PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH
YAHIA FARÈS UNIVERSITY OF MÉDÉA

FACULTY OF TECHNOLOGY

DOCTORAL THESIS

To obtain the degree of DOCTOR

In: Automatic

Speciality: Automatic And Systems

Presented by: **CHARFI Zakaria**

Thesis title

Modeling and Control of Grid-Forming Inverters

Publicly defended before the jury composed of:

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Academic Year 2025–2026

RÉPUBLIQUE ALGÉRIENNE DÉMOCRATIQUE ET POPULAIRE
MINISTÈRE DE L'ENSEIGNEMENT SUPÉRIEUR ET DE LA RECHERCHE SCIENTIFIQUE
UNIVERSITÉ YAHIA FARÈS DE MÉDÉA

FACULTÉ DE TECHNOLOGIE

THESE DE DOCTORAT

Présentée en vue de l'obtention du grade de DOCTEUR

Filière: Automatique

Spécialité: Automatique et Systèmes

Par : **CHARFI Zakaria**

Thème

Modélisation et contrôle des onduleurs Grid- forming

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Année Universitaire 2025-2026

ملخص :

تُقدِّم هذه الأطروحة استراتيجية تحكم جديدة لمحولات تشكيل الشبكة (GFMIs) تعتمد على التحكم القائم على السلبية باستخدام تخصيص التوصيل والتخميد .(IDA-PBC) تعمل الطريقة المقترحة على تحسين التحكم الكلاسيكي بالتراخي من خلال دمج مُدمجين ديناميكيين لتنظيم القدرة الفعالة والمتفاعلة، مما يسمح بدقة أفضل في الحالة المستقرة واستقرار ديناميكي مُحسَّن. تم نمذجة المحول كنظام هاميلتوني بمنفذ، وتم اشتقاق قانون التحكم من خلال تشكيل دالة الطاقة وتخصيص مصفوفات التوصيل والتخميد المطلوبة. تؤكد الدراسات المُحاكاة أن وحدة التحكم تضمن استقرار التردد والجهد، وتوزيعاً فعالاً للطاقة، وتشغيلاً سلساً في وضعي الاتصال بالشبكة والعمل المستقل

الكلمات المفتاحية

محول تشكيل الشبكة ، التحكم بالتراخي، التحكم غير الخطي، التصميم القائم على السلبية، الشبكات المصغرة.

Abstract:

This thesis presents a novel control strategy for grid-forming inverters (GFMIs) based on Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC). The proposed method enhances classical droop control by integrating two dynamic integrators for active and reactive power regulation, allowing for improved steady-state accuracy and dynamic stability. The inverter is modeled as a port-Hamiltonian system, and the control law is derived by shaping the energy function and assigning the desired interconnection and damping matrices. Simulation studies confirm that the controller ensures frequency and voltage stability, effective power sharing, and seamless operation in both grid-connected and islanded modes.

Keywords

Grid-forming inverter, Droop control, Nonlinear control, Passivity-based design, Microgrids.

Résumé :

Cette thèse propose une stratégie de commande innovante pour les onduleurs de type grid-forming, basée sur le contrôle passif par attribution d'interconnexion et d'amortissement (IDA-PBC). Cette approche améliore la commande droop classique en intégrant deux actions intégrales — pour la puissance active et réactive — ce qui permet d'atteindre une meilleure précision stationnaire et une stabilité dynamique renforcée. L'onduleur est modélisé comme un système hamiltonien à ports, et la loi de commande est obtenue par mise en forme de l'énergie et assignation des matrices d'interconnexion et d'amortissement. Les simulations valident la robustesse du système dans divers scénarios, y compris les modes connectés au réseau et en îlotage.

Mots clés

Onduleur grid-forming, Commande droop, Commande non linéaire, Conception basée sur la passivité, Microréseaux.

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List of Abbreviations and Symbols

Abbreviations

Abbreviation	Definition
AC	Alternating Current
DC	Direct Current
DG	Distributed Generator
MG	Microgrid
RES	Renewable Energy Source
VSI	Voltage Source Inverter
GFM	Grid-Forming
GFL	Grid-Following
PBC	Passivity-Based Control
IDA-PBC	Interconnection and Damping Assignment Passivity-Based Control
PH	Port-Hamiltonian
VSG	Virtual Synchronous Generator
VOC	Virtual Oscillator Control
PI	Proportional–Integral
PWM	Pulse Width Modulation
LCL	Inductor–Capacitor–Inductor Filter
PCC	Point of Common Coupling

Abbreviation	Definition
PLL	Phase-Locked Loop
RMS	Root Mean Square
AVR	Automatic Voltage Regulation

Symbols

Symbol	Description	Unit
v_{abc}	Three-phase voltages in the abc frame	Volt (V)
i_{abc}	Three-phase currents in the abc frame	Ampere (A)
v_{dq}	dq-axis voltages	Volt (V)
i_{dq}	dq-axis currents	Ampere (A)
P	Active power	Watt (W)
Q	Reactive power	Volt-Ampere Reactive (VAR)
V	Voltage	Volt (V)
I	Current	Ampere (A)
ω	Angular frequency	Radian per second (rad/s)
ω_0	Nominal angular frequency	Radian per second (rad/s)
$\Delta\omega$	Frequency deviation	Radian per second (rad/s)
θ	Phase angle	Radian (rad)
V_{dc}	DC-link voltage	Volt (V)

Symbol	Description	Unit
L	Inductance	Henry (H)
C	Capacitance	Farad (F)
R	Resistance	Ohm (Ω)
$H(x)$	Hamiltonian energy function	Joule (J)
J	Interconnection matrix	
R_d	Damping matrix	
x	State vector	
$\dot{x}$	Time derivative of state vector	
u	Control input vector	
y	Output vector	
i_d, i_q	dq components of current	Ampere (A)
v_d, v_q	dq components of voltage	Volt (V)
V_{ref}, f_{ref}	Voltage and frequency reference values	V, Hz
P_{ref}, Q_{ref}	Reference active and reactive power	W, VAR
D_p, D_q	Droop coefficients for active/reactive power	
E	Energy stored in the system	Joule (J)
$\nabla H(x)$	Gradient of the Hamiltonian function	
$G(s)$	Transfer function	
V_{load}	Load voltage	Volt (V)

Symbol	Description	Unit
I_{load}	Load current	Ampere (A)
f	Frequency	Hertz (Hz)

General Introduction

GENERAL INTRODUCTION

Context and Motivation

Modern power systems are undergoing a rapid transformation driven by the increasing integration of renewable energy sources such as photovoltaic (PV) and wind energy [1], [2]. These distributed energy resources are typically interfaced with the grid through power electronic inverters, which inherently lack the inertial and synchronizing characteristics of conventional synchronous generators [3], [4]. Consequently, the growing penetration of inverter-based resources (IBRs) has introduced new challenges related to frequency stability, voltage regulation, and system reliability [5],[6].

To address these challenges, new paradigms of control and operation have been developed. Among them, grid-forming inverters (GFMIs) have emerged as a promising technology capable of supporting grid stability by establishing their own voltage and frequency references [7], [8]. Unlike grid-following inverters, which rely on a phase-locked loop (PLL) to synchronize with an existing grid voltage, GFMIs can operate autonomously and maintain voltage and frequency even in islanded conditions [9]. Their ability to emulate the electromechanical dynamics of synchronous machines makes them particularly suitable for microgrid and weak-grid applications [10], [11].

However, the design of stable and robust GFMI control strategies remains a major technical challenge [12], [13]. Effective control must ensure synchronization, stable power sharing, and dynamic performance even under grid disturbances or multiple-inverter interactions [14].

Problem Statement

Classical grid-forming control strategies—particularly proportional droop control—are inspired by the steady-state power–frequency and voltage–reactive power relationships of synchronous generators [15], [16]. Droop control regulates active and reactive power by adjusting the inverter's frequency and voltage amplitudes, thus enabling decentralized power sharing among parallel units [17].

Despite its simplicity and widespread adoption, proportional droop control suffers from key limitations. It introduces steady-state errors in both frequency and voltage [18]; it is sensitive to grid strength and parameter variations [19]; and it does not ensure global stability in nonlinear or multi-inverter systems [20], [21]. These drawbacks become particularly critical in low-inertia or islanded microgrids, where precise frequency and voltage regulation are essential [22].

As microgrids continue to expand with higher shares of renewable energy, improved control strategies are required to ensure robustness, stability, and scalability [23]. Several enhanced approaches have been proposed, including virtual synchronous generator (VSG) control, virtual oscillator control (VOC), and passivity-based control (PBC) [24]–[26]. Among them, PBC provides a rigorous mathematical framework for stability assurance and energy balance [27], making it well-suited for nonlinear inverter systems.

Objectives of the Study

The primary objective of this research is to conduct a comparative analysis between conventional droop control and droop control with integral action (DCI) in the context of a microgrid system, using a passivity-based voltage source inverter (VSI) as the main control platform [28].

Passivity-Based Control (PBC) has attracted significant attention in recent years due to its ability to ensure stability and robustness against uncertainties and disturbances [29], [30]. By maintaining the passivity property—meaning the system does not generate net energy—PBC ensures that the overall system remains stable even under complex operating conditions [31].

This study emphasizes several performance aspects, including:

- Stability and robustness under different grid scenarios.
- Control flexibility in response to dynamic load variations.
- Transient and steady-state performance during disturbances.
- Implementation complexity and computational efficiency.

MATLAB/Simulink is used as the main simulation environment for modeling and analysis. Both droop control and DCI-based control are tested under different operating conditions, including load changes, grid connection, and islanding scenarios. Comparative evaluations reveal the strengths and weaknesses of each approach, helping identify the most suitable strategy for autonomous microgrid operation.

Specific Objectives

This thesis aims to develop and validate a novel grid-forming inverter control method that:

- Combines classical droop control with integral action to eliminate steady-state frequency and voltage errors.
- Is formulated within the Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC) framework to guarantee formal stability.
- Employs a port-Hamiltonian model for physically consistent control synthesis.
- Ensures reliable performance under load variations, islanding, and reconnection scenarios.

Methodology Overview

The research methodology follows a systematic structure designed to ensure both theoretical depth and practical validation:

1. **System Modeling:**
   Development of the inverter and microgrid dynamic models using dq transformation and port-Hamiltonian formalism.
2. **Control Design:**
   Application of the IDA-PBC framework to integrate droop control with integral action, achieving robust voltage and frequency regulation.
3. **Simulation and Validation:**
   Implementation and testing of the proposed control in MATLAB/Simulink under various operating conditions, including load steps and islanded operation.

4. **Performance Analysis:**
   Evaluation of transient behavior, steady-state accuracy, and stability margins for both conventional and proposed control strategies.

This approach ensures the proposed method maintains physical consistency, passivity, and robustness throughout the control design process.

Thesis Organization

The thesis is organized into four main chapters, in addition to the general introduction and conclusion.

- **Chapter 1: Evolution of Power Systems and the Emergence of Microgrids**

  This chapter presents a historical overview of power system development, describing the transition from centralized generation to decentralized architectures. It introduces the concept of microgrids, discusses their components and operation modes, and highlights their importance in the global energy transition.

- **Chapter 2: Modeling and Control of Microgrids**

  This chapter focuses on the mathematical modeling of microgrid systems and inverter-based control structures. It explains internal control strategies such as Proportional-Integral, Proportional-Resonant, Predictive, and Passivity-Based approaches, and explores primary control strategies for parallel inverters, including Grid-Following and Grid-Forming methods.

