

Modelling of a Networked AC Microgrid System with a Distributed Primary - Secondary Voltage and Frequency Control Scheme

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Thesis

Submitted by

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Declaration

This is to certify that the thesis entitled **Modelling of a Networked AC Microgrid System with a Distributed Primary - Secondary Voltage and Frequency Control Scheme**, submitted by me to the Department of Electronics and Electrical Engineering, Indian Institute of Technology Guwahati, for the award of the degree of M.Tech, is a bonafide work carried out by me under the supervision of **Dr. Sreenath J G & Dr Parijat Bhowmick, Department of Electronics and Electrical Engineering Indian Institute of Technology, Guwahati**. The content of this thesis, in full or in parts, has not been submitted to any other University or Institute for the award of any degree.

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Sincerely

Shivraj Vishwakarma

Abstract

This project aims to describe a distributed cooperative control scheme designed for the secondary voltage and frequency controller in a networked AC microgrid. The implemented method is entirely distributed, relying on local information exchange between neighbouring distributed generators (DGs), eliminating the need for a centralized controller and reducing communication overhead. The approach utilizes Input-Output Feedback Linearization (IOFL) to transform the nonlinear dynamics of DGs into linear forms, facilitating the application of effective linear control techniques. Control parameters are carefully optimized to achieve the desired response speed and robustness against uncertainties. The control scheme is validated through extensive simulations on a microgrid testbed, demonstrating its capability to maintain stable voltage and frequency under various operating conditions. This research advances microgrid control strategies by emphasizing decentralized approaches to enhance system reliability, scalability, and performance.

Index Terms - Distributed Cooperative Control(DCC), distributed generator (DG), feedback linearization, microgrid, multi-agent systems(MAS).

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Chapter 1

Introduction

1.1 Background

For over a century, power systems have been designed around centralized generation, unidirectional flow of power, non-active dissemination, and & operation driven by demand. Recent advancements, such as distributed generation from renewable sources, energy storage, flexible transmission systems, active demand management, microgrids, and intelligent control systems, have opened up new possibilities for power systems. However, further research is needed to realize these advanced systems' potential fully [1].

1.2 Motivation

Microgrids are capable of functioning in both islanded and grid-connected modes. The main grid is connected to the microgrid under ordinary conditions. The microgrid switches to islanded operation and disconnects from the main grid in the case of a disruption. After being in islanded mode, voltage and frequency stability in the microgrid is maintained through a mechanism known as primary control. However, even with primary control in place, There is still a chance that voltage and frequency will vary from what is stated. A secondary control mechanism is also needed to bring back the voltage and frequency of DGs to their nominal values.

Traditional secondary control schemes for microgrids rely on a centralized control architecture, necessitating a complex communication network & in certain instances, bidirectional communication links. This can have a detrimental impact on system reliability. Sparse communication networks and distributed cooperative structures for control provide

workable options for microgrid secondary control.

Because of their computational efficiency and inherent flexibility, networked multi-agent systems (MAS) have attracted much interest during the past 20 years. The laws of thermodynamics serve as an inspiration for these systems. synchronization, phase transitions in physical and chemical systems, and natural phenomena like flocking birds and insects. Each agent in these phenomena must exchange information with other agents by particular, frequently constrained communication protocols for the coordination and synchronization process [2].

Distributed cooperative control (DCC) of multi-agent systems (MAS) is a promising approach for implementing secondary voltage control in microgrids. It offers several advantages over traditional centralized control methods, including:

- Decentralized control: Each agent in the MAS only needs to communicate with its neighbours, eliminating the need for a central controller. This makes the system more resilient to failures and reduces communication overhead.
- Flexibility: The MAS framework can easily accommodate the addition or removal of distributed generators (DGs), making it well-suited for dynamic microgrids.
- Adaptability: The control parameters can be dynamically adjusted to compensate for uncertainties in the microgrid, ensuring stable voltage regulation under varying operating conditions.

The two main categories of DCC are regulatory synchronization and tracking synchronization. Agents align with a common goal in regulatory synchronization without a predetermined reference value. During tracking synchronisation, agents synchronize to a leader node that serves as a reference signal generator. The issue with secondary voltage regulation in a microgrid is similar to the tracking synchronization problem because of the nonlinear and non-identical dynamics of DGs. Input and output feedback linearization (IOFL), which transforms the nonlinear dynamics into linear forms, enables linear control methods. Next, fully distributed control protocols are derived using the Lyapunov technique so that each DG only needs information from its neighbours. The suggested DCC-based secondary voltage control methodology provides several noteworthy features:

- Distributed control: eliminates the requirement for a central controller, enhancing system resilience and reducing communication overhead.
- Non-linearity handling: IOFL effectively addresses the nonlinear dynamics of DGs.
- Sparse communication: reduces communication expenses by requiring a minimal communication structure with one-way communication links.
- Tunable response: Control settings can be changed to obtain desired reaction speeds.

1.3 Objectives

This thesis aims to design a comprehensive networked AC test microgrid incorporating primary and distributed cooperative secondary control schemes for optimal voltage and frequency regulation. The specific objectives of this research are as follows:

1. Review and Analyze Existing Control Strategies for Microgrids:

- Conduct a thorough literature review to examine the current methodologies and technologies used in microgrid control.
- Identify the strengths, weaknesses, and gaps in existing primary and secondary control strategies, focusing on how they manage voltage and frequency regulation in dynamic environments.

2. Design a Primary Control System for Basic Stability:

- Develop a robust primary control system that ensures the fundamental stability of the microgrid under both grid-connected and islanded modes.
- Focus on achieving immediate voltage and frequency stabilisation through efficient control algorithms that respond swiftly to disruptions and maintain the microgrid's stability.

3. Develop a Distributed Cooperative Secondary Control Scheme for Enhanced Voltage and Frequency Regulation:

- Create an innovative distributed cooperative control (DCC) strategy using net-

worked multi-agent systems (MAS) to enhance voltage and frequency regulation.

- Ensure the control scheme supports decentralized decision-making, reducing reliance on complex communication infrastructures and enhancing system resilience.
- Integrate Input-Output Feedback Linearization (IOFL) to manage the nonlinear dynamics of distributed generators (DGs), applying linear control techniques for precise regulation.

4. Implement and Validate the Control Schemes Using MATLAB Simulations:

- Utilize MATLAB to model and simulate the proposed control schemes, providing a detailed analysis of the microgrid's behaviour under various scenarios.
- Include simulations involving solar generation with Maximum Power Point Tracking (MPPT) and wind generation to reflect realistic operating conditions.
- Construct and test the control strategies on a microgrid testbed with four interconnected DGs according to the specified topology, demonstrating the efficacy and reliability of the proposed methods in maintaining stable voltage and frequency.

By achieving these objectives, this research aims to advance the field of microgrid control, providing scalable and efficient solutions for voltage and frequency regulation in decentralized power systems.

1.4 Thesis Organization

This thesis provides a structured overview of microgrid structures and control techniques. The organization is as follows:

- **Chapter 1: Introduction** - Introduces the fundamental concepts and motivations behind the thesis work.

- **Chapter 2: Theoretical Background & Literature Review** - Reviews the theoretical foundations and existing literature on microgrid systems and control schemes.
- **Chapter 3: Inverter-Based Distributed Generation System Design** - Discusses the design principles and integration strategies for inverter-based distributed generators in the microgrid.
- **Chapter 4: Control Scheme Design** - Outlines the steps for designing appropriate primary and secondary control schemes.
- **Chapter 5: Design & Simulation of Solar and Wind Power Generation Systems**
 - Details the design and simulation of solar and wind power systems, including modelling techniques and performance analysis.
- **Chapter 6: Ensuring Stability in Microgrid Operation** - Examines methods for maintaining stability, including synchronization techniques and control mechanisms.
- **Chapter 7: MATLAB Simulations & Analysis** - Presents MATLAB simulations and analysis of the designed microgrid systems.
- **Chapter 8: Conclusion and Future Works** - Summarizes key findings and discusses potential microgrid control and operation developments.

Chapter 2

Literature Survey

2.1 Microgrid

The electrical power system rapidly evolves towards smart grids, with microgrids as key components. Microgrids are small-scale power systems that integrate loads, energy storage devices (EEDs), and distributed generation from various energy sources. They can operate independently or in conjunction with the main electrical grid. Renewable energy sources, like wind and solar, are ideal for microgrids due to their scalability and flexible connection points. Non-renewable sources, such as petrol or diesel generators, ensure a reliable power supply. Energy storage systems are essential, especially with renewable sources, to manage their intermittent nature [3].

Microgrids are classified into AC (Alternating Current) and DC (Direct Current) types with unique characteristics.

2.1.1 AC Microgrids

AC microgrids are common and compatible with existing electrical infrastructure. They integrate various AC sources and loads and can easily connect to the main grid. Benefits include seamless integration, flexibility, and established standards. Challenges include complex control and potential power quality issues.

2.1.2 DC Microgrids

DC microgrids are gaining popularity due to the increased use of DC-based renewable sources (e.g., solar PV) and DC loads (e.g., LED lighting). They offer efficiency by redu-

cing conversion losses, simplifying control, and easier integration of DC-based sources. Challenges include the need for new standards, protection technologies, and regulatory frameworks.

In summary, AC and DC microgrids are vital for smart grid development. The choice depends on specific needs, existing infrastructure, and types of generation and loads. Effective management and integration of these microgrids are essential for a robust, flexible, and sustainable smart grid.

2.2 Distributed Generators in an AC Microgrid

Distributed generation (DG) plays a crucial role in modern power systems. Still, its widespread adoption raises concerns about system reliability due to technical challenges associated with voltage stability & constraints on power flow. These challenges stem partly from the traditional perception of DG as additional units of generation with limited controllability from transmission and distribution system operators (TSOs/DSOs). This has led to predominantly passive and inflexible distribution networks, not having the capacity to isolate particular areas to function as microgrids in the event of emergencies or grid failures. Moreover, this lack of controllability hinders the efficient utilization of DG capacity. It necessitates the operation of the growing penetration of distributed generation (DG), which leads to an unwarranted increase in the total installed capacity of traditional power plants at their bare minimum point of operation as auxiliary reserves.

Despite these challenges, A high degree of integration of DG systems can promote more adaptable and efficient grid operation. DG networks, as contrasted with large-scale power plants, are usually closer to end users because they are connected to distribution networks. This proximity reduces overall transmission losses. Energy storage systems (ESS) can also be integrated with distributed generation (DG) plants to create active islands, or microgrids, powered by local generation. This can improve supply continuity and offer a variety of additional amenities. Future power grids are anticipated to rely heavily on microgrids, especially in low-voltage (LV) distribution grids, which are the primary means of connecting distributed generation (DG) systems.

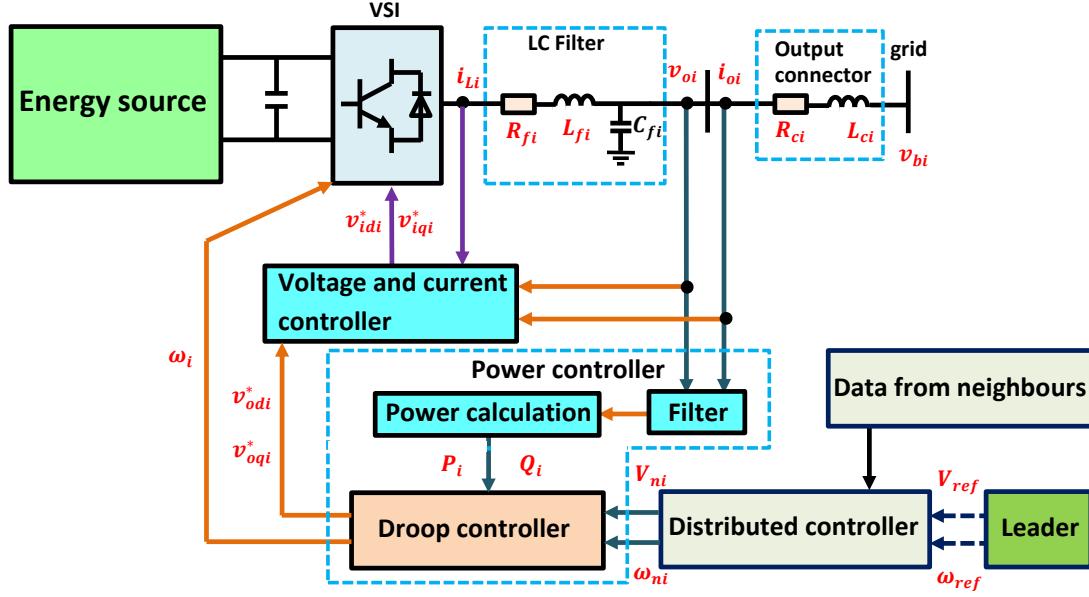


Figure 2.1: Block diagram of VSI based DG.

2.3 The Power Electronic Converters Used in AC Microgrids

Power electronic converters used in AC microgrids can be categorized into three types based on their operational characteristics [4]:

- **Grid-Forming (GFM) Power Converters:** These converters serve as the perfect source of low-output impedance AC voltage, establishing the local grid's voltage (E^*) and frequency (ω^*) through a control loop. They can operate in islanded mode and regulate frequency and voltage. However, they may face small-signal instability in stiff grids and are susceptible to overload conditions (Figure 2.2).
- **Grid-Following (GFL) Power Converters:** Also known as grid-feeding converters, these converters operate as current sources connected in parallel to the grid at a high impedance. They rely on an existing grid voltage, making them unsuitable for island mode operation. GFL control includes an outer power loop for regulating converter output power and an inner current loop for regulating grid current according to the outer loop's reference (Figure 2.3).
- **Grid-Supporting (GSP) Power Converters:** These converters provide ancillary

services to the grid, such as voltage and frequency regulation, without directly affecting the grid's voltage and frequency. They typically operate with grid-forming converters, acting as an intermediary to regulate grid voltage and frequency.

Grid-supporting converters are essential components of AC microgrids, contributing to system stability and reliability. They can be modelled as either current or voltage sources, effectively controlling the voltage amplitude and frequency of the grid. The choice of representation depends on the specific implementation and control strategies employed.

2.3.1 A. Grid-Forming Power Electronic Converters

Grid-forming power converters are designed to act as the primary grid voltage source, typically operating in microgrids where the primary grid is unavailable. They serve as excellent AC voltage sources with a defined amplitude (E^*) and frequency (ω^*) through a closed-loop control system. Their low output impedance necessitates a highly precise synchronization mechanism for parallel operation with additional converters for grid formation [5].

A real-world illustration of a grid-forming power conversion device is a standby UPS. During regular operations, this system stays disconnected from the main power grid. However, in the event of a grid outage, the UPS's power converter assumes responsibility for generating the grid voltage. All connected grid-feeding energy converters in a microgrid use the AC voltage generated from the grid-forming power converter as a reference.

Control Strategy

A control system using two controllers that cascade synchronously operating in the dq reference frame is shown for a grid-forming converter. The system receives the desired amplitude (E^*) and frequency (ω^*) of the voltage to be generated as inputs at the point of common coupling (PCC) by the power converter. At the same time, the internal loop keeps an eye on the current, and the external loop adjusts the converter supplies and the grid voltage to coincide with its reference value. Consequently, the regulated current passing through the inductor L_F charges capacitor C_F , effectively maintaining the voltage at output more closely to the reference value given to the voltage control loop.

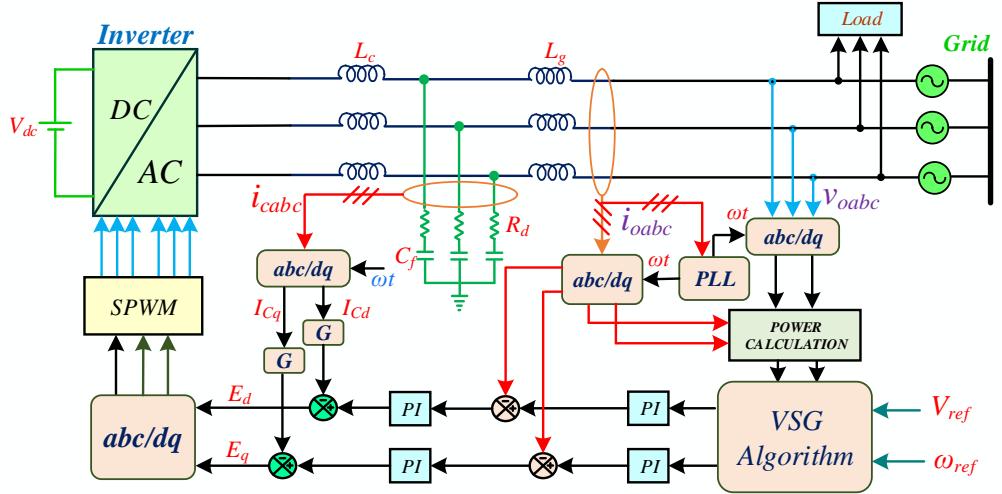


Figure 2.2: Control structure in a 3ϕ grid-forming VSI

2.3.2 B. Grid-Following Power Converters

Grid-following converters, also known as grid-feeding converters, are designed to function as current sources with a high parallel output impedance. This characteristic makes them ideal for parallel connecting to the grid operation alongside other grid-feeding converters. These converters are widely used in distributed generation (DG) systems, such as photovoltaic (PV) and wind power systems. By adjusting the active (P^*) and reactive (Q^*) power references at a higher control level, grid-following power converters assist in controlling the voltage amplitude and frequency of the microgrid. However, for them to function in island mode, they need a local synchronous generator or a grid-forming or grid-supporting energy converter to set the voltage, amplitude, and frequency of the AC microgrid [5].

Control Strategy

Grid-following control includes an outer power loop for regulating converter output power and an inner current loop for regulating grid current as per the outer loop's reference. The Phase-Locked Loop (PLL) synchronises the phase angle with the Point of Common Coupling (PCC), ensuring proper synchronization with the electrical grid voltage.

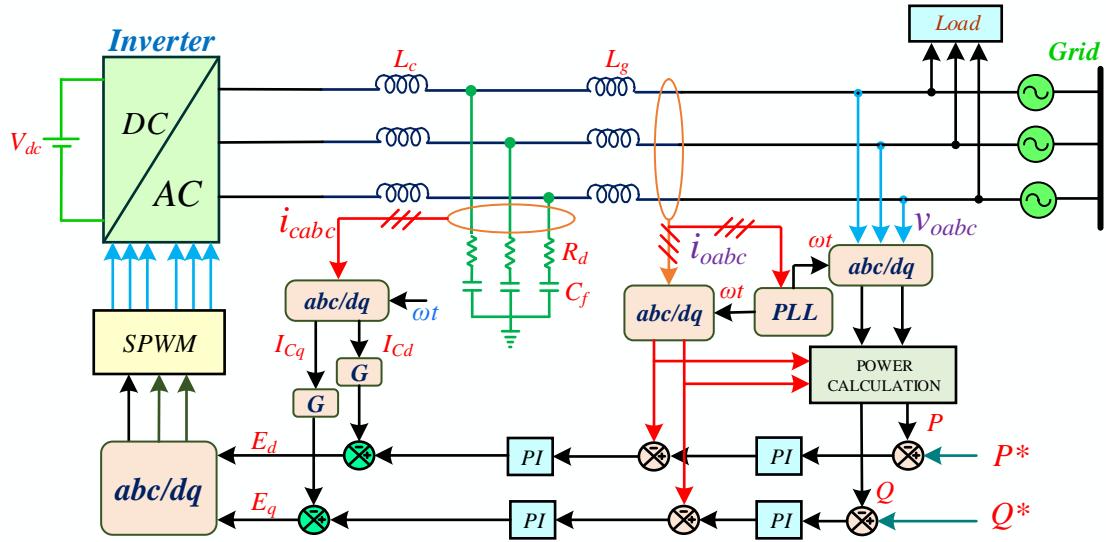


Figure 2.3: Fundamental PQ control architecture of a grid-following converter.

2.3.3 C. Grid Supporting Power Converter

Power converters that support the grid play a crucial role in maintaining the stability and reliability of AC microgrids. They can be controlled as either voltage sources with link impedance or current sources with parallel impedance. Regardless of the chosen control strategy, their primary function is to regulate the electricity supplied to the grid, both active and reactive, thereby influencing the grid's voltage amplitude (E^*) and frequency (ω^*). By effectively managing these parameters, grid-supporting power converters contribute to the overall stability and resilience of the AC microgrid.

Grid-supporting converters can be categorized into two main types based on their control strategies:

- **Current-Controlled Grid-Supporting Power Converters:** These converters, controlled as current sources, provide power to connected loads and regulate voltage amplitude and frequency in the AC grid and the DC microgrid.
- **Voltage-Controlled Grid-Supporting Power Converters:** These converters, emulating how an AC voltage supply behaves, use a link impedance for connecting to the grid. They resemble a simplified synchronous generator, dynamically adjusting operational parameters in response to microgrid conditions.

Table 2.1: Grid-Forming, Grid-Following, and Grid-Supporting Comparison

Feature	Grid-Forming (GFM)	Grid-Following (GFL)	Grid-Supporting (GSP)
Grid Dependency	Independent, can operate without a grid	Dependent on existing grid	Supports and stabilizes the grid
Primary Function	Establishes voltage and frequency	Synchronizes with existing voltage and frequency	Provides ancillary services like voltage and frequency support
Control Complexity	High, complex algorithms for voltage/frequency control	Moderate, primarily uses PLL for synchronization	High, advanced control for grid support
Common Applications	Microgrids, isolated systems, weak grids	Solar inverters, simple renewable installations	Wind turbines, battery storage, smart grids
Grid Stability Contribution	Creates stable grid environment	Relies on stable grid	Enhances grid stability

2.4 Hierarchical Control structure of AC Microgrids

A microgrid's hierarchical control structure is essential to minimize operating costs and maximize efficiency, reliability, and controllability. This structure consists of interconnected power-producing systems with varying technologies and power levels. The microgrid's ideal operating point is influenced by variables such as power ratings, load and generation distribution, generation costs, market prices, and energy availability from stochastic sources.

