are explained next along-with the results.

6.3.6 Base case with no control

The system was simulated considering no control and voltage profile of selected buses (735, 737, 738, 711, 740, 741, 710) is presented in figure 6.14. These buses are located at the end of the feeder and have more chances of voltage violations. From figure it is clear that bus735 first violated the lower limit, thus it is considered as the target bus (critical point).

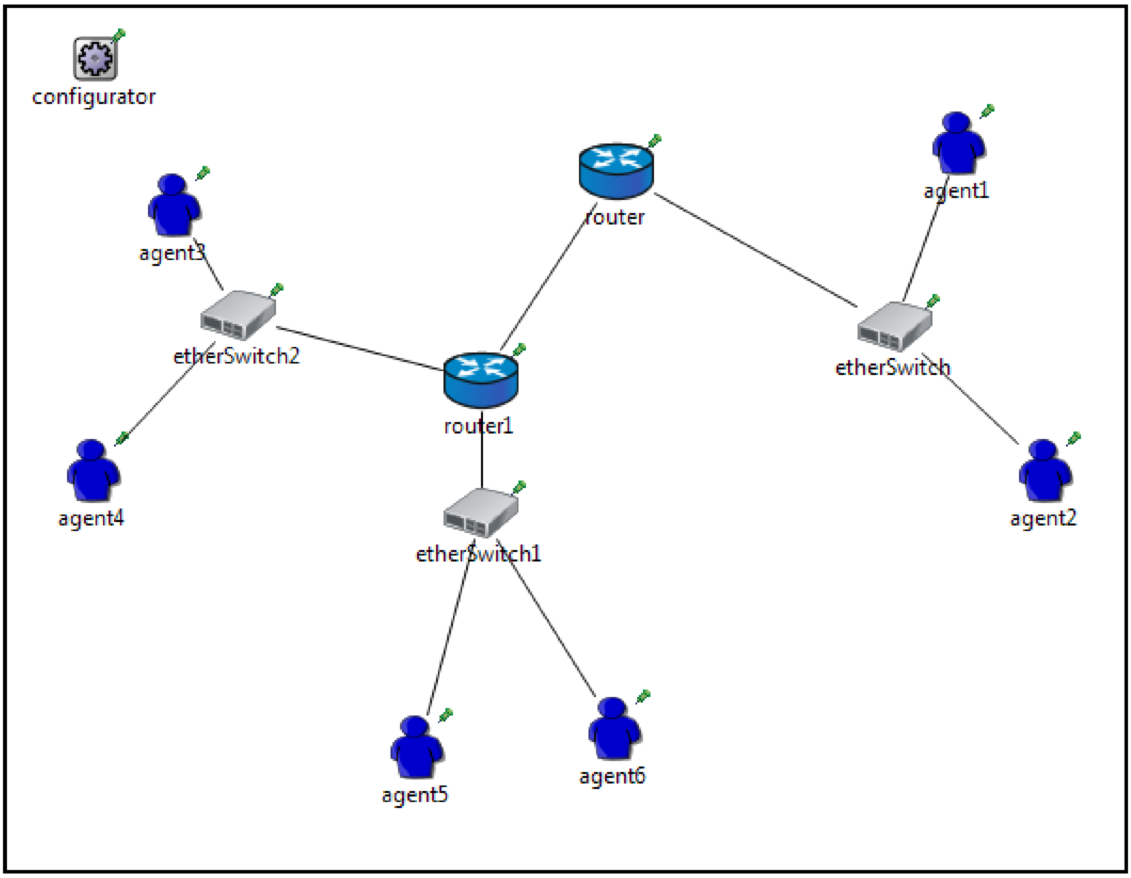

Figure 6.13: Communication network with low bandwidth(10Mbps).

Table 6.2: Parameters for Communication scenarios.

Network Scenarios	**Backbone Bandwidth**	**Background Traffic Intensity**
Scenario 1	10Mbps	1 Packet every 40 seconds
Scenario 2	10Mbps	1 packet every 2 seconds
Scenario 3	1Gbps	1 Packet every 40 seconds
Scenario 4	1Gbps	1 packet every 2 seconds

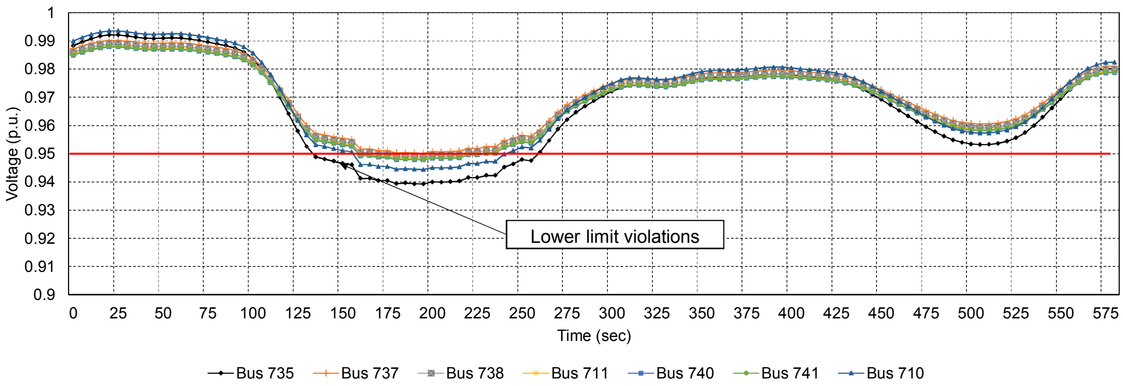

Figure 6.14: Voltage profile of some buses in the network. These buses are more likely to violate lower voltage limits.

6.3.7 Control using Distributed iterative algorithm considering ideal communication between agents

Distributed algorithm as explained in the previous section was used to remove the voltage violations (figure 6.14). At $time = 135$ sec voltage at bus 735 goes down from 0.95 p.u. Required reactive power for voltage boost of 0.02 p.u. was estimated as 0.67 and $DGAgent6$ starts the iterative algorithm to compute the new reactive power set points for all the DGs in the network. Figures 6.15, 6.16 and 6.17 show the evolution of σ, ν and Q respectively. Value of Q for all the agents was computed as;

$$Q_i^{new} = \begin{cases} Q_1^{new} = Q_1 + Q_1^{current} = 0.0372 \\ Q_2^{new} = Q_2 + Q_2^{current} = 0.1682 \\ Q_3^{new} = Q_3 + Q_3^{current} = 0.0454 \\ Q_4^{new} = Q_4 + Q_4^{current} = 0.2243 \\ Q_5^{new} = Q_5 + Q_5^{current} = 0.1989 \\ Q_6^{new} = Q_6 + Q_6^{current} = 0.0521 \end{cases}$$

It took 40 iterations for the algorithm to converge and computation of final required Q. After updating the reactive power of each DGs, voltage for bus numbers, 735,737,738,711,740,741,710, remains in allowable limit for all the time. It is to be noted that in base case without control, voltage at some buses also goes down gradually. However, voltage boost at bus 735 helps in increasing the voltage at other buses also. Figure 6.18 shows voltage at bus 735 with and without control. While voltage profile at other buses under observation(710,711,737,738, 740, 741) is given in figure 6.19, 6.20, 6.21, 6.22, 6.23 and 6.24, respectively. Further, as all the DGs are injecting reactive power into the system, voltage at DG buses will rise and is shown in figure 6.25. It is clear from the figure that voltage at all the generation buses is well within the limits. Also there is no delay in control action as it is considered that agents communicate with each other without any delay.

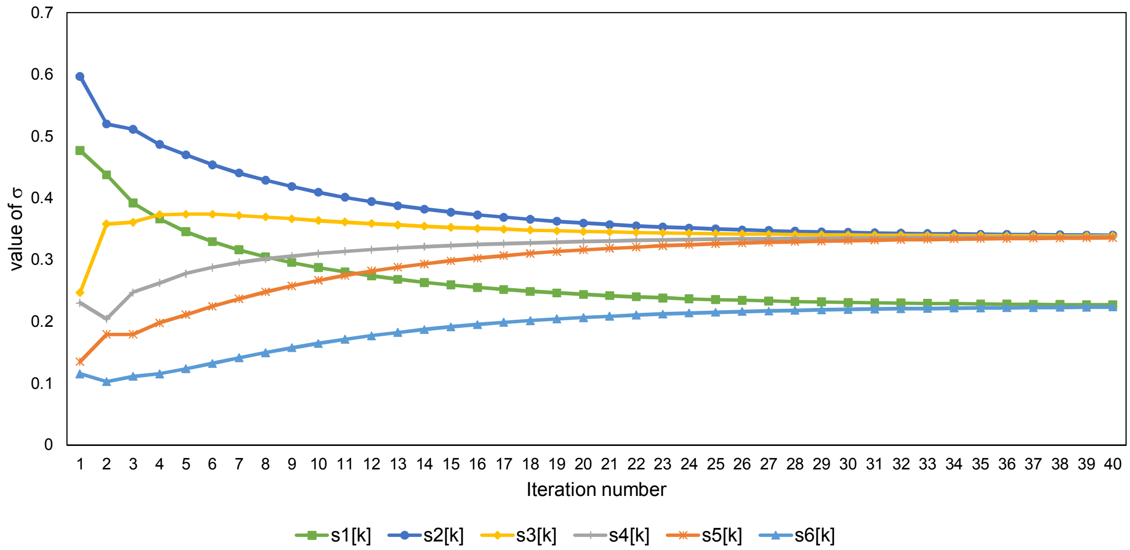

Figure 6.15: Evolution of σ for all the agents.

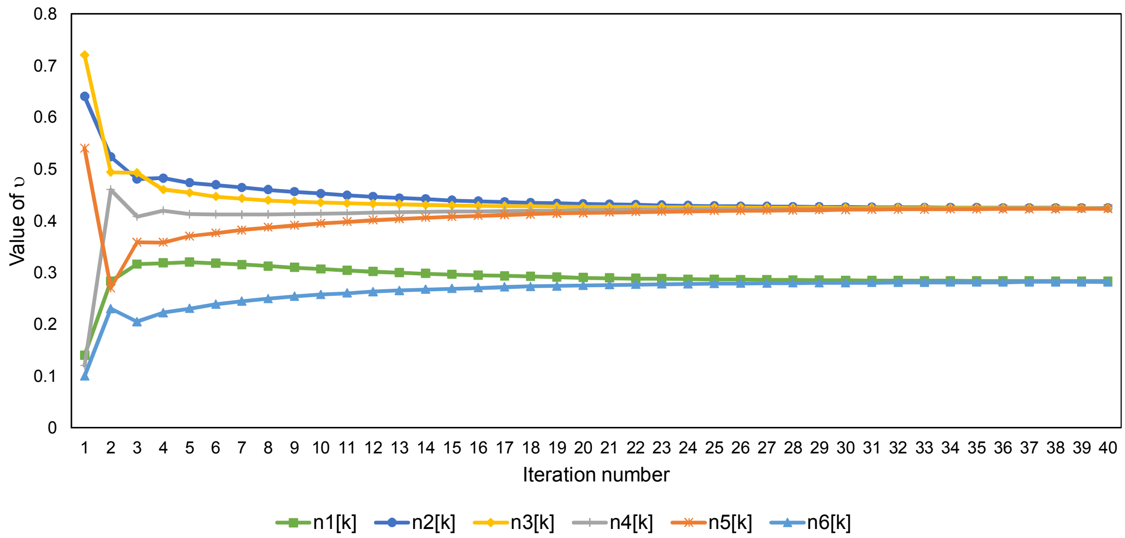

Figure 6.16: Evolution of ν for all the agents.

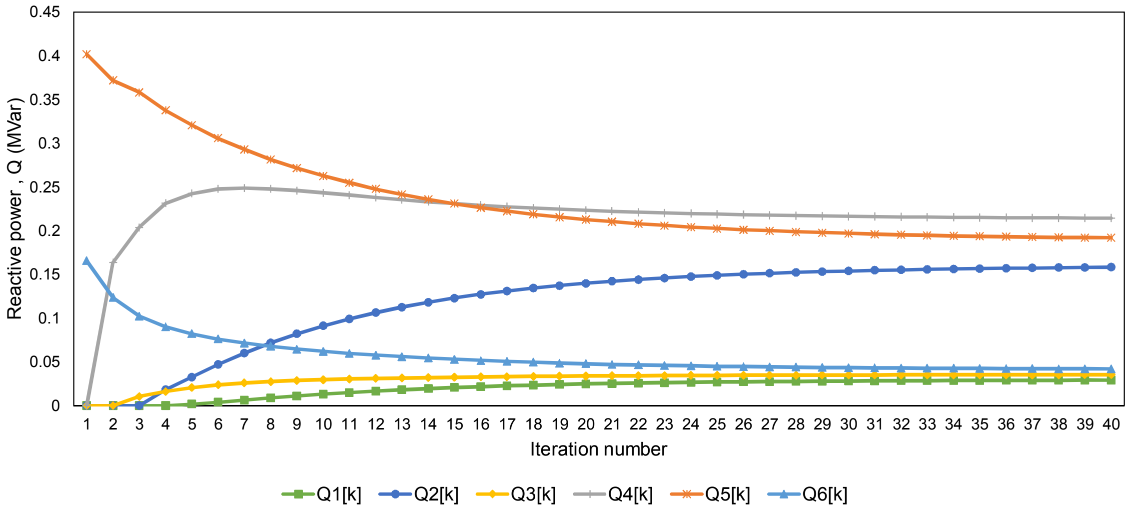

Figure 6.17: Evolution of Q for all the agents.

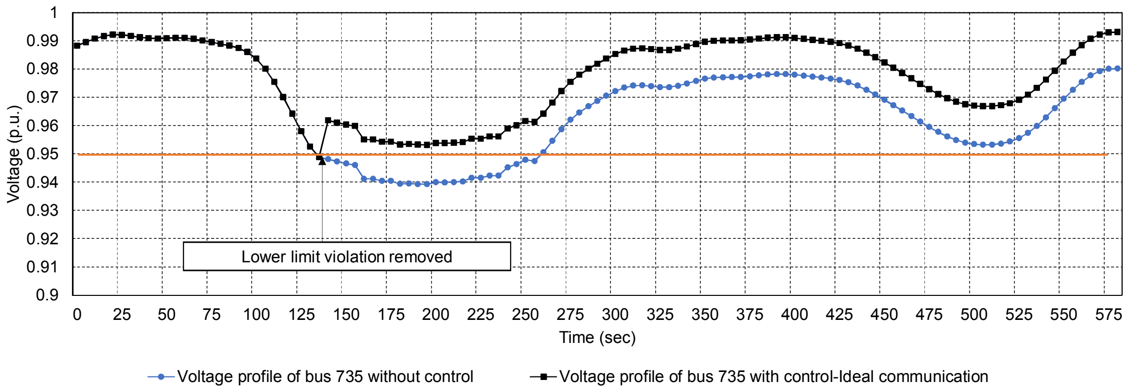

Figure 6.18: Voltage at bus 735 without and with control.

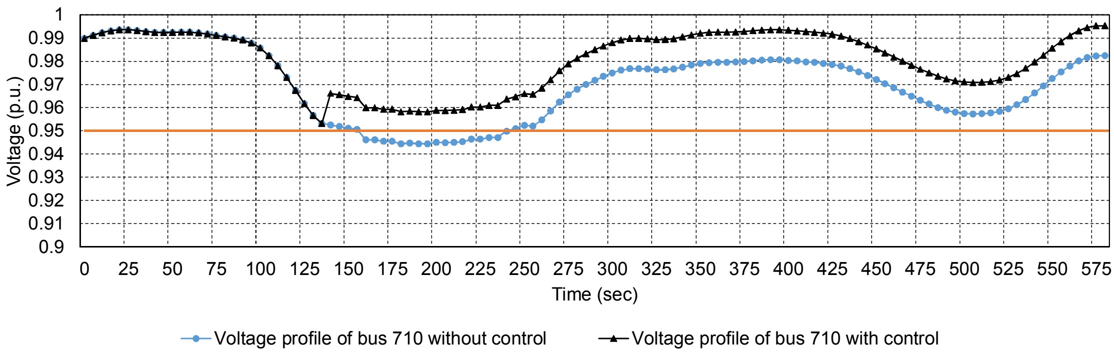

Figure 6.19: Voltage at bus 710 without and with control.