- **Chapter 3: Grid-Forming Control**

  This chapter explores grid-forming control strategies that allow inverters to autonomously regulate voltage and frequency. It analyzes the conventional droop control method, identifies its limitations, and presents improved variants such as Transient Droop Control and Droop Control with Two Integrators.

- **Chapter 4: Proposed Control Strategy**

  This chapter presents the proposed advanced control method based on the Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC)

framework. The approach integrates droop control with dual integral action to enhance damping, stability, and power sharing accuracy in islanded microgrids. MATLAB/Simulink simulations are conducted to validate its performance against conventional strategies.

- **General Conclusion**

  The final section summarizes the main findings of the thesis, highlights the advantages of the proposed control approach, and outlines perspectives for future research in advanced microgrid control and renewable energy integration.

CHAPTER I:

Evolution of Power Systems and the Emergence of Microgrids

Chapter 1: Evolution of Power Systems and the Emergence of Microgrids

1.1 Introduction

Over the past decades, electricity consumption has increased considerably due to industrial growth, urbanization, and the rapid integration of new electrical devices and digital technologies [32]. Traditional power systems, mainly based on centralized generation, have been pushed to their technical and economic limits in order to meet this rising demand [33]. While centralized structures have historically enabled the expansion of modern power grids, they are increasingly challenged by issues related to efficiency, environmental impact, and supply reliability [34].

At the same time, global concerns about climate change and resource depletion have led to a strong push toward renewable energy sources such as wind, solar, hydro, and biomass [35]. However, the intermittent and distributed nature of these resources cannot be fully accommodated by conventional centralized generation models [36].

In response, a new paradigm has emerged: microgrids [37]. These localized power systems integrate distributed generators (DGs), inverters, and loads in a coordinated manner, providing flexibility, resilience, and improved energy management [38]. Microgrids are capable of operating either in connection with the main grid or in islanded mode, making them a key solution to the challenges of modern power systems [39].

This chapter reviews the evolution from centralized to distributed generation, introduces the concept of microgrids, and outlines their structure, operation, and challenges. It establishes the foundation for the following chapters, which will explore in detail the control strategies of inverter-based microgrids.

1.2 Centralized Power Generation

For more than a century, centralized generation has been the backbone of electrical power systems [40]. Large-scale power plants, typically fueled by coal, natural gas, oil, or nuclear energy, have been designed to produce bulk electricity and deliver it through extensive transmission and distribution networks to end-users. This model of generation and delivery has enabled the electrification of entire nations, supporting economic development, industrialization, and social progress [41].

The centralization of electricity production was motivated by several factors. First, economies of scale made large power plants cost-effective, as producing electricity in bulk significantly

reduced the unit cost of generation. Second, centralization facilitated the planning and operation of transmission systems by ensuring controllable and reliable supply. Third, by locating power plants outside urban areas, environmental and health risks associated with emissions and cooling systems were partially mitigated.



Fig 1.1 Centralized Power Generation System

Despite these advantages, centralized generation systems present several limitations and challenges in the context of modern energy transitions. These challenges can be analyzed from technical, economic, environmental, and societal perspectives [42].

1.2.1 Technical and Economic Constraints

Centralized generation requires complex infrastructure for electricity transmission over long distances, which increases both costs and energy losses [43]. Transmission and distribution losses can account for a significant percentage of total generated energy, thereby reducing overall system efficiency [44].

Moreover, centralized systems are highly dependent on fossil fuels, whose availability and prices are subject to global market fluctuations. This dependency leads to unstable production costs, directly impacting consumer electricity prices. Additionally, maintaining grid reliability requires continuous investment in transmission expansion, reinforcement, and equipment maintenance, which further increases costs [49].

From a technical standpoint, centralized generation also struggles with operational flexibility. The rigid structure of large-scale plants is poorly adapted to manage sudden variations in demand or to accommodate the variability of renewable energy sources.

1.2.2 Environmental Impact

The environmental drawbacks of centralized systems are considerable. Fossil fuel-based plants are major contributors to greenhouse gas emissions, including carbon dioxide (CO_2) and sulfur dioxide (SO_2), which exacerbate global warming and air pollution. Combustion processes also produce solid residues such as fly ash, which pose disposal challenges and environmental hazards [45].

Nuclear power plants, while reducing greenhouse gas emissions, generate radioactive waste requiring highly secure and costly storage solutions for thousands of years. Furthermore, water resources are heavily exploited in cooling processes, often leading to thermal and chemical pollution of rivers and lakes [46].

These environmental consequences highlight the unsustainability of centralized systems in the long term.



Fig 1.2 Drawbacks of Centralized Systems

1.2.3 Societal and Strategic Considerations

In addition to technical and environmental issues, centralized generation raises societal and strategic concerns. Concentrating production in a few large plants creates vulnerability to failures, since the outage of one unit can affect millions of consumers [47]. Moreover, the reliance on fossil fuels, often imported, reduces national energy independence and exposes countries to geopolitical risks [48].

Societal expectations are also evolving. Citizens and local communities increasingly demand cleaner energy, decentralized participation, and autonomy in their energy consumption. This change of perspective has fostered the development of distributed generation (DG), which allows individuals and communities to install small-scale renewable-based systems and contribute directly to electricity production [49].

1.3 Distributed Generation

The limitations of centralized generation, combined with the rapid development of renewable energy technologies, have driven the evolution of Distributed Generation (DG) [50]. Unlike centralized plants that rely on large facilities located far from consumers, DG systems are small- to medium-scale generation units placed close to end-users. They typically rely on renewable resources such as solar photovoltaic (PV), wind, micro-hydro, and biomass, but may also include small gas turbines or diesel generators.



Fig 1.3 City with DG vs. City with Centralized System

The integration of DG has transformed the structure of modern electrical networks, enabling the transition from a unidirectional, supply-driven system to a more decentralized and participatory model. In this context, consumers are no longer passive recipients of electricity; they can also act as “prosumers”, generating and even selling their surplus energy to the grid.

1.3.1 Technical Benefits

From a technical perspective, DG enhances the flexibility and reliability of the power system. Placing generation units close to loads reduces the need for long-distance transmission, thereby lowering line losses and improving efficiency. In addition, DG units can provide ancillary services such as reactive power support and voltage stabilization, which are essential in maintaining grid quality.

Furthermore, distributed systems allow for modular deployment [51]. New generation units can be added progressively according to local demand growth, avoiding the heavy upfront investment required for large centralized plants. This modularity is particularly valuable in remote or rural areas, where extending transmission lines would be costly and inefficient.

1.3.2 Economic Advantages

The economic appeal of DG lies in both investment and operational savings. By deferring or avoiding the need for transmission and distribution infrastructure expansion, DG reduces capital expenditure. Moreover, the reliance on renewable resources shields consumers and utilities from fossil fuel price volatility.

On the microeconomic level, DG creates opportunities for households, businesses, and communities to reduce their electricity bills by producing their own energy. In many countries, regulatory frameworks encourage such practices through feed-in tariffs, net metering policies, or tax incentives [52].

1.3.3 Environmental Considerations

One of the strongest motivations for DG deployment is its environmental impact. Most distributed generation technologies are based on renewable and low-emission sources, significantly reducing greenhouse gas emissions and air pollutants [53]. Unlike centralized fossil fuel plants, DG systems typically have minimal water usage and land impact, making them more sustainable and environmentally friendly.

The deployment of renewable-based DG also supports national and international policies aimed at combating climate change.

1.3.4 Societal and Strategic Implications

DG fosters a new energy paradigm where local actors—households, communities, and municipalities—actively participate in energy management. This participatory model increases consumer autonomy, strengthens local economies, and promotes social acceptance of renewable energy projects [59].

Strategically, DG contributes to energy security by reducing dependence on imported fuels and enhancing resilience against large-scale outages. In the event of failures in the main grid, distributed systems can maintain supply to critical loads through microgrids, which represent the natural evolution of DG structures.

1.4 Classification of Small-Scale Grids

The increasing penetration of distributed generation units has led to new concepts of localized power systems, classified into nano-grids, micro-grids, and mini-grids [60]. These systems differ mainly in terms of installed capacity, scale of deployment, and functional objectives, but they all share the common goal of improving energy autonomy, reliability, and sustainability at the local level.



Fig 1.4 Small-Scale Grids System

1.4.1 Nano-Grids

A nano-grid represents the most basic building block of modern decentralized power systems. It typically serves a single household, small office, or an individual consumer [54]. With an installed power capacity usually limited to around 1 kW, a nano-grid can produce, store, and manage electricity to meet its internal demand.

Nano-grids can operate in two modes:

- **Autonomous mode**, where generation (e.g., rooftop solar panels) and storage are sufficient to cover local loads.
- **Grid-connected mode**, where the nano-grid exchanges power with the main grid, either importing when demand exceeds generation or exporting surplus electricity.

Due to their simplicity, nano-grids are often the first step toward consumer participation in decentralized energy systems. They are also well-suited for rural electrification projects or as emergency backup systems in urban areas.

1.4.2 Micro-Grids

Micro-grids extend the concept of nano-grids by interconnecting multiple distributed generators, inverters, and loads within a power range of 1 kW to 10 MW [55]. They are considered the most representative form of decentralized energy systems and are widely studied in both research and practice.

Micro-grids are designed to:

- Integrate diverse distributed energy sources such as photovoltaic panels, wind turbines, biomass units, and micro-hydro systems.
- Provide higher reliability and efficiency by sharing power among multiple generation units.
- Operate in both grid-connected and islanded modes, ensuring resilience during main grid outages.

The parallel operation of different distributed units offers significant advantages in terms of continuity of service, robustness, and power quality. However, it also introduces technical challenges such as circulating currents, harmonic distortion, and system stability issues. Addressing these challenges requires the development of advanced control strategies, which will be discussed in later chapters.

1.4.3 Mini-Grids

A mini-grid represents the next level of decentralization, achieved by interconnecting several micro-grids to form a larger autonomous system. With a capacity greater than 10 MW, mini-grids are capable of supplying electricity to entire villages, industrial zones, or urban districts [63].

Mini-grids play an important role in:

- **Rural electrification**, particularly in developing countries where extending national transmission networks is economically unfeasible.
- **Energy security**, by reducing dependence on centralized systems and ensuring local self-sufficiency.
- **Scalability**, since they can be progressively expanded as demand grows.

While mini-grids require higher investment compared to nano- and micro-grids, their larger scale allows them to achieve economies of scale, improved efficiency, and greater integration of renewable resources.

1.4.4 Comparative Analysis

The distinction between nano-, micro-, and mini-grids lies not only in their size but also in their functional role:

- Nano-grids serve individual consumers.
- Micro-grids represent community-scale systems that balance multiple local resources.
- Mini-grids extend decentralization to regional or village-scale electrification.

Together, these systems illustrate the progressive evolution from individual energy autonomy to community-based and regional-scale resilience. They also highlight the flexibility of

distributed generation concepts, which can be adapted to different technical, economic, and societal contexts [64].

1.5 Definition and Characteristics of Microgrids

A microgrid can be broadly defined as a localized, small-scale power system that integrates distributed energy resources (DERs), energy conversion units such as inverters, controllable and non-controllable loads, and, in some cases, storage devices, into a unified and manageable entity. Unlike traditional centralized power systems, microgrids are designed to operate either in connection with the main utility grid or in an autonomous islanded mode, ensuring continuous energy supply under diverse operating conditions [56].