The hierarchical control comprises three primary levels [6]:

- **Primary Control:** Maintains voltage and frequency stability on the quickest timescale. It reacts instantaneously to disturbances, ensuring rapid adjustments to power imbalances. This layer typically uses droop control mechanisms to adjust output or consumption dynamically based on voltage and frequency deviations.
- **Secondary Control:** Acts more slowly to restore the microgrid's power balance and reference voltage. It focuses on longer-term adjustments, such as power sharing among generation units, economic optimization, and energy storage management.

Centralized controllers communicate with distributed resources to optimize power allocation.

- **Tertiary Control:** Operates at the slowest timescale, managing the overall energy balance by optimizing energy consumption and generation over extended periods. It considers energy prices, demand forecasts, grid interactions, scheduling generation and consumption patterns to minimize costs and maximize efficiency.

Additionally, ancillary services enhance the microgrid's ability to provide grid support and maintain stability, including voltage and frequency regulation, black start capability, and fault ride-through.

Hierarchical control ensures efficient, reliable, and controllable microgrid operation by coordinating diverse generation and storage systems, providing stable and resilient power while optimizing energy usage and minimizing costs.

2.5 The conventional primary & secondary control scheme

There are two forms of operation for a microgrid: islanded and grid-connected. The main grid controls the microgrid's voltage & frequency when it is in grid-connected mode. The microgrid may enter an islanded mode due to unforeseen disruptions or prearranged scheduling. Following the islanding process, the primary control maintains the microgrid's voltage & frequency stability. By maintaining voltage & frequency in the predetermined ranges, primary control helps to prevent instability in these variables. It may not restore the microgrid's regular operational environment; instead, a higher control level is needed to return the voltage & frequency to normal. The secondary control, which counteracts the primary control's effects on voltage and frequency variations, performs this purpose. Compared to primary control, secondary control has a longer time frame for operation. This makes it easier for the primary and secondary control degrees to operate and be designed independently.

Usually, each DG has a local controller in place for primary control. In the case of disruptions, this control level intervenes and is always present. The primary local controllers can be controlled in unison by employing strategies for active & reactive power droop.

A desired relationship between reactive power and voltage amplitude, as well as between frequency and active power, is prescribed by the droop technique. This gives the i_{th} DG's frequency and voltage droop characteristics.

$$\omega_i = \omega_{ni} - m_{P_i} P_i \quad (2.1)$$

$$v_{o_{magi}}^* = V_{ni} - n_{Q_i} Q_i \quad (2.2)$$

where $v_{o_{magi}}^*$ is the output voltage reference value sent to the DG internal voltage control loop, ω_i is the DG's angular frequency as determined by the main control, P_i and Q_i are the measured active and reactive power at the DG's terminal, m_{P_i} and n_{Q_i} known as the droop coefficients, V_{ni} and ω_{ni} are the primary control references. Each DG's active and reactive power ratings are taken into consideration while choosing the droop coefficients. The references V_{ni} and ω_{ni} are determined by the secondary controller for the primary controller to control both the amplitude of voltage & frequency to the set nominal levels. Traditional secondary control relies on a centralized controller with a PI structure, requiring a star communication network. This centralized approach poses potential reliability challenges due to its reliance on a single communication hub. As an alternative, A cooperative control system that is distributed in nature is suggested, eliminating the need for a central controller and enhancing system reliability [1].

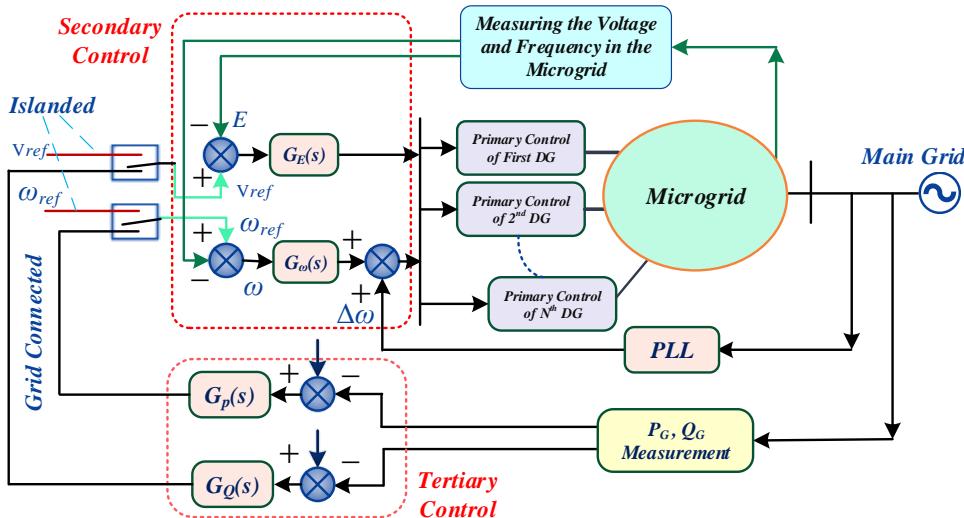


Figure 2.4: Block diagram of conventional secondary control structure

Chapter 3

Architecture of an Inverter-Based DG unit

3.1 Design of Voltage Source Inverter with Sinusoidal Bipolar PWM Scheme

3.1.1 Introduction

This design uses a Voltage Source Inverter (VSI) to convert DC to AC power using a sinusoidal bipolar Pulse Width Modulation (PWM) scheme. This method generates a high-quality AC output with controllable frequency and amplitude [7].

3.1.2 Sinusoidal Bipolar PWM Scheme

The sinusoidal bipolar PWM scheme compares a reference sinusoidal waveform with a high-frequency triangular carrier waveform. The resulting PWM signal controls the inverter switches to approximate the sinusoidal reference [8].

Modulation Index (m_a)

The modulation index (m_a) is a critical parameter defined as:

$$m_a = \frac{V_{\text{ref}}}{V_{\text{tri}}} \quad (3.1)$$

where V_{ref} is the peak value of the sinusoidal reference waveform, and V_{tri} is the peak value of the triangular carrier waveform.

Frequency Ratio (m_f)

The frequency ratio (m_f) is defined as the ratio of the carrier frequency (f_c) to the reference signal frequency (f_{ref}):

$$m_f = \frac{f_c}{f_{\text{ref}}} \quad (3.2)$$

To avoid specific harmonics, m_f should be chosen as an odd multiple of three (e.g., 3, 9, 15, ...). This choice helps to cancel out triplen harmonics (multiples of three), as detailed in [8].

3.1.3 Output Voltage Calculation

The output voltages of the VSI, both phase and line-to-line, are expressed in terms of the modulation index.

Phase Voltage (V_{ph})

The fundamental component of the phase voltage for a sinusoidal bipolar PWM is given by:

$$V_{\text{ph}} = \frac{m_a V_{\text{dc}}}{2} \sin(\omega t) \quad (3.3)$$

where V_{dc} is the DC bus voltage, and ω is the angular frequency of the reference sinusoidal waveform.

Line-to-Line Voltage (V_{ll})

The line-to-line voltage is derived from the phase voltages. For a balanced three-phase system, it is:

$$V_{\text{ll}} = V_{ab} = V_{\text{ph},a} - V_{\text{ph},b} = \frac{m_a V_{\text{dc}}}{2} (\sin(\omega t) - \sin(\omega t - 120^\circ)) \quad (3.4)$$

Using trigonometric identities, this simplifies to:

$$V_{\text{ll}} = \sqrt{3} \frac{m_a V_{\text{dc}}}{2} \sin(\omega t + 30^\circ) \quad (3.5)$$

3.1.4 Under-Modulation and Over-Modulation

Under-Modulation ($m_a \leq 1$)

The output voltage is directly proportional to the modulation index in the under-modulation region. The VSI operates linearly, and the phase voltage is given by:

$$V_{\text{ph}} = \frac{m_a V_{\text{dc}}}{2} \sin(\omega t). \quad (3.6)$$

Over-Modulation ($m_a > 1$)

In the over-modulation region, the reference sinusoidal waveform exceeds the carrier waveform, causing the output voltage to be clipped. The VSI no longer operates linearly, and the output voltage includes significant harmonic distortion. The fundamental line-to-line RMS voltage in the over-modulation case is approximately [8]:

$$V_{\text{ll,RMS}} = 0.74 V_{\text{dc}} \quad (3.7)$$

3.2 Design and Comparison of LC and LCL Filters for Microgrid Inverters

Filters play a critical role in grid-connected inverters by reducing harmonic distortion and enhancing power quality. This section outlines the step-by-step design procedures for LC and LCL filters, followed by comparing their performance characteristics, advantages, and disadvantages [9].

3.2.1 LC Filter Design

An LC filter, consisting of an inductor (L) and a capacitor (C), filters out high-frequency harmonics from the inverter output.

Design Steps

1. **Calculate the Cutoff Frequency:** The cutoff frequency (f_c) is given by:

$$f_c = \frac{1}{2\pi\sqrt{LC}} \quad (3.8)$$

2. **Select Inductor (L):** Choose an inductor value based on the desired current ripple and system requirements.
3. **Determine Capacitor (C):** Using the selected inductance and the cutoff frequency, calculate the capacitance:

$$C = \frac{1}{(2\pi f_c)^2 L} \quad (3.9)$$

Component Parameters

The inductor should be rated to handle the maximum expected current, while the capacitor should have a voltage rating exceeding the peak inverter output voltage.

Performance Analysis

The LC filter provides single-pole attenuation, effectively reducing high-frequency harmonics with an attenuation rate of 20 dB per decade.

3.2.2 LCL Filter Design

An LCL filter, which includes two inductors (L_1 and L_2) and a capacitor (C), offers better attenuation of high-frequency harmonics than an LC filter.

Design Steps

1. **Calculate the Resonant Frequency:** The resonant frequency (f_r) is determined by:

$$f_r = \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1 L_2 C}} \quad (3.10)$$

2. **Select Inductors (L_1 and L_2):** Choose L_1 and L_2 values to meet the desired current ripple and resonant frequency.

- 3. Calculate Capacitor (C):** Using the selected inductances and the resonant frequency, determine the capacitance:

$$C = \frac{1}{(2\pi f_r)^2(L_1 + L_2)} \quad (3.11)$$

- 4. Add Damping Resistor (R) (Optional):** Include a damping resistor to control resonance if necessary.

Component Parameters

L1 is typically chosen to limit the inverter's current ripple, while L2 handles the grid-side current ripple. The capacitor should be rated for a voltage higher than the peak inverter output voltage.

Performance Analysis

The LCL filter offers a higher attenuation rate of 60 dB per decade, providing superior high-frequency harmonic suppression, but it may require damping to mitigate resonance issues.

3.2.3 Comparison of LC and LCL Filters

The table below summarizes the key advantages and disadvantages of LC and LCL filters:

Table 3.1: Comparison of LC and LCL Filters

Filter Type	Advantages	Disadvantages
LC Filter	Simpler design, fewer components, cost-effective	Lower high-frequency attenuation, larger size for equivalent performance
LCL Filter	Superior high-frequency attenuation, more compact	More complex design, potential resonance issues, higher cost

3.2.4 Conclusion

In summary, both LC and LCL filters have distinct advantages and drawbacks. The LC filter is simpler and less expensive but provides less effective high-frequency harmonic

attenuation. Conversely, the LCL filter offers better performance in harmonic suppression but at the cost of increased complexity and potential resonance issues. The choice between these filters should be based on specific application requirements such as harmonic suppression needs, budget constraints, and system complexity.

3.3 Output Connector Design & Connection to PCC

An RL connector, consisting of a resistor (R) and an inductor (L), is used to connect the inverter to the Point of Common Coupling (PCC).

3.3.1 Role of RL Connector

- **Resistor (R):** Helps to dampen oscillations and improve system stability.
- **Inductor (L):** Limits inrush currents and smooths the current waveform.

Each Distributed Generator (DG) inverter, equipped with its LC filter and RL connector, is connected to the PCC. The control strategy ensures that the voltage and frequency at the PCC are maintained within the desired parameters.

3.4 Reference Transformation Matrices

The abc to dq0 transformation, also known as the Park and Clarke transformations, is a mathematical technique widely used in the analysis and control of three-phase electrical systems. This transformation converts three-phase time-domain signals into a rotating reference frame, simplifying the analysis and control of AC machines and power systems [10].

3.4.1 Importance and Uses

The dq0 transformation offers several benefits:

- **Simplified Control:** In the dq0 frame, AC quantities become DC quantities, making it easier to design and implement control strategies.

- **Decoupled Control:** The transformation decouples the active and reactive power components, allowing independent control of these quantities.
- **Harmonic Analysis:** It aids in analysing harmonic content and implementing harmonic mitigation techniques.

3.4.2 Stationary and Rotating Frames of Reference

In electrical engineering, two primary frames of reference are used for analysis: the stationary frame and the rotating frame [10].

- **Stationary Frame:** In this frame, the abc and $\alpha\beta0$ components are observed. The Clarke transformation is used to convert abc components into $\alpha\beta0$ components.
- **Rotating Frame:** In this frame, the $\alpha\beta0$ components are transformed into dq0 components using the Park transformation. The rotating frame rotates synchronously with the reference frequency of the system, converting AC quantities into DC quantities.

3.4.3 Clarke Transformation

The Clarke transformation converts three-phase quantities into two orthogonal components in the stationary reference frame, denoted as $\alpha\beta0$.

The Clarke transformation matrix is given by:

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3.12)$$

3.4.4 Park Transformation

The Park transformation converts the $\alpha\beta0$ components into the rotating dq0 reference frame.

The Park transformation matrix is given by:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} \quad (3.13)$$

Here, θ is the angular position of the rotating reference frame.

3.4.5 abc to dq0 Transformation Matrix

The abc to dq0 transformation is a mathematical conversion used in three-phase power systems to simplify the analysis of AC quantities. This transformation converts three-phase time-domain signals into a rotating reference frame, resulting in two constant (DC) components (d and q) and one zero-sequence component (0).

The transformation matrix for converting abc components to dq0 components is given by:

$$\mathbf{T} = \frac{2}{3} \begin{bmatrix} \cos(\omega t) & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \\ -\sin(\omega t) & -\sin\left(\omega t - \frac{2\pi}{3}\right) & -\sin\left(\omega t + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \quad (3.14)$$

3.4.6 Power Equations in abc and dq0 Domains

The instantaneous active and reactive power in the abc domain can be calculated using the following expressions:

$$\begin{aligned} P_{abc} &= v_a i_a + v_b i_b + v_c i_c \\ Q_{abc} &= \frac{\sqrt{3}}{2} (v_b i_c - v_c i_b) \end{aligned} \quad (3.15)$$

In the dq0 domain, the active and reactive power can be expressed as:

$$\begin{aligned} P_{dq0} &= \frac{3}{2} (v_d i_d + v_q i_q) \\ Q_{dq0} &= \frac{3}{2} (v_q i_d - v_d i_q) \end{aligned} \quad (3.16)$$

Table 3.2: Active and Reactive Power Equations in abc and dq0 Domains

Domain	Active Power	Reactive Power
abc	$P_{abc} = v_a i_a + v_b i_b + v_c i_c$	$Q_{abc} = \frac{\sqrt{3}}{2} (v_b i_c - v_c i_b)$
dq0	$P_{dq0} = \frac{3}{2} (v_d i_d + v_q i_q)$	$Q_{dq0} = \frac{3}{2} (v_q i_d - v_d i_q)$

3.4.7 Visual Representation of Reference Frames

To provide a visual representation of the reference frames, the following figure shows the axes for abc, $\alpha\beta0$, and dq0 transformations.

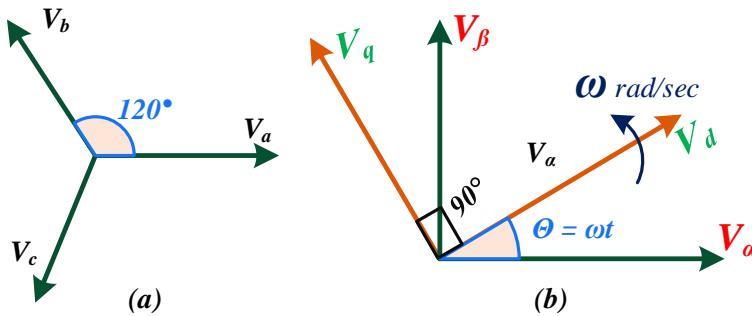


Figure 3.1: Reference frames for ABC, $\alpha\beta0$, and DQ0 Transformations

3.4.8 Conclusion

The abc to dq0 transformation is an essential tool in the analysis and control of three-phase electrical systems. It simplifies the control strategies by converting AC quantities into DC quantities in a rotating reference frame, facilitating decoupled control of active and reactive power. The transformation involves the Clarke and Park transformations, each serving a specific purpose in the overall process. The stationary and rotating frames of reference are critical in understanding and implementing these transformations.

3.5 Bipolar Sinusoidal PWM in closed loop

3.5.1 Modulation Index (m_a) and Reference Voltage Scaling

The modulation index (m_a) is a key parameter in PWM control, defined as:

$$m_a = \frac{V_{\text{ref}}}{V_{\text{tri}}} \quad (3.17)$$

where V_{ref} is the peak of the sinusoidal reference signal, and V_{tri} is the peak of the triangular carrier wave.

3.5.2 Role of Scaling dq Voltages

The reference dq voltages (V_d^* and V_q^*) generated by the current controller are in the dq frame and must be transformed into abc frame voltages for PWM generation. However, to ensure the correct operation of the PWM scheme and maintain a constant modulation index, these dq reference voltages need to be appropriately scaled.

Reason for Scaling by $\frac{V_{dc}}{2}$

- The DC bus voltage (V_{dc}) represents the maximum voltage that the inverter can apply.
- By dividing the reference dq voltages by $\frac{V_{dc}}{2}$, we normalize the reference voltages to a scale compatible with the inverter's capability.
- This scaling ensures that the reference voltages remain within the bounds of the inverter's output range, preventing over-modulation and maintaining the desired m_a within the range of [0,1] for linear operation.

Mathematically, the scaled dq voltages are:

$$V_d^{\text{scaled}} = \frac{V_d^*}{\frac{V_{dc}}{2}} = \frac{2V_d^*}{V_{dc}} \quad (3.18)$$

$$V_q^{\text{scaled}} = \frac{V_q^*}{\frac{V_{dc}}{2}} = \frac{2V_q^*}{V_{dc}} \quad (3.19)$$

3.5.3 Observations on Reference Signal Behavior

1. Maintaining Constant m_a :

- The reference voltages in the abc frame must be compared to the triangular carrier wave to generate PWM signals.
- As observed, the peak of the reference waveform increases proportionally with the peak of the triangular wave to maintain a constant m_a . This behaviour ensures that the ratio $\frac{V_{ref}}{V_{tri}}$ remains constant, which is critical for stable and predictable PWM operation.

2. Effect of V_{dc} on Reference Voltages:

- Increasing V_{dc} from a minimum required value to a higher value reduces the scaled reference voltages. This happens because the normalization factor $\frac{V_{dc}}{2}$ increases, causing the scaled reference voltages to decrease, ensuring $m_a < 1$ for linear operation.
- When V_{dc} is increased, the same output voltage can be achieved with a lower m_a , which reduces the risk of entering the over-modulation region and maintains the inverter's linear performance.

3.5.4 Practical Implementation in PWM Generation

Current Controller Output

The current controller generates V_d^* , V_q^* , and V_0^* based on the desired current references and feedback from the system.

Scaling and $dq0$ to abc Transformation

The reference $dq0$ voltages are scaled by $\frac{V_{dc}}{2}$ to ensure they are within the appropriate range. These scaled voltages are then transformed from the $dq0$ frame to the abc frame using the inverse Park and Clarke transformations:

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ \cos(\theta - 120^\circ) & \sin(\theta - 120^\circ) \\ \cos(\theta + 120^\circ) & \sin(\theta + 120^\circ) \end{pmatrix} \begin{pmatrix} V_d^{\text{scaled}} \\ V_q^{\text{scaled}} \end{pmatrix} + \begin{pmatrix} V_0^{\text{scaled}} \\ V_0^{\text{scaled}} \\ V_0^{\text{scaled}} \end{pmatrix} \quad (3.20)$$

PWM Reference Signal

The resulting abc reference voltages are then compared to the triangular carrier wave to generate the PWM signals. The comparison produces the necessary switching signals for the inverter transistors to synthesize the desired AC output.

3.6 Utilizing Low Pass Filters for Power Controller Design

In the design of microgrid primary controllers, low pass filters (LPFs) are instrumental in passing the average value of calculated power in the dq domain while mitigating high-frequency noise and disturbances. This is essential for achieving stable and accurate power flow control within the microgrid.

3.6.1 Effect of Cut-Off Frequency on Output Response

The cut-off frequency (f_c) of an LPF significantly affects the power controller and microgrid performance. Higher f_c values allow faster response times but can cause overshoot and instability. Lower f_c values produce smoother power waveforms but may delay the power controller's response. Thus, selecting f_c requires balancing noise attenuation and control dynamics to optimize microgrid performance.

Chapter 4

Primary and Secondary Control Scheme Design

4.1 Primary Control scheme

The block diagram of the primary control scheme, based on the architecture of the grid-forming converter, is provided here. The following subsections cover the design steps of this scheme.