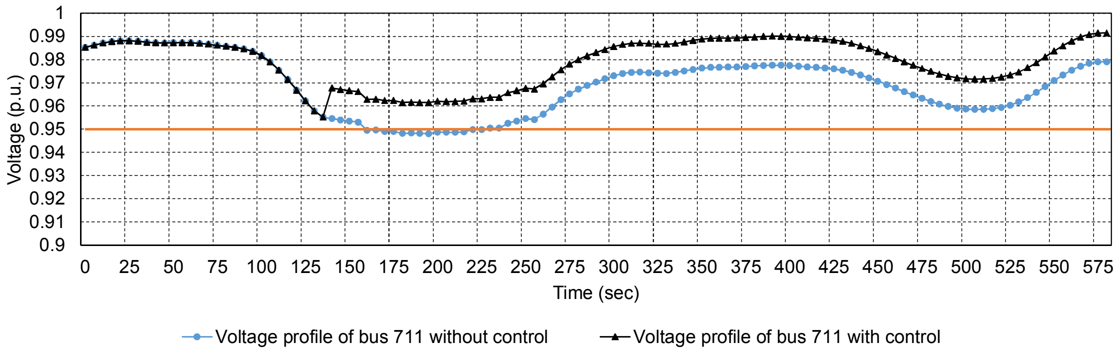

Figure 6.20: Voltage at bus 711 without and with control.

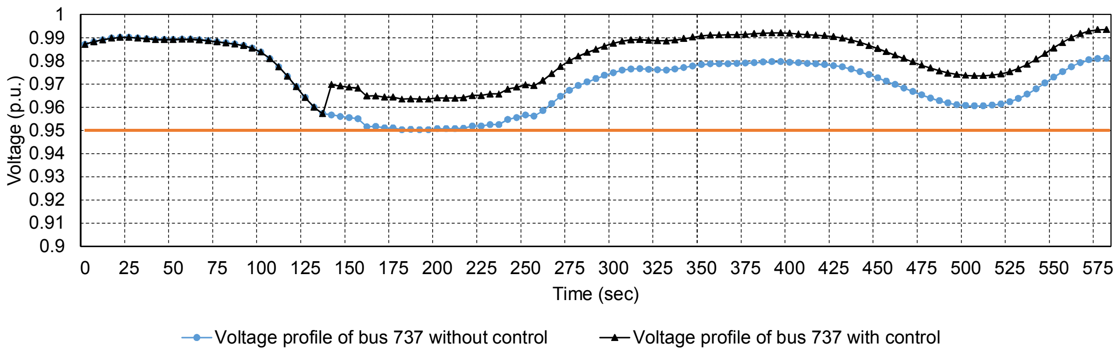

Figure 6.21: Voltage at bus 737 without and with control.

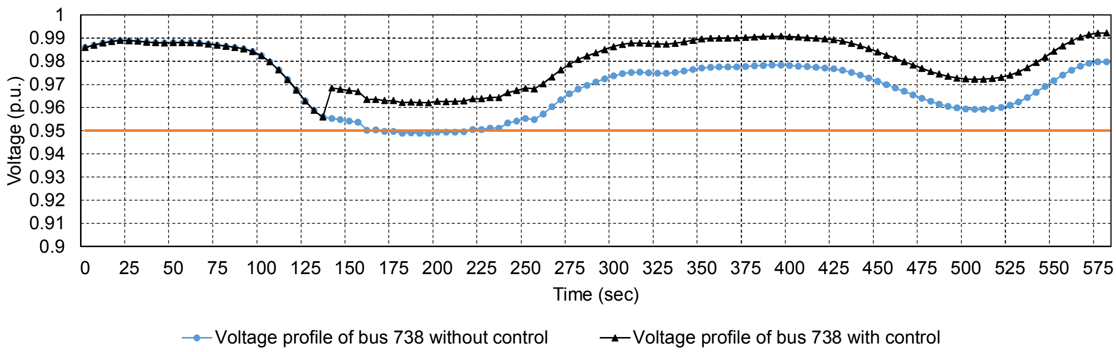

Figure 6.22: Voltage at bus 738 without and with control.

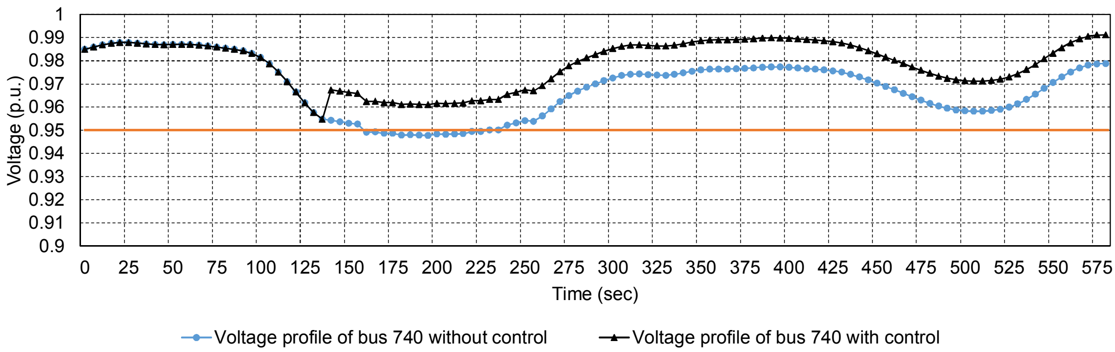

Figure 6.23: Voltage at bus 740 without and with control.

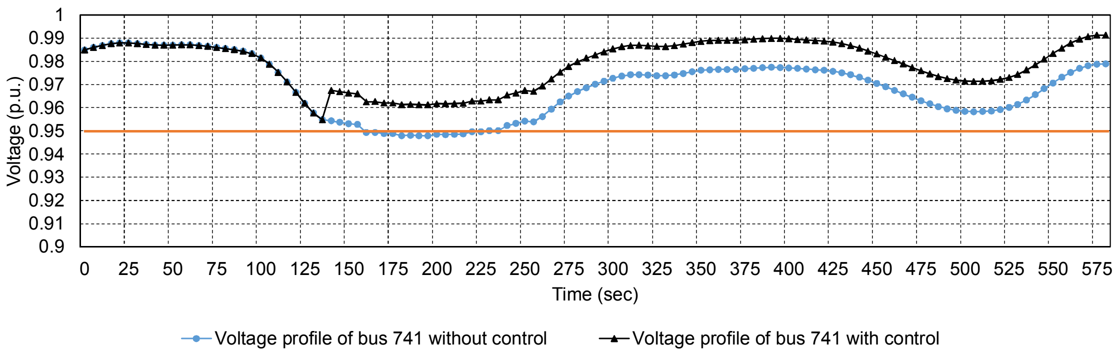

Figure 6.24: Voltage at bus 741 without and with control.

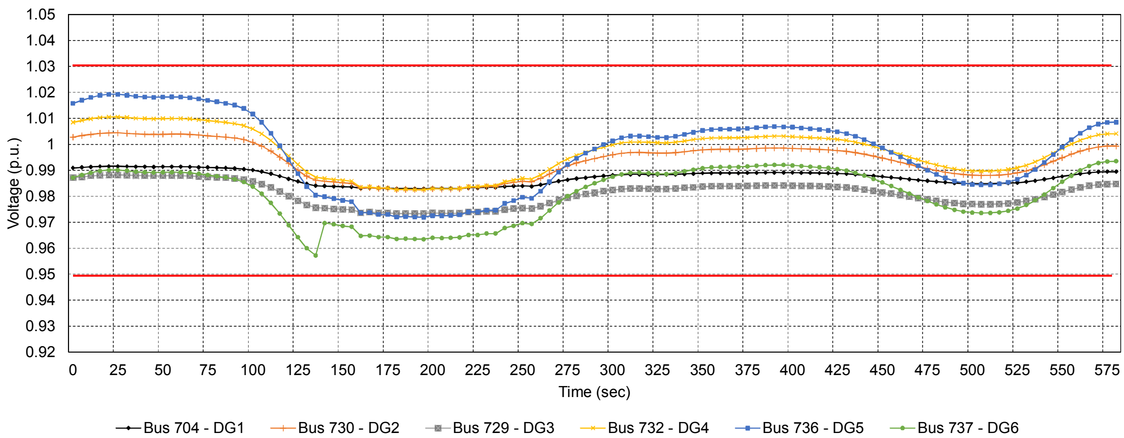

Figure 6.25: Voltage profile at generation buses with control

6.3.8 Control using distributed iterative algorithm considering communication network

As in case of ideal communication there is no delay due to exchange of messages between agents. However, this is unrealistic as practically there will be communication delays and it is very important to know the effects of this delay on the performance of the system. Thus, system was simulated again considering four simulation scenarios and the time taken by the agents to compute the final desired reactive power is given in table 6.3, while results for each scenario are given next.

Table 6.3: Time taken by the MAS algorithm to converge for the four scenarios.

Network Scenarios	Time (sec)
Reference-Scenario (ideal communication)	0
Scenario 1	43
Scenario 2	130
Scenario 3	35
Scenario 4	103

6.3.8.1 Scenario 1 - low bandwidth and low background traffic intensity:

In this scenario, a packet is generated every 40 seconds by each node in communication network to create low intensity background traffic. The backbone network (between the routers connecting) has a bandwidth of 10Mbps. From figure 6.26, it is clear that there is overall delay in control action by 43 seconds.

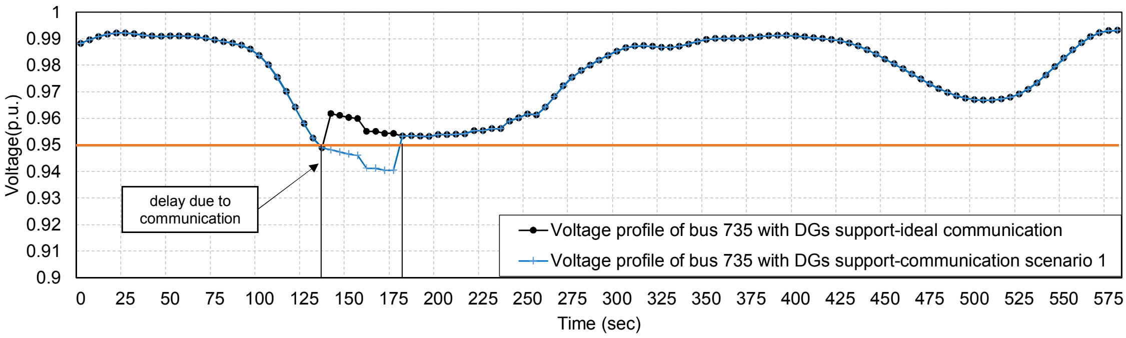

Figure 6.26: Voltage profile at bus 735 - ideal communication vs communication scenario 1.

6.3.8.2 Scenario 2 - low bandwidth and high background traffic intensity:

In this scenario, the bandwidth of the backbone network remains the same as previous scenario but now a packet is generated every 2 seconds by each node to create high intensity background traffic. In this case, it is clear from figure 6.27 that time taken by the control action is more as compared to scenario 1, which is 130 sec and almost four times more.

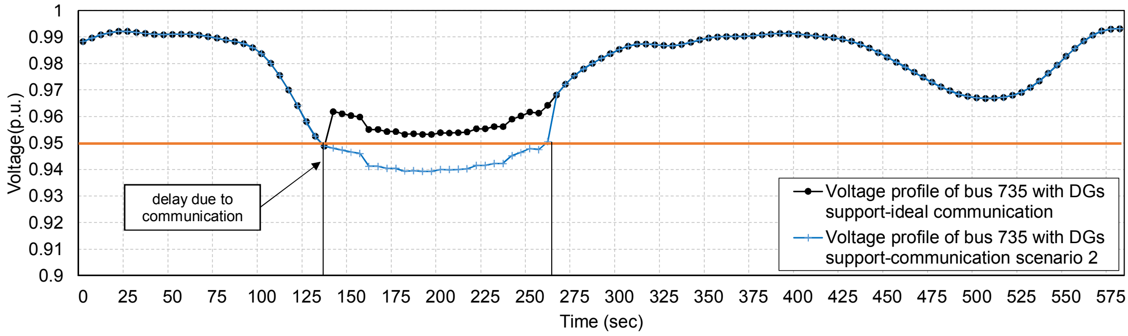

Figure 6.27: Voltage profile at bus 735 - ideal communication vs communication scenario 2.

6.3.8.3 Scenario 3 - high bandwidth and low background traffic intensity:

In this scenario, although a packet is generated after every 40 seconds by each node to create low intensity background traffic, bandwidth of the backbone network has been increased 10 times to 1Gbps. In this scenario, time taken by the control action is less than the scenario 1, which is due to increased bandwidth. Figure 6.28 shows voltage profile for scenario 3.

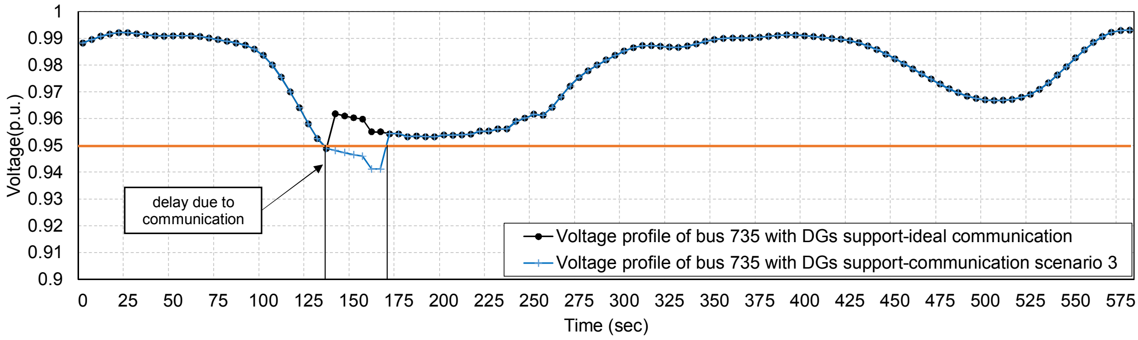

Figure 6.28: Voltage profile at bus 735 - ideal communication vs communication scenario 3.

6.3.8.4 Scenario 4 - high bandwidth and high background traffic intensity:

In this scenario, the bandwidth of the backbone network remains the same as previous scenario but now a packet is generated every 2 seconds by each node to create high intensity background traffic. In this case time taken by control action is more than scenario 3 but less than scenario 2. It indicates that bandwidth has effect on the overall time of control action. Figure 6.29 shows the voltage profile with delay.

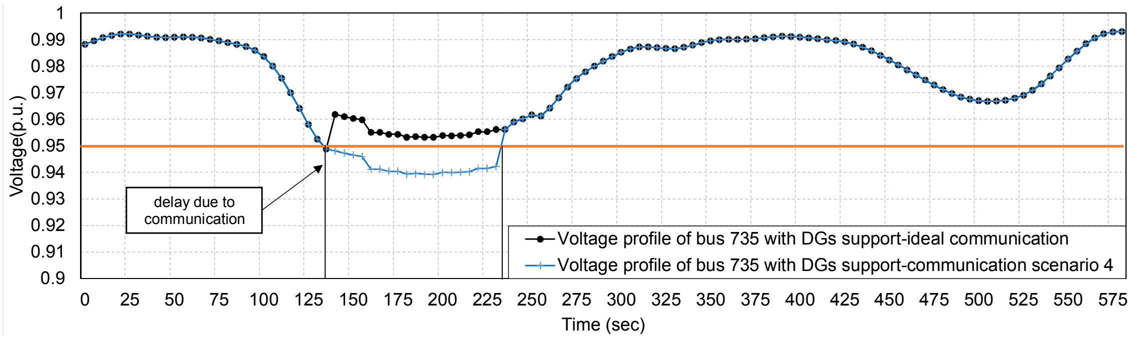

Figure 6.29: Voltage profile at bus 735 - ideal communication vs communication scenario 4.

7 Zone based Control using Multi-Agent System

7.1 Overview

This chapter presents hierarchical distributed approach for voltage control in distribution network using distributed generation. In chapter 5 purely decentralized control which is equivalent to primary control is presented. Further, a centralized control scheme based on FIPA contract-net-protocol is also developed and investigated. Chapter 6 presents a distributed iterative algorithm in which there is no need of central computation and control node. Every agent decides its reactive power set point according to an iterative algorithm by information exchange with the pre-defined neighbors.

These schemes proved to be effective on smoothing the voltage profile as all the generators in the network change their reactive power set points which result in net effect of voltage regulation. Control scheme used in chapter 5 required all the generators to communicate with only central node which does the decision making according to some rule for the control action. While in chapter 6 distributed control scheme was presented and there is no need of central controller in this scheme. However, in case of a large network more communication infrastructure required for information exchange with the central node (in case of central control scheme), which can result in increased communication cost and more information flow, even if the problem is local and can be reduced by the generators in the small area of the network. On the other hand, problem can arise when generators in a small area have not sufficient capacity to remove the voltage violation. In this case, small area should also be able to get support from generators in the neighboring areas. In this scenario size and requirements of the control area becomes very important for a control scheme which have not only good performance in terms of voltage profile improvement but also minimum communication requirements.