One of the most distinguishing features of microgrids lies in their flexibility and modularity. They can accommodate various types of distributed generation, such as photovoltaic panels, wind turbines, or small-scale diesel generators, and connect them through inverters that provide the required voltage and frequency support. This modular nature makes microgrids scalable, enabling their deployment across different contexts, from remote rural areas to urban districts or industrial facilities.

Another fundamental characteristic of microgrids is their ability to enhance reliability and resilience [57] [58]. By decentralizing power generation and embedding control intelligence close to the demand centers, microgrids reduce dependency on long transmission lines and mitigate the risks associated with large-scale blackouts. Their capacity to seamlessly disconnect from the main grid and maintain operation autonomously allows them to provide secure and uninterrupted power supply even under fault or disturbance conditions.

Furthermore, microgrids are inherently designed to promote energy efficiency and sustainability. By locally balancing generation and consumption, energy losses in transmission and distribution are significantly reduced. The integration of renewable energy resources not only decreases reliance on fossil fuels but also contributes to reducing greenhouse gas emissions, aligning with global targets for sustainable development [59] [60].

From a control perspective, microgrids require advanced strategies capable of coordinating multiple distributed resources. The presence of inverters as essential components introduces the need for precise synchronization, voltage and frequency regulation, and power-sharing mechanisms among units. These control requirements highlight microgrids as both a

technological opportunity and a scientific challenge, positioning them at the forefront of modern power system research.

1.6 Advantages of Microgrids

The adoption of microgrids provides a wide range of advantages that address the limitations of traditional centralized power systems. These advantages extend across technical, economic, and environmental dimensions, making microgrids an attractive option for both developed and developing countries [61] - [64].

1.6.1 Reliability and Resilience

One of the foremost benefits of microgrids is their ability to enhance the reliability of electricity supply. By integrating distributed generators and enabling autonomous operation in islanded mode, microgrids can continue providing power during faults, natural disasters, or blackouts affecting the main grid. This resilience is especially critical for hospitals, military facilities, data centers, and other infrastructures where uninterrupted power supply is essential.

1.6.2 Flexibility and Scalability

Microgrids are inherently modular systems. They can be designed to serve small communities, industrial zones, or large urban districts. Their scalability allows them to expand incrementally as demand grows, without requiring massive infrastructure investments comparable to centralized grids [65].

1.6.3 Energy Efficiency

By generating electricity close to the point of consumption, microgrids minimize transmission and distribution losses. This localized approach improves overall system efficiency and reduces the need for costly upgrades of transmission infrastructure [66].

1.6.4 Renewable Energy Integration

Microgrids provide an effective platform for incorporating renewable energy sources, such as solar and wind. The local use of these resources not only reduces dependence on fossil fuels

but also supports international commitments to reduce greenhouse gas emissions. Furthermore, through inverters and smart control systems, microgrids can effectively manage the variability and intermittency of renewables [67] - [69].

1.6.5 Economic Benefits

Microgrids can reduce operational costs by optimizing local generation and consumption. They also provide opportunities for demand-side management, peak shaving, and energy trading, which can generate additional revenues. In remote or rural areas, where extending the main grid may be prohibitively expensive, microgrids offer a cost-effective alternative to provide electricity access [70].

1.6.6 Support for Smart Grids

Microgrids can be considered building blocks of the larger smart grid concept. They integrate advanced monitoring, control, and communication technologies, enabling interaction with the main grid and enhancing overall system performance [71].

1.6.7 Environmental Sustainability

By encouraging the integration of renewable resources and improving energy efficiency, microgrids directly contribute to environmental sustainability. They help reduce greenhouse gas emissions, promote clean energy solutions, and align with global strategies for sustainable development.

Microgrids present a comprehensive set of advantages, ranging from technical robustness and economic viability to environmental benefits. These advantages justify the growing interest in microgrid deployment worldwide and establish them as a central component in the future of power systems.

1.7 Challenges and Limitations of Microgrids

Despite their numerous advantages, the large-scale deployment of microgrids still faces several technical [72], economic [73], and regulatory [74] challenges. Understanding these limitations is crucial for developing effective solutions and ensuring the reliable integration of microgrids into modern power systems.

1.7.1. Technical Challenges

- **Control Complexity:** Coordinating multiple distributed generators (DGs), inverters, and loads within a microgrid requires advanced hierarchical control strategies [75]. Ensuring stability during transitions between grid-connected and islanded modes remains a complex task.
- **Protection Issues:** Conventional protection schemes designed for centralized systems may not operate effectively in microgrids due to bidirectional power flows, variable fault currents, and the dominance of inverter-based sources. Developing adaptive protection schemes is an ongoing research challenge [76].
- **Stability Concerns:** The integration inverter-based resources introduces new dynamic behaviors that differ significantly of from synchronous generators. Issues such as voltage stability, frequency regulation, and power sharing must be carefully addressed to maintain system reliability.
- **Energy Management:** Optimal scheduling of local generation and load demand requires advanced energy management systems (EMS). This is especially challenging when dealing with intermittent renewable energy resources, which increase uncertainty.

1.7.2. Economic Challenges

- **High Initial Investment:** Implementing microgrids requires significant capital expenditure for distributed generators, advanced control equipment, protection devices, and communication infrastructure.
- **Cost of Storage and Inverters:** Although inverters are an essential part of microgrids, they add cost and require sophisticated designs for grid-forming functionality. Similarly, energy storage systems (ESS) – when integrated – increase the total investment.
- **Uncertain Payback Period:** While microgrids may reduce operational costs, their financial viability depends on regulatory support, electricity tariffs, and the ability to monetize services such as frequency support and peak shaving.

1.7.3. Regulatory and Policy Challenges

- **Lack of Standards:** The absence of universally accepted technical standards for microgrids complicates their integration into national grids. Harmonized standards for communication protocols, control strategies, and protection coordination are urgently needed.
- **Grid Interconnection Rules:** In many countries, existing regulations were designed for centralized grids and do not adequately address the operational and legal aspects of microgrids. Issues such as ownership, liability, and operational rights require clearer policies.
- **Market Participation:** Microgrids may provide valuable services such as ancillary support, yet mechanisms for fair market participation are not always in place.

1.7.4. Social and Operational Challenges

- **Public Acceptance:** The successful deployment of microgrids depends on awareness and acceptance by local communities. Resistance may arise due to concerns about reliability, costs, or environmental impacts.
- **Operational Expertise:** Managing microgrids requires skilled personnel capable of handling advanced control and protection systems. Training and capacity-building remain essential for sustainable operation.

while microgrids represent a promising solution for modern power systems, their challenges must not be underestimated. Addressing these technical, economic, and regulatory issues will be vital to achieving large-scale deployment and unlocking their full potential in the global energy transition [77].

1.8 Microgrid Architectures and Components

The design and configuration of a microgrid depend largely on the type of distributed energy resources (DERs), the nature of the loads, and the control and protection strategies employed. In general, a microgrid can be described as a localized electrical system that integrates generation units, inverters, and consumer loads, all coordinated to operate either autonomously or in connection with the main grid.

1.8.1 Microgrid Architectures

Microgrids can be classified into different architectures depending on their physical layout, connection points, and type of distribution system:

- **AC Microgrids** In AC microgrids, both generation and consumption are based on alternating current. These are the most common types due to compatibility with existing utility grids. AC microgrids facilitate easier integration with the main grid but require sophisticated synchronization and power quality control. For example wind



Fig 1.5 AC Microgrid System

- **DC Microgrids** DC microgrids are particularly suited for systems with large shares of photovoltaic (PV) generation, battery storage, and DC loads (e.g., data centers, electric vehicles, LED lighting). They offer higher efficiency by reducing conversion losses but face challenges with protection and standardization.



Fig 1.6 DC Microgrid System

- **Hybrid AC/DC Microgrids** Hybrid configurations combine both AC and DC subsystems, interconnected via bidirectional converters. This architecture leverages the advantages of both AC and DC microgrids, providing flexibility in integrating diverse resources and loads. However, it increases system complexity and cost [78].



Fig 1.7 Hybrid AC/DC Microgrid System

1.8.2 Core Components of Microgrids

A microgrid typically consists of three essential elements: distributed generators (DGs), inverters, and loads.

1. **Distributed Generators (DGs)**

- DGs are the primary energy sources in a microgrid. They may include renewable sources such as solar PV, wind turbines, and small hydro, or conventional generators like micro-turbines and diesel units.
- Their decentralized placement close to consumption points reduces transmission losses and improves efficiency.
- The variability of renewable DGs requires complementary control and possibly backup units to ensure reliability.

2. **Inverters**

- Inverters are the cornerstone of modern microgrids, as they provide the interface between DGs (often producing DC power) and the AC system.
- They play multiple roles: power conversion, voltage and frequency regulation, and grid support.
- Depending on the control strategy, inverters can operate in grid-following mode (tracking the voltage and frequency of the main grid) or grid-forming mode (defining local voltage and frequency in islanded operation).
- Advanced inverters also provide functionalities such as reactive power compensation, fault ride-through, and harmonic mitigation.

3. **Loads**

- Loads in microgrids can range from residential and commercial to industrial applications.
- They may be classified as critical loads, which require uninterrupted supply (e.g., hospitals, communication centers), and non-critical loads, which can be curtailed or shifted to balance the system.
- The increasing adoption of smart loads and demand response technologies enhances the flexibility of microgrid operation.

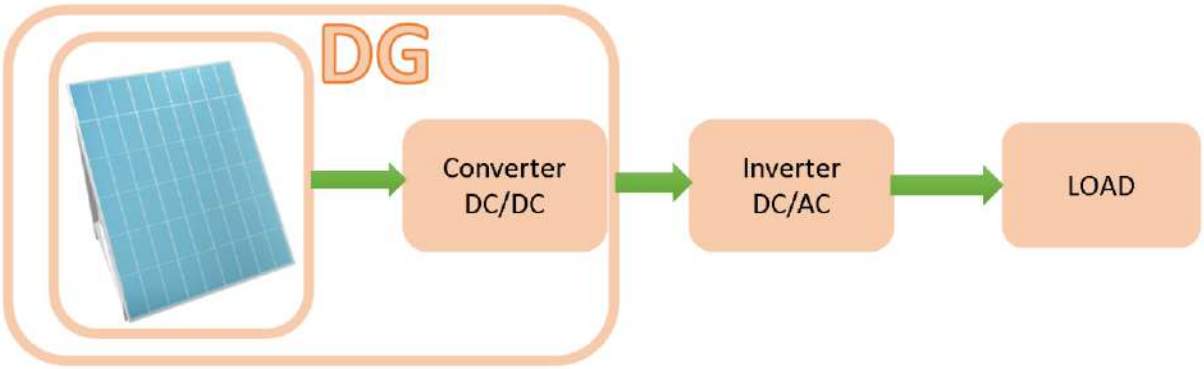


Fig 1.8 Main Components of the Microgrid

As shown in the figure above, part of the core components of the microgrid includes the distributed generation (DG) unit, which consists of a photovoltaic (PV) panel and a DC/DC converter. This DG unit is connected to a DC/AC inverter, which then supplies power to the load [79].

1.8.3 Supporting Elements

While DGs, inverters, and loads constitute the core, additional elements often complement microgrid operation:

- **Control and Communication Systems** – Enable real-time monitoring, scheduling, and coordination of resources.
- **Protection Devices** – Ensure safety and stability against faults and abnormal conditions.