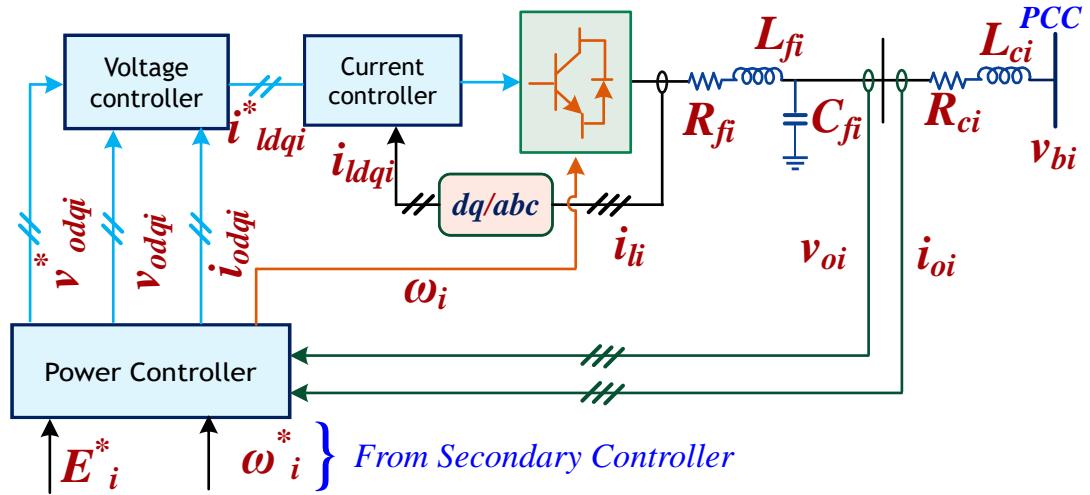


Figure 4.1: The block diagram for the Primary controller of DG.

4.1.1 Large-Signal Dynamical Model of VSI-based DGs

The distributed generator's (DG) detailed nonlinear dynamical model establishes the suggested strategy. An inverter-based DG's schematic diagram is displayed in Figure 1.1. It comprises a main DC power supply coupled to an inverter bridge(fuel cells or photovoltaic panels). The controllers for voltage, current, and power that make up the control loops

control the inverter bridge's output frequency as well as voltage. Average-value modelling allows for the safe disregard of switching artefacts because of the inverter bridge's relatively high switching frequency. As previously stated, if the DG side has an ideal source, DC bus dynamics are safe to overlook. Here, it's crucial to note that every DG's nonlinear dynamics are stated in a unique (dq) reference frame. It is our understanding that the frame of reference for the i^{th} DG revolves at the corresponding reference frame's frequency, and With a rotating frequency, the reference frame of one DG is regarded as the common one. The angle of the i^{th} DG reference frame relative to the common reference frame, is denoted as δ and follows the differential equation [2]:

$$\dot{\delta}_i = \omega_i - \omega_{com}. \quad (4.1)$$

The frequency-droop characteristic causes all reference frames to rotate synchronously at the same angular frequency even though different angular frequencies are considered for each reference frame. The power controller block offers the voltage references v_{odi}^* and v_{oqi}^* as well as ω_i the inverter bridge's operating frequency and incorporates the droop approach for the voltage controller, as well as ω_i the operating frequency for the inverter bridge. Two low-pass filters(LPFs) with the cut-off frequency as ω_{ci} are used to obtain the

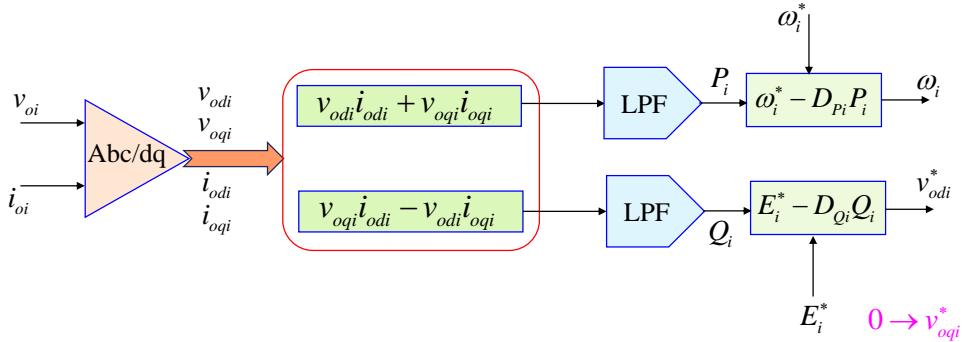


Figure 4.2: Block diagram for the power controller used in primary control.

fundamental active and reactive powers of output, denoted as P_i and Q_i , respectively. For this power controller block, the differential equations can be written as,

$$\dot{P}_i = -\omega_{ci}P_i + \omega_{ci}(v_{odi}i_{odi} + v_{oqi}i_{oqi}) \quad (4.2)$$

$$\dot{Q}_i = -\omega_{ci}Q_i + \omega_{ci}(v_{oqi}i_{odi} - v_{odi}i_{oqi}) \quad (4.3)$$

Where v_{odi} , v_{oqi} , i_{odi} , and i_{oqi} are known as direct and quadrature components of output voltage and current. Every DG's primary control technique lines up the output voltage's magnitude with the appropriate reference frame's d-axis [11]. Therefore

$$\begin{cases} v_{odi}^* = V_{ni} - n_{Qi} Q_i \\ v_{oqi}^* = 0 \end{cases} \quad (4.4)$$

Fig. 3 displays the voltage controller's block diagram. The voltage controller's differential-algebraic equations are expressed as follows []:

$$\dot{\phi}_{di} = v_{odi}^* - v_{odi} \quad (4.5)$$

$$\dot{\phi}_{qi} = v_{oqi}^* - v_{oqi} \quad (4.6)$$

$$i_{ldi}^* = F_i i_{odi} - \omega_b C_{fi} v_{oqi} + K_{PVi}(v_{odi}^* - v_{odi}) + K_{IVi}\phi_{di} \quad (4.7)$$

$$i_{lqi}^* = F_i i_{oqi} + \omega_b C_{fi} v_{odi} + K_{PVi}(v_{oqi}^* - v_{oqi}) + K_{IVi}\phi_{qi} \quad (4.8)$$

where ω_b is the nominal angular frequency, and ϕ_{di} , ϕ_{qi} are the auxiliary state variables defined for PI controllers in Fig. 3. Additional parameters are displayed in the figure.

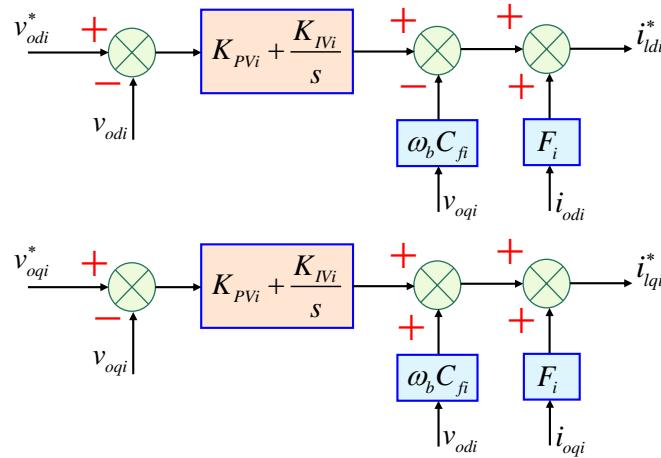


Figure 4.3: Block diagram of voltage controller

Figure 4 displays the current controller's block diagram, and its differential-algebraic equations are expressed as:

$$\dot{i}_{di} = i_{ldi}^* - i_{ldi} \quad (4.9)$$

$$\dot{i}_{qi} = i_{lqi}^* - i_{lqi} \quad (4.10)$$

$$v_{idi}^* = -\omega_b L_{fi} i_{lqi} + K_{PCi}(i_{ldi}^* - i_{ldi}) + K_{ICi}\gamma_{di} \quad (4.11)$$

$$v_{iqi}^* = \omega_b L_{fi} i_{ldi} + K_{PCi}(i_{lqi}^* - i_{lqi}) + K_{ICi}\gamma_{qi} \quad (4.12)$$

i_{ldi} & i_{lqi} are the direct component & quadrature components of i_{li} and γ_{di} & γ_{qi} are the auxiliary state variables provided for the PI controllers in Fig. 4. Additional parameters are depicted in the figure.

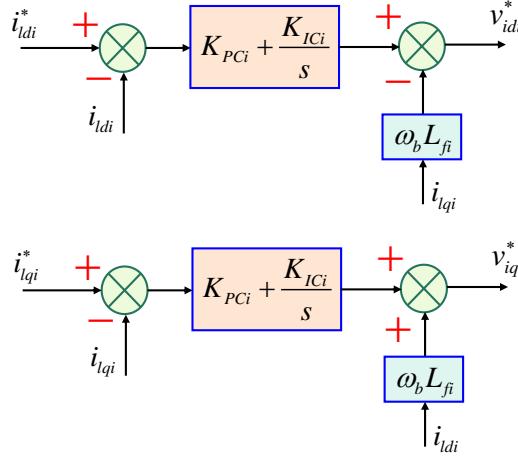


Figure 4.4: Block Diagram of the Current Controller.

The below differential equations which apply to the output LC filter and output connector are [12]:

$$\dot{i}_{ldi} = -\frac{R_{fi}}{L_{fi}}i_{ldi} + \omega_i i_{lqi} + \frac{1}{L_{fi}}v_{idi} - \frac{1}{L_{fi}}v_{odi} \quad (4.13)$$

$$\dot{i}_{lqi} = -\frac{R_{fi}}{L_{fi}}i_{lqi} - \omega_i i_{ldi} + \frac{1}{L_{fi}}v_{iqi} - \frac{1}{L_{fi}}v_{oqi} \quad (4.14)$$

$$\dot{v}_{odi} = \omega_i v_{oqi} + \frac{1}{C_{fi}}i_{ldi} - \frac{1}{C_{fi}}i_{odi} \quad (4.15)$$

$$\dot{v}_{oqi} = -\omega_i v_{odi} + \frac{1}{C_{fi}}i_{lqi} - \frac{1}{C_{fi}}i_{oqi} \quad (4.16)$$

$$\dot{i}_{odi} = -\frac{R_{ci}}{L_{ci}}i_{odi} + \omega_i i_{oqi} + \frac{1}{L_{ci}}v_{odi} - \frac{1}{L_{ci}}v_{bdi} \quad (4.17)$$

$$\dot{i}_{oqi} = -\frac{R_{ci}}{L_{ci}}i_{oqi} - \omega_i i_{odi} + \frac{1}{L_{ci}}v_{oqi} - \frac{1}{L_{ci}}v_{bqi} \quad (4.18)$$

The large-signal model(dynamic) for the i^{th} DG is composed of equations (2.3)–(2.20). A compact form of the large-signal dynamical model is as follows:

$$\begin{cases} \dot{X}_i = f_i(X_i) + k_i(X_i)D_i + g_i(X_i)u_i \\ y_i = h_i(X_i) \end{cases} \quad (4.19)$$

where the state vector is:

$$X_i = [\delta_i \ P_i \ Q_i \ \phi_{di} \ \phi_{qi} \ \gamma_{di} \ \gamma_{qi} \ i_{ldi} \ i_{lqi} \ v_{odi} \ v_{oqi} \ i_{odi} \ i_{oqi}]^T \quad (4.20)$$

and $D_i = [\omega_{com} \ v_{bdi} \ v_{bqi}]^T$, is considered as a known disturbance. The expressions of $f_i(X_i)$, $g_i(X_i)$ & $k_i(X_i)$ can be obtained from equation 2.3 to 2.20.

The secondary controller selects V_{ni} such that the terminal voltage of every DG tending to the nominal value, i.e. $v_{o,magi} \rightarrow v_{ref}$.

The value of the output voltage is

$$v_{o,magi} = \sqrt{v_{odi}^2 + v_{oqi}^2} \quad (4.21)$$

By selecting appropriate control input V_{ni} such that $v_{odi} \rightarrow v_{ref}$, the amplitude of voltage can be brought into synchronization. Therefore to achieve required secondary voltage control the output & control input are set to

$y_i = v_{odi}$ and $u_i = V_{ni}$, respectively.

4.2 Secondary Voltage control

The block diagram of the secondary control scheme is provided here. The following subsections cover the design steps of this scheme.

4.2.1 An Introduction to Graph Theory

A directed graph(digraph) can be used to simulate the communication network of a multi-agent cooperative system. A digraph is often expressed as $G_r = (V_G, E_G, A_G)$ by a finite, nonempty collection of nodes, $V_G = [v_1, v_2, v_3, \dots, v_N]$, a group of branches or edges, $E_G \subset V_G \times V_G$, & the corresponding adjacency matrix $A_G = [a_{ij}] \in R^{N \times N}$. DGs are thought of as the communication digraph nodes in a microgrid. The communication links

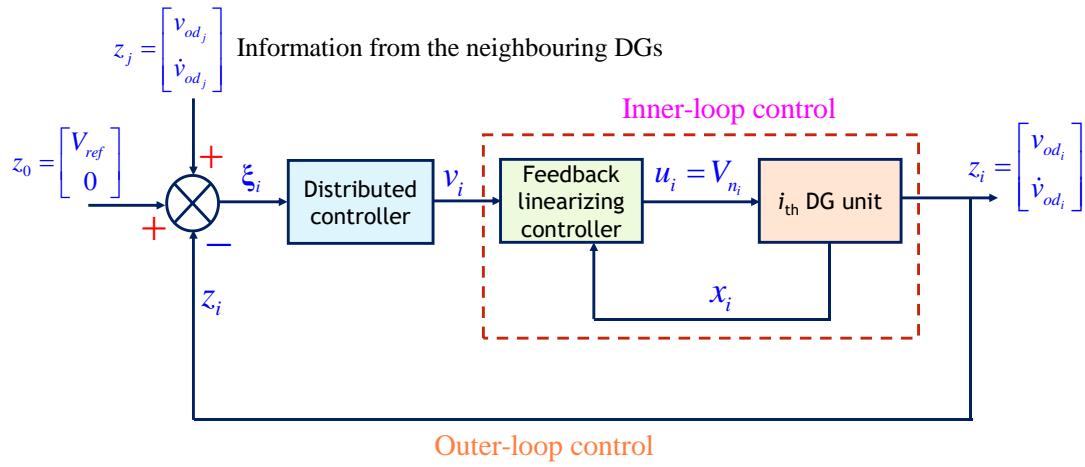


Figure 4.5: The block diagram for the secondary voltage controller.

are indicated by the edges of the digraph in the communication network [2]. The digraph is taken to be time-invariant in this instance i. e. A_G is constant. The representation of an edge from node j to node i is (v_j, v_i) , showing that node j sends information to node i , a_{ij} represents the edge's weight, (v_j, v_i) , and $a_{ij} > 0$ if $(v_j, v_i) \in E_G$, otherwise $a_{ij} = 0$. The neighbor node of node j is identified as node i if $(v_i, v_j) \in E_G$. For node j , the collection of its neighbour nodes is represented as $N_j = \{i | (v_i, v_j) \in E_G\}$.

For a digraph, if node j is a neighbour of node i , node i can acquire information from node j , but not vice versa. The definition of the so-called in-degree matrix is as, $D = diag\{d_i\} \in R^{N \times N}$ with $\sum_{j \in N_i} a_{ij}$. We shall define the Laplacian matrix as, $L = D - A_G$. A series of edges, expressed as $\{(v_i, v_k), (v_k, v_l), (v_l, v_m), \dots, (v_x, v_j)\}$, shows the straight route between nodes i and j . If every other node in the graph can be reached directly from the root node of a digraph, then that digraph supposedly has a spanning tree.

4.2.2 Utilization of Distributed Cooperative scheme

In a microgrid, which is comparable to a heterogeneous multi-agent system that is nonlinear, each DG functions as an agent. The task of secondary control for microgrids is similar to tracking synchronization, where all DGs try to synchronize their terminal voltage amplitude towards the pre-specified reference values. For this reason, each DG should only communicate with its neighbors. A communication graph can be used to model the necessary communication network. Here is a quick overview of graph theory. First, input-

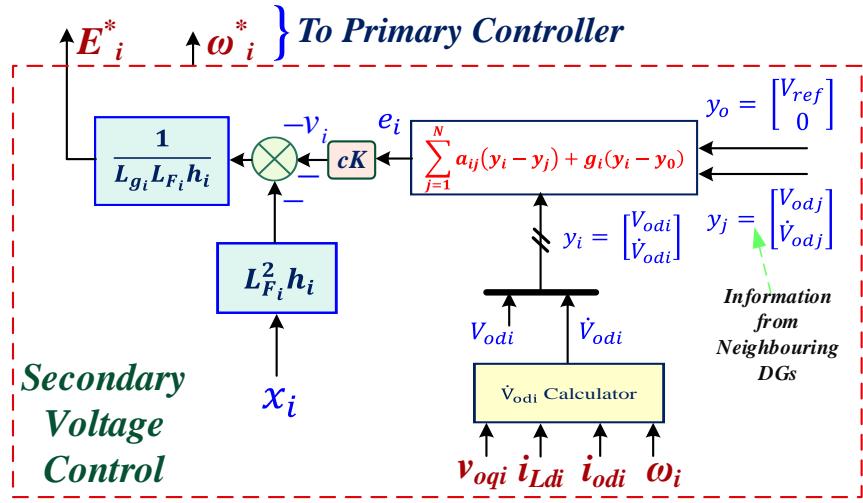


Figure 4.6: Distributed secondary cooperative voltage control mechanism.

output feedback linearization and distributed cooperative control of systems with multiple agents are employed to perform secondary voltage control. The final section of the discussion covers the communication network specifications for the suggested secondary voltage control.

4.2.3 Distributed Cooperative Voltage Control Utilizing Feedback Linearization and Tracking Synchronization.

To synchronize the voltage magnitudes of the DGs with the reference voltage, v_{ref} , as explained earlier, the secondary voltage control selects the proper control inputs, V_{ni} in (1). It is equivalent to synchronizing the direct term of output voltages, v_{odi} to synchronize the voltage magnitudes of DGs, $v_{o, magi}$. Consequently, to get $y_i \rightarrow y_0, \forall i$, where $y_0 \equiv v_{ref}$, Suitable u_i must be chosen by the secondary voltage regulator [13].

The secondary voltage control design can be made easier using input-output linearization with feedback because distributed generation (DG) dynamics in a microgrid are nonlinear and may not all be the same. By repeatedly differentiating concerning time, A direct link is established between the dynamics of the control input u_i (or equivalently V_{ni}) and the output y_i (or equivalently v_{odi}) by input-output feedback linearization process. For the

dynamics of the i^{th} DG in (21), the direct relationship between the y_i and u_i is generated after the second derivative of the output y_i as,

$$\ddot{y}_i = L_{\mathbf{F}_i}^2 h_i + L_{\mathbf{g}_i} L_{\mathbf{F}_i} h_i u_i \quad (4.22)$$

where,

$$\mathbf{F}_i(\mathbf{x}_i) = \mathbf{f}_i(\mathbf{x}_i) + \mathbf{k}_i(\mathbf{x}_i) \mathbf{D}_i. \quad (4.23)$$

In the above equation the term $L_{\mathbf{F}_i} h_i$ is known as the Lie Derivative of h_i with respect to F_i , that is described by

$$L_{\mathbf{F}_i} h_i = \Delta h_i F_i = \frac{\partial(h_i)}{\partial x_i} F_i. \quad (4.24)$$

and $L_{\mathbf{F}_i}^2 h_i$ is defined by

$$L_{\mathbf{F}_i}^2 h_i = L_{\mathbf{F}_i}(L_{\mathbf{F}_i} h_i) = \frac{\partial(L_{\mathbf{F}_i} h_i)}{\partial x_i} F_i. \quad (4.25)$$

we can define an auxiliary control v_i as,

$$v_i = L_{\mathbf{F}_i}^2 h_i + L_{\mathbf{g}_i} L_{\mathbf{F}_i} h_i u_i. \quad (4.26)$$

so now we can have a second-order linear system as,

$$\ddot{y}_i = v_i, \quad \forall i \quad (4.27)$$

By selecting the proper v_i , y_i may be synchronised. v_i may now be used to implement the control input as,

$$u_i = (L_{\mathbf{g}_i} L_{\mathbf{F}_i} h_i)^{-1} (-L_{\mathbf{F}_i}^2 h_i + v_i). \quad (4.28)$$

We can follow the below procedure to design an appropriate v_i : Initially, the very first derivative of y_i will be written as,

$$\left. \begin{array}{l} \dot{y}_i \equiv y_{i,1} \\ \dot{y}_{i,1} = v_i \end{array} \right\} \quad \forall i. \quad (4.29)$$

or similarly in state-space representation as,

$$\dot{\mathbf{y}}_i = \mathbf{A}\mathbf{y}_i + \mathbf{B}v_i, \quad \forall i \quad (4.30)$$

where $\mathbf{y}_i = [\mathbf{y}_i \ \mathbf{y}_{i,1}]^T$, $\mathbf{B} = [0 \ 1]^T$ and $\mathbf{A} = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}$

The reference generator's correspondingly reformulated dynamics can be written as

$$\dot{\mathbf{y}}_0 = \mathbf{A}\mathbf{y}_0. \quad (4.31)$$

where $y_0 = [y_0 \ \dot{y}_0]^T$. It is important to note that $\dot{y}_0 = 0$ because $y_0 = v_{ref}$ is constant.

Presumably, the network of communications, represented by the digraph G_r , allows DGs to interact with one another. The i^{th} DG might have to send y_i in (30) over the communication network based on the digraph G_r . A weight factor called the pinning gain g_i is assumed to grant access to the reference y_0 in (31) to only one DG. Finding a distributed vi in (28) such that $y_i \rightarrow y_0, \forall i$ is the secondary voltage control problem. The cooperative team's goals are stated in terms of the local neighbourhood tracking error to tackle this issue,

$$\mathbf{e}_i = \sum_{j \in N_i} a_{ij}(\mathbf{y}_i - \mathbf{y}_j) + g_i(\mathbf{y}_i - \mathbf{y}_0) \quad (4.32)$$

where a_{ij} represents the components of the communication digraph's adjacency matrix. For a single DG, the pinning gain $g_i \neq 0$.

The global error vector for graph G_r for a microgrid with N DGs can be obtained from (32) as

$$\mathbf{e} = ((L + G) \otimes I_2)(\mathbf{Y} - \mathbf{Y}_0) \equiv ((L + G) \otimes I_2)\delta. \quad (4.33)$$

where $\mathbf{Y} = [y_1^T \ y_2^T \ \dots \ y_N^T]^T$, $\mathbf{e} = [e_1^T \ e_2^T \ \dots \ e_N^T]^T$, $\mathbf{Y}_0 = 1_N y_0$ (1_N is a one-dimensional vector of length N), The global disagreement vector is δ , I_2 is the identity matrix with two rows and two columns, and $G = \text{diag}\{g_i\}$.

The Kronecker product [14] is denoted as \otimes & $\dot{\mathbf{Y}}$ can be written as,

$$\dot{\mathbf{Y}} = (I_N \otimes \mathbf{A})\mathbf{Y} + (I_N \otimes \mathbf{B})\mathbf{v} \quad (4.34)$$

where $\mathbf{v} = [v_1 \ v_2 \ \dots \ v_N]^T$ is the global auxiliary control vector. $\dot{\mathbf{Y}}_0$ can be written as,

$$\dot{\mathbf{Y}} = (I_N \otimes \mathbf{A})\mathbf{Y}_0. \quad (4.35)$$

The detailed calculations of the neighbouring error & above-mentioned matrices are given in the Appendix section at the end of this thesis (Appendix A). The following definitions and lemmas are required for designing the auxiliary controls v_i [2].

- **Definition 1:** (\mathbf{A} , \mathbf{B}) are stabilizable if there exists a matrix \mathbf{S} such that all eigenvalues of $\mathbf{A} - \mathbf{BS}$ have a strictly-negative real part.
- **Definition 2:** A matrix is Hurwitz if all of its eigenvalues have a strictly negative real part.
- **Definition 3:** A symmetric matrix \mathbf{P} is positive definite if $X^T \mathbf{P} X$ is positive for all non-zero column vector x , and $X^T \mathbf{P} X$ is zero only for $X = 0$.
- **Lemma 1:** Let (\mathbf{A} , \mathbf{B}) be stabilizable. Let the digraph G_r have a spanning tree and $g_i \neq 0$ for one DG placed on a root node of the digraph G_r . Let $\lambda_i(i \in \{1, 2, 3, \dots, N\})$ be the eigenvalues of $(L + G)$. The matrix.

$$\mathbf{H} = I_N \otimes \mathbf{A} - c(L + G) \otimes \mathbf{B}K \quad (4.36)$$

with $c \in R$ and $K \in R^{1 \times 2}$ is Hurwitz if and only if all of the matrices $A - c\lambda_i BK$, $\forall i \in \{1, 2, 3, \dots, N\}$ are Hurwitz.

- **Lemma 2:** Let (\mathbf{A} , \mathbf{B}) be stabilizable and matrices $Q = Q^T$ and $R = R^T$ be positive definite. Let feedback gain K be chosen as,

$$K = R^{-1} \mathbf{B}^T P_1 \quad (4.37)$$

where P_1 is the unique positive definite solution of the control Algebraic Riccati Equation (ARE),

$$\mathbf{A}^T \mathbf{P}_1 + \mathbf{P}_1 \mathbf{A} + \mathbf{Q} - \mathbf{P}_1 \mathbf{B} \mathbf{R}^{-1} \mathbf{B}^T \mathbf{P}_1 = \mathbf{0}. \quad (4.38)$$

Then, all of the matrices $A - c\lambda_i BK$, $\forall i \in \{1, 2, 3, \dots, N\}$ are Hurwitz if,

$$c \geq \frac{1}{2\lambda_{min}}, \text{ where } \lambda_{min} = \min_{i \in N} Re(\lambda_i).$$

- **Theorem:** Let the digraph G_r have a spanning tree and $g_i \neq 0$ for one DG placed

on a root node of the digraph G_r . It is assumed that the internal dynamics of each DG are asymptotically stable. Let the auxiliary control v_i in (28) be,

$$v_i = -cK\mathbf{e}_i \quad (4.39)$$

where $c \in R$ is the coupling gain and $K \in R^{1 \times 2}$ is the feedback control vector. Then, all y_i in (30) synchronize to y_0 in (31) and, hence, the direct term of DG output voltages v_{odi} synchronizes to v_{ref} , if K is chosen as in (37) and,

$$c \geq \frac{1}{2\lambda_{\min}} \quad (4.40)$$

where $\lambda_{\min} = \min_{i \in N} \text{Re}(\lambda_i)$.

4.2.4 Design of Feedback Linearization Control (FLC) Scheme

In input-output feedback linearization, we must establish a relationship between the output and input by repeatedly differentiating the output dynamics equation. The second derivative of the v_{odi} equations can be expressed as follows:

$$\begin{aligned} \ddot{v}_{odi} = & \left(-m_{pi} \cdot w_{ci} \cdot v_{oqi} \cdot i_{odi} - w_{ni}^2 + 2 \cdot m_{pi} \cdot w_{ni} \cdot P_i - (m_{pi}^2) \cdot P_i^2 - X \cdot Z - X \cdot L \right) \cdot V_{ni} \\ & + \left(n_{qi} \cdot Q_i - \frac{1}{K_{pvi}} \cdot (i_{ldi}^* - F_i \cdot i_{odi} + w_b \cdot C_f \cdot v_{oqi} - K_{ivi} \cdot \phi_{di}) \right) \\ & \cdot \left(-m_{pi} \cdot w_{ci} \cdot v_{oqi} \cdot i_{odi} - w_{ni}^2 + 2 \cdot m_{pi} \cdot w_{ni} \cdot P_i - (m_{pi}^2) \cdot P_i^2 - X \cdot Z - X \cdot L \right) \\ & + m_{pi} \cdot w_{ci} \cdot v_{oqi} \cdot P_i - m_{pi} \cdot v_{oqi}^2 \cdot i_{oqi} + 2 \cdot X \cdot w_n \cdot i_{lqi} - 2 \cdot X \cdot w_{ni} \cdot i_{oqi} \\ & - 2 \cdot m_{pi} \cdot X \cdot P_i \cdot i_{lqi} + 2 \cdot m_{pi} \cdot X \cdot P_i \cdot i_{oqi} - X \cdot Y \cdot i_{ldi} - X \cdot Z \cdot v_{idi} \\ & - X \cdot K \cdot i_{odi} + X \cdot L \cdot v_{bdi} \end{aligned} \quad (4.41)$$

Let

$$\begin{aligned} X &= \frac{1}{C_{fi}} \\ Y &= \frac{R_{fi}}{L_{fi}} \\ Z &= \frac{1}{L_{fi}} \\ K &= \frac{R_{ci}}{L_{ci}} \\ L &= \frac{1}{L_{ci}} \end{aligned} \quad (4.42)$$

and

$$N = -m_{\text{pi}} \cdot w_{ci} \cdot v_{oqi} \cdot i_{odi} - w_{ni}^2 + 2 \cdot m_{\text{pi}} \cdot w_{ni} \cdot P_i - (m_{\text{pi}}^2) \cdot P_i^2 - X \cdot Z - X \cdot L \quad (4.43)$$

and

$$\begin{aligned} M = & \left(n_{qi} \cdot Q_i - \frac{1}{K_{pvi}} \cdot (i_{ldi}^* - F_i \cdot i_{odi} + w_b \cdot C_f \cdot v_{oqi} - K_{ivi} \cdot \phi_{di}) \right) \\ & \cdot (-m_{\text{pi}} \cdot w_{ci} \cdot v_{oqi} \cdot i_{odi} - w_{ni}^2 + 2 \cdot m_{\text{pi}} \cdot w_{ni} \cdot P_i - (m_{\text{pi}}^2) \cdot P_i^2 - X \cdot Z - X \cdot L) \\ & + m_{\text{pi}} \cdot w_{ni} \cdot v_{oqi} \cdot P_i - m_{\text{pi}} \cdot v_{oqi}^2 \cdot i_{oqi} + 2 \cdot X \cdot w_n \cdot i_{lqi} - 2 \cdot X \cdot w_{ni} \cdot i_{oqi} \\ & - 2 \cdot m_{\text{pi}} \cdot X \cdot P_i \cdot i_{lqi} + 2 \cdot m_{\text{pi}} \cdot X \cdot P_i \cdot i_{oqi} - X \cdot Y \cdot i_{ldi} - X \cdot Z \cdot v_{idi} \\ & - X \cdot K \cdot i_{odi} + X \cdot L \cdot v_{bdi} \end{aligned} \quad (4.44)$$

Then,

$$\ddot{v}_{odi} = \frac{V_{ni}}{N} + M \quad (4.45)$$

Furthermore,

$$V_{ni} = \frac{U_{\text{aux}} - M}{N} \quad (4.46)$$

By substitution of V_{ni} and \ddot{v}_{odi} , we get

$$\ddot{v}_{odi} = U_{\text{aux}} \quad (4.47)$$

where U_{aux} is the auxiliary control input.

4.2.5 Secondary Frequency Control Scheme

To design the secondary control scheme, we'll follow the following schematic:

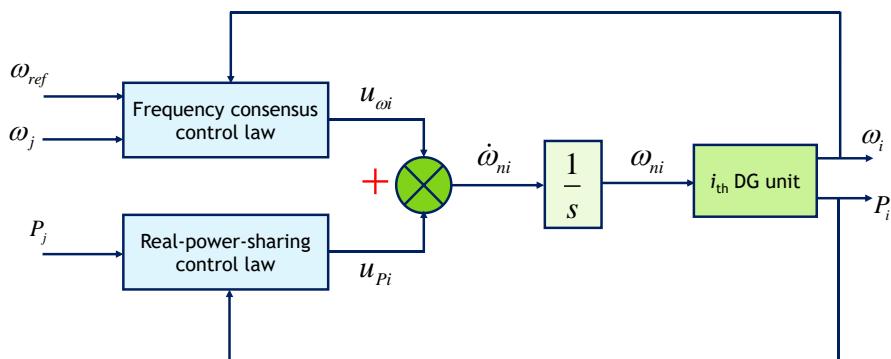


Figure 4.7: Distributed secondary cooperative frequency control mechanism.

4.3 Sparse Communication Topology

A robust local communication network is essential to facilitate the suggested secondary voltage regulation and provide the necessary information flows within a microgrid. The design of this communication graph should prioritize minimizing the necessary information flows and transmission delays to ensure efficient operation. Long communication channels are not desirable as they introduce latency and potential points of failure. Therefore, selecting suitable communication protocols and designing an optimal network topology are critical to achieving a reliable system.

For microgrids located in small geographic areas, CAN Bus and PROFIBUS communication protocols are particularly well-suited. These protocols are known for their reliability and efficiency in industrial environments, making them ideal for constructing microgrid communication networks. Below are detailed descriptions of each protocol:

- **CAN Bus:**

- **High Reliability:** CAN Bus is known for its robustness and error detection capabilities, making it highly reliable for critical communication.
- **Real-Time Performance:** It supports real-time data transmission with low latency, which is crucial for control applications.
- **Scalability:** CAN Bus can easily scale to accommodate additional devices without significant changes to the network structure.
- **Cost-Effective:** It is relatively inexpensive to implement, which is beneficial for budget-conscious microgrid projects.

- **PROFIBUS:**

- **Versatility:** PROFIBUS supports a wide range of communication needs, from simple sensor data to complex device configurations.
- **High Data Rates:** It can handle high data rates, making it suitable for applications requiring large data volumes.

- **Flexibility:** PROFIBUS networks can be configured in various topologies, including star, line, and tree structures.
- **Interoperability:** It is widely used in industrial automation, ensuring compatibility with a broad range of devices and systems.

It should be mentioned that there is inherent latency in communication channels. Despite this, our study assumes that there are no significant communication link delays. This assumption is based on the premise that such delays do not substantially impact system performance due to the sufficiently large time scale of the secondary control mechanisms [15].

Considering the physical setup of the microgrid, it is crucial to design a communication graph that efficiently connects each DG unit. A spanning tree structure is often used for this purpose, ensuring that all units are interconnected with the minimum number of links. This approach reduces the complexity and potential points of failure within the network.

To create an optimal communication graph, solutions from assignment problems or operations research can be employed. These methodologies help determine the best possible configurations for the communication network by considering various optimization criteria, such as:

- **Shortest Communication Link Lengths:** Ensuring that the physical distances between communication nodes are minimized to reduce latency and signal degradation.
- **Optimal Use of Existing Communication Lines:** Leveraging pre-existing infrastructure to minimize additional installation costs and the number of communication links simplifies the network and improves its reliability.

By addressing these optimization requirements, the design of the communication network can achieve an efficient and reliable system that supports the necessary data flows for secondary voltage regulation. This ensures that each DG unit can quickly and accurately exchange information, facilitating coordinated control actions across the microgrid.

4.4 Integration of primary & secondary control scheme

The secondary control generates the voltage and frequency references for the primary control. A detailed discussion of these two schemes is provided in their respective sections. Figure 4.8 shows the integration of the two schemes, ensuring seamless and coordinated microgrid operation. The primary control maintains local stability and performance, while the secondary control corrects steady-state errors and achieves system-wide objectives.

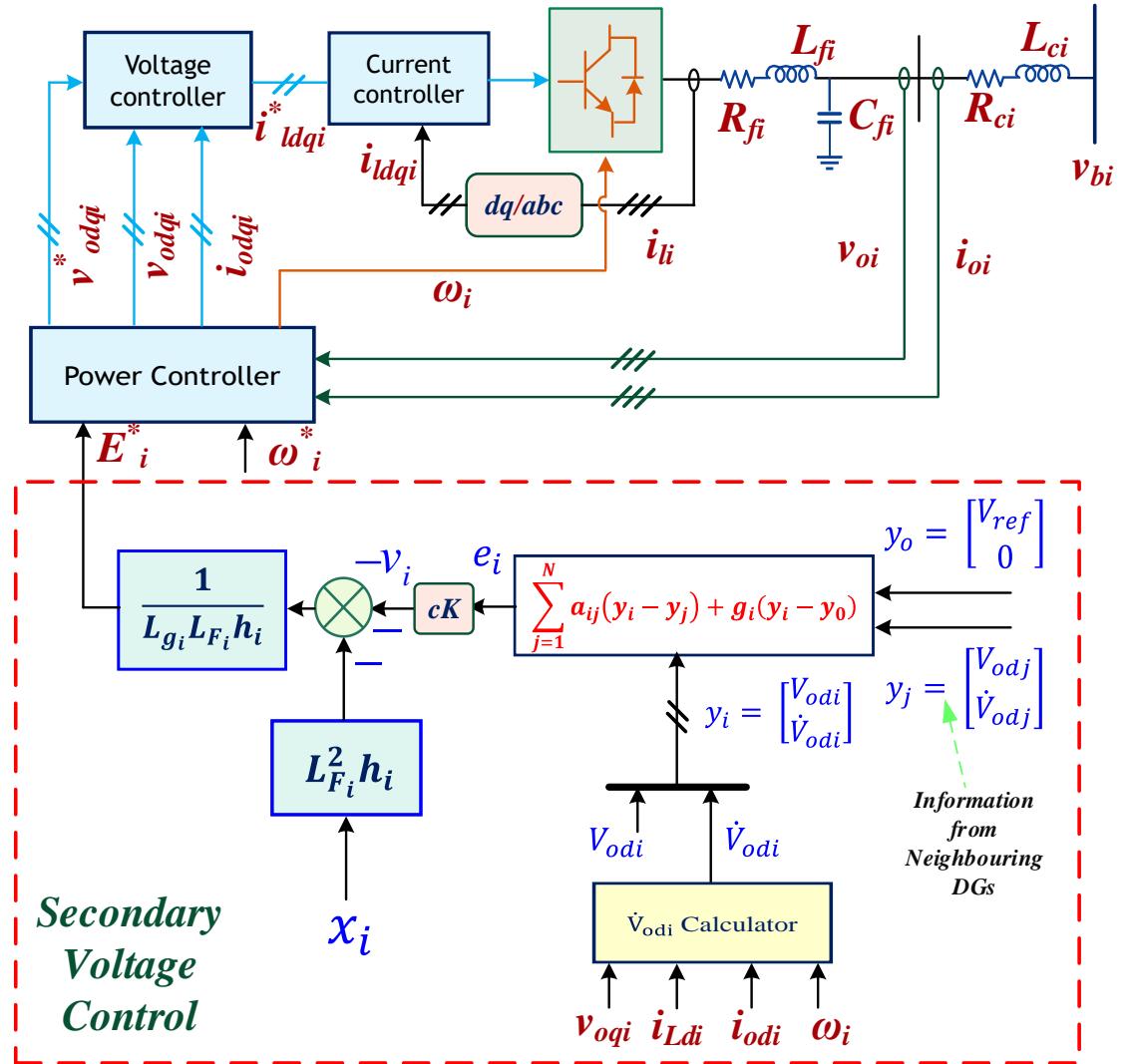


Figure 4.8: The complete primary & secondary voltage controller.

Chapter 5

Solar Energy Fed Generation Unit

5.1 Solar Power Generation

Solar energy is a sustainable and abundant source of renewable energy. A Solar PV generation system converts sunlight directly into electricity using photovoltaic cells. This system is especially beneficial for reducing dependence on fossil fuels and minimizing environmental impacts [16].

here we will see the design and implementation of a Solar Photovoltaic (PV) generation system intended to produce 45 kVA of power and supply 700V or more at the DC terminal of an inverter. The system features a Maximum Power Point Tracking (MPPT) controller using the Perturb and Observe (P & O) method. Key components discussed include the PV array, boost converter, MPPT controller, and inverter. Detailed design aspects of each component are provided, encompassing the selection and configuration of the PV array, the design and operation of the boost converter, and the integration of the MPPT controller.

5.2 Basic Concepts of Solar Power Generation

5.2.1 Photovoltaic Effect

The photovoltaic effect refers to generating voltage and electric current in a material upon exposure to light. Solar cells, typically composed of semiconductor materials like silicon, exploit this effect to produce electricity.

5.2.2 Solar PV Modules

A solar PV module consists of multiple solar cells connected in series and/or parallel to achieve the desired voltage and current levels. The power output of a module is influenced by factors such as sunlight intensity, temperature, and the angle of incidence.

5.2.3 I-V Characteristics

The current-voltage (I-V) characteristics of a PV module depict the relationship between the output current and voltage under different levels of irradiance and temperature. The Maximum Power Point (MPP) is the point on the I-V curve where the product of current and voltage is at its maximum.

5.3 System Design

5.3.1 PV Array Design

Power Requirement

- Desired Power Output: 45 kVA
- Assuming inverter efficiency (η) of 95%, DC power required = $\frac{45\text{kVA}}{0.95} = 47.37\text{kW}$

PV Module Selection

- Typical module specifications: $V_{mp} = 29V$, $I_{mp} = 7.35AV$, series connected modules in one string $N_s = 10$.

The number of parallel strings in a solar power generation system can be calculated using the following equation:

$$\text{Number of parallel strings} = \frac{P_{pv}}{V_{mp} \cdot I_{mp} \cdot N_s} \quad (5.1)$$

where:

- P_{pv} is the total power required to be generated.
- V_{mp} is the voltage at the maximum power point of a single module.

- I_{mp} is current at the maximum power point of a single module.
- N_s is the number of series-connected modules in each string.

Considering the above specifications and formula, the number of parallel strings is approximately **23**.

5.3.2 Boost Converter Analysis and Design

A boost converter is a DC-DC converter that moves the input voltage to a higher output voltage. It operates in two main modes: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM) [17].

5.3.3 Continuous Conduction Mode (CCM)

In CCM, the inductor current never falls to zero during the switching cycle. The key formulas in CCM are as follows:

- **Output Voltage:**

$$V_o = \frac{V_s}{1 - D} \quad (5.2)$$

- **Duty Cycle:**

$$D = 1 - \frac{V_s}{V_o} \quad (5.3)$$

- **Inductor Current Ripple:**

$$\Delta I_L = \frac{V_s \cdot D}{L \cdot f_s} \quad (5.4)$$

- **Average Inductor Current:**

$$I_L = \frac{I_o}{1 - D} \quad (5.5)$$

- **Minimum Inductor Current:**

$$I_{L_{min}} = I_L - \frac{\Delta I_L}{2} \quad (5.6)$$

- **Maximum Inductor Current:**

$$I_{L_{max}} = I_L + \frac{\Delta I_L}{2} \quad (5.7)$$

- **Critical Capacitance:**

$$C_{crit} = \frac{I_o \cdot D}{V_{o_{ripple}} \cdot f_s} \quad (5.8)$$

where $V_{o_{ripple}}$ is the permissible output voltage ripple.

5.3.4 Discontinuous Conduction Mode (DCM)

In DCM, the inductor current falls to zero during part of the switching cycle. The key formulas in DCM are as follows:

- **Output Voltage:**

$$V_o = V_s \sqrt{\frac{L \cdot I_o \cdot f_s}{2V_s(1 - D)}} \quad (5.9)$$

or alternatively,

$$V_o = V_s \sqrt{\frac{V_s \cdot D^2}{2 \cdot L \cdot f_s \cdot R}} \quad (5.10)$$

- **Duty Cycle:**

$$D = \sqrt{\frac{2L \cdot f_s \cdot R \cdot I_o}{V_s}} \quad (5.11)$$

- **Inductor Current at the Boundary of DCM/CCM:**

$$I_{L_{crit}} = \frac{V_s \cdot D \cdot (1 - D)}{2L \cdot f_s} \quad (5.12)$$

- **Critical Capacitance:**

$$C_{crit} = \frac{I_o \cdot D}{V_{o_{ripple}} \cdot f_s} \quad (5.13)$$

5.3.5 Design of Inductor and Capacitor

The design of the inductor and capacitor is crucial for ensuring proper operation in either mode.

- **Inductor Design:**

- **CCM Mode:**

$$L = \frac{V_s \cdot D}{\Delta I_L \cdot f_s} \quad (5.14)$$

where ΔI_L is the desired inductor current ripple.

- **DCM Mode:**

$$L_{crit} = \frac{R \cdot (1 - D)^2}{2 \cdot f_s} \quad (5.15)$$

- **Capacitor Design:**

- **Capacitance to limit output voltage ripple:**

$$C = \frac{I_o \cdot D}{V_{o_{ripple}} \cdot f_s} \quad (5.16)$$

5.3.6 PWM Control and Closed-Loop Operation

In a closed-loop system, a PWM block generates the duty cycle for the boost converter. This design's modulation index (m) and feedback mechanisms are critical.

- **PWM Duty Cycle:** The duty cycle in PWM is controlled by comparing a reference signal with a carrier signal (usually a sawtooth or triangular waveform).

- **Modulation Index:**

$$m = \frac{V_{ref}}{V_{carrier}} \quad (5.17)$$

where V_{ref} is the reference voltage and $V_{carrier}$ is the peak of the carrier waveform.

- **Control Loop:**

- **Voltage Mode Control:** The output voltage is sensed and compared with a reference voltage. The error is processed through a compensator (usually a PID controller) to generate the PWM signal.
 - **Current Mode Control:** Both the inductor current and output voltage are sensed. The current is used for inner loop control to improve response time and stability.

- **Designing L and C in Closed-Loop:**

- **Inductor (L):** Ensure that L meets the requirements for both ripple current and critical inductance to avoid falling into DCM unintentionally.
- **Capacitor (C):** The capacitor should be chosen to minimize voltage ripple and meet transient response requirements.

5.3.7 Practical Considerations in DCM

In DCM, the inductor current falling to zero means that the exact time it takes to reach zero may vary from cycle to cycle due to load, input voltage, and other factors.

- **Variable Off-Time:** The time during which the inductor current is zero can vary. This affects the duty cycle and requires a dynamic control strategy.
- **Control Strategy:**
 - **Peak Current Mode Control:** Regulates the peak inductor current to maintain the desired output voltage.
 - **Average Current Mode Control:** Averages the current over a switching cycle for smoother control.

In summary, Boost converters in CCM and DCM require tailored designs for inductors and capacitors. PWM control is vital for stable operation in closed-loop systems. Proper component design and control strategies ensure efficient performance across varying loads.

5.3.8 Purpose of the Input Capacitor

Voltage Stabilization:

The input capacitor stabilizes the voltage supplied to the boost converter, compensating for fluctuations or noise in the PV panel output.

Ripple Reduction:

It filters out current and voltage ripples introduced by the boost converter's switching mechanism, providing a smoother DC voltage.

Energy Buffering:

Provides local energy storage, ensuring a steady energy supply during transient conditions like changes in irradiance or load.

Calculating the Value of the Input Capacitor

considering allowable ripple voltage (ΔV) at the input of the boost converter, the required capacitance is given by:

$$C = \frac{I_{\text{pv}}}{f_s} \cdot \Delta V \quad (5.18)$$

5.3.9 Calculations:

1. Input Current (I_{in}):

$$I_{\text{in}} = \frac{P_{\text{P}}}{V_{\text{in}}} = \frac{47370 \text{ W}}{290 \text{ V}} \approx 163.34 \text{ A}$$

2. Duty Cycle (D):

$$D = 1 - \frac{V_{\text{in}}}{V_{\text{out}}} = 1 - \frac{290}{1130} \approx 0.743$$

3. Inductor Value (L_L):

$$\Delta I_L = 0.3 \times I_{\text{in}} \approx 49 \text{ A}, \text{ considering ripple current as 30\%}$$

$$L_L = \frac{V_{\text{in}} \times D}{\Delta I_L \times f_s} = \frac{290 \times 0.743}{49 \times 5000} \approx 0.879 \text{ mH}$$

4. Output Capacitor Value (C_C):

$$\Delta V_{\text{out}} = 0.01 \times V_{\text{out}} \approx 11.3 \text{ V}$$

$$I_{\text{out}} = \frac{P_{\text{P}}}{V_{\text{out}}} = \frac{47370 \text{ W}}{1130 \text{ V}} \approx 41.92 \text{ A}$$

$$C_C = \frac{I_{\text{out}} \times D}{\Delta V_{\text{out}} \times f_s} = \frac{41.92 \times 0.743}{11.3 \times 5000} \approx 551 \mu\text{F}$$

5. Load Resistance (R_R):

$$R_R = \frac{V_{\text{out}}^2}{P_{\text{P}}} = \frac{1130^2}{47370} \approx 26.95 \Omega$$

5.3.10 MPPT Controller Design

Perturb and Observe (P&O) Algorithm

The Perturb and Observe (P&O) algorithm is widely used for MPPT in photovoltaic systems. It perturbs the system's operating voltage and observes the resulting power change to find the optimal operating point for maximizing power output [18].

Algorithm 1 Perturb and Observe Algorithm

```
1: Initialize variables:  $V_{ref}$ ,  $I_{ref}$ ,  $P_{ref} \leftarrow 0$ 
2: while True do
3:   Measure current voltage  $V$  and current  $I$ 
4:   Calculate power  $P \leftarrow V \times I$ 
5:   if  $P > P_{ref}$  then
6:     Increase voltage perturbation:  $V_{ref} \leftarrow V_{ref} + \Delta V$ 
7:   else
8:     Decrease voltage perturbation:  $V_{ref} \leftarrow V_{ref} - \Delta V$ 
9:   end if
10:  Update  $P_{ref} \leftarrow P$ 
11:  if Maximum Power Point (MPP) reached then
12:    Break
13:  end if
14: end while
15: End
```

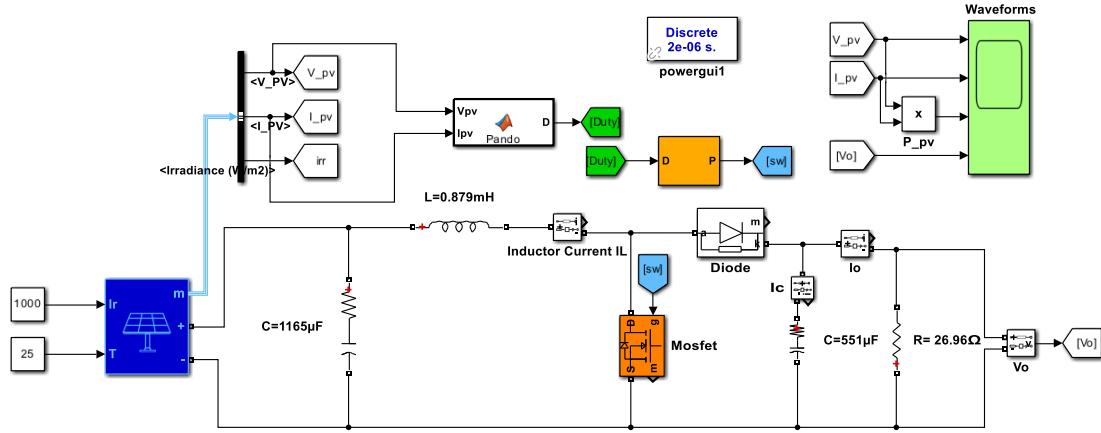
5.3.11 DC Link Capacitor Selection

When connecting the boost converter's output to the DC to AC inverter for generating 400V AC, the DC link capacitor plays a crucial role in smoothing out voltage ripples and providing sufficient energy storage. The selection of the DC link capacitor depends on factors such as the desired output voltage ripple, the switching frequency of the converter, and the maximum permissible voltage fluctuation. The capacitance C_{dc} can be calculated using the formula:

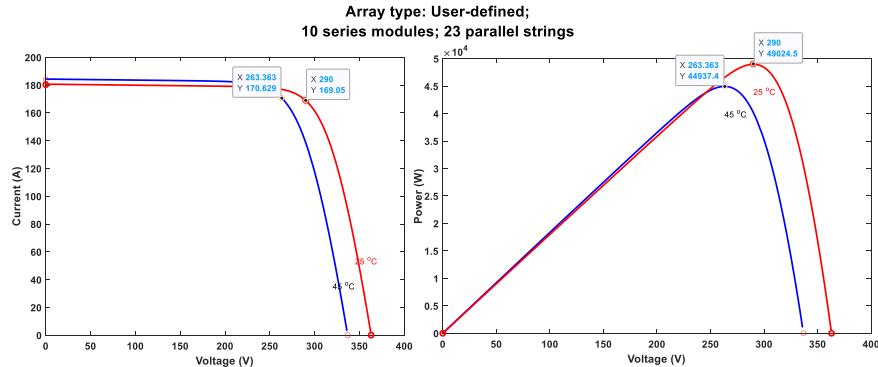
$$C_{dc} = \frac{I_{dc} \times \Delta t}{\Delta V_{dc}} \quad (5.19)$$

Where I_{dc} is the DC output current, Δt is the maximum permissible time interval between consecutive charging cycles of the capacitor, and ΔV_{dc} is the allowable voltage ripple on the DC link.

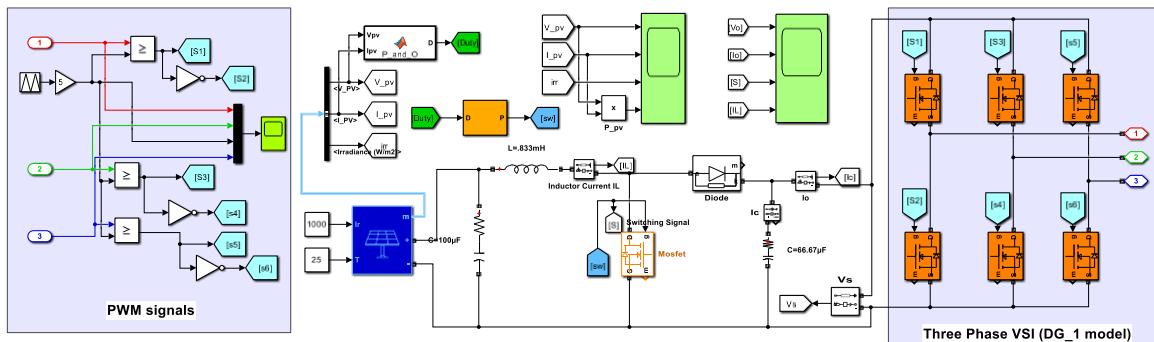
5.4 Simulation Model & Results



(a) Simulation Model of Solar Power Generation.

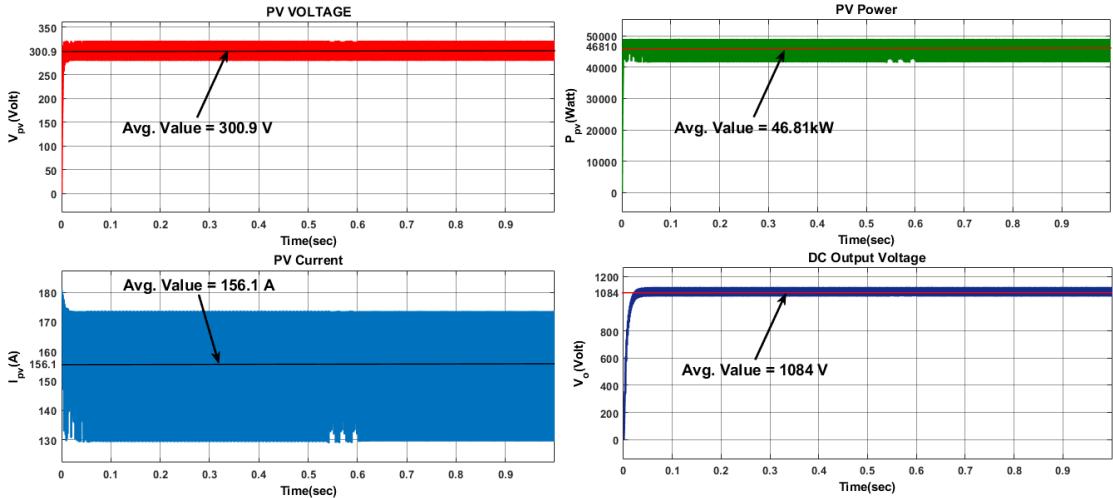


(b) The I-V & P-V characteristic curve for the PV unit

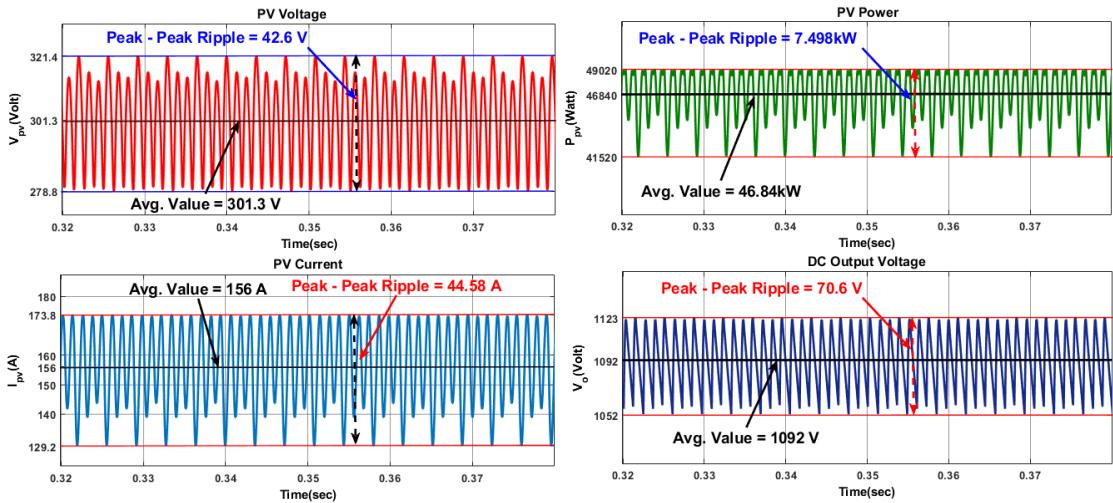


(c) A solar energy based DG Unit

Figure 5.1: Solar PV simulation model and characteristic curve



(a) PV Voltage, Current, Power & Output Voltage Waveforms for 1 sec. window.



(b) PV Voltage, Current, Power & Output Voltage Waveforms at steady state.

Figure 5.2: Output waveforms of Solar PV simulation model

5.5 Discussion

Simulink's solar power generation model demonstrates effective performance under the specified conditions. Using the Perturb and Observe (P & O) Maximum Power Point Tracking (MPPT) technique, the system was tested at an irradiance level of 1000 W/m². The design incorporated a boost converter and employed a configuration of 23 parallel modules connected in series with 10 modules, aiming for a maximum power output of 47.375 kW.

The results from the simulation indicate a desirable performance, with the mean power output measured at 46.84 kW and the maximum power output reaching 49.020 kW. This

performance aligns closely with the theoretically expected maximum power of 49.024 kW derived from the Maximum Power Point (MPP) waveform. The system consistently generated a DC voltage output of 1130 V.

These results affirm the efficacy of the P & O MPPT technique's efficacy in optimising the solar array's power output. The close agreement between the mean power output and the theoretical maximum power demonstrates the system's efficiency. Furthermore, the stable DC voltage output indicates the boost converter's reliable performance in maintaining the desired voltage level. Overall, the developed model shows promising potential for practical applications in solar power generation, providing both efficiency and stability under standard test conditions.

Chapter 6

MATLAB Simulations & Result Analysis

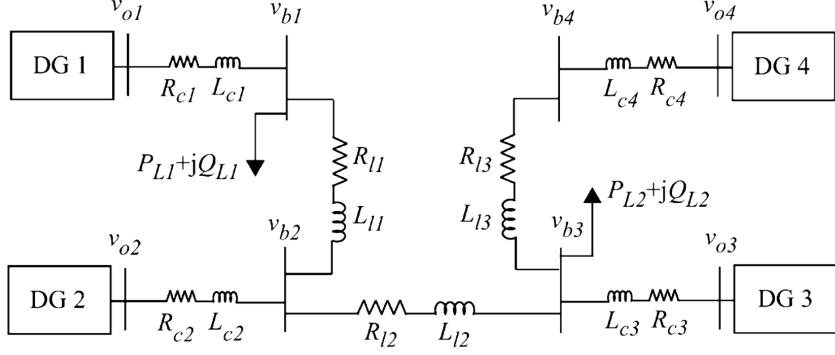
6.1 Simulation Model Development

In this study, we aim to develop a microgrid using solar and wind energy systems in conjunction with battery energy storage. Each distributed generator (DG) employs a primary controller using droop control. A secondary controller, which is fully distributed and based on a cooperative control mechanism, is developed to enhance coordination and consensus among the DGs.

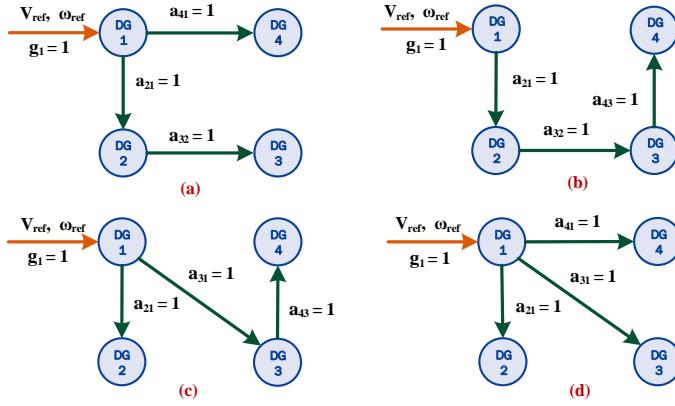
The MATLAB Simulink model of an islanded microgrid has established the implementation of the secondary voltage regulation. The single-line schematic of the microgrid test system is shown in Fig. 6.1a. There are four DGs in this microgrid. The bus lines are represented as series R-L branches. Table 6.1 overviews the DGs, lines, and loads' parameters. It is assumed that the communication digraph shown in Fig. 6.1b is how DGs exchange messages with one another. The geographic location of the DGs influences the choice of this communication topology. The digraph's associated adjacency matrix in Fig-

ure 6.1b(a) is $A_G = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$. The only DG linked to the leader node is DG 1, with pinning gain $g_i = 1$.

In this case, the condition of coupling gain is satisfied by choosing $c = 400$. The state feedback control vector K is computed using the ARE. The ARE parameters are selected as $Q = \begin{bmatrix} 50000 & 0 \\ 0 & 1 \end{bmatrix}$, $R = 0.01$, and we are getting $K = [2236 \quad 67.6]$ as the output feedback control vector.



(a) Single line diagram of test grid



(b) Communication Digraph (a) Topology 1, (b) Topology 2, (c) Topology 3, and (d) Topology 4.

Figure 6.1: The test grid system & communication topology

6.2 Validation of Primary and Secondary Control Schemes

Detailed circuit diagrams and simulation results for both the single DG and 4 DG models with primary and secondary controls have been included to illustrate the performance and effectiveness of the control schemes. These results demonstrate the smooth integration and operation of the DGs, validating our control strategy.

6.2.1 Simulink Model of a Single DG unit

The initial phase focuses on implementing and validating the primary control scheme. Droop control is utilized for that in such a way the power converter of the DG unit operates as a grid-forming converter.

Table 6.1: DG Parameters, Line Parameters, and Load Parameters

DG Parameters		
Parameter	DG 1 and 2 (9-kVA rating)	DG 3 and 4 (7-kVA rating)
m_p	9.4×10^{-5}	12.5×10^{-5}
n_q	1.3×10^3	1.5×10^3
R_c	0.03Ω	0.03Ω
L_c	0.35mH	$0.35\mu\text{H}$
R_f	0.1Ω	0.1Ω
L_f	1.35mH	1.35mH
C_f	$50\mu\text{F}$	$50\mu\text{F}$
K_{PV}	0.1	0.05
K_{IV}	420	390
K_{PC}	15	10.5
K_{IC}	20,000	16,000

Line Parameters		
Line	Resistance	Inductance
Line 1	$R_{l1} = 0.23\Omega$	$L_{l1} = 318\mu\text{H}$
Line 2	$R_{l2} = 0.35\Omega$	$L_{l2} = 1847\mu\text{H}$
Line 3	$R_{l3} = 0.23\Omega$	$L_{l3} = 318\mu\text{H}$

Load Parameters		
Load	Active Power	Reactive Power
Load 1	12 kW	12 kVAr
Load 2	15.3 kW	7.6 kVAr

Single DG Model with Primary Control

The primary control scheme was first tested on a single DG model. Validation confirmed the primary control loop's ability to maintain grid stability and reliability. The single DG successfully formed the grid, adhering to droop control principles.

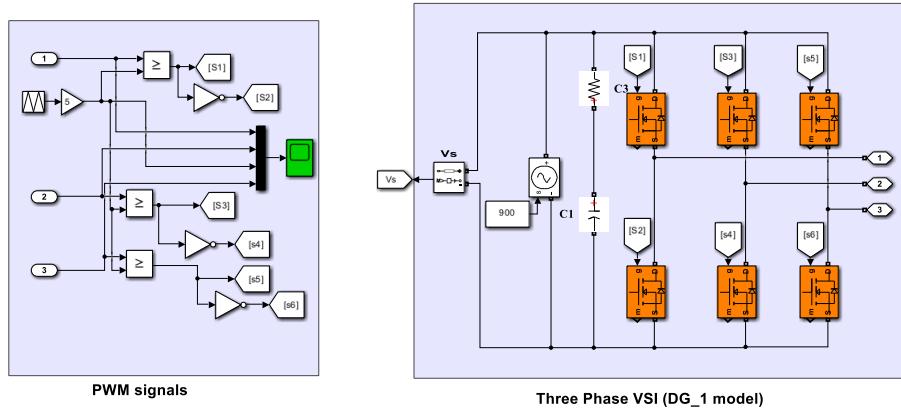
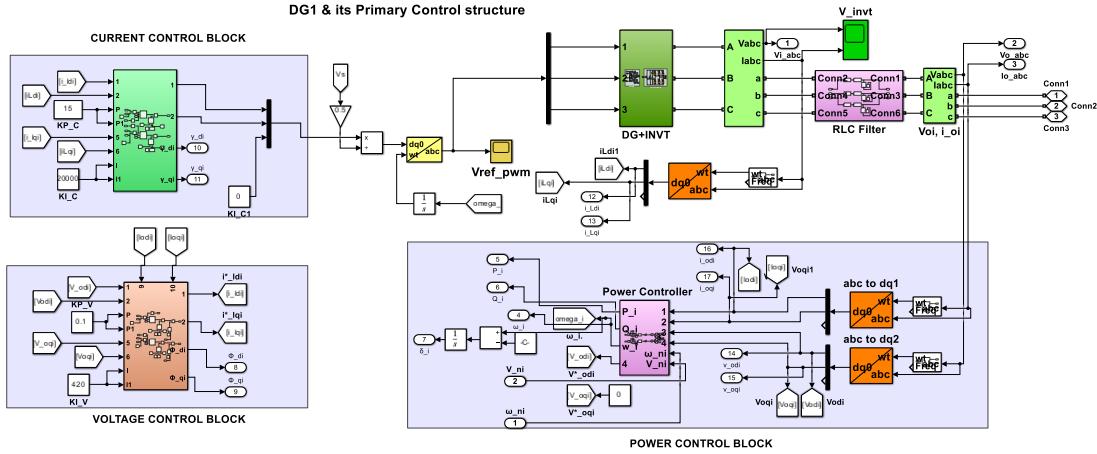
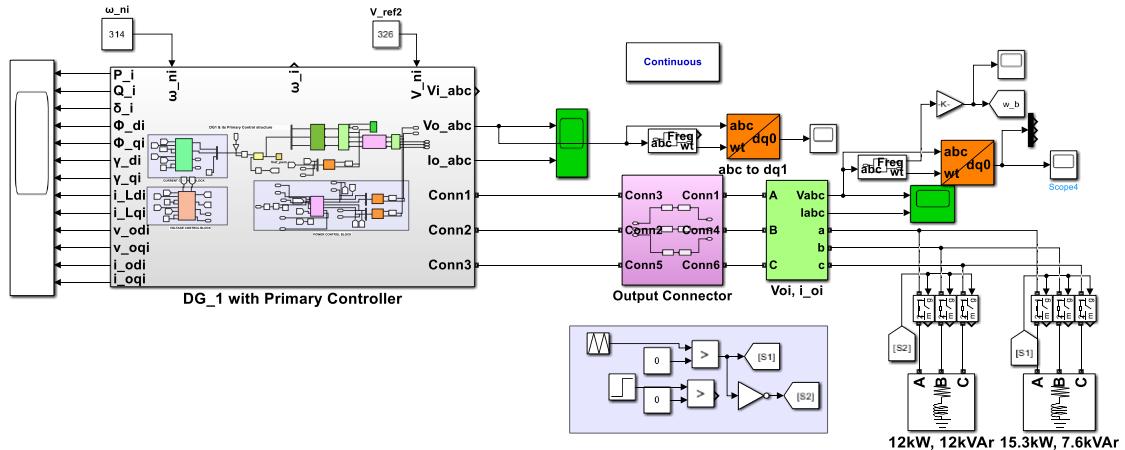


Figure 6.2: Three phase Inverter & PWM switching



(a) Primary control scheme



(b) Single DG simulation model

Figure 6.3: Simulation model of single DG unit with primary control

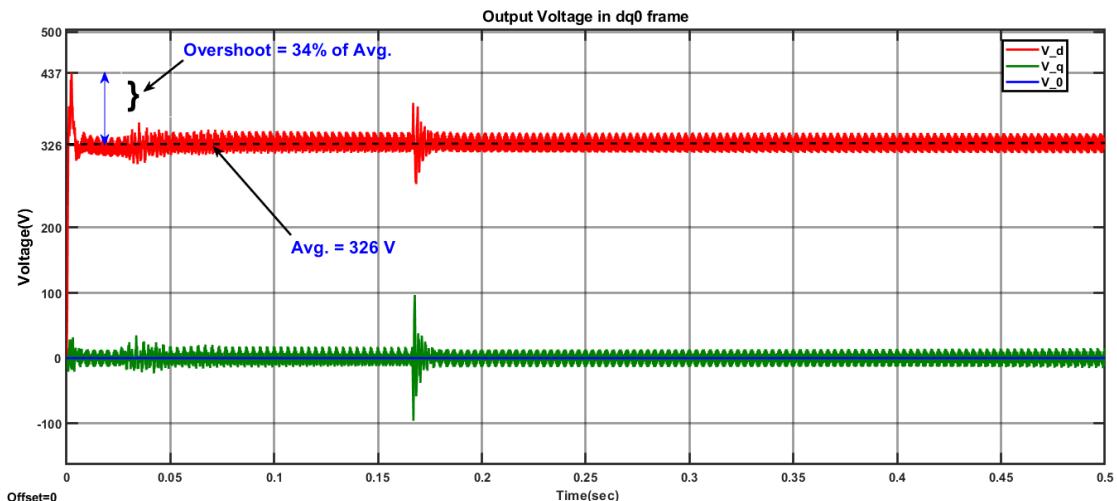


Figure 6.4: Output Voltage in $dq0$ frame

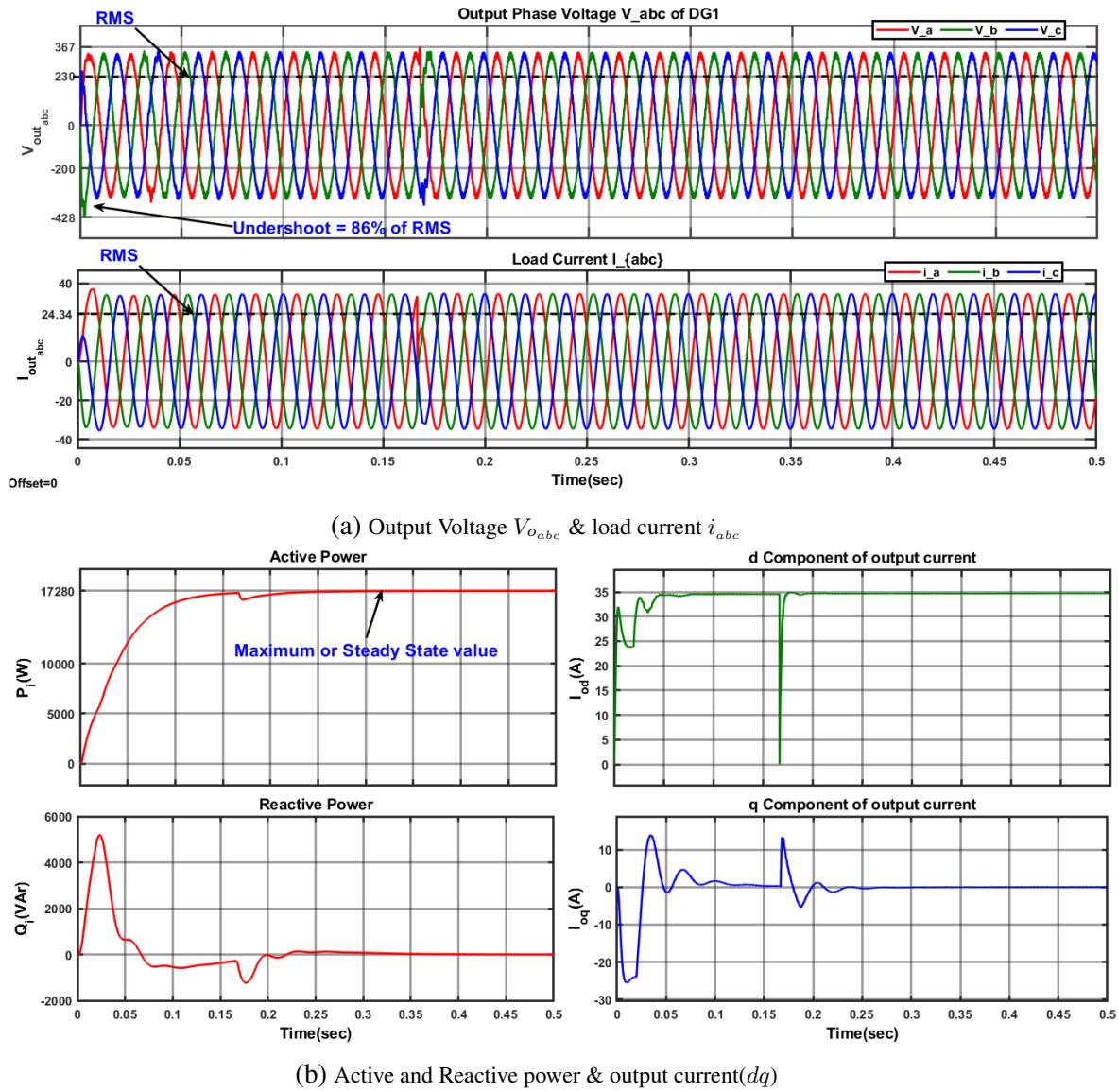
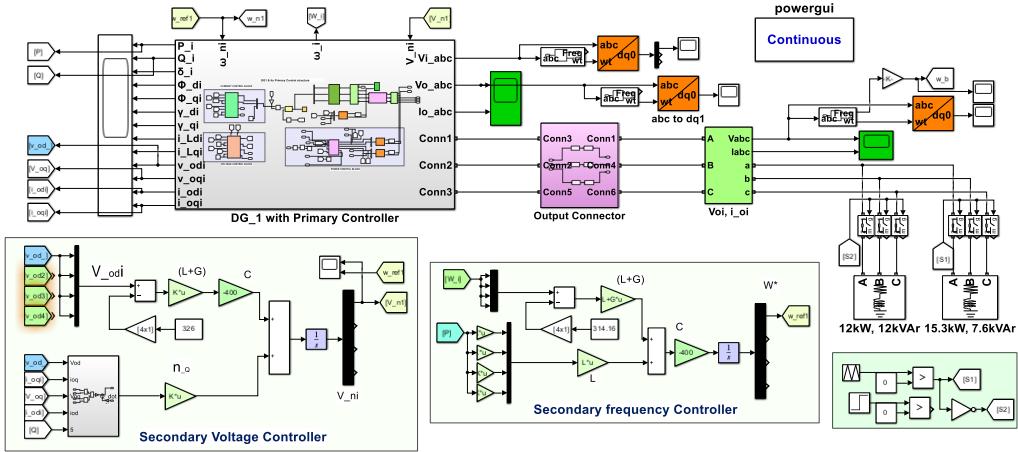


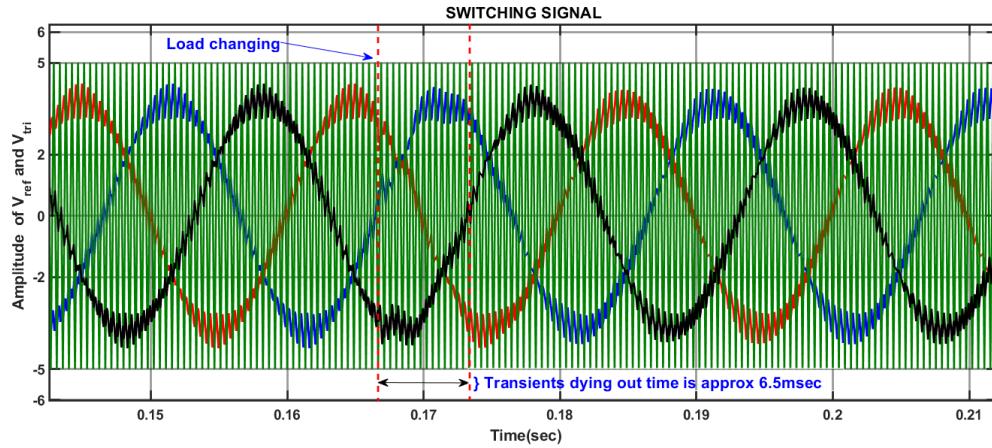
Figure 6.5: Output three-phase voltage and current, Power waveforms

Single DG Model with Primary and Secondary Control

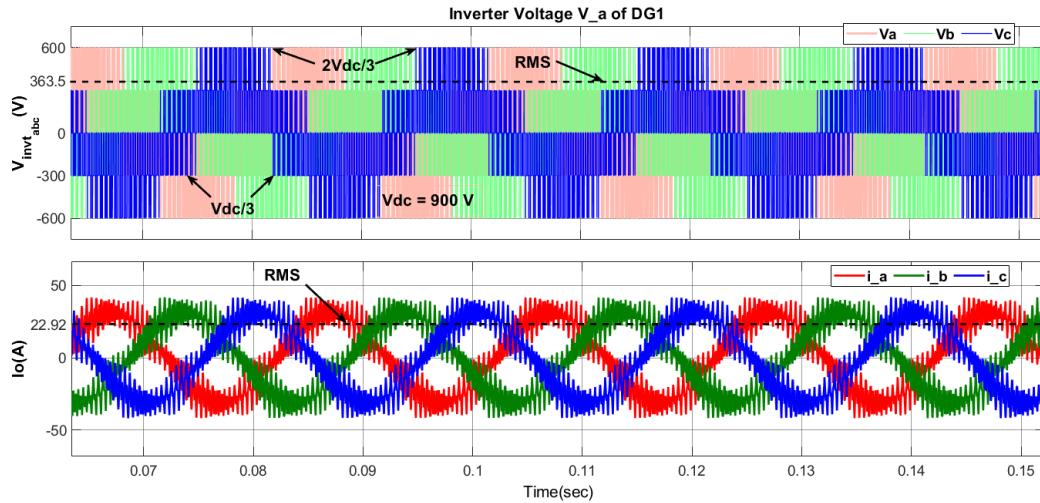
The secondary control scheme was first tested on a single DG model with the primary control. The secondary controller provided the necessary reference to the primary controller, and simulation results indicated proper operation. The secondary control effectively adjusted the references, confirming its functionality and compatibility with the primary control.



(a) Single Distributed Generator model with primary & secondary control scheme

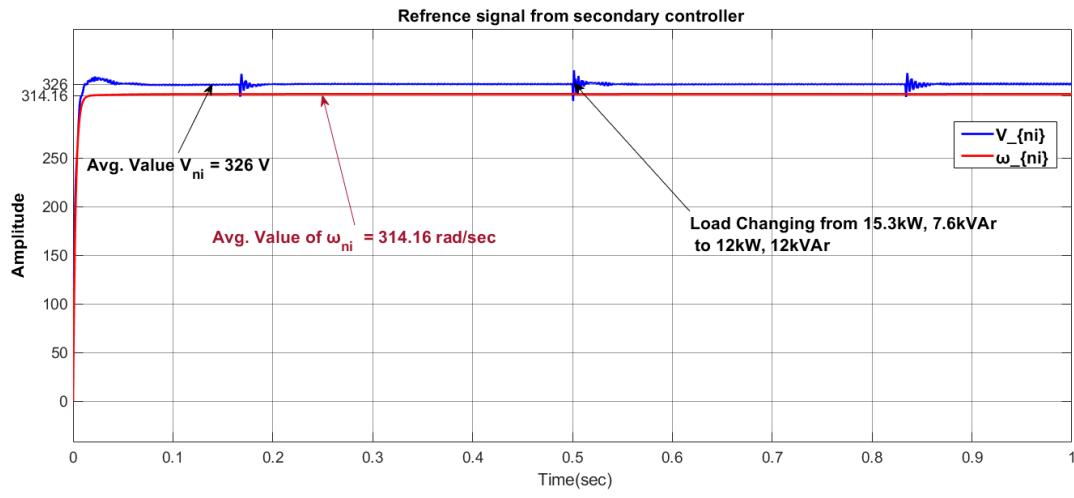


(b) PWM switching action

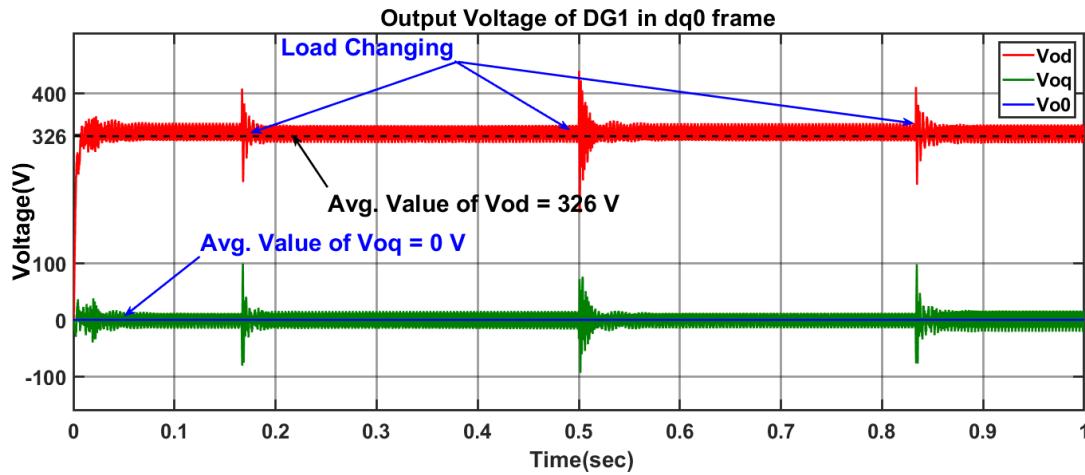


(c) Voltage & current at inverter terminal

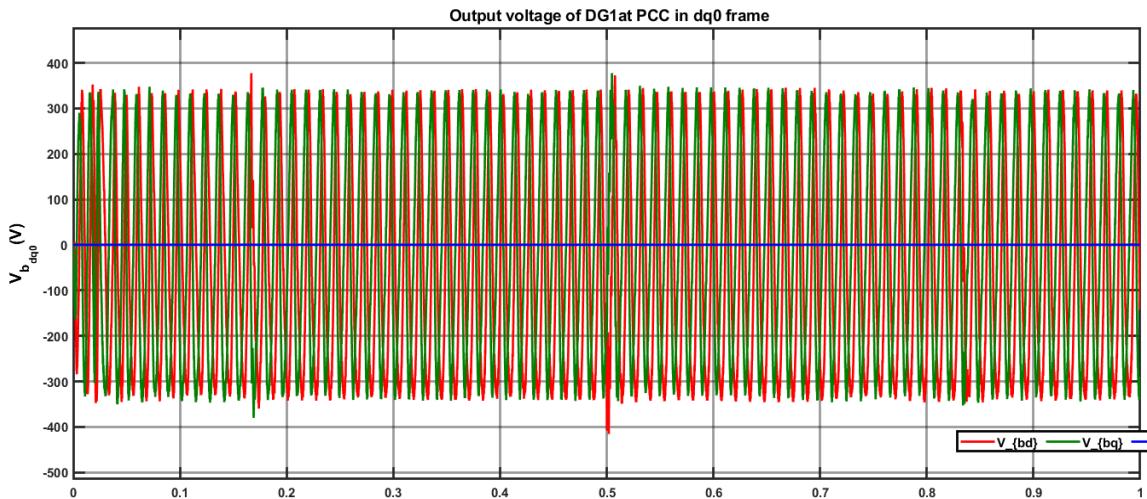
Figure 6.6: Circuit diagram, PWM switching & inverter output



(a) References generated by secondary controller i.e. V_{ni} and ω_{ni}

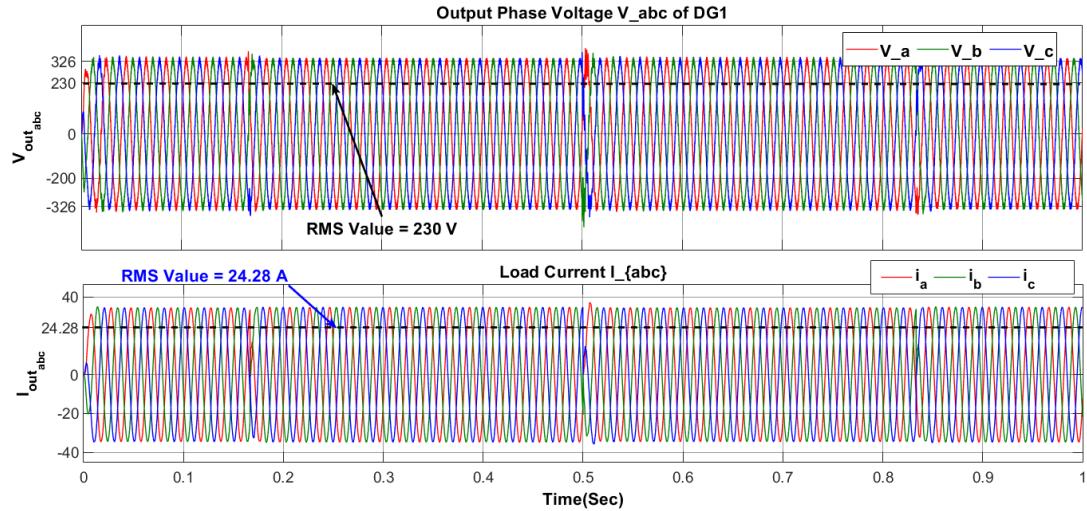


(b) Output Voltage in $dq0$ frame

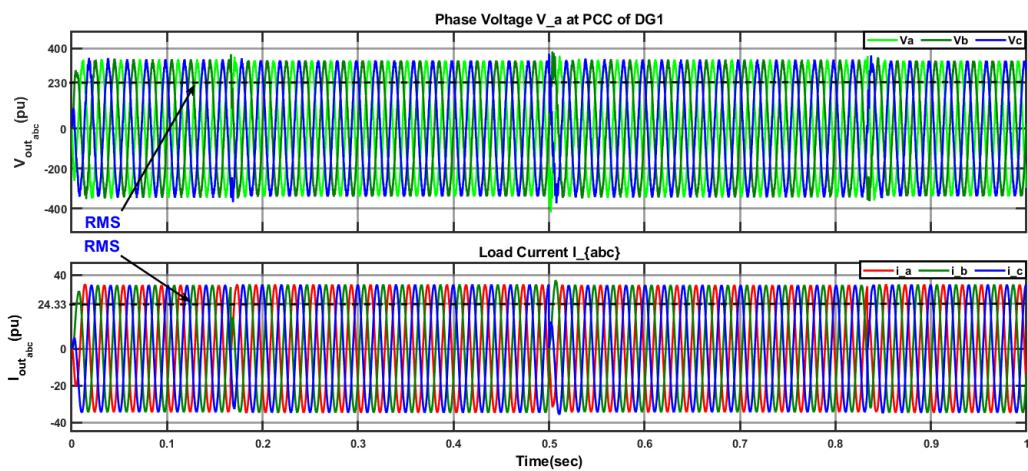


(c) PCC Voltage in $dq0$ frame

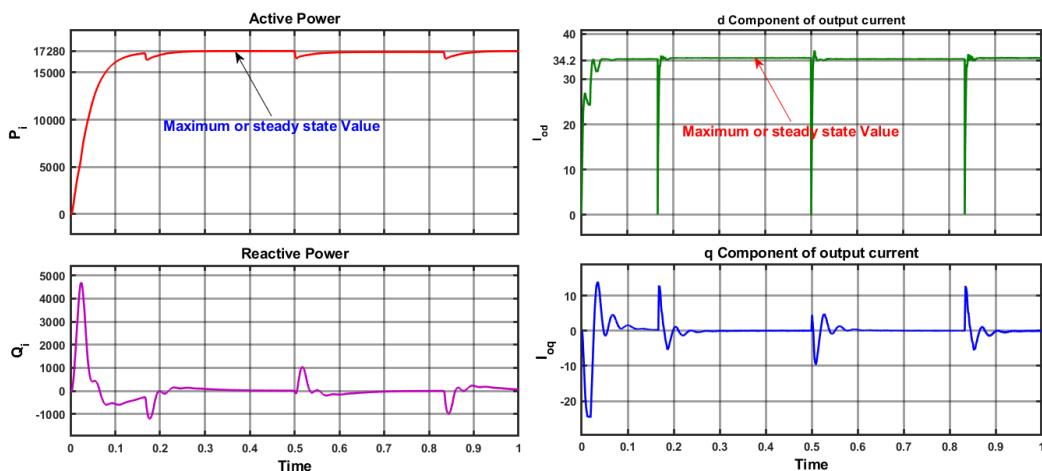
Figure 6.7: References from secondary, output voltage and current in $dq0$ frame



(a) Output Voltage V_{oabc} & load current i_{abc}



(b) Voltage and current at PCC



(c) Active and Reactive power & output current(dq)

Figure 6.8: Output three-phase voltage and current, Power waveforms

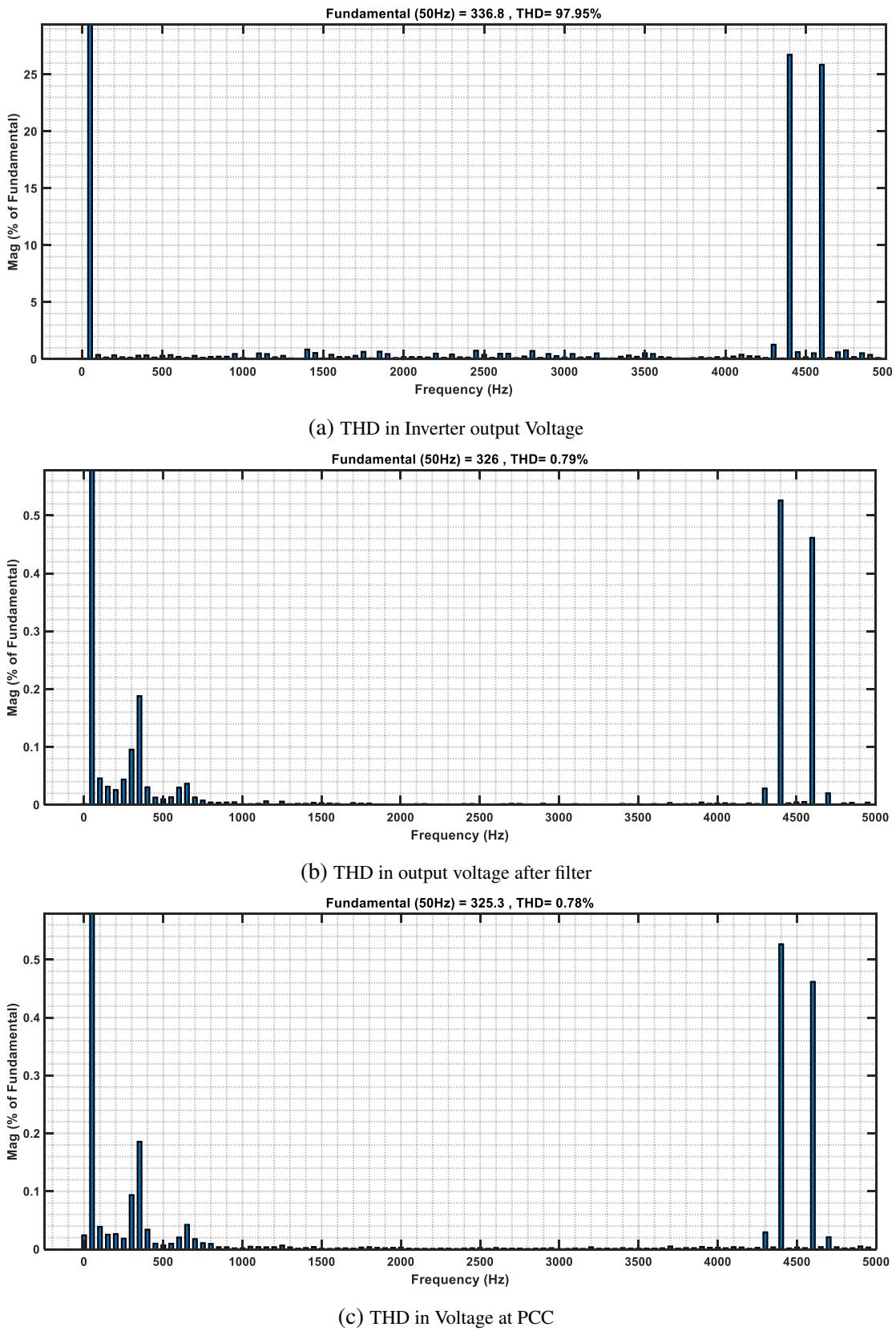


Figure 6.9: Total Harmonic Distortion(THD) analysis of voltage waveform

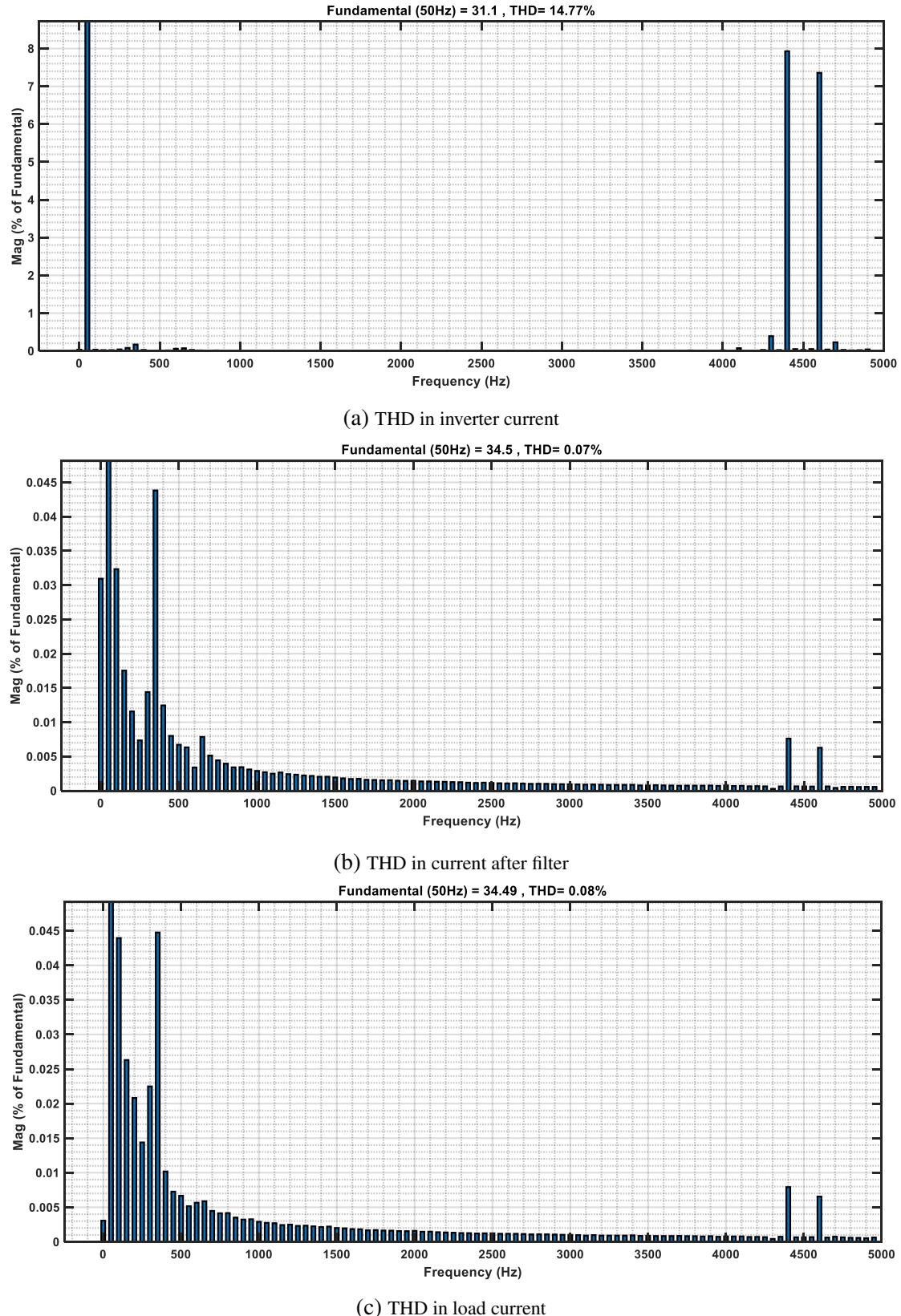


Figure 6.10: Total Harmonic Distortion(THD) analysis of current waveform

6.2.2 Discussion and Observations

Single DG Unit with Primary Control

- **Voltage Regulation:** The primary control mechanism successfully maintained the output voltage at 400 V LL RMS (230 V phase RMS) with a DC input ranging from 700 to 900 V. This validates the effectiveness of the primary control in achieving the desired voltage regulation (fig:6.5).
- **Transient Response:** During the startup, an overshoot of approximately 34 % of the average value (326 V) was observed, lasting for about 6.5 ms. This overshoot, although significant, is short-lived and does not compromise the system's stability in the long term (fig:6.5).
- **Load Changes:** When the load was changed from 15 kW, 7.6 kVAr to 12 kW, 12 kVAr, and vice versa, slight ripples and overshoots were observed. However, the system quickly stabilized within 5 to 6 ms. This indicates that the primary control is robust enough to handle load variations, maintaining stable operation shortly after disturbances (fig:6.5).

Single DG Unit with Primary and Secondary Control

- **Elimination of Overshoot:** The application of secondary control effectively eliminated the initial overshoot observed with primary control alone. The reference voltage generated by the secondary controller smoothly reached 326 V without any transient spikes (fig: 6.7).
- **Steady-State Performance:** The system maintained a stable 400 V LL output at the PCC with secondary control. The secondary control ensured minimal fluctuations and ripples, particularly during load changes, stabilizing the system within 5 to 6 ms (fig: 6.8).
- **Improved Reference Tracking:** The secondary control mechanism significantly improved reference tracking, ensuring that the voltage reference generated was as desired, leading to a more stable and precise output (fig: 6.7).

6.2.3 THD Analysis Discussion

The Total Harmonic Distortion (THD) analysis for a single Distributed Generation (DG) unit in the microgrid system designed using MATLAB Simulink was conducted to evaluate the effectiveness of the implemented control schemes and the filtering components. The THD values were measured at various points in the system, including just after the three-phase inverter, after the LC filter, and after the RL connector at the Point of Common Coupling (PCC).

Voltage THD Analysis (fig:6.9)

- **At the Inverter Terminal:** The THD in voltage immediately after the three-phase inverter was found to be **97.95%**. This high level of distortion is attributed to the quasi-square wave nature of the voltage waveform at the inverter terminal, which inherently contains significant harmonic components due to the switching operations of the inverter.
- **After the LC Filter:** Post the LC filter, the voltage THD drastically reduces to **0.79%**. The LC filter acts as a low-pass filter, effectively attenuating the high-frequency harmonics generated by the inverter. This significant reduction justifies the inclusion of the LC filter in the system design, highlighting its crucial role in improving power quality by smoothing the voltage waveform.
- **At the PCC (After the RL Connector):** Further down the line, after the RL connector at the PCC, the voltage THD slightly decreases to **0.78%**. The RL connector provides additional damping to any residual high-frequency harmonics and helps stabilize the voltage, ensuring that the power delivered to the load is of high quality.

Current THD Analysis (fig:6.10)

- **At the Inverter Terminal:** The current THD at the inverter terminal was measured to be **14.77%**. Similar to voltage, the current distortion is primarily due to the quasi-square wave nature of the waveform produced by the inverter's switching actions.
- **After the LC Filter:** The current THD drops significantly to **0.07%** after the LC

filter. This demonstrates the LC filter's effectiveness in not only voltage harmonic suppression but also in reducing current harmonics. The inductance and capacitance in the filter work together to filter out high-frequency harmonic currents, resulting in a cleaner current waveform.

- **At the PCC (After the RL Connector):** Finally, the load current THD after the RL connector at the PCC is **0.08%**. The RL connector further ensures the current harmonics are minimized before reaching the load, contributing to the overall power quality improvement by providing additional damping and reducing harmonic resonance.

6.2.4 Justification of LC Filter and RL Connector

The LC filter and RL connector are critical components in the microgrid system for mitigating harmonic distortion. The LC filter's primary function is to eliminate high-frequency harmonics caused by the quasi-square wave output of the inverter, thereby significantly reducing both voltage and current THD. The RL connector further enhances the power quality by providing additional damping, stabilizing the voltage and current waveforms at the PCC, and ensuring the delivery of clean power to the load.

In conclusion, the implementation of the LC filter and RL connector in the microgrid system is justified by the substantial reduction in THD for both voltage and current. These components are vital in enhancing power quality, ensuring efficient and reliable microgrid operation, and protecting sensitive loads from harmonic distortion.

6.2.5 Simulink model of the test grid with 4 DG units

After validating the Primary and Secondary Control scheme for a single DG, I am extending the same for the 4 DG microgrid model based on the topology mentioned in Fig 6.1(b).

4 DG Model with Primary Control

I extended the primary control scheme to a model with four distributed generators (DGs), as depicted in the block diagram of Figure 6.1(a). Each DG has primary controllers. To

avoid issues from simultaneous startup, each DG was started sequentially: DG1 first, followed by DG2 at 0.1 seconds, DG3 at 0.15 seconds, and DG4 at 0.2 seconds. This ensured a smooth transition and stable integration into the microgrid. The primary control scheme worked correctly for all four DGs, demonstrating the design's robustness. The accompanying phase voltage waveforms confirm the successful operation. The d -Component of Output phase voltages of all the DGs are getting synchronized with other DGs. This can be verified by examining the simulation waveform obtained.

4 DG Model with Primary and Secondary Control

To evaluate the secondary control scheme's effectiveness in a multi-DG setup, it was implemented in the 4 DG model. The DGs shared information with their neighbouring units, working towards achieving consensus. Simulation results demonstrated that the DGs reached a consensus, validating the distributed cooperative control mechanism. The secondary control ensured coordinated operation among the DGs, maintaining stability and reliability in the microgrid.

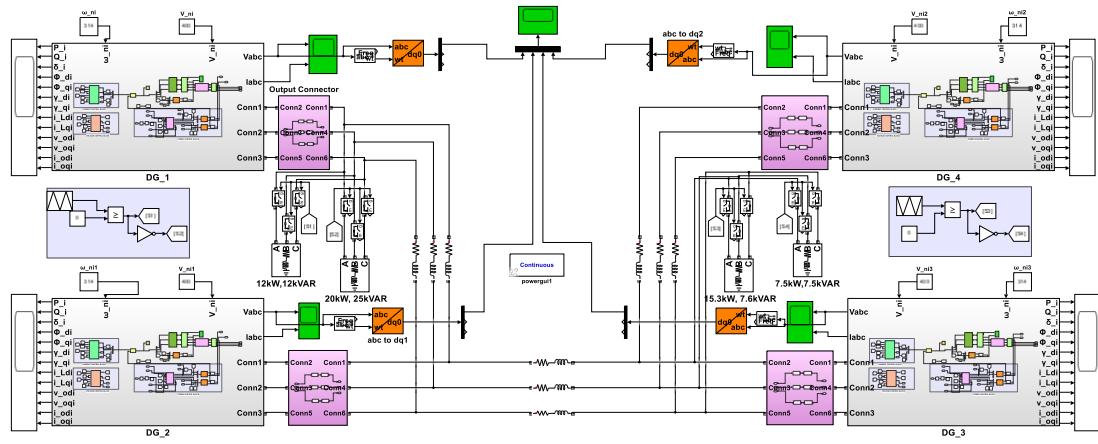
6.2.6 Diagrams and Results

Detailed circuit diagrams and simulation results for both the single DG and 4 DG models with primary and secondary controls will be included to illustrate the performance and effectiveness of the control schemes. These results demonstrate the smooth integration and operation of the DGs, validating our control strategy.

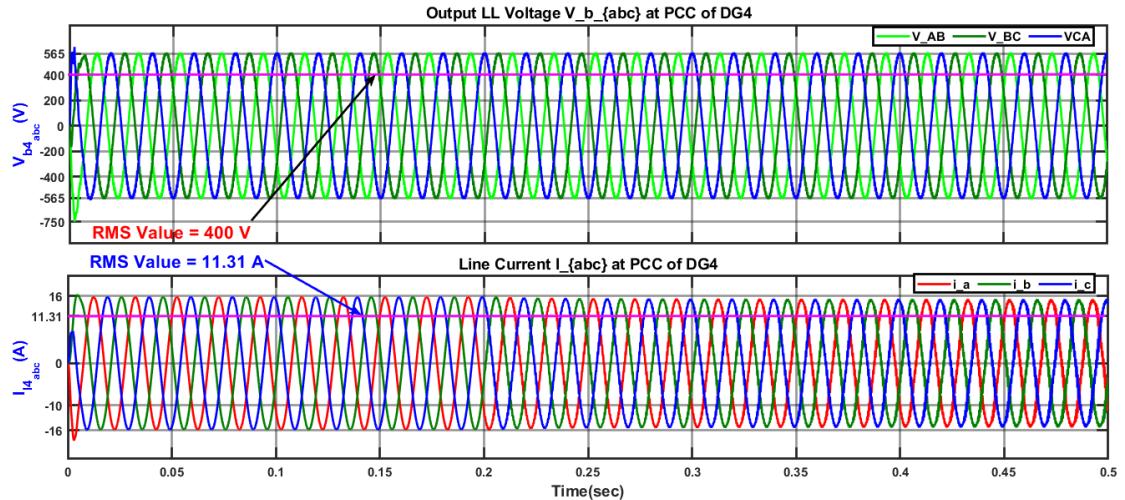
6.2.7 Discussion and Observations

Primary Control Scheme

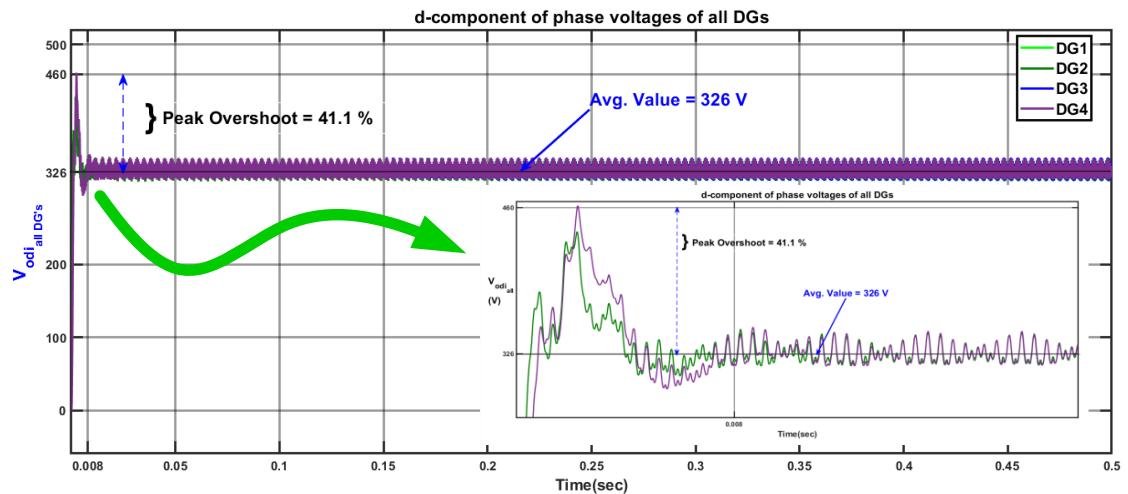
- **Sequential DG Connection:** When connecting the DG units sequentially, each DG unit maintained an output close to the desired 400 V LL. Minor deviations were observed, which can be attributed to the lack of synchronization and communication between the units (fig: 6.11).
- **Transient Response:** An initial overshoot of approximately 41.1 % of the average 326 V was noted when the DG units were connected. Despite this, the system



(a) The Test Model of Microgrid with 4 Distributed Generators



(b) Phase voltage(V_{abc}) at DG1



(c) d- Component of Output Phase voltage of All DGs

Figure 6.11: Output waveforms with primary controller

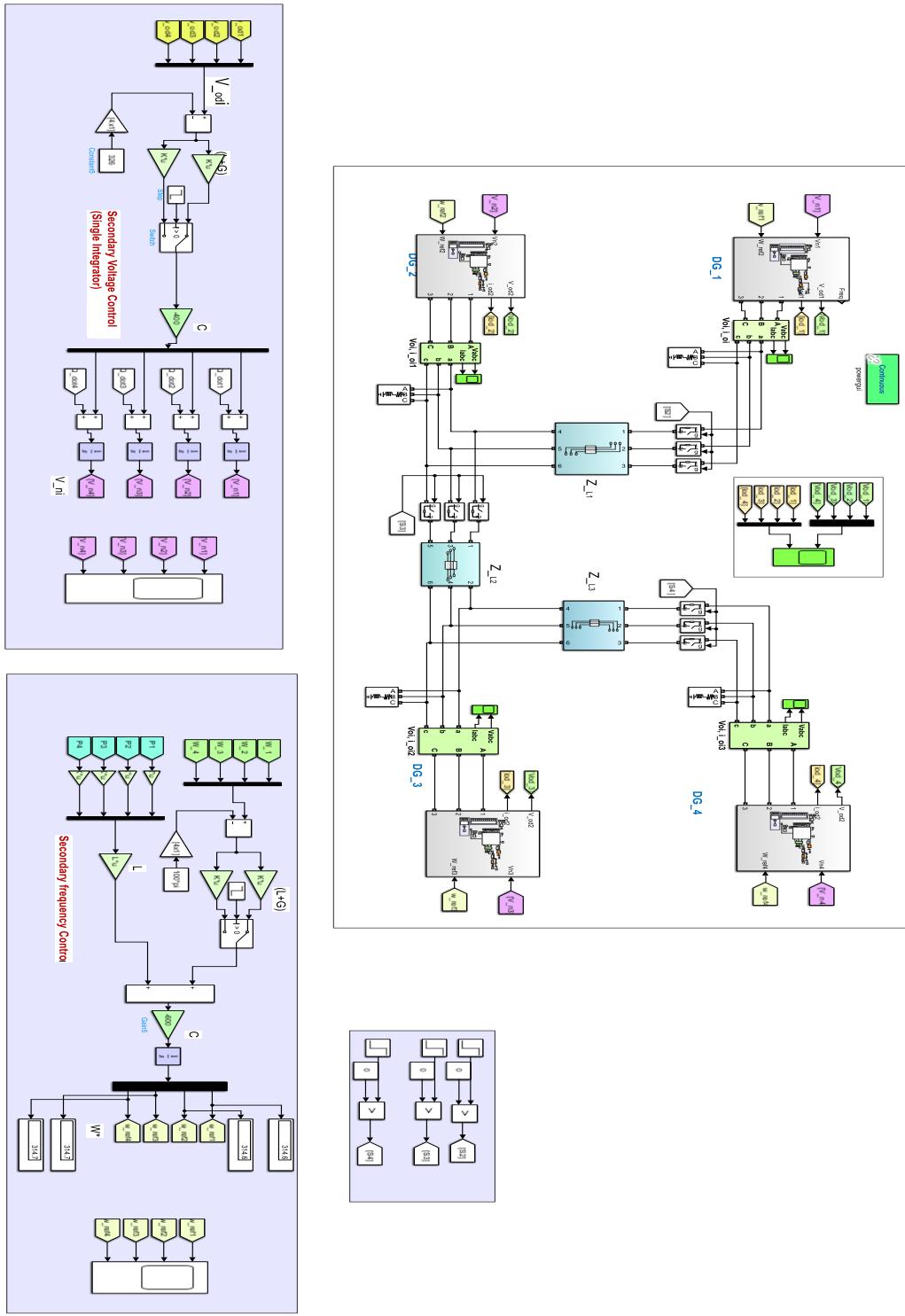
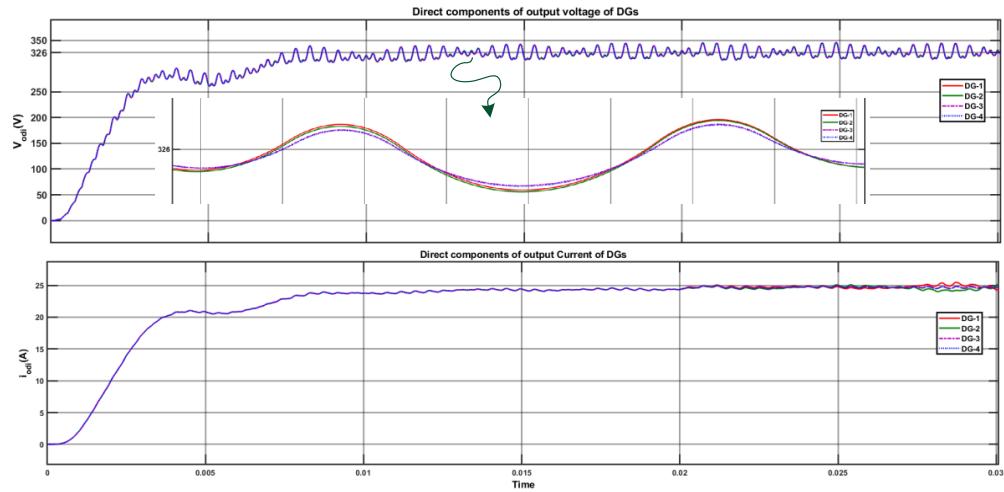
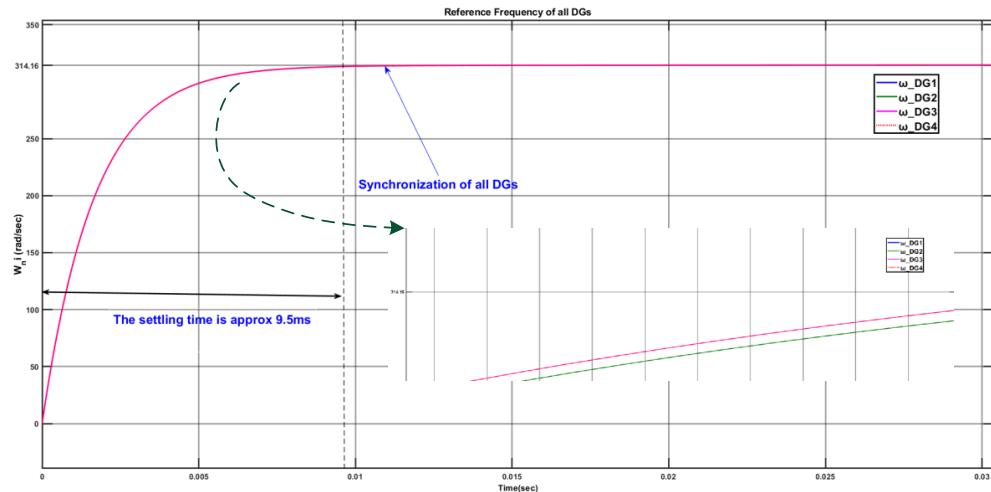


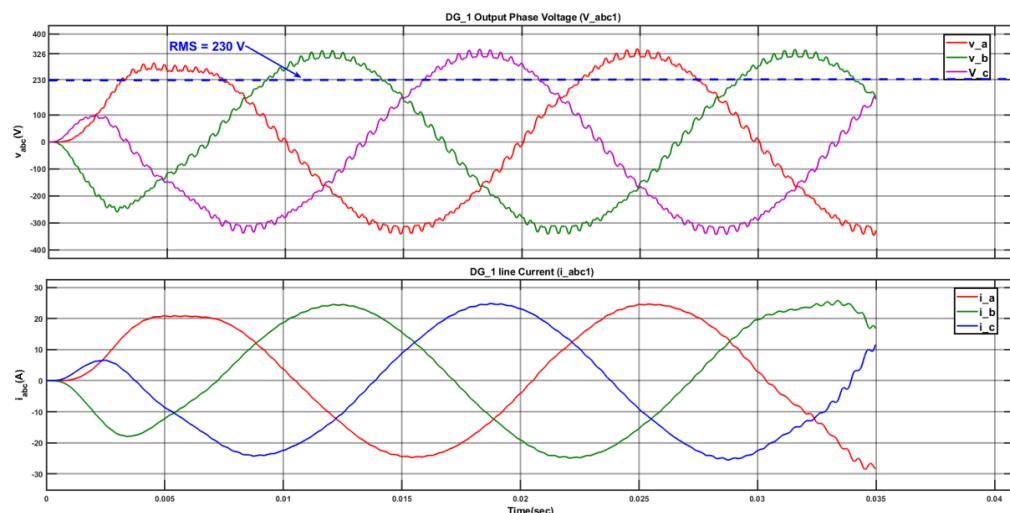
Figure 6.12: Simulation model of test grid with primary and secondary control



(a) Output voltages V_{odi} of all DGs

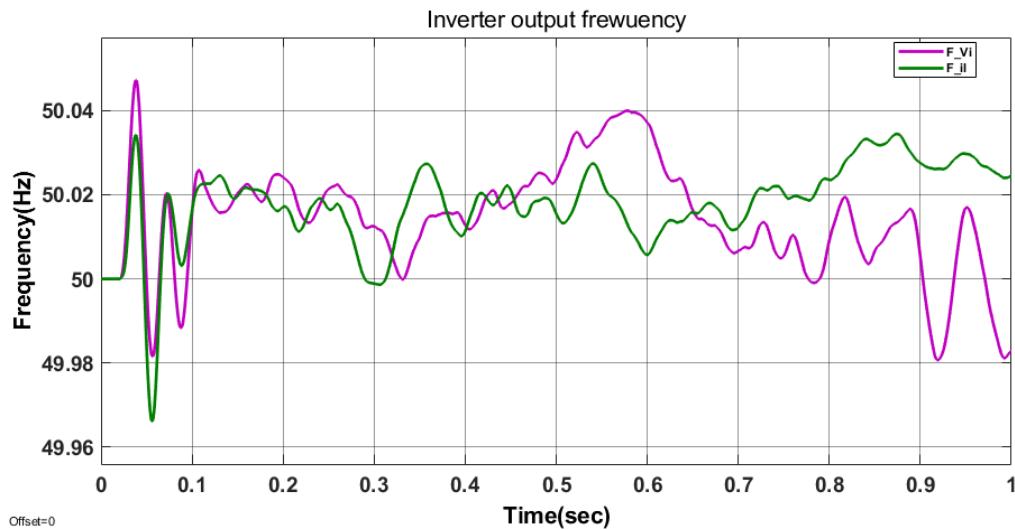


(b) Frequency references of all DGs

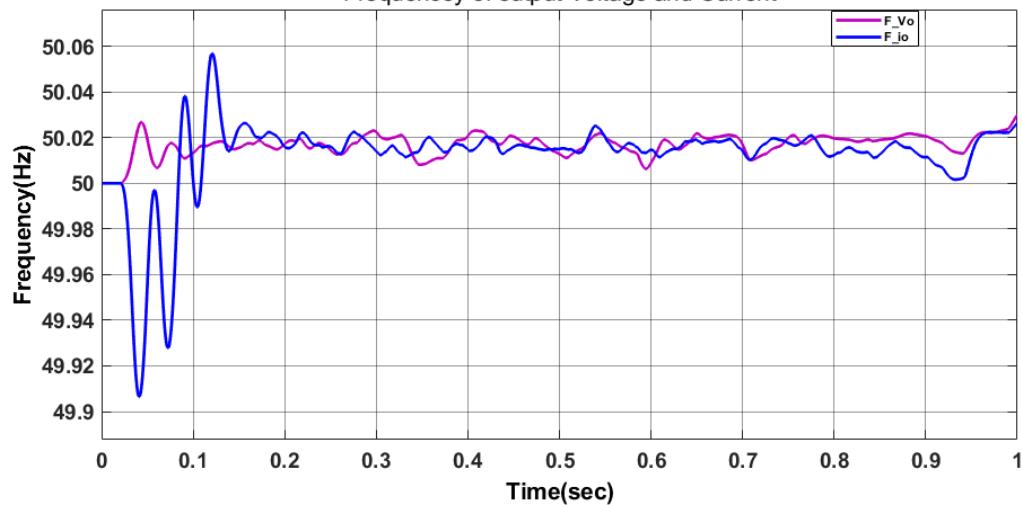


(c) Output phase voltage & current of DG1

Figure 6.13: Output waveforms with primary & secondary controller



(a) Frequency of DGs output at inverter terminal



(b) Frequency of DGs output at PCC

Figure 6.14: Output frequency of DGs

quickly stabilized, indicating the primary control's capability to handle multiple DG units, with some initial instability (fig: 6.11).

- **Deviation Minimization:** The slight deviations observed in the outputs of each DG unit suggest that while primary control alone is effective, it is insufficient to ensure complete synchronization and stability across multiple DG units.

Combined Primary and Secondary Control Scheme

- **Synchronization and Stability:** The combined primary and secondary control schemes successfully synchronized the voltage and frequency of all DG units. Each DG unit's

output voltage V_{od} followed one another, demonstrating the effectiveness of the distributed cooperative control mechanism in achieving consensus among the units (fig: 6.13).

- **Frequency Response:** A slight delay in frequency response was observed, particularly due to the communication topology where the first DG unit provided references to the second and fourth units, and the second unit provided references to the third. This delay is expected and reflects the inherent characteristics of the chosen topology, we have to change the topology while forming the grid & after that, we can move to the desired topology to maintain the grid stability.
- **Stable Operation:** With both control schemes in place, the microgrid achieved a stable operation with no initial overshoot and synchronized output voltages and frequencies. The system maintained a steady 400 V LL RMS at the PCC, indicating successful stabilization and consensus across the DG units.
- **Closed-Loop Necessity:** The observations underline the necessity of a fully closed-loop system for the secondary control to generate accurate and stable references. The secondary control's reference generation was inconsistent and unreliable when the system was not fully closed-loop. This emphasizes the importance of a complete closed-loop implementation for optimal performance.

Outcomes Based on Frequency of Output Voltage and Current

- **Primary Control Reference Alignment:** The reference for primary control is highly accurate, ensuring all DGs' references are well-aligned (fig: 6.13).
- **Inverter Terminal Performance:** At the inverter terminal, the frequency deviation ranges from 49.97 Hz to 50.05 Hz, indicating a maximum overshoot and undershoot within this narrow band. Other deviations are even smaller, demonstrating stable performance (fig: 6.14).
- **Output Frequency Stability:** The output frequency deviation is from 49.91 Hz to 50.058 Hz for a 50 Hz fundamental frequency. This range signifies the system's ability to adhere closely to the desired frequency with minimal deviation (fig: 6.14).

- **Transient Behavior:** The system exhibits initial transient oscillations but stabilizes quickly, maintaining the frequency close to the desired value over time, as seen in the figure.

These outcomes indicate that the primary control scheme is effective in maintaining frequency stability with minor deviations, both at the inverter terminal and the output, ensuring the reliable performance of the microgrid.

6.3 Overall Observations

- **Primary Control Effectiveness:** The primary control scheme is effective for individual DG units and maintains voltage regulation well. However, it shows limitations in handling multiple units and ensuring synchronization without secondary control.
- **Secondary Control Importance:** Secondary control is crucial for eliminating overshoots, improving reference tracking, and ensuring synchronization and stability in a multi-DG microgrid. It addresses the limitations of primary power, particularly in dynamic conditions and load changes. After applying secondary control, the frequency stability improved with deviations at the inverter terminal ranging from 49.97 Hz to 50.05 Hz and at the output from 49.91 Hz to 50.058 Hz.
- **Distributed Secondary Cooperative Control:** Implementing distributed secondary cooperative control has achieved voltage and frequency consensus among the four DG units. This control mechanism ensures that all DG units work harmoniously, maintaining consistent and synchronized output.
- **Communication Topology Impact:** The chosen communication topology impacts the frequency response delay, but overall stability and synchronization are achieved, validating the design.
- **System Robustness:** The system demonstrates robustness in handling transient conditions, load changes, and maintaining stable operation with both control schemes in place. Minor delays and deviations are within acceptable limits and do not compromise overall performance.

These observations indicate a successful implementation and validation of the primary and secondary control schemes, including distributed secondary cooperative control, in single-DG and multi-DG microgrid scenarios. The findings provide a strong foundation for further testing and practical deployment of the microgrid system.

Chapter 7

Conclusion and Future Works

7.1 Conclusion

The successful implementation and testing of both primary and secondary control schemes in single and multi-DG models highlight the robustness and scalability of our microgrid design. Based on droop control principles, the primary control and the fully distributed secondary control mechanism ensure efficient and reliable microgrid operation.

7.2 Future Works

The designed primary and secondary controllers are successfully controlling the voltages. Future work includes the following:

- **Frequency Control Enhancement:** The feedback linearization scheme should also be implemented for frequency control. Since DG voltage dynamics depend on frequency, integrating frequency control will enhance the overall stability and performance of the microgrid [19].
- **Experimental Validation:** Experimental validation will be conducted after successfully verifying the simulated model. This will substantiate the model's accuracy and effectiveness, providing real-world evidence of the control schemes' performance.
- **Advanced Communication Protocols:** Investigate the implementation of more advanced communication protocols and technologies to improve the synchronization and response times of the DG units. This can include exploring wireless commu-

nication, blockchain for secure and transparent data exchange, or other emerging communication technologies.

- **Integration of Renewable Energy Sources:** Extend the control schemes to integrate more diverse renewable energy sources, such as wind or biomass. This will test the flexibility and adaptability of the control mechanisms in a more varied and dynamic energy environment [20].
- **Optimization of Control Parameters:** Conduct further research into optimizing the control parameters for both primary and secondary control schemes. This can include adaptive control strategies that adjust parameters in real-time based on load conditions and other external factors [21].
- **Scalability Analysis:** Perform a detailed scalability analysis to understand the limitations and potentials of the current control schemes when applied to larger microgrid systems. This will involve simulation and experimental studies on larger setups with more DG units and more complex load profiles [22].
- **Economic Analysis and Cost-Benefit Studies:** Assess the economic viability of the implemented control schemes. This includes a detailed cost-benefit analysis considering installation, maintenance, and operational costs, as well as the potential savings from improved efficiency and reliability.
- **Impact of Cyber-Physical Security:** Evaluate the impact of cyber-physical security measures on the microgrid. This will involve designing and implementing security protocols to protect the microgrid from potential cyber-attacks and assessing their effectiveness [23].
- **Real-Time Monitoring and Control:** Develop a real-time monitoring and control system for the microgrid. This system will utilize advanced sensors and IoT technologies to provide continuous monitoring and control, ensuring optimal performance under varying conditions.

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Appendix A

Cooperative Control Scheme Design

The objectives of the cooperative team are described based on local neighbourhood tracking errors.

$$e_i = \sum_{j \in \mathcal{N}_i} a_{ij}(y_i - y_j) + g_i(y_i - y_0) \quad (\text{A.1})$$

where, a_{ij} - elements of adjacency matrix in digraph

g_i - pinning gain

$$\begin{aligned} e_1 &= a_{12}(y_1 - y_2) + a_{13}(y_1 - y_3) + a_{14}(y_1 - y_4) + g_1(y_1 - y_0) \\ e_2 &= a_{21}(y_2 - y_1) + a_{23}(y_2 - y_3) + a_{24}(y_2 - y_4) + g_2(y_2 - y_0) \\ e_3 &= a_{31}(y_3 - y_1) + a_{32}(y_3 - y_2) + a_{34}(y_3 - y_4) + g_3(y_3 - y_0) \\ e_4 &= a_{41}(y_4 - y_1) + a_{42}(y_4 - y_2) + a_{43}(y_4 - y_3) + g_4(y_4 - y_0) \end{aligned} \quad (\text{A.2})$$

The global error vector, including NDCs, can be written as:

$$e = \begin{bmatrix} a_{21} + a_{31} + a_{41} + g_1 & -a_{12} & -a_{13} & -a_{14} \\ -a_{21} & a_{12} + a_{32} + a_{42} + g_2 & -a_{23} & -a_{24} \\ -a_{31} & -a_{32} & a_{13} + a_{23} + a_{43} + g_3 & -a_{34} \\ -a_{41} & -a_{42} & -a_{43} & a_{14} + a_{24} + a_{34} + g_4 \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} - \begin{bmatrix} g_1 & 0 & 0 & 0 \\ 0 & g_2 & 0 & 0 \\ 0 & 0 & g_3 & 0 \\ 0 & 0 & 0 & g_4 \end{bmatrix} \begin{bmatrix} y_0 \\ y_0 \\ y_0 \\ y_0 \end{bmatrix} \quad (\text{A.3})$$

A.1 The Global Error Vector in Compact Form

$$e = ((L + G) \otimes I_n)Y - G(\mathbf{1}_n \otimes y_0), \quad \text{since } c = 1, y_0 = 0 \& Y_0 = \mathbf{1}_v \otimes y_0 \quad (\text{A.4})$$

$$e = ((L + G) \otimes I_n)Y - (L + G) \otimes I_n)Y_0 \quad \text{The global error vector} \quad (\text{A.5})$$

$$e_v = ((L + G) \otimes I_n)(Y - Y_0) = e_{v1} \quad \text{The global error vector} \quad (\text{A.6})$$

$$e_v = ((L + G) \otimes I_n)e_{v1} \quad (\text{A.7})$$

Where,

- N - number of agents
- n - number of states
- L - Laplacian matrix
- G - pinning gain matrix
- \otimes - Kronecker product
- δ - global disagreement vector

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{bmatrix}, \quad e = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ \vdots \\ e_N \end{bmatrix}, \quad Y_0 = \begin{bmatrix} \mathbf{1}_n \otimes y_0 \\ \mathbf{1}_n \otimes y_0 \\ \mathbf{1}_n \otimes y_0 \\ \vdots \\ \mathbf{1}_n \otimes y_0 \end{bmatrix} \quad (\text{A.8})$$

A.2 Auxiliary Control Input

The auxiliary control input is determined by:

$$v_i = -cKe_i \quad (\text{A.9})$$

where K is the feedback gain matrix determined from the algebraic Riccati equation (ARE) as:

$$K = R^{-1}B^TP \quad (\text{A.10})$$

and c is coupling gain, chosen as:

$$c \geq \frac{1}{2\lambda_{\min}}, \quad \text{where, } \lambda_2 \text{ is eigenvalue of } (L + G) \quad (\text{A.11})$$