Distributed Robust Optimal Control and Proportional Power Sharing of Distributed Generators in DC Microgrid

Submitted by:
Ali Arsalan 2016-MS-EE-57

Supervised by: Dr. Muhammad Tahir

Department of Electrical Engineering
University of Engineering and Technology
Lahore

Distributed Robust Optimal Control and Proportional Power Sharing of Distributed Generators in DC Microgrid

Submitted to the faculty of the Electrical Engineering Department
of the University of Engineering and Technology Lahore
in partial fulfillment of the requirements for the Degree of

Master of Science

in

Electrical Engineering.

Internal Examiner	External Examiner
Dean Faculty of Electrical Engineering	Chairman Electrical Engineering Department

Department of Electrical Engineering

University of Engineering and Technology
Lahore

Declaration

I, Ali Arsalan declare that the work contained in this thesis is my own, except where explicitly stated otherwise. In addition this work has not been submitted to obtain another degree or professional qualification.

Signed: ____________________
Date: ____________________

Acknowledgments

First of all, I am very thankful to Almighty Allah, the most Beneficent and the most merciful, who embraced me with opportunity, ability and courage that let me complete this research work. I would also like to appreciate and express my gratitude to my respectable supervisor, Dr. Muhammad Tahir (Associate Professor, UET, Lahore) for his support, encouragement, patience and sympathetic attitude. I will always miss the sincere cooperation, gentle company and pleasant attitude of my family and friends.

Dedicated to my beloved Family . . .

Contents

List of Figures

List of Tables

Abstract

Integration of DC Nanogrids (NGs) with distributed generators (DGs) have seen an unprecedented growth for rural electrification. Stable and coordinated operation of these NGs needs to meet up many challenges such as interactive power sharing among NGs, distribution losses, economic dispatch (ED) and power transients. Various communication-less control schemes fall short to fulfill these challenges. In this paper, a multi-agent system (MAS) based coordinated control strategy is proposed to provide optimal resource sharing among NGs with minimized distribution losses, ED and an improved load/generation side power transient control for NGC. The system architecture presented in this research consists of a group of NGs/-households, which can operate independently as well as with the coordination of neighboring NGs with minimum distribution/line losses. Further, an optimization based ED problem provides a trade-off between DG power and power shared from neighboring NGs to meet up the load demand of each NG. An improved power transient control for ED problem is achieved by Augmented Lagrangian based proportional integral derivative (PID) controller. A multi-agent communication structure is utilized for distributed coordinated control of NGs. The efficiency of proposed model is validated by various case study scenarios using MATLAB. The results show that ED problem is solved for each NG, which result in an optimal resource sharing considering distribution losses and an improved power transient control in response to the power variations in load/generation side.

Chapter 1

Introduction

1.1 Introduction

Rural electrification is the process to electrify the rural/remote communities. According to a survey of World Energy Outlook (WEO) 2016, there are around 16% of entire world population which don't have access to electricity. Most of them are living in remote areas of Asia and Africa. So, one approach to provide electricity to these areas is through conventional AC grid. But this centralized approach is not economically a viable solution with many underlying challenges such as, synchronization problems, unwanted harmonics and reactive power. DC microgrids are mostly preferred in comparison to the previously described approach because it overcome most of the challenges incurred by conventional AC grid. Moreover, DC nature of new emerging loads, an efficient interconnection with energy storage devices and renewable energy sources, natural availability of solar power with no CO_2 emission have given an unprecedented growth to islanded DC microgrids in recent years. However, centralized architecture of these microgrids give rise to a major limitation of distribution losses, which becomes more significant for low distribution voltages and high power levels. As a result, this non-scalable and non-modular centralized approach is not a viable approach for future expansions. Moreover, such type of architectures also requires a large initial investment due to their centralized approach. However, in order to electrify these rural areas, various PV/battery based islanded distributed structures are proposed. Such distributed structures with bottom up sizing develop sustainability for a local consumer. Though the distributed architecture minimizes the high distribution losses incurred by centralized microgrid, but it makes the coordinated resource sharing a highly challenging task. To address this issue, an MAS based NG architecture with DGs is proposed in this paper. The interconnection of DG in each NG constitutes a self-sustainable islanded residential NGC. Further, an ED problem is formulated, which provides an optimal trade-off between DG power and power shared from neighboring NGs to fulfill the load demand. Power transfer among NGs is line losses dependent, i.e NG which offers less line resistance will share more power. Moreover, an Augmented Lagrangian based PID controller is proposed to overcome the power transients on load/generation side, which results in a better dynamic performance.

1.2 Organization of the Thesis

The rest of the thesis is outlined as follows: chapter 2 describes a detailed overview of conventional AC power system and emerging smart grid technologies. In chapter 3 distributed control and power managment among NGs is discussed. In chapter 4 proposed approach for power mangment among NGs is explained. Chapter 5 focuses on simulation results and analysis for two differnt NGs models. In the end, chapter 6 presents the conclusion and possible future developments and expansions in proposed solution approach.

Chapter 2

Traditional AC grids and Modern Microgrids

2.1 Conventional AC Power System

Power systems deals with the energy conversion from one form to other form in order to supply electricity to its consumers. Conventional AC power system comprises centralized generation point with large transmission lines, substations and distribution network. Power is produced by generation units through non renewable energy resources. Then the produced power is delivered all the way to each subscriber through transmission network.

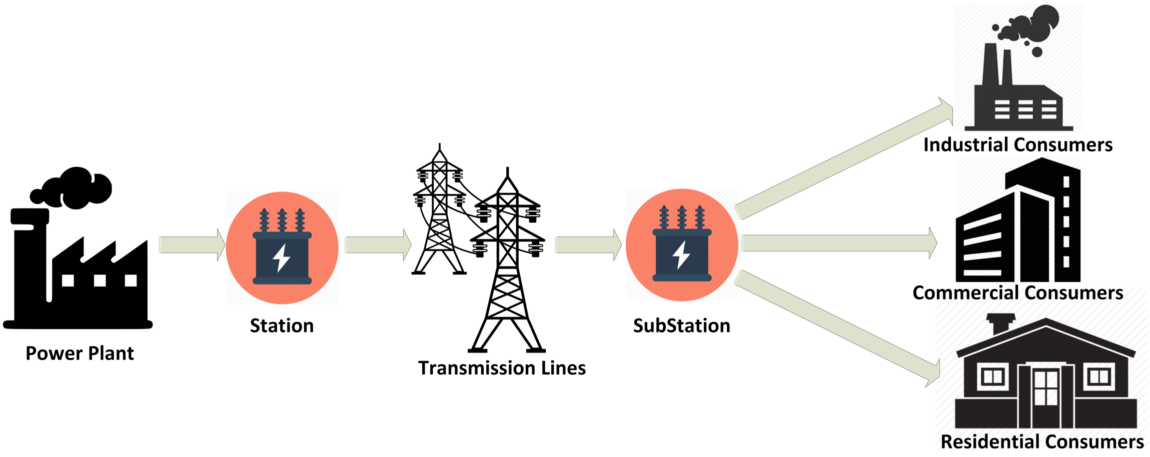


Figure 2.1: Conventional AC Power system Architecture

In this power system, generation units are placed far away from the end users and electric power is delivered all the way through transmission lines to each consumer. This centralized architecture with unidirectional pipeline provides electricity to all connected consumers. This ancient architecture face many reliability problems and is not a viable solution for modern power sector. With the rise in power requirement day by day, this power system is falling short to fulfill the power requirements. This traditional infrastructure is coming across various challenges and some of them are outlined as follow.

2.1.1 Aging Infrastructure

AC Power systems are filling up the load demands of industrial, commercial and residential consumers for over a century. In these AC grids, power produced by generating units is delivered to all consumers though large transmission lines, substations and distribution networks. These power systems with this huge infrastructure is not economically a viable solution. Further, it also requires a continuous maintenance which give rise to the running cost of AC grid. So, it is required to develop a new alternate technology that overcome these challenges.

2.1.2 Environmental Impact

Green house gases have a permanent and severe environmental effect on global scale. An extreme environmental changes are occurring due to greenhouse effect, which results in a rise in global temperature. According a survey almost 40 percent of carbon emission results in by power production through fossil fuels, used as a conventional resource in AC grids. Further, coal power plants are also making the environment un-breathable day by day. Due to these environmental concerns, it is needed to make some necessary modification in conventional AC power system. So, these environmental issues is one reason for an unprecedented growth towards renewable energy resources such as solar and wind. Further, smart grid technologies with renewable energy resources are helping the end users to fulfill their load demand more efficiently with zero carbon emission.

2.1.3 Natural Resource Depletion

These power systems mostly utilize fossil fuel as a conventional power generating resource. But due to the widespread of these natural energy resources in power plants, different transport and domestic system, these resources are becoming inadequate and insufficient day by day. Moreover, for agriculture sector fertilizers and pesticides industries also consume a huge amount of these natural resources.

As, economic sector is largely depending on these natural resources (fossil fuel) and their widespread use results in exponential increase in these natural resources depletion rate. So, it is necessary to take mandatory actions in order to overcome the predefined challenges in this conventional power system infrastructure.

2.1.4 Electricity Cost and Centralized Architecture

With the exponentially increase in load demand and natural resource depletion rate, electricity cost is increasing. This rise in electricity cost majorly contributed in modernization of conventional grid. Further, there are some rural areas which don't have access to electricity and provision of electricity to these areas require a large upfront cost. Moreover, Regulatory authorities have been focusing on the alternate approaches with more reasonable electricity prices. So, this result in a rise of renewable energy power systems, which help in to decrease the electricity prices and dependence on conventional grid as well.

Centralized architecture is another drawback of conventional grid. As in this power system, power is generated at a far away point and then delivered to end users through transmission and distribution network. This give rise to transmission losses at a large extent which result in the regulation authorities to increase the electricity cost. So, an alternate strategy in place of centralized architecture in needed, which is known as distributed generation. Where the overall central control is divided in a distributed manner with an inexpensive and more reasonable infrastructure.

2.2 Microgrid

Conventional power grid is revolutionized as a smart grid by introducing different computer and communication based technologies. A smart grid is a modern intelligent electrical grid based on bidirectional power and communication flow pipeline. This is a close loop system with digital machinery that fulfills the load demand of end users in a more profitable way. The smart grid involves the integration of various generation and load side control technologies as shown in figure 2.2 that give rise to the reliability of power system.

A smart grid is capable of following characteristics:

1) It stimulate the end users to contribute in grid operation.

2) It is self repairable.

3) It makes sure the provision of reliable ongoing power operation that minimize the power losses.

4) It has a better and efficient control.

Micro grid (MG) is defined as a localized small scale power station having its own distributed generation and storage energy sources with loads that are capable of operating individually or in parallel with the main grid. Smart MG also produce, transmit, distribute and adjust the power flow to utility just like the main power grid but manage it locally. Smart MG is the most perfect and reliable approach to integrate renewable energy resources locally at community level, which decrease the line losses as well. In these smart MGs, integration of distributed generation sources (DGs) with renewable energy resources is on rise to keep up the supply demand balance. Smart MGs with high numbers of DGs and renewable energy resources requires a communication infrastructure for continuous monitoring of supply and demand side. An inappropriate communication framework will result in information loss and potentially effect the MG performance. So, an appropriate communication structure is required for continuous monitoring and data sharing among generation and distribution points. For this purpose, different communication based control strategies are proposed, which result in a continuous and reliable operation of MG. Further, for rural electrification coordinated power sharing is achieved among different households using an efficient communication network in order to fulfill the supply demand mismatch.

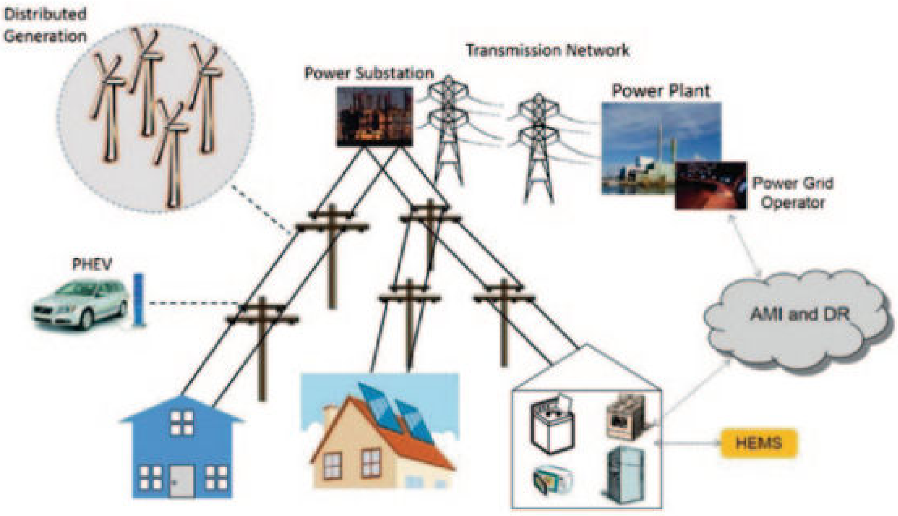


Figure 2.2: Smart Grid System Architecture

2.2.1 Smart Grid MG Technologies

2.2.1.1 Renewable Energy Generation

To overcome the severe effects of fossil fuel usage in power sector, human being have been trying to find an alternate approach for over a century. This results in the usage of wind, sunlight and tides in smart grid MGs, which efficiently reduced the use of fossil fuel. From all of these natural resources, solar power systems are becoming more and more famous. Solar power systems have been very successful in most of rural areas of Asia due to large availability of sun light, with zero running cost and no co_2 emission. So, in this way the end user is now independent from the main grid by fulfilling its power requirements using solar power systems locally.

To promote this concept government bodies are offering special incentives on this new technology installation. In this modern grid, a consumer can sell back the excess power to the grid. So, in this way these modern power systems have tremendously reduced the load demand of main grid by giving sustainability to local users.

2.2.1.2 Demand Response

Demand response is an important feature of smart grid, which requires a bidirectional communication network among power suppliers and end users. Through continuous monitoring, it allows a collective power management among supplier and consumers through coordinated power sharing. Through this technology, consumers will be able to optimize their power usage. By shifting their load from peak hours to non peak hours, consumer will be able to reduce the stress on peak hours in order to have extra incentives and to reduce electricity bills [7]. So, this result in a collective efforts for power management. This is the technique, which helps the utilities to get familiarize with their daily power usage pattern, electricity prices in peak/non peak hours and allow them to adjust the load demand for an optimized power usage pattern.

2.2.1.3 Net Metering Infrastructure

The net metering [13] is another important feature of smart grid. Through net metering technique, consumers can monitor their real time power usage using energy meters. These energy meters are a very important part of this future grid, that gives certain information to its users and help them to optimize their business actions in a more profitable way.

2.2.1.4 Energy Management System

A single household contains different electrical appliances that requires a significant amount of power for daily operation. Energy management system is computer technology based system in a smart grid, which manage the power usage of electrical appliances according to the information obtained from generation and load side through a communication network. The main feature of this system is to maximize the users benefits with minimum possible generation cost in an optimized way. This vital feature of modern grid is known as Energy Management Systems (EMS) [14]. EMS helps the consumers to reschedule the daily power consumption in order to minimize utility bills.

2.2.2 Microgrid Operation Modes

Microgrids can operates in two different modes as grid-connected mode and islanded mode. In grid-connected mode, microgrid is connected with the main grid and allows the bidirectional flow of power depending upon the load demand of end user. While in case of islanded mode, microgrid works independently with no connection to the main grid. In this approach, consumers achieve sustainability locally and don't depend on the main grid to fulfill their load demand. This approach is mostly preferred in remote/rural areas, due to its modular and scalable nature. Different control objectives for grid-connected and islanded microgrid can be summarized as:
1) Voltage and frequency regulation in both operating modes of microgrid.
2) The coordinated power sharing among DGs according to load demand.
3) To Re-synchronize the microgrid and main grid.
4) To control the bidirectional power flow between microgrid and main grid.
5) Optimizing the operation cost of microgrid.

These control objectives requires a three layered (primary, secondary and tertiary) hierarchical control. The primary layer preserve the voltage and frequency stability as well as the power sharing among DERs in MG. The secondary control handles the voltage and frequency variations produced because of primary control. The tertiary control includes the economic dispatch problem with multi-objective optimization. Further, there are some key benefits of microgrid considering a real time EMS. First, EMS allows the microgrid to operate in either grid connected mode or in islanded mode. Second, it controls the power sharing among DERs to fulfill the load demand using the forecasted information and in this way it can readjust the non critical loads. Third, it regulate the voltage and frequency variations. Fourth, it optimize the operation of MG in such a way that it operates at minimum economic cost will maximum output power.

Microgrids can be categorized as AC and DC microgrids. power electronics interface (PEI) are an essential part of microgrids. In case of AC MG, PEI is responsible to give output power to the system and ensuring nominal voltage and frequency at the output. But in DC MG, PEI is used to control the DC bus voltage. Specifically, control scheme of AC MG ensure an appropriate system frequency, AC bus voltage stability with real and reactive power sharing among DERs. In case of DC MG, control levels are responsible for DC bus voltage stability and real power sharing among DERs with no reactive power. The comparison between AC and DC microgrid is given in Table 2.1.

TABLE 2.1: Difference between AC and DC Microgrid

Sr. No.	AC Microgrid	DC Microgrid
1.	Real and Reactive power	Real power
2.	Voltage and frequency monitoring	Voltage monitoring
3.	Large line resistance with skin effect	Small line resistance with no skin effect
4.	Reactance in transmission line	No Reactance in transmission lines
5.	Large transmission losses	Small transmission losses
6.	Magnitude and phase analysis exist	Only magnitude analysis exist

2.3 DC Microgrid

Alot of efforts have been put towards AC microgrid. However, there are multiple issues in AC microgrid that is making it less competitive as compared to DC microgrid. Islanded DC microgrid provides several advantages including an efficient interconnection with energy storage system as well as renewable energy sources. Moreover, most of the consumer loads are DC in nature, even traditional AC loads such as induction motor also act as DC load when operated by drives [24]. Furthermore, DC distribution network can also eliminate many of the disadvantages of conventional AC grid such as unwanted harmonics, reactive power and synchronization problems [4]. Therefore, low initial investment, advancements in power converter technologies and PV/battery systems have given an unprecedented growth to islanded microgrid approach [38]. In addition, islanded microgrids are also preferred due to natural availability of solar power in remote areas, better efficiency as compared to AC, environment friendly with no CO_2 emission, reduction of power loss in AC/DC inter-conversion stages and gradually decreasing prices of PV and battery energy storage system (BESS) [19, 22, 30]. However, centralized architecture of these microgrids give rise to a major limitation of distribution losses, which becomes more significant for low distribution voltages and high power levels. As a result, this non-scalable and non-modular centralized approach is not a viable approach for future expansions[31]. Moreover, such type of architectures also requires a large initial investment due to their centralized approach[11].

Further, coupling of DERs in microgrid cause an unexpected power circulation in DC microgrid. This result in the deviations of DC bus voltage, which leads to system instability. So, the most challenging task in DC microgrid is optimal power sharing among DERs. The basic architecture of DC microgrid consist of a DC distribution network, DERs, PEI and distribution loads having following characteristics:

-DC distribution network: A distribution feeder consist of a point of common coupling for possible grid connected or islanded mode.

-DERs: It includes diesel generators and renewable energy resources such as solar system, wind turbine and energy storage system including batteries, fuel cells and super capacitors.

-PEI: DC microgrid mostly involve DC/DC converters for DC sources and loads, rectifiers and inverters for AC sources and loads.

-Distribution loads: Distribution loads includes both AC and DC loads.

2.3.1 DC Nanogrid for Rural Electrification

A nanogrid (NG) is a small-scale configuration of PV and battery, which is a suitable solution for a single household/building. It can easily be connected or disconnected from other NGs through a DC bus gateway [6]. For rural and remote areas electrification, main grid is not a feasible solution due to the requirement of its large infrastructure. Therefore, due to the modular and scalable nature of DC NG, it is always preferred for rural electrification. In this approach, each household act as a NG and multiple households are connected with each other through a DC bus. This result in sustainability of this approach by optimal power sharing among NGs. Though the distributed architecture of NGs minimizes the high distribution losses incurred by centralized architecture, but it makes the coordinated resource sharing a highly challenging task. Therefore, a well defined control scheme is required for optimal operation of nanogrid cluster (NGC).

Chapter 3

DC Microgrid Control Architectures

3.1 Introduction

To fulfill the control objectives of DC microgrid, a sophisticated and efficient control scheme is required. The main challenging task in a NGC is optimal power sharing among operating devices. These control objectives can be achieved by three basic control architectures, including centralized, decentralized and distributed control architectures. These control schemes are implemented using controller with specific control algorithm, so that the overall system can meet the control objectives. Control strategies vary from linear control such as proportional integral (PI) control, linear quadratic control (LQR) to non-linear control such as adaptive or hysterics controllers.

3.1.1 Centralized Control Architecture

Centralized control is also know as centralized hierarchical control[12, 21, 36]. This control architecture is a two layered control scheme, including local control and central control. The basic architecture of centralized control is shown in figure 3.1. The local controllers on source and load side are responsible to apply droop control. The central controller will manage the bus voltage stability along with economic dispatch (ED). The central controller receives information from local controllers on both load and source side through a communication link. Then according to a power management strategy, operational commands are given back to local controllers for, such as voltage and ED information on source side along with

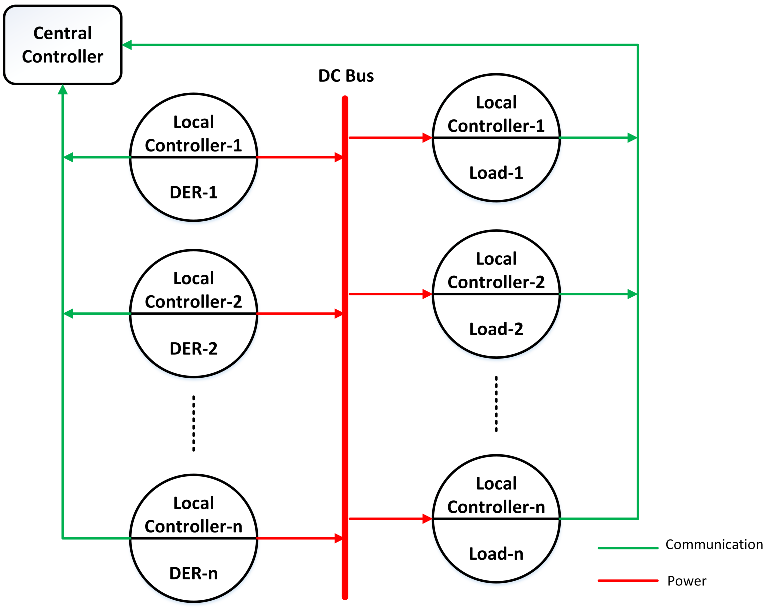


FIGURE 3.1: Centralized Control Architecture

shedding information on load side. The DERs local controllers, manage the voltage stability and current control through PEI, according to the commands of central controller. Similarly, controllable loads execute the load shedding commands received from central controller according to its power management strategy. The advantage of centralized control is that all the DERs and loads can be controlled through a single point, so it offers simplicity in control and maintenance. But this a non-scalable approach because of its non-modular nature. However, this central architecture face many problems due to the need of large number of control cables and sensors. There is also a huge computational load on central controller to implement power management strategy on real time. Further, this approach has low reliability because a small error in sensor or control information will result in system instability.

3.1.2 Decentralized Control Architecture

This is a control architecture, which require very little or no communication as shown in figure 3.2. In this control scheme, each source and load controller fulfill its own objective locally instead of global scale[17, 20, 37]. Fundamentally, each controller with DER perform its operation independently within a specific voltage levels by applying droop control. The voltage variations are proportional to the droop resistance, large value of droop resistance leads to large voltage variations,

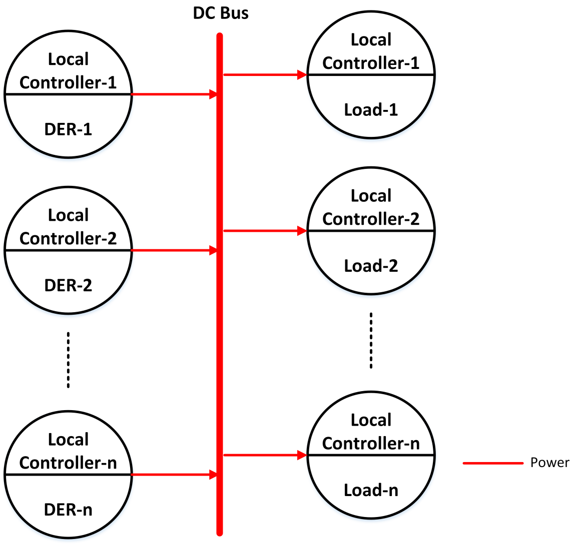


FIGURE 3.2: Decentralized Control Architecture

which result in systems instability. This also cause an additional effect of unwanted current circulation among DERs.

The disadvantage of uneven power sharing among DERs is mainly due to following two reasons[2]:

1) Each DER has it own dynamic characteristics and its relevant controller works according to those characteristics. further, droop resistance is kept very low to have less voltage deviations. This create a difference in output voltage levels of DERs and result in a non-proportional power sharing among DERs.

2)The distributed loads connected in DC microgrid have plug-n-play characteristics. Further, the equivalents impedance of DERs is unpredictable and it changes every-time when a distributed load is either turned on or off. This issue is managed by increasing the droop resistance but it also create a drawback of voltage deviations. So, droop resistance is kept very low, which may result in an unequal power sharing among DERs.

This control scheme has low cost requirements and low complexity level, as there is a need of very little communication or no communication network. However, this is not an effective scheme for voltage stability and equal power sharing. Therefore, the overall system efficiency is not up to the mark for this control scheme.

3.1.3 Distributed Control Architecture

As discussed before, centralized control scheme is avioded due to its complicated and costly infrastructure along with large computational load on central controller. Moreover, decentralized control is incurred with voltage deviations and unproportional power sharing. However, distritributed control reduce the computational load on central controller as well as improve system performacne in term of power sharing and bus voltage stability. Moreover, it also give shedding commands to distributed loads to meet system performance threshold. A distributed control scheme can provide following benfits to a multiagent system (MAS).

1) distributed control provide an independent control to each distributed source and load, which result in an improved reliability of the power system.

2) Distributed controllers can exchange information among themself, which allows them to produce a gobal solution for overall power system.

A basic distributed control scheme architecture is shown in figure 3.3. It includes an extra secondary control layer for each distributed load and source, this secondary layer is responsible for system stability. This control scheme has been extensively investigated for DC microgrids. A distributed control strategy is presented in [2], where distributed Proportional integral (PI) controllers share sources current information using a communication network to find an average value of

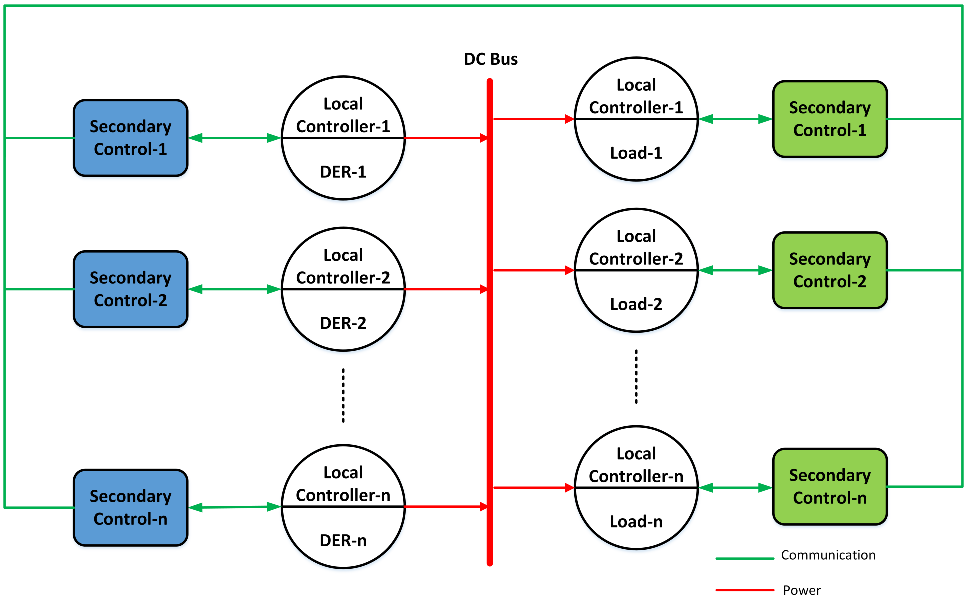


FIGURE 3.3: Decentralized Control Architecture

source current, which compensate the mismatch between DC-DC converters output voltage. Authors in [28]proposed a distributed secondary layer, which includes average voltage and current controller. Primary layer implements the droop control and average current and voltage information are shared between the two controllers through a communication link. These control schemes have proved their capabilities through experimental results, however, in case of power disturbances on load and source may effect system dynamics. So, an optimal control method is required that can make it up to these challenges.

3.2 Control Architectures Review

For rural electrification, Mashood et al. in [32] proposed a droop control scheme focusing on resource sharing. The control algorithm in [32] is perturbation dependent, a small perturbation in duty cycle will make the system dynamics slow and large perturbations will lead to instability. Moreover, Xiaonan et al. in [29] present a dual loop adaptive droop control scheme based on battery state of charge (SoC) balancing. The proposed control scheme considers the resource sharing in proportion to SoC of battery during discharging mode but this doesn't apply during charging. So, it results in the charging of all batteries with same power independent of their resource availability and SoC.

Further, Zheming et al. in [16] present a comparison between V-I and I-V droop control, where V-I dynamic response is slower as compared to I-V droop control. Moreover, a two level bus DC microgrid architecture based on droop control with DC-DC buck/boost bidirectional converter is proposed in [34, 39] for power sharing. The bidirectional converter operation mode is selected from DC bus voltage variations and SoC of battery. In addition, the conventional droop control leads to a trade off between voltage regulation and load sharing with slow dynamic response [35]. These are multiple communication less droop control schemes which fall short to obtain optimal resource sharing. Mashood et al. in [33] proposed an adaptive I-V droop control for coordinated resource sharing among contributing households in Nanogrid Cluster (NGC), where the line resistance among households leads to distribution losses. A NG is a small-scale configuration of PV and battery, which is a suitable solution for a single household/building. It can easily be connected or disconnected from other NGs through a DC bus gateway [6].

At the end, there are also some communication based control architectures to address the above mentioned challenges. For example, Nian Liu et al. in [26] proposed a hybrid peer-to-peer power sharing framework based on Lyapunov optimization. This presented work utilizes a central controller for communication among NGs, failure in that central controller will lead to the whole system blackout. Moreover, a communication based power management algorithm for a single building is presented in [18], where each room appliance is connected to a room controller through a power switch, which further lead to a central controller. This will increase the complexity of communication structure as well as the uncomfortable level of end users. Saeed et al. in [27] propose a distributed secondary control with a low bandwidth communication framework. The proposed solution utilizes a droop gain for voltage/current regulation and higher value of droop gain will result in instability in the system [9]. All of the above mentioned solution approaches do not provide the optimal power sharing with minimized line losses among NGs. Arsalan et al in [3] proposed a power management distributed control scheme for rural electrification. This presented solution provides optimal power sharing among NGs with ED and minimized distribution losses.

3.3 Multi-Agent Based System Architecture

MAS based distributed control is an extensively employed technique, as discussed in literature [23]. MAS framework has also been discussed for distributed optimization [41]in microgrids along with active/reactive power controlling [23]. Further, coordinated operation of DGs for better dynamic control in microgrid can be implemented by MAS based architecture [10]. In this MAS scheme, DGs exchange information of system status and control vectors each other act as an communication agents, which result in an optimized operation of microgrid. The coordination between DG agents is done based on communication protocols [40]. Moreover, a secondary control layer based distributed scheme is proposed using a MAS structure in [5]. In [15],a MAS based framework is proposed for DC distributed resources in a microgrid. A hierarchical control based technique is proposed in [8] using a MAS framework, which compensate the inaccuracy of reactive power sharing among DGs. Jameel et al. in [1] proposed an ED problem with improved dynamic performance utilizing augmented Lagrangian based PID control and multi-agent communication structure. Further, a multi-agent coordination via wireless network is also a promising solution to avoid single point failure and provides a low deployment cost [25].

Chapter 4

Proposed Approach

4.1 Problem Statement

There is around 16% of global population living without electricity and 95% of them are the residents of sub-Saharan Africa and developing countries of Asia, according to a survey of WEO 2016. To electrify these rural areas via conventional AC grid having a centralized control, large transmission lines, substations and distribution network is not economically a viable solution. Whereas, in comparison to AC grid, islanded DC microgrid provides several advantages including an efficient interconnection with energy storage system as well as renewable energy sources. Furthermore, DC distribution network can also eliminate many of the disadvantages of conventional AC grid such as unwanted harmonics, reactive power and synchronization problems. Therefore, low initial investment, advancements in power converter technologies and PV/battery systems have given an unprecedented growth to islanded microgrid approach. However, centralized architecture of these microgrids give rise to a major limitation of distribution losses, which becomes more significant for low distribution voltages and high power levels. As a result, this non-scalable and non-modular centralized approach is not a viable approach for future expansions. To electrify these rural areas, various PV/battery based islanded distributed structures are proposed. Such distributed structures with bottom up sizing develop sustainability for a local consumer. Though the distributed architecture minimizes the high distribution losses incurred by centralized microgrid, but it makes the coordinated resource sharing a highly challenging task. So, to address these challenges, the main focus of this research work is to propose an alternate power management scheme for rural electrification.

4.2 Nano Grid System Architecture

In this thesis, a distributed power management scheme is proposed for ED and optimal power sharing considering line losses. First of all, an optimization based ED problem is formulated for optimal power sharing. This ED constrained optimization problem is then mapped into an unconstrained optimization problem using Lagrangian method. After that, primal dual dynamic equations are obtained by gradient descent method. The corresponding dynamic equations result in an integral control action and do the convergence on global scale. Then an Augmented Lagrangian based PID controller is implemented on corresponding dynamic equations for better dynamic performance under supply/load side transients. This proposed approach in the form of a block diagram is shown in figure 4.1.

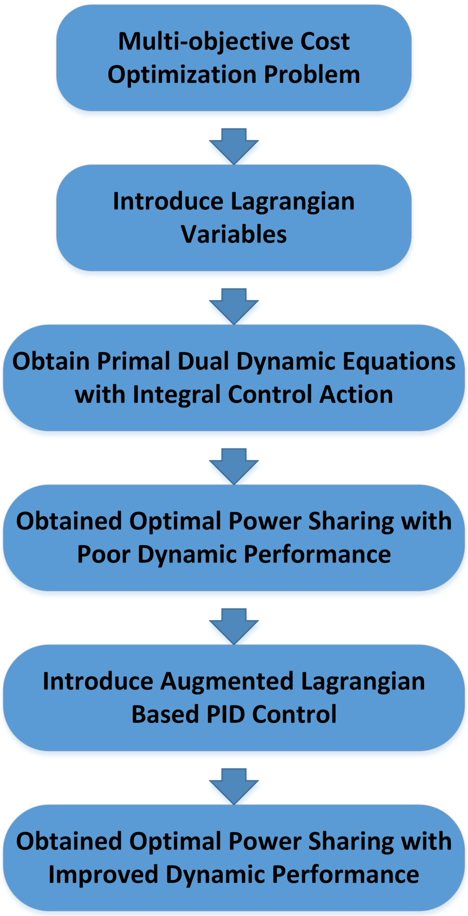


FIGURE 4.1: Block diagram of proposed approach

Our proposed NG system architecture consists of N number of NGs/households connected through a DC link as shown in Fig. 4.2. Each NG contains renewable

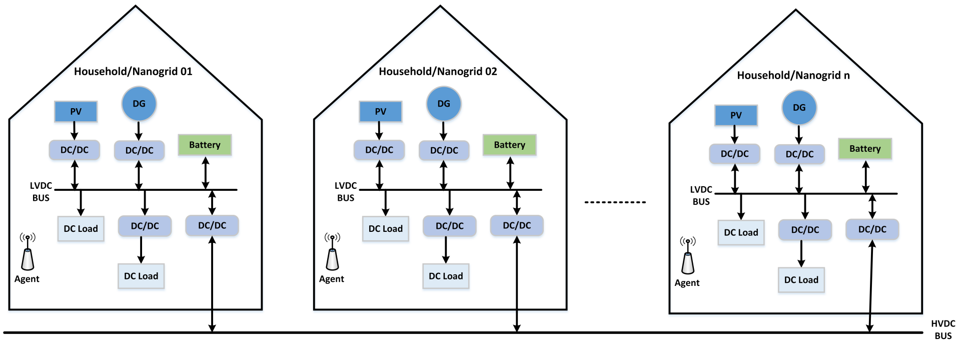


FIGURE 4.2: Nanogrid Cluster system Model

source (Solar), existing diesel generator and DC loads. There is a communication agent in each NG to implement distributed control via MAS communication structure. In this model, the modularity and subsequent integration of an individual NG to DC bus yields scalability in proposed architecture. Each NG works independently, when it is self-sufficient in resource availability and power sharing among NGs will be enabled via a bidirectional DC-DC converter, when one of the NGs has either deficiency or excess of resources.

4.2.1 Multi-Agent Communication Framework for Nanogrid Cluster

For the above proposed model, consider a group of Z NGs, defined with a corresponding set as $\mathcal{Z} = \{1, 2, \cdots, Z\}$. Each NG$i$ has an associated set of neighboring NGs, denoted by $\mathcal{Z}_i \subset \mathcal{Z}$. The set $\mathcal{Z}_i$ contains all the NGs that can communicate with NG$_i$, assuming a bidirectional underlying communication link. For this scenario, an undirected graph $H = \{Z, S\}$ is modeled, where S represents the communication links among communicating NGs. Similarly for a graph H, an adjacency matrix $A \in R^{Z \times Z}$ is defined as $A = A(H)$. Each entry $a_{i,j} \in A$ is set to 1, if there is a communication link between NG$_i$ and NG$_j$ otherwise 0. Further, from communication perspective, the degree $d_i = \sum_{j \in Z_i, j \neq i} a_{i,j}$, $\forall i$ of NG$_i$ is defined as the number of NGs adjacent to it. It is assumed that, for graph H a diagonal matrix $D \in R^{Z \times Z}$ with entries $d_i, i \in \{1, 2, \cdots, Z\}$ is defined as the degree matrix. To represent the communication links among adjacent NGs, we define a Laplacian matrix as $M = D - A$ with all row sums equal to zero, i.e. $M\mathbf{1} = 0$.

4.2.2 Multi-objective Cost Optimization Problem

A convex cost optimization problem is formulated in this section, which results in ED with a trade-off between power shared from neighboring NGs and DG. An ED problem determines the optimal output of NGC at minimized power generation cost, while making sure that load demand is also fulfilled. This proposed multi-objective optimization problem implement the ED with optimal power sharing between DG and neighboring NGs to fulfill the load demand. This also result in minimized distribution losses. is convex in nature and its objective is to minimize the total generation cost of DGs. The generation cost of DG for i^{th} NG is defined by a quadratic cost function as given below,

$$C(P_i^{(G)}) = \alpha_i P_i^2 + \beta_i P_i + \gamma_i, \quad \forall i \in \mathcal{Z} \tag{4.1}$$

Similarly, a quadratic cost function for power shared from i^{th} to j^{th} NG can be defined as

$$D(P_{i,j}) = \mu_{i,j} P_{i,j}^2, \qquad \forall i,j \in \mathcal{Z}_i \tag{4.2}$$

Where, for (4.1) $P_i \in \mathbf{P}, \mathbf{P} \in \mathbb{R}^N$ represents the power delivered by DG$_i$ with α_i, β_i and γ_i as cost coefficients. Further, for (4.2) $\mu_{i,j}$ represents the cost coefficient for power shared between NG$_i$ and NG$_j$. Thus, a multi-objective ED cost optimization problem for all Z NGs is defined as,

$$\begin{gathered}
\textbf{minimize} \sum_i \left\{ \delta C(P_i^{(G)}) + (1-\delta) \sum_j D_i(P_{i,j}) \right\} \\
\textbf{s.t.} \quad \mathbf{P_i^{(G)}} + \mathbf{P_i^{(PV)}} + \mathbf{P_i^{(B)}} + \mathbf{M}.\mathbf{P_{i,j}} \geq \mathbf{L_d}, \\
P_{min}^{(G)} \leq P_i^{(G)} \leq P_{max}^{(G)}\ , \quad -P_{min} \leq P_{i,j} \leq P_{max}.
\end{gathered} \tag{4.3}$$

4.2.3 Optimal Power Sharing with Integral Control

In (4.3), the first constraint is a supply demand balance constraint with $\mathbf{M}$ as Laplacian matrix. Further, L_d is the load demand for NG$_i$ with $P_i^{(G)}$, $P_i^{(PV)}$, $P_i^{(B)}$ as power delivered by DG, PV panel and battery respectively. Further, $P_{i,j}$ a bipolar entity, represents the power transfer between NGs, which will be positive if NG will act as source and otherwise negative. The constrained optimization problem (4.3) can be mapped in to an equivalent unconstrained problem by using the Lagrangian method as follows,

$$
\begin{aligned}
L(\mathbf{P_i}^{(G)}, \mathbf{P_{i,j}}, \lambda, \rho, \sigma, \phi, \zeta) = \sum_i \Big\{ \delta C(P_i^{(G)}) + (1-\delta) \\
.\sum_j D_i(P_{i,j}) \Big\} + \lambda(\mathbf{L_d} - \mathbf{P_i^{(G)}} - \mathbf{P_i^{(PV)}} - \mathbf{P_z^{(B)}} \\
- \mathbf{M}.\mathbf{P_{i,j}}) + \sum_i \Big\{ \rho(P_{min}^{(G)} - P_i^{(G)}) + \sigma(P_i^{(G)} - P_{max}^{(G)}) \\
+ \sum_j (\phi(-P_{min} - P_{i,j}) + \zeta(P_{i,j} - P_{max})) \Big\}. \qquad (4.4)
\end{aligned}
$$

In (4.4), $\lambda \geq 0$, $\rho \geq 0$, $\sigma \geq 0$, $\phi \geq 0$ and $\zeta \geq 0$ are the Lagrangian variables associated with inequality constraints. The primal optimization problem in (4.3) is convex problem with linear constraints and results in a strong duality with zero duality gap. If one can solve the minimization problem in (4.3) iteratively, it will result in convergence to an optimal solution. From (4.4) we can write a primal dual dynamic equations as follows,

$$
\begin{aligned}
\dot{P}_i &= k_{P_i}\left(\delta C'(P_i^{(G)}) - \lambda_i - \rho + \sigma\right) \\
\dot{P}_{i,j} &= k_{P_{i,j}}\left((1-\delta)D_i'(P_{i,j}) - \lambda_i M_i - \phi + \zeta\right) \\
\dot{\lambda}_i &= k_{\lambda_i}\Big\{ L_d - P_i^{(G)} - P_i^{(PV)} - P_i^{(B)} - [\mathbf{M}.\mathbf{P_{i,j}}]_i \Big\}^+ \\
\dot{\rho} &= k_\rho \Big\{ P_{min}^{(G)} - P_i^{(G)} \Big\}^+ \quad , \quad \dot{\sigma} = k_\sigma \Big\{ P_i^{(G)} - P_{max}^{(G)} \Big\}^+ \\
\dot{\phi} &= k_\phi \{ -P_{min} - P_{i,j} \}^+ \quad , \quad \dot{\zeta} = k_\zeta \{ P_{i,j} - P_{max} \}^+ \qquad (4.5)
\end{aligned}
$$

In (4.5), the coefficients k_{P_i}, $k_{P_{i,j}}$, k_{λ_i}, k_ρ, k_σ, k_ϕ and k_ζ represents the controller gains, with $\{P\}^+ = max\,\{P, 0\}$. From (4.5) the primal optimization problem (4.3) will be solved by iteratively updating the Lagrangian variables, which results in an optimal power sharing to meet the load demand. Let $u_i = -\lambda_i - \rho + \sigma$ and $u_{i,j} = -\lambda_i M_i - \phi + \zeta$ are two control actions for DG power and power shared between NGs. Now, by substituting the Lagrangian variables λ, ρ, σ, ϕ and ζ expressions in u_i and $u_{i,j}$, the updated dynamic equations will be as follows,

$$
\begin{aligned}
u_i = -\int_0^t k_{\lambda_i}\Big\{ L_d - P_i(\tau)^{(G)} - P_i(\tau)^{(PV)} \\
- P_i(\tau)^{(B)} - [\mathbf{M}.\mathbf{P_{i,j}}(\tau)]_i \Big\}^+ d\tau - u_\rho + u_\sigma \\
u_\rho = \int_0^t k_\rho \left\{ P_{min}^{(G)} - P_i^{(G)} \right\}^+ d\tau \\
u_\sigma = \int_0^t k_\sigma \left\{ P_i^{(G)} - P_{max}^{(G)} \right\}^+ d\tau.
\end{aligned}
\tag{4.6}
$$

Similar dynamic equations will be obtained for $u_{i,j}$. In (4.6) u_i, u_ρ and u_σ are the auxiliary variables, which effectively implements the integral control and results in convergence to global optimal point for primal optimization problem in (4.3).

4.2.4 Optimal Power Sharing with proposed PID Control

Due to underlying integral control action, the dynamic performance will not be satisfactory under power transients. The poor dynamic performance caused by variations in load demand and PV/battery power is improved by an augmented Lagrangian based controller. The controller is designed by modifying the dynamic equations in (4.5). For this purpose, the Lagrangian equation in (4.4) is extended to an augmented Lagrangian function L_a as follows,

$$
\begin{aligned}
L_a(\mathbf{P_i}^{(G)}, \mathbf{P_{i,j}}, \lambda, \rho, \sigma, \phi, \zeta) = \sum_i \Big\{ \delta C(P_i^{(G)}) \\
+ (1-\delta). \sum_j D_i(P_{i,j}) \Big\} \\
+ \sum_i \frac{K_p}{2} \Big(L_d - P_i^{(G)} - P_i^{(PV)} - P_i^{(B)} - [\mathbf{M}.\mathbf{P_{i,j}}]_i \Big)^2 \\
+ \sum_i K_i \Big\{ \lambda_i \Big(L_d - P_i^{(G)} - P_i^{(PV)} - P_i^{(B)} - [\mathbf{M}.\mathbf{P_{i,j}}]_i \Big) \\
+ \rho(P_{min}^{(G)} - P_i^{(G)}) + \sigma(P_i^{(G)} - P_{max}^{(G)}) \\
+ \sum_j \left(\phi(-P_{min} - P_{i,j}) + \zeta(P_{i,j} - P_{max}) \right) \Big\} \\
+ \sum_i \frac{K_d}{2} \left((P_i - \tilde{P}_i)^2 + \sum_j (P_{i,j} - \tilde{P}_{i,j})^2 \right)
\end{aligned}
\tag{4.7}
$$

Where K_p, K_i and K_d are controller gains, with $\tilde{P}_i$ and $\tilde{P}_{i,j}$ as two auxiliary state variables in (4.7). From (4.7) the updated primal dual dynamics equations with improved dynamic response are given as,

$$
\begin{aligned}
\dot{P}_i &= k_{P_i}\left(\delta C'(P_i^{(G)}) + u_i\right)\\
\dot{P}_{i,j} &= k_{P_{i,j}}\left((1-\delta)\sum_{y} D_i'(P_{i,j}) + u_{i,j}\right)\\
\dot{\tilde{P}}_i &= \tilde{K}_d(P_i - \tilde{P}_i) \quad , \quad \dot{\tilde{P}}_{i,j} = \tilde{K}_d(P_{i,j} - \tilde{P}_{i,j})\\
\dot{\lambda}_i &= k_{\lambda_i}\left\{L_d - P_i^{(G)} - P_i^{(PV)} - P_i^{(B)} - [\mathbf{M}.\mathbf{P_{i,j}}]_i\right\}^+\\
\dot{\rho} &= k_\rho\left\{P_{min}^{(G)} - P_i^{(G)}\right\}^+ \quad , \quad \dot{\sigma} = k_\sigma\left\{P_i^{(G)} - P_{max}^{(G)}\right\}^+\\
\dot{\phi} &= k_\phi\left\{-P_{min} - P_{i,j}\right\}^+ \quad , \quad \dot{\zeta} = k_\zeta\left\{P_{i,j} - P_{max}\right\}^+\\
u_i &= -K_i(\lambda_i + \rho - \sigma) + K_d(P_i - \tilde{P}_i) - K_p\eta(\dot{\lambda}_i)\\
u_{i,j} &= K_i(-\lambda_i M_i - \phi + \zeta)\\
&\quad + K_d(P_{i,j} - \tilde{P}_{i,j}) - K_p M_i \eta(\dot{\lambda}_i)
\end{aligned}
\tag{4.8}
$$

In (4.8), the first two expressions represents the power dynamics of DG and power shared between NGs respectively, with their associated control law as u_i and $u_{i,j}$. Both control laws implement the control to improve power dynamic performance. The first term in u_i and $u_{i,j}$ implements the integral control action with integral gain K_i. The second term implements the derivative control on P_i and $P_{i,j}$, which can be verified. This second term converges to zero as $\tilde{P}_i$ and $\tilde{P}_{i,j}$ converges to P_i and $P_{i,j}$ respectively at equilibrium. It is responsible for derivative control action, which can be verified as following. By taking the Laplace transform of $\dot{\tilde{P}}_i = \tilde{K}_{P_i}(P_i - \tilde{P}_i)$, which results $\tilde{P}_i(s) = \frac{\tilde{K}_{P_i}}{s+\tilde{K}_{P_i}}P_i(s)$ and now by substituting this value in expression $K_d(P_i - \tilde{P}_i)$, it becomes $\frac{\tilde{K}_d}{s+\tilde{K}_{P_i}}sP_i(s)$, where $\frac{\tilde{K}_d}{s+\tilde{K}_{P_i}}$ represents a low pass filter and $sP_i(s)$ implements the derivative control. Higher the value of K_d higher will be the bandwidth of derivative controller. Similar scenario will be for $P_{i,j}$. Further, the third term in u_i and $u_{i,j}$ will implements a proportional control action, where $\eta(.)$ represents a linear functional mapping as $\eta(\dot{\lambda}_i) = \dot{\lambda}_i$. In $u_{i,j}$, the third term includes the Laplacian matrix, which represents the coordination between two NGs to meet up the load demand.

Chapter 5

Results and Discussion

5.1 Introduction

The proposed control scheme is implemented at algorithmic level and numerical results are obtained using (4.8) for optimal power sharing and better dynamic performance. For the proposed model performance analysis, we consider two networks of three NGs and four NGs. The proposed models are expected to give optimal power flow control from DG and among NGs according to their associated line resistance. It is assumed that each DG interconnected with a NG is conventional thermal generator with power converter, controller module and energy source. The power generation limits and cost coefficients of these thermal generators are given in Table I and Table II respectively. The connectivity graph for three NGs and four NGs network is shown in Fig. 5.1. For the above mentioned NG networks the corresponding Laplacian matrices are given below,

$$M3 = \begin{bmatrix} 2 & -1 & -1 \\ -1 & 1 & 0 \\ -1 & 0 & 1 \end{bmatrix}, M4 = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 2 & 0 & -1 \\ -1 & 0 & 2 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}$$

TABLE 5.1: Parameters for numerical results.

Parameter	Value
DG1, DG2, DG3 and DG4 rating	10 kVA
Load demand	2 kW - 10 kW
Line Resistance: R_{12}, R_{13}, R_{14}	50Ω , 90Ω ,140Ω
Line Resistance: R_{24}, R_{34}	90Ω , 50Ω

Table 5.2: Cost coefficients for DGs.

Parameter	DG1	DG2	DG3	DG4
α	0.07	0.04	0.09	0.12
β	10	12.5	13	16
γ	0	0	0	0

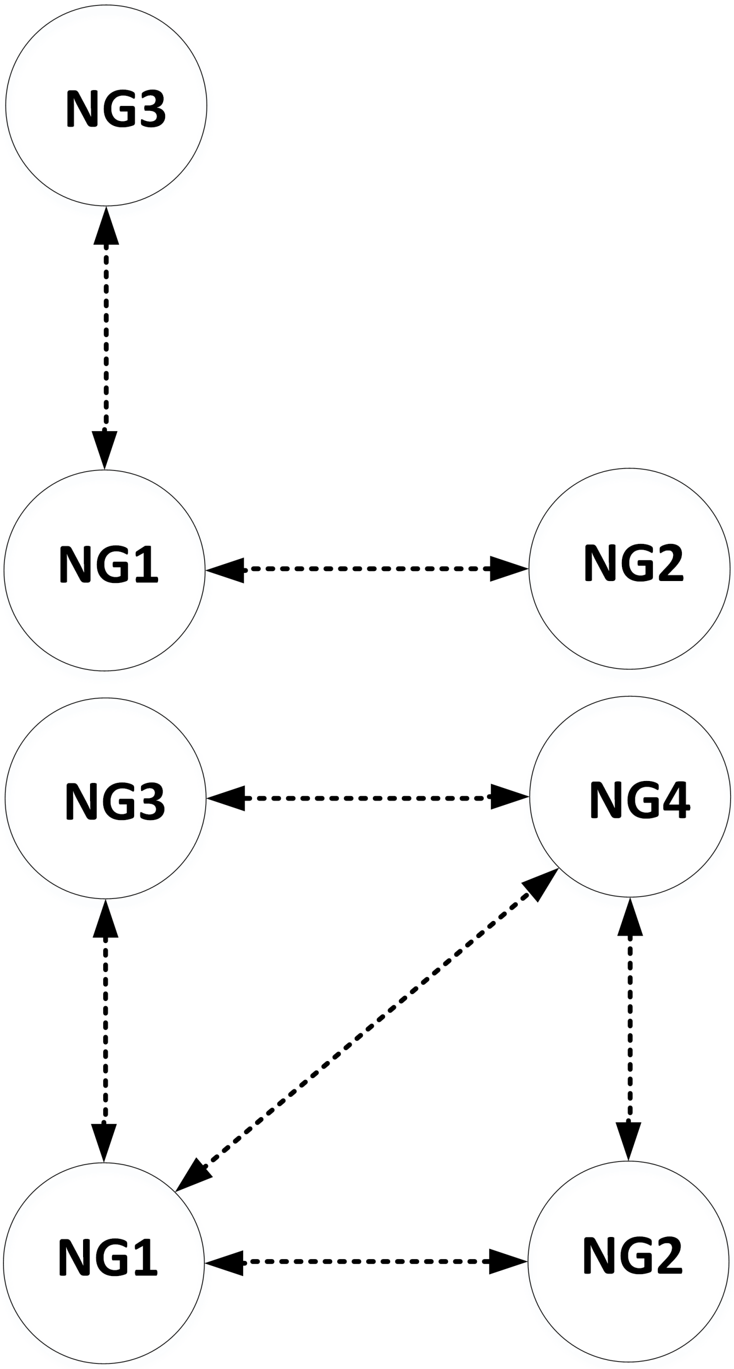


Figure 5.1: NG Models with communication structures (a) Three NGs (b) Four NGs.

5.1.1 Case1: Effect of Line Resistance on Power Sharing

For a three NGs star network in Fig. 5.1(a), it is assumed that the NG1 is power deficient whereas NG2 and NG3 have excess power to share. Therefore DG1, NG2 and NG3 will coordinate with each other to fulfill the load demand of NG1. The sum of line resistance from NG1 to NG2 (R_{12}) and from NG1 to NG3 (R_{13}) is assumed to be constant. Now, if the value of (R_{12}) is increased, it results in a decrease in power shared from NG2 to NG1 and increase in power shared from NG3 to NG1 as shown in Fig. 5.2. An increase in R_{12} causes R_{13} to decrease, therefore the power transfer from NG2 to NG1 and NG3 to NG1 changes in the similar manner. Both NGs will share equal power, when they offer same line resistance. Thus, optimal power sharing is achieved with minimized distribution losses.

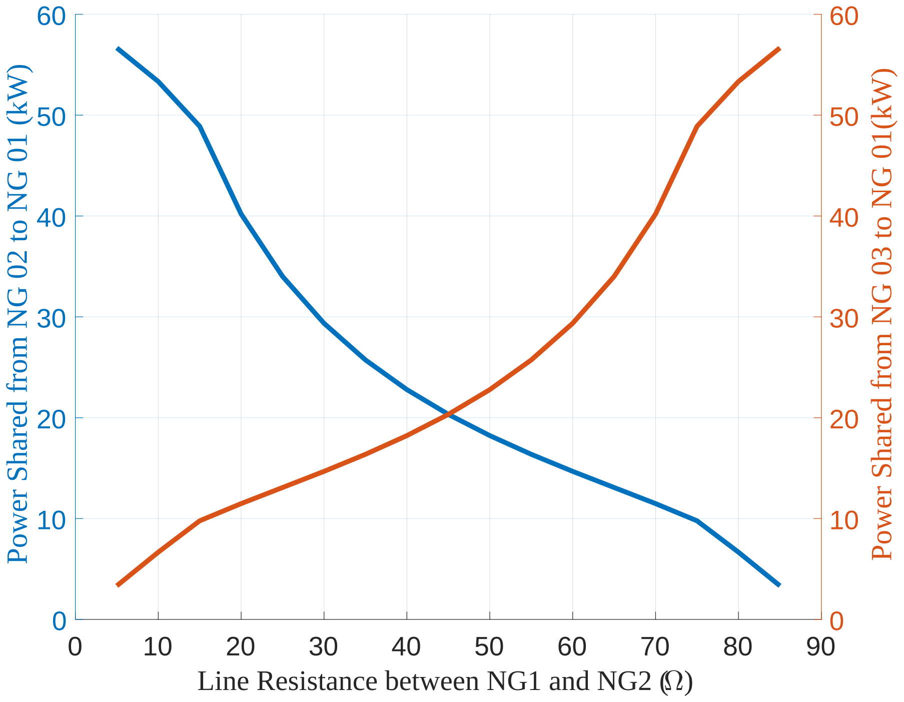


FIGURE 5.2: Line resistance sensitivity and power sharing

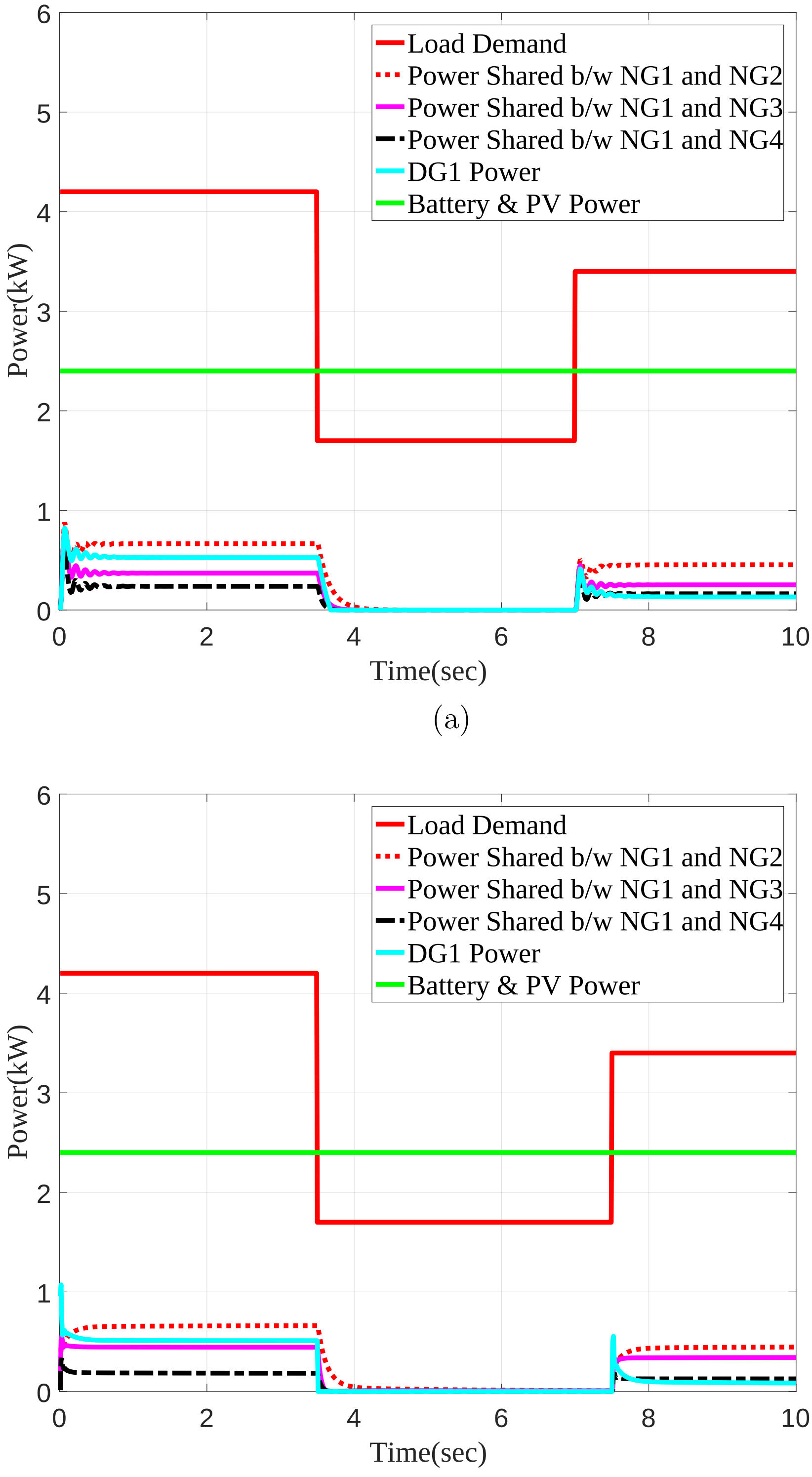
5.1.2 Case2: One NG is Power Deficient

Considering a four NGs model in Fig. 5.1(b), where NG1 is linked with NG2, NG3 and NG4 via a communication network. It is assumed that the NG1 is power deficient with NG2, NG3 and NG4 have excess power to share. Then, considering the cost coefficients (α, β, γ) of DG1 and line resistances R_{12}, R_{13} and

R_{14} acting as cost coefficients (μ_z) for power transfer, an optimal power sharing is achieved with minimized generation cost and distribution losses. According to the line resistances given in Table I, it is expected that the power shared by NG2 will be greater then NG3, and NG3 will share more power as compared to NG4 as shown in Fig. (5.3). Further, it is also assumed that battery/PV power remains constant. When load demand of NG1 is 4.2kW, most of the supply demand mismatch is managed by cooperation among DG1 and neighboring NGs. The NG associated with minimum line resistance will deliver maximum power compared to the other NGs. When load varies from 4.2kW to 2.8kW, DG1 power and all powers shared from neighboring NGs becomes zero, because now NG1 is self sufficient in resource availability. Then load again varies to 4.2kW and now NG1 will operate similarly as discussed before, which results in ED and minimized distribution losses. Further, system dynamics are observed by two control schemes in this case. 1) conventional control, which results in a poor dynamic performance under load variations. 2) augmented Lagrangian based control, where the control law proposed in (4.8) is observed, which results in an improved dynamic response.

5.1.3 Case3: Two NGs are Power Deficient

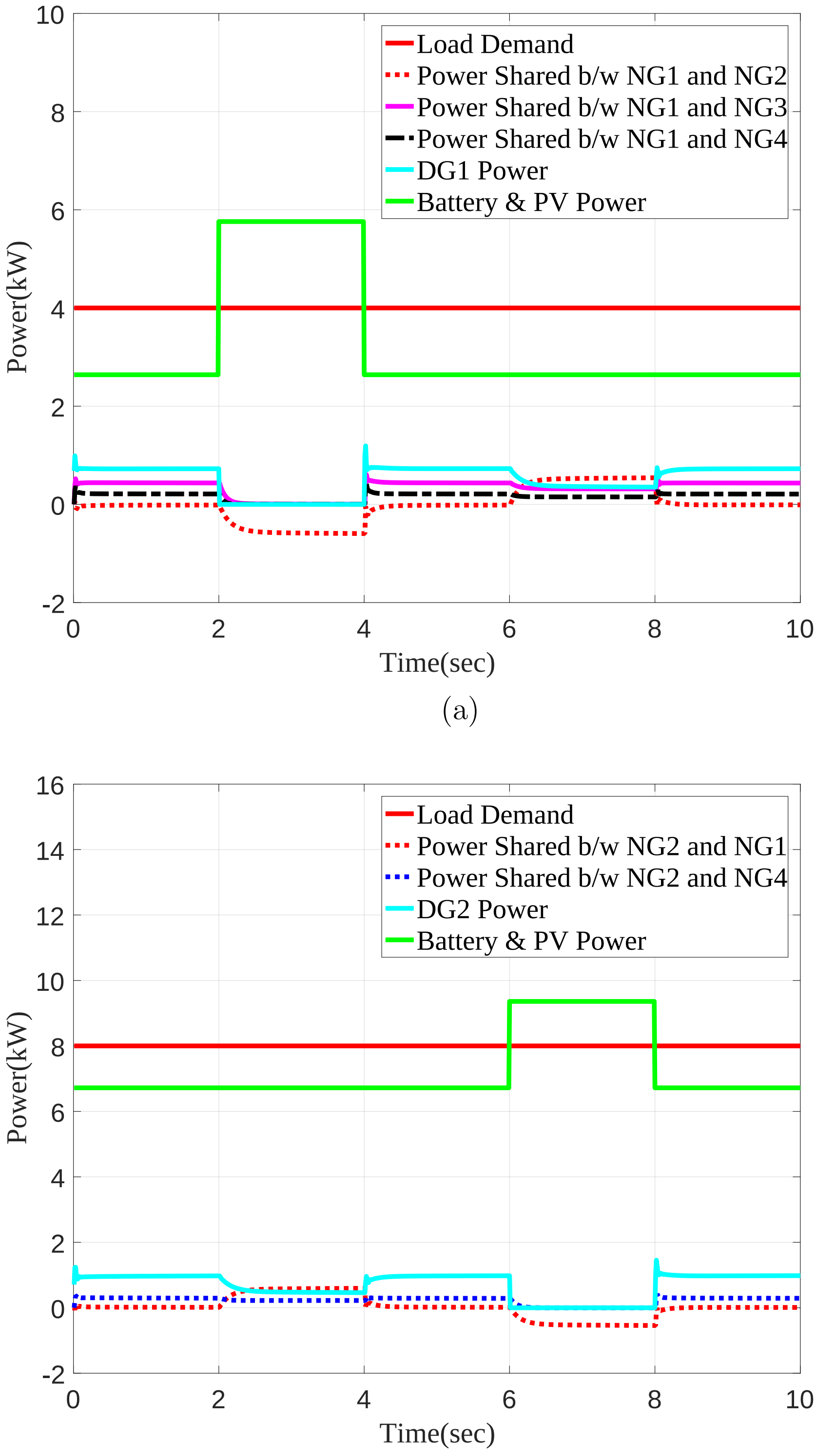
For a four NGs model, the power sharing between two NGs is observed under PV and Battery power variations. As shown in Fig. 5.4 (a), NG1 and NG2 are power deficient initially, when PV and battery power is less then load demand. NG1 is connected with DG1 as well as NG2, NG3 and NG4 for providing the backup power, with NG2 having least line resistance. As a result, the supply demand mismatch power will be optimally distributed among NG3, NG4 and DG1 to minimize the power generation cost and distribution losses as shown in Fig. 5.4(a). NG2 will share zero power as it is power deficient itself. Similarly, NG2 can interact with DG2, NG1 and NG4 to meet its demand needs. As NG1 is also power deficient, so, NG2 is interacting with DG2 and NG4. Then, PV and battery power increased for NG1. Therefore, the power generated by DG1 and power shared from NG3 and NG4 becomes zero in this case. Now, instead of receiving excess power from its neighbors, NG1 is now sharing its excess power with NG2. After that, both NG1 and NG2 again becomes resource deficient and will operate similarly as discussed previously. Then, NG2 becomes self sufficient with excess PV and battery power and NG1 is still resource deficient. Now, NG2 will share its excess power with the neighboring power deficient NGs such as NG1 as shown Fig. 5.4 (b). These results validate that the proposed control scheme is



. (a)

. (b)

Figure 5.3: Optimal power sharing for NG1 (a) Conventional control (b) Augmented Lagragian based control.



. (a)

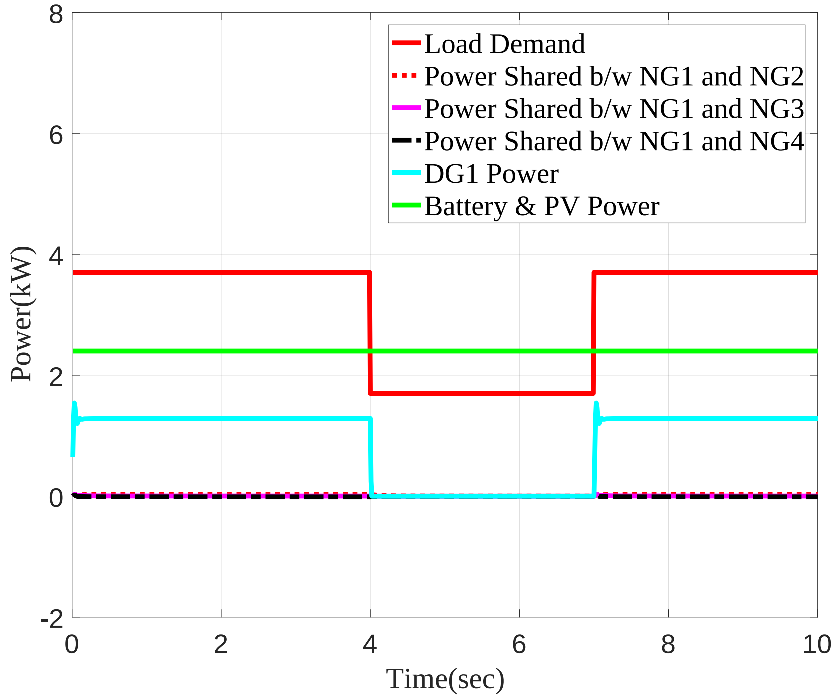
. (a)

FIGURE 5.4: Power Sharing between NG1 and NG2 (a) NG1 (b) NG2.

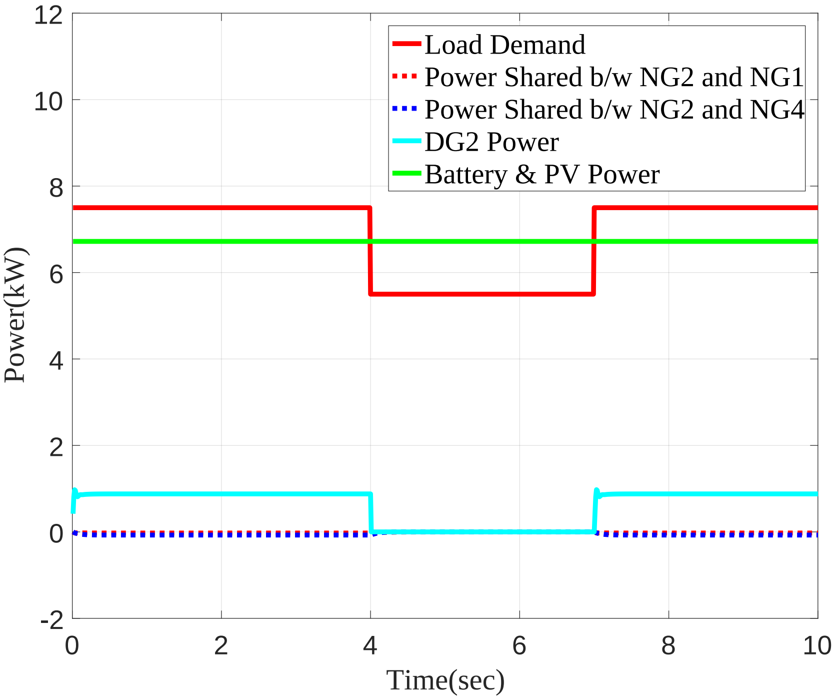
providing optimal power sharing with ED and distribution losses minimization.

5.1.4 Case4: All NGs are Power Deficient

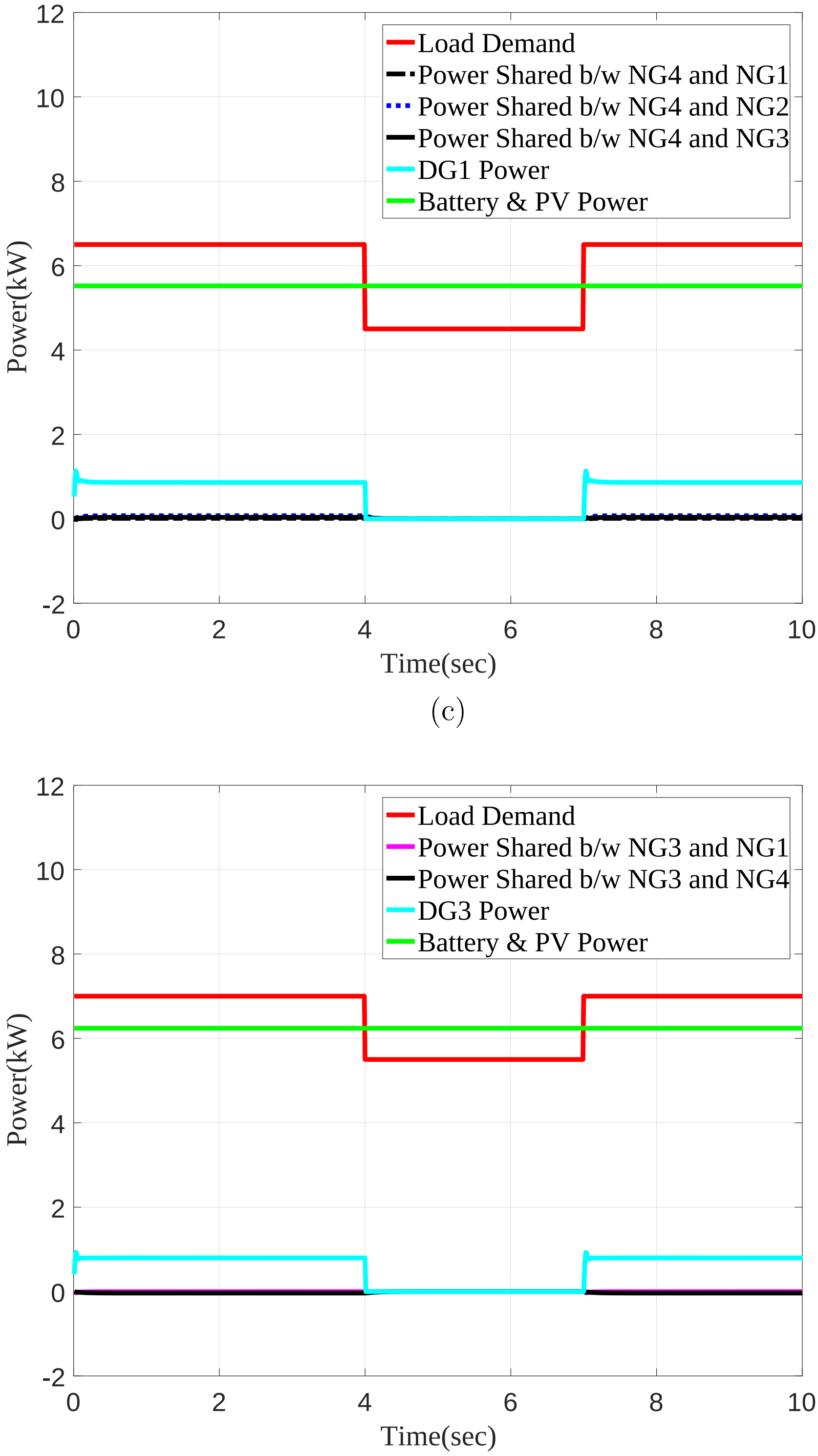
In this case, it is assumed that all the NGs in the cluster are deficient in resource availability. In this scenario, it is expected that there will be zero power sharing among NGs and the supply demand miss-match will be overcome by DGs of each NG as shown in Fig. (5.5). And when all NGs are self-sufficient with excess power of PV and battery, NGs will operate independently with zero DG power and shared power from neighboring NGs.


Load Demand
Power Shared b/w NG1 and NG2
Power Shared b/w NG1 and NG3
Power Shared b/w NG1 and NG4
DG1 Power
Battery & PV Power
Power(kW)
Time(sec)
8
6
4
2
0
-2
0
2
4
6
8
10

. (a)


Load Demand
Power Shared b/w NG2 and NG1
Power Shared b/w NG2 and NG4
DG2 Power
Battery & PV Power
Power(kW)
Time(sec)
12
10
8
6
4
2
0
-2
0
2
4
6
8
10

. (b)



. (c)

. (d)

FIGURE 5.5: All NGs are power deficient (a) NG1 (b) NG2 (c) NG3 (d) NG4.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

For an NGC, the problem of optimized power sharing with minimized distribution losses is considered. For this purpose, the NGs with minimum line resistance between them will share more power compared to the NGs which are associated with high line resistance. There's is a trade-off between power generated by DG and power shared from neighboring NGs, this results in an optimal power sharing with minimum generation cost. Further, an augmented Lagrangian based controller is implemented to overcome the transients occur due to generation/load side power variations. This results in a better dynamic performance of proposed model in comparison to the integral control.

6.2 Future Work

The proposed model can be further extended by considering heterogeneous NG structures with and without inevitable loads.

References

[1] J. Ahmad, M. Tahir, and S. K. Mazumder. Dynamic economic dispatch and transient control of distributed generators in a microgrid. *IEEE Systems Journal*, 13(1):802–812, March 2019. ISSN 1932-8184. doi: 10.1109/JSYST.2018.2859755.

[2] S. Anand, B. G. Fernandes, and J. Guerrero. Distributed control to ensure proportional load sharing and improve voltage regulation in low-voltage dc microgrids. *IEEE Transactions on Power Electronics*, 28(4):1900–1913, April 2013. ISSN 0885-8993. doi: 10.1109/TPEL.2012.2215055.

[3] A. Arsalan, J. Ahmad, M. Tahir, and S. K. Mazumder. Distributed control and power management of islanded dc nanogrids with applications to rural electrification. *IEEE Systems Journal*, 2019.

[4] R. S. Balog, W. W. Weaver, and P. T. Krein. The load as an energy asset in a distributed dc smartgrid architecture. *IEEE Transactions on Smart Grid*, 3 (1):253–260, March 2012. ISSN 1949-3053. doi: 10.1109/TSG.2011.2167722.

[5] Ali Bidram, Ali Davoudi, and Frank L Lewis. A multiobjective distributed control framework for islanded ac microgrids. *IEEE Transactions on industrial informatics*, 10(3):1785–1798, 2014.

[6] Daniel Burmester, Ramesh Rayudu, Winston Seah, and Daniel Akinyele. A review of nanogrid topologies and technologies. *Renewable and Sustainable Energy Reviews*, 67:760 – 775, 2017. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2016.09.073.

[7] Soojeong Choi, Sunju Park, Dong-Joo Kang, Seung-jae Han, and Hak-Man Kim. A microgrid energy management system for inducing optimal demand response. In *Smart Grid Communications (SmartGridComm), 2011 IEEE International Conference on*, pages 19–24. IEEE, 2011.

[8] Chunxia Dou, Zhanqiang Zhang, Dong Yue, and Yuhang Zheng. Mas-based hierarchical distributed coordinate control strategy of virtual power source voltage in low-voltage microgrid. *IEEE Access*, 5:11381–11390, 2017.

[9] F. Gao, S. Bozhko, A. Costabeber, C. Patel, P. Wheeler, C. I. Hill, and G. Asher. Comparative stability analysis of droop control approaches in voltage-source-converter-based dc microgrids. *IEEE Transactions on Power Electronics*, 32(3):2395–2415, March 2017. ISSN 0885-8993. doi: 10.1109/TPEL.2016.2567780.

[10] Xiaohua Ge and Qing-Long Han. Distributed formation control of networked multi-agent systems using a dynamic event-triggered communication mechanism. *IEEE Transactions on Industrial Electronics*, 64(10):8118–8127, 2017.

[11] S. Groh, D. Philipp, B. E. Lasch, and H. Kirchhoff. Swarm electrification - suggesting a paradigm change through building microgrids bottom-up. In *2014 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET)*, pages 1–2, May 2014. doi: 10.1109/ICDRET.2014.6861710.

[12] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla. Hierarchical control of droop-controlled ac and dc microgrids—a general approach toward standardization. *IEEE Transactions on Industrial Electronics*, 58(1):158–172, Jan 2011. ISSN 0278-0046. doi: 10.1109/TIE.2010.2066534.

[13] David G Hart. Using ami to realize the smart grid. In *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, pages 1–2. IEEE, 2008.

[14] Nadeem Javaid, Imran Khan, MN Ullah, Anzar Mahmood, and Muhammad Umar Farooq. A survey of home energy management systems in future smart grid communications. In *Broadband and Wireless Computing, Communication and Applications (BWCCA), 2013 Eighth International Conference on*, pages 459–464. IEEE, 2013.

[15] Zhenhua Jiang. Agent-based control framework for distributed energy resources microgrids. In *Proceedings of the IEEE/WIC/ACM international conference on Intelligent Agent Technology*, pages 646–652. IEEE Computer Society, 2006.

[16] Z. Jin, L. Meng, and J. M. Guerrero. Comparative admittance-based analysis for different droop control approaches in dc microgrids. In *2017 IEEE Second*

International Conference on DC Microgrids (ICDCM), pages 515–522, June 2017. doi: 10.1109/ICDCM.2017.8001095.

[17] B. K. Johnson, R. H. Lasseter, F. L. Alvarado, and R. Adapa. Expandable multiterminal dc systems based on voltage droop. *IEEE Transactions on Power Delivery*, 8(4):1926–1932, Oct 1993. ISSN 0885-8977. doi: 10.1109/61.248304.

[18] S. C. Joseph, S. Ashok, and P. R. Dhanesh. An effective method of power management in dc nanogrid for building application. In *2017 IEEE International Conference on Signal Processing, Informatics, Communication and Energy Systems (SPICES)*, pages 1–5, Aug 2017. doi: 10.1109/SPICES.2017.8091303.

[19] Jackson John Justo, Francis Mwasilu, Ju Lee, and Jin-Woo Jung. Ac-microgrids versus dc-microgrids with distributed energy resources: A review. *Renewable and Sustainable Energy Reviews*, 24(C):387–405, 2013.

[20] P. Karlsson and J. Svensson. Dc bus voltage control for a distributed power system. *IEEE Transactions on Power Electronics*, 18(6):1405–1412, Nov 2003. ISSN 0885-8993. doi: 10.1109/TPEL.2003.818872.

[21] F. Katiraei, R. Iravani, N. Hatziargyriou, and A. Dimeas. Microgrids management. *IEEE Power and Energy Magazine*, 6(3):54–65, May 2008. ISSN 1540-7977. doi: 10.1109/MPE.2008.918702.

[22] J. Khan and M. H. Arsalan. Solar power technologies for sustainable electricity generation–a review. *Renewable and Sustainable Energy Reviews*, 2016.

[23] AL Kulasekera, RARC Gopura, KTMU Hemapala, and N Perera. A review on multi-agent systems in microgrid applications. In *Innovative Smart Grid Technologies-India (ISGT India), 2011 IEEE PES*, pages 173–177. IEEE, 2011.

[24] A. Kwasinski and C. N. Onwuchekwa. Dynamic behavior and stabilization of dc microgrids with instantaneous constant-power loads. *IEEE Transactions on Power Electronics*, 26(3):822–834, March 2011. ISSN 0885-8993. doi: 10.1109/TPEL.2010.2091285.

[25] H. Liang, B. J. Choi, W. Zhuang, X. Shen, A. S. A. Awad, and A. Abdr. Multiagent coordination in microgrids via wireless networks. *IEEE Wireless Communications*, 19(3):14–22, June 2012. ISSN 1536-1284. doi: 10.1109/MWC.2012.6231155.

[26] N. Liu, X. Yu, W. Fan, C. Hu, T. Rui, Q. Chen, and J. Zhang. Online energy sharing for nanogrid clusters: A lyapunov optimization approach. *IEEE Transactions on Smart Grid*, 9(5):4624–4636, Sep. 2018. ISSN 1949-3053. doi: 10.1109/TSG.2017.2665634.

[27] P. C. Loh, F. Blaabjerg, S. Peyghami-Akhuleh, and H. Mokhtari. Distributed secondary control in dc microgrids with low-bandwidth communication link. In *2016 7th Power Electronics and Drive Systems Technologies Conference (PEDSTC)*, pages 641–645, Feb 2016. doi: 10.1109/PEDSTC.2016.7556935.

[28] X. Lu, J. M. Guerrero, K. Sun, and J. C. Vasquez. An improved droop control method for dc microgrids based on low bandwidth communication with dc bus voltage restoration and enhanced current sharing accuracy. *IEEE Transactions on Power Electronics*, 29(4):1800–1812, April 2014. ISSN 0885-8993. doi: 10.1109/TPEL.2013.2266419.

[29] X. Lu, K. Sun, J. M. Guerrero, J. C. Vasquez, and L. Huang. State-of-charge balance using adaptive droop control for distributed energy storage systems in dc microgrid applications. *IEEE Transactions on Industrial Electronics*, 61 (6):2804–2815, June 2014. ISSN 0278-0046. doi: 10.1109/TIE.2013.2279374.

[30] P. A. Madduri, J. Poon, J. Rosa, M. Podolsky, E. A. Brewer, and S. R. Sanders. Scalable dc microgrids for rural electrification in emerging regions. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 4(4): 1195–1205, Dec 2016. ISSN 2168-6777. doi: 10.1109/JESTPE.2016.2570229.

[31] M. Nasir, N. A. Zaffar, and H. A. Khan. Analysis on central and distributed architectures of solar powered dc microgrids. In *2016 Clemson University Power Systems Conference (PSC)*, pages 1–6, March 2016. doi: 10.1109/PSC.2016.7462817.

[32] M. Nasir, H. A. Khan, A. Hussain, L. Mateen, and N. A. Zaffar. Solar pv-based scalable dc microgrid for rural electrification in developing regions. *IEEE Transactions on Sustainable Energy*, 9(1):390–399, Jan 2018. ISSN 1949-3029. doi: 10.1109/TSTE.2017.2736160.

[33] M. Nasir, Z. Jin, H. A. Khan, N. A. Zaffar, J. C. Vasquez, and J. M. Guerrero. A decentralized control architecture applied to dc nanogrid clusters for rural electrification in developing regions. *IEEE Transactions on Power Electronics*, 34(2):1773–1785, Feb 2019. ISSN 0885-8993. doi: 10.1109/TPEL.2018.2828538.

[34] T. L. Nguyen and G. Griepentrog. A self-sustained and flexible decentralized control strategy for dc nanogrids in remote areas/islands. In *2017 IEEE Southern Power Electronics Conference (SPEC)*, pages 1–6, Dec 2017. doi: 10.1109/SPEC.2017.8333581.

[35] Estefanía Planas, Asier Gil de Muro, Jon Andreu, Iñigo Kortabarria, and Iñigo Martínez de Alegría. General aspects, hierarchical controls and droop methods in microgrids: A review. *Renewable and Sustainable Energy Reviews*, 17:147 – 159, 2013. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2012.09.032.

[36] A. G. Tsikalakis and N. D. Hatziargyriou. Centralized control for optimizing microgrids operation. *IEEE Transactions on Energy Conversion*, 23(1):241–248, March 2008. ISSN 0885-8969. doi: 10.1109/TEC.2007.914686.

[37] A. Tuladhar and H. Jin. A novel control technique to operate dc/dc converters in parallel with no control interconnections. In *PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No.98CH36196)*, volume 1, pages 892–898 vol.1, May 1998. doi: 10.1109/PESC.1998.702005.

[38] K. Ubilla, G. A. Jiménez-Estévez, R. Hernádez, L. Reyes-Chamorro, C. Hernández Irigoyen, B. Severino, and R. Palma-Behnke. Smart microgrids as a solution for rural electrification: Ensuring long-term sustainability through cadastre and business models. *IEEE Transactions on Sustainable Energy*, 5(4):1310–1318, Oct 2014. ISSN 1949-3029. doi: 10.1109/TSTE.2014.2315651.

[39] H. Zhang, C. Ren, W. Qin, X. Han, and P. Wang. Coordinated control strategy for a dc microgrid with two-level bus voltage. In *2017 12th IEEE Conference on Industrial Electronics and Applications (ICIEA)*, pages 1712–1717, June 2017. doi: 10.1109/ICIEA.2017.8283115.

[40] Qin Zhang, Lionel Lapierre, and Xianbo Xiang. Distributed control of coordinated path tracking for networked nonholonomic mobile vehicles. *IEEE Transactions on Industrial Informatics*, 9(1):472–484, 2013.

[41] Bozju Zhao, CX Guo, and YJ Cao. A multiagent-based particle swarm optimization approach for optimal reactive power dispatch. *IEEE transactions on power systems*, 20(2):1070–1078, 2005.