The architecture and components of a microgrid determine its operational flexibility, stability, and efficiency. The integration of DGs, inverters, and loads—combined with advanced control and protection systems—forms the backbone of modern microgrids, enabling them to serve as both resilient local networks and integral parts of the larger power system [80].

1.9 Microgrid Operation Modes (Grid-Connected vs. Islanded)

Microgrids are designed to function flexibly under two primary modes of operation: grid-connected mode and islanded (standalone) mode [81]. The ability to seamlessly transition between these modes, referred to as resilience or flexibility, is one of the key advantages of microgrids.

1.9.1 Grid-Connected Mode

In this mode, the microgrid is connected to the main utility grid through a point of common coupling (PCC). The grid provides voltage and frequency references, as well as additional power support when local generation is insufficient [82].

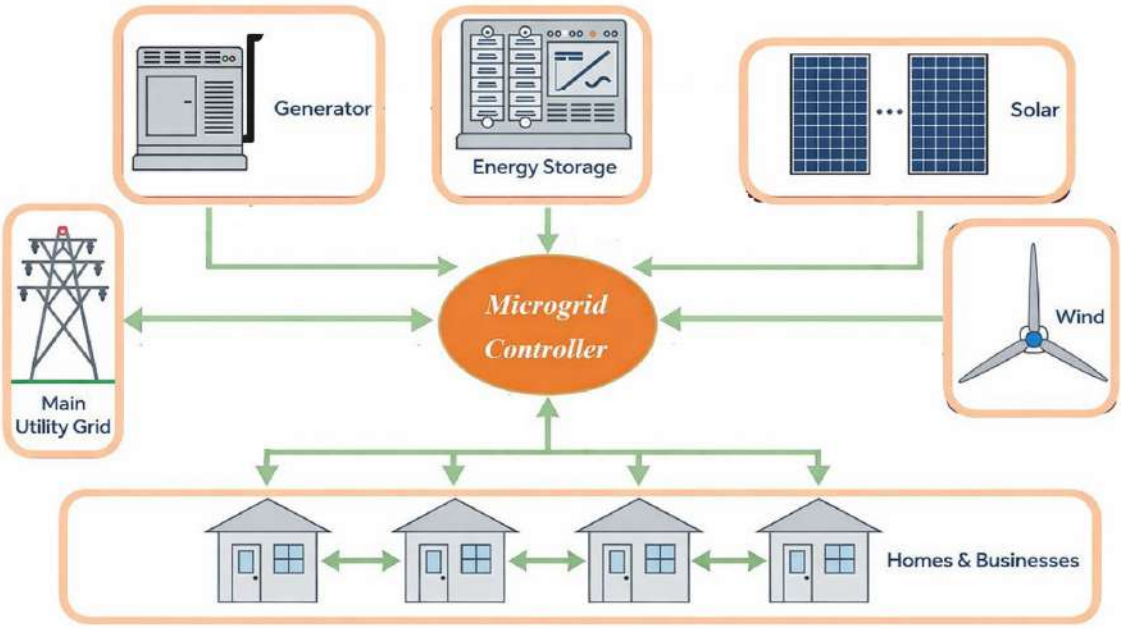


Fig 1.9 Grid Connected Mode

- **Characteristics:**
- The main grid dictates the voltage and frequency.
- Local distributed generators (DGs) operate in a grid-following mode, injecting active and reactive power according to set points.
- Surplus generation from DGs can be exported to the utility grid, while shortages are covered by importing energy.
- The grid acts as a stabilizing backbone, reducing the need for local reserves.
- **Advantages:**
    - High reliability due to backup support from the utility.

- Economic benefits through energy trading and tariff optimization.
- Facilitates large-scale integration of renewables with minimal stability risks.

- **Challenges:**
  - Requires careful synchronization and protection coordination at the PCC.
  - Power quality may be affected by disturbances originating from the utility grid.
  - Over-reliance on the main grid reduces local autonomy.

1.9.2 Islanded Mode

In this mode, the microgrid operates independently from the main grid, either intentionally (planned islanding) or due to grid faults or outages (unplanned islanding) [83].

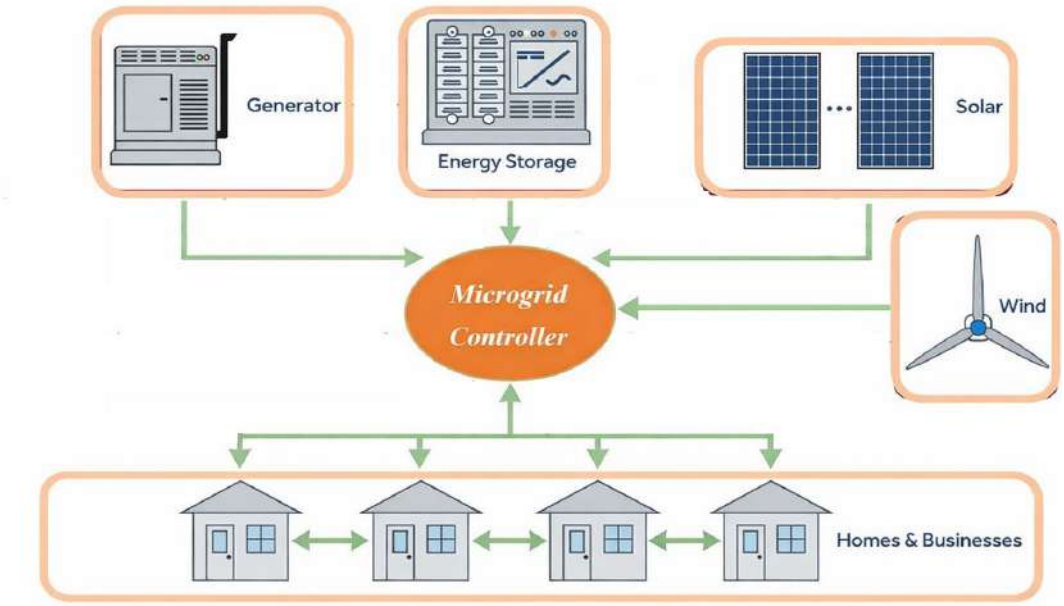


Fig 1.10 Islanded Mode

- **Characteristics:**
  - Local DGs and inverters take full responsibility for maintaining voltage and frequency.
  - Typically, grid-forming inverters provide the reference for system operation.

  - The balance between generation and consumption must be carefully managed to ensure stability.

- **Advantages:**
  - Ensures continuity of supply for critical loads during utility outages.
  - Enhances autonomy, particularly in remote or rural regions.
  - Offers improved reliability for sensitive applications such as hospitals, data centers, and military facilities.
- **Challenges:**
  - Requires sophisticated control strategies for voltage and frequency stability.
  - Limited generation and storage capacity may restrict the power available to loads.
  - Protection coordination becomes more complex, as fault currents are lower compared to the grid-connected case.

1.9.3 Seamless Transition Between Modes

A critical feature of microgrids is their ability to transition seamlessly between grid-connected and islanded operation. This requiers :

- Fast detection of grid faults or instability at the PCC.
- Smooth resynchronization when reconnecting to the grid, avoiding transients and instability.
- Advanced inverter controls capable of switching between grid-following and grid-forming modes.

Such operational flexibility is crucial for ensuring resilient, stable, and reliable performance, especially under scenarios of grid disturbances or high renewable penetration.

1.10 Conclusion

This chapter has presented a comprehensive overview of microgrids, starting from their historical evolution to their fundamental definition, architectures, components, and control

hierarchy. It has been shown that microgrids represent a key solution for integrating distributed generation, inverters, and loads while ensuring flexibility, reliability, and sustainability. Their ability to operate in both grid-connected and islanded modes highlights their importance in modern power systems, especially under increasing renewable penetration. Furthermore, the discussion of applications, challenges, and future trends has emphasized that microgrids are not only technical solutions but also socio-economic enablers for resilient and decarbonized energy systems. This foundational understanding sets the stage for the following chapter, which will focus on inverter-based resources, with a particular emphasis on the distinction between grid-following and grid-forming inverters.

CHAPTER II:

Modeling and Control of Microgrids

Chapter 2 – Modeling and Control of Microgrids

2.1 Introduction

The growing penetration of renewable energy sources and distributed generation has transformed the way electrical networks are conceived and operated. Microgrids have emerged as a key solution, integrating diverse energy resources, storage systems, and controllable loads within localized, flexible, and sustainable power networks [84].

Unlike conventional systems dominated by synchronous machines, microgrids rely heavily on inverter-based resources, which require carefully designed control strategies to ensure reliable and stable operation. These strategies are essential for regulating voltage, frequency, and power sharing under both grid-connected and islanded conditions [85].

This chapter focuses on the mathematical modeling and control architecture of microgrids. It introduces the dynamic representation of distributed generation units, outlines the hierarchical layers of control, and discusses the methods applied at both internal and primary levels. The objective is to provide a coherent framework for understanding how inverters are controlled to achieve stability, reliability, and efficient energy management in modern microgrids [86], [87].

2.2 Modeling of Distributed Generation (DG) Unit

A typical microgrid unit consists of three main components: the DG source, the inverter, and the load, with an LC filter connecting the inverter to the point of common coupling [88], [89]. The LC filter plays a critical role in smoothing the high-frequency switching signals produced by the pulse-width-modulated (PWM) inverter, thereby reducing harmonic distortion and ensuring a high-quality voltage waveform at the load [90]. The inverter itself acts as an interface between the DC generation source and the AC network, controlling both the voltage amplitude and frequency delivered to the PCC [91].

2.2.1 Microgrid Unit Structure

A schematic representation of the DG unit consists of:

- **DC Source**: Provides the input power to the inverter. Its dynamics can vary depending on technology (e.g., PV panels governed by irradiance, batteries influenced by state of charge) [97]. In most control studies, it is modeled as a controllable DC voltage source.

- **Inverter**: The core component that converts DC to AC. It uses pulse-width modulation (PWM) techniques to synthesize sinusoidal voltages from a DC link. From the control perspective, the inverter can be approximated as an ideal voltage source with controllable output v_C [92], [93].
- **LC Filter**: The filter is critical in attenuating high-frequency components generated by the inverter switching process. A simple LC filter, consisting of a series inductance L_f and a shunt capacitance C_f, is widely used because of its effectiveness and relatively low cost [94], [95].
- **Load**: Represents either local consumption or the grid to which the inverter is connected. Loads can be linear (resistive, inductive) or nonlinear (rectifiers, electronic devices) [96]. Accurate modeling of the load is essential to analyze harmonic propagation and system stability.

The inverter and its filter are connected to the point of common coupling (PCC), which is the interface where multiple DG units and loads interact. Proper control at this point is essential for ensuring voltage quality and power sharing[97].