7.2 Dividing Network into Zones

The general idea behind zone formation is the delegation of autonomy and independence to subsystems in order to perform tasks which are localized in nature and do not require global knowledge of the whole system. A localized/zonal reactive power management for voltage control can be an appropriate approach due to local nature of reactive power and it is common practice among utilities to divide the whole system into many reactive power zones or voltage control areas.

Thus in this work whole distribution network has been divided into various local zones, each having agents comprising a Multi-agent system. Inside each MAS, agents can solve the problems(voltage control) locally and autonomously through coordination and co-operation between them, instead of waiting for the commands from central controller to perform control action. Further, each MAS can coordinate and cooperate with other systems to find the solutions, if needed.

However, it is a big challenge to find ideal number of control zones for a given network in order to achieve best autonomy and performance. It largely depends upon the criteria established for making zones as;

- **Physical proximity:** Physical proximity plays main role in defining a control zone. Nodes with close proximity cab be linked to the same zone as any change in near by node can have effect on the other nodes. Further cost of physical communication link also depends upon the distance between the nodes.

- **Availability of a certain resource:** In order to define any control zones, it is important to have certain resources which are required to fulfill the control objective. For example, for voltage control areas, there should be some generators which are capable of absorbing or injecting reactive power into the network.

- **control equipment:** Zone should have necessary equipment required for control process i.e. data processing unit for centralized control, monitoring and measurement devices at important points of the network.

- **Communication infrastructure:** Communication infrastructure is also an important feature for zone formation. Available of strong communication links between nodes can be included in the same zone.

- **Objective for zone formation:** Finally, objective of zone formation is also an important consideration for defining the zone area. A system in which a control action that utilizes the local equipment and has only effect in certain local area and also does not have effect on the global settings of the system is ideal for dividing into zones. However, if a change in local setting also have effect on larger part of the network, it must take care of such settings and should include the larger area.

- **Structure of the network:** While determining the zone physical structure should also be considered. For example, in radial network DGs on a particular branch can be grouped into the similar zone.

7.2.1 Zone Identification

There is no unique way for zone identification. One of the widely used method is devision of zones on the basis of electrical distance [BHP+09], [SSS10]. Electrical distance can be measured by different methods and some of the methods are listed below.

7.2.2 Electrical Distance

Zones based on electric distances ensure that the reactive power injection at any bus in a particular control area/zone is able to control the voltage at all the buses lying in the same zone. The amount of reactive power injected or absorbed at any bus can be determined by using the sensitivity matrix (i.e. inverse Jacobian matrix) of the system for a particular state of the power system. In literature following methods have been used for determining electrical distances between two nodes.

7.2.2.1 Bus Admittance

Bus admittance matrix can also be used for electrical distance calculations. Inverse of bus admittance matrix can be considered as distance matrix $[D]$ and elements d_{ij} represents the active and reactive power sensitivity with respect to voltage changes between bus i and j. Buses with small electrical distance will have higher impact on voltage changes. [BHP+09]

7.2.2.2 Sensitivity Based

The electrical distance between two nodes can be represented through sensitivity matrix $\partial V/\partial Q$. This matrix can be obtained after load flow computation. This is basically inverse of the Jacobian matrix [ZNBB04], [BNCP15]. In this work sensitivity based method was used and explained below.

Re-writing the equation 5.17

$$\begin{bmatrix} \Delta P[t] \\ \Delta Q[t] \end{bmatrix} = \begin{bmatrix} H & N \\ K & L \end{bmatrix} \begin{bmatrix} \Delta \vartheta[t] \\ \Delta V[t] \end{bmatrix} \tag{7.1}$$

By the using the supposition of decoupling active and reactive power we can write equation 7.1 for only voltage and reactive power as;

$$\Delta Q[t] = [L]\Delta V[t] \tag{7.2}$$

In generalized form we can write

$$\Delta Q = [L]\Delta V$$
$$\Delta V = [L]^{-1}\Delta Q$$

where

$$L^{-1} = \left[\tfrac{\partial Q}{\partial V}\right]^{-1}$$

Thus

$$\Delta V = \left[\tfrac{\partial Q}{\partial V}\right]^{-1}\Delta Q$$
$$\Delta V = \frac{\partial V}{\partial Q}\Delta Q \tag{7.3}$$

Here $\frac{\partial V}{\partial Q}$ is inverse of part of power flow Jacobian matrix and is called sensitivity matrix. The elements of sensitivity matrix represent the variation in voltage with respect to the variation in reactive power at a certain bus. From this matrix we can obtain the matrix of voltage attenuation which quantifies the voltage variation with respect to the certain bus. By dividing the elements of each column of sensitivity matrix by the diagonal term we will get this matrix of attenuation. Thus voltage coupling between two buses i and j can be expressed by the variable of attenuation and given below;

$$\Delta V_i = \alpha_{ij} \Delta V_j \tag{7.4}$$

where

$$\alpha_{ij} = \frac{\partial V_i}{\partial Q_j} / \frac{\partial V_j}{\partial Q_j} \tag{7.5}$$

In order to have symmetric property, the formulation for electrical distance between two nodes is adopted from [LSLP89] where

$$D_{ij} = D_{ji} = -Log(\alpha_{ij}.\alpha_{ji}) \tag{7.6}$$

Figure 7.1 shows step wise calculation of electrical distance.

7.2.3 Method of Zone Formation

Zones are to be formed in a way that each zone must contains at least two buses which are capable of injection/absorption of reactive power such as buses with generator, synchronous condenser, tap change transformers etc. (This is same as described above that requirement of a certain resource should be kept in mind for a zone formation). In this work only distributed generations were considered for voltage control, therefore, zones were formed in a way that at least two buses with distributed generator is present. If clustering algorithm found only one generation bus in a zone then nearby generation bus is included in the same zone.

The idea behind zone formation is two fold. One is as, it is fact that issues on a certain bus voltage are localized in nature i.e. it will have effect on nearby buses. Thus a local control action will be enough to remove any violation in the voltage and if we define some zones and controller acts only in this limited zone, it will be more efficient and require less effort. The other aspect is information exchange. However, there is no way to find out number of zones in a given network, which are best in term of control effort and performance. In this work, criteria for determining the number of zones are on the based of amount of information exchange between agents and voltage profile of the network.

In order to find the suitable number of zones, network was investigated from a single zone to n number of zones, where n is the total number of generation buses in the network. In fact, these n zones imply that the system is purely decentralized. While single zone means centralized system. K-mean clustering algorithm was used to determine buses in each zone on the basis of electrical

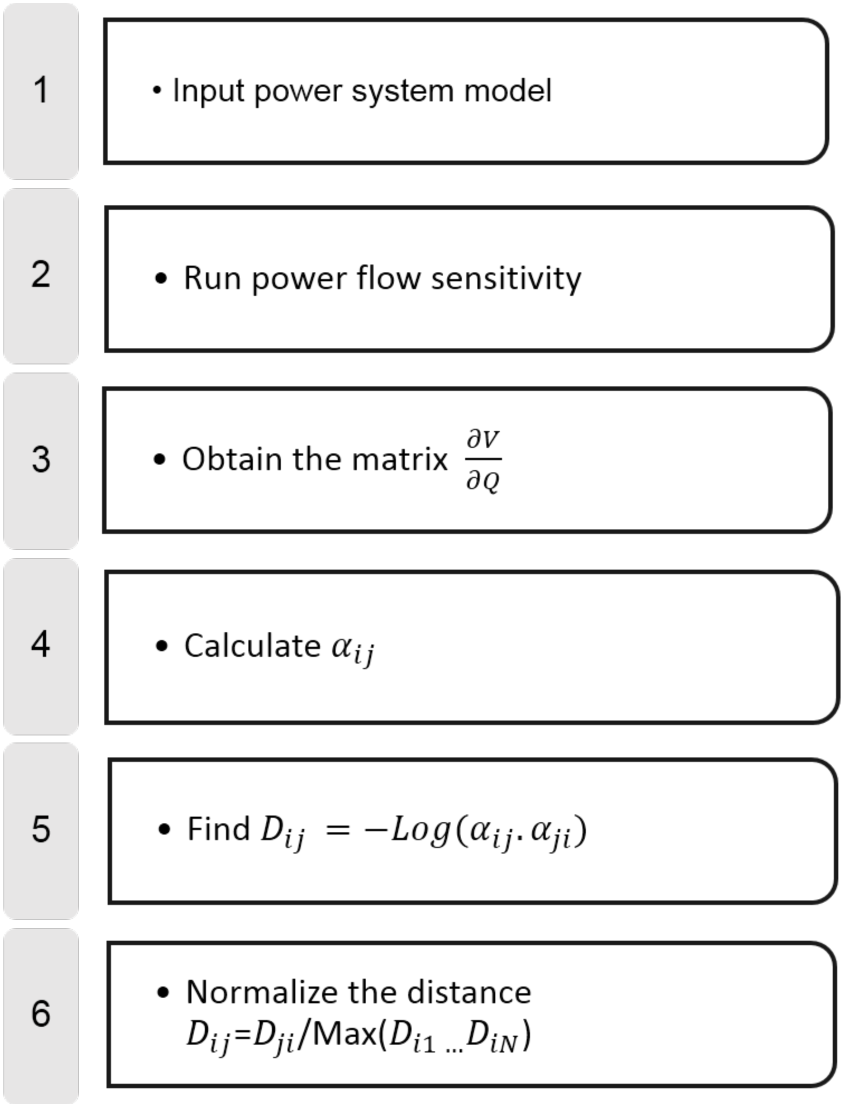

Figure 7.1: Steps for calculation of electrical distance between buses.

distance. Pseudo-code given below shows how zones are determined in each division.

Algorithm 7.1: Algorithm for zone formation

```
Result: Zones with BusNumbers
input : Set Number of Divisions N_D ;
Distance Matrix D ;
for i=0 to N_D do
    Set Number of Zones = i ;
    Run K-mean Algorithm;
    for j=0 to i do
        Analyse each j ;
        if DG Buses in Zone j < 2 then
            include DG Bus from nearest zone;
```

7.3 Zone based control by agents

This section provides details about the agents definition and algorithms for voltage control using reactive power. The whole network is divided into different number of zones and upon any voltage violation in a particular zone, only agents in the zone participate in the remedial measures. Three types of agents were defined for the zone based voltage control scheme. These are;

- **DGAgent:** *DGAgents* represents distributed generators in the network. These agents communicate with the *ZoneAgent* and carry out their control action.
- **MonitoringAgent:** *MonitoringAgent* represents the buses in the network and continuously monitor the bus voltage. In case of violation, it starts voltage control process by sending message to *ZoneAgent* or *DGAgents* as per algorithm.
- **ZoneAgent:** *ZoneAgent* is responsible for the voltage control process in a specific zone. It coordinates with the *DGAgents* in the zone for reactive power dispatch. It also maintains the list of *DGAgents* in the zone. Further, it can also communicates with the other *ZoneAgents* if required. Algorithm for *ZoneAgent* is given next.

Algorithm 7.2: Coordination and control algorithm for each *ZoneAgent i*

```
if Mode = 1 then
    ΔV_i ← M_i, receive change in voltage from monitoring agent ;
    set Mode = 0 ;
    Call-For-Proposal(ΔQ_k → DG_j, j = 1,2,....m);
    Receive Proposals (Q_j^limits, Q_j^current, S_j) ← A_j, j = 1,2,...m;
    if (received all responses )||(deadline reached) then
        List ← Descend(S_j, Q_j^available), j = 1,2,...k, k =number of proposals received
        Accept_Proposals (ΔQ_j S_j = ΔV_i) from A_h h ∈ List;
        if (ΔQ_j S_j < ΔV_i) then
            Calculate (ΔV_i^Remaining=ΔQ_j S_j - ΔV_i);
            send ΔV_i^Remaining to neighboring ZoneAgent i + 1 ;
        MessageDone ← A_h ;
        SendMessage → M_j;
        set Mode = 1;
```

Table 7.1: Generation data for IEEE 123 node network

DG Number	P(MW)	Q(MVar)	Q^{max}	$\Delta V/\Delta Q$	Location Bus
DG01	0.1	0.01	0.04	0.0201	2
DG02	0.1	0.01	0.04	0.0243	4
DG03	0.01	0.001	0.004	0.0262	5
DG04	0.05	0.01	0.02	0.0299	6
DG05	0.1	0.01	0.04	0.0275	12
DG06	0.1	0.01	0.04	0.0281	13
DG07	0.01	0.001	0.004	0.0373	17

Continued on next page

Table 7.1 – continued from previous page

DG Number	P(MW)	Q(MVar)	Q^{max}	$\Delta V/\Delta Q$	Location Bus
DG08	0.01	0.001	0.004	0.0377	16
DG09	0.01	0.001	0.004	0.0378	11
DG10	0.05	0.01	0.02	0.0500	22
DG11	0.1	0.01	0.04	0.0533	24
DG12	0.1	0.01	0.04	0.0506	28
DG13	0.05	0.01	0.02	0.0558	27
DG14	0.1	0.01	0.04	0.0604	32
DG15	0.1	0.01	0.04	0.0584	30
DG16	0.05	0.01	0.02	0.0361	53
DG17	0.1	0.01	0.04	0.0446	56
DG18	0.1	0.01	0.04	0.0463	58
DG19	0.1	0.01	0.04	0.0502	59
DG20	0.1	0.01	0.04	0.0551	62
DG21	0.1	0.01	0.04	0.0639	65
DG22	0.1	0.01	0.04	0.0512	36
DG23	0.1	0.01	0.04	0.0987	114
DG24	0.1	0.01	0.04	0.0496	42
DG25	0.01	0.001	0.004	0.0572	48
DG26	0.01	0.001	0.004	0.0585	49
DG27	0.01	0.001	0.004	0.0647	51
DG28	0.01	0.001	0.004	0.0599	46
DG29	0.01	0.001	0.004	0.0925	111
DG30	0.05	0.01	0.02	0.0800	107
DG31	0.05	0.01	0.02	0.0727	103
DG32	0.05	0.01	0.02	0.0640	101
DG33	0.05	0.01	0.02	0.0643	98
DG34	0.1	0.01	0.04	0.0613	72
DG35	0.05	0.01	0.02	0.0775	75
DG36	0.1	0.01	0.04	0.0703	78
DG37	0.05	0.01	0.02	0.0929	84
DG38	0.1	0.01	0.04	0.0885	83
DG39	0.1	0.001	0.04	0.0812	88
DG40	0.1	0.01	0.04	0.0785	87
DG41	0.1	0.01	0.04	0.0854	90
DG42	0.1	0.01	0.04	0.0894	92
DG43	0.1	0.02	0.04	0.0876	93
DG44	0.1	0.01	0.04	0.0945	96
DG45	0.1	0.01	0.04	0.0559	31
DG46	0.05	0.01	0.02	0.0635	33
DG47	0.05	0.01	0.02	0.0846	450
DG48	0.1	0.01	0.04	0.0595	61
DG49	0.1	0.01	0.04	0.0599	64
DG50	0.1	0.01	0.04	0.0275	9

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Table 7.1 – continued from previous page

DG Number	P(MW)	Q(MVar)	Q^{max}	$\Delta V/\Delta Q$	Location Bus
DG51	0.1	0.01	0.04	0.0702	70
DG52	0.1	0.01	0.04	0.0651	69
DG53	0.1	0.01	0.04	0.0449	23
DG54	0.1	0.03	0.04	0.0731	79
DG55	0.01	0.001	0.004	0.0378	10

Table 7.2: Total number of zones and bus numbers in each zone.

Total Zones	Zone	Buses Numbers
4	1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 34, 52, 53, 54, 55, 56, 152, 149
	2	18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 29, 30, 40, 41, 42, 43, 44, 45, 37, 38, 31, 32, 33, 35, 36, 49, 50, 51, 46, 47, 28, 250, 151, 39, 135
	3	58, 59, 60, 61, 62, 63, 64, 65, 66, 71, 67, 72, 68, 73, 69, 74, 70, 75, 99, 97, 98, 105, 110, 106, 111, 107, 112, 108, 113, 109, 114, 57, 610, 160, 100, 101, 102, 103, 450, 300, 197, 104
	4	76, 77, 78, 79, 80, 81, 86, 82, 87, 83, 88, 84, 85, 96, 93, 89, 94, 90, 95, 91, 92
7	1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 34, 152, 149
	2	25, 29, 30, 28, 250
	3	58, 59, 60, 61, 62, 63, 64, 65, 66, 71, 67, 72, 68, 73, 69, 74, 70, 75, 99, 97, 98, 105, 110, 106, 111, 107, 112, 108, 113, 109, 114, 57, 610, 160, 100, 101, 102, 103, 450, 300, 197, 104
	4	76, 77, 78, 79, 80, 81, 86, 82, 87, 83, 88, 84, 85, 96, 93, 89, 94, 90, 95, 91, 92
	5	26, 27, 31, 32, 33
	6	40, 41, 42, 43, 44, 45, 37, 38, 35, 36, 49, 50, 51, 52, 53, 54, 55, 56, 46, 47, 48, 151, 39
	7	18, 19, 20, 21, 22, 23, 24, 135
10	1	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 34, 152, 149
	2	25, 29, 30, 28, 250
	3	86, 87, 88, 96, 93, 89, 94, 90, 95, 91, 92
	4	76, 77, 78, 79, 80, 81, 82, 83, 84, 85
	5	26, 27, 31, 32, 33
	6	40, 41, 42, 43, 44, 45, 37, 38, 35, 36, 49, 50, 51, 46, 47, 48, 151, 39
	7	18, 19, 20, 21, 22, 23, 24, 135
	8	105, 110, 106, 111, 107, 112, 108, 113, 109, 114, 101, 102, 103, 300, 104
	9	58, 59, 52, 53, 54, 55, 56, 57
	10	60, 61, 62, 63, 64, 65, 66, 71, 67, 72, 68, 73, 69, 74, 70, 75, 99, 97, 98, 610, 160, 100, 450, 197
	1	8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 34, 152
	2	25, 29, 30, 28, 250

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13

Table 7.2 – continued from previous page

Total Zones	Zone	Buses Numbers
	3	86, 87, 88, 96, 93, 89, 94, 90, 95, 91, 92
	4	77, 78, 79, 80, 81, 82, 83, 84, 85
	5	26, 27, 31, 32, 33
	6	40, 41, 42, 43, 44, 45, 37, 38, 35, 36, 49, 50, 51, 46, 47, 48, 151, 39
	7	18, 19, 20, 21, 22, 23, 24, 135
	8	110, 111, 112, 113, 109, 114
	9	58, 59, 52, 53, 54, 55, 56, 57
	10	105, 106, 107, 108, 101, 102, 103, 300, 104
	11	1, 2, 3, 4, 5, 6, 7, 149
	12	71, 76, 67, 72, 68, 73, 69, 74, 70, 75, 99, 97, 98, 100, 450, 197
	13	60, 61, 62, 63, 64, 65, 66, 610, 160
16	1	7, 8, 9, 10, 11, 12, 14
	2	25, 29, 30, 28, 250
	3	86, 87, 88, 96, 93, 89, 94, 90, 95, 91, 92
	4	76, 77, 78, 79, 80
	5	26, 27, 31, 32, 33
	6	40, 41, 42, 43, 44, 45, 37, 38, 35, 36, 49, 50, 51, 46, 47, 48, 151, 39
	7	18, 19, 20, 21, 22, 23, 24, 135
	8	110, 111, 112, 113, 109, 114
	9	52, 53, 54, 55, 56
	10	105, 106, 107, 108, 101, 102, 103, 300, 104
	11	1, 2, 3, 4, 5, 6, 149
	12	71, 67, 72, 68, 73, 69, 74, 70, 75, 99, 97, 98, 100, 450, 197
	13	60, 61, 62, 63, 64, 65, 66, 610, 160
	14	81, 82, 83, 84, 85
	15	13, 15, 16, 17, 34, 152
	16	58, 59, 57
19	1	7, 8, 9, 12
	2	25, 29, 30, 28, 250
	3	86, 87, 88, 96, 93, 89, 94, 90, 95, 91, 92
	4	76, 77, 78, 79, 80
	5	26, 27, 31, 32, 33
	6	40, 41, 42, 43, 44, 45, 37, 38, 35, 36, 49, 50, 51, 46, 47, 48, 151, 39
	7	18, 19, 20, 21, 22, 23, 24, 135
	8	110, 111, 112, 113, 109, 114
	9	52, 53, 54, 55, 56
	10	105, 106, 107, 108, 101, 102, 103, 300, 104
	11	1, 2, 3, 4, 5, 6, 149
	12	67, 72, 73, 74, 75, 99, 97, 98, 100, 450, 197
	13	71, 68, 69, 70
	14	81, 82, 83, 84, 85
	15	13, 15, 16, 17, 34, 152
	16	58, 59, 57
	17	10, 11, 14
	18	63, 64, 65, 66

Continued on next page

Table 7.2 – continued from previous page

Total Zones	Zone	Buses Numbers
	19	60, 61, 62, 610, 160
22	1	7, 8, 9, 12
	2	25, 29, 30, 28, 250
	3	86, 87, 88, 96, 93, 89, 94, 90, 95, 91, 92
	4	77, 78, 79, 80
	5	31, 32
	6	40, 41, 42, 43, 44, 45, 37, 38, 35, 36, 49, 50, 51, 46, 47, 48, 151, 39
	7	23, 24
	8	110, 111, 112, 113, 109, 114
	9	52, 53, 54, 55, 56
	10	105, 106, 107, 108, 101, 102, 103, 300, 104
	11	1, 2, 3, 4, 5, 6, 149
	12	76, 67, 72, 73, 74, 75, 97, 197
	13	71, 68, 69, 70
	14	81, 82, 83, 84, 85
	15	13, 15, 16, 17, 34, 152
	16	58, 59, 57
	17	10, 11, 14
	18	63, 64, 65, 66
	19	60, 61, 62, 610, 160
	20	99, 98, 100, 450
	21	18, 19, 20, 21, 22, 135
	22	26, 27, 33

7.4 Simulation & Results

7.4.1 1 Division - Single System

One division corresponds to the single system. It means there is only one centralized control scheme for the whole system. Voltage at bus number 85 goes down from 0.95 at time $t = 28$ seconds. $MonitoringAgent$ sends request to the zone agent for control action and a message is sent to all the DGAgents in the network, according to the algorithm 7. Figure 7.4 shows the voltage profile of some buses. From figure it is clear that voltage at bus 85 goes down and has minimum voltage. Thus, this bus was taken as the target bus. Figure 7.5 shows the voltage at the selected buses after control. If we consider Total Messages=T_{msg}, Useful Messages=U_{msg} and Extra Messages=E_{msg} while values for these messages are are $T_{msg} = 124$, $U_{msg} = 26$ and $E_{msg} = 98$ then Message efficiency, $M_{efficiency}$, is given below;

$$M_{efficiency} = \frac{T_{msg} - E_{msg}}{T_{msg}} = \frac{124 - 98}{124} = 0.2096$$

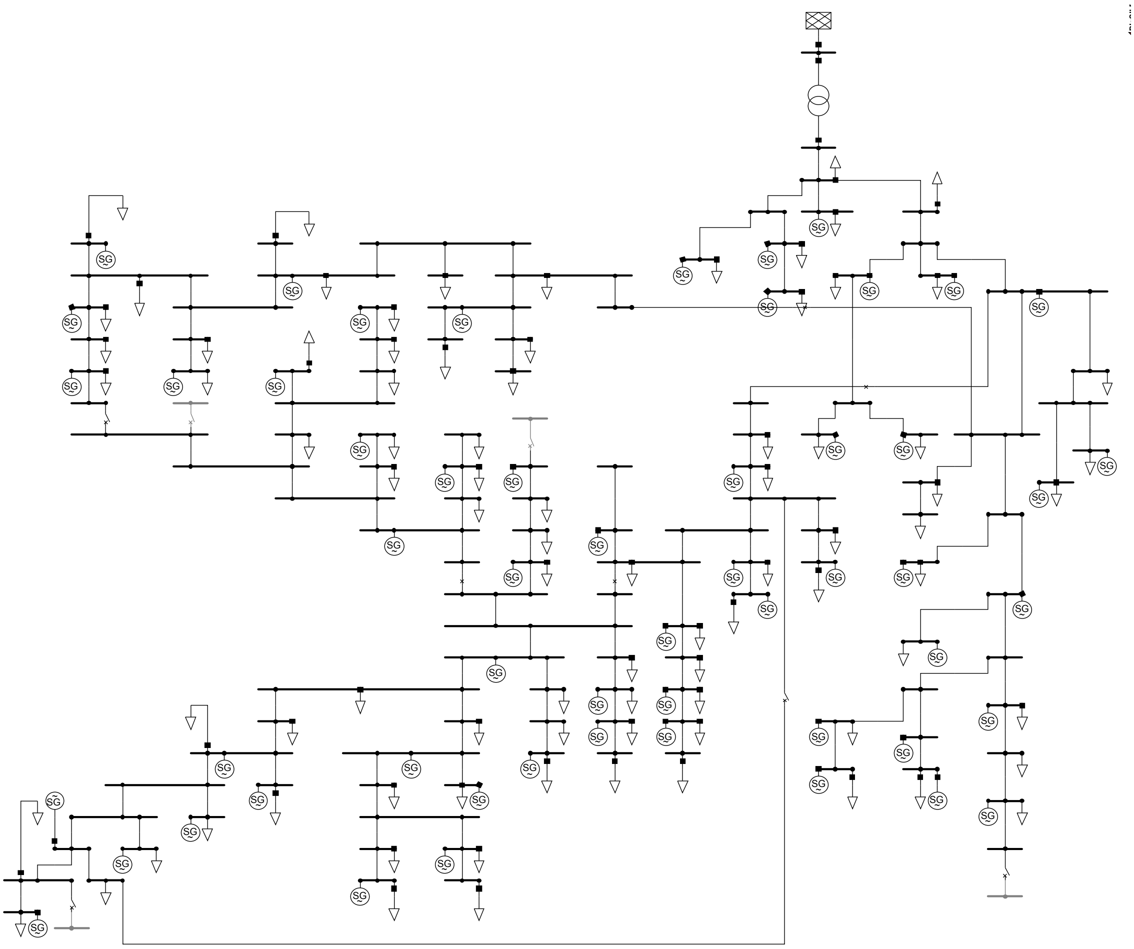

Figure 7.2: Modified IEEE123 bus system including distributed generation.

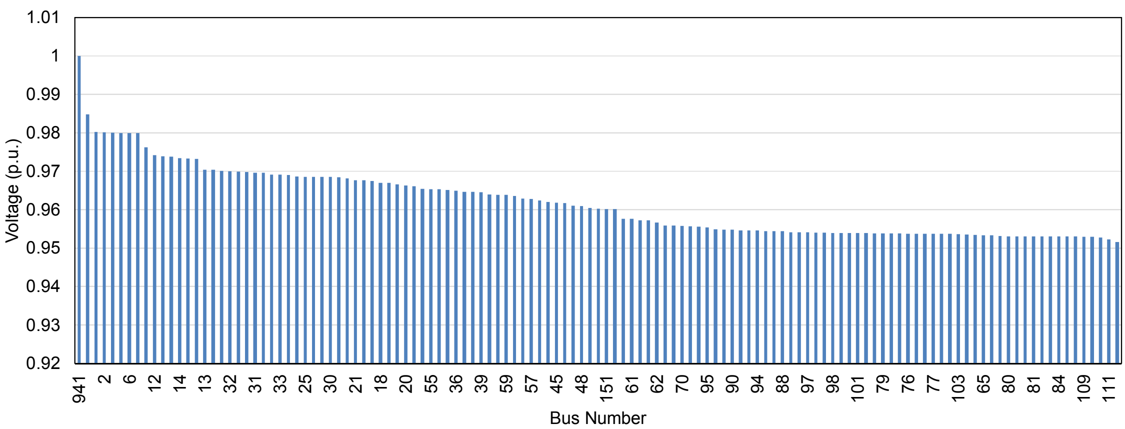

Figure 7.3: Voltage at all the buses in the system during normal condition.

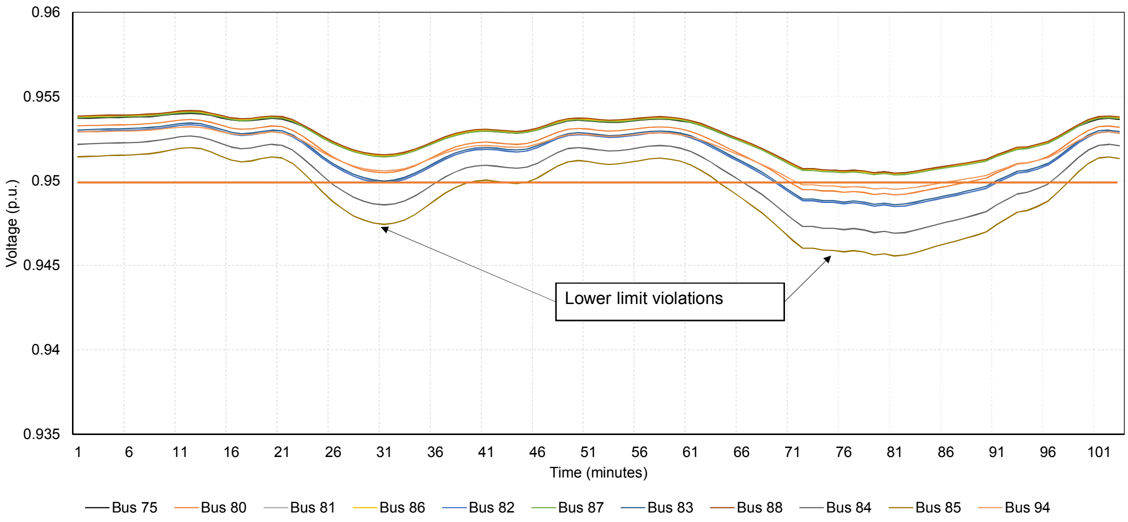

Figure 7.4: Voltage at the selected buses without control, it is clear that voltage at bus 85 goes down first, thus this bus was selected as target bus.

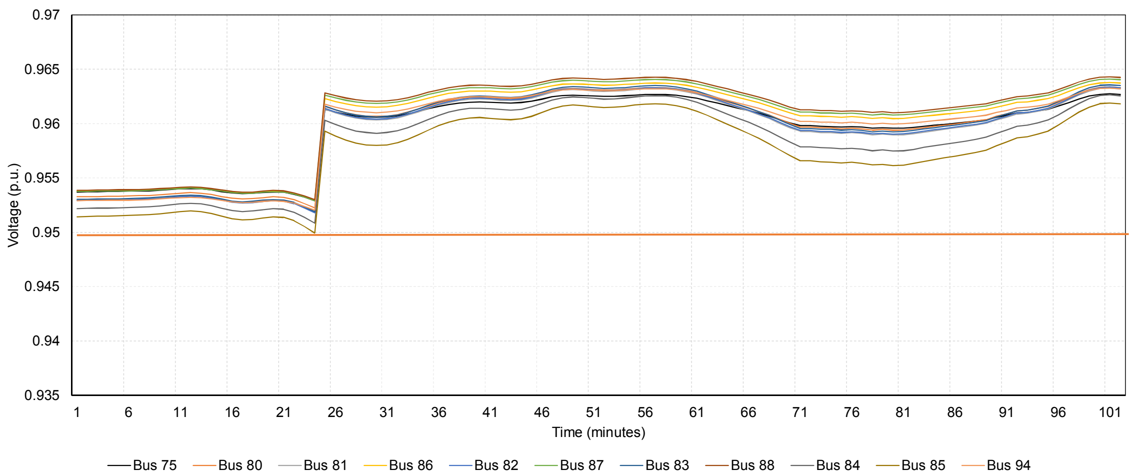

Figure 7.5: Voltage at the selected buses after centralized control using MAS.

7.4.2 4 Divisions

In this scheme the whole system was divided into four zones using the zoning algorithm. In base case voltage at bus 85 goes down firstly, while this bus lies in the zone 4. Voltage control process is done by the control agent in the zone 4. Table 7.2 gives the details of the buses in each zone for 4 divisions. As in this scheme again six DG update their reactive power set point, which is same for centralized system, voltage on the buses are as per centralized scheme and given in figure 7.6. However information exchange is reduced and message data is $T_{msg} = 34$, $U_{msg} = 26$ and $E_{msg} = 8$ then Message efficiency $M_{efficiency}$ is given below;

$$M_{efficiency} = \frac{T_{msg} - E_{msg}}{T_{msg}} = \frac{34 - 26}{34} = 0.764$$

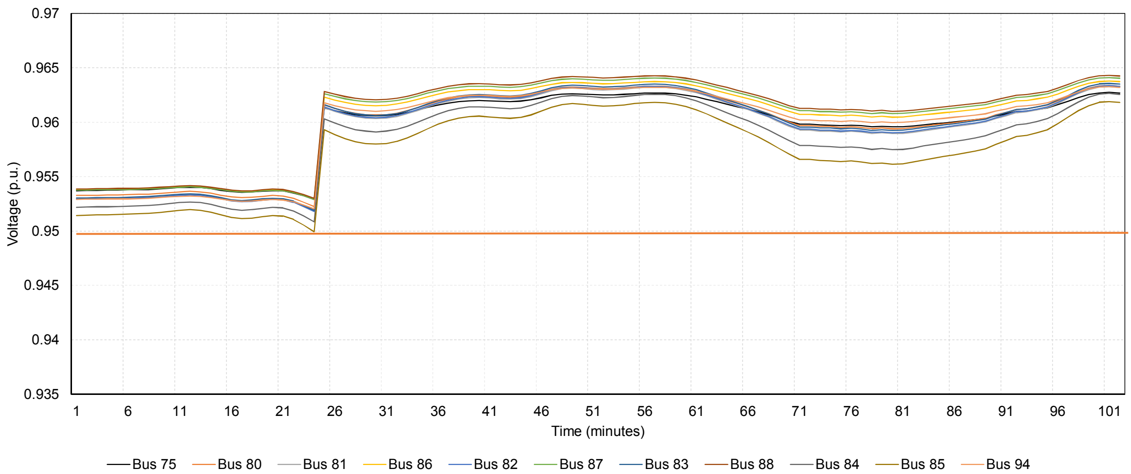

Figure 7.6: Voltage at the selected buses after control using MAS, in 4 - divisions.

7.4.3 7 Divisions

In seven divisions target bus 85 lies in the zone number 4 and bus numbers are the same as in 4 divisions. Thus voltage profile and message exchange remain equal to the 4 divisions. Message efficiency is given below and voltage profile on selected buses is reproduced in figure 7.7.

$$M_{efficiency} = \frac{T_{msg} - E_{msg}}{T_{msg}} = \frac{34 - 26}{34} = 0.764$$

7.4.4 10 Divisions

In 10 divisions target bus 85 lies in zone 4 while total number of DGs in this zone are 4. Reactive power for the desired voltage boost (0.01) was estimated as 0.1. However total available capacity for the four DG in the network was 0.08 and according to the sensitivities, voltage boost of 0.0061

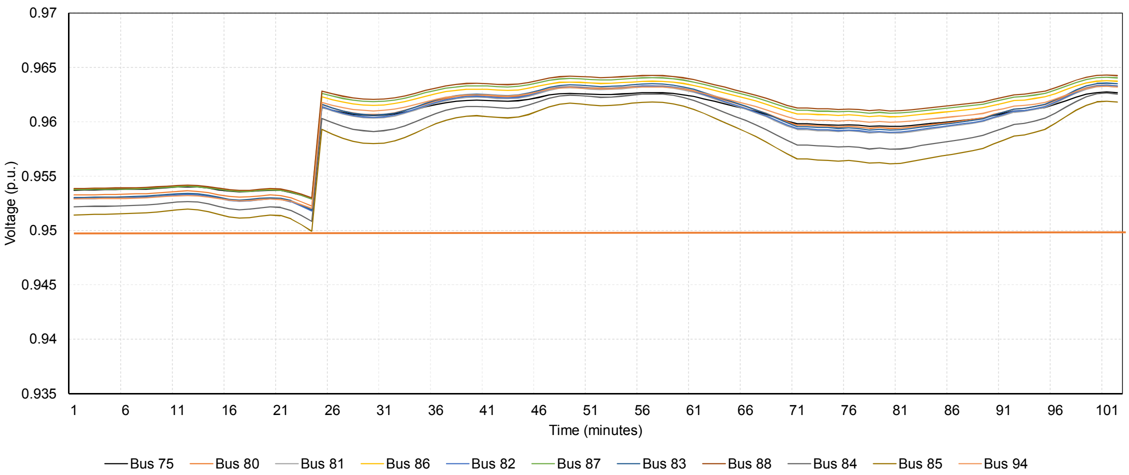

Figure 7.7: Voltage at the selected buses after control using MAS, in 7 - divisions.

was achieved. Voltage profile of the selected buses are given in figure 7.8, while message efficiency is given below.

$$M_{efficiency} = \frac{T_{msg} - E_{msg}}{T_{msg}} = \frac{18 - 0}{18} = 1$$

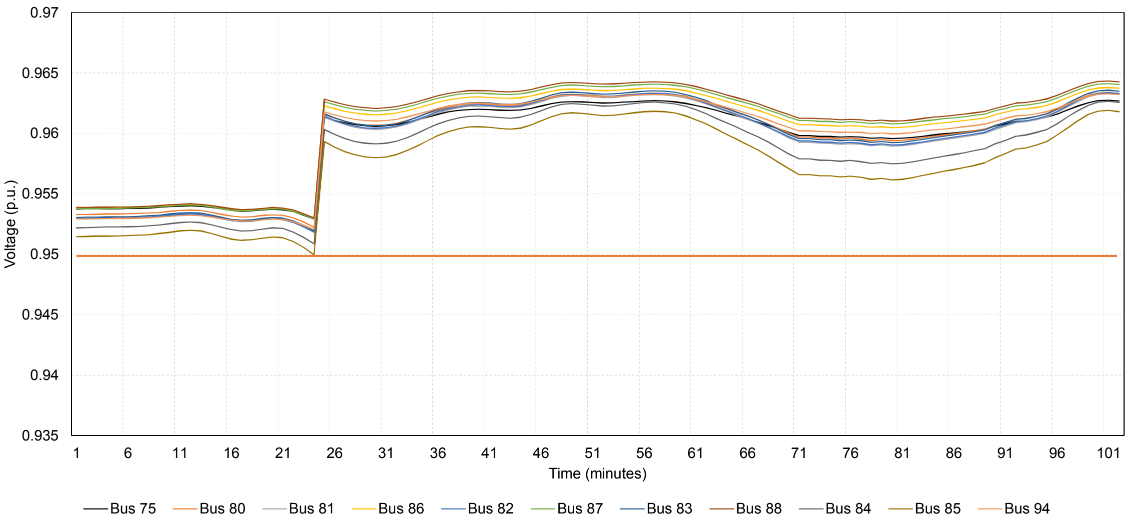

Figure 7.8: Voltage at the selected buses after control using MAS in 10 - divisions.

7.4.5 13 Divisions

In 13 divisions, there were total nine buses and four DGs. Results for 13 divisions are same as of 10 divisions, because same DGs are present. voltage profile is given in 7.9 and message efficiency is given below.

$$M_{efficiency} = \frac{T_{msg} - E_{msg}}{T_{msg}} = \frac{18 - 0}{18} = 1$$

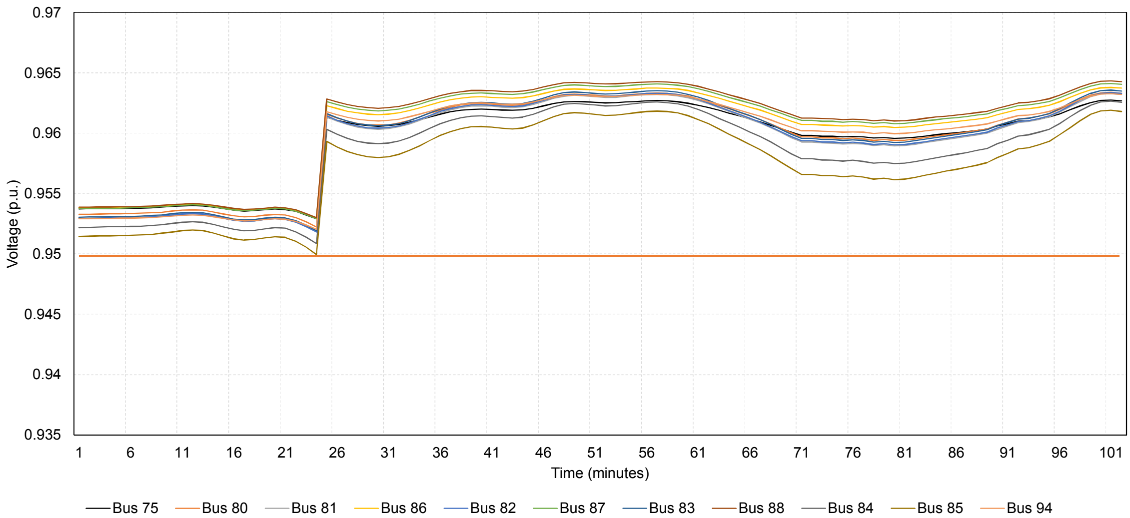

Figure 7.9: Voltage at the selected buses after control using MAS in 13 - divisions.

7.4.6 16 Divisions

Target bus 85 lies in the zone 14 of 16 divisions. There were total five buses while two of them were DG buses. In this zone the desired voltage boost of 0.01 could not be achieved as total capacity of the two DGs was not enough. A voltage boost of 0.0033 was possible, which was not enough to remove all the voltage violations Voltage Profile at the selected buses is given in figure 7.10, while message efficiency is given below.

$$M_{efficiency} = \frac{T_{msg} - E_{msg}}{T_{msg}} = \frac{10 - 0}{10} = 1$$

7.4.7 19 Divisions

Network with 19 divisions has the same buses as in 16 divisions. Therefore, voltage profile and message efficiency are same. Voltage profile is given in figure 7.11 and message efficiency is given below.

$$M_{efficiency} = \frac{T_{msg} - E_{msg}}{T_{msg}} = \frac{10 - 0}{10} = 1$$

7.4.8 22 Divisions

In 22 divisions target bus 85 lies in the zone 14 and number of buses are same as in zone 19 and 16. Thus voltage profile and message efficiency for 22 divisions is same as of 16 and 19 divisions.

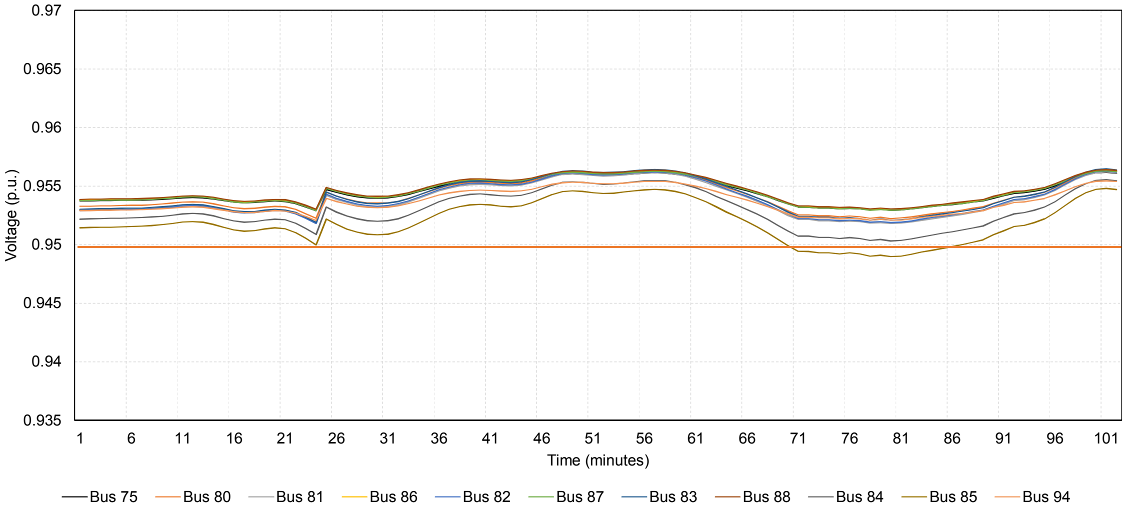

Figure 7.10: Voltage at the selected buses after control using MAS in 16 - divisions.

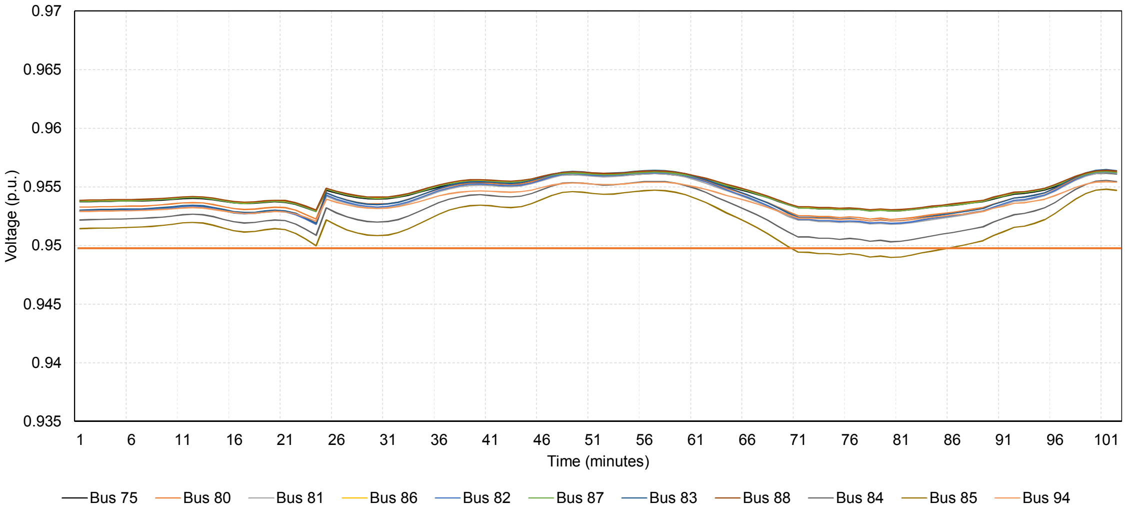

Figure 7.11: Voltage at the selected buses after control using MAS in 19 - divisions.

7.4.9 55 Divisions - Purely Decentralized

As there are total 55 DGs, dividing network into 55 zones with one DG in each zone means purely decentralized system. Each DG try to regulate the voltage at the connection point or a certain target bus. In this case there is no need of *ControlAgent* for each Zone. *DGAgent* itself find new reactive power set point as soon as receives voltage violation message from *MonitorAgent*. Bus 85 was taken as target bus as it observes higher number of voltage violations. However, there is no DG connected at bus 85. The second higher number of voltage violations occur at bus 84 which has a DG and was taken as target bus in decentralized case. Voltage at t=24 goes down at bus 84 and DG37 at this bus update its reactive power set point. However, this was not enough to raise voltage up-to 0.95 p.u. After some time voltage at bus 83 also goes down from 0.95, DG at bus 83 update its reactive power set point, which raise voltage at this bus. Voltage profile at the selective buses is shown in figure 7.12. From figure, one can see that although voltage from base case is improved in purely decentralized control, but still there are voltage violations at bus 85 and bus 84. In decentralized control, no communication is required so there is not any information exchange.

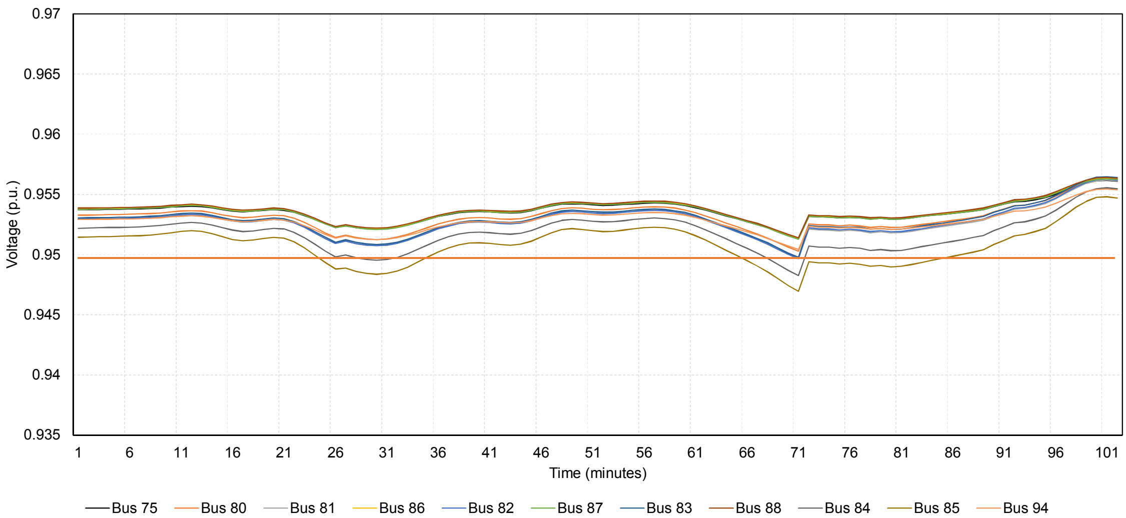

Figure 7.12: Voltage at the selected buses after decentralized control using MAS.

8 Results & Discussion

8.1 Overview

This chapter presents the detailed discussion on the results obtained in chapter 5, 6, 7 in the light of research questions. These chapters cover the three control schemes for voltage control using MAS. These schemes represent the three control architectures which are decentralized, centralized and distributed.

8.2 Suitability of Multi-agent System for control

As MAS system has potential for use in smart grid applications due to its properties explained the chapter 2. It is necessary to show the suitability of the MAS for smart grid solutions. A MAS based voltage control scheme was developed and simulations were performed. In the first case, only decentralized functionality of agents was developed and tested through simulations. DGAgents were defined which correspond to distributed generators in the network. A voltage sensitivity based reactive power dispatch scheme was used by each DGAgent. Figure 8.1 shows the voltage at the buses in normal condition, high-load condition without control and with MAS based control.

In this test case, voltage at the target bus (bus 13) goes out of limit ($V < 0.95$) in high load condition. DGAgent at this bus calculates new reactive power set-point on the basis of voltage sensitivity to boost the voltage by 0.01 (p.u.). Thus, after voltage support by the DGAgent4, voltage violation at the target bus is removed. This shows that even decentralized control by agents without any communication and cooperation, intelligent feature, is effective and can be used as an alternative to the current local control (decentralized) schemes and offers more features like cooperation, coordination, intelligence, if desired.

8.3 Decentralized or Centralized control

Control architecture for any system largely depends upon the requirements and objectives of control. Agents can work in a centralized fashion as well as decentralized. Both the schemes were applied for voltage control using distributed generation and results are given in figure 8.2. For the particular case simulated using decentralized and centralized control, results show that

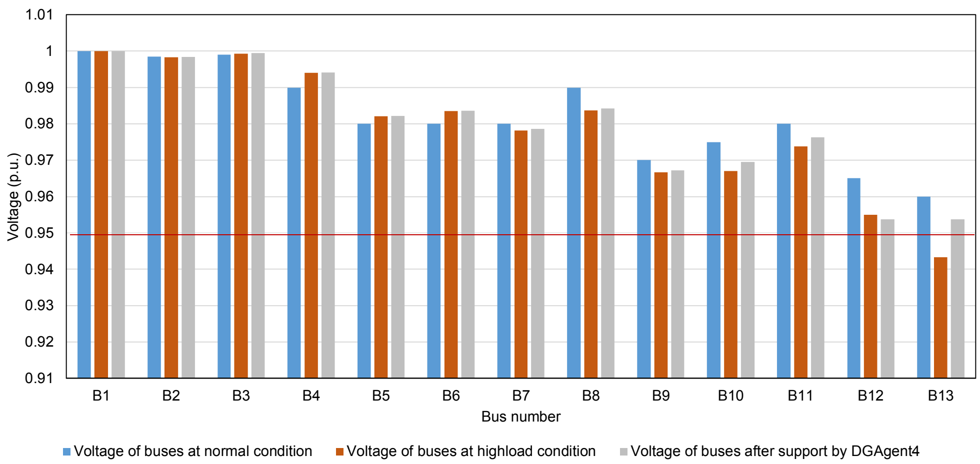

Figure 8.1: Voltage at all the buses. 1) Normal condition. 2) High load condition. 3) After voltage support by DGAgent4.

centralized control is better as compared to decentralized for voltage violation removal at the target bus. However, in centralized control communication infrastructure is required in order to send commands from central controller to the units in the field. As an agent can communicate with other agents through messages and can send commands to take action, agent technology can easily be used for the centralized control in which information exchange and communication is required. In a truly centralized setting, some agents can run in passive mode while some agents in active mode. For example, in the simulated test cases, MonitorAgent acts as active agent while DGAgents act as passive agents, which takes actions upon request from controlAgent which is active agent. Following are the key aspects of the centralized control in regards to information and communication.

- **Communication Infrastructure:** For a centralized control scheme, it is necessary to have a communication link between each node and control center. As long as network is small and number of nodes are not large, communication infrastructure requirements are not very high. As in the case of 13 node test system, there were six distributed generators which communicate with the central control agent.
- **Information exchange:** Again, in small system, information exchange between the control center and other nodes is not very large. In 13 node test case, only total number of messages exchanged for one control action is 18. These messages contain necessary information in order to coordinate the control action. In such cases, a low cost, low bandwidth communication infrastructure can be used.
- **Computing Complexity:** Central control does not need to process a large amount of information and computation time will not be large in small system. Thus computing time and complexity is not an issue as long as system has less number of communicating nodes.

Thus in general for a small system communication and computing requirements are not very high. Further impacts of control/communication failures are limited due to limited size of the system.

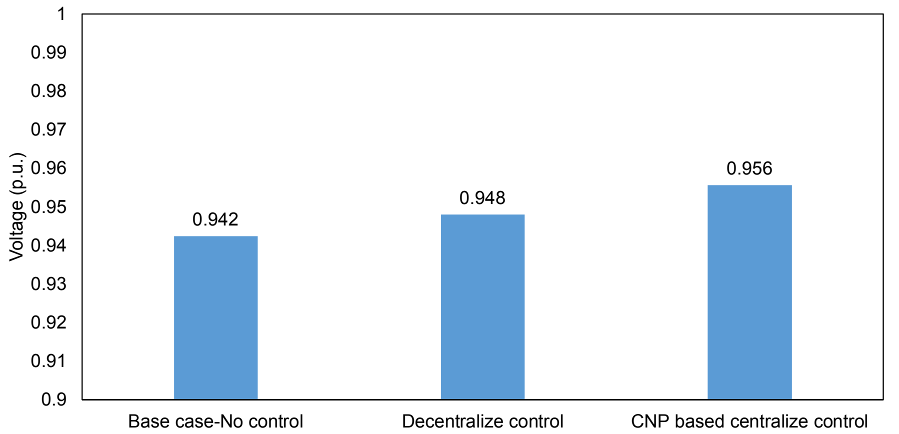

Figure 8.2: Voltage at bus 13 after second violation with 1) Base Case-no control. 2) Decentralize control. 3) CNP based centralize control.

8.4 Distributed control

In previous section, results from decentralized and centralized control schemes for MAS based control were discussed. As in case of 13 node system information exchange between agents were not high and only 18 number of messages were exchanged for control action computation. Number of exchanged messages very much depend upon the algorithm used for control. In centralized control, Contract-Net-Protocol based algorithm was used in which controlAgent decides the control action after receiving information from the participating agents(*DGAgents*). In chapter 6, distributed iterative algorithm was used for voltage regulation by DGAgents. In this algorithm each agent computes a value and exchanges it with the pre-defined neighbors. This process is repeated till the algorithm converges or the desired error tolerance is achieved. There were total six agents and neighbors were defined. Each agent maintained three variables. The criteria for stopping the iteration can be fixed number of iterations or error tolerance. It was observed that after 31 iterations desired error torrence was achieved, therefore, total number of iterations were fixed as 32. Further, convergence speed depends upon the number of participating agents in the algorithm. If number of agents increase, then more iterations are required to achieve the desired accuracy. Figure 8.3 shows the evolution of reactive power Q with number of iterations. Following are the considerations for use of this distributed algorithm;

- **Addition or Deletion of agent:** If any of the agent is deleted or added in the network, algorithm can be reconfigured. In such cases each agent needs to update its neighbors list and number of agents with which neighboring agent can communicate. This is because weight matrix P depends upon the communication network between agents as given in chapter 6, equation 6.3, and reproduced below;

$$\sigma_i[t+1] = \frac{1}{1+D_i^+}\sigma_i[t] + \sum_{j\in N_i} \frac{1}{1+D_j^+}\sigma_j[t] \tag{8.1}$$

  Also, there is no need to know the total number of agents in the network in advance. This algorithm can be reconfigured in case of any change in the network by updating the neighboring information. This can be accomplished by another algorithm in which each agent update its neighboring list and exchange with other agents which are in its neighbors list. This algorithm can be run in case of addition/deletion of an agent in the network. Further, this algorithm can be run before each control action, this dynamic update mechanism can leads to plug and play feature.

- **Synchronization:** Another important aspect of distributed algorithm is synchronization among agents. In this work a simple algorithm was used in which each agent waits till the receipt of messages from the neighboring agents. Any delay in sending or receiving messages will increase the time for convergence of algorithm and hence will have impact on the performance of the system. This impact is analyzed in the next section. Further, this algorithm can make all the agents to wait for infinite time, if there is any communication link failure between two agents.

- **Size of the network:** It has been observed that convergence time for the algorithm increases as number agents in the network increase. Thus, number of iterations required for the desired accuracy increases. It was observed that, for four node network, iterations required to converge the algorithm (up-to desired accuracy) was 14 while for six node network, it reaches to more than double(32). Thus size of network have significant effect on this iterative algorithm in terms of convergence speed.

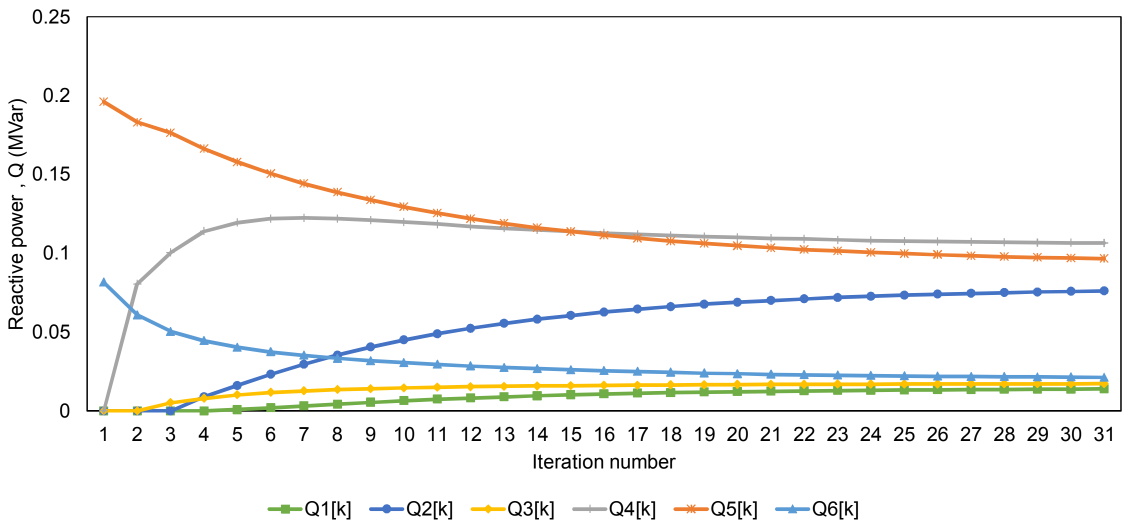

Figure 8.3: Evolution of Q for each *DGAgent* in distributed iterative algorithm.

Figure 8.4 shows the voltage at all the buses in the network after control using distributed iterative algorithm, while figure 8.5, shows the voltage profile at the target bus 735. The advantage of this algorithm is that it does not requires any central node to process information, thus reducing the computation and control cost. However, communication failures effect need to be investigated.

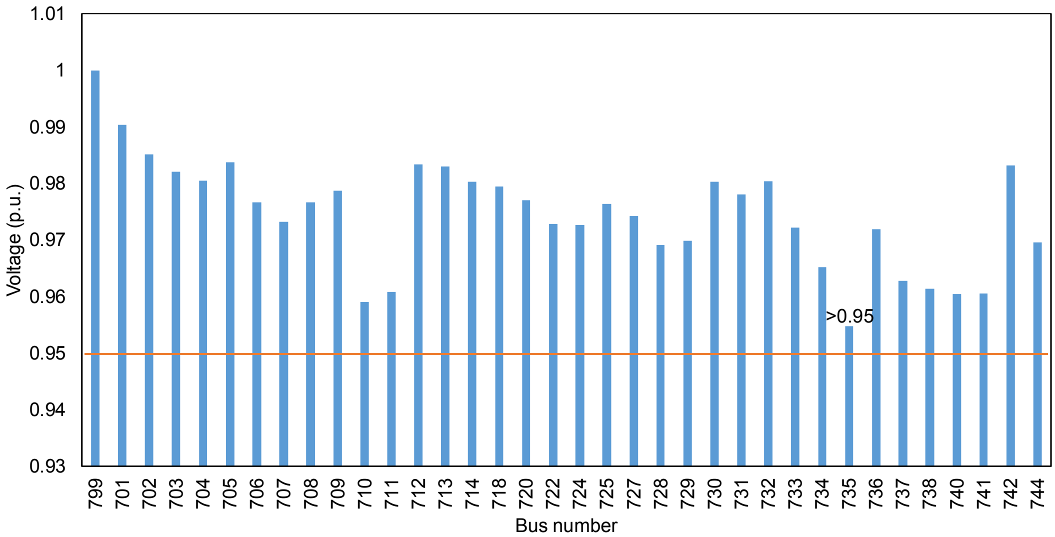

Figure 8.4: Voltage at all the buses after voltage support by the *DGAgents*. Voltage at the critical bus (735) is well above the lower limit.

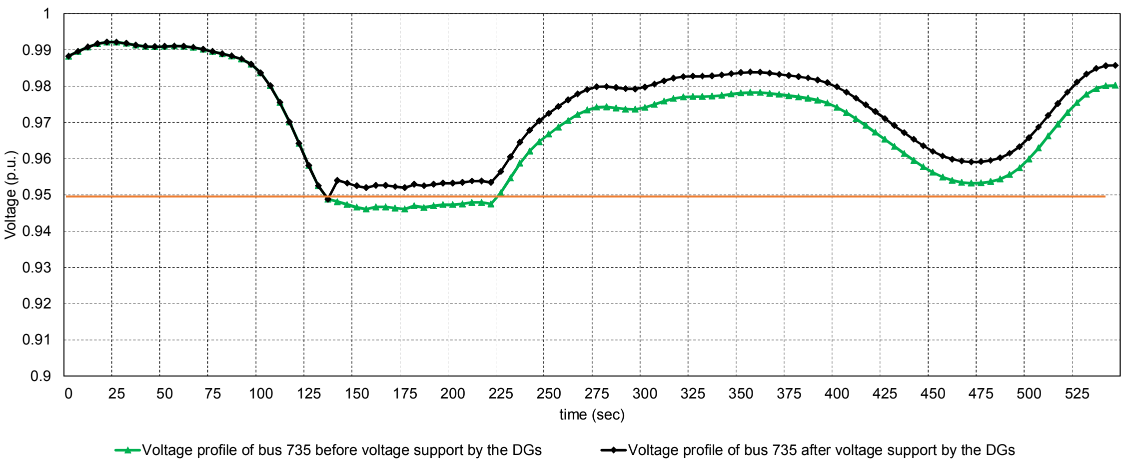

Figure 8.5: Voltage profile of bus 735 before and after voltage support by the DGs using agent based iterative algorithm.

8.5 Impact of communication network parameter changes on MAS based distributed control

As stated in previous section, communication parameter changes have effect on the convergence speed of the algorithm. This also impacts the overall system performance. In order to analyze the performance of power system in the presence of real communication between agents, investigation was carried out in a co-simulation framework. In this analysis four network scenarios were considered with different network parameters. These scenarios represent low bandwidth, high bandwidth, low background traffic and high background traffic. These scenarios are explained in chapter 6 and presented in table 6.2. Comparison of voltage profile of the target bus 735 considering ideal communication and four communication scenarios is given in figures 8.6, 8.7, 8.8 and 8.9 respectively. There were total 40 iterations of the algorithm and time taken by these iterations in the four scenarios (s1,s2,s3,s4) was 43, 130, 35, 103 seconds. This shows that total time taken by the agents to compute the control action depends upon network parameters like bandwidth, background traffic etc. Thus while designing MAS based application, communication network effects must be studied and taking into account.

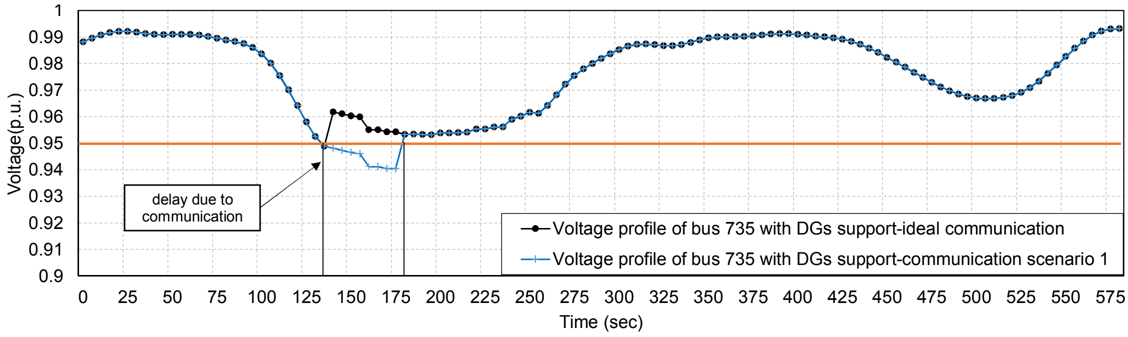

Figure 8.6: Voltage profile at bus 735 - ideal communication vs communication scenario 1.

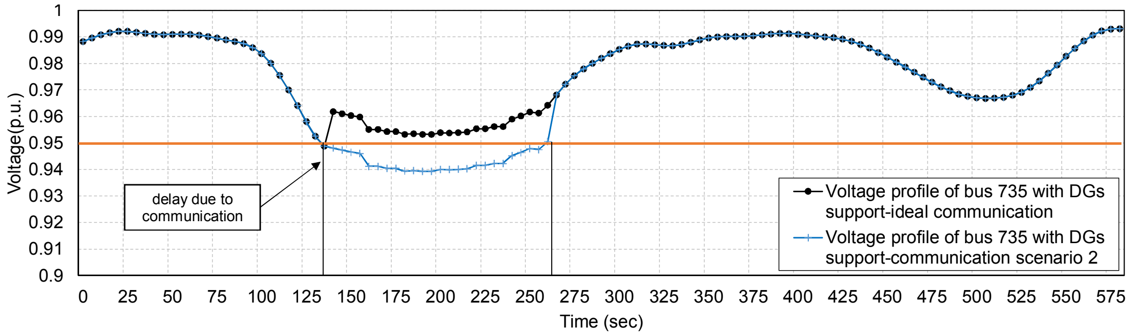

Figure 8.7: Voltage profile at bus 735 - ideal communication vs communication scenario 2.

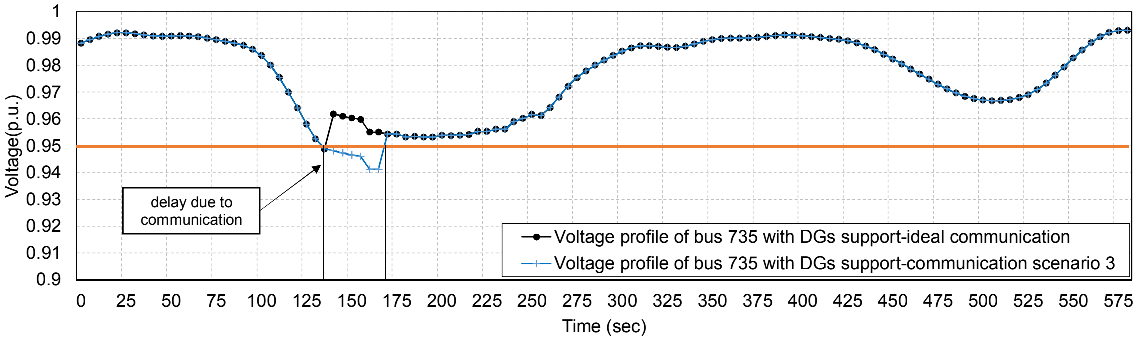

Figure 8.8: Voltage profile at bus 735 - ideal communication vs communication scenario 3.

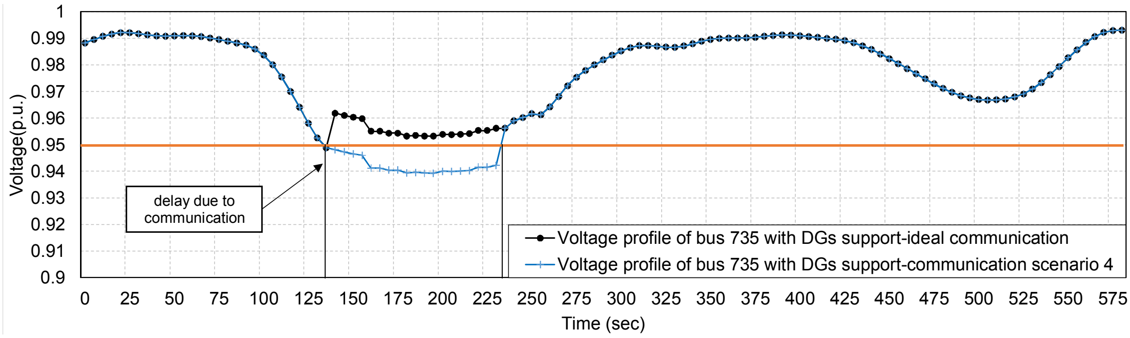

Figure 8.9: Voltage profile at bus 735 - ideal communication Vs communication scenario 4.

8.6 Dividing network into MAS control zones

This section discusses the results from chapter 7, which is about zone based control using MAS. Network was divided into zones and each zone was controlled by the separate MAS system. As it was discussed earlier that centralized control is quite effective as long as system is small. Large system can be distributed into zones and each zone can be controlled by a MAS system so that local problem can be solved locally. The requirements for the zone are discussed in chapter 7. However, what should be the suitable number of zones in a network in order to have good performance (power system point of view) and less information exchange and computation complexity, remains a question. In chapter 7, IEEE 123 node test network was used for investigation and was analyzed by dividing the network into different zones. Total 8 divisions were made using k-mean clustering algorithm based on electrical distance between nodes. Performance of the system (voltage profile) along-with information exchange(number of messages between agents) were analyzed in each division. Voltage profile of the selected buses in different divisions (4, 10, 19) and n divisions (purely decentralized) is shown in figures 8.10, 8.11, 8.12 and 8.13 respectively. Voltage profile of the remaining divisions are given in chapter 7.

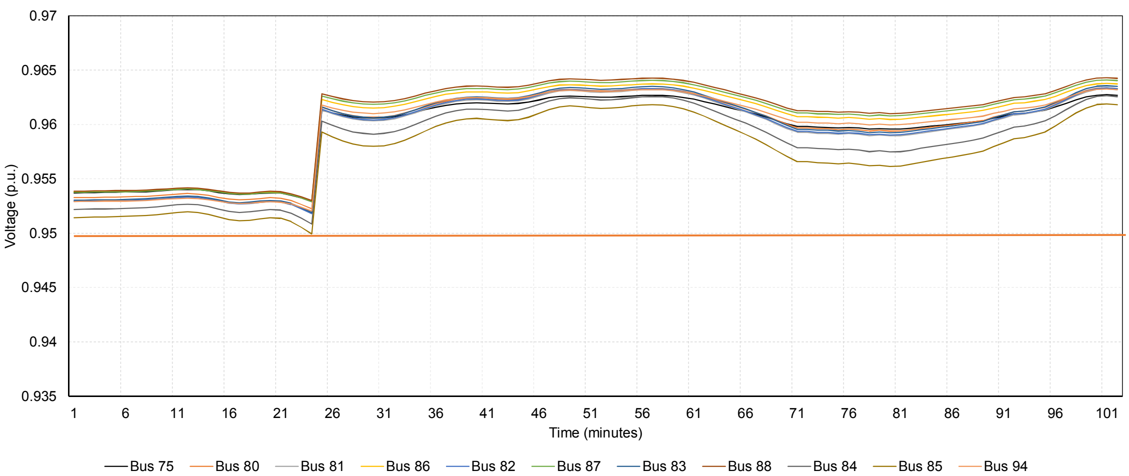

Figure 8.10: Voltage at the selected buses after control using MAS, in 4 - divisions.

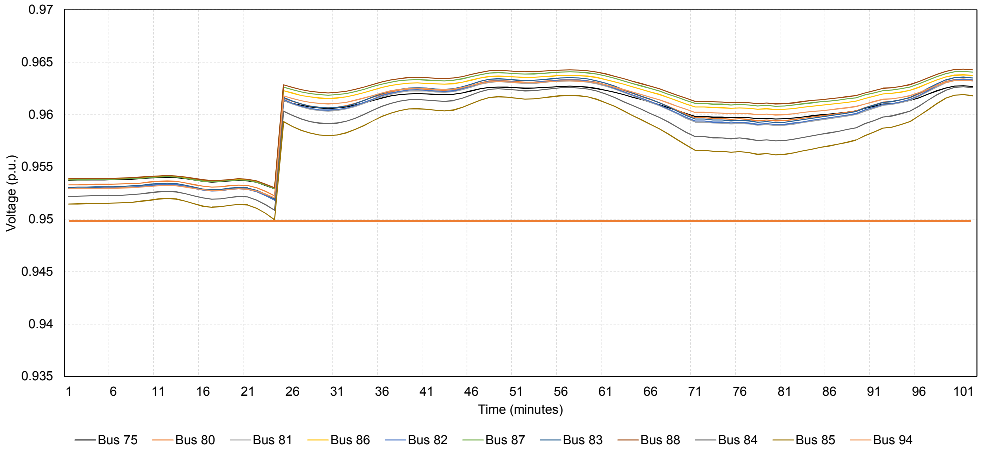

Figure 8.11: Voltage at the selected buses after control using MAS in 10 - divisions.

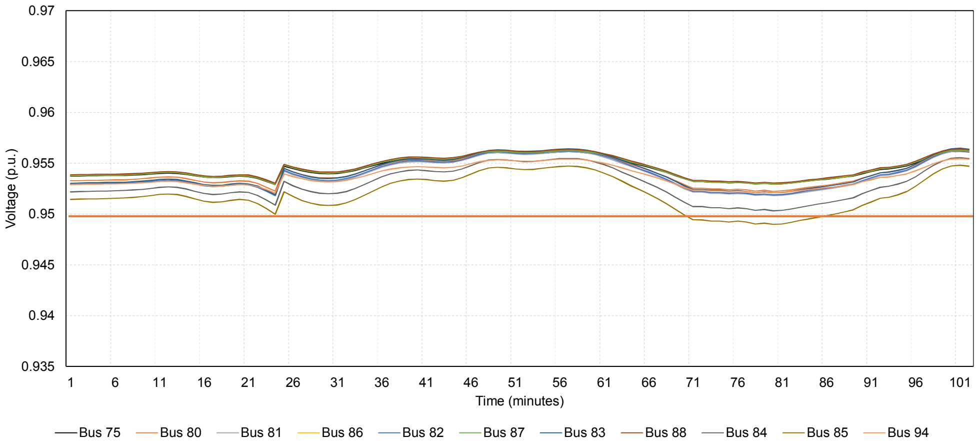

Figure 8.12: Voltage at the selected buses after control using MAS in 19 - divisions.

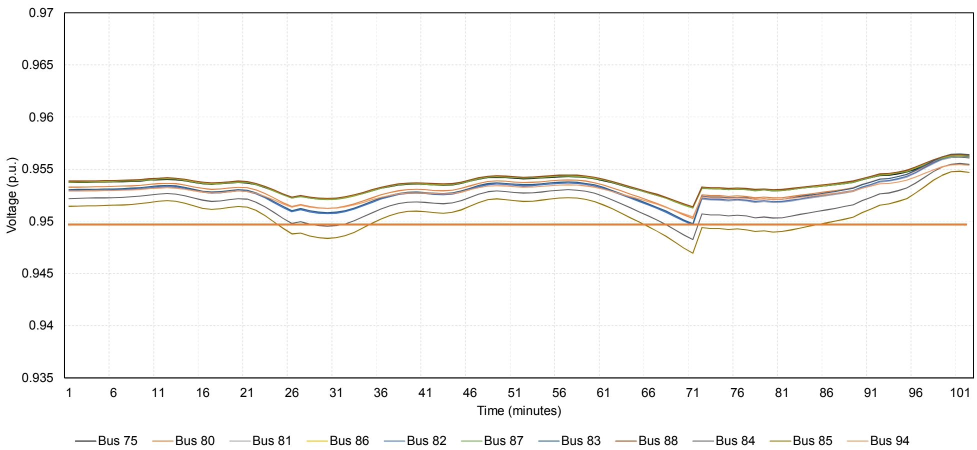

Figure 8.13: Voltage at the selected buses after decentralized control using MAS.

8.6.1 Power system performance

It is clear from above figures that performance of the network decreases as number of divisions increases. Voltage violations for each each division is given in figure 8.14. It can be observed that as we move from centralization towards decentralization voltage violations increase. This is quite intuitive as in case of centralized control, all the agents in the network participate in control process and resource (reactive power) for control is sufficient. However, in case of small zone, it was not possible for agents to provide the desired resource to remove voltage violation. One way to account for this problem is to have inter-zone communication through control agent of each zone. However, still if there are many small zones, zones will interact more frequently.

8.6.2 Information flow

Figure 8.15 shows the total messages exchanged between agents for a single control action in each division. It is clear that information flow (messages exchanged) keeps on decreasing as we keep on dividing the network. It is clear that in case of centralize control information flow is maximum as, each agent needs to communicate with the control agent. While in purely decentralize control, there is no communication among agents and no information flow. Figure 8.16 shows the total messages exchanged between agents and total number of violations from centralization to decentralization. Figure 8.17 shows the messages which were not required for the control action and named as extra information/messages. These messages (normalized between 0 and 1) are highest in centralize control as each agent communicates with the control agent, however a fewer agents participate in voltage control process by updating their reactive power set-points. Message efficiency in each case is given in figure 8.18, which tells about utilization of information/messages. Figure 8.19 shows the voltage violations, message efficiency and extra messages. It can be observed that message efficiency is lowest in centralized control while violations are minimum. However, even if we divide the system into 10 zones and apply MAS based control in each zone separately still violations are minimum but message efficiency is high. Thus the power network used for investigation with particular operating conditions best suitable to divide into 10 zones for voltage control purpose.

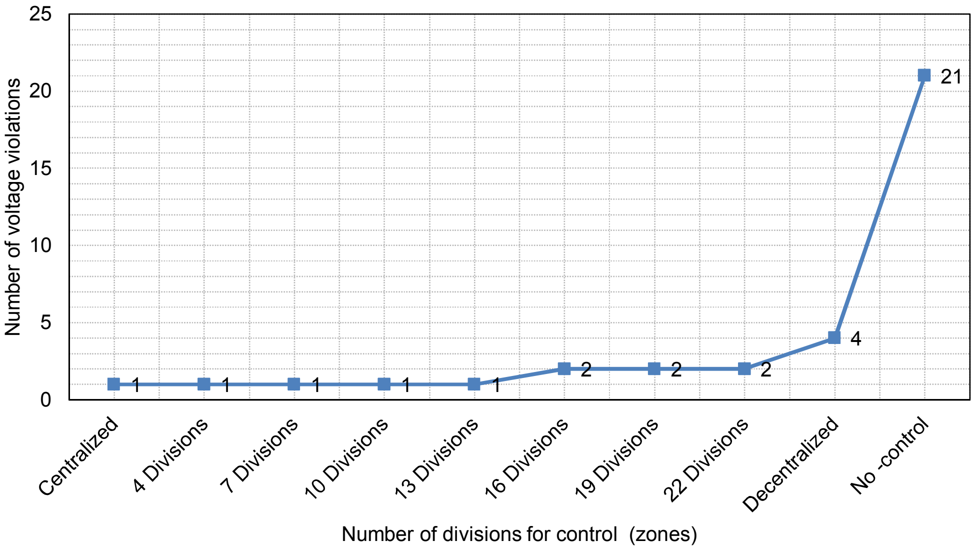

Figure 8.14: Number of voltage violations in each division (for all buses in the network).

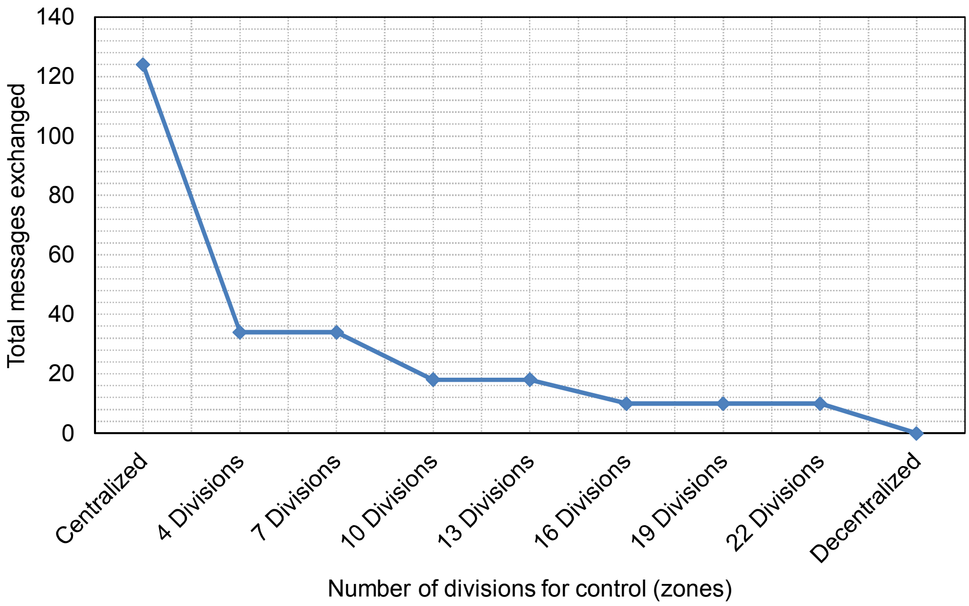

Figure 8.15: Total messages exchanged for control action in each set of divisions.

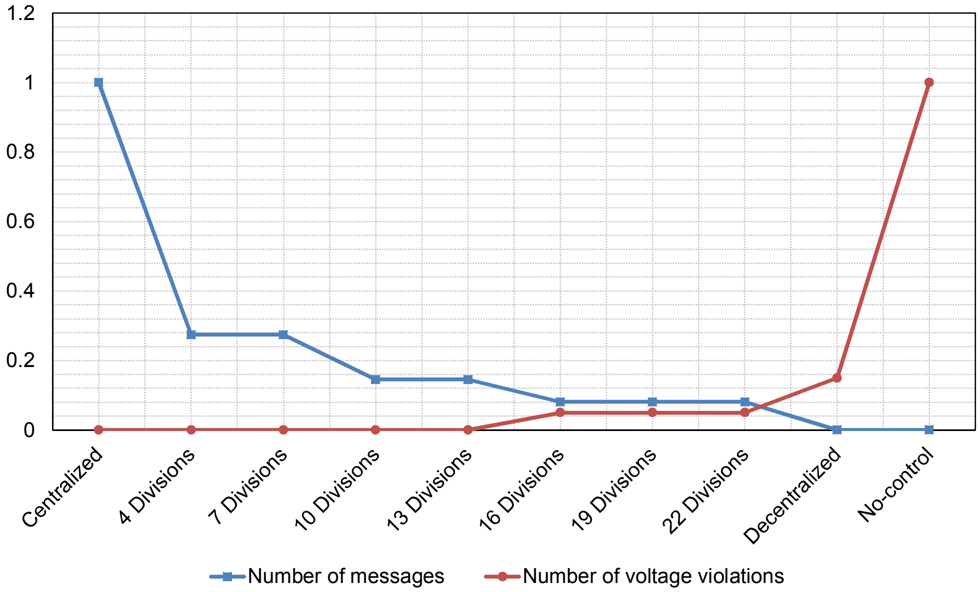

Figure 8.16: Messages exchanged between agents and voltage violations in each division (normalized between 0 and 1)

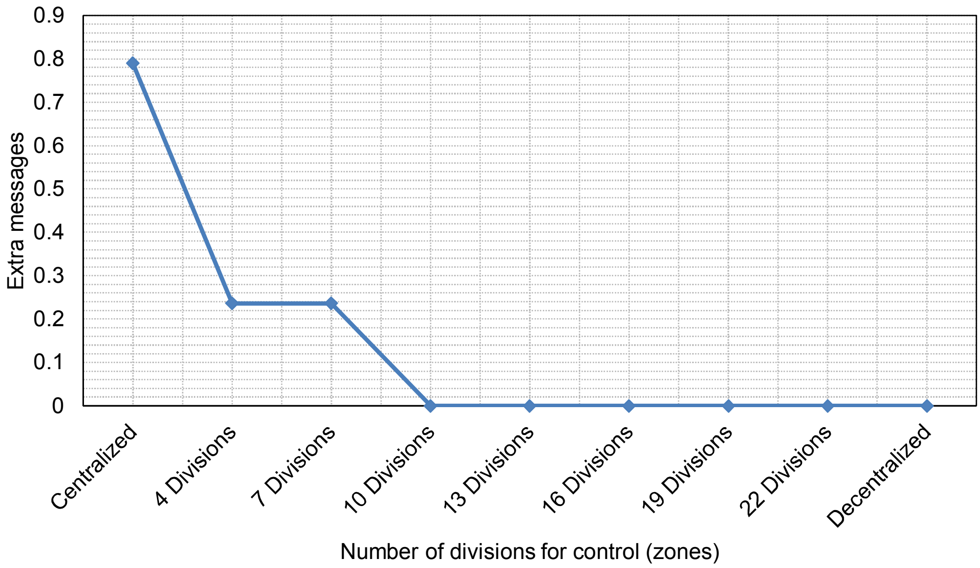

Figure 8.17: Messages exchanged which were not required for control action.

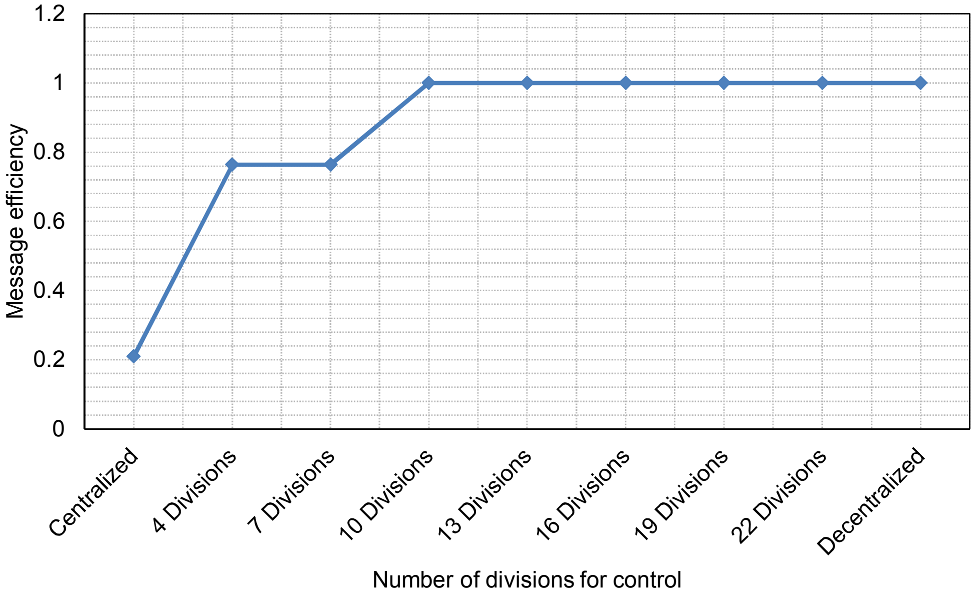

Figure 8.18: Message efficiency (utilization of messages).

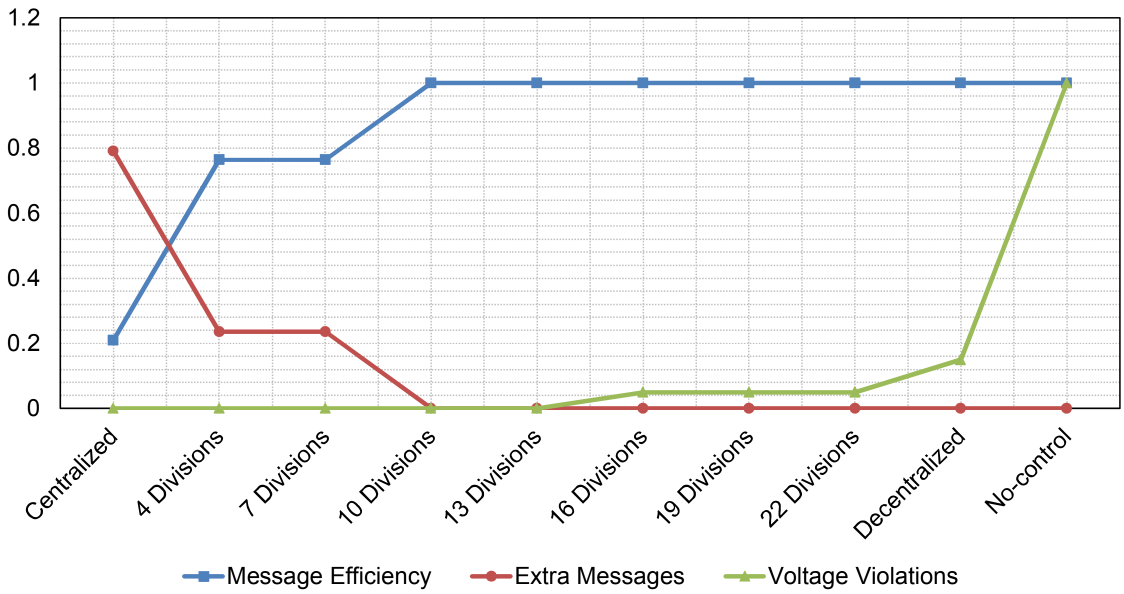

Figure 8.19: Message efficiency, extra messages and voltage violations (normalized between 1 and 0)

9 Conclusion & Future Direction

9.1 Conclusion

Power system transition demands new concepts for operation and control of power system components as it is difficult with traditional approaches which were meant for the conventional vertically operated power system comprising mainly large centralized generating units, to effectively operate and control the future, horizontally operated power system with a large number of small generating units (renewable) at low and medium voltage levels. In this regard new control architectures with coordination and cooperation between different components of power system are required. This transition also pushes towards decentralization of power system due to increased use of these distributed generating units. A distributed paradigm based on multi-agent system was investigated in this study. Multi-agent system consists of agents which can coordinate their control actions with the other agents in the system. Through communication these can decide their control actions to achieve their designed objectives through the actuators. Agents in a MAS system can work in purely decentralized fashion or can be controlled through the centralized control agent. The choice of control architecture depends upon the requirements of the system.

Decentralized voltage control scheme based on agents were developed and investigated on IEEE 13 node test system including distributed generation. DG Agents which correspond to distributed generator in the network were defined. Agents do not communicate with each other in the network and decide their control action only on the basis of available information while satisfying the constraints on the reactive power of distributed generator. Although purely decentralized voltage control was not able to keep the voltage within limits all the time, however it does provide better results than the no control strategy. Thus agents can be used for even purely decentralized strategy. This shows flexibility in use of agent based paradigm.

In centralized control scheme, Contract-Net-Protocol (CNP) based algorithm was developed for coordination and carrying out the control actions. CNP proved to be quite effective for devising the plan of agent interaction and computation of algorithm. The challenge of making plan for coordination between agents can be tackled by using this interaction protocol. Communicative acts can be defined by the user as per requirement of the problem. In this study standard communicative acts as per Foundation for Intelligent Physical Agents (FIPA) document were used. Some of them are CFP, $refuse$, $propose$, $accept-proposal$, $inform-done$, $agree$ etc. FIPA presents a comprehensive list of communicative acts for inter agent communication plans and can be used to model the complex interaction between agents. In centralized control three types of agents were defined which include control agent, monitor agent and DG Agent and roles were assigned to accomplish the desired task. Thus, in MAS system, agents role can be defined as per requirements with the desired functionality and can be modeled as autonomous, reactive, goal oriented etc.

A distributed iterative algorithm for voltage control was also investigated. In this scheme agents only communicate with the neighboring agents and decide their control action. After observing voltage violation, an agent starts voltage control process by computing the amount of desired reactive power as per algorithm and exchanging this value to the pre-defined neighbors. This process is repeated until the desired convergence is achieved. When algorithm terminates the calculation process, each agent sets its final computed value as new reactive power set point. Agents carry out synchronization through exchange of messages. Thus problem of coordinating of agents to decide their control action is solved in a distributed manner by the iterative algorithm.

This algorithm is quite effective in cases where only information on the states of neighboring agents are known due to limited transmission capacity having less communication costs. Thus networks in which

- There is no centralized control system for computation, communication, synchronization
- Network topology are not completely known to the nodes in the network

are best candidates for such solutions. Further, it can be concluded that, it is possible to reduce the amount of information which needs to be transmitted in networks, thereby saving communication cost, extending the existing network lifetime. MAS system can easily be used to implement such distributed algorithms and can applied for operation and management of power system having a large number of spatially distributed nodes.

One important aspect of iterative distributed algorithm is number of iterations. As number of agents in the whole network increase, required iterations for the desired accuracy increase which results in increase in convergence time. Thus, it is necessary, to determine/estimate the number of iterations for a particular network according to the control period.

If network consists of

- large number of nodes
- spatially scattered,
- change in state of some nodes have less or no direct effect on state of some other nodes

It can be divided into control zones with each zone containing nodes which have effect on other nodes. This results in small autonomous regions in which agents interact with the agents in a single zone. This has particular significance, especially if control requirement is to influence only some part or local nodes in the network. However, there is a need to find the best number of zones satisfying certain requirements/performance. A zone based control using agents was presented and best number of zones according to the key performance indices were determined. Zone formation was carried out using electrical distance between two nodes using voltage sensitivities. KPI of power system was examined while network was divided gradually from centralized system to purely decentralized. Results show that purely centralized system has maximum information exchange, however, best voltage KPI. As we move towards decentralization information exchange decreases, but voltage KPI also starts decreasing. With this methodology, we can find a point after which decentralization can result in low performance of the network in terms of voltage profile. Decision of number of zones depends upon the used KPIs. According to this methodology best number of zones for a given network can vary, if we change/add the KPI. As information exchange is the key element in distributed control and one objective of this study is to use minimum communication infrastructure and less information flow to a central point for control of DERs, amount of information exchange was taken as key performance index along with voltage violations. More KPI i.e. robustness, power quality etc can also be considered, if needed. This investigation concludes that ideal number of zones of a network depends upon many factors and can be determined on the basis of selected KPIs.

9.2 Future direction

Main focus of the study was on agent based decentralized, distributed and centralized control strategies. Control objective was voltage regulation, however, the same strategies can be used for frequency control. Further, agent based technology can be used for many other applications in power system i.e. protection, reconfiguration and restoration etc.

While investigating the control strategies, it was assumed that there is ideal communication between agents and it is unknown that what will happen if a communication failure occurs. A study was made to know the effects of communication parameter changes in distributed control approach, which shows performance of the network is varied with the changes in communication parameters. However, more thorough insight is required to determine performance of the network in case of communication failures (physical disconnection between two nodes).

Further, size of a control zone depends upon many factors and, to the best knowledge of author, currently only qualitative research is available to describe the size of control zones in power distribution network. This study gives a methodology to find best/optimum number of control zones, which is a step forward to describe the size of a control zone quantitatively. However, more KPIs need to be considered to know the size of control zone which will be best to fulfill overall operation and control objective of power distribution network leading towards intelligent autonomous operation.

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Curriculum Vitae

Personal Information

Name	:	Ishtiaque Ahmad
Date of Birth	:	01.01.1980
Nationality	:	Pakistan
Email	:	c2ishtiaq@hotmail.com

Education

PhD Scholar	PhD Scholar at Faculty of Electrical Engineering and Information Technology, Technische Universität Wien, Vienna, Austria, supervised by Prof. Wolfgang Gawlik. (Since 2013)
MSc Computer Engineering	Center for Advanced Studies in Engineering, UET Taxila, Pakistan, www.case.edu.pk (2008-2010)
MSc Computer Science	University of Agriculture , Faisalabad, Pakistan, www.uaf.edu.pk (2002-2004)
Bachelor of Science	Govt College University, Faisalabad, Pakistan , www.gcuf.edu.pk (1997-1999)

Professional Experience

Research Fellow	Energy Department, Austrian Institute of Technology, Vienna, Austria (2013 to 2017)
Programmer	University of Engineering & Technology, Taxila, Pakistan (2007 to 2012)
Visiting lecturer	University of Engineering & Technology, Taxila, Pakistan. University of Arid Agriculture, Rawalpindi, Pakistan. Mohi-ud-din Islamic University, Islamabad Campus, Pakistan (2008-2012)
Junior Programmer	University of Engineering & Technology, Taxila, Pakistan. (2005-2007)
Software Developer	ICON Solutions Islamabad, Pakistan. (2006-2007) part time.

Research Publications

- Ahmad I, Palensky, P; Gawlik, G. "MAS as a tool for modernization of power grid: A case study on control of distributed energy resources". Book chapter on Multi-Agent System, INTECH (accepted).
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