DISTRIBUTED CONTROL OF AUTONOMOUS MICROGRIDS

BY

SYED AZHER HUSSAIN

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This thesis, written by **SYED AZHER HUSSAIN** under the direction his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN SYSTEMS ENGINEERING.**

Dr. MAGDI S. MAHMOUD
(Advisor)

Dr. ADEL F. AHMED
Department Chairman

Dr. FOUAD AL-SUNNI
(Member)

Dr. SALAM A. ZUMMO
Dean of Graduate Studies

Dr. MOHAMMAD ALI ABIDO
(Member)

17/5/15
Date

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بسم الله الرحمن الرحيم

DEDICATED TO

MY PARENTS AND MY BROTHER

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All praise to Allah, the Cherisher and Sustainer of the worlds, none is worthy of worship but Him. Peace and blessings be upon the beloved Prophet (Alaihissalam), the mercy for worlds, and on his blessed family, his companions and all those that follow his guidance until the end of time.

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THESIS ABSTRACT

Name: Syed Azher Hussain

Title: Distributed Control of Autonomous Microgrids

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In this thesis, we will concentrate on the control problem of autonomous inverter based microgrid system. It is a challenging task to operate more than one distributed generating units on the island. Once a microgrid is formed, it is important to assure that the generating units on the island are protected, variations in the output voltage due to load changes should also be taken care of. To address these concerns, a novel control approach will be used for the stable operation of microgrid system and to regulate the voltage and frequency so that quality power is delivered. The control technique used will be of multi-level type implemented in a distributed fashion. The effectiveness of the technique will be illustrated with the help of simulation results. Real Time Digital Simulation (RTDS) implementation of the control technique will also be carried out. A new approach based on reinforcement learning solutions are also applied to the linearized model of the microgrid. A controller is designed using the heuristic dynamic programming method. The controller is tested for the voltage control of microgrid.

XML

Chapter 1

INTRODUCTION

1.1 Conventional Power Gird

The concept of power grid is based on the technology introduced around 120 years ago. It is facing lot of issues in keeping up with modern challenges. One of the main challenges is to guarantee quality electricity supply to customers and maintaining long-term energy security. The existing grid has small number of producers, long distribution ways and high maintenance cost, it is also difficult to achieve load balancing. Moreover, the depleting fossil fuels and the adverse effect on environment by its consumption has gain multi-national interest in reducing the excess use of nonrenewable energy resources and many nations are keeping tap on CO_2 emissions [1].

The main concerns with the existing centralized power system grid are summarized below [2]

- Increasing demand and lack of high reliability
- No scope of expansion on power system expansion
- Limitations of centralized power system planning
- Risks of volatile bulk power markets
- Security Threats
- Limited power quality
- Environmental effect (Release of CO_2, Nuclear waste etc.)

Therefore increased reliability/efficiency is very much needed in todays world where the demand of electricity is ever-growing.

1.2 Distributed Generation Systems

All the above issues urges the need to incorporate Distributed Generating (DG) units into the existing power systems [3]. The concept of DG is of early 1990's, it has multiple advantages for both source and consumers [4]. In literature, there exists various definitions of DG which are summarized in [5]. DG is defined as , "*Generation of electricity by facilities that are sufficiently smaller than central generating plants so as to allow interconnection at nearly any point in the power system*" [6].

DG units are the emerging micro-generating technologies such as micro turbines, fuel cells, Internal Combustion (IC) engines. It also make use of renewable energy sources such as Photo Voltaic (PV) arrays and wind turbines. The DG units have low emission rates, environment friendly and are economical.The introduction of DG units should reduce the pressure on central power grid principally but in technically speaking, penetration of distributed generation into the power grid creates a new class of issues different from those found in traditional power sources. Random applications of DG units will cause as many issues as it may solve [7]. Some of the problems are discussed below

- First of all, DG units operates close to the distribution voltage level of 480V as it is geographically located near the loads and provides a DC or variable frequency AC output and hence requires power electronic devices in order to interface with the power-grid/load. The power electronic interface leads to development of new control strategies [8].

- The output of renewable energy systems fluctuates with conditions of weather which is also a debatable issue when DG units are connected to power grid [9].

- The existing power grid follows a multi-level flow of power from transmission to distribution network, any change in power flow causes problems because DG units behavior is different than a conventional load [1].

- Finally, the initial energy balance for a new load is taken care by the power stored in the generator inertia and the micro generating units are inertia less. This lack of inertia is the major problem leading to power imbalances between the generation and load. There are also number of barriers in form of technical, business and regulatory issues when it comes to connecting DG's to electrical grid [8].

1.3 The Concept of Microgrid

To overcome these issues and to utilize the potential of distributed generation, the concept of MicroGrid (MG) was introduced in [8]. Using power electronic devices in addition with *Distributed Energy Resources* (DER), integration of DG into the utility grid is possible. Power electronic devices improve the flexibility and adaptability of the system by converting the power from source to a fixed frequency AC power. They also provide various ancillary services to the grid [10]-[11].

In microgrids, generating units are commissioned within the scope of the conventional distribution network so that power can directly flow from the generators to the load without having to pass through the transmission network. The other advantage of using such an architecture is that loads can be served even if the transmission network is down due to a fault, increasing the overall reliability of the system. A microgrid is generally known as the system consisting of small distributed generating stations along with the loads which is capable of going into islanded operation at times of need [12].

Among the many benefits of having a microgrid, one is that it facilitates distributed generation (DG) and high penetration of renewable energy sources [13]-[15]. They increase power quality and reliability of electric supply. A microgrid having renewable energy sources will help to alleviate some of the environmental issues related to burning fossil fuels. There is extensive literature on the various challenges posed by microgrids. Despite having some benefits of microgrid architecture in the grid environment, there are some challenges related to this also. Implementation is an issue. Microgrid protection is also considered one of the most important challenges facing the implementation of microgrids. Once a microgrid is formed, it is important to assure that the loads, lines, and DGs on the island are protected because conventional unidirectional power flow protection method is no longer viable [16]. Solid regulatory base is another issue related to microgrids.

Control of the voltage and frequency during islanded operation of DGs is also a major challenge. A method for intentionally islanding a single DG to feed a local load was proposed in [17]. A much more complex and challenging task is to operate more than one DG on the island. With more than one DG on the island, it is necessary to regulate the voltage during microgrid operation, which could be achieved by using a voltage versus reactive power droop controller [18]. There needs to be an algorithm that should complete the resynchronization process once the grid is restored. A supervisory control mechanism will monitor the overall process and provide information to the local controller to respond accordingly.

1.4 Problem Formulation

In the autonomous or islanded mode of operation, MG supplies its local load and is not connected to the utility grid. The main challenges in this mode are

- To maintain the output voltage of microgrid under pre-defined limits
- To maintain the output frequency of microgrid under pre-defined limits
- To regulate the deviations produced in output voltage due to load disturbances
- To regulate the deviations produced in output frequency due to load disturbances
- When more than one DG supports the load, proper load sharing has to be ensured among the DG units to avoid overloading

To provide quality power to consumer control of the voltage and frequency during islanded operation of MG is a major challenge. A much more complex and challenging task is to operate more than one DG on the island. With more than one DG on the island, it is necessary to regulate the voltage and frequency during MG operation [18]. Proper sharing of load should also be taken care of to avoid overloading of any one DG unit.

1.5 Proposed Objectives

The main focus of this research aims at the *distributed control* of microgrid. The deviations produced in output voltage and frequency due to load disturbances are to be regulated towards zero. The objectives of the thesis would therefore can be described as follows

- Developing a nonlinear model of inverter based autonomous MG system consisting of multiple DG units.
- Developing a suitable control technique addressing the problem statement which will be implemented in a distributed way for each DG unit. Evolutionary optimization techniques will be employed to obtain the optimized parameters for the controller.
- Implementing the distributed controller on the Real Time Digital Simulation (RTDS) environment.
- Applying Reinforcement Learning solutions to solve voltage control problem of microgrid.

1.6 Proposed Methodology

The above mentioned thesis objectives is manifested by the following tasks

Task I: Construct an extensive database of the published literature on the research performed on the modeling and control of MG. Identifying the advantages and disadvantages of various control techniques available in the literature.

Task II: Designing an autonomous MG system consisting of multiple DG units in the Matlab/Simulink environment.

Task III: Developing an improved control technology and testing it on the designed MG system.

Task IV: Implementation of control technique using Real Time Digital Simulation (RTDS) environment.

Task V: Developing controller by making using of reinforcement learning techniques for microgrid application.

Task VI: Report writing.

1.7 Thesis Outline

The outline of this thesis is organized as follows.

Chapter 2

The chapter presents extensive literature survey on advancements in the field of microgrid modelling and control. State of art literature covering two main aspects of microgrid namely modeling and control are presented. The advantages and disadvantages of various control techniques, modeling approaches available in the published literature are studied. Aspects related to both the grid-connected mode and islanded mode of microgrid are discussed in this chapter.

Chapter 3

In this chapter, we formulate the non-linear dynamics of an autonomous MG system consisting of multiple DG units. Modeling of inverter-based MG with its primary control level is presented.

Chapter 4

In this chapter, neural-network-based distributed secondary control scheme for an autonomous smart microgrid system is proposed. The proposed control technique is discussed in detail which involves concepts of evolutionary optimization, selection and training of neural networks. The proposed control technique is tested for quality output voltage and frequency against load disturbances. Comparative study between the proposed technique and traditional technique is also presented. The controller performance when subjected to time varying load is also summarized.

Chapter 5

This chapter deals with the real-time implementation of distributed multi-level control of microgrid. Both the primary and secondary control levels are implemented in real time environment using Real-Time Digital Simulator (RTDS). The experimental results of RTDS are compared with that of simulated results in MATLAB. Load sharing performance of controller under fault conditions is also presented.

Chapter 6

In this chapter, a new approach based on reinforcement learning is used to design controller for the microgrid. Heuristic dynamic programming based on value iteration techniques with actor-critic implementation is utilized to develop online and offline algorithms to solve Bellman equation. The proposed controller is tested for voltage regulation of a inverter-based microgrid sullying a parallel RLC load.

Chapter 7

This chapter summarizes the contributions of the thesis and provides the suggestions for the future work and developments of the research.

Chapter 2

LITERATURE SURVEY

2.1 Introduction

The burden on the transmission network is increasing at an unexpected pace due to the increasing demand of power. Since updates to the transmission network are economically challenging, microgrids have evolved to become an economically viable alternative. Microgrids incorporate various distributed generator units into the utility grid and solves and solves many problems of existing power systems. It is also the vital building block of the future Smart Grid [18]. In this chapter, motivation towards development of MG and an overview will be presented on the two key aspects,modeling and control, of MG. State of art literature review in these two key aspects will be presented.

2.2 Microgrid: Definition and Applications

A microgrid can be defined as, "*A network of low voltage power generating units, storage devices and loads capable of supplying a local area such as suburban area, an industry or any commercial area with electric power and heat*". The components of Microgrid are interfaced through quick response power electronics and presents itself as a single entity and therefore can be connected to traditional power grid or can also be operated in stand-alone mode as a self-sustained power system [18].

As stated in [8], *"The heart of the microgrid concept is the notion of a flexible, yet controllable interface between the microgrid and the wider power system*". Microgrid acts as a *Good Citizen*, that is, ideal conventional load behavior towards the grid which is less troublesome than distributed generation system. It also has environmental benefits because it uses renewable energy sources.

Different countries around the world adopts various topologies and structure basing on their priorities on functionality offered by microgrid. The research on microgrid is more active in US, Canada, Europe and Japan. Several demonstration projects and laboratory facilities are developed and a lot of research is in progress concerning various issues in the microgrid [19]. Various objectives which can be achieved by the use of microgrid are listed below, ride through capability provided by energy-storage is a common objective of microgrid.

- Reliability of power supply

- Reduction of environmental impact of electric supply
- Reduction of investment in plant, equipment and cost
- Increase of energy efficiency Stable
- Ensure diversity of energy supply
- Power supply to a remote site
- Ride-through capability provided by energy storage

The future *Smart grid* is expected to be a well organized plug-and-play integration of microgrids connected via dedicated highways for exchange of command, data and power. The emerging standards, research, development and demonstration are also discussed in [20].

2.3 Microgrid: Components and Formation

A generalized structure of microgrid is shown in fig (2.1). The microgrid can be connected to the utility grid through single Point of Common Coupling (PCC). The isolating device is used to isolate the microgrid from the utility grid.

The Distribution Generation (DG) unit is responsible for generation of electricity. It consists of rotating type and inverter type generating devices. Rotating type includes IC engines, gas turbines, micro alternator etc. whereas the inverter

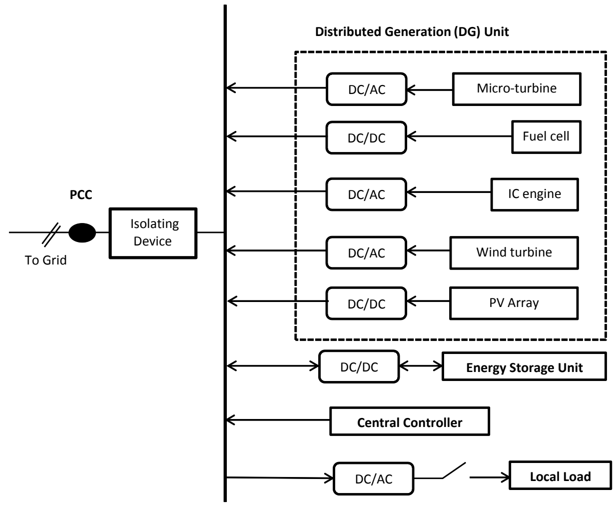

Figure 2.1: Generalized microgrid structure

type includes photovoltaic, fuel cells and wind turbines etc. Both rotating and inverter type requires power electronic converters for their interface. The power range of DG unit components is small-scale ranging from 4KW-10000KW [2].

Energy storage unit is essential to balance the flow of power at the onset of islanding mode of operation. It is also used to control the flow of power to and from the main grid. They help in improving the quality of power and assist in voltage control. Batteries, flywheels, super-capacitors, superconducting magnetic energy storage etc. can be used to store the energy. All these devices again require power electronic devices for their interface [2].

There has to be a *Control System* for the safe operation of microgrid in various modes of its operation. This system can be based on a central controller or distributed controller. The selection of controller depends mainly on the operation mode of microgrid and its requirements [21].Various control strategies will be discussed in this chapter in other sections.

The purpose of microgrid is not obtained until the customer is served with nominal voltage and frequency by a stable system during all the modes of operation [21].

2.4 Microgrid: Modes of Operation

Microgrid can operate autonomously and can also be connected to the utility/main grid. In case any fault occurs while operating in grid connected mode, microgrid has an ability to disconnect itself from grid and operate independently supplying its local load [22]. Therefore, the microgrid modes of operation can be classified into grid connected, islanded, transition between grid-connected mode to the islanded mode and vice-versa [23].In any mode of operation, the heat generated by some of the micro-sources can be used to supply the heat demand of the local load.

When functioning in parallel with the utility (main) grid, it acts as a Model or Good citizen and the voltage and frequency is controlled by main grid. Depending on load of the main grid, it will either supply or absorb power and act as either controllable load or controllable source. If any fault or disturbance occurs in the main grid, microgrid has an ability to disconnect and operate autonomously. This ability of microgrid increases the quality of power to its local customer by providing local voltage control. In this mode of operation, the points to be noted are

- The frequency and voltage magnitude are controlled by utility grid
- DG units supply the total or a part of the load

Islanding of microgrid can be due to unplanned faulty events discussed in [23] and can also be due to planned actions like maintenance etc. The microgrid controls the voltage and frequency in autonomous mode by continuously adjusting the output active and reactive power. This is very common mode of operation. In this mode, it supplies a local load which is closely located geographically. The local load can be a small village, a university, an industry or a commercial building etc. The main issues which the microgrid should address in this mode is the management of voltage and frequency, Quality of Power (QoP), balancing between load and supply, communication among its components etc. In this mode of operation, the points to be noted are

- The DG units control the frequency and voltage magnitude
- It supplies active and reactive power to the load

2.5 Microgrid: Overview of Modeling

A microgrid integration of various units. Basically, it consists of DG unit, energy-storage unit, controller unit and conventional load. The DG unit again compromises of various micro-generating devices. Therefore, microgrid modeling varies from one configuration to other depending on the components used. Various approaches for the modeling and control of microgrid can be found in the literature [24]. We will discuss the different models available in the literature.

A small signal dynamic analysis of an autonomous hybrid system is performed in [25]. The configuration of the system is shown in fig (2.2).

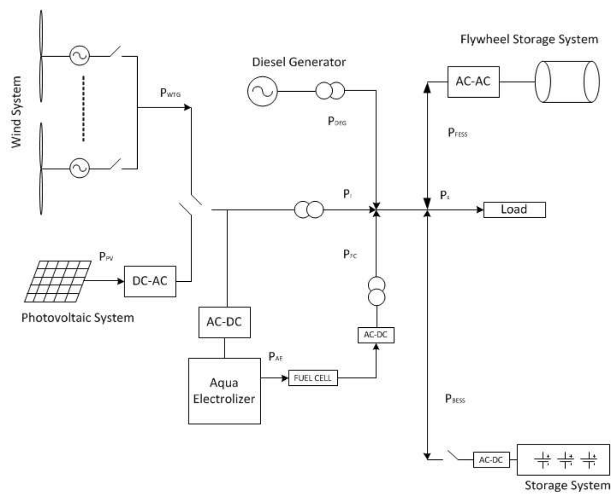

Figure 2.2: Configuration of a microgrid system [25]

The dynamics of all the DG units are approximated by a first order linear model with a time constant and a gain factor while the network is neglected [25, 26]. The transfer functions of various components are obtained and time domain analysis is performed by considering various components at each time. The transfer functions of various components are given as follows and fig (2.3) shows the configuration in one of the cases.

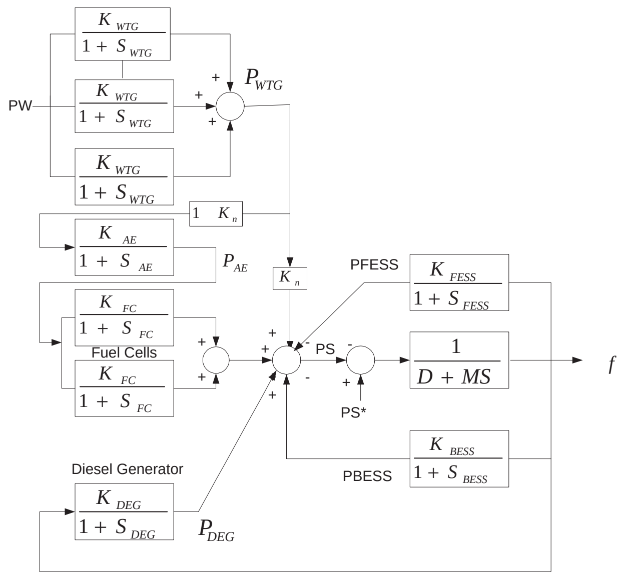

Figure 2.3: Block diagram of a microgrid

$$\begin{aligned}
Wind\ \ Turbine : G_{WTG}(s) &= \frac{K_{WTG}}{1+sT_{WTG}} \\
PV\ \ System &= \frac{K_{PV}}{1+sT_{PV}} \\
Fuel\ \ Cell &= \frac{K_{FC}}{1+sT_{FC}} \\
Diesel\ \ Engine\ \ Generator &= \frac{K_{DEG}}{1+sT_{DEG}} \\
Aqua\ \ Electrolyser &= \frac{K_{AE}}{1+sT_{AE}} \\
Storage\ \ System &= \frac{K_{sto}}{1+sT_{sto}}
\end{aligned}$$

Since a MG is a power generating unit, it can be represented by a DC source. This concept of modeling a MG with an RLC load in islanded mode is proposed in [27]–[28]. As shown in Fig. 2.4, MG is represented by a DC source connected to a voltage-sourced converter (VSC). The MG is connected to the grid by means of a R-L filter, step-up transformer and a circuit breaker. The circuit breaker is open when the MG is islanded. The load which is passive RLC type is connected on the high voltage side of the transformer. A control system is used to control the VSC.

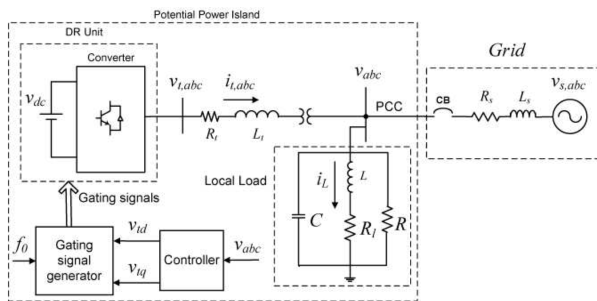

Figure 2.4: Model of microgrid in [27, 29, 30]

The dynamic model of Fig. 2.4 is represented by the nonlinear equations below. After performing the linearization, whose details can be seen in [27, 29, 30] , the state space matrices are obtained as mentioned below. The overall test system was simulated in the *Matlab Simulink* and *ATPDraw* environment.

$$\frac{dI_{td}}{dt} = -\frac{R_t}{L_t}I_{t,d} + \omega_0 I_{tq} - \frac{1}{L_t}V_d + \frac{1}{L_t}V_{td} \tag{2.1}$$

$$\frac{dI_{tq}}{dt} = \omega_0 I_{td} - \frac{R_l}{L}I_{tq} - 2\omega_0 I_{Ld} + (\frac{R_l C\omega_0}{L} - \frac{\omega_0}{R})V_d \tag{2.2}$$

$$\frac{dI_{Ld}}{dt} = \omega_0 I_{tq} - \frac{R_l}{L}I_{Ld} + (\frac{1}{L} - \omega_0^2 C)V_d \tag{2.3}$$

$$\frac{dV_d}{dt} = \frac{1}{C}I_{td} - \frac{1}{C}I_{Ld} - \frac{1}{RC}V_d \tag{2.4}$$

$$\tag{2.5}$$

$$A = \begin{bmatrix} -\frac{R_t}{L_t} & \omega_0 & 0 & -\frac{1}{L_t} \\ \omega_0 & -\frac{R_l}{L} & -2\omega_0 & \frac{R_l C\omega_0}{L} - \frac{\omega_0}{R} \\ 0 & \omega_0 & -\frac{R_l}{L} & \frac{1}{L} - \omega_0^2 C \\ \frac{1}{C} & 0 & -\frac{1}{C} & -\frac{1}{RC} \end{bmatrix} B = \begin{bmatrix} \frac{1}{L_t} & 0 & 0 & 0 \end{bmatrix}^T C = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathrm{x} = \begin{bmatrix} i_{td} & i_{tq} & i_{Ld} & v_d \end{bmatrix}^T$$

This concept of representing MG as a combination of DC source with VSC is also presented in [31, 32]. This paper models the islanded operation of MG consisting of two parallel DG units. Again the local load is a passive RLC network located at the PCC. The schematic diagram of such an arrangement is shown in Fig. 2.5. The MG structure is used for the application of decentralized control and hence there is a separate controller for each DG unit.

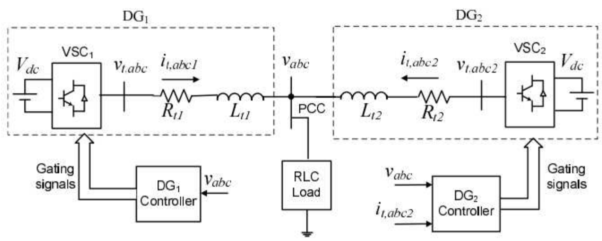

Figure 2.5: Radial configuration of generating units used in [31]

By applying KVL and KCL and further application of frame transformation, gives the below dynamic equations governing the MG. The model is then represented in state space which is simulated using *Matlab SimPowerSystems* toolbox [31].

$$
\begin{aligned}
\frac{dV_{dq}}{dt} &= -\frac{1}{RC}V_{dq} - \frac{1}{C}i_{t,dq1} - \frac{1}{C}I_{L,dq} + \frac{1}{C}I_{t,dq2} \\
\frac{I_{t,dq1}}{dt} + j\omega_0 I_{t,dq1} &= -\frac{1}{L_{t1}}V_{dq} - \frac{R_{t1}}{L_{t1}}I_{t,dq1} + \frac{1}{L_{t1}}V_{t,dq1} \\
\frac{I_{L,dq}}{dt} + j\omega_0 I_{L,dq} &= \frac{1}{L}V_{dq} - \frac{R_l}{L}i_{L,dq} \\
\frac{i_{t,dq2}}{dt} + j\omega_0 I_{t,dq2} &= -\frac{1}{L_{t2}} - \frac{R_t 2}{L_t 2}i_{t,dq2} + \frac{1}{L_t 2}v_{t,dq2}
\end{aligned}
$$

A microgrid consisting of only inverter based DG's is modeled in [33] [34]. Typical structure of such microgrid is shown in Fig. 2.6. The modeling approach considered the full dynamic model of the complete network rather than algebraic equations.

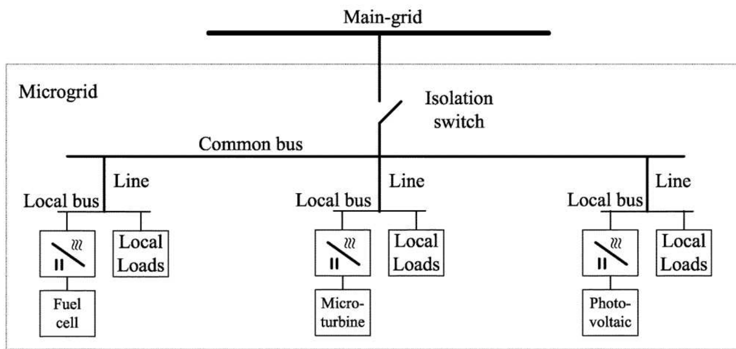

Figure 2.6: Inverter based microgrid structure in [33]

The approach of modeling was divided in three modules namely inverter, network and loads. The inverter model compromises of dynamics of controller, output filter and coupling inductor. The state equations of network and load are represented on one of the inverters reference frame which is assumed to be common reference. Then using the transformation technique [35], all the other inverters are transformed to this common frame. Each sub-module is modeled in state-space form and combined together on this common reference frame. Block diagram of state space model of the MG is shown in Fig. 2.7.

By combining individual sub-modules, the overall state-space model of MG is given below. The subscript represents states of inverter, network and load. Detailed derivation and information on the state-space matrices can be found in [33].

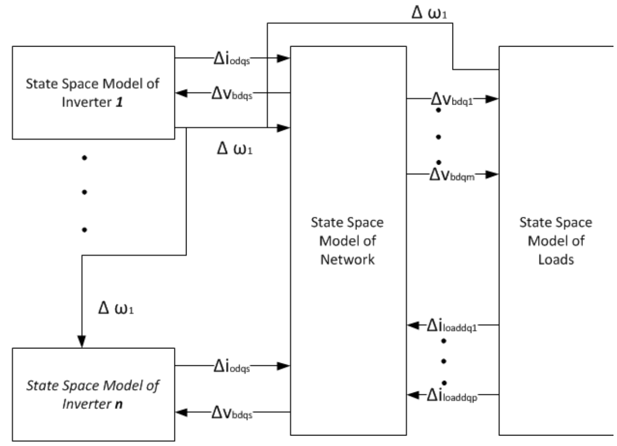

Figure 2.7: State-space model of microgrid in [33]

$$\begin{bmatrix} \Delta\dot{x}_{Inv} \\ \Delta\dot{i}_{networkdq} \\ \Delta\dot{i}_{loaddq} \end{bmatrix} = A_{mg} \begin{bmatrix} \Delta x_{Inv} \\ \Delta i_{networkdq} \\ \Delta i_{loaddq} \end{bmatrix}$$

A small signal dynamic model of MG which includes synchronous generator based DG and power electronically interfaced DG is presented in [36]. Fig. 2.8 shows the single line diagram of the MG. DG1 is a synchronous machine (diesel or gas-turbine generator) with excitation and governor control system whereas DG2 is a dis-patchable source (micro-turbine or wind generator etc) equipped with a Voltage-Source Converter (VSC). The system parameters are given in [23]

To obtain the linearized mathematical model of the above system the following

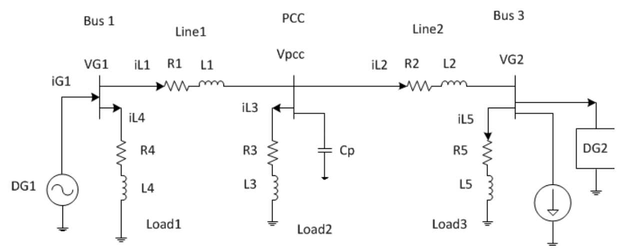

Figure 2.8: Small signal of synchronous generator model [36]

steps are followed

- The ordinary differential equations (ODE) of DG units including network components are developed in their respective local *dq0* reference frames
- The obtained equations are transformed to the global *dq0* frame of MG
- Linearized about a nominal operating point and arranged in the state space form

The dynamic model of DG1 in its local reference *dq0* frame is obtained from [37] and the dynamic model of DG2 can be found in [38, 39]. The electrical network modeling is carried out on the basis outlined in [40] and can be found in [39]. The overall system model is represented by the block diagram in Fig. 2.9. The small signal model was validated in the *PSCAD/EMTDC* environment.

The same MG structure is taken into account in [23] and the stability analysis for various transient conditions such as energizing load, transition from grid-connected mode to islanded mode and vice-versa is performed. An operational architecture developed within EU R&D microgrids projects [41] is adopted in

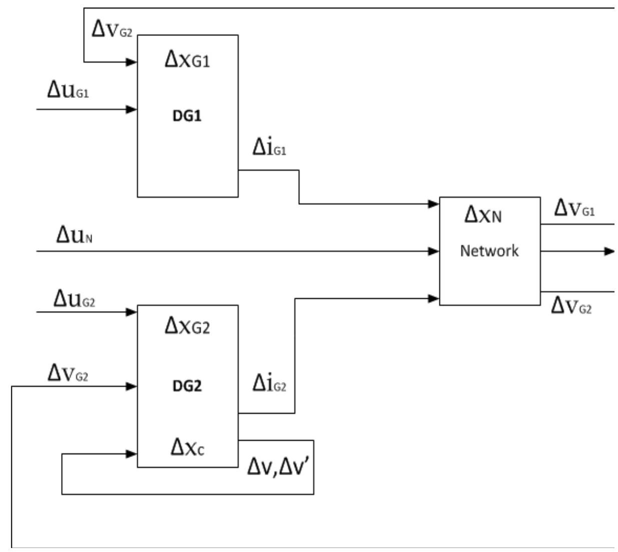

Figure 2.9: Block diagram of microgrid model [36]

[42]. This concept is shown in Fig. 2.10. It is a multi-level type control and management scheme supported by a communication infrastructure.

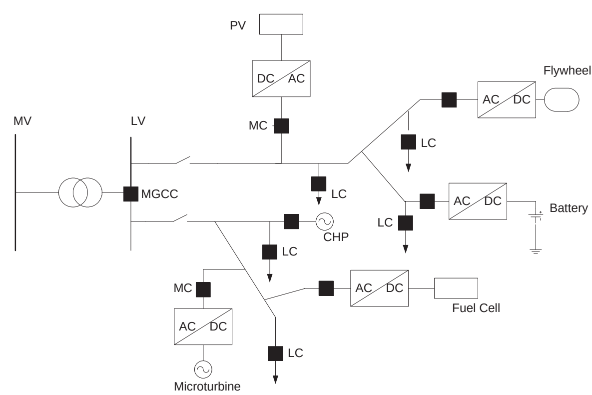

Figure 2.10: Microgrid structure in [42]

The head of this multi-level control system is MicroGrid central controller (MGCC) installed at the MV/LV substation and centrally controls the MG. Load controllers (LC) and micro source controller (MC) forms the second level of Hierarchy and exchange information with the MGCC. LC acts as an interface to controllable loads and MC controls the active and reactive power of each micro source. Both LC and MC receives their set-points from MGCC.

The dynamic modeling of each DG components was picked from different literature. The dynamic model of solid oxide fuel-cell (SOFC) is described in detail with the values of each parameters in [43, 44]. A gas turbine (GAST) was used for the primary unit of micro turbine. The dynamic model of GAST is adopted from [43]. A fifth-order induction generator connected directly to the network serves as a wind generator. This model was available in *Matlab Simulink* toolboxes. An empirical model for the PV generator based on experimental results was adopted from [45].

Flywheels and batteries are used for the modeling of storage devices. They were modeled as a constant dc voltage sources and were coupled to the electrical network using power electronic interface.

The inverter modeling can be derived as per two control strategies, PQ inverter control modeling [46] and Voltage Source Inverter Control (VSI) model [47, 48]. Inverters are modeled based only on their control functions for the purpose of analyzing the dynamic behavior of MG [23, 49, 50, 51, 52]. Two types of loads were considered, one is constant impedance load and other is motor load.

An LV test network was built in *Matlab/Simulink SimPowerSystems*environment. The implementation of this network is shown in Fig. 2.11 whose detailed description can be found in [53] and [54].

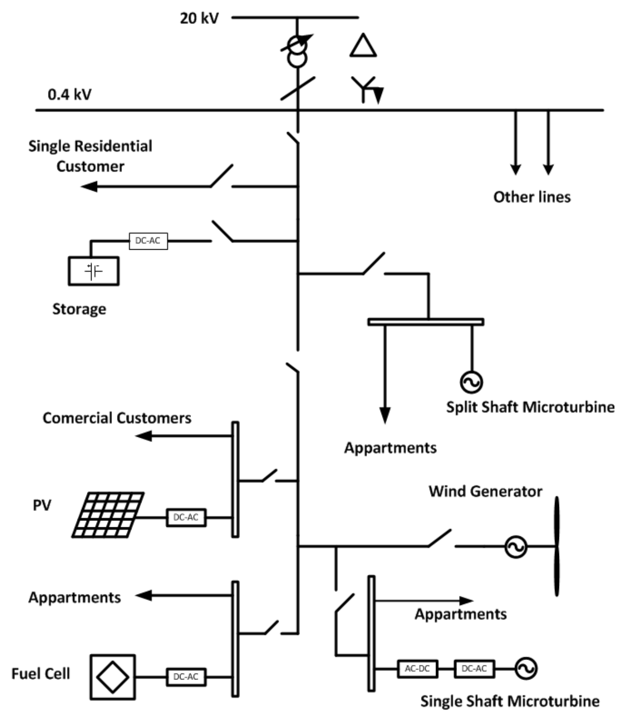

Figure 2.11: Implementation of microgrid on low voltage network

A low voltage MG with three unbalanced phases was proposed in [55], Fig. 2.12 shows the *Matlab Simulink*implementation of the structure used. Inverters droop controls were used to interface DG's and loads were modeled as constant power. Simulations were carried out for both grid connected and isolated modes. This model has an advantage of modeling small unbalanced networks but lacks the analytic details required for stability analysis.

A new method to form the system matrices of large MG's in islanded mode is discussed in [56]. The MG under consideration has DG's power electronically interfaced and hence the dynamics are similar to that shown in [33]. There were

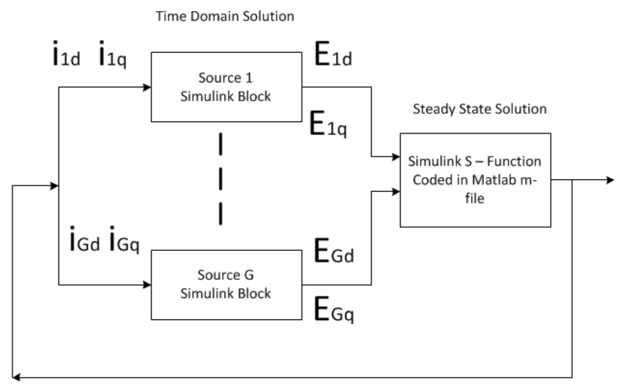

Figure 2.12: Microgrid network structure used in [55]

two types of DG's, one was PQ regulated and other was Vf regulated which are introduced in [36].

The proposed modeling approach is based on four dened complex vectors. These vectors allow for complex-valued system matrices to be formed in a quite automated way. Moreover, a convenient partition of the system matrices is proposed, which in turn allows fast and easy modications. Additionally, a multivariable methodology is proposed to simultaneously determine the control system gains in an optimal sense.

An alternative approach is based on the "hub model" for microgrids [57] in which the couplings between an integrated electricity and natural gas system to yield optimal operation are modeled by energy hubs. It turns out that this concept serves as interface between the loads and the transmission infrastructures and supports the application of distributed control schemes. Similarly, hybrid modeling control techniques are applied to a two generator power system connected to the grid and the plant consists of a solar field and a secondary power source formed by an electrolyzer, hydrogen tank and fuel cell stack. It is shown that the system has essentially hybrid dynamics, as it can operate in four distinct modes, depending on the power circuit configuration and the fuel cell stack state [58]. With focus on bulk power flow of microgrids, research investigations are reported in [59, 60] in which an optimal design of an electrical microgrid and sizing of its components is sought to balance capital investment with expected operational cost while meeting performance requirements. In [61], an comprehensive review on current control technology is presented with emphasis on challenges of microgrid controls. The impact of frequency and voltage regulation on the optimal design of an autonomous military microgrid, comprized of a solar panel and vehicles as power sources, with each vehicle incorporating a battery and generator, is developed in [62, 63]

2.6 Microgrid - Overview of Control

The control strategies for microgrid depends on the mode of its operation. The aim of control technique should be to stabilize the operation of microgrid. When designing a controller, operation mode of MG plays a vital role. Therefore, after modelling the key aspect of the microgrid is control. In this section we will discuss the various control paradigms.

2.6.1 Microgrid Control: Grid-Connected Mode

In grid connected mode, microgrid acts as a controllable load/source. It should not actively regulate the voltage at the point of common coupling (PCC). Its main function is to satisfy its load requirements with good citizen behavior towards main grid. The balance between generation and demand, control of the parameters of the system is taken care by the utility grid. The voltage and frequency reference of the microgrid is also set by the main grid. Therefore the main task of a DG unit is to control the output real power (P) and reactive power (Q) [64]-[65]. The P, Q generated by a DG can be controlled either by current-based or by voltage-based power flow control [66].

2.6.2 Power Flow Control by Current Regulation

The control scheme for *power flow control through current regulation* is illustrated in Fig. 2.13. It is desired to control both the real and reactive power. The real power control loop is used to obtain the synchronous frame d-axis reference current and reactive power control loop is used to obtain the q-axis current. The synchronous d-q frame current can then be controlled in a closed loop manner [65].

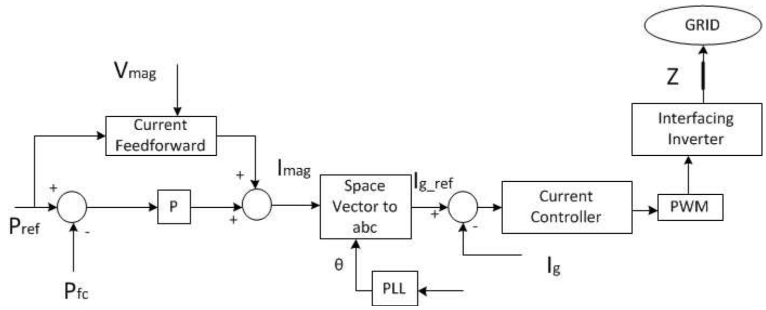

Figure 2.13: PQ power control through output current regulation[66]

2.6.3 Power Flow Control by Voltage Regulation

The other method to control the power flow is based on the output voltage of DG. Therefore it is know as *power flow control through voltage regulation*. It can be shown that real power (P) flow is proportional to the voltage phase angle (δ) and reactive power (Q) flow is proportional to voltage difference (V_l - V_g), where V_l is DG voltage and V_g is PCC voltage and δ is the phase angle difference between these two voltages. Therefore the flow of P can be regulated using δ and flow of Q can be regulated using V_l - V_g. This scheme is illustrated in Fig. 2.14. To improve the accuracy of reactive power control, integral control can be included into the reactive power controller [64, 67, 68].

Power control through voltage regulation is more sensitive than current regulation to the line impedance between the DG and the PCC.

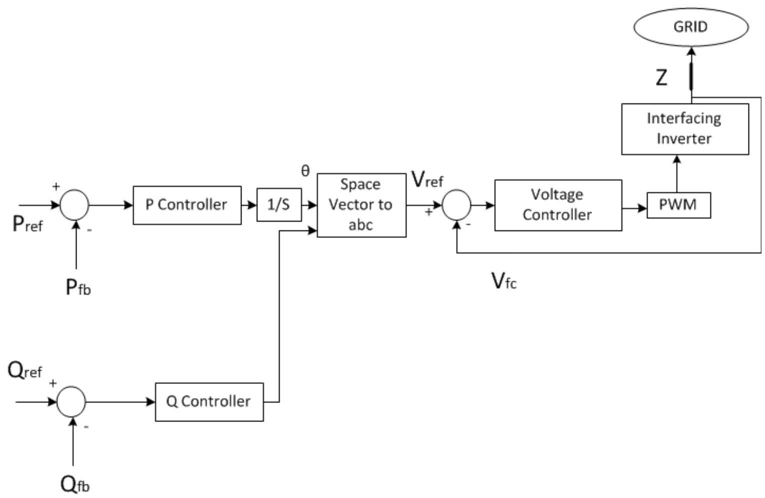

Figure 2.14: PQ power control through output voltage regulation [66]

2.6.4 Agent-Based Control

Microgrid management system was developed using agent based technology in [69]. Microgrid agents were developed on JADE (Java Agent Development Framework). The proposed system has several functionalists like SCADA system, selling bids managing system, load shifting system etc. The software architecture of the management system is shown in Fig. 2.15.

Microgrid agent platform consists of following components

1. Microgrid Central Controller (MGCC) : It includes Pulling Agent, Database Agent, Control Agent, Shifting Agent, Curtailment Agent

2. Micro source Controller : It includes Generator Agent, Schedule Agent, Bid Agent

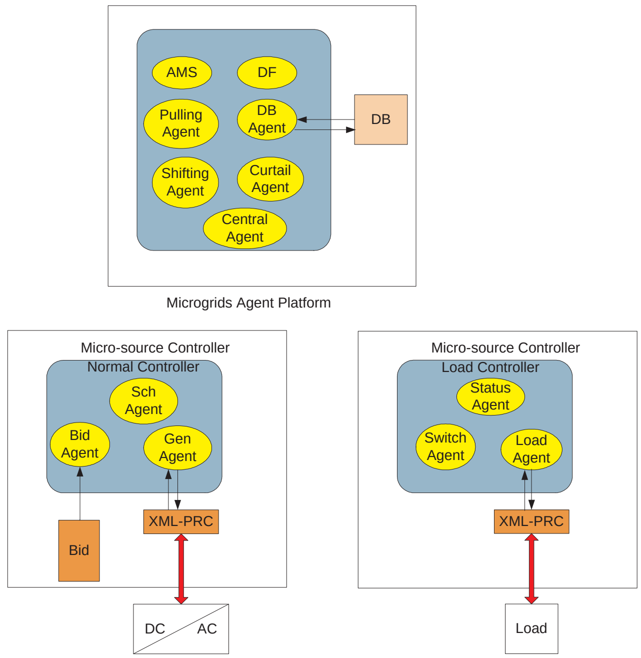

Figure 2.15: Architecture of management system

3. Load Controller : It includes Load Agent, Status Agent, Switch Agent

The effectiveness and applicability of the introduced software has been evaluated on a laboratory environment.

2.6.5 Multi-Agent Distributed Control

A distributed control approach based on Multi Agent System (MAS) for micro-grids is proposed in [70], where advantages of MAS technology is utilized for controlling microgrids. As shown in Fig. 2.16, a fully decentralized approach is adopted with 3 distinguished control level.

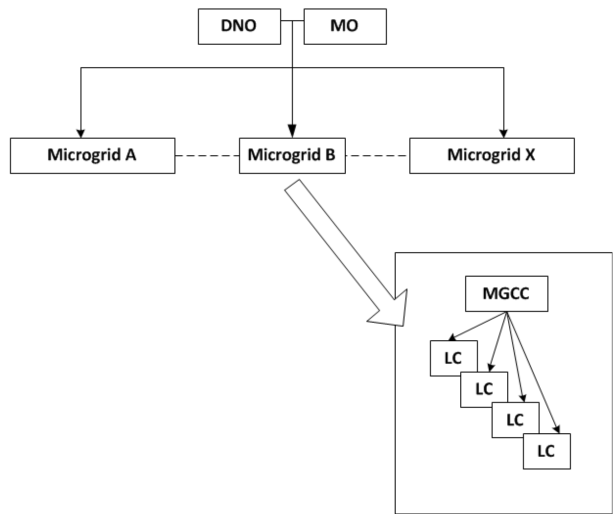

Figure 2.16: Control levels of multi-agent environment

Distribution Network Operator (DNO) and Market Operator (MO)are at medium voltage level and does not belong to microgrid. DNO refers to the operational functions of the system and is responsible for technical operation of one or more microgrids whereas one or more MO are responsible for market functions of the area.

Microgrid Central Controller (MGCC) is the main interface between DNO/MO and the microgrid. Its main function is to optimize the operation of microgrid and coordinate the local controllers. On the lower level, Load Controllers (LC) control the DG, production, storage and some of the local loads.

Using MAS technology, model of the system is obtained in detail where every agent uses the the exact piece of information it needs, leaving the technical details for the agents that are below it in the organization chart. The paper proposes three types of agent. *Control Agent* which controls physical units of the system directly. *Management Agents* which manage the microgrid and takes the decision. *Ancillary Agents* which performs tasks like communication and storage of data. The proposed MAS platform is depicted in the Fig. 2.17.

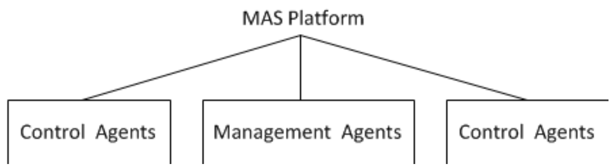

Figure 2.17: Types of multi-agents

In [70], internal operation of the microgrid and its participation in energy market was focused particularly. The algorithm is proposed so that the every Distributed Energy Resource (DER) or controllable load decides what is best for it.

2.6.6 H_∞ Control

A new power balancing method based on H_∞ control theory is proposed in [71]. The power fluctuations were considered as the disturbances added to the MG. Fig. (2.18) shows the block diagram of MG structure.

where G_{ge} and $G_{bt}$are the first order transfer function representation of gas turbine [72] and K_{ge} and K_{bt} are controller gains for gas turbine and battery, respectively. F is the low/high pass filter gain.

Using the Robust Control Toolbox of *MATLAB*, the controller gains K_{ge} and K_{bt} were determined as standard controllers. Fig. 2.19 shows the block diagram

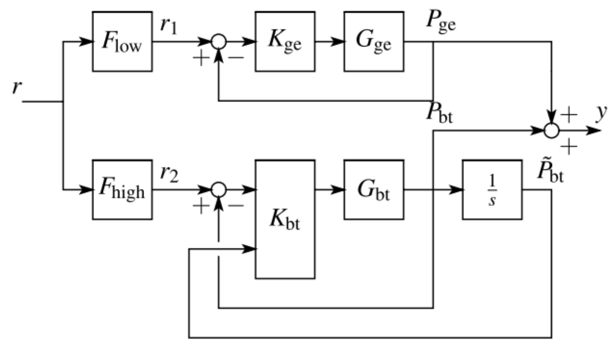

Figure 2.18: Structure of microgrid [71]

of these controller designs, where W with subscript 1, 2 and 3 are weighing functions for tracking performance, gain margin of the microgrid system, and robustness for power fluctuations respectively.

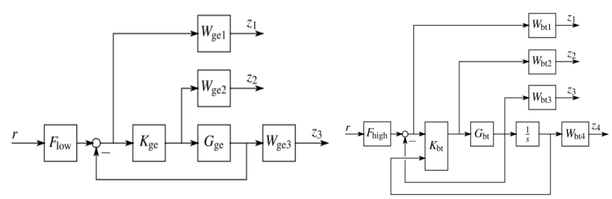

Figure 2.19: Design of H_∞ controllers [71]

In [73], technical challenges and stability of DG's when connected into the distribution system is detailed. Since high penetration of the DG's can be considered as a microgrid the same technical challenges can be assumed correct for a grid connected microgrid.

2.6.7 Microgrid Control : Autonomous/Islanded mode

In the autonomous or islanded mode of operation, microgrid supplies its local load and is not connected to the utility grid. The main challenges in this mode are

1. Voltage and frequency control
2. Balance between supply and demand
3. Power quality
4. Issues relating to micro-sources
5. Communication among microgrid components

Lot of research has been done on control of microgrid in autonomous/islanded operation [74] which will be discussed in this section. The two main control strategies PQ and VSI control is discussed first, detailed description and explanation on these two controls can be found in [51].

When connected to grid, all the DG's can operate in PQ control mode because the voltage and frequency is dictated by the utility grid but at least one DG has to follow VSI control in islanded mode since the voltage and frequency reference is set by the MG.

2.6.8 PQ and Volatge Source Inverter Control

The aim of *PQ control* is to provide constant active and reactive power at a desired power factor [42, 56]. The reference values of power is defined by a local controller or centrally from the MGCC. This scheme can be implemented as a current controlled voltage source or voltage controlled current source as discussed earlier in sections. Current or voltage components in direct (I_d or V_d) and in quadrature (I_q or V_d) with inverter terminal voltage are computed based on method given in [46].

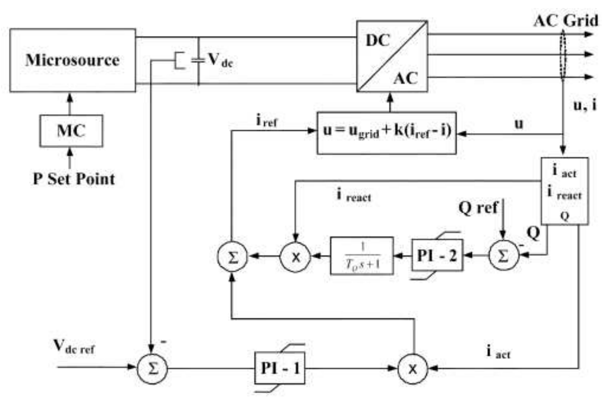

Figure 2.20: PQ control scheme [42]

Fig. 2.20 shows the control block for this strategy using current control. The direct component (I_d) of the current is used for the control of active power and the quadrature component (I_q) is used for the reactive power control.

Voltage source inverter (VSI) matches the behavior of a synchronous machine controlling the voltage and frequency on the ac system [49, 75, 46]. It acts as a voltage source whose output voltage's magnitude and frequency is controlled through *Vf* droop characteristics which are shown in fig. (3.3). Hence, this method is also known as *Droop Method*.

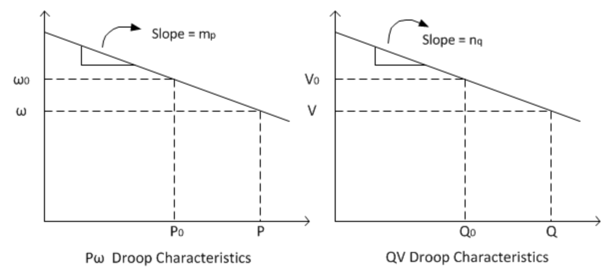

Figure 2.21: *Vf* characteristics

In VSI control, voltage is related to reactive power $(V-Q)$ whereas frequency/phase shift is related to active power $(f - P)$ by the below shown equations.

$$f = f_0 - K_p \Delta P$$
$$V = V_0 - K_q \Delta Q$$

where K_p and K_q are respective slopes of droop characteristics and f_0 and V_0 are the idle values of frequency and voltage [47]. The micro-sources will change their output by ΔP (or ΔQ) when the frequency (or voltage) changes by Δf (or Δv) from the nominal values f_0 (or v_0).

A VSI model is shown in fig (2.22) [47, 48]. The active and reactive powers are computed using the VSI terminal voltage. The output voltage frequency

f is determined by the active power droops and magnitude V is determined by reactive power droops. The output voltage are the reference signals which control the VSI switching sequence.

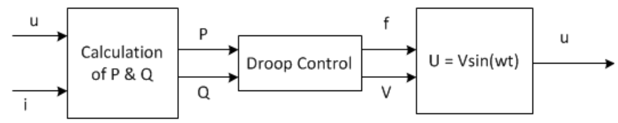

Figure 2.22: Model of a voltage source inverter

The key point to be observed here is VSI uses the local measurements at its terminals and reacts to any system disturbances quickly and hence does not require any communication infrastructure [49, 75]. But there will be a communication infrastructure within the DG for the optimal management [42].A complete review of *Vf* control strategies can be found in [76] and validation of *Vf* control in both grid and islanded mode is performed in [21].

2.6.9 Autonomous Control

The concept of utilizing *VQ* and *Pf* droops for controlling the microgrid is also proposed in the [3, 7, 77]. They propose an autonomous control for the *peer-to-peer* and *plug-and-play* model of the microgrid components. The concept of peer-to-peer allows the continuous operation of microgrid even with loss of any component/DG because there are no master controller or central storage unit. The concept of plug-and-play ensures that any component can be added at any point in the system without re-engineering the controls.

Micro-source controller based on droop characteristics is shown in Fig. 2.23. P,Q and V are calculated and then the droops are implemented in two separate blocks. Then the controller generates the voltage at desired magnitude and frequency at the inverter terminals.

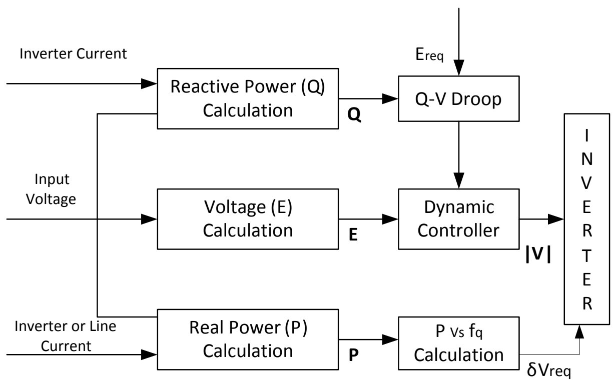

Figure 2.23: Micro-source controller using droops

2.6.10 New $Q - \dot{V}$ Droop Control

In islanded mode, the reactive power sharing is highly dependent on impedance of power line. Due to the different distances among DER interface converters (DIC), the equivalent transmission line impedance could be unequal [47]. *Pf* and QV droop characteristics are used in DER interface converters for power sharing operations [78, 77]. The *Pf* droop control provides an accurate real power sharing among the DIC's but the problem arises in QV droop control. Because of these unequal impedance load sharing performance of QV control can be affected. Various control methods addressing this issue has been proposed [79, 80, 81] but with some constraints.

Therefore a new droop control method for the islanded operation of MG is proposed in [82] to overcome the effect of line impedance on the reactive power flow, this method is known as Q-$\dot{V}$ droop control method where $\dot{V}$ represents the rate of change of voltage. By regulating the voltage with $\dot{V}$, the reactive power sharing can be made independent of the line impedance. The operation principle of the proposed method is shown in fig (2.24).

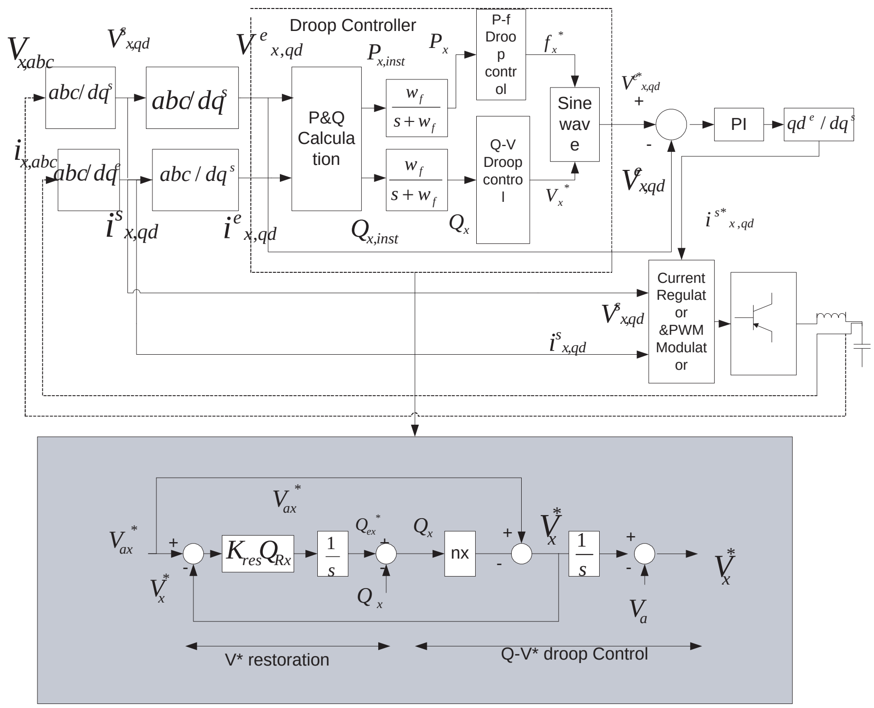

Figure 2.24: Block diagram of interface converter with $Q\dot{V}$ droop control [82]

2.6.11 Control Design Based on Transfer Function

Controller based on the transfer function of the plant is designed in [27, 30], this is adopted from the classical feedback control approach presented in [83].

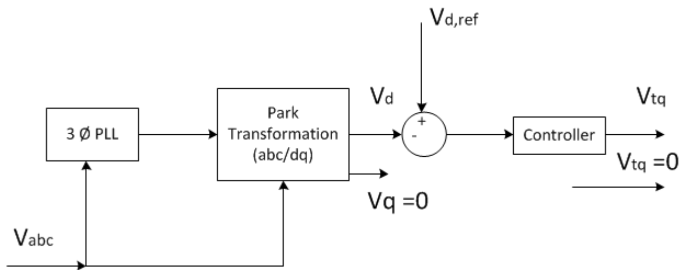

Figure 2.25: Control strategy in [27, 30]

For the islanded mode of operation, fig(2.25) shows the structure of controller. Reference angle is provided by a three phase PLL. The q component of load voltage is set to zero and d component is regulated to the desired peak value. Regulation of v_d is done by comparing with reference signal and the error is applied to the controller. The controller then provides inputs to the gating signal generator of the VSC (Fig. 2.4). More details can be found in [27, 30].

Instead of using frequency droops, an internal oscillator is used to design a multivariable controller in [29]. The function of this oscillator is to control the frequency in open loop way. The robust servomechanism controller was designed using the parameter optimization methods [84, 85] in addition with non-conservative robustness constraint [86].

2.7 MG - Control in Both Modes

A novel control strategy which can be applied to MG in both the modes is introduced in [28]. This scheme of control allows a DG to control its real &

reactive power components in grid-connected mode and to control the voltage & frequency in autonomous mode.

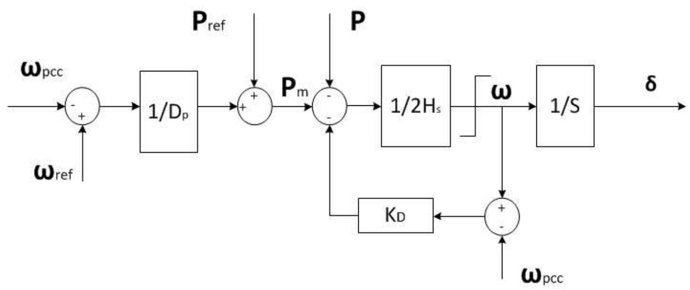

Figure 2.26: Block diagram for the *frequency* control [28]

The proposed VSC frequency control is similar to that of a synchronous machine and is shown by the block diagram in fig (2.26). In grid-connected mode, the frequency at PCC (ω_{pcc}) is equal to the grid frequency and hence have no impact on the system dynamics and only the output real power reference has to be set. In autonomous mode, is same as VSC frequency determined by the droop characteristics.

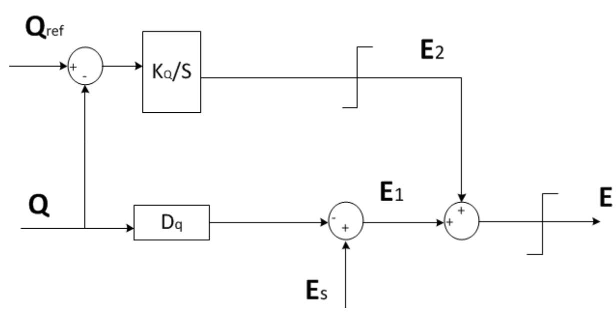

Figure 2.27: Block diagram for the *voltage* control [28]

The block diagram in fig (2.27) shows the proposed voltage control scheme. During grid-connected mode, output reactive power of VSC at PCC is set while in autonomous mode, the DG has to supply the load with reactive power, which is achieved by setting E_2 to zero and only E_1 remains effective.

2.8 Sysytem of System Control - Application to Microgrid

The key issue of Sysytem of System (SoS), which is control, faces a main challenge of developing a comprehensive SoS model, analytically or by simulation. Availability of a proper model is necessary to design a controller. If a proper mathematical model is available then there are several available control strategies. Also control strategy for each system is not only dependent on its own sensory information but also on the communication links among its neighboring systems or components, this is another difficulty which rises from the control point of view. Control of SoS, which is different for each application domain, is still an open research area. In this section we will discuss several potential control strategies.

2.9 Introduction to System of Systems

To understand the concept of system of systems (SoS) or cyberphysical system (CPS), let us consider an airplane which is an example of large scale complex system. Various parts of airplane are operated by different systems but the plane flies only when all its systems operate collectively and does not fly if they operate individually. Therefore, a SoS is the large-scale integration of many systems that combine their capabilities together to form a more complex system offering more functionalities than the individual sum of the constituent systems [87].

SoS is inherently multidisciplinary. The synthesis of multi systems requires the study of their interdependency because each effects the other. This will result in different problems ranging from modeling to control. Therefore almost all the key issues of systems engineering have to be revised. The methodology of developing models, tools and control of SoS is typically referred to as system of systems engineering. SoS methodology finds large number of applications in the defense sector but recently it is also being used in auto transportation, space exploration, search and rescue and many other non-defense areas [88].

For SoS engineering branch, all aspects of systems engineering have to be revised. But the main problem arises in the two key aspects which are modeling and control. The challenge in modeling point of view lies in the indirect effects, the cause and effect need not be directly related, any change *here* can produce effect *over there* because of their interdependency.It is clear that these systems are very large and posses unpredictable behavior which is difficult to model. SoS models available so far are still immature and there should be focus on additional development. These models are quite complex and needs a multidisciplinary approach [88, 89, 90, 91, 92].

Control is perhaps the most critical challenge facing SoS designers. Due to the difficulty or impossibility of developing a comprehensive SoS model, either analytically or through simulation, SoS control remains an open problem and is, of course, different for each application domain. Moreover, real-time control which is required in almost all application domains of interdependent systems poses an especially difficult problem [93, 94].

2.9.1 Decentralized Control

Another control lacking real-time consideration is *decentralized control* [88]. In this scheme of control, SoS is assumed to be having multiple input and output variables. The control design aims at assigning proper inputs for proper controller which can observe a set of outputs. Thus there are multiple controllers, each one controls a particular operation of SoS. As it can be seen in Fig. 2.28, this scheme avoids storage of data.

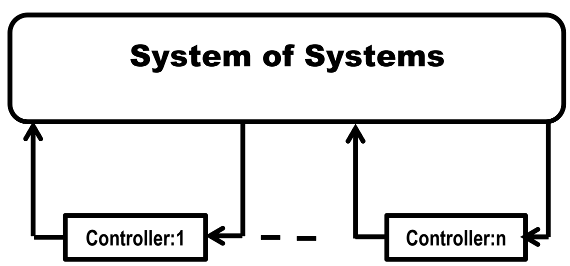

Figure 2.28: Decentralized control scheme

2.9.2 Microgrid - Decentralized Control

A robust decentralized control strategy is proposed in [31] for the islanded operation of a MG. The proposed model of MG is shown in fig (2.5). It is shown that the MG can be represented by an interconnected composite system consisting of two subsystems [95] and each subsystem can be controlled using the local controllers.

The dynamic model of the MG is decomposed into two subsystem as follows

- Master Subsystem
- Slave subsystem

Since the two subsystems are controllable and observable, it is shown that the composite system is stabilizable by using only local controllers i.e., decentralized control strategy can be applied.

For the master subsystem, an H_∞ controller was designed to meet the robust characteristics [96]. This control strategy fulfills the voltage and frequency requirements of the load. The configuration of H_∞ control is shown in Fig. 2.29. *Matlab LMI* toolbox is used to synthesize H_∞ controller [97].

A simple PI controller was designed for the slave subsystem using the conventional *dq* current control method [98, 99]. This is depicted in Fig. 2.30. The

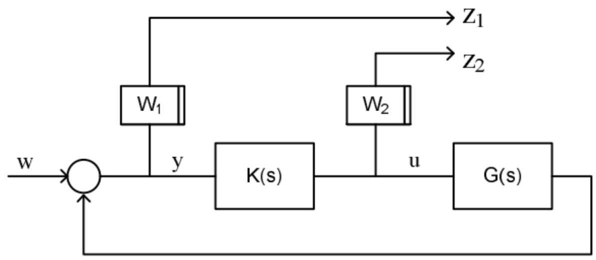

Figure 2.29: H_∞ control for master subsystem [31]

overall model and its controllers were simulated in *Matlab/SimPowerSystems* toolbox.

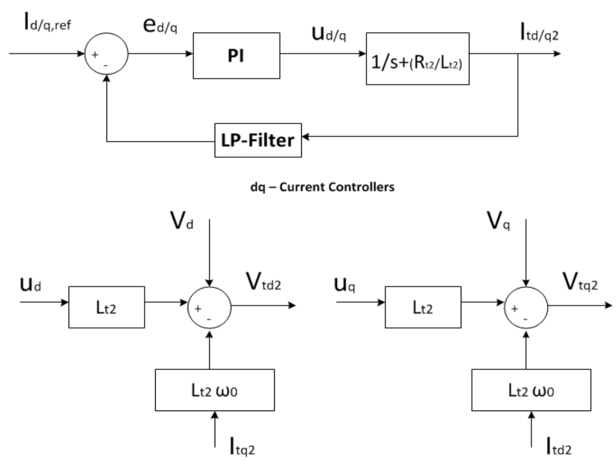

Figure 2.30: DQ current control method for slave subsystem [31]

A fundamental concepts of Power Management System (PMS) and robust decentralized control strategy for the islanded MG is proposed in [100]. The schematic diagram of proposed control is illustrated in fig (2.31). It consists of a PMS, Local Controller (LC) for each DER and MG frequency control and synchronization scheme.

A low bandwidth communication system is used to supply the instantaneous

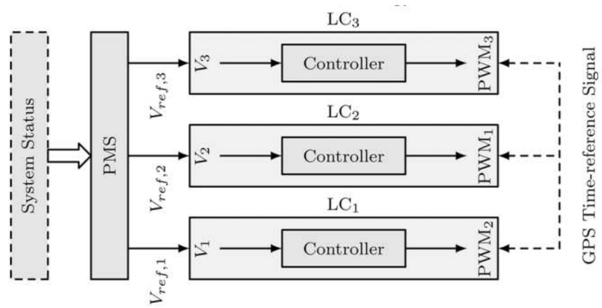

Figure 2.31: Power management system and control scheme in [100]

values of real/reactive power of each DER unit and load to the PMS. The PMS determines the set points of real, reactive power and voltage for the PC buses and transmits to LC's which measures the magnitude of voltage at its PC bus provides voltage tracking based on the received reference set point.

A decentralized inverter control based on wireless communication is proposed in [101]. wireless communication is used to enhance the stability of droop based decentralized inverter control. A wireless network is developed so that each inverter can communicate with a certain set of inverters. Fig. 2.32 shows the block diagram on inverter control.

Droop based inverter control scheme is adopted [102, 33]. The controller of each individual inverter consists of three parts, i.e., the power controller, voltage controller, and current controller. Only the stability of power controller is considered whereas the voltage and current controllers are based on traditional PI controllers. A fully decentralized communication is considered which implies any inverter only needs to communicate with its immediate neighbors to calculate the total power generation of all DG units. Stability analysis with and

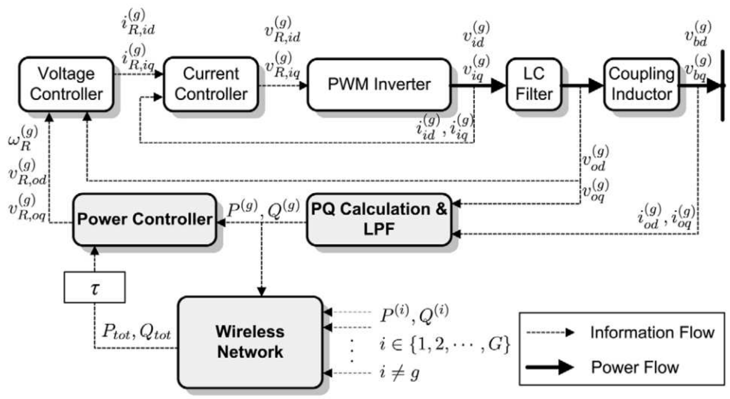

Figure 2.32: Inverter control scheme in [101]

without incorporating communication delay is presented.

A novel decentralized controller for load sharing among parallel connected inverters in an islanded MG is proposed in [103]. The controller has 3 nested loops

1. Inner loop
    - Regulates the output voltage of inverter
    - Voltage gain is responsible for good output voltage tracking
2. Resistive output impedance loop
    - Reduces the impact of line impedance unbalance
    - Used to fix the output impedance of the inverter in terms of magnitude and phase
    - The output impedance presented to harmonic components can be fixed

3. P/Q sharing outer loop

    - Used to obtain proper P/Q sharing
    - Droop/boost control scheme is used

2.9.3 Multilevel Control

As discussed earlier SoS is integration of large-scale systems and large-scale systems can be decomposed into subsystems. *MultiLevel control* assumes SoS is characterized by N finite set of subsystems coordinated by system coordinator as shown in Fig 2.33. By employing any optimal control method the subsystems can be optimized and repeatedly performing the modeling, the interactions between the coordinator and subsystems can be converged to an optimal solution. In literature, multi-level control is obtained by classical steady state approach but lot issues has to be dealt while its implementation in real time [88, 89, 90, 91, 92].

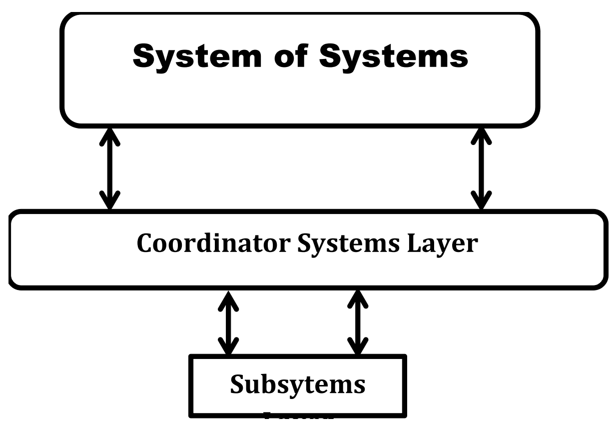

Figure 2.33: Multilevel control

2.9.4 Microgrid - Multilevel Control

In this scheme of control there are three main levels namely primary control, secondary control and tertiary control as shown in fig (2.33) [104, 105].

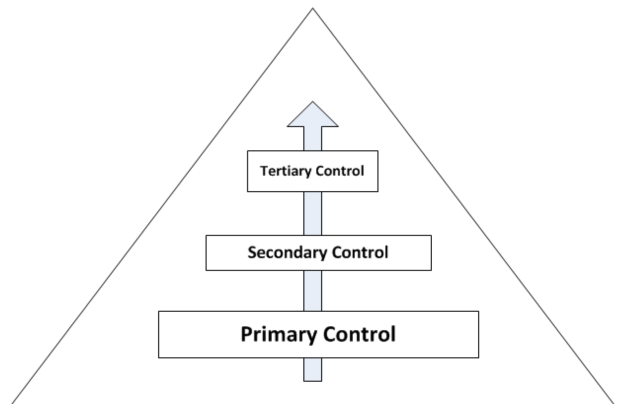

Figure 2.34: Structure of multilevel control scheme

The key points related to *Primary Control* are listed below

1. Used to share load between converters
2. Improves the system performance and stability
3. Regulate the output frequency and voltage magnitude
4. *Droop-control* method is often used
5. Can also include virtual impedance control loop to provide proper output impedance

The key points related to *Secondary Control* are listed below

1. Restores the f and V to nominal values whenever load change occurs
2. Removes any steady-state error introduced by the droop control
3. During transition from islanded to grid-connected mode, this control can perform synchronization to the main grid before interconnection
4. Make use of low bandwidth communication
5. More global responsibilities

The primary control loop makes use of only local output voltage and current to perform calculations of droop control method whereas the secondary control level consists of an external centralized controller to correct the errors produced by the primary control. Both controls are depicted in Fig 2.35.

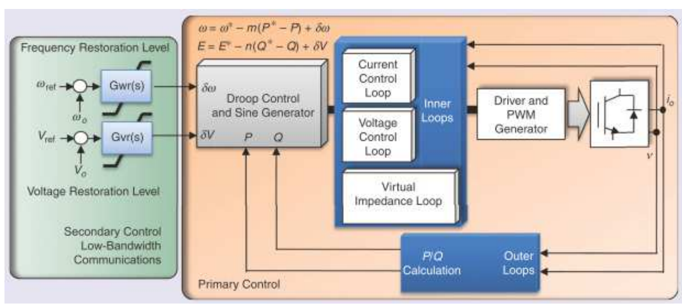

Figure 2.35: Primary and secondary control

The tertiary control level comes into play mainly when the MG interacts with the utility grid. The key points related to *Tertiary control* are listed below

1. Controls the power flow between MG and the utility grid

2. Send the frequency and voltage references to the secondary control
3. Can perform islanding detection or voltage harmonic reduction
4. Can also improve the quality of power at PCC

The proposed multilevel control scheme allows the system to integrate more and more MG's and with this scheme of control microgrids can operate in both grid connected and islanded mode.

2.9.5 Networked Control Systems

In modern control systems, we find more and more application of networks owing to impressive advancements in network technology. One such example is *Networked Control System* (NCS). In NCS, the feedback channel is closed using a real time communication network and all the data among the components of system is exchanged through this communication network [106]. In [107], NCS is properly defined as, *"Network Control Systems (NCS) are spatially distributed systems in which the communication between sensors, actuators and controllers occurs through a shared band limited digital communication network"*. This definition explains that the components of NCS are distributed and may operate asynchronously to reach some overall objective [108].

One of main issues in NCS is the transmission delays and packet dropouts, therefore the challenge in NCS for SoS is to develop an SoS distributed control system which can overcome these issues. As mentioned in [109], these communication infractions can be compensated by

1. Adjusting control power and controlling distances between systems (power control)

2. Trading off modulation, coding, and antenna diversity versus throughput (adaptive modulation coding)

3. The (non-wireless) intra-feedback (on-board hardware) loop of the autonomous control within S_i is lower latency than the inter-wireless distributed control loop between S_i and S_j or the inter-wireless System of systems controller and the S_i controller

Another way to check on these communication is to design a wireless network control system (WNCS) taking account of all the aspects of the ad hoc network [110]. In this design, the distributed control will generate two components at each sampling period, one is local controller which is classical or modern control and the other is correction component of the controller which compensates for the ad hoc network quality of service (QoS) parameters. As shown in Fig. 2.36, with the combination of a local controller, correction component and adaptive sampler the stability and robustness will be enhanced.

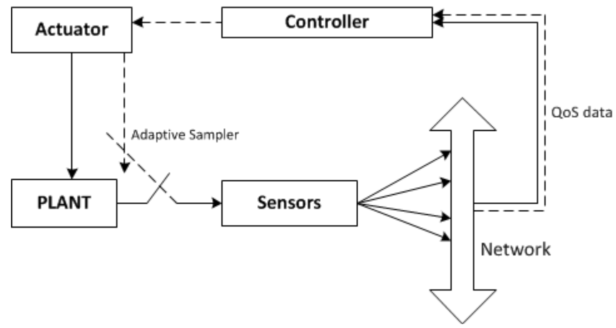

Figure 2.36: Networked control with sampler

2.9.6 Microgrid - Networked Control

In previous section multilevel control scheme for MG is discussed. The primary and tertiary control levels are decentralized and centralized respectively because one aims at the control of DG and other at global optimization of MG. Conventionally secondary control is implemented in the MGCC but recently a new distributed control scheme for the secondary known as *networked control system* (NCS) is proposed in [111] which is shown in Fig. 2.37.

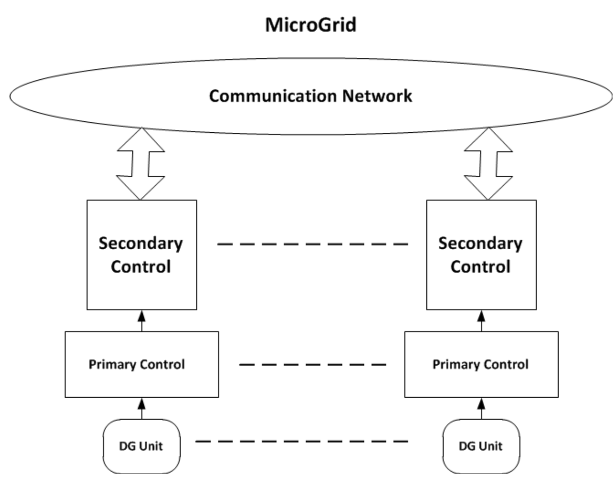

Figure 2.37: Networked controlled microgrid [111]

This strategy is proposed for power electronically based MG's. The primary and secondary control are implemented in DG unit. The primary control which is generally droop control is already discussed in section VII. The secondary control has frequency, voltage and reactive power controls in a distributed manner. The secondary control gathers all the measurements from DG units using the communication system, average them and generates the proper control signal for the primary control level. The schematic diagram of this proposed control scheme can be seen in Fig. 2.38 and the detailed explanation can be found in [111].

In another approach, a real time network is used for the control of parallel multi-inverter system [112]. Microgrid makes use of this type of inverter connections to deliver energy.

The considered system is shown in Fig. 2.39. It consists of a central controller, communication network and inverters with their local controllers. The control strategy is as follows, local controllers sends the voltage and current measurements to the central controller via network frame. A closed loop control inside the central controller produces the satisfactory PWM duty ratio for each inverter module and sends it back to local controller via another network frame. This is a centralized control strategy where central controller has all the central information.

A PID controller is used to achieve better inverter performance [113] and D-partition method is used to determine the stability region of PI controller [114].

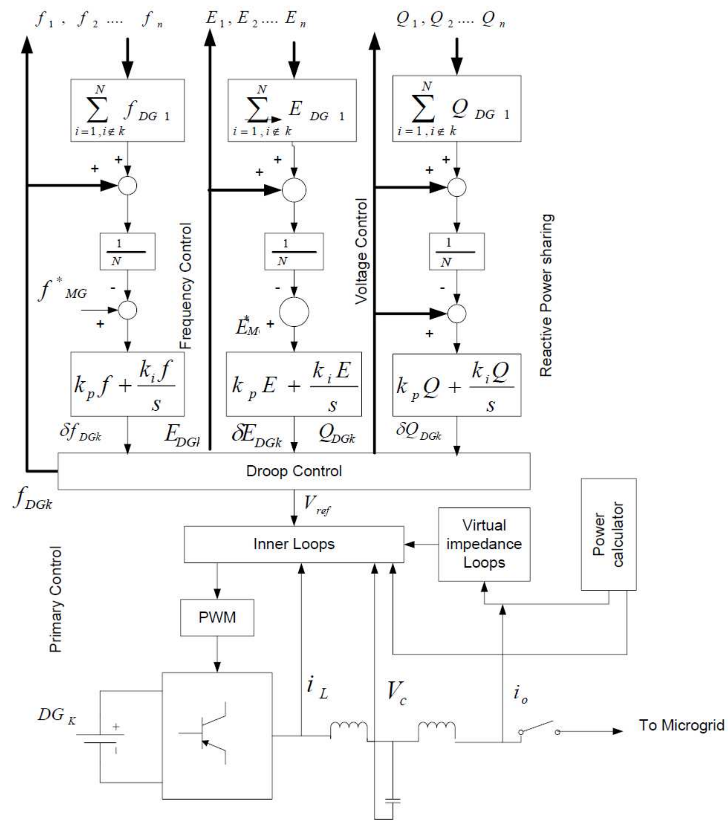

Figure 2.38: Distributed secondary control [111]

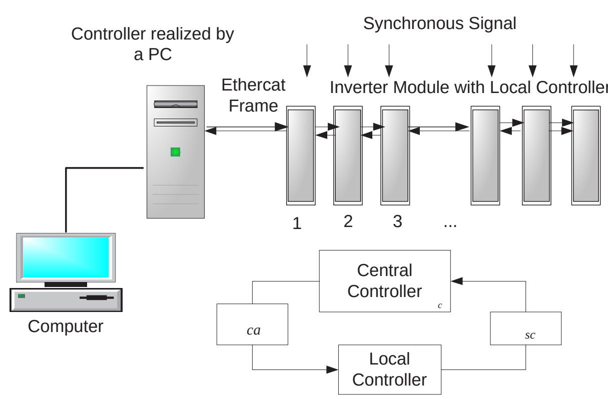

Figure 2.39: Control of parallel multi-inverter system [112]

It was found that network induced delay brings about a considerable effect on closed loop control of a single inverter. The practical model implementing the NCS is shown in Fig. 2.40.

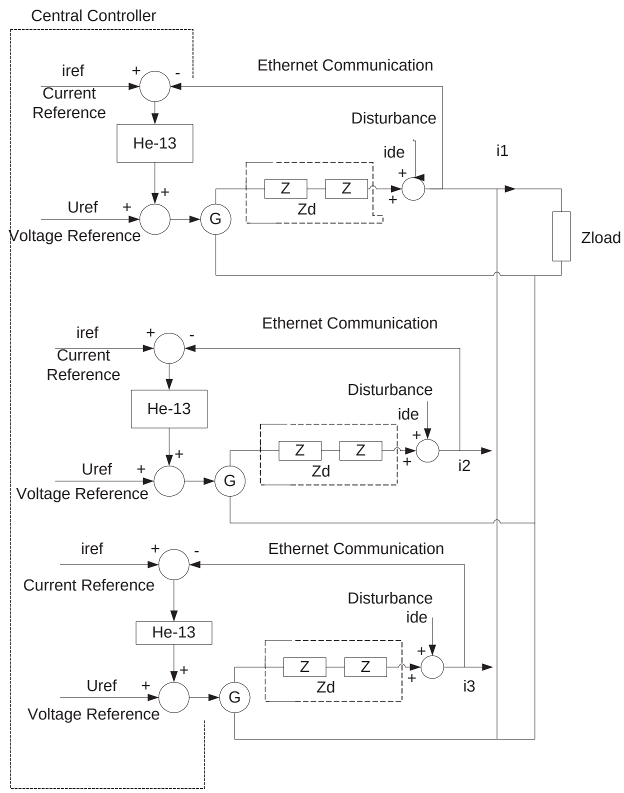

Figure 2.40: Networked controlled parallel multi-inverter model [112]

2.10 Comparative Analysis

After discussing the control techniques, it is worth performing the comparative analysing of the control techniques which are most commonly used. In this section, we will classify the control techniques considering vital aspects for the purpose of simplification and better understanding. Control strategies for MG are very vast and detailed comparison of each techniques with another is out of scope of this chapter.

MG control (depending on architechture) can be generally classified into two main streams namely Centralized, Distributed (or Decentralized). Multi-Level control is also most widely used one but again depending on architechture of control levels, even this control techniques falls in former mentioned categories. For instance in multi-level control, the secondary control level can be single (Centralized) [105, **?**] or it can be implemented in a distributed way [111]. Fig (2.41) shows the performance of the controller when implemented in centralized and decentralized manner. The time delay in the communication network is taken in account here. It is obvious from the figure that, the control implemented in distributed way is better.

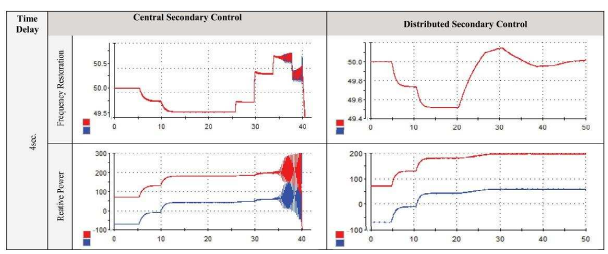

Figure 2.41: Performance analysis of centralized and distributed controller [111]

Depending on the power sharing, the methods available in literature can be broadly divided in two groups, one using communication medium and another is non-communication based. Because of thier inherent advantages, only communication-less control which is also known as Droop-based Control is used. It was initially proposed in [75] and since then there were many variations performed keeping the basic idea droop control [67, 1, 82]. One such comparision is shown in fig (2.42). A modified droop control technique, designed to improve the reactive power sharing among the DG units, is proposed and analysed with the conventional one [82].

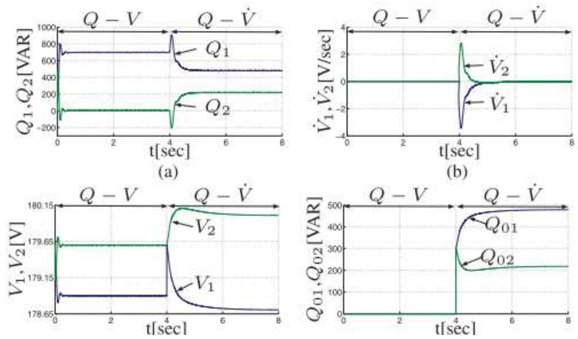

Figure 2.42: Comparison of QV and $Q\dot{V}$ control[82]

Chapter 3

Modelling of Autonomous Inverter-Based Microgrid System

3.1 Introduction

The concept of Microgrid (MG) was originally introduced in [8], it can be operated in Autonomous mode or can be connected to the utility grid. MG concept has evolved to a great extent with respect to both modeling and control. An overview of the different methods of modeling and control is reported in [115]. The definition of microgrid is evolving into the smart microgrid within the context of smart grids. The definition of 'smart grid' is quite flexible and its framework varies with individual vision [116].

A networked microgrid is termed as *'smart microgrid'* [20], Fig. (3.1) shows its simple architecture. It will have high penetration of Distributed Generation (DG) units which when integrated alone raises number of issues [7]. It also makes use of renewable energy resources making it cost effective and environment friendly. The most vital aspect of smart MG is *Distributed/Decentralized* control using communication network. In other words, it will employ Networked Control System (NCS) so that we can have a network of DG units exchanging information. Control is the key point here which will be implemented in a distributed fashion contrary to centralized control in several conventional techniques which can be seen in the literature [24],[74]. This will ensure stability of system, power balancing, proper load sharing and voltage and frequency regulation.

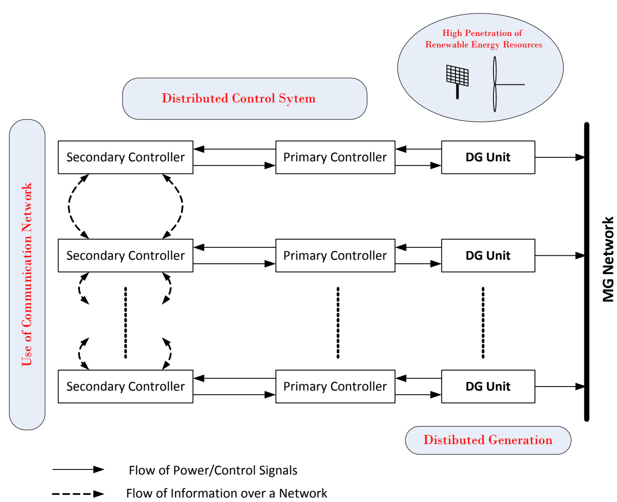

Figure 3.1: Architecture of smart autonomous microgrid

3.2 Autonomous Microgrid System

Autonomous mode operation of MG is also know as *Islanded* MG, which can be caused by two reasons. One is due to any network fault or some failure in the utility grid and another is due to performance of maintenance at planned intervals. An electrical switch will disconnect the MG from main utility grid and resulting the autonomous operation of MG [23]. As explained in [117], without loss of generality, the prime mover can be replaced with a *DC* source because they both essentially serve the same purpose. This simplification allow us to study the behavior of inverter based generators without actually using a prime mover.

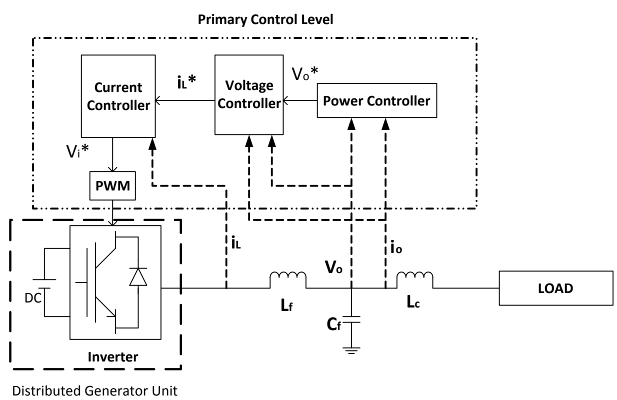

Figure 3.2: Block diagram of inverter-based DG unit

In this thesis, *MG* involving only inverter-interfaced *DG* units is considered. Fig 3.2 shows the block diagram of an inverter based DG unit. It consists of an inverter connected to a primary dc source (e.g., wind system, PV array etc), control loops containing power, voltage and current controllers. Due to their ride through capability and improved power quality [105, 118] , voltage source inverters (VSI) is used. Load is connected through a LC filter and coupling inductance. The power, voltage and current controllers constitute the primary control level of any individual DG unit. Small signal modelling of each of the part of MG can be carried out by following the procedure outlined in [33][119].

As mentioned in [33], d-q reference frame was used to formulate the nonlinear dynamics of DG units. The reference frame of one DG is considered as the common reference frame with frequency ω_{com}. The angle δ between an individual reference frame and common reference frame, satisfies the following equation.

$$\dot{\delta} = \omega - \omega_{com} \tag{3.1}$$

3.3 Primary Control

The control technique used at this level is know as *Droop* based control [75, 1]. This type of control makes use of local measurements and does not need any communication medium for its operation. Droop control is a decentralized strategy which ensures proper load sharing. Its main purpose is to share active and reactive powers among DG units at the same time maintaining the output levels of voltage and frequency within limits. In droop technique, there is a desired relationship between the active power P and angular frequency ω and between reactive power Q and voltage V as given below:

$$\omega = \omega_n - m_p P \tag{3.2}$$

$$V = V_n - n_q Q \tag{3.3}$$

Where V_n and ω_n is the nominal values of output voltage and angular frequency respectively. P and Q are the real and reactive powers respectively. m_p and n_q are the real and reactive power droop gains respectively. The frequency ω is set according to the droop gain m_p and output voltage V is set as per droop gain n_q.

Therefore, the output frequency/voltage is decreased when there is an increase in the load real/reactive power and vice versa. The $P\omega$ and QV droop characteristics is shown in Fig. 3.3.

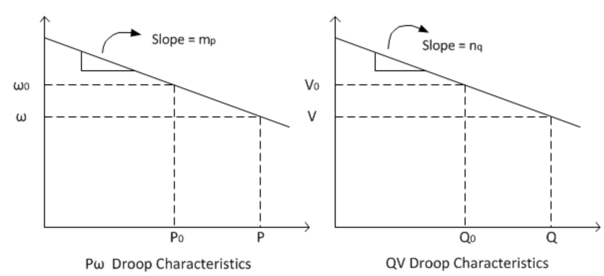

Figure 3.3: Droop characteristics

The primary control level can be divided into three different parts namely power, voltage and current controller. The power controller, shown in Fig. 3.4, sets the inverter output voltage magnitude and frequency with the help of 'Droop' characteristics. Basically, it mimics the operation of a synchronous generator which will change the frequency of the output voltage if any change in load is sensed. First, the instantaneous powers are calculated using output voltages and currents, by filtering these instantaneous values by a low pass filter (LPF) we get the average real and reactive powers. These average values are passed through their respective droop gains to obtain the angular frequency and voltage [120]. The control strategy is chosen such that the output voltage magnitude reference is aligned to the d-axis of the inverter reference frame and q-axis reference is set to zero.

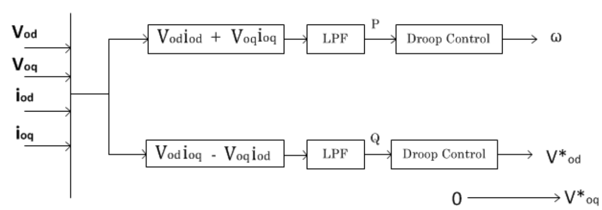

Figure 3.4: Block diagram of power controller

The block diagram of voltage controller is shown in Fig. 3.5, a PI controller is used to achieve the output voltage control. The corresponding state equations are given by

$$\dot{\phi}_d = v_{od}^* - v_{od}, \quad \dot{\phi}_q = v_{oq}^* - v_{oq} \tag{3.4}$$

Where ϕ_d and ϕ_q are the d-q axis state variables of voltage controller (integrator states) respectively.

$$i_{ld}^* = Fi_{od} - \omega_n C_f v_{oq} + K_{pv}(v_{od}^* - v_{od}) + K_{iv}\phi_d \quad (3.5)$$

$$i_{lq}^* = Fi_{oq} + \omega_n C_f v_{od} + K_{pv}(v_{oq}^* - v_{oq}) + K_{iv}\phi_q \quad (3.6)$$

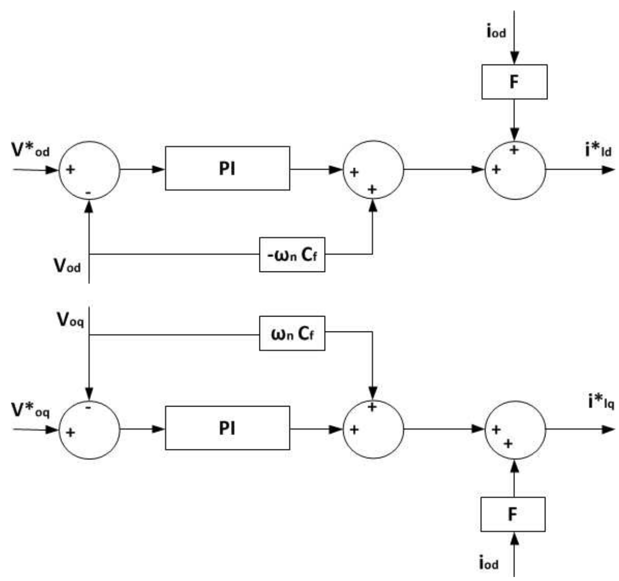

Figure 3.5: Block diagram of voltage controller

The block diagram of Current controller is shown in Fig. 3.6, a PI controller is used to achieve the output filter inductor current. The corresponding state equations are given by

$$\dot{\gamma}_d = i_{ld}^* - i_{ld}, \quad \dot{\gamma}_q = i_{lq}^* - i_{lq} \quad (3.7)$$

Where γ_d and γ_q are the d-q axis state variables of current controller (integrator states) respectively.

$$v_{id}^* = -\omega_n L_f i_{lq} + K_{pc}(i_{ld}^* - i_{ld}) + K_{ic}\gamma_d \quad (3.8)$$

$$v_{iq}^* = \omega_n L_f i_{ld} + K_{pc}(i_{lq}^* - i_{lq}) + K_{ic}\gamma_q \quad (3.9)$$

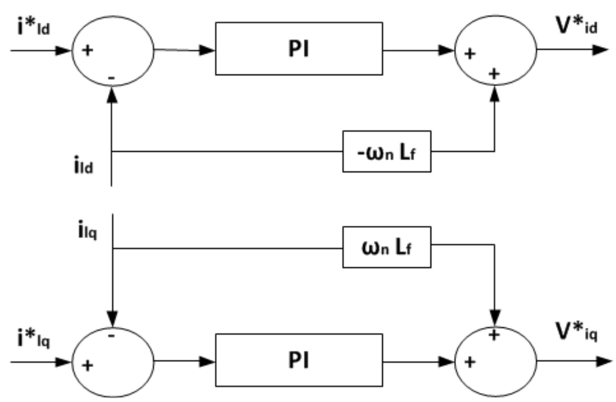

Figure 3.6: Block diagram of current controller

The main purpose of voltage and current controllers is to reject the high frequency disturbances and damp the output filter to avoid any resonance with the external network. The PI controller provides zero steady state error and stabilizes the system. As it can be seen in figures, additional feed forward gain and decoupling terms are also used. These PI controllers make use of the local measurements to perform the control action.

The dynamic equations of output LC filter and coupling inductance are as follows

$$\dot{i}_{ld} = \frac{-r_f}{L_f} i_{ld} + \omega i_{lq} + \frac{1}{L_f} v_{id} - \frac{1}{L_f} v_{od} \tag{3.10}$$

$$\dot{i}_{lq} = \frac{-r_f}{L_f} i_{lq} + \omega i_{ld} + \frac{1}{L_f} v_{iq} - \frac{1}{L_f} v_{oq} \tag{3.11}$$

$$\dot{v}_{od} = \omega v_{oq} + \frac{1}{C_f} i_{ld} - \frac{1}{C_f} i_{od} \tag{3.12}$$

$$\dot{v}_{oq} = -\omega v_{od} + \frac{1}{C_f} i_{lq} - \frac{1}{C_f} i_{oq} \tag{3.13}$$

$$\dot{i}_{od} = \frac{-r_c}{L_c} i_{od} + \omega i_{oq} + \frac{1}{L_c} v_{od} - \frac{1}{L_c} v_{bd} \tag{3.14}$$

$$\dot{i}_{oq} = \frac{-r_c}{L_c} i_{oq} + \omega i_{od} + \frac{1}{L_c} v_{oq} - \frac{1}{L_c} v_{bq} \tag{3.15}$$

3.4 Dynamic Model of Microgrid

The large signal dynamic model of any inidvidual DG unit can be derived from equations (3.1) - (3.15) [33]. Therefore, the nonlinear dynamics of a DG unit can be written in compact form as

$$\dot{x} = f(x) + k(x)D + g(x)u \tag{3.16}$$

$$y = h(x) \tag{3.17}$$

$$\mathrm{x} = \begin{bmatrix} \delta & P & Q & \phi_d & \phi_q & \gamma_d & \gamma_q & i_{Ld} & i_{Lq} & v_{od} & v_{oq} & i_{od} & i_{oq} \end{bmatrix}^T$$

Chapter 4

Neural Network Based Secondary Control for Smart Autonomous Microgrid System

4.1 Introduction

One of the widely used and crucial control technique is the 'Multilevel Control' [121]–[122]. There are three main control levels, each taking care of specific tasks. Primary Control level ensures the proper load sharing among generating units. The secondary Control removes any steady state error introduced by primary control. Tertiary Control deals with global responsibilities like energy transfer to and from the grid. In some cases, tertiary control in autonomous mode comes into picture for economical reasons, otherwise it is mostly incorporated when the MG is connected to the utility grid. In our work, we will be focusing on the primary and secondary control levels only.

The primary control which is the first level, make use of the *Droop* based control techniques for its operation. But due to various reasons discussed in next sections, primary level alone is not sufficient for the stable operation of MG. To achieve global controllability, a secondary control level is often used, this concept is already seen in large electrical power systems [123] but is recently adopted in the MG concept.

Secondary control strategies using NCS have been proposed in literature. A pseudo-decentralized control architecture is proposed in [124] which can be used for the optimization of Wireless Communication Network (WCN) with the help of a Global Supervisory Control (GSC) and local controllers. In [125], NCS strategy is applied to a parallel inverter system to achieve superior load sharing and good robustness. Investigation of centralized secondary controller in MG with primary voltage droops is carried out in [126]. This controller regulates the voltage at pilot points within the MG. In [127], a networked controlled parallel multi-inverter system is proposed to achieve precise load sharing among each module, a centralized controller is used here along with the local controllers.

Most of the works in the literature are based on the *Centralized* secondary control, where all the DG's in the MG are supervised by a common centralized secondary control. This controller is often termed as MicroGrid Central Controller (MGCC), wherein all DG units measure signals and send them to a centralized single controller which in turn produces suitable control signals and sends them to primary control of DG units. It makes use of communication channel for both sensing the measurements and to send the control signal. [104, 128, 129, 130]. MGCC is relatively slow in functioning. Any fault in the MGCC can result in failure of secondary control action for all the DG units [105]. This single point failure is not higly reliable and can result to bad performance of the system. Depending on only one central control unit for the proper operation is a big drawback in itself.

Secondary control of microgrid is performed in [131] using input-output feedback linearization technique, it focuses only on the secondary voltage control of autonomous microgrid. A fully distributed secondary control is proposed in [132], the control scheme is based on distributed cooperative control and is implemented using one-way communication links. The communication network required is modeled using graph theory. A distributed secondary controller based on averaging algorithms is proposed in [133], the controller, which is also termed as Distributed Averaging Proportional Integral ($DAPI$) controller, regulates the system frequency under time varying loads. Recently, a new method of implementing secondary control in a distributed fashion using the Networked Control Systems (NCS) approach is proposed in [111]. This concept has proved to be better as both the primary and secondary control are implemented in a distributed way, resulting in individual secondary control for each DG unit.

But the proposed controller in [111] is based on fixed PI gains which may perform well under some operating conditions only but not all. The gains of the secondary controller are tuned randomly without using proper defined procedure. Consequently, improper tuning of controller will result in bad adaptation to varying operating conditions. Moreover, proportional-plus-integral (PI) controllers are not robust enough to accommodate the variations in the load. It is desired to have an intelligent PI-type controller, which when load changes can self-tune its controller gain [134, 135].

In this chapter, a distributed secondary controller proposed in [111] is utilized. The concept of artificial neural networks is added to the existing controller so that it can operate over a wide range of operating points. The use of neural network is to make the existing PI control more adaptive to load disturbance. Using *Differential Evolution* (DE), optimized gains of the secondary PI control are obtained and also serves as training pattern for the artificial neural network. The salient features of the proposed controller are listed below

- Each DG has its own local secondary controller which obviates the need for a central controller
- Neural network learns by example which avoids traditional programming algorithms
- Better performance as the controller parameters are optimized values
- Optimized transient behavior of the system is obtained under load distur-

bances

- Trained neural network enhances the adaptability of the controller
- The proposed controller can react faster to load changes and can operate over a wide range of operating points

Although the concept of using NN approach to enhance the performance of traditional PI controller exists in the literature, it has not been used in the field of microgrid systems. The voltage and frequency regulation, load sharing ability of the overall controller is demonstrated using Matlab/Simulink simulations. Performance comparison between the proposed controller and fixed-gain controller is also performed. The simulation results show that the proposed secondary control ensures stable operation of the system under varying loads.

4.2 Distributed Secondary Control

Primary control is a tradeoff between voltage regulation and power sharing. Good sharing of power is achieved at an expense of error in output voltage and vice versa. Poor transient performance, lack of robustness and steady state error are its main drawbacks. Therefore, a secondary control level is deployed which brings back the deviated output voltage and frequency within their allowable limits.

The block diagram of distributed secondary controller is shown in fig 4.1. As

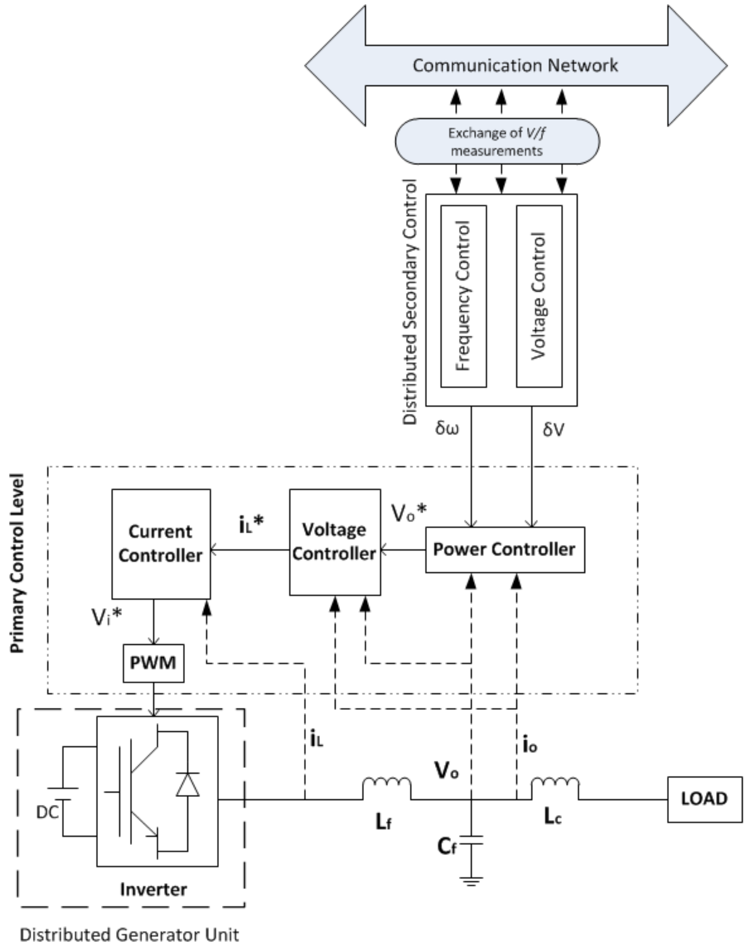

Figure 4.1: Distributed secondary controller

can be seen, the idea is to implement both primary and secondary controllers together as local controller at each generating unit. This controller is located between the primary control and communication network. This controller ensures zero steady state error and regulates the deviations produced in output frequency and voltage due to load change towards zero.

Secondary control of microgrid is a tracking synchronization problem where the DG units are interconnected. They communicate with each other in order to synchronize at a pre-defined set point. The secondary control makes use of communication network for this purpose. From networked control system perspective, distributed secondary control requires that every generating unit obtains the global average of the parameter (voltage, frequency etc.) [?], in order to derive the control signals. In our case, this global average is achieved by using distributed averaging algorithms [?], where a series of local exchange among neighboring units ultimately yields the same global average at every DG. Therefore, the control layer drives operation of every DG in the direction of the global average.

4.2.1 Regulation of Output Frequency

The output frequency is decreased when there is an increase in load real power and vice versa because of the droop characteristics. Load variations will cause the frequency to deviate from its set-point resulting in steady-state error. The secondary frequency control compensates the deviations produced in output frequency by the $P\omega$ droop control.

At each sample time, the DG units measures the level of angular frequency, averages the measurements by other DG's and compares it with the reference values to produce an error signal. The secondary control then processes this error signal to produce suitable control signals. Frequency control law at the secondary level is given by the equation (4.1)

$$\delta\omega \;\; = \;\; K_{p\omega}(\omega_n - \omega_{avg}) + K_{i\omega} \int (\omega_n - \omega_{avg}) dt \tag{4.1}$$

Where $K_{p\omega}$, $K_{i\omega}$ are the frequency controller parameters, ω_n is the angular frequency set point, ω_{avg} is the angular frequency average. $\delta\omega$ is the control signal produced by the secondary controller. Because the deviations are produced by the droop control, these control signals are sent to the primary control level to remove the steady state error. The output frequency is restored to their nominal values as follows

$$\omega = \omega_n - m_p P + \delta\omega \tag{4.2}$$

4.2.2 Regulation of Output Voltage

A similar technique is used to compensate the deviations caused by QV droop control. The output voltage too deviates from its set-point whenever the load changes. This is because of change in load reactive power. In this case, the voltage restoration by the secondary controller is obtained as follows

$$\delta V = K_{pv}(V_n - V_{avg}) + K_{iv} \int (V_n - V_{avg})dt \tag{4.3}$$

Where K_{pv}, K_{iv} are the voltage controller parameters, V_n is voltage set points, V_{avg} is average voltage and δV is the control signal produced by the secondary controller to be sent to primary control to restore voltage to its nominal value as follows

$$V = V_n - n_q Q + \delta V \tag{4.4}$$

4.3 Neural-Network-Based Distributed Secondary Control

The controller discussed in the above section is based on the fixed-gain PI scheme. Under certain operating points or conditions, this fixed-gain scheme may work fine but its performance degrades at other operating conditions. Also fixed-gains of the secondary controller are obtained using time-consuming trail-and-error methods. To obtain desired performance, it is required the parameters are well tuned, poor tuning of gains deteriorates the system performance. Therefore, in some cases traditional PI controller has a limited application due to its non-adaptive parameters [136].

In this section, to increase the robustness of traditional fixed-gain secondary PI controller, we propose a neural-network-based secondary controller. This controller can self-tune the PI gains as per various operating conditions. Evolutionary computational techniques gives a systematic procedure for obtaining the optimized gains of the secondary controller and neural network is used to estimate the controller parameters for different loads. Therefore by using evolutionary optimization and neural network, the proposed controller increases the robustness and adaptability of traditional controller maintaining its simplicity and feasibility.

Over the past few years, artificial neural networks are being widely used in the field of control system for various purposes like non-linear modeling, tuning controller parameters, system identification etc [137]. A trained neural network have remarkable ability to analyze and derive meaning from the given data, it is self-organizing and adaptive in nature.

Fig 4.2 illustrates the block diagram of neural-network-based secondary controller. A trained artificial neural network provides optimal gains to the secondary controller whenever the load changes i.e., input to the NN is the total load on the system and its output are the corresponding optimal PI gains. The secondary controller then produces a control signal as per the control law given by expression in (1) and (2). The control signals produced are sent to the primary control level of the respective DG unit for compensating the errors. This

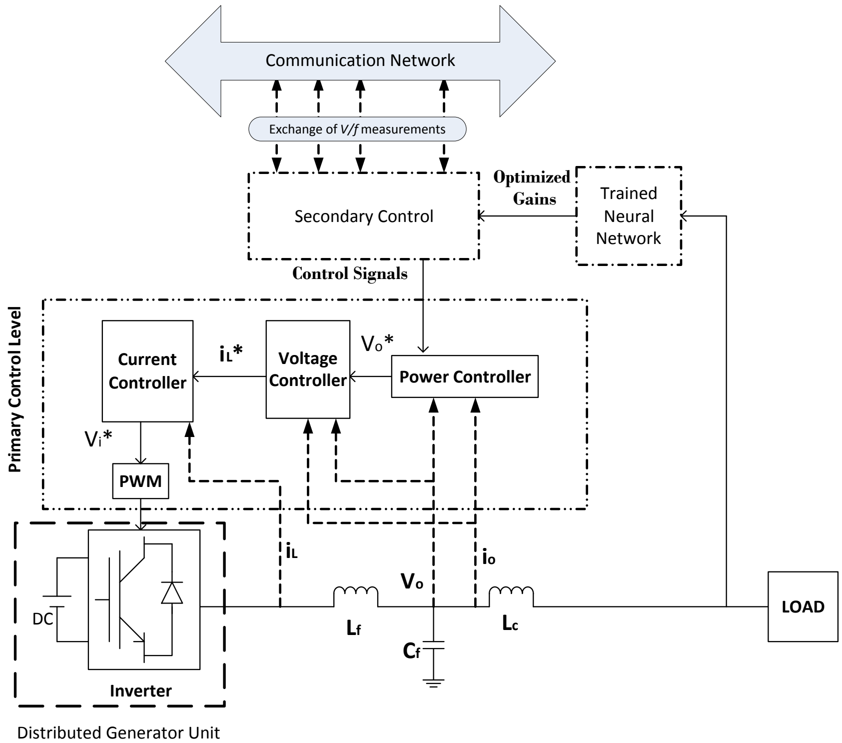

Figure 4.2: Neural network based distributed secondary control

way the proposed secondary controller dynamically regulates the output voltage and frequency for time varying load.

Following are the stages required to design the proposed neural-network-based distributed secondary controller. Each stage has its own importance and are discussed in the following sections

4.3.1 Stage 1: Selection of Training Data

Before using the NN for self tuning, it has to be trained offline by learning (or training) process. Training is effective only if the network output matches the desired output for each training pattern. For this purpose, a training set is required, which is a set of input and desired output data. It is very important to have a proper training set which can otherwise effect the accuracy of NN [138].

Therefore, *Evolutionary* computational technique known as *Differential Evolution* (DE) is used to obtain a proper training set. For each operating point, *DE* is employed to perform the optimization process to give the optimal values of secondary PI gains. The process of optimization and obtaining of proper training set in explained in following sections.

Differential Evolution:

Most of problems relating to engineering science cannot be solved using analytical methods, especially global optimization problems. For such problems *Evolutionary* Algorithms [139] are used, which provides the near optimal solution. *Differential Evolution* (DE) is one such novel evolutionary algorithm using simple population based stochastic search for optimizing functions with real value parameters [140].

DE produces a new vector by adding perturbation of two vectors to a third vector. This process is the main differential and is termed as *Mutation*. The new vector produced is combined with pre-defined parameters in accordance with a set of rules. This process is called as *Crossover*. This operation is performed to enhance the searching process. Thereafter an operator is applied which compares the fitness function of two competing vectors to determine who can survive for the next generation. This process is known as *Selection* process [141, 142].

In our work, the objective function (or performance index) used is the Integral of Time Multiply Squared Error (ITSE) which is defined as follows

$$J_{ITSE} = \int te^2(t)dt \tag{4.5}$$

where e is the error which is equal to $(\omega_n - \omega_{avg})$ for frequency control and $(V_n - V_{avg})$ for voltage control. The optimization problem is defined as

$$\min[\max(J_{ITSE})] \tag{4.6}$$

DE algorithm is coded in MATLAB/Simulink and implemented on-line on the

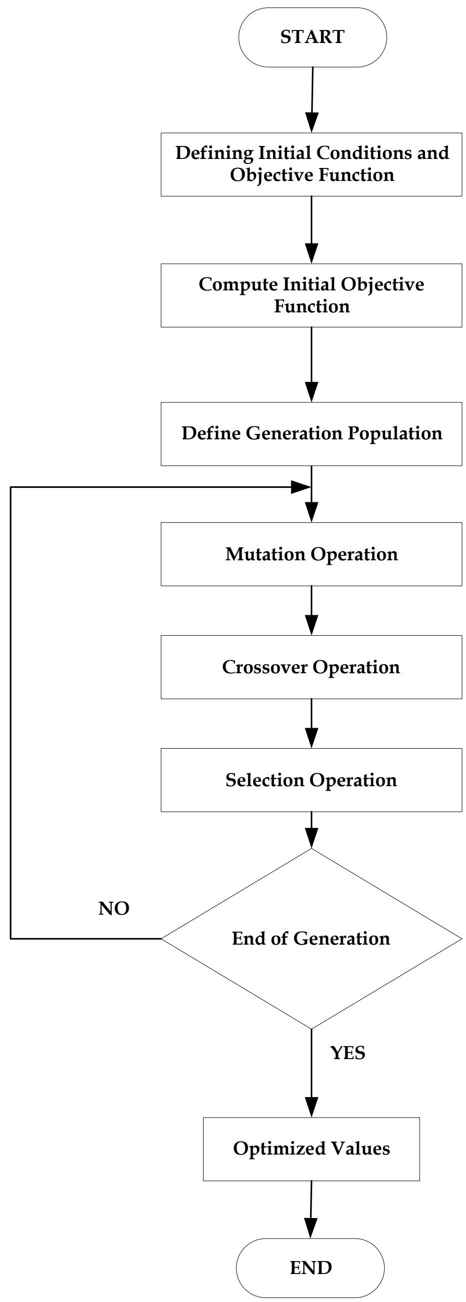

Figure 4.3: Flow chart of differential evolution

system. The complete DE optimization process is clearly illustrated by flowchart in fig 4.3. A total load of 4.5 KW is applied on the system, the optimization process is started with an initial population of 20. The process iterates repeatedly minimizing the objective function J_{ITSE}.

The fitness (ITSE) vs number of iterations graph for frequency control corresponding to 4.5 KW of load is shown in fig 4.4. Number of iterations is represented by x-axis and y-axis represents fitness value. It can be seen that the fitness value gradually decreases which in turn reduces the steady state error. After 100 iterations, the error is minimal and we get the tuned optimized gains of controller. DE specifications and the final optimized gains for frequency and voltage regulation are shown in fig 4.5.

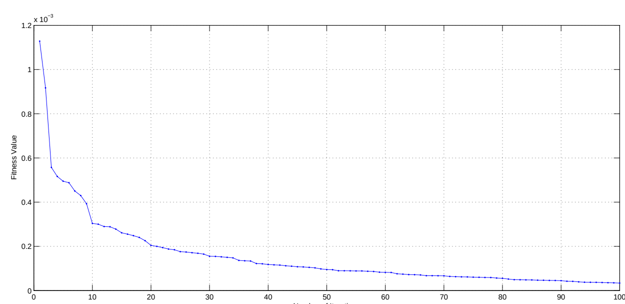

Figure 4.4: Fitness vs Iteration curve

Specifications	No. of Iterations	Initial Population	Mutation Factor	Crossover Factor	ODE Solver
Value	100	20	0.5	0.6	ODE45

Optimized Values / Load Value	Frequency Control		Voltage Control	
	Proportional Gain	Integral Gain	Proportional Gain	Integral Gain
4500 Watts	7.4072	10.8121	10.5367	10.7784

Figure 4.5: Optimization Details

To obtain the optimized PI gains for one operating point (i.e., one load value), approximately 1 hour is required. To reduce the collection time of training set, only 37 different operating points are considered. The range of operating points is varied from 100 watts to 7500 watts with an approximate interval of 200 watts. For each operating point, the DE optimization process is repeated to obtain optimized secondary gains for frequency and voltage control. The load values and their corresponding optimized secondary controller gains (for both frequency and voltage control) forms the *Training Set* for the neural network. Therefore, input to neural network is the system total load and its output are the optimal secondary gains corresponding to input load.

4.3.2 Stage 2: Selection of Artificial Neural Network

The next stage is the selection of artificial Neural Network (NN) structure and its properties. NN consists of *Neurons* which are simple computational units. A neuron is a building block of NN and it resembles information processing model of the human brain. Any k-th neuron can be defined mathematically as [143]

$$v_k = \sum_{j=1}^{p} w_{kj} x_j + w_{ko}, \quad y_k = f(v_k)$$

Where $x_1, x_2 ... x_p$ denotes inputs signals, $w_{k1}, w_{k2} ... w_{kp}$ denotes the synaptic weights of k-th neuron, w_{k0} is the bias, v_k denotes the linear combiner output,

$f(.)$ is the activation function and y_k denotes the output of the neuron.

To design and train an artificial neural network, the *Neural Network Toolbox* [144] available in Matlab/Simulink is used. The command '*nntool*' opens the Network/Data Manager window, which allows import, create, use and export neural networks. In this study, neural network used is of feed-forward type. It consists of 1 input node and 4 output nodes and 10 nodes in the hidden layer. As can be seen, the flow of signal is unidirectional i.e., output of each neuron is connected to the input of a neuron in the next layer. Depending on the activity level at the input of a neuron, the activation function defines its output [145].

4.3.3 Stage 3: Neural Network Training

The next stage in designing the controller is training of *Neural Network*. NN resembles the adaptive control since they learn from the set of example data rather than having to be programmed in a conventional way [146]. Therefore, a set of data called *Training Set* is required to adjust the synaptic weights and thresholds of NN. This process is called training of NN. The process of obtaining training set is explained in section 5.1.

To train the neural network, Levenberg-Marquardt backpropagation [147] algorithm is used. It is a type of back propagation algorithm [148] mostly used for approximation of function, mode identification and classification, data compression, and so on. A detail of network properties used during training process

Table 4.1: Neural Network Training Details

S.No.	Network Property
1	Adaption Learning : Gradient descent with momentum weight and bias learning
2	Performance Function : Mean squared normalized error
3	Transfer Function in hidden layer: Hyperbolic tangent sigmoid transfer function
4	Transfer Function in output layer: Linear transfer function

is tabulated in Table 4.1. The neural network inputs are the load values R_L and the outputs generated by the neural network are the corresponding optimal secondary controller gains.

4.4 Simulation Results

The simulations are performed in MATLAB/Simulink environment. A non-linear model of the multiple DG units is designed using *SimPowerSystems* Library. Fig (4.6) shows an autonomous MG system developed in the Simulink. There are a total number of 3 DG units connected to the a three phase load by means line impedance given by $R_{l1} = 0.23\Omega$, $L_{l1} = 31.8\mu H$, $R_{l2} = 0.35\Omega$, $L_{l2} = 184.7\mu H$ and $R_{l3} = 0.18\Omega$, $L_{l3} = 0.0022$. The other parameters of the system, controller parameters and their values are given in Table 4.2.

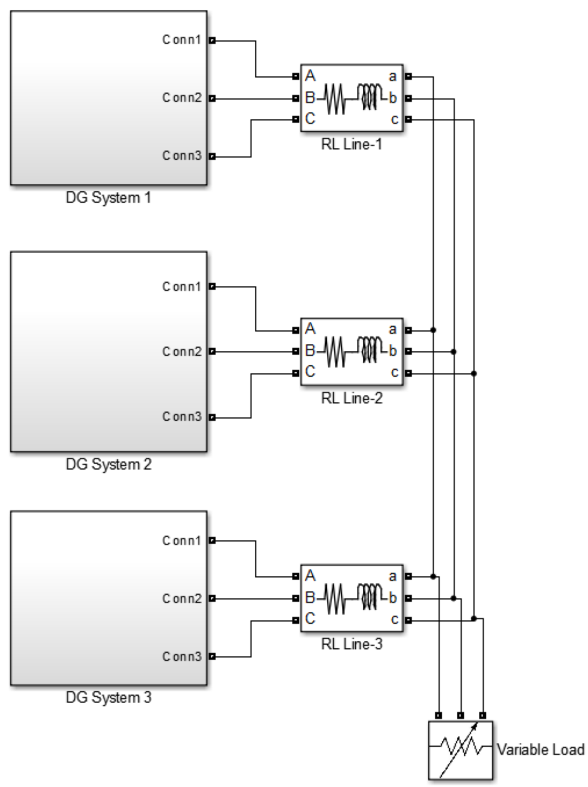

Figure 4.6: Simulink model of three distributed generating system

Table 4.2: Microgrid Parameters With Primary Control

SYMBOL	QUANTITY	VALUE
L_f	Filter Inductance	1.35 mH
r_f	Filter Resistance	0.1 Ω
C_f	Filter Capacitance	50 μ F
L_c	Coupling Inductance	0.35 mH
r_c	Coupling Resistance	0.03 Ω
V_n	Nominal Voltage	381v
ω_n	Nominal Frequency	314 rad/sec
ω_c	Cutoff Frequency of Low Pass Filter	31.4 rad/sec
f_s	Switching Frequency	8 Khz
m_p	Real Power Droop Gain	9.4×10^{-5}
n_q	Reactive Power Droop Gain	1.3×10^{-3}
K_{pv}	Proportional gain of Voltage Controller	0.05
K_{iv}	Integral gain of Voltage Controller	390
K_{pc}	Proportional gain of Current Controller	10.5
K_{ic}	Integral gain of Current Controller	16000
F	Feed forward gain of Voltage Controller	0.75

4.4.1 No Load Operation

Initially, the MG system is operated with secondary control action disabled. Under no load conditions with only primary control enabled, a load of 4.5 KW is applied to the system after t = 5 seconds. The response of output frequency and voltage from no load condition to sudden application of load is illustrated in fig 4.7 and fig 4.8 respectively. As a result of sudden application of load, transients can be seen at t = 5 seconds in both output voltage and frequency. These transients result in the steady state error which deviates the output values from their nominal values. This steady state error results in the poor quality of power supplied to consumers.

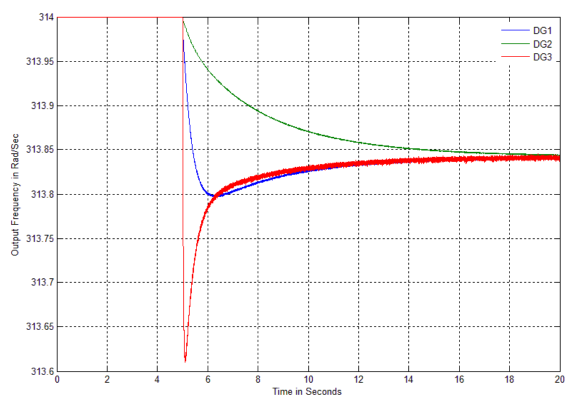

Figure 4.7: Frequency response under sudden application of load

By observing the above figures, it can also be concluded that major part of the transient is taken up by the DG-3 unit whereas DG-1 and DG2 have responded more slowly. This is because the load is closely located to DG-3, which implies that during large load changes DG's located nearer to load can be overloaded

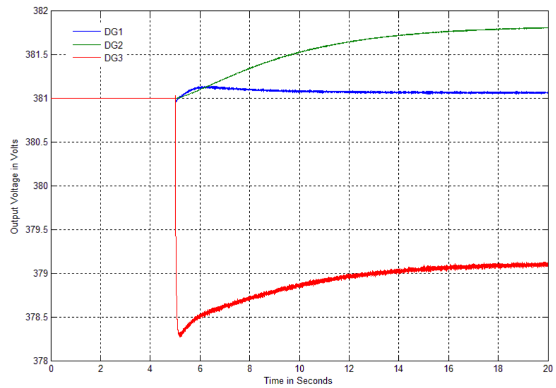

Figure 4.8: Voltage response under sudden application of load

and may trip out. The frequency and voltage are seen going to different values other than the pre-defined set points. Thus a need for secondary control action can be seen to achieve global controllability.

4.4.2 Comparative Analysis

To regulate the output voltage and frequency to their nominal values and to eliminate the steady state error, a secondary control action is enabled. To demonstrate the effectiveness, a comparative analysis is performed between proposed and traditional secondary controller.

Fig. 4.9-4.11 summarizes the performance comparison of the two secondary controllers. The figures illustrates analysis for output voltage regulation, output frequency regulation and load sharing capability respectively of the two controllers. The gains of traditional controller are tuned by trail and error method and gains

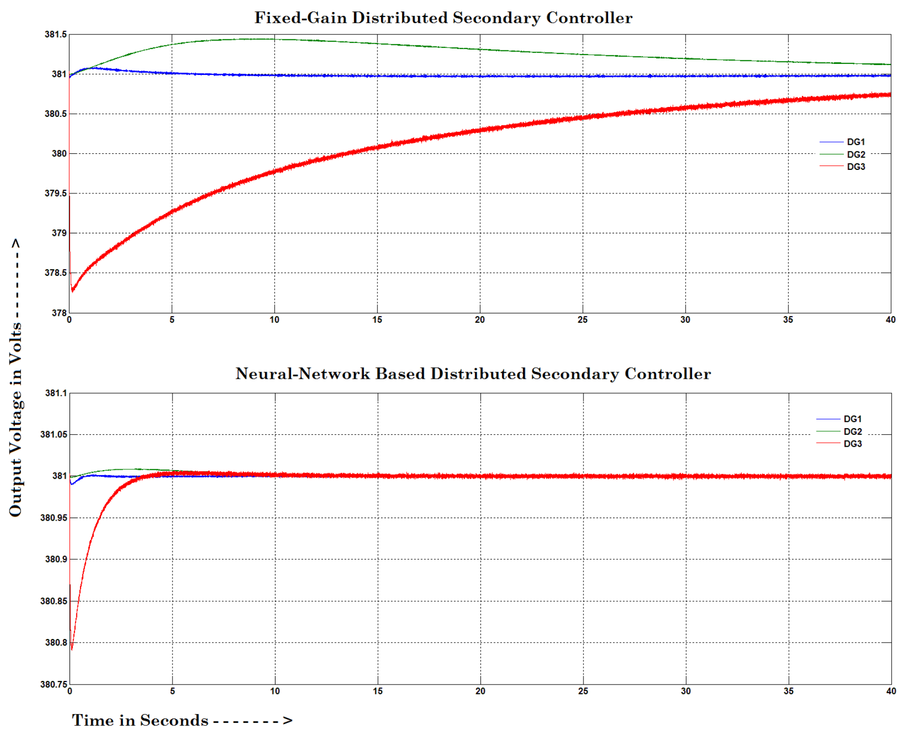

Figure 4.9: Performance comparison for voltage regulation

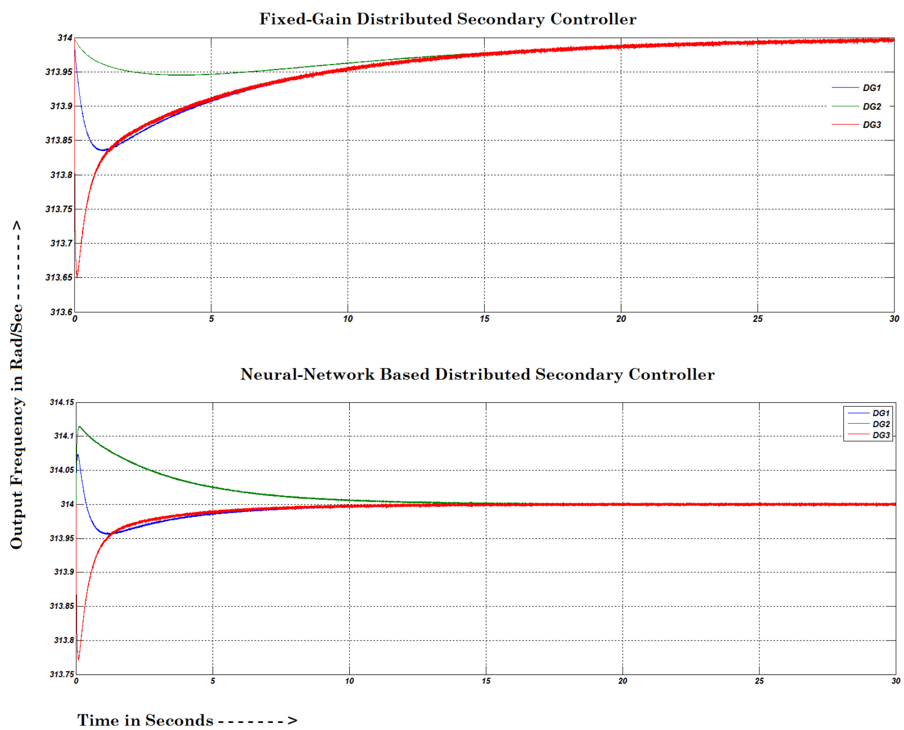

Figure 4.10: Performance comparison for frequency regulation

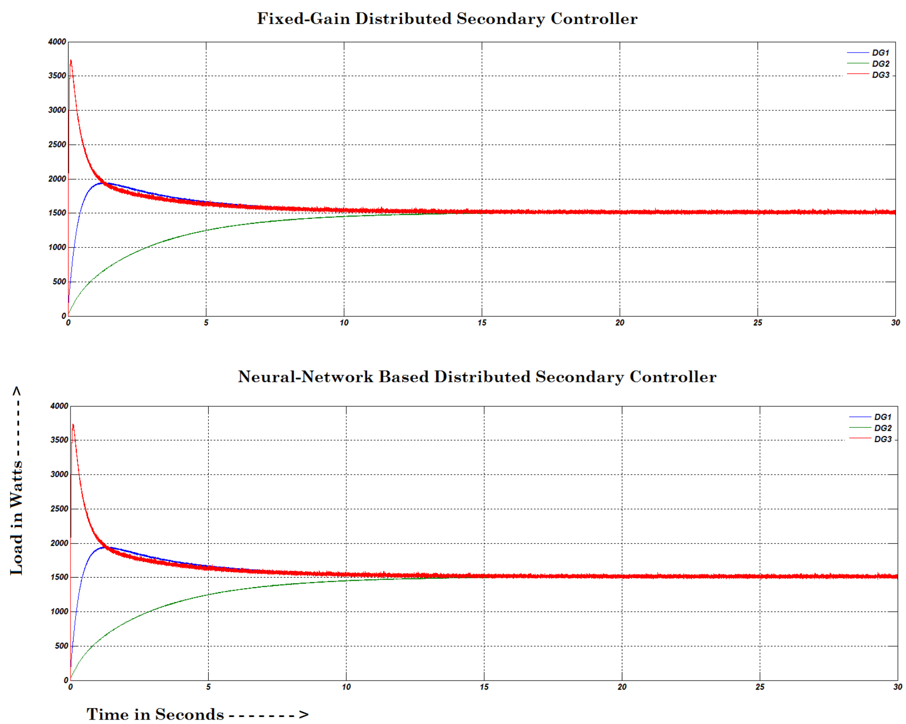

Figure 4.11: Performance comparison for load sharing

of proposed controller are optimized gains provided by the neural network.

By observing the comparison results, it can be seen that both the controllers are eliminating the steady state error and regulating output voltage and frequency to their nominal values. However, it is also important to note the following points

- The response of proposed controller to load changes is much quicker and drives the output values to their set points in a shorter time, therefore has better performance.
- The proposed controller eliminates the error faster, which indicates the controller parameters are well optimized by DE.
- The proposed controller is designed by optimizing ITSE function and therefore provides optimized transient behavior.
- The proposed controller avoids overloading of any DG unit for a longer time as it maintains equal load sharing property of the base line controller.

Therefore the proposed controller works more effectively and is superior than the conventional one in responding to the load changes.

4.4.3 Response Under Time Varying Load

In our study, the robustness and adaptability of controller is tested with respect to change of operating conditions i.e., when the system is subjected to continous load disturbances with respect to time. In this section we demonstrate the adaptive nature of NN under time varying loads. One load change indicates one operating point of the system.

Response of the proposed controller under time varying loads is summarized by fig 4.12 - fig 4.14. As can be seen in fig 4.12, the simulation is performed over a span of 100 seconds and the system is subjected to change in load after each *20* seconds indicating 5 different operating points. Transients can be observed at the instant when the load is applied on the system. As can be seen, DG-1 and DG-2 reacted slow to the load change compared to DG-3, which shared the major part after every change in load. The controller is able to share the load equally among the DG units within considerable amount of time.

The corresponding response of output frequency and voltage under the same load change pattern is illustrated in fig (4.13) and (4.14). Because the load change at each interval is same, the transients in these figures are in coherence. It can be seen that the deviations in output frequency and voltage after every load change are regulated towards zero by the controller so that output voltage and frequency are restored to their nominal values. The adaptive nature and faster response of NN adjusts the secondary control parameters at every load disturbances to regulate the output voltage and frequency.

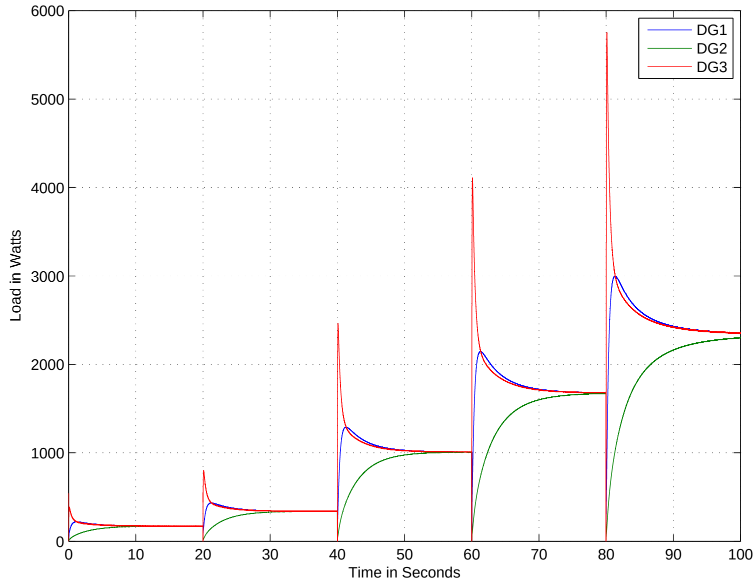

Figure 4.12: Output Frequency under varying load

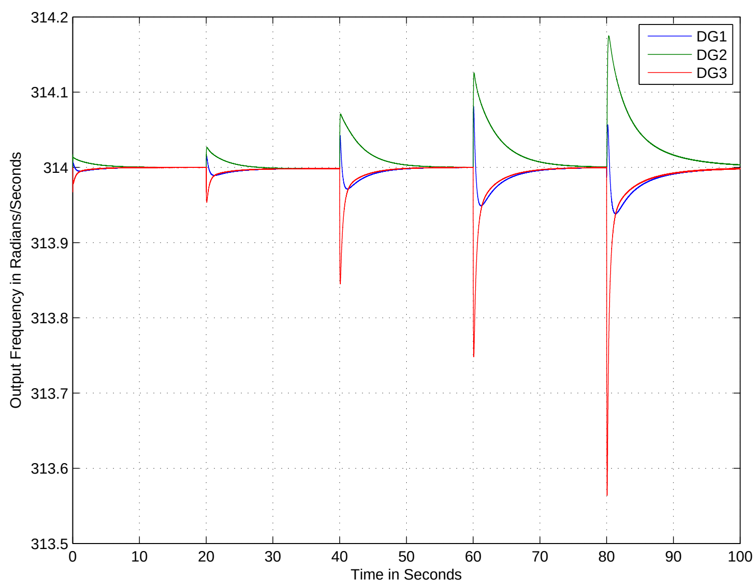

Figure 4.13: Output Voltage under varying load

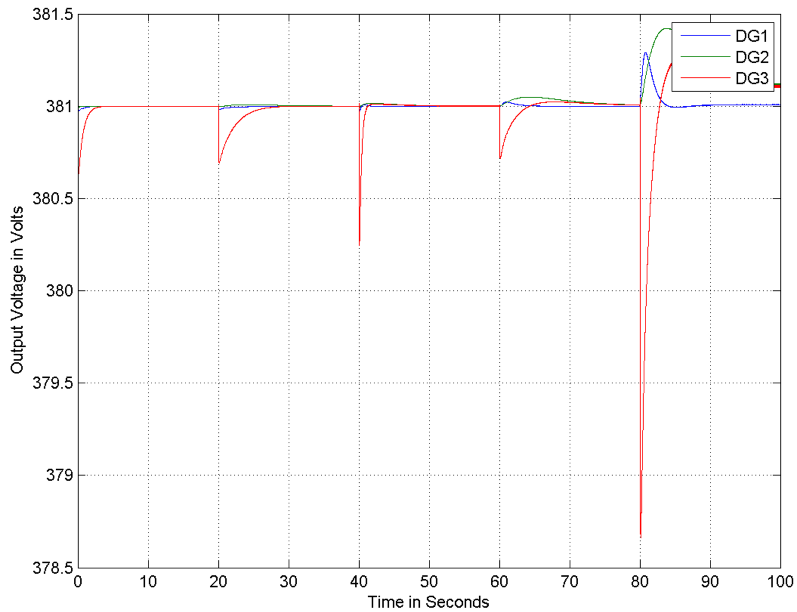

Figure 4.14: Load sharing among the DG units

Chapter 5

Real Time Implementation of Distributed Control for Autonomous Microgrid

5.1 Introduction

Real Time Digital Simulator (RTDS) is a power system simulator widely used in the industry. It is a fully digital simulator based on dommel algorithm, developed by Dr. Herman Dommel [149], to solve the electromagnetic transient simulation algorithm. It is specially designed for real-time power system transient electromagnetic simulation. RTDS facilitates reliable and cost effective study of power systems. The computations are fast because of distributed parallel processing. It has improved ability of the simulation accuracy and better capturing of switching events. Therefore, power electronic converters operating at high switching frequency can be simulated with sufficient accuracy [150]. It can perform analytical studies of a system and can also be used to educate or train operators, engineers and students. In our work, we use the capability of RTDS for implementation of distributed control for an autonomous microgrid system.

The work in this chapter is aimed towards implementing distributed multi-level control scheme for an autonomous MG system in a real-time environment using RTDS. Both the primary and secondary controllers are implemented in distributed way resulting in individual primary and secondary control for each generating unit. Performance of controller is also analyzed under fault conditions. The results of real-time simulation are compared with that of MATLAB simulations to validate the model and performance of controller. The secondary controller is based on averaging algorithms and uses communication network for its operation. The controller reacts faster to load changes and obviates the need for a centralized structure as each generating unit has its own local secondary control action.

5.2 Real Time Digital Simulator

The Real Time Digital Simulator (RTDS) was developed by Manitoba HVDC Research Center in 1980's. It is a fully digital, real time power system simulator used to conduct close-loop testing of protection, power electronics and control equipment [151, 152].

RTDS generally simulates power systems in real time environment with a time step size of the order 50 micro seconds with the help of parallel operating digital signal processors (DSP). Power electronic devices with time step as small as 1.4 - 2.5 seconds i.e., devices with higher switching frequency can be simulated with sufficient accuracy. Additionally, it has capability of incorporating real devices in closed loop simulation environment. RTDS works in continuous sustained real time, which means equations representing any power system or network can be solved fast enough to simultaneously produce the output conditions. As the solver is real time, it can be connected to power system components for tuning purposes [153].

The RTDS equipment used to carry out this study is basically a combination of advanced computer hardware and comprehensive software [154] which are discussed in following sections.

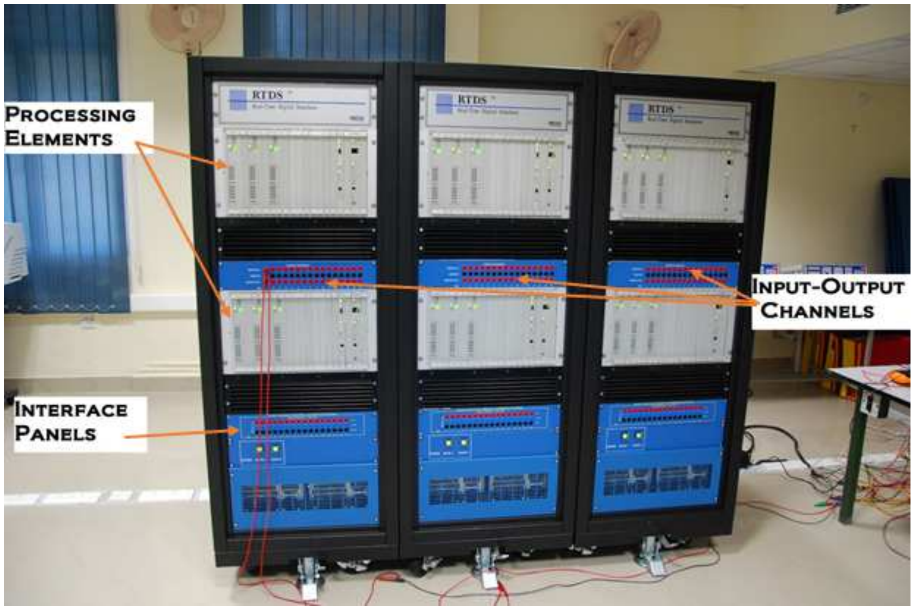

Figure 5.1: Standard racks

5.2.1 Description of RTDS Hardware

RTDS have a customized parallel processing architecture. It is made up of standard 19” rack as shown in fig 5.1. Each rack has a provision for 18 Processing Element (PE) cards, 1 Inter-Rack Communication (IRC) and 1 Workstation Interface Card (WIC) [155]. The communication and processor cards are linked through a common back-plane which facilitates exchange of information.

The PE cards are equipped with a processor responsible for calculating the overall network behavior. The processor capacity is up to 13 Millions of Floating Point Operations Per Second (MFLOPS). The PE card has interface to connect external signals. Two analogue channels can be selected to monitor variables being computed on that card and these channels can be scaled online to suit the external device. In general, PE cards perform two different types of calculation namely nodal analysis (network solution) and the auxiliary components. The former solves the branch currents and node voltages based on network impedance and contribution of the auxiliary components. The later is nothing but transmission lines, networks, transformers etc which provides admittance matrix overlays and current injections to the network solution. The overall network response is simulated by the combined solution of network solution and auxiliary components.

Two different types of PE cards are used by current RTDS Triple Processor Card (3PC)and Giga Processor Card (GPC). In our work, we are using GPC which is recently developed and contains two RISC processors running at 1 GHz. A typical GPC processor is shown in fig 5.2. The processors can communicate directly at any time using shared memory without accessing the back-plane. GPC has strong computational power enabling simultaneous calculation of more than one component model.

Figure 5.2: A giga processor card

The IRC card comes into picture when multiple racks are connected with each other. Its function is to transfer the data generated on one rack to another rack and share the information among racks. The information transfer takes place at a speed of 500 MHz.

WIC is not involved in the real time simulation rather its purpose is to download a case prior to its run. WIC is the communication between RTDS and the host computer network over a Ethernet communication link during on-line run. The rate of data transfer is 10 MHz. It also synchronizes the calculations and coordinates between the PE cards to ensure their proper operation.

5.2.2 Description of RTDS Software

The software of RTDS is a organized three-level hierarchy structure with a low-level operating system, a mid-level compiler and communication and a graphical user interface at the top level. The user works only with the highest level user interface.

In this work, a high level graphical user interface known as RSCAD is used to construct, run, operate the simulation circuits and also to record/document the results. This user interface is installed in the host workstation. There are two modules namely *Draft* and *RunTime* in RSCAD as shown in fig 5.3.

The *Draft* module contains component selection library on the right side containing icons representing various system elements which have been coded for real time simulation. Any component can be dragged on to the left side where

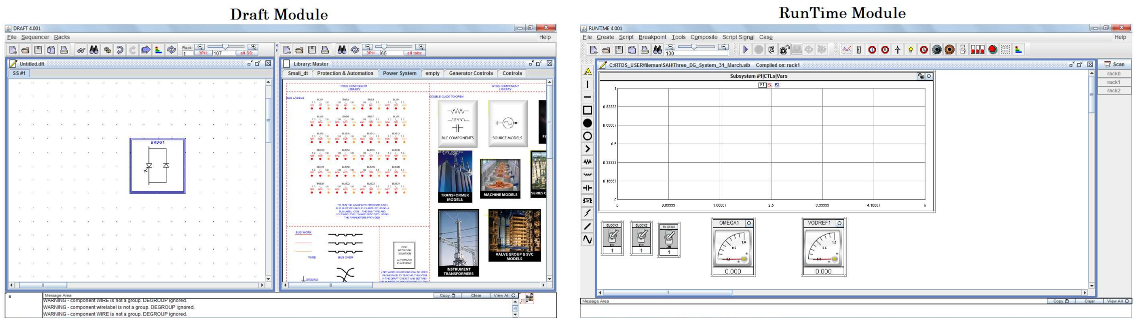

Figure 5.3: Screenshots of draft and runtime modules

a blank area is provided to assemble the system model. With the help of a data menu, the parameters of any particular component can be entered. After drafting any network or system the next step is to compile it by which a simulation code is generated. Once after compilation, *RunTime* module can be used to run.

The *RunTime* module with the help of a WIC and Ethernet, communicates back and forth with the simulator. This bidirectional communication allows in downloading the simulations and as well as running them on the screen. This module has variety of options from plotting a response to changing a parameter online or can even switch ON/OFF any particular variable. The plots are of high resolution displaying every time-step recorded by the WIC. Slow moving signals such as RMS voltage of a bus can be monitored on a continuous basis to allow observation of transient behavior.

5.3 Distributed Control of Autonomous Microgrid

This research aims towards distributed secondary control of autonomous microgrids, wherein both primary and secondary controls are implemented in distributed fashion resulting in individual secondary control for each generating unit. Autonomous operation of MG is considered to carry out this study wherein it is responsible for supplying a load on its own control structure. This mode can be caused by any of the following reasons. Any network fault/failure in the utility grid causing the MG to isolate or to carry out scheduled maintenance [42, 156]and at some times due to economical optimization (when the power from main grid is too costly or if the MG is having excess of stored energy) [157]. An electrical switch will disconnect the MG from main utility grid, resulting in an autonomous operation of MG [23].

The main task of MG in this mode is to ensure that the voltage and frequency supplied are within the pre-specified limits and also to take care that the load is equally shared among its generating units. As explained in [117], without loss of generality, the prime mover can be replaced with a DC source because they both essentially serve the same purpose. This simplification allows to study the behavior of inverter based generators without actually using a prime mover.

Therefore in this work, MG involving only inverter-interfaced DGs units is considered [33]. The block diagram of such microgrid model is shown in Fig. 5.4.

It consists of inverter based DG units supplying a load via LC filter and coupling inductance. Further details regarding this inverter based MG model can be found in [33][119].

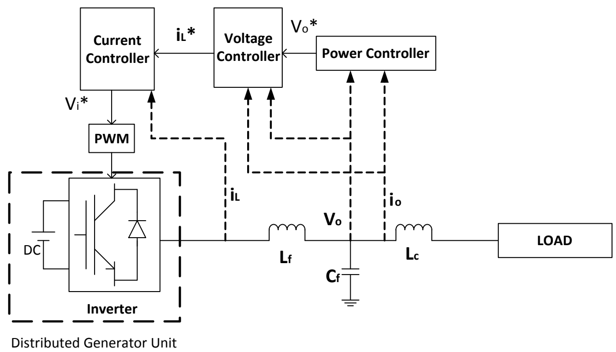

Figure 5.4: Block diagram inverter-based generating unit supplying a load

The power, voltage and current controllers constitute the primary control level of any individual DG unit. It is a droop control strategy which ensures proper load sharing among generating units, makes use of local measurements and does not need any communication medium for its operation. In droop technique, there is a desired relationship between the active power P and angular frequency ω and between reactive power Q and voltage V as given below:

$$\omega = \omega_n - m_p P, \quad V = V_n - n_q Q$$

Where V_n and ω_n are the nominal values of output voltage and angular frequency, P and Q are the real and reactive powers, m_p and n_q are the real and reactive power droop gains respectively. The frequency ω is set according to the droop gain m_p and output voltage V is set as per droop gain n_q.

The power controller sets the inverter output voltage magnitude and frequency with the help of droop characteristics. Basically, it mimics the operation of a synchronous generator which will change the frequency of the output voltage if any change in load is sensed. Voltage and current controllers reject the high frequency disturbance and damp the output filter to avoid any resonance with the external network.

Primary control alone is not sufficient for the stable operation of overall MG, to achieve global controllability a secondary control is deployed. Distributed PI controller based on averaging algorithm is used at the secondary level of control. The secondary control of microgrid is a tracking synchronization problem where all the DG units try to synchronize their output voltage and frequency to pre-defined set points. For this purpose, DG units exchange measurements information using communication medium. This exchange of information is only of measurements and it is to be noted that each DG has its own secondary controller which sends control signals only to its corresponding DG unit and not to other DG units.

Fig. 5.5 shows the overall control block diagram of distributed control of islanded microgrid. The control law at the secondary level is given by following equations

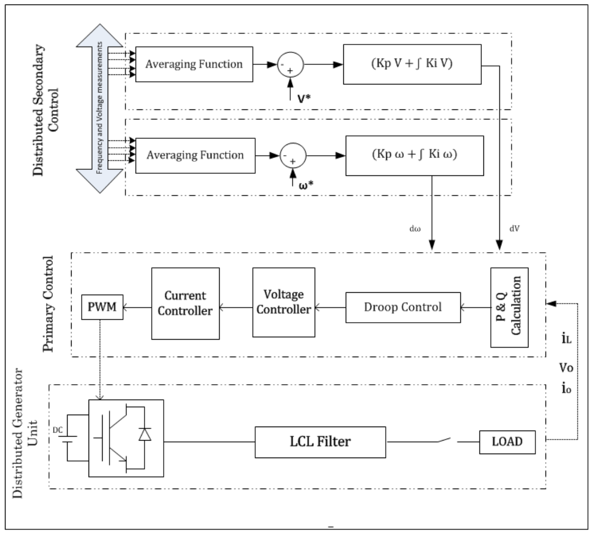

Figure 5.5: Distributed secondary control for individual generating unit

$$\delta\omega = K_{p\omega}(\omega_n - \omega_{avg}) + K_{i\omega}\int(\omega_n - \omega_{avg})dt \tag{5.1}$$

$$\delta V = K_{pv}(V_n - V_{avg}) + K_{iv}\int(V_n - V_{avg})dt \tag{5.2}$$

Where $K_{p\omega}$, $K_{i\omega}$ are the PI controller parameters for frequency control, K_{pv}, K_{iv} are the PI controller parameters for voltage control. ω_n and V_n are the frequency and voltage set points. ω_{avg} and V_{avg} are the average values of frequency and voltage respectively. $\delta\omega$ and δV are the control signals produced by secondary controller.

The secondary control regulates the deviations produced due to load changes to zero. It collects the measurements (voltage, frequency) of all DG units via communication system, averages them and produces a suitable control signal as per control law defined in equations 5.1-5.2. This control signal is sent to primary control level [111]. The controller removes steady state error in output voltage and frequency produced by the primary control.

5.4 RTDS Implementation of Distributed Control for Autonomous Microgrid System

In this section, the real time implementation of autonomous MG model and its distributed control is explained in detail. Fig 5.6 shows the laboratory setup of equipments, the studies were carried out using one standard RTDS rack developed by RTDS Technologies [158] and a work station installed with RSCAD is used to develop the complete simulation test bed of microgrid system. To carry out the simulations various components from power system library, control system library and VSC (voltage-sourced converter) small time-step components from the RTDS model library [159] are used.

Inverter-based microgird can be conveniently constructed using the VSC small time-step modeling library. All the VSC components are assembled in VSC bridge box. Fig 5.7 shows the blue VSC bridge box icon, detailed circuit inside the box and configuration table for inverter bridge. As can be seen, the

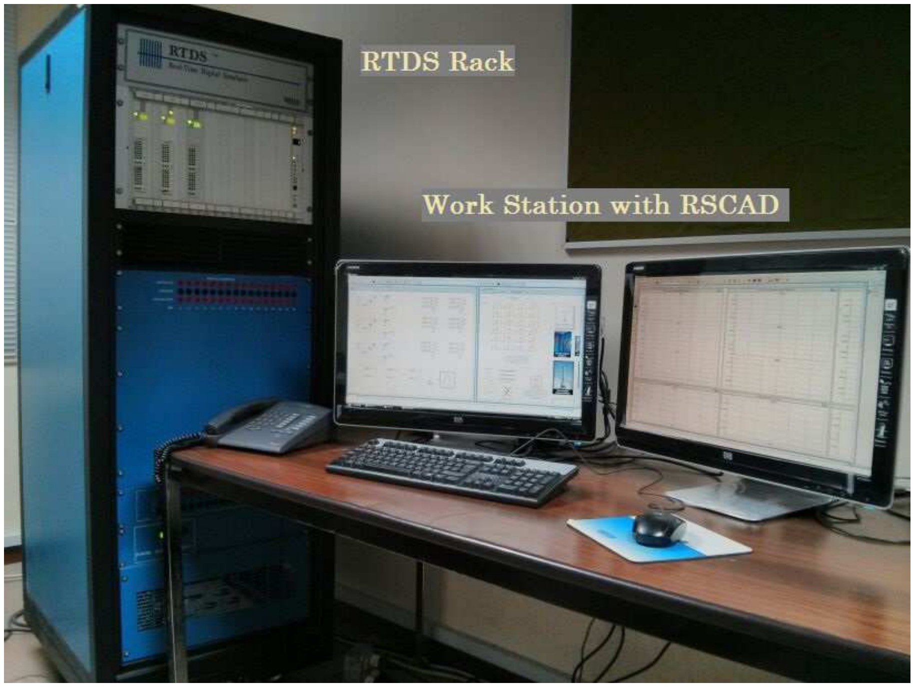

Figure 5.6: RTDS/RSCAD setup in the laboratory

microgrid system consists of 3 distributed generating units supplying a common load through LC filters and coupling inductances. The three phase inductor currents, output voltage and output currents, represented as as I_L, V_O and I_O respectively, of all the three DG units are monitored here at this stage.

The study involves the use of power electronic device inverters which requires pulse width modulation (PWM) for its operation. A triangular wave generator along with firing pulse generator is used for this purpose. Fig 5.8 illustrates these blocks with their respective configuration tables used to fire the inverter of DG-1 unit.

To perform the circuit analysis, three phase AC voltages and currents are re-

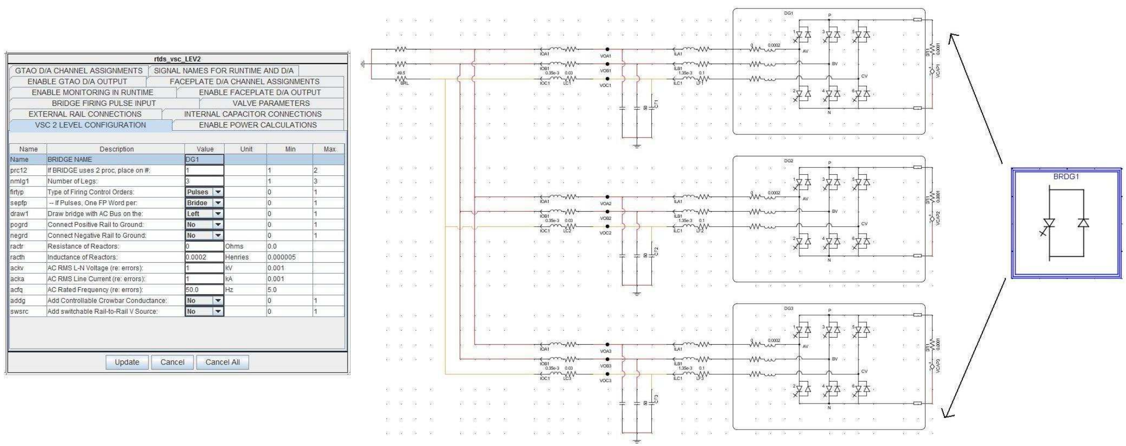

Figure 5.7: RTDS equivalent model for autonomous microgrid system

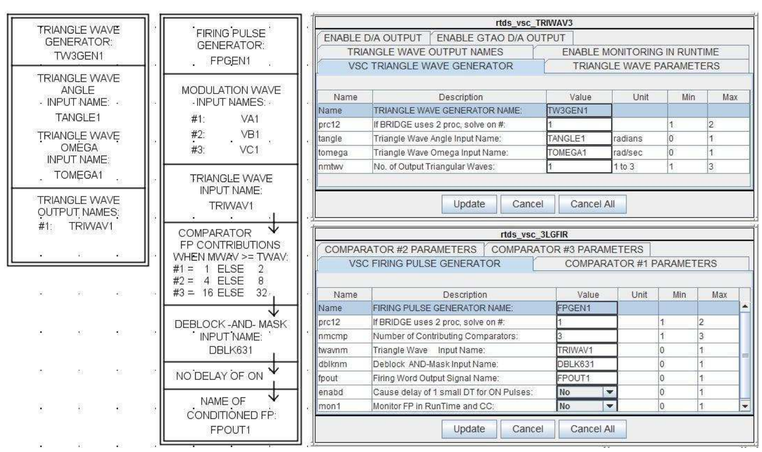

Figure 5.8: Triangular wave generator and firing pulse blocks

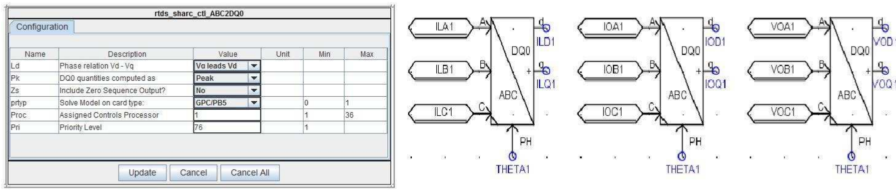

Figure 5.9: Block for ABC to DQ0 transformation

duced into two phase DC quantities using *ABC-DQ0* transformation. Fig 5.9 shows the block with its configuration table which performs this transformation for DG-1. The angle *THETA* used here is obtained from the power controller circuit discussed ahead.

The power controller model of DG-1 is implemented as shown fig 5.10, it is based on droop action. Instantaneous value of active and reactive powers are calculated using output voltages and currents. To filter out the harmonics at this level, these instantaneous values passed through a low pass butter-worth filter with a cutoff frequency of 5 Hz. We then obtain the average real and reactive powers which are passed through their respective *droop* gains to obtain the angular frequency and voltage respectively [120]. As is evident from the figure, active power (P), reactive power (Q), output voltage ($VODREF$) and frequency ($OMEGA$) are monitored variables at this level. Power controller along with voltage and current controllers constitute the primary control level of a DG unit.

The steady state error is produced by the droop control and to regulate this error, secondary control signals are sent to power controller. Therefore, the secondary controller is implemented near to the primary controller. The fig 5.10

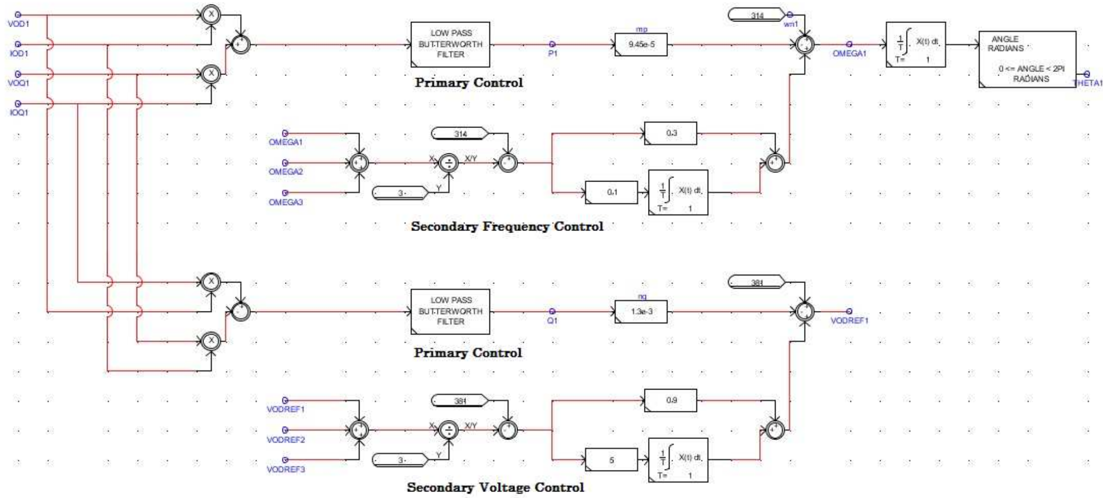

Figure 5.10: RTDS equivalent model for Power Controller

also explains the implementation of the distributed secondary controller. The controller is distributed since each DG unit is having its own individual secondary controller to regulate the output voltage and frequency. The secondary control processes frequency and voltage measurements to produce a control signal as per control law explained in equations (1) and (2).

The voltage controller and current controllers of DG-1 consisting of PI controls are implemented as shown in fig 5.11. These controllers are part of primary control. The controllers rejects high frequency disturbances and damp the output filter to avoid any resonance with the external network. The PI controllers make use of the local measurements to perform the control action, an additional feed forward gain and decoupling terms are also used. Details on these controllers can be found in [160, 161].

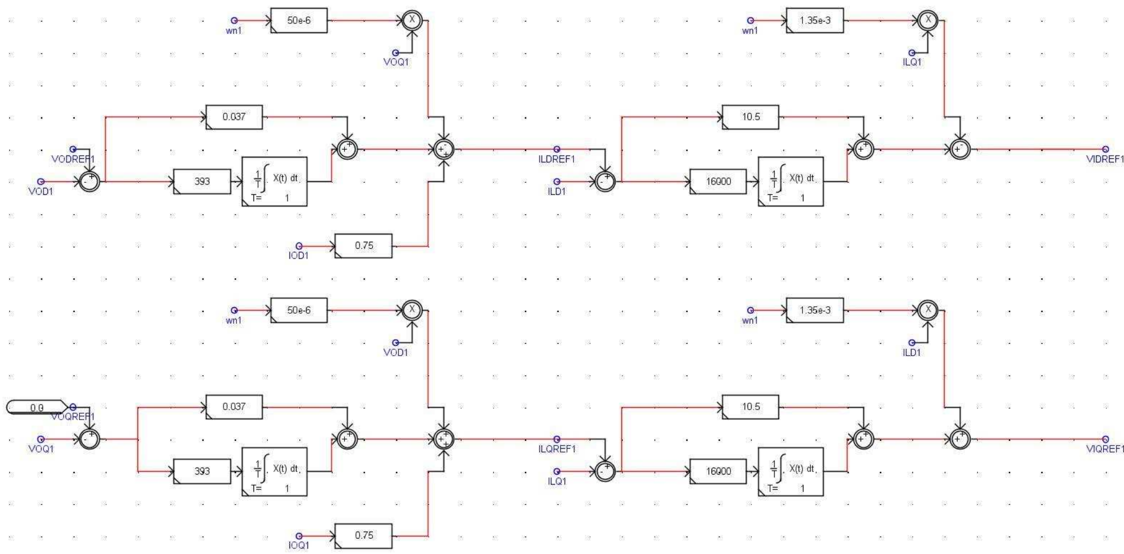

Figure 5.11: RTDS equivalent model for voltage and current controllers

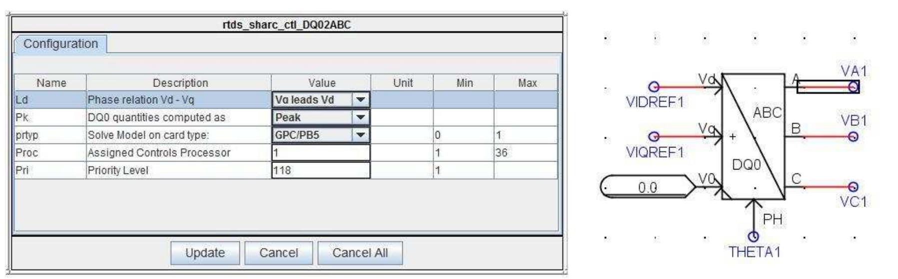

Figure 5.12: Block for DQ0 to ABC transformation

The output signals of current controller is transformed into three phase voltage signals which serves as modulation waves to generate firing pulses for inverters. Fig 5.12 shows *DQ0-ABC* transformation block of DG-1 with configuration table.

Table 5.1: System Parameters

PARAMETER	VALUE
Filter Inductance (L_f)	1.35 mH
Filter Resistance (r_f)	0.1 ohms
Filter Capacitance (C_f)	50 μ F
Coupling Inductance (L_c)	0.35 mH
Coupling Resistance (r_c)	0.03 ohms
Nominal Voltage (V_n)	381v
Nominal Frequency (ω_n)	314 rad/sec
Cutoff Frequency of Low Pass Filter (ω_c)	31.4 rad/sec or 5 Hz

5.5 Results and Discussions

In this section, in order to confirm the real-time performance of the proposed distributed secondary controller, the microgrid system described in the section IV is simulated in RTDS/RSCAD. Simulation results of the RTDS/RSCAD are compared with the results of the same system simulated in MATLAB environment. Response of the controller and its load sharing capability under fault disturbance is also shown.

The specifications of the MG are described in Table 5.1. The primary controller parameters for RTDS and MATLAB are given in Table 5.2. The Secondary controller parameters for RTDS and MATLAB are given in Table 5.3.

Fig 5.13-5.15 shows the waveforms of three phase inductor currents, output voltage and currents of the inverter respectively when supplying a load of 5

Table 5.2: Primary Control Parameters

PARAMETER	VALUE
Real Power Droop Gain (m_p)	9.4 x 10^{-5}
Reactive Power Droop Gain (n_q)	1.3 x 10^{-3}
Proportional gain of Voltage Controller (K_{pv})	0.037
Integral gain of Voltage Controller (K_{iv})	393
Proportional gain of Current Controller (K_{pc})	10.5
Integral gain of Current Controller (K_{ic})	16000
Feed-forward gain of Voltage Controller (F)	0.75

Table 5.3: Secondary Control parameters

PARAMETER	RTDS	MATLAB
Proportional gain for Secondary Frequency Control	0.5	4.3656
Integral gain for Secondary Frequency Control	0.1	9.1206
Proportional gain for Secondary Voltage Control	0.9	7.3677
Integral gain for Secondary Voltage Control	0.5	3.6765

KW. It can be seen that the inductor currents are balanced sine waves but with little distortion due to non-linearity of inductors. The output waveforms of voltages and currents are also balanced set of sinusoidal nature.

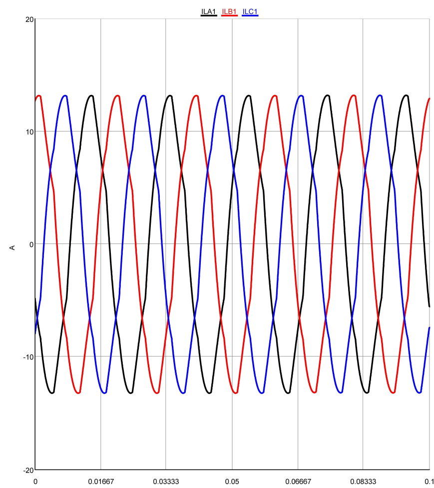

Figure 5.13: Three-phase inductor current

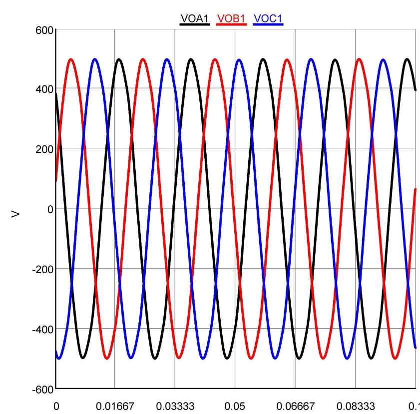

Figure 5.14: Three-phase output voltage

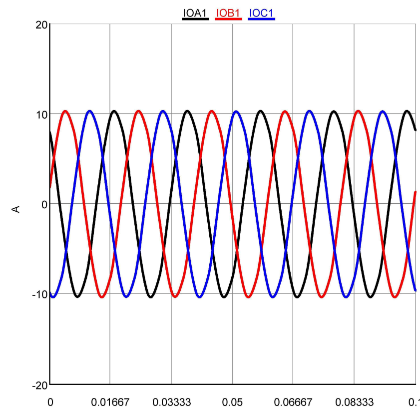

Figure 5.15: Three-phase output current

5.5.1 Comparison of RTDS and MATLAB Results

The system shown in fig 5.7, is also implemented in MATLAB/Simulink/SimPowerSystems environment. Comparative study between RTDS and MATLAB simulations are presented below using the results obtained for power sharing between the DG units, output voltage and frequency regulations.

Initially, the system is operated under no load condition and at t = 4 seconds, a load of 3 KW is suddenly realized on the system in both MATLAB and RTDS. From the RTDS response, it looks as if the load is applied before 4 sec. This is because the output recording of RTDS starts to time after manually switching the refresh button while the simulation is running in the real-time.

Fig 5.16 illustrates the load sharing among the DG units. Fig 5.17 and 5.18 and presents the regulation of output frequency and output voltage respectively under load change. By observing the figures, following analysis can be made

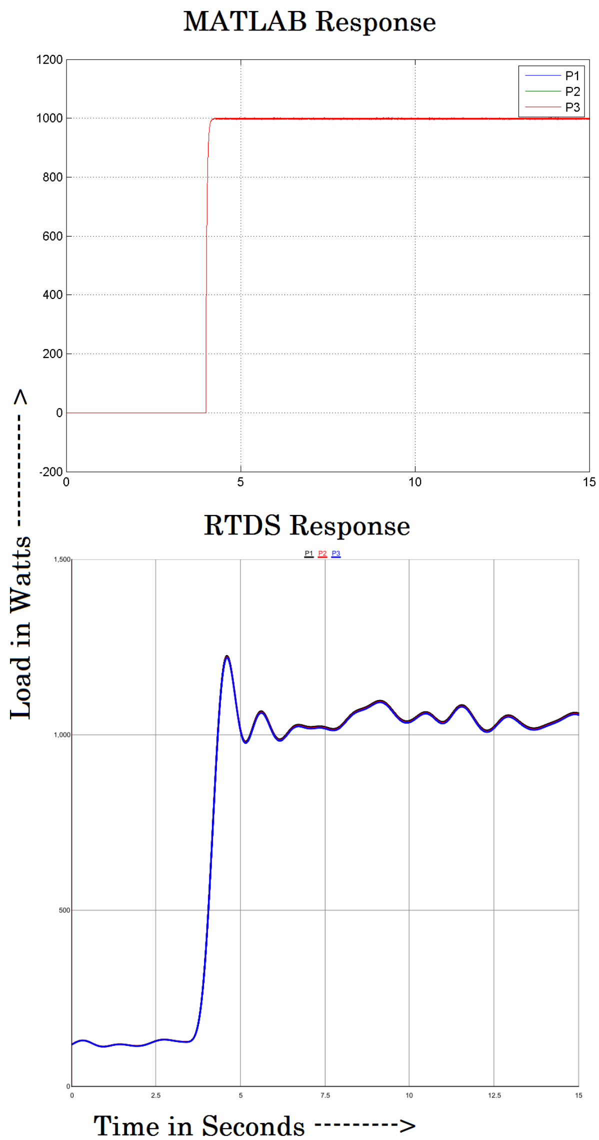

Figure 5.16: Load sharing response of MATLAB and RTDS

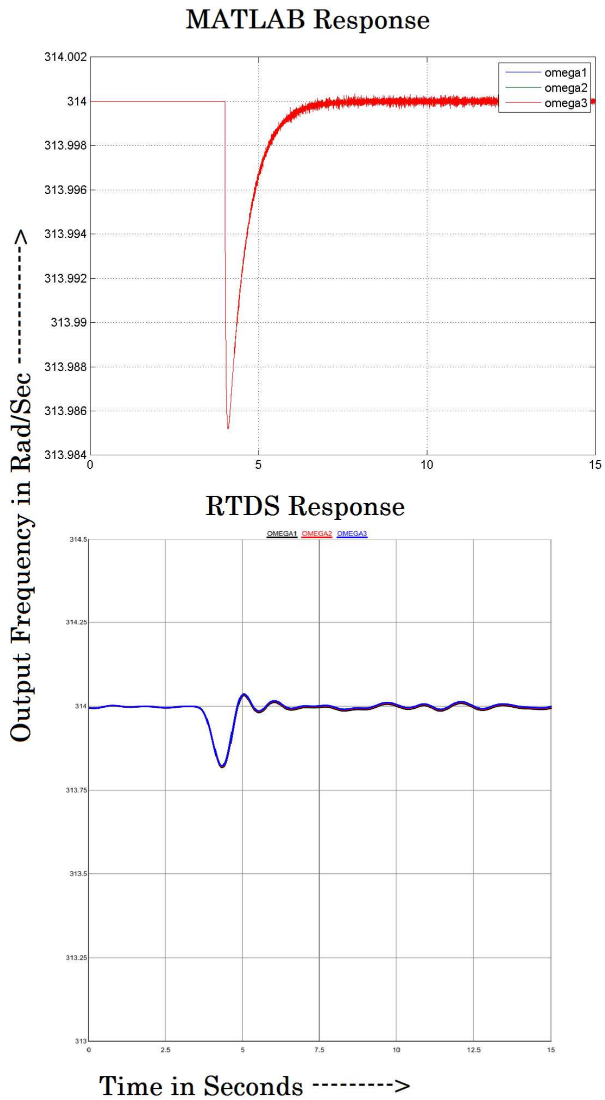

Figure 5.17: Output frequency response of MATLAB and RTDS

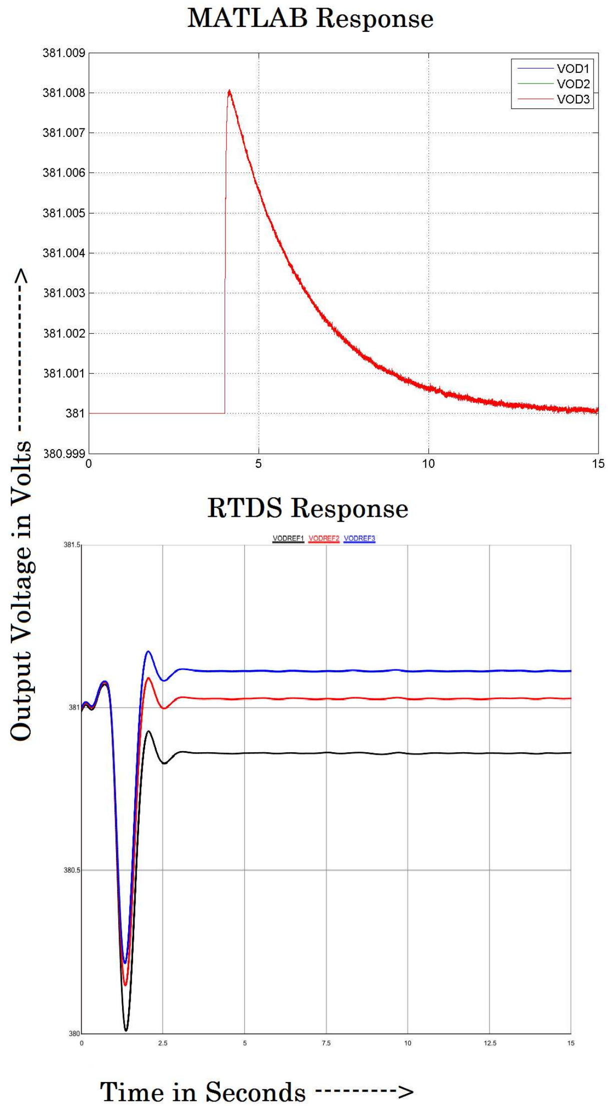

Figure 5.18: Output voltage response of MATLAB and RTDS

- From t=0 sec to t=4 sec in fig 5.16, there is no active power shared as the load is zero on the system. It can be seen from RTDS response that under no load condition, a very negligible amount of active power is shared. This is due to presence of internal inductance of reactors and small bridge resistance in the inverter model of RTDS, as can be seen in fig 5.7.

- In fig 5.16 After t=4 sec, each DG unit shares equal load of 1 KW which sums up to 3 KW as there are 3 DG units. This is the total load on the system. It is clear from comparison that both MATLAB and RTDS observe similar response to load change.

- In fig 5.17 and 5.18, transients can be seen at t=4 sec due to sudden application of load. The transient response of RTDS is slightly different from MATLAB response. This is because of the systematic differences between the simulation platforms i.e., difference in 'VSC Bridge Inverter' model in RTDS and 'IGBT Inverter' in Simulink.

- From fig 5.17-5.18, it can be observed that the transients in output voltage and frequency are regulated towards zero by the controller. The controller operates as expected and successfully restores the deviated output values back to their nominal set points. The set points for output frequency is 314 rad/sec and for output voltage is 381 V.

5.5.2 Load Sharing During Faults

In this section, load sharing capability of the controller during faults is demonstrated. For better understanding, we simplify the microgrid system by considering only two DG units. A three-phase *VSC valve breaker* from small time step library is used to apply the fault. This fault is applied manually using a switch and will completely isolate the DG unit from the system.

Initially, a load of 5 KW is applied on the system. The DG units are seen sharing the equal load of 2.5 KW which is illustrated by fig 5.19. If due to some fault condition, DG-1 shuts down then the total load has to be supplied by DG-2. This condition is illustrated by fig 5.20, where a fault on DG-1 is applied isolating from the network. As can be seen from the figure, the controller acts quickly and the total load of 5 KW is supplied by DG-2 alone whereas power delivered by DG-1 is now reduced to zero.

Same is the case when a similar fault is applied on DG-2 isolating it from the network and the total load has to be delivered by DG-1 alone which is demonstrated in fig 5.21. Fig 5.22 illustrates the condition when the fault on DG-2 is removed, as can be seen both the DG's start to share the same load.

Finally, a step change of 7 KW is added to the load, due to this addition an increase in power delivered by both the DG's is observed as can be seen in fig 5.23. As the total load on system now is 12 KW, both DG units are now seen sharing equal load of 6 KW. Therefore, the controller shares the load evenly among generating units.

Figure 5.19: Load shared by DG units at 5 KW load

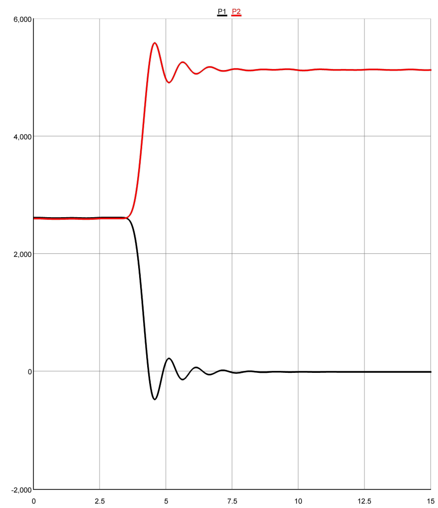

Figure 5.20: Load sharing when the fault is on DG-1

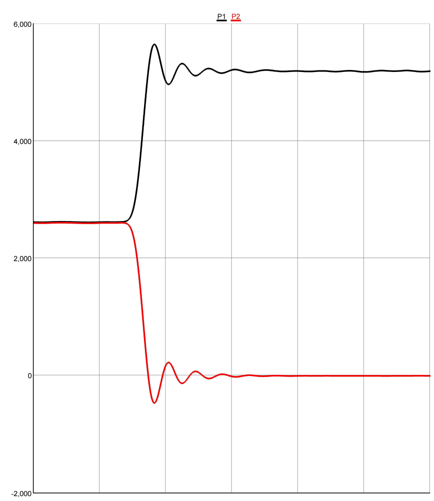

Figure 5.21: Load sharing when the fault is on DG-2

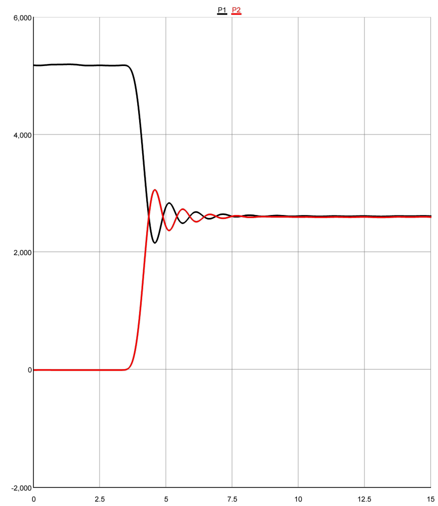

Figure 5.22: Load sharing when the fault on DG-2 is removed

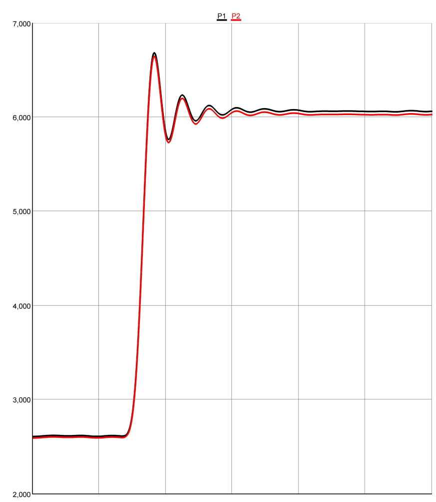

Figure 5.23: Load shared when the load is increased from 5 KW to 12 KW

Chapter 6

Reinforcement Learning Solutions for Microgrid Control

Reinforcement Learning (RL) is concerned with how an agent can pick its actions in a dynamic environment to transit to new states in such a way that optimizes the sum of cumulative reward [162]. It is an area of machine learning which allows development of online algorithms to obtain solutions to problems related to optimal control for dynamic systems that are described by difference equations [163, 164]. It involves two techniques known as Value Iteration (VI) or Policy Iteration (PI) [165]. Policy iteration and value iteration algorithms have been developed for continuous time systems in [166, 167, 168]. Adaptive Dynamic Programming (ADP) is a kind of RL technique proposed by Werbos [169] to solve dynamic programming problems. There are different levels of applications within the scope of ADP namely Heuristic Dynamic Programming (HDP), Dual Heuristic Dynamic Programming (DHP), Action-Dependent HDP (ADHDP) and Action-Dependent Dual HDP (ADDHP) [164].

The concept of microgrid (MG) is well known from the time it was originally introduced a decade ago [8]. It can operate in both grid connected mode and autonomous mode and facilitates high penetration of distributed generating (DG) units into the grid. An electrical switch will disconnect the MG from main utility grid, resulting in an autonomous operation of MG [23], but random applications of DG units will cause as many issues as it may solve [115]. Therefore, control of MG is a key aspect which aims towards the stable operation of microgrid and has been the focus of researchers over the past few years. During the islanded operation, the main task of MG is to deliver quality power by regulating the output voltage. The MG with its own control structure should be able to regulate any disturbances in the load towards zero to ensure the stability of the system [170].

Multi-level control [121] of MG is extensively studied in the literature, it is widely used and consists of primary, secondary and tertiary control levels [122]. A pseudo-decentralized control architecture is proposed in [124] which can be used for the optimization of Wireless Communication Network (WCN) with the help of a Global Supervisory Control (GSC) and local controllers. A networked control scheme based on system of systems is proposed for microgrid in [171]. A MG with multiple DG units is treated as system of systems and an output feedback control scheme is applied. A communication network subjected to packet dropouts and delays is used for the application of control. A two-level coordinating control approach for islanded MG is presented in [172]. An MG with n parallel connections of DG units connected to a common load is considered for the study, this parallel connections is conveniently controlled in a two level coordinating scheme as it forms an interconnected control system. Control of autonomous MG with a local load is introduced in [27], it develops a dynamic model of MG and presents a classical control approach to design the controller. A robust servomechanism controller for autonomous MG is presented in [29]. This approach uses the same dynamic model developed in [27] and uses a optimal control design procedure to guarantee the robust stability.

In this chapter, a novel approach for the control of MG using RL technique is proposed. The dynamic model of islanded MG proposed in [27] is adopted to carry out the research. HDP algorithm based on actor-critic value iteration is used to develop the control of MG [173]. The actor component applies actions or control policies to their environment, while the critic component assesses the values of these actions. Based on this assessment, the actor policy is updated at each learning step [162]. Both offline and online learning algorithms are used in the implementation of control technique. To the best of authors knowledge, this is the first time that RL techniques are applied to the concept of MG.

6.1 Autonomous Microgrid System

Autonomous or islanded mode of MG can be caused by network faults/failures in the utility grid, scheduled maintenance, [42, 156] and due to economical optimization or management constraints [157].

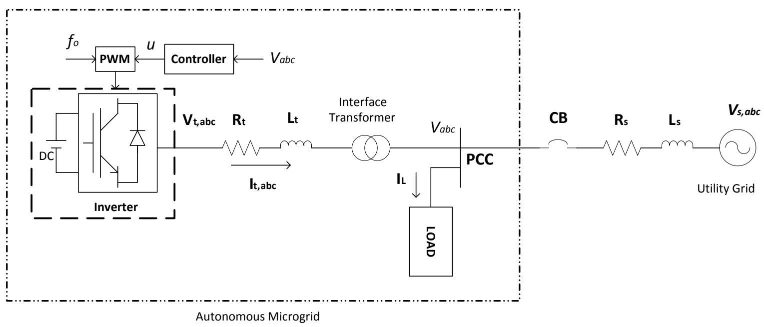

Figure 6.1: Schematic diagram of microgrid

The schematic single-line diagram of an electronically coupled microgrid model is shown in fig. 6.1. A switch at point of common coupling (PCC) will isolate the MG from utility grid [23]. The islanded system consists of inverter based DG units supplying a load via series filter and a transformer. The interface transformer is of step-up type with 2.5 MVA rating [27], it is used to step up the MG voltage. The dc voltage source represents generating unit, R_t and L_t represents the series filter. A local load, modeled by a three-phase parallel RLC network, is connected at the PCC. The system parameters are tabulated in Table 6.1.

During the islanded operation, the main task of MG is to deliver quality power by regulating any disturbances in the load towards zero. The MG with its own

Table 6.1: Parameters Values For Microgrid System

Quantity	**Value**
R_t	1.5 m Ω
L_t	300 μ H
V_{dc}	1500 V
PWM Carrier Frequency	1980 Hz
Load Parameters	
R	76 Ω
L	111.9 mH
C	62.855 μ F
R_l	0.3515 Ω
Grid Parameters	
R_s	1 Ω
L_s	10 μ H
Nominal Frequency f_o	60 Hz
Nominal Voltage (rms)	13.8 kV
Interface Transformer Parameters	
Type	Wye/Delta
Rating	2.5 MVA
Voltage Ratio (n)	0.6/13.8 kV

control structure should be able to maintain the load voltage level at a desired pre-specified set point.

6.1.1 State Space Model of Autonomous Microgrid

Consider the system described in Fig. 6.1 to be balanced then the equations governing MG are given by

$$V_{t,abc} = L_t \frac{dI_{t,abc}}{dt} + R_t I_{t,abc} + V_{abc} \tag{6.1}$$

$$I_{t,abc} = \frac{1}{R} V_{abc} + I_{L,abc} + C \frac{dV_{abc}}{dt} \tag{6.2}$$

$$V_{abc} = L \frac{dI_{L,abc}}{dt} + R_l I_{L,abc} \tag{6.3}$$

The above equations are in abc-frame. Since the system is under balanced conditions, the three-phase quantity x_{abc} can be transferred to a stationary $\alpha\beta$-reference frame with the help of following transformation

$$\begin{bmatrix} x_\alpha \\ x_\beta \\ x_0 \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & -\frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{6.4}$$

In $\alpha\beta$-frame, the resulting equations are:

$$\frac{dI_{t,\alpha\beta}}{dt} = -\frac{R_t}{L_t} I_{t,\alpha\beta} - \frac{V_{\alpha\beta}}{L_t} + \frac{V_{t,\alpha\beta}}{L_t} \tag{6.5}$$

$$\frac{dV_{\alpha\beta}}{dt} = \frac{1}{C} I_{t,\alpha\beta} - \frac{1}{RC} V_{\alpha\beta} - \frac{1}{C} I_{L,\alpha\beta} \tag{6.6}$$

$$\frac{dI_{L,\alpha\beta}}{dt} = \frac{1}{L} V_{\alpha\beta} - \frac{R_l}{L} I_{L,\alpha\beta} \tag{6.7}$$

which can be transferred to rotating reference frame using the following transformation:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \begin{bmatrix} cos(\theta) & -sin(\theta) \\ sin(\theta) & cos(\theta) \end{bmatrix} \begin{bmatrix} x_\alpha \\ x_\beta \end{bmatrix} \tag{6.8}$$

where $V_{\alpha\beta}$ is taken as reference vector such that $V_q = 0$. In autonomous mode, the system frequency is controlled in an open-loop manner as VSC generates three-phase voltages at frequency ω_0 by employing an internal oscillator of constant frequency of $\omega_0 = 2\pi f_0$. Moreover, the steady state voltage and current signals are at frequency ω_0 if the local load is passive. Therefore, the dq state variables are given by

$$\frac{dI_{td}}{dt} = -\frac{R_t}{L_t} I_{t,d} + \omega_0 I_{tq} - \frac{1}{L_t} V_d + \frac{1}{L_t} V_{td} \tag{6.9}$$

$$\frac{dI_{tq}}{dt} = \omega_0 I_{td} - \frac{R_l}{L} I_{tq} - 2\omega_0 I_{Ld} + (\frac{R_l C \omega_0}{L} - \frac{\omega_0}{R}) V_d \tag{6.10}$$

$$\frac{dI_{Ld}}{dt} = \omega_0 I_{tq} - \frac{R_l}{L} I_{Ld} + (\frac{1}{L} - \omega_0^2 C) V_d \tag{6.11}$$

$$\frac{dV_d}{dt} = \frac{1}{C} I_{td} - \frac{1}{C} I_{Ld} - \frac{1}{RC} V_d \tag{6.12}$$

Putting the foregoing autonomous MG system into the standard time state-space representation

$$\dot{x}(t) = A_c x(t) + B_c u(t); \quad yt = C_c x(t); \quad u(t) = v_{td}$$

it follows that the system matrices are given by

$$A_c = \begin{bmatrix} -\frac{R_t}{L_t} & \omega_0 & 0 & \frac{1}{L_t} \\ \omega_0 & \frac{R_l}{L} & -2\omega_0 & \frac{R_l C \omega_0}{L} - \frac{\omega_0}{R} \\ 0 & \omega_0 & -\frac{R_l}{L} & \frac{1}{L} - \omega_0^2 C \\ \frac{1}{C} & 0 & -\frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, \quad B_c = \begin{bmatrix} \frac{1}{L_t} \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad C_c^T = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \tag{6.13}$$

where the state vector is

$$x^T = \begin{bmatrix} I_{td} & I_{tq} & I_{Ld} & V_d \end{bmatrix} \tag{6.14}$$

For the purpose of convenience later on, we will discretize model (**??**)–(6.13).

6.2 Reinforcement Learning Techniques

Reinforcement Learning (RL) [174], also known as action-based learning, refers to interactions of an actor with its environment so as to improve its actions/control policies depending on the evaluative information received from the environment. It implies a relationship between actions and reward or lack of reward. One category of RL techniques is based on the *Actor-Critic* architecture. The actor agent applies a control (action) to the environment and the value of this control is assessed by the critic agent. These agents must prefer past actions that were found to be effective in order to obtain reward but they also need to explore in order to select a better actions in the future. The key feature of RL is it starts with a complete goal-directed agent. The agents have explicit goals, can sense the characteristics of uncertain environment and have ability to influence the environment. RL technique is an indirect adaptive controller wherein system parameters are calculated first and then the controller is estimated. The key feature of RL is that it provides an adaptive control which converges to the optimal control [175].

In this study, we will consider HDP algorithm, the simplest but powerful form to minimize a performance index. A simple HDP system consists of two sub-networks namely actor and critic networks. These networks have a feed forward and feedback components.

6.2.1 Heuristic Dynamic Programming

Heuristic Dynamic Programming (HDP) is based on adaptive critics [176] which uses function value function approximation to solve the dynamic programing problems. Fig 6.2 shows the structure of HDP design, it consists of a system to be controlled and two sub-networks namely *Actor* and *Critic* networks [177]. The control structure does not require the desired control signals to be known. Both the cost function and control policy are approximated at each step by these two networks.

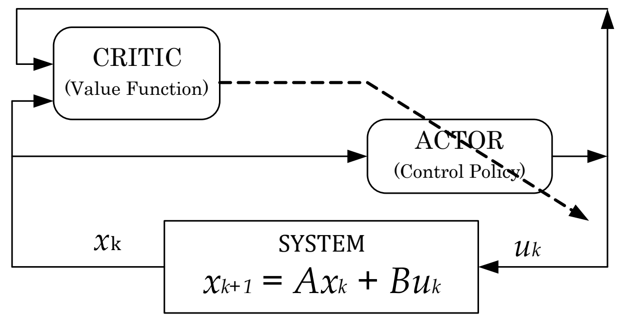

Figure 6.2: Block diagram of actor-critic

The actor network provides the control policy to minimize the value function. For each iteration, in feedforward mode the output of actor network is a series of control signals and in feedback mode it adjusts the internal network weights. Critic network establishes a relationship between the control signals and value function. After learning the relationship, the critic network provides a proper feedback to the actor so as to generate the desired control policy. The working of critic is two folded, in the feedforward mode it predicts the value function for a initial set of control signals and in the feedback mode it assists the actor network to generate a control policy which minimizes the value function. The HDP application often begins with assuming some random initial control signals. It involves iteration of two key process, one is critic network training to learn the relationship between a set of controls and corresponding value function and the next is actor network training to generate the desired control signals [178].

6.2.2 Discrete-Time Bellman Equation

Consider the following discrete-time system in state-space form

$$x_{k+1} = Ax_k + Bu_k \tag{6.15}$$

which is an appropriate discrete version of system (6.13), where the states $x_k \in \mathbb{R}^n$ and control input $u_k \in \mathbb{R}^m$ and k is the discrete time index. Assume that the system (6.15) is stabilizable on some set $\Omega \in \mathbb{R}^n$.

Definition 6.2.1 *Stabilizable System: A system is said to be stabilized on a set $\Omega \in \mathbb{R}^n$ if there exists a control input $u \in \mathbb{R}^m$ such that the closed loop system given by x_{k+1} is asymptotically stable on Ω.*

A function $h(\cdot) : \mathbb{R}^n \to \mathbb{R}^m$ from state space to control space is known as control policy such that for every state x_k there is a control $u_k = h(x_k)$. This describes the actor mathematically as it is the one generating control policy in RL techniques i.e., the actor takes states x_k as input and gives control output u_k. It is desired to find the control policy $u(x_k)$ which minimizes the following performance measure/value function

$$V(x_k) = \sum_{i=k}^{\infty} \frac{1}{2}(x_k^T Q x_k + u_k^T R u_k), \tag{6.16}$$

where the matrices $Q = Q^T > 0 \in \mathbb{R}^{n \times n}$ and $R = R^T > 0 \in \mathbb{R}^{m \times m}$ so that performance measure is well defined.

Definition 6.2.2 *Admissible Control [179]: A control policy $u_k = h(x_k)$ is said to be admissible if it stabilizes system (6.15) and yields a finite performance $V(x_k)$.*

For any admissible control $u_k = h(x_k)$, $V(x_k)$ is known as cost or value and can be selected based on minimum energy, minimum cost requirements etc. We can write (6.16) as follows

$$V(x_k) \quad = \quad \frac{1}{2}(x_k^T Q x_k + u_k^T R u_k) + V(x_{k+1}), V(0) = 0 \tag{6.17}$$

Therefore, by using current control policy u the cost can be evaluated by solving the above difference equation. Equation (6.17) is known as *Bellman equation*. It is a fixed-point equation that the value must satisfy if it is consistent with the current control policy. Bellman equation is a functional equation consisting of dynamical systems state and a value or optimal return function.

According to Bellman's optimality principle [180], the optimal value can be obatined by

$$\begin{aligned} V^*(x_k) &= \min_{u_k}[\frac{1}{2}(x_k^T Q x_k + u_k^T R u_k) + V^*(x_{k+1})] \\ u_k^* &= -R^{-1} B^T \nabla V^*(x_{k+1}) \end{aligned} \tag{6.18}$$

The key concept in developing RL techniques is to assess the current policy value by using bellman equation. To solve the above equation one must know the policy at $k+1$ to determine the policy at k, therefore Bellman equation is a dynamic programing algorithm which yields backwards in time. These techniques can be based of value iterations or policy iterations [165]. Policy iteration and value iteration algorithms have been developed for continuous time systems in [166, 168, 167]. Unlike value iterations, an initial stabilizing control action is needed for policy iterations [162]. In this study we are interested in the value iteration techniques, an iterative method for determining optimal control. This technique does not require initial stabilizing policy.

6.2.3 Value Iteration Algorithm

In this section, a value optimality iteration algorithm for autonomous microgrid system is developed and used to solve the discrete-time Bellman equation. It can be considered as simple backup operation that integrates the policy improvement and truncated policy evaluation steps. The value iteration algorithm is summarized by **Algorithm 1**.

Remark 6.2.1 *It is important to note that the value iteration depends on solution of simply recursive equation (6.19), which is easy to compute and is called partial backup in reinforcement learning. Value iteration successfully mixes one sweep of policy evaluation and one sweep of policy improvement in each of its sweep.*

Algorithm 1 (Value Iteration Algorithm for Autonomous Microgrid)

1. **Initialization:** *Select any arbitrary initial values for the policies u_k and $V(x_k)$, not necessarily admissible or stabilizing.*
2. **Value Update:** *Solve the Bellman equation to get $V^{l+1}(xk)$ as follows*

$$V^{l+1}(xk) = \frac{1}{2}(x_k^T Q x_k + u^{lT} R u^l) + V^l(x_{k+1}) \tag{6.19}$$

   where l *is the iteration index.*

3. **Policy Improvement:** *The control policy u_k is updated as follows*

$$u_k^{l+1} = -R^{-1} B^T \bigtriangledown V(x_{k+1})^{l+1} \tag{6.20}$$

   where the gradient is defined as $\bigtriangledown V(x_{k+1}) = \frac{\partial V(x_{k+1})}{\partial x_{k+1}}$.

4. **Convergence:** *The above steps are repeated until $\|V(x_k)^{l+1} - V(x_k)^l\|$ converges.*

6.2.4 Actor-Critic Networks Implementation

The performance function (6.16) is now approximated by a critic network and the control policy (6.19) is approximated by an actor network. Let $W_c \in \mathbb{R}^{n\times n}$ and $W_a \in \mathbb{R}^{n\times m}$ are the critic and actor weights respectively. Therefore, the performance function and control policy approximations can be written as follows

$$\hat{V}_k(W_c) = x_k^T W_c^T x_k \tag{6.21}$$

$$\hat{u}_k(W_a) = W_a^T x_k \tag{6.22}$$

Hence, the network approximation error of the actor is given as

$$\zeta_{u_k}^{V(x_k)} = \hat{u}_k(W_a) - u_k \tag{6.23}$$

the control policy in (6.20) is given in terms of critic network such that

$$u_k = -R^{-1}B^T \ \nabla\hat{V}(x_{k+1}) \tag{6.24}$$

On expressing this target control in terms of critic weights, one obtains

$$u_k = -R^{-1}B^T W_c^T x_k \tag{6.25}$$

The squared approximation error is given by $\frac{1}{2}(\zeta_{u_k}^{V(x_k)})^T\zeta_{u_k}^{V(x_k)}$, the change in the actor weights is given by the gradient descent method. Therefore, the actor update rule is given as follows

$$W_a^{(l+1)T} = W_a^{lT} - \lambda_a[(W_a^{lT}x_k - u_k^l)(x_k)^T] \tag{6.26}$$

Where $0 < \lambda_a < 1$ is the actor learning rate.

Let $\psi_{x_k}^{V(x_k)}$ be the target value of critic network and value update is given by (6.19), therefore we have

$$\psi_{x_k}^{V(x_k)} = \frac{1}{2}[(x_k^T Q x_k + u_k^{lT} R u_k^l)] + V^l(x_{k+1}) \tag{6.27}$$

The network approximation error of the critic is $\zeta_{x_k}^{V(x_k)} = \psi_{x_k}^{V(x_k)} - \hat{V}_k(W_c)$

Similarly, the squared approximation error is given by $\frac{1}{2}(\zeta_{x_k}^{V(x_k)})^T \zeta_{x_k}^{V(x_k)}$, the change in the critic weights is given by gradient descent method. Therefore, critic update rule is given as follows

$$W_c^{(l+1)T} = W_c^{lT} - \lambda_c[\psi_{x_k}^{V(x_k)} - x_k^T W_c^{lT} x_k] x_k x_k^T \tag{6.28}$$

where $0 < \lambda_c < 1$ is the critic learning rate.

6.3 Simulation Results

6.3.1 Actor-Critic Offline Implementation

Algorithm 2 presented in this section is used for solving the microgrid control problem by tuning of actor-critic networks. Partial knowledge of the dynamics is required. Only matrix B is needed. In this algorithm, random initial states are used to guarantee sufficient exploration in computing the weights of actor and critic.

Algorithm 2 (Actor-Critic Implementation of Algorithm 1)

1. *The weights of actor W_a and critic W_c are initialized randomly. Initializing $W_a = I_{4\times4}$ and $W_c = rand_{1\times4}$.*

2. ***Loop-1*** *The loop-1 begins with q as iteration index.*

   Start with random initial values for the system state i.e., initializing $x_0 = rand_{4\times1}$.

   Loop-2

   (a) *The iteration loop begins with l as iteration index*
   (b) *The control policy $\hat{u}_k^l$ is evaluated using equation (6.22)*
   (c) *The dynamics of the system x_{k+1}^l as evaluated using (6.15)*
   (d) *The performance measure $\hat{V}_{k+1}^l$ is calculated using equation (6.21)*
   (e) *The critic network is updated based on equation (6.28)*
   (f) *The actor network is updated based on equation (6.26)*
   (g) *On convergence of the actor-critic weights end loop-2*

3. *Calculating the difference $\hat{V}(x_k)^{l+1} - \hat{V}(x_k)^l$*

4. *On convergence of $\|\hat{V}(x_k)^{l+1} - \hat{V}(x_k)^l\|$ end loop-2.*

   Transfer the actor-critic weights to the next iterations i.e., q+1 *as initialization for the next iteration. End loop-1*

The learning rates are taken as $\lambda_a = 0.01, \lambda_c = 0.01$ and the weighting matrices are selected as $Q = 10I_{4\times4}, R = I$. Fig (6.3) - (6.5) illustrates the simulation results of **Algorithm 2**. Fig (6.3) and (6.4) represents the tuning of actor weights and critic weights respectively. There are 4 weights for the actor and 16 weights for the critic. Some of the critic weights are overlapping with each other. Fig (6.5) shows the error dynamics of the system.

It can be seen that approximately after 100 iteration steps the weights of actor and critic converges and error dynamics is also seen to be going towards zero, thereby finding the optimal control policy u_k. This control is fed back to the system by actor. Fig (6.6) shows the response of all four states when subjected to the generated control signal. At $t = 0.2$ seconds, a pulse disturbance is introduced in the system states. By observing the figure, it can be concluded that the offline algorithm yields stability and proves the synchronization of the weights.

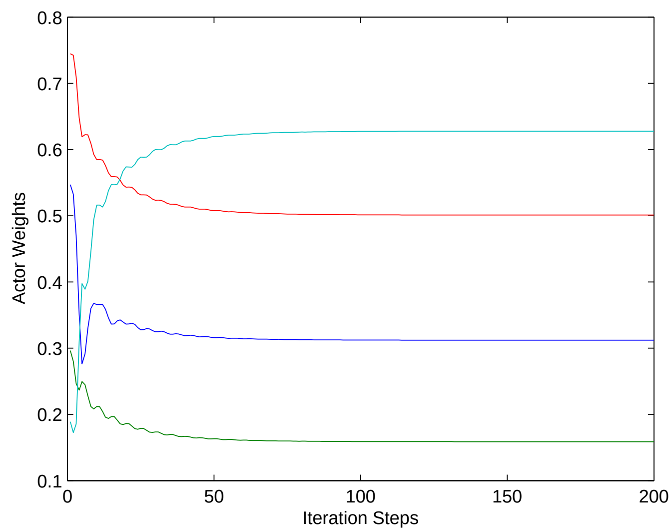

Figure 6.3: Actor weights update during iterations

6.3.2 Actor-Critic Online Implementation

The following **algorithm 3** is used for solving the microgrid control problem by *online* tuning of actor-critic networks. In this algorithm, we start with given

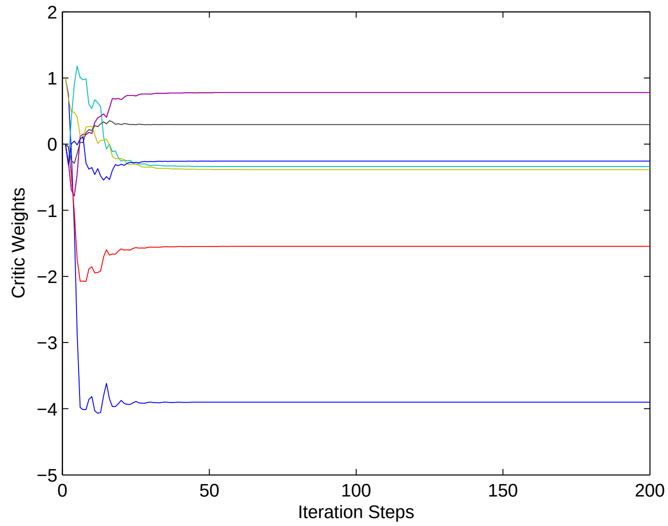

Figure 6.4: Critic weights update during iterations

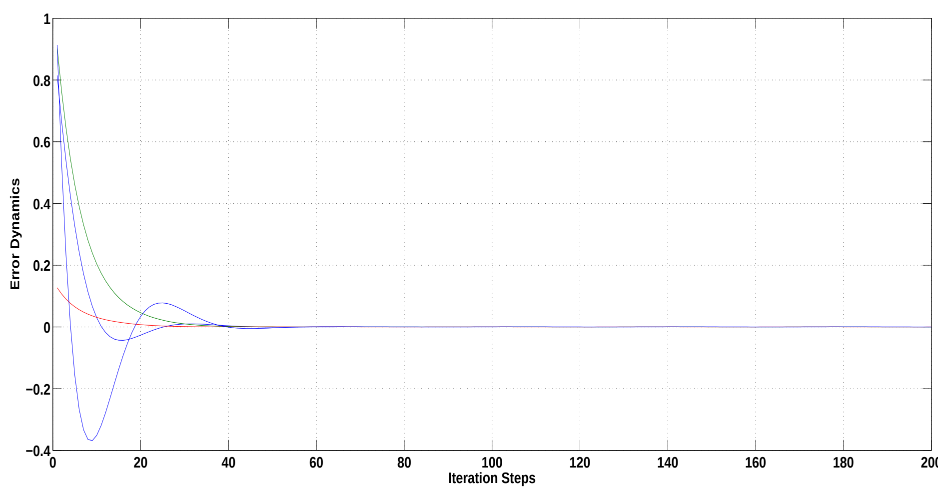

Figure 6.5: Error dynamics during iterations

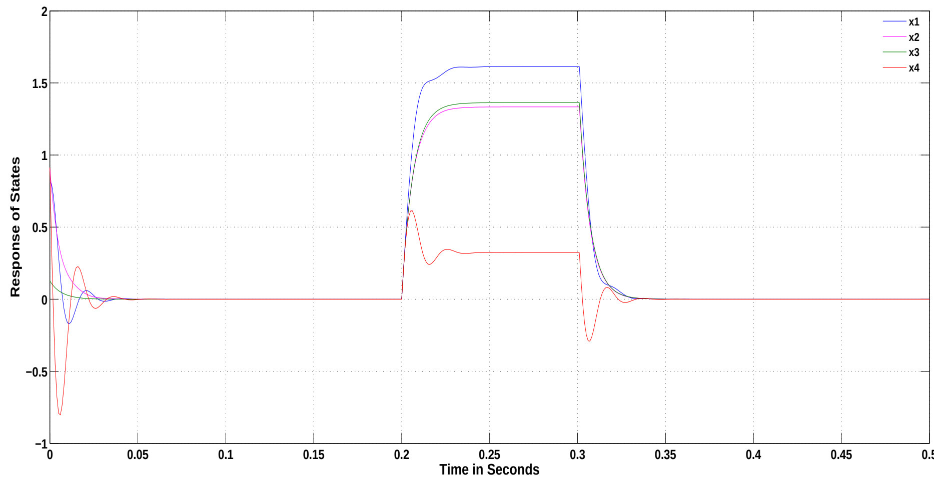

Figure 6.6: Response of the system states

initial conditions for the system states. The algorithm makes use of real-time data measured along the system trajectories and tunes the actor-critic structure to generate the suitable control policy.

The parameters for the online algorithm were chosen as $\lambda_a = 0.2, \lambda_c = 0.2, Q = I_{4\times 4}, R = I$. Fig 6.7 describes the simulink structure for implementation of algorithm-3 for the system. The control generated is fed online to the system, at time $t =$ seconds a a pulse disturbance is introduced in the system states. Fig (6.8) - (6.10) represents the tuning of actor weights, tuning of critic weights and error dynamics respectively. Fig (6.11) shows the response of all four states By observing the figure, it can be concluded that the online algorithm too yields stability and proves the synchronization of the weights.

Algorithm 3 (Actor-Critic Online Implementation of Algorithm 1)

1. *The weights of actor* W_a *and critic* W_c *are initialized randomly. Initializing* $W_a = I_{4\times 4}$ *and* $W_c = rand_{1\times 4}$.

   Loop Iterations Begins

   (a) *The iteration loop begins with* l *as iteration index*

   (b) *Start with given initial values for the system state.*

   (c) *The control policy* $\hat{u}_k^l$ *is evaluated using equation (6.22)*

   (d) *The dynamics of the system* x_{k+1}^l *as evaluated using (??)*

   (e) *The performance measure* $\hat{V}_{k+1}^l$ *is calculated using equation (6.21)*

   (f) *The critic network is updated based on equation (6.28)*

   (g) *The actor network is updated based on equation (6.26)*

2. *Calculating the difference* $\hat{V}(x_k)^{l+1} - \hat{V}(x_k)^l$

3. *On convergence of* $\|\hat{V}(x_k)^{l+1} - \hat{V}(x_k)^l\|$ *end loop-2.*

6.4 Performance Evaluation of Proposed Controller

The microgrid system described in fig (6.1) is simulated using SimPowerSystems library in the MATLAB/Simulink. Fig (6.12) shows the Simulink implementation of microgrid system. An IGBT inverter is used as converter and the Simulink model is built using Table I. A parallel RLC load is supplied by both utility grid and DG unit. Two simulation cases are considered. First, the microgrid is isolated from the grid and operated in the islanded mode. Second, the microgrid starts to operate in islanded mode, a load disturbance is included to observe the behavior of system. Both cases are carried out independently.

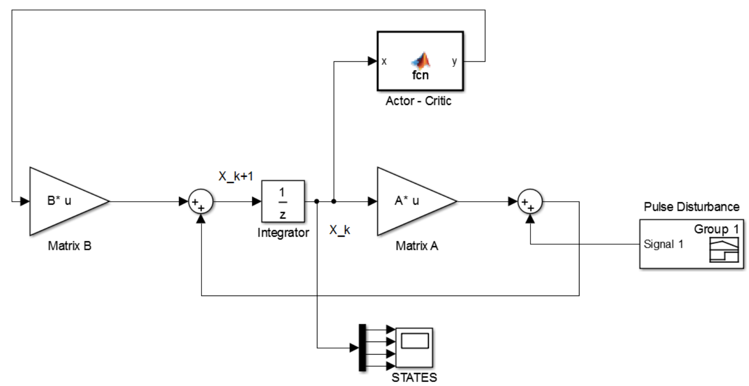

Figure 6.7: Simulink blocks for algorithm-3 implementation

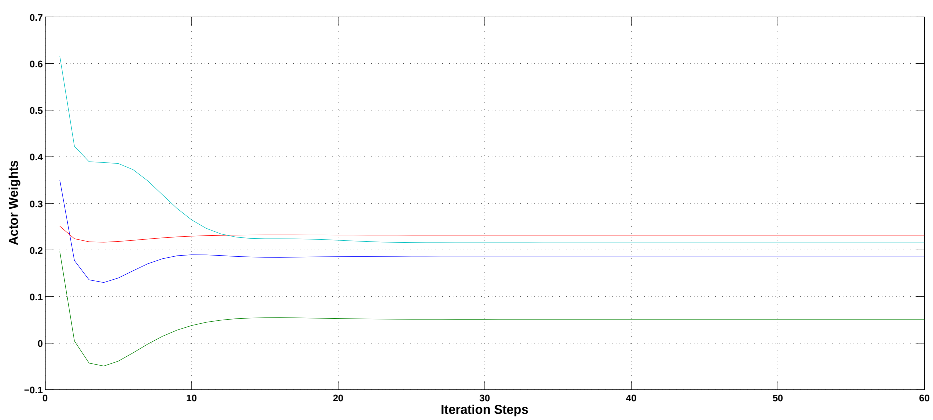

Figure 6.8: Actor weights

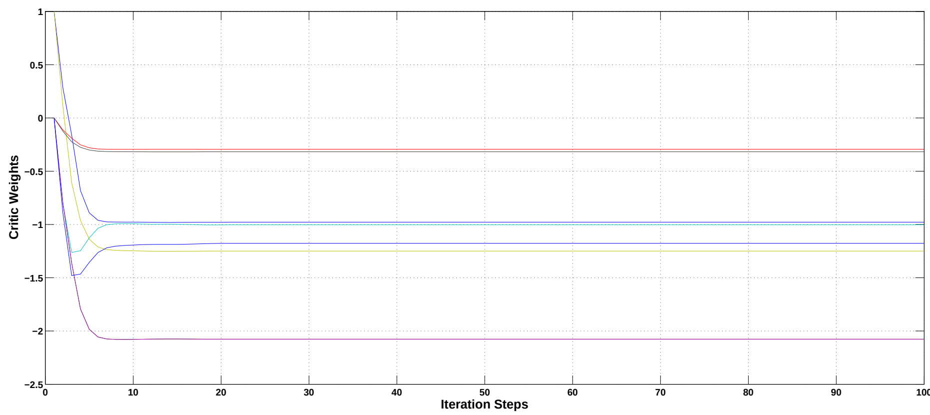

Figure 6.9: Critic weights

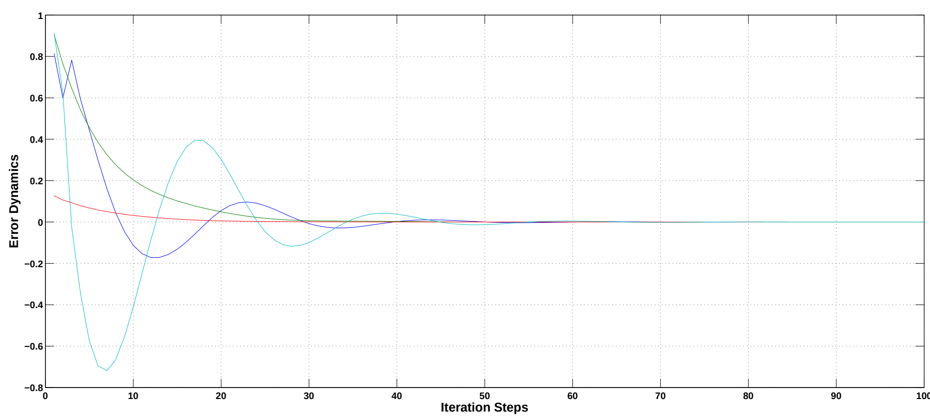

Figure 6.10: Error dynamics

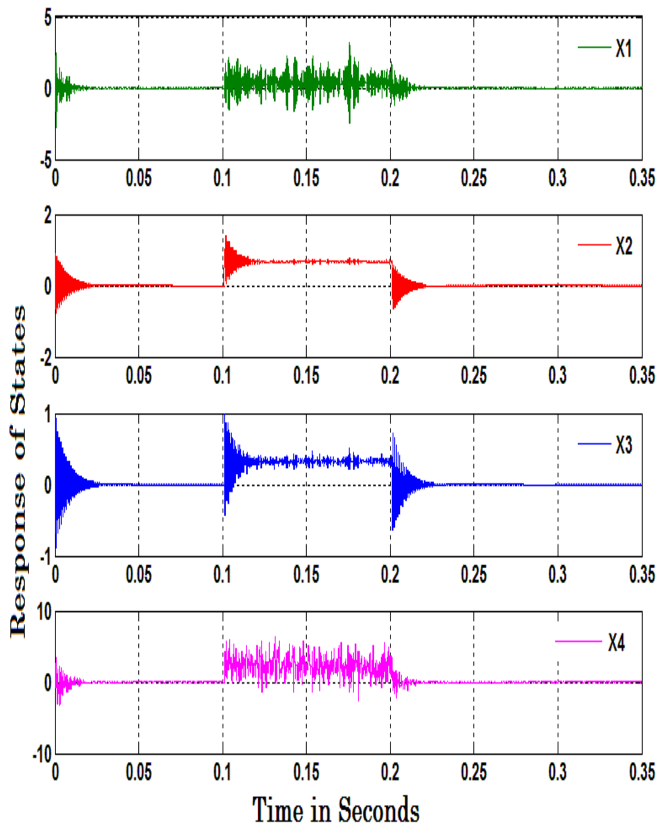

Figure 6.11: Response of the system states

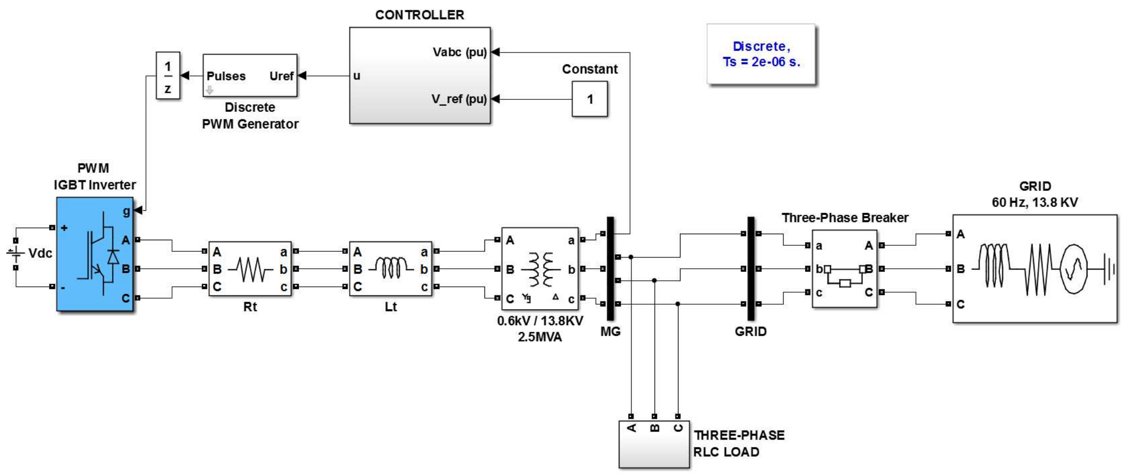

Figure 6.12: Simulink implementation of an autonomous microgrid

To evaluate the performance of controller, at $t = 0.2$ seconds, the circuit breaker (CB) is opened and at the same time, the control strategy is changed from conventional i_d/i_q [27] control to the proposed RL based control. The control policy u_k generated by the **Algorithm-2** is fed to gating signal generator. Fig (6.13) shows the instantaneous three-phase voltage at point of common coupling (V_{pcc}) and control effort. It has be noted here that the scale of V_{pcc} and control effort are not the same. The units of V_{pcc} is in p.u. scale with 13.8 KV as base value and the units of control effort are in normal volts scale. At $t = 0.2$ seconds transients can be seen due to disconnection of the grid from the network. The voltage at PCC is brought back to desired reference value of 1 p.u.

The system is now completely isolated from the grid. The microgrid is supplying the load on its own control structure and is said to be operating in autonomous mode. Now, another set of experiment is carried out on the system. To verify the robustness of proposed controller, the system is subjected to disturbance in the

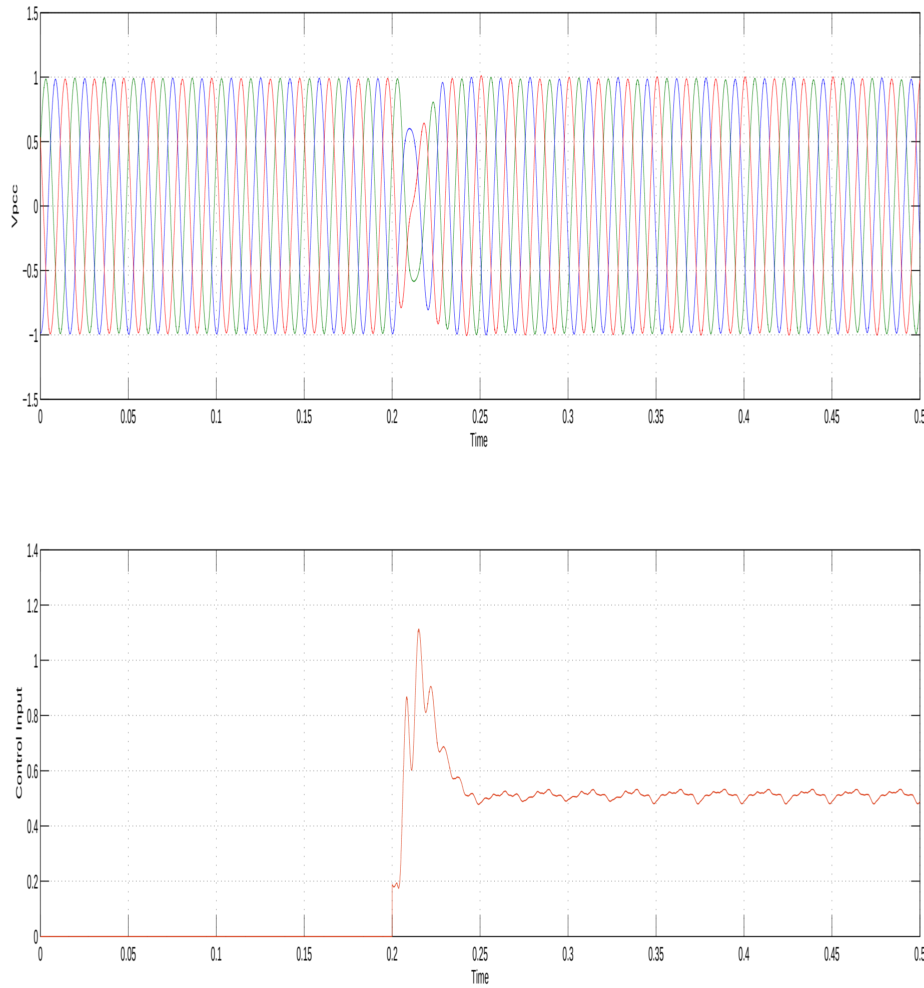

Figure 6.13: Dynamic response of system under islanding

load. An additional parallel RLC load of $R = 42.8\Omega, L = 0.2119H, C = 10\mu F$ is added to the local load at $t = 0.4$. Fig (6.14) shows the instantaneous three-phase voltage at PCC and control effort of the proposed scheme. Again the scale of V_{pcc} is p.u. and control effort is volts. Transients can be seen in load voltage at $t = 0.2$ seconds due to change in load parameters. Within few cycles, the load voltage is maintained at desired reference value of 1 p.u. by the proposed scheme.

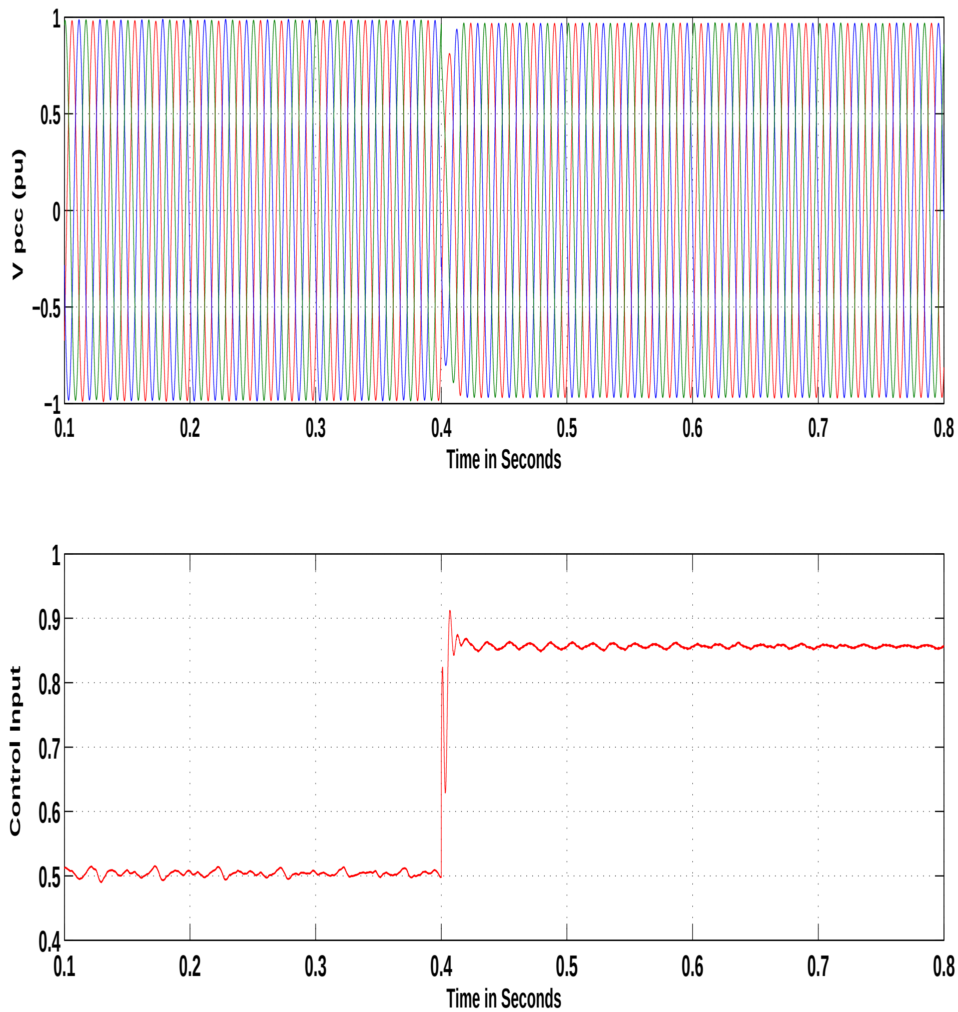

Figure 6.14: Dynamic response of system under load disturbance

Chapter 7

Conclusion and Future Work

To sum up the work presented in the thesis, we have provided novel control techniques for the stable operation of microgrid system. In chapter 1 and 2, the role of Microgrid in penetration of DG's in the present utility network is discussed. The most recent developments in the modeling of microgrid are presented in both grid-connected and autonomous mode. The control techniques of microgrid available in literature for various modes of operation are also discussed. The microgrid can be viewed as a special case of SoS. It can be concluded that using networked control system, a better control of microgrid can be obtained.

In chapter 3 and 4, dynamic model of microgrid system is presented. A neural-network-based distributed secondary control scheme for an autonomous smart microgrid system has been proposed. In this scheme, the controller is designed to act dynamically to load changes and the associated optimized gains have been evaluated using differential evolution optimization procedure. Performance comparison between the proposed controller with traditional fixed-gain controller is also shown. The controller performance when subjected to time varying load is also summarized. The ensuing results have emphasized that the proposed controller has been able to restore the output voltage and frequency to their nominal values, by eliminating the transients, whenever there is a change in load. Proper load sharing among the generating units have been also achieved. The simulation results shows that the proposed controller is much faster with greater adaptability and robustness when operating point changes and therefore ensures superior performance when compared to traditional one.

In the next part, chapter 5 describes the real-time implementation of multi-level distributed control for autonomous microgrid system using RTDS platform. The effectiveness of the model and controller is demonstrated with the help of experimental results in RTDS compared with the simulated results in MATLAB. Additionally, fault analysis with respect to load sharing aspect of the controller is also displayed. The proposed controller dynamically regulates the output voltage and frequency during load changes to their nominal values. Results verify the controller to be reliable and robust.

In the last part, chapter 6, reinforcement learning technique for the control of autonomous microgrid based heuristic dynamic programming is proposed. The strategy is based on value iteration algorithm and is implemented using actor-critic networks. Based on this structure, both offline and online learning algorithms are developed to solve the Bellman equation. From the simulation results, it is evident that the converging weights of actor-critic stabilizes the system and regulates the output voltage to nominal value. The proposed control strategy is also robust against any disturbances in the states and load.

There is vast scope for research in the field of microgrid. The work carried out in this thesis has a great potential to be expanded in several directions. Following subjects are suggested for the future study

1. The work in this thesis addresses autonomous operation of microgrid. Studies can be carried out for various control problems related to grid-connected mode of microgrid.

2. The DC voltage of inverter in microgrid model is assumed to be constant. In practice, the dc coming from energy source might contain fluctuations. Microgrid model with variable DC source can be considered for the control problem.

3. Different optimization techniques other differential evolution and different performance index other than ITSE can be used to check the effectiveness of the controller.

4. The communication network at the secondary control level is assumed to be ideal. A research can also be performed by considering communication delays in network.

5. Other forms of reinforcement learning such as Dual Heuristic Dynamic Programming (DHP), Action-Dependent HDP (ADHDP) and Action-Dependent

Dual HDP (ADDHP) can also be taken into consideration for the design of controller

Chapter 8

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Vitae

- Name: Syed Azher Hussain
- Nationality: Indian
- Date of Birth: 13 July 1987
- Email: *hussain.syedazher@gmail.com*
- Permenant Address: Hyderabad, India

- Received Bachelor of Engineering (BE) degree in Electrical & Electronics Engineering from Osmania University in 2009.
- Joined King Fahd University of Petroleum and Minerals in January 2012 in Systems Engineering Department (Automation and Control).
- Publications

1. M.S. Mahmoud, S. Azher Hussain, et al., "Modeling and control of microgrid: An overview", Journal of the Franklin Institute, Vol. 351, no. 5, pp. 28222859, 2014.
2. M.S. Mahmoud, S. Azher Hussain, Adaptive PI secondary control for smart autonomous microgrid systems, Int. J. Adapt. Control Signal Process, DOI: 10.1002/acs.2559.