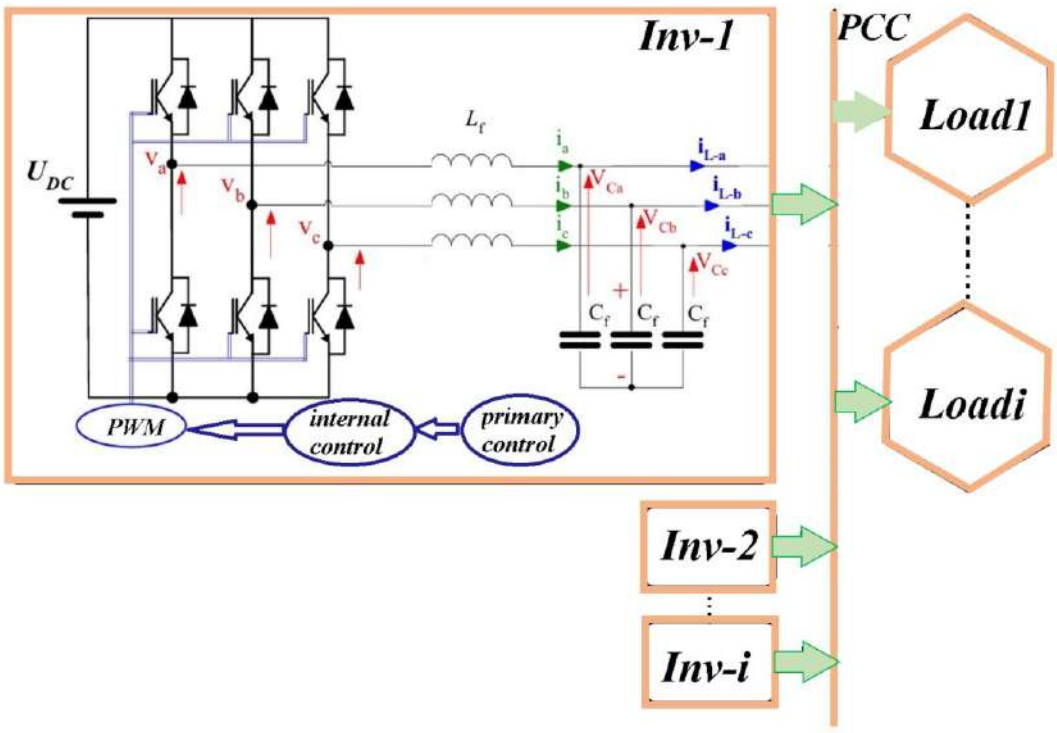


Fig 2.1 Microgrid Unit Configuration

A- Phase (abc) domain dynamic equations

The mathematical modeling of this system begins with the abc-frame representation. Considering each phase of the LC filter, this system can be described using Kirchhoff's voltage law:

$$L\frac{di_{abc}}{dt} = v_{abc} - v_{Cabc} \tag{2.1}$$

$$C\frac{dv_{abc}}{dt} = i_{abc} - i_{Labc} \tag{2.2}$$

Where v_{abc} and i_{abc} are the voltage and the current at the output of the inverter, v_{Cabc} is depicted as the voltage at the capacitor, and i_{Labc} is the three-phase current at the load [98] [99].

2.2.2 dq Transformation Derivation

Three-phase systems are naturally represented in the abc reference frame, but this frame is inconvenient for control because the variables are sinusoidal and time-varying. To simplify analysis, the Park transformation converts abc quantities into the synchronous dq reference frame, where they appear as DC signals under steady-state balanced conditions [100], [101].

The Park transformation is defined as:

$$\begin{bmatrix} x_d \\ x_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ -\sin\theta & -\sin(\theta-2\pi/3) & -\sin(\theta+2\pi/3) \end{bmatrix}\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix} \tag{2.3}$$

where θ is the instantaneous angle of the rotating reference frame. In practice, θ is obtained by a phase-locked loop (PLL), which synchronizes the inverter with the PCC voltage.

The dq transformation has several advantages :

- It decouples active and reactive power. Active power is mainly controlled by i_{di}, while reactive power is controlled by i_{qi}.
- It allows PI controllers to be used effectively since the signals become DC quantities in steady state.
- It simplifies dynamic equations, enabling easier stability analysis.

2.2.3 LC Filter Dynamics

The LC filter dynamics in dq-frame are derived from Kirchhoff's laws.

For the inductor:

$$L\frac{di_d}{dt} = L\omega i_q + v_d - v_{Cd} \tag{2.4}$$

$$L\frac{di_q}{dt} = v_q - L\omega i_d - v_{Cq} \tag{2.5}$$

For the capacitor:

$$C\frac{dv_{Cd}}{dt} = i_d - i_{Ld} + C\omega v_{Cq} \tag{2.6}$$

$$C\frac{dv_{Cq}}{dt} = i_q - i_{Lq} - C\omega v_{Cd} \tag{2.7}$$

These equations reveal cross-coupling terms: the d-axis dynamics are affected by q-axis currents and vice versa. This coupling complicates control and motivates the use of decoupling feedforward terms in PI and PR controllers[102]-[105].

The filter plays a dual role: it attenuates switching harmonics and defines the inverter's dynamic response. Improperly designed filters can introduce resonance peaks, leading to instability or excessive distortion. Therefore, control strategies must account for the filter dynamics to guarantee both stability and power quality [106], [104], [107].

2.3 Hierarchical Control Structure of Microgrids

The operation of microgrids requires a carefully designed control architecture that can handle both the fast dynamics of inverter-based units and the slower variations in load and generation. Since microgrids integrate diverse distributed energy resources (DERs) and storage systems, each with its own dynamic behavior, the control framework must provide stability, scalability, and reliability under both grid-connected and islanded modes of operation [108], [109].

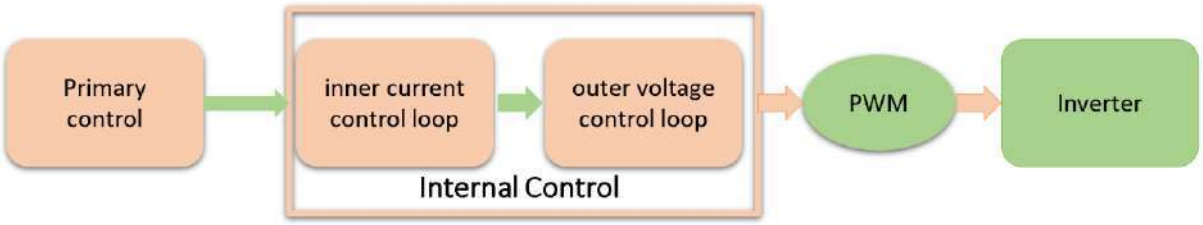


Fig 2.2 Microgrid Hierarchical Control Structure

To manage these requirements, a hierarchical control structure is typically adopted. The hierarchy is divided into two conceptual levels [110], [111].:

1. **Internal Control** (or local control)
2. **Primary Control**,

These two layers are the foundation of microgrid dynamics and form the focus of this chapter.

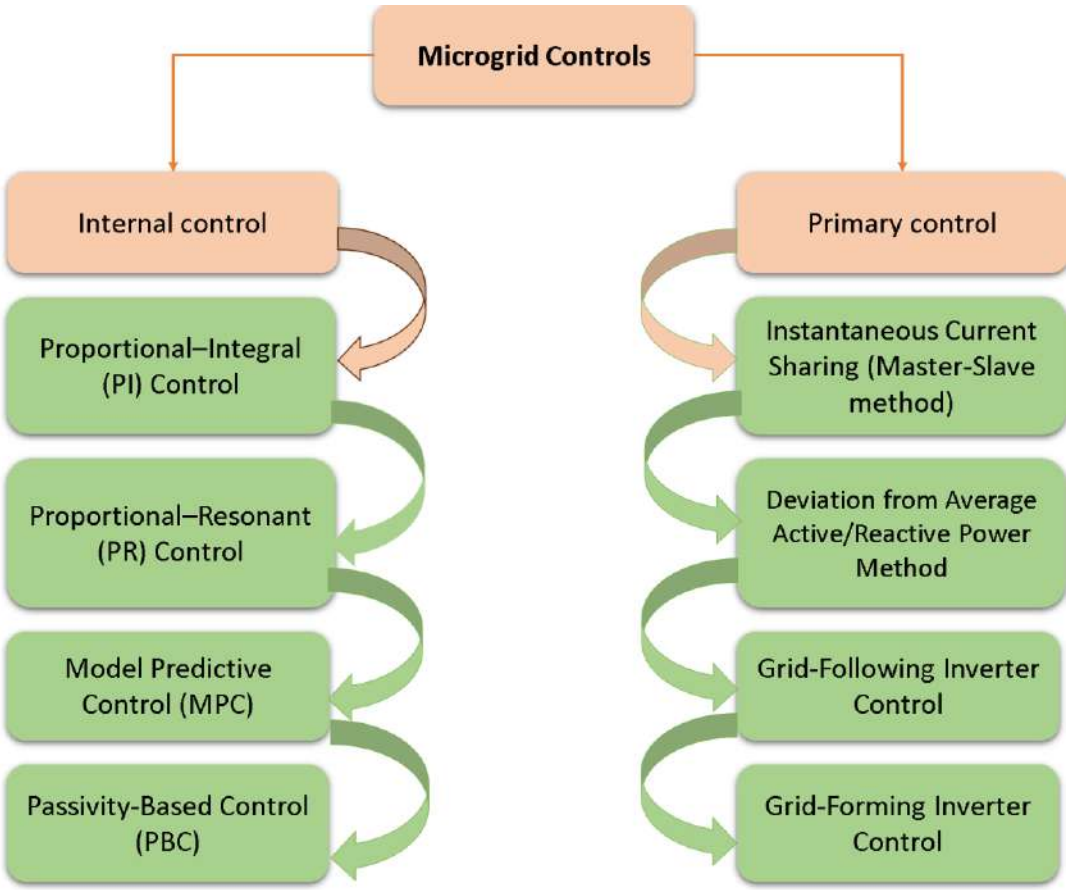


Fig 2.3 Overview of Microgrid Control Strategies

2.3.1 Control Levels in Microgrids

- **Internal Control**:

  This is the fastest layer of control, implemented directly inside each inverter. Its primary purpose is to regulate the converter's output voltage and current. The internal loops typically consist of an inner current control loop and an outer voltage control loop, arranged in a cascaded structure. The inner loop provides fast current regulation, limiting overcurrent and protecting the inverter, while the outer loop ensures voltage stability at the point of common coupling (PCC). Proportional–Integral (PI) controllers in the synchronous dq-frame are most widely used, although more advanced techniques (PR, MPC, PBC) have been developed to handle harmonic distortion, nonlinear dynamics, and parameter uncertainties[112], [113].

- **Primary Control**:

  Operating at a slightly slower timescale, primary control defines how multiple inverters interact in parallel. Its main objective is to share active and reactive power proportionally among distributed sources and to regulate system frequency and voltage under load variations. In conventional power systems, synchronous generators inherently perform this function through their droop characteristics and mechanical inertia. In inverter-dominated systems, however, primary control must be explicitly designed. Depending on the architecture, primary control can be implemented using methods such as instantaneous current sharing, deviation-from-average power sharing, grid-following inverters, or grid-forming inverters[110], [111].

2.3.2 Role of Internal vs Primary Control

Although both internal and primary control layers act locally on the inverter, they operate at different timescales and address distinct objectives. Their roles can be summarized as follows:

- **Internal Control** ensures that the inverter accurately tracks its voltage and current references. It is responsible for immediate stability, fast transient response, and protection. Without robust internal control, any higher-level control strategy would fail because the inverter would not reliably follow the commands.

- **Primary Control** establishes the references that internal control must follow. It enables decentralized coordination by defining how each inverter contributes to

overall active and reactive power. In this sense, primary control provides the "macroscopic" setpoints, while internal control enforces them at the "microscopic" level.

The complementarity between the two can be expressed metaphorically:

- Primary control **"**decides what to do",
- Internal control "makes sure it happens."

This layered approach ensures that microgrids can remain stable and flexible, even when composed of dozen or hundreds of inverter-based DERs.

2.4 Internal Control Strategies

The internal control layer represents the lowest level of regulation in inverter-based distributed generation (DG) systems. Its primary objective is to ensure that the inverter operates as a reliable and stable voltage or current source, providing fast dynamic response and robust tracking of reference signals under varying load and grid conditions. Without well-designed internal control, higher-level strategies such as droop or predictive primary control cannot be effectively implemented [108], [110] [112].

Internal control is typically organized in a cascaded structure, composed of:

1. An inner current control loop, which regulates the inverter current injected into the filter and provides fast protection against overcurrent.
2. An outer voltage control loop, which ensures that the voltage at the point of common coupling (PCC) is maintained at the desired amplitude and phase.

To implement these loops, several control strategies have been developed. The most widely used are the Proportional–Integral (PI) controller, the Proportional–Resonant (PR) controller, Model Predictive Control (MPC), and Passivity-Based Control (PBC). Each has its own advantages, limitations, and domains of applicability.

2.4.1 Proportional–Integral (PI) Control

The PI controller is the classical and most widely adopted technique for inverter internal control, especially in synchronous dq-frame implementations. Its popularity is due to its

simplicity, ease of tuning, and robust steady-state performance under balanced conditions [108].

Mathematical Derivation in dq-Frame

PI controllers are widely adopted due to their simplicity and robustness. In the synchronous dq-frame, the PI controller eliminates steady-state error for DC variables representing AC signals. The transfer function is given by:

$$G_{PI}(s) = K_p + \frac{K_i}{s} \tag{2.8}$$

where $K_p$and $K_i$are proportional and integral gains, respectively. PI control achieves excellent performance under balanced and synchronized conditions [106], [107].

Performance Characteristics

- **Advantages:**
    - Very simple and well-understood design.
    - Effective in eliminating steady-state error for DC quantities in dq-frame.
    - Low computational demand, making it suitable for digital controllers with limited resources.
- **Limitations:**
    - Poor harmonic rejection in stationary (abc) frame, since PI cannot track sinusoidal signals without error.
    - Sensitive to parameter variations and coupling effects under unbalanced or nonlinear loads.
    - Performance deteriorates under weak grid conditions, where dynamics become more nonlinear [101], [102].

For these reasons, PI control is usually applied in dq-frame current/voltage loops, where signals are constant in steady-state, rather than in stationary frame.

2.4.2 Proportional–Resonant (PR) Control

The PR controller was introduced to overcome the main limitation of PI controllers: their inability to perfectly track sinusoidal signals in stationary reference frames. Instead of relying on dq transformation, the PR controller operates directly in the αβ stationary frame and provides infinite gain at the fundamental frequency, thus ensuring zero steady-state error for sinusoidal signals.

Mathematical Formulation

The transfer function of a basic PR controller is:

$$G_{PR}(s) = K_p + \frac{2K_r s}{s^2 + \omega_0^2} \tag{2.9}$$

where K_p is the proportional gain, K_r is the resonant gain, and ω_0 is the fundamental angular frequency.

The denominator introduces poles at $\pm j\omega_0$, leading to infinite gain at the fundamental frequency. This allows the PR controller to eliminate steady-state error for sinusoidal signals without requiring dq transformation.

Performance Characteristics

- **Advantages:**
    - Excellent performance in stationary frame, making it suitable for single-phase inverters.
    - Can directly reject harmonics by adding resonant terms.
    - Avoids PLL-based dq transformation, reducing complexity.
- **Limitations:**
    - More difficult to tune compared to PI controllers.
    - Resonant peaks may reduce robustness if damping is not properly included.
    - Sensitive to frequency deviations, since resonance is tuned at a fixed frequency [103], [104].

PR controllers are therefore attractive for systems with strong fundamental sinusoidal signals and where harmonic suppression is critical, such as single-phase PV inverters or grid-connected converters with nonlinear loads.

2.4.3 Model Predictive Control (MPC)

Model Predictive Control (MPC) is a more advanced strategy that directly uses a mathematical model of the inverter to predict its future behavior. At each sampling instant, MPC evaluates all possible switching states of the inverter and selects the one that minimizes a predefined cost function.

Prediction Model

The discrete-time model of the inverter can be written as:

$$x(k+1) = A_d x(k) + B_d u(k) \tag{2.10}$$

where $x(k)$ is the state vector at time step k, $u(k)$ is the control input (switching state), and A_d, B_d are discrete system matrices derived from dq equations.

Cost Function

The most common cost function for current control is:

$$J = \sum_{j=1}^{N_p} \|x(k+j) - x^*(k+j)\|^2 + \lambda \|\Delta u(k+j-1)\|^2 \tag{2.11}$$

This function penalizes the deviation between predicted and reference currents. The controller evaluates J for all possible inverter switching states and applies the one that minimizes it.

More advanced formulations include weighting terms to penalize switching frequency, voltage errors, or power imbalances [105].

Performance Characteristics

- **Advantages:**
    - Fast dynamic response due to predictive nature.
    - Explicitly handles multivariable systems and constraints.
    - Flexible: cost function can be designed to meet different objectives.

- **Limitations:**
    - High computational demand, especially with long horizons.
    - Performance depends heavily on model accuracy; parameter uncertainties degrade results.
    - Sensitive to measurement noise and delays.

MPC is increasingly applied in experimental microgrids thanks to improvements in digital processors, but its complexity remains a challenge for large-scale implementation.

2.4.4 Passivity-Based Control (PBC)

PBC exploits the system's passivity properties to ensure stability through energy shaping and damping injection. For inverter systems, the control law reshapes the stored energy function $H(x)$and assigns desired dynamics via interconnection and damping matrices [111], [112]. PBC has strong theoretical guarantees but may be complex in practical implementation.

The system can be written in port-controlled Hamiltonian form:

$$\dot{x} = [\mathcal{J}(x) - \mathcal{R}(x)]\nabla H(x) + g(x)u + d \tag{2.12}$$

where:

- *J(x)* is a skew-symmetric interconnection matrix,
- *R(x)* is a dissipation matrix,
- *g(x)* is the input matrix,
- *u* is the control input.

IDA-PBC Method

The Interconnection and Damping Assignment PBC (IDA-PBC) technique modifies the energy function and damping characteristics to assign desired closed-loop dynamics. By reshaping the Hamiltonian and injecting damping, the controller ensures global asymptotic stability [107].

Performance Characteristics

- **Advantages:**
    - Rigorous nonlinear stability proof based on passivity.
    - Robust to parameter uncertainties.
    - Naturally energy-based, making it physically interpretable.
- **Limitations:**
    - Complex mathematical derivation.
    - Requires accurate energy modeling.
    - Less mature in industrial adoption compared to PI/PR [108].

2.5 Primary Control Strategies

The role of primary control in microgrids is to guarantee stable voltage and frequency while enabling autonomous power sharing among distributed energy resources (DERs). Unlike internal control, which operates locally on an inverter's dynamics, primary control determines how each unit contributes to the collective operation of the microgrid.

In conventional power systems, synchronous generators inherently provide primary control through their electromechanical dynamics. For example, when a load increases, the frequency of a generator tends to drop due to reduced rotor speed, and the governor adjusts input power accordingly. This natural droop behavior provides decentralized stability. However, inverter-based DG units lack mechanical inertia and must rely entirely on control algorithms to emulate such characteristics.

Primary control strategies can be broadly classified into four main categories:

1. Instantaneous Current Sharing (Master–Slave method)
2. Deviation-from-Average Power Sharing
3. Grid-Following Control (GFL)
4. Grid-Forming Control (GFM)

Each strategy provides different trade-offs in terms of scalability, robustness, and autonomy, as discussed below.

2.5.1 Instantaneous Current Sharing (Master–Slave Method)

One of the earliest methods for controlling parallel inverters is the master-slave approach, which relies on instantaneous current sharing. In this method, one inverter is designated as the master unit, responsible for regulating the voltage magnitude and frequency at the PCC. The remaining inverters act as slave units, which attempt to inject currents proportional to the master unit's output. The master unit maintains the reference voltage using an outer voltage control loop, typically implemented with a proportional-integral (PI) controller, while the slave units track the master's output current through outer current control loops.

A key requirement of this method is that all units must synchronize to a common phase reference, often implemented using phase-locked loops (PLLs). The main advantage of the master-slave method is its simplicity and the ability to provide momentary load sharing without complex communication. However, the method has significant limitations: if the master unit fails, the entire system loses voltage reference, compromising reliability. Additionally, the physical wiring between units and the need for precise current measurement increase system complexity.

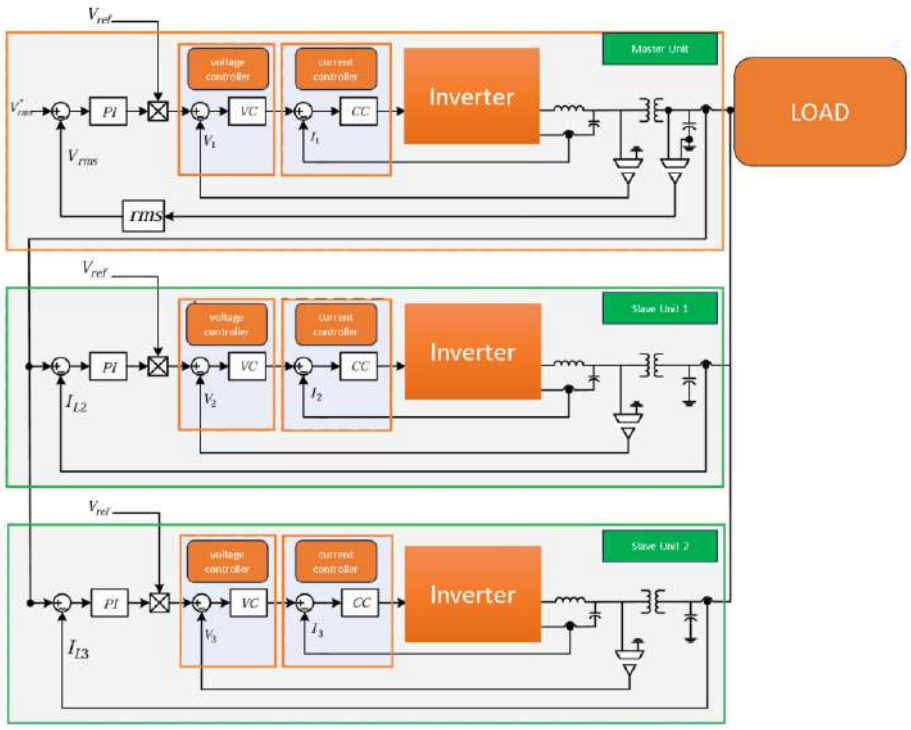


Fig 2.4 Master–Slave Method Structure

Advantages

- Very simple to implement.
- Provides precise current sharing if communication and synchronization are reliable.
- Useful for small-scale systems such as UPS applications.

Limitations

- Single point of failure: if the master fails, the entire system collapses.
- Poor scalability: adding/removing inverters requires reconfiguration.
- High dependency on fast communication and synchronization.
- Not suitable for autonomous islanded microgrids [101].

Because of these drawbacks, the master–slave method is rarely used in modern microgrids, but it provides historical insight into the evolution of control strategies.

2.5.2 Deviation-from-Average Power Sharing

To overcome the dependency on a master unit, the deviation from average power method was introduced. This strategy is grounded in the fundamental AC power flow equations, which indicate that active power P is primarily affected by voltage phase angle differences, while reactive power Q depends on voltage magnitude. For two inverters supplying a common load through inductive lines, the power equations can be approximated as:

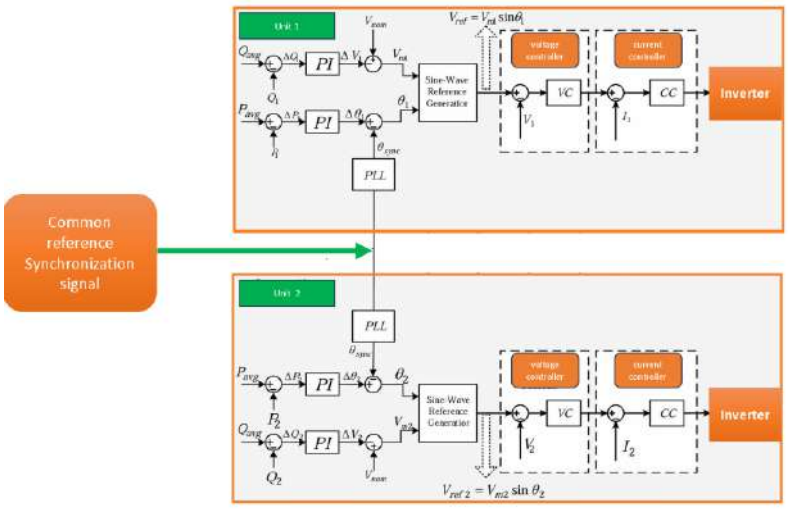


Fig 2.5 Deviation-from-Average Power Sharing Structure

Where: $P_{avg} = P_1 + P_2$,and $Q_{avg}=Q_1+Q_2$

In the deviation-from-average method, each inverter measures its output active and reactive powers and compares them with the average power shared among all units. The differences are then used to adjust the inverter's voltage magnitude and phase, effectively balancing power contributions.

This method eliminates the reliance on a single master unit, enhancing reliability. It allows accurate active and reactive power sharing while minimizing circulating currents. However, it requires communication among inverters to exchange power measurements and generally assumes purely sinusoidal load currents. Consequently, the method may not handle nonlinear loads effectively, and the communication link introduces potential reliability and latency issues.

Advantages

- No single master; system is more reliable.
- Provides fair load sharing.
- Simple mathematical foundation.

Limitations

- Requires communication between inverters to exchange power measurements.
- Communication introduces delays, reducing stability under fast transients.
- Performance deteriorates with nonlinear or unbalanced loads [102].

This method is more decentralized than master–slave but less scalable than fully autonomous grid-forming approaches.

2.5.3 Grid-Following Control

A grid-following inverter is one of the fundamental approaches used in inverter-based microgrids. It is designed to synchronize with the existing grid voltage and inject a controlled amount of active and reactive power. These inverters operate under current control and rely heavily on a phase-locked loop (PLL) to accurately track the grid phase angle. The main components of a grid-following inverter are generally as follows:

Phase-Locked Loop (PLL): To detect and lock onto the phase angle, frequency, and voltage of the grid at the point of common coupling (PCC).

- **Inner Current Control Loop:** This loop regulates the inverter's output current to match desired active and reactive power references. It operates in a rotating reference frame (dq-frame), ensuring fast and decoupled control of active (d-axis) and reactive (q-axis) power components.
- **Power Controller (Outer Loop):** Computes the reference currents based on power setpoints, which may come from a higher-level energy management system (EMS) or a microgrid central controller.

The reference voltage is not generated by the inverter. Instead, the inverter relies on the grid to provide this reference. Therefore, grid-following inverters are unsuitable for black-start conditions or weak-grid operation unless another provides voltage and frequency regulation.

The Phase-Locked Loop (PLL) is critical in grid-following control. It ensures that the inverter can track the grid frequency and maintain phase alignment. However, PLLs introduce two key challenges :

- **Delayed Response:** The PLL introduces a time delay, especially under weak or distorted grid conditions, affecting control speed and stability.
- **Grid Dependence:** Grid-following inverters cannot operate autonomously in islanded mode unless a voltage source (e.g., a synchronous generator or grid-forming inverter) is present.

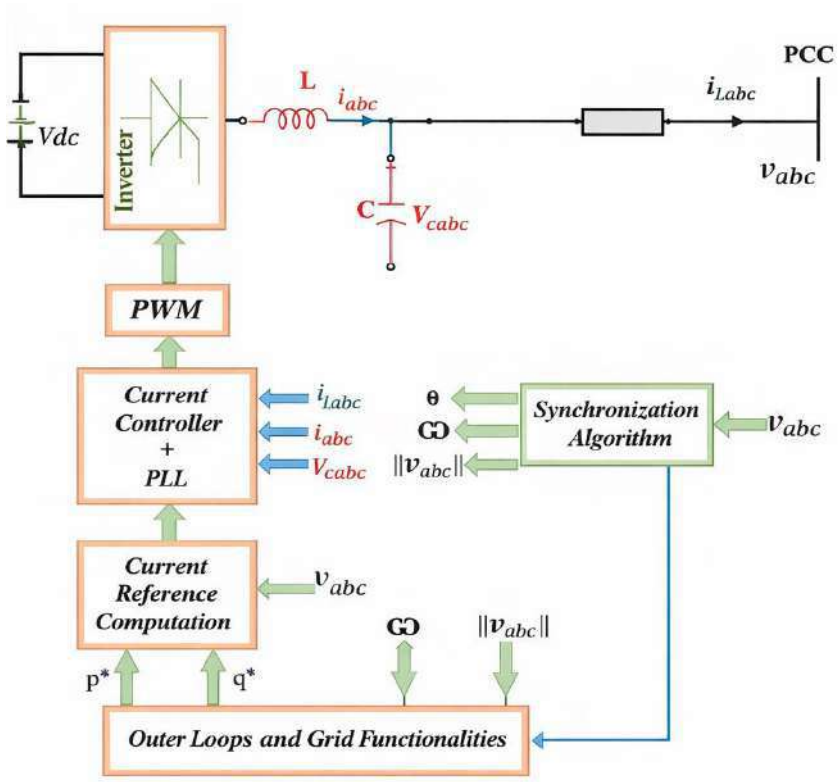


Fig 2.6 Grid-Following Control

Advantages

- Simple and mature; widely used in grid-connected renewable inverters (PV, wind).
- Allows precise injection of active and reactive power under strong grid conditions.
- Compatible with existing power system infrastructure.

Limitations

- Cannot operate autonomously in islanded mode.
- Dependent on a stiff grid voltage reference.
- PLL introduces delays and may lose stability in weak or distorted grids [3].

Grid-following control is an essential strategy for inverter-based DERs connected to a stable grid. However, its inability to operate independently in islanded mode necessitates the use of grid-forming control strategies in autonomous microgrids. This leads us to the next section, where we explore grid-forming control and its three major subcategories.

2.5.4 Grid-Forming (GFM) Control

Grid-forming inverters are designed to behave as voltage sources that actively generate and regulate voltage magnitude and frequency. Unlike grid-following units, they do not rely on PLLs. Instead, they establish the reference themselves, making them essential for islanded operation or weak grids dominated by inverters.

Three main strategies exist under the grid-forming paradigm: Droop Control, Virtual Synchronous Generator (VSG), and Virtual Oscillator Control (VOC).

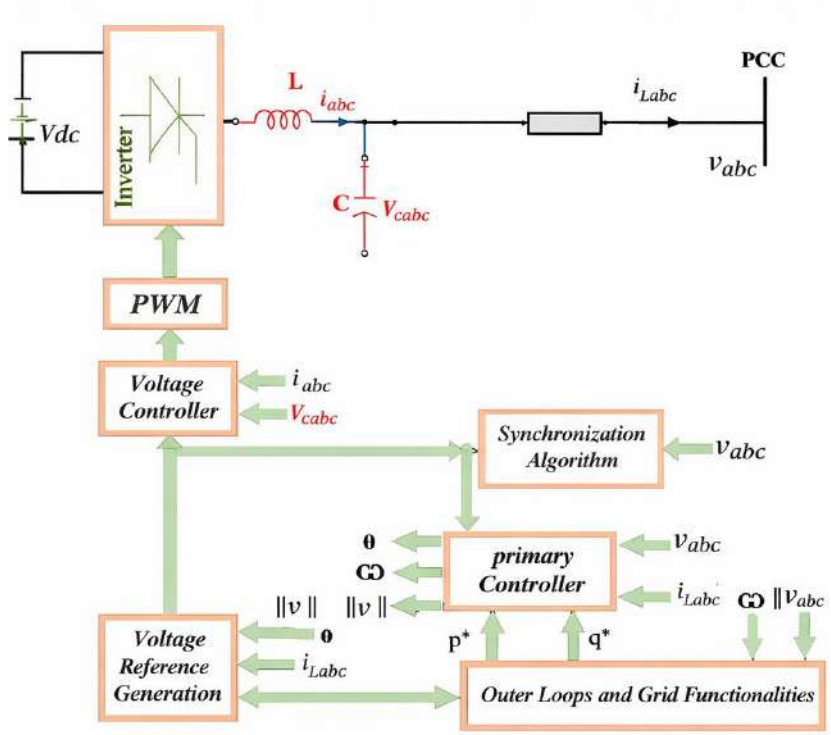


Fig 2.7 Grid-Forming Control

• Droop Control – The most widely adopted method, first reported for power sharing in UPS systems in the late 1980s. It leverages the inherent active and reactive power-sharing characteristics of synchronous generators [113].

• Virtual Synchronous Generator (VSG) – Emulates a synchronous generator, reproducing its electromechanical dynamics for improved stability [115].

• Virtual Oscillator Control (VOC) – Uses coupled oscillator theory to achieve autonomous voltage formation and power sharing [107].

These methods share the common objective of making inverters behave as independent voltage sources but differ in control structure, dynamics, and implementation complexity.

Comparative Discussion of Grid-Forming Methods

- **Droop Control**: simple, mature, widely implemented, but introduces steady-state deviations.
- **VSG**: adds inertia and damping, improving stability but requiring more complexity.
- **VOC**: offers elegant oscillator-based synchronization, but less mature in practice.

In general, droop control remains the most practical and widely used grid-forming strategy, while VSG and VOC are promising research directions for enhancing stability and scalability in future inverter-dominated systems.

Grid-forming control provides autonomy by generating its own voltage and frequency references. Among these, droop control stands out as the most practical and widely implemented method, thanks to its decentralization, scalability, and similarity to synchronous generator behavior. VSG offers improved stability through virtual inertia but requires more sophisticated tuning, while VOC represents an emerging but promising oscillator-based alternative.

PI control for the internal layer and droop control for the primary layer are the most widely adopted solutions in practice, forming the backbone of current microgrid architectures.

2.6 Conclusion

This chapter has developed the mathematical modeling and control framework of inverter-based microgrids, highlighting both the internal and primary control layers. Internal control, implemented through cascaded voltage and current loops, ensures fast regulation and system stability at the inverter level. Among the reviewed strategies, PI controllers in dq-frame remain the most practical and widely adopted solution, despite the theoretical advantages of PR, MPC, and PBC.

At the primary control level, several methods were discussed, ranging from legacy approaches such as master–slave and deviation-from-average, to modern grid-following and grid-forming paradigms. Grid-following inverters dominate in grid-connected renewable plants, but their dependence on PLLs limits their role in islanded microgrids. By contrast, grid-forming

inverters provide autonomy and robustness, with droop control emerging as the most popular and scalable method for decentralized power sharing.

A comparative analysis confirmed that the PI + Droop combination forms the backbone of practical microgrid architectures, while advanced techniques such as MPC, VSG, and VOC remain promising directions for future research.

In conclusion, the chapter established that while several innovative methods exist, the optimal and most widely used control structure is based on PI for internal loops and droop control for primary regulation. Building on this foundation, the next chapter will focus exclusively on droop control, examining its different variants, mathematical derivations, and performance comparisons through simulations.

CHAPTER III:

Grid-Forming Control Strategies Based on Droop Methods

Chapter 3 – Grid-Forming Control Strategies Based on Droop Methods

3.1 Introduction

This chapter focuses specifically on grid-forming inverters, exploring their control principles, structural configurations, and the evolution of their control strategies. Given the vast number of available grid-forming control methods, each with various enhancements and extensions, a systematic selection was made to analyze the most prominent and widely adopted approaches.

Particular emphasis is placed on the Droop Control technique and its modern developments, which have become the cornerstone of primary control in inverter-dominated microgrids due to their simplicity, decentralized nature, and effective power-sharing capability. The chapter provides a detailed mathematical modeling of the complete inverter system under grid-forming operation, followed by an in-depth analysis of different droop-based developments, including their advantages, limitations, and dynamic performance characteristics [114], [115].

To validate the theoretical findings, MATLAB/Simulink simulations are conducted under various operational scenarios. These simulations demonstrate the effectiveness and robustness of the selected control strategies in maintaining voltage and frequency stability, achieving proper power sharing, and responding efficiently to load and network disturbances.

3.2 Fundamentals of Grid-Forming Control

The concept of grid-forming control represents a paradigm shift in the operation of inverter-based microgrids. Whereas traditional power systems are stabilized by synchronous machines with inherent electromechanical dynamics, microgrids increasingly rely on distributed inverters to establish and maintain the fundamental grid quantities of voltage amplitude and frequency. A grid-forming inverter is one that is capable of autonomously generating these references at its point of common coupling (PCC), thus functioning as the backbone of the microgrid in both islanded and weak-grid conditions [116],[117].

3.2.1 Role of Grid-Forming Inverters in Microgrids

In a conventional large-scale grid, the collective inertia of synchronous machines provides natural frequency stability, while excitation systems regulate terminal voltages. The integration of renewable energy resources challenges this paradigm because photovoltaic (PV) panels and fuel cells inherently produce DC power, and wind turbines often generate variable-frequency AC. These sources must be interfaced through power electronic converters, which lack inertia and do not possess inherent frequency-voltage characteristics.

Consequently, without proper control, inverter-dominated systems would suffer from poor stability margins, degraded power quality, and lack of coordination among parallel units [118].

Grid-forming inverters address this challenge by emulating the role of synchronous machines. Through advanced control algorithms, they enforce sinusoidal voltage waveforms of fixed frequency and amplitude, while simultaneously enabling power sharing among distributed generation (DG) units. Their ability to set grid references makes them indispensable for:

- **Islanded operation**, where no external voltage source exists and the microgrid must regulate itself.
- **Black-start capability**, allowing a microgrid to re-energize after a fault or blackout.
- **Operation in weak grids**, where the strength of the upstream system is insufficient to stabilize inverter-based resources.

3.2.2 Mathematical Basis of Grid-Forming Control

A crucial property of grid-forming control is the exploitation of power–frequency and voltage–reactive power relationships. By approximating the power flow between two nodes connected through an impedance-dominated line, the following relationships can be established:

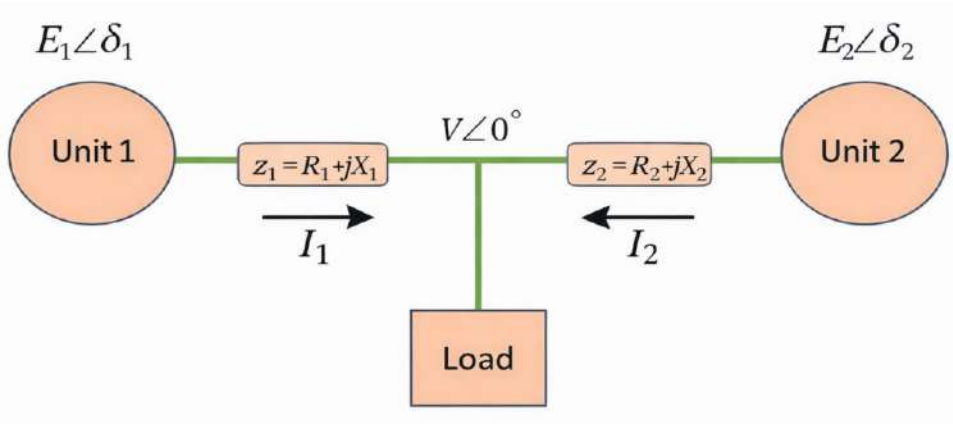


Fig 3.1 Power Sharing Structure

Each distributed generation (DG) unit is modeled using a Thevenin equivalent circuit, consisting of:

- an ideal voltage source of amplitude $E_i$and internal angle δ_i,
- connected in series with an output impedance $Z_i = R_i + jX_i$.

This output impedance includes:

- the internal impedance of the generator,
- the filter impedance at the inverter output,
- and the line impedance connecting each DG to the Point of Common Coupling (PCC).

Let $V_i$and i_{Li}denote respectively the voltage and current at the output of each DG unit.

The voltage equation is:

$$V_i(p) = E_i(p) - Z_i(p)\, i_{Li}(p) \tag{3.1}$$

The apparent complex power supplied by DG unit *i* to the PCC is given by:

$$S_i = V_i\, I_{Li}^* = V_i(\frac{E_i - V_i}{Z_i^*}) \tag{3.2}$$

$$S_i = V^*(\frac{E_i - V}{Z_i^*}) = P_i + jQ_i \tag{3.3}$$

This is the complex power equation for a distributed generator modeled by a Thevenin equivalent circuit.

Where:

- E_i: internal voltage of DG *i*
- V: PCC voltage
- $Z_i = R_i + jX_i$: output impedance
- $S_i = P_i + jQ_i$: complex power delivered by DG*i*
- $*$means complex conjugate

$$\begin{aligned} P_i &= \frac{V}{|Z_i|}[(E_i\cos\,\delta_i - V)\cos\,\theta_i + E_i\sin\,\delta_i\sin\,\theta_i] \\ Q_i &= \frac{V}{|Z_i|}[(E_i\cos\,\delta_i - V)\sin\,\theta_i - E_i\sin\,\delta_i\cos\,\theta_i] \end{aligned} \tag{3.4), 3.5}$$

Case A — θ = 90° (output impedance predominantly inductive)

Set $\theta_i = 90°$. Then $\cos\ \theta_i = 0, \sin\ \theta_i = 1$. Use small internal angle $\delta_i \ll 1$ so $\sin\ \delta_i \approx \delta_i, \cos\ \delta_i \approx 1$.

Simplified steady-state power

$$\begin{aligned} P_i &\approx \frac{V}{|Z_i|}[\, E_i \sin\ \delta_i \cdot 1\,] \approx \frac{VE_i}{X_i}\ \delta_i, \\ Q_i &\approx \frac{V}{|Z_i|}[(E_i \cos\ \delta_i - V) \cdot 1\,] \approx \frac{V}{X_i}\ (E_i - V), \end{aligned} \qquad (3.6), (3.7)$$

(where for inductive case $|\ Z_i\ | \approx X_i$).

Conventional droop mapping (standard)

Because P mainly depends on $\delta$and Qon E, use the usual droop laws:

$$\omega_i = \omega_0 - K_{Pi}(P_i - P_i^*), E_i = E_0 - K_{Qi}(Q_i - Q_i^*) \qquad (3.8)$$

(With $\omega_i = \dot{\delta}_i$.)

Case B — θ = 0° (output impedance predominantly resistive)

Set $\theta_i = 0°$. Then $\cos\ \theta_i = 1$, $\sin\ \theta_i = 0$. Use small $\delta_i$approximations.

with $\theta_i = 0$:

$$\begin{aligned} P_i &\approx \frac{V}{|Z_i|}(E_i \cos\ \delta_i - V) \approx \frac{V}{R_i}(E_i - V), \\ Q_i &\approx -\frac{V}{|Z_i|}(E_i \sin\ \delta_i) \approx -\frac{VE_i}{R_i}\ \delta_i. \end{aligned} \qquad (3.9),(3.10)$$

(Here $|\ Z_i\ | \approx R_i$.)

Conventional droop mapping (swapped)

Because Pnow depends mainly on $E$and Qon δ, swap the droop mapping:

$$E_i = E_0 - K_{Pi}(P_i - P_i^*), \omega_i = \omega_0 - K_{Qi}(Q_i - Q_i^*). \qquad (3.11)$$

3.2.3 Dynamic Considerations and Stability

While static droop laws establish the equilibrium points for power sharing, dynamic behavior is equally critical. Poorly tuned droop coefficients can result in:

- **Excessive frequency or voltage deviations**, leading to violations of power quality standards.
- **Slow transient responses**, which compromise the microgrid's ability to respond to sudden load changes.
- **Circulating currents among inverters**, caused by mismatched voltage references and dynamic inaccuracies.

To mitigate these problems, grid-forming control must be augmented by inner voltage and current loops, typically implemented with PI regulators. These loops ensure that the commanded references from the droop laws are faithfully tracked, filtering harmonics and providing fast disturbance rejection [119].

3.2.4 From Fundamentals to Advanced Droop Variants

The simplicity and decentralized nature of conventional droop control make it an appealing starting point, but its inherent steady-state and dynamic limitations necessitate more sophisticated variants. Two prominent approaches are:

1. **Transient Droop Control**, which introduces virtual inertia-like terms through dynamic filters, enhancing stability during abrupt load changes [120].
2. **Droop Control with Two Integrators**, which incorporates integral actions into the droop law to eliminate steady-state deviations in both frequency and voltage, thereby improving power sharing accuracy [121].

These strategies preserve the decentralized philosophy of droop control while addressing its shortcomings. They form the subject of the following sections, where each method is analyzed in detail, mathematically formulated, and evaluated through MATLAB/Simulink simulations under various load scenarios

3.3 Conventional Droop Control

3.3.1 Concept and Motivation

In inverter-based microgrids, Conventional Droop Control emulates this natural property. By imposing linear relationships between frequency and active power, and between voltage and reactive power, inverters are enabled to autonomously adjust their setpoints in response to power exchange. This results in decentralized power sharing, scalability, and plug-and-play operation, which are critical for microgrids [122].

The two basic droop equations are given as:

$$\omega = \omega_0 - m_p(P - P^*) \tag{3.13}$$

$$v_{cd}^* = E_0 - n_q(Q - Q^*) \tag{3.14}$$

where:

- ω: angular frequency of the inverter,
- ω_0: nominal frequency (rad/s),
- P: measured active power,
- P^*: active power reference,
- v_{cd}^*: inverter terminal voltage,
- E_0: nominal voltage,
- Q: measured reactive power,
- Q^*: reactive power reference,
- m_p: frequency droop coefficient,
- n_q: voltage droop coefficient.

Equations (3.13) and (3.14) constitute the droop laws. By properly tuning $m_p$and n_q, multiple inverters connected in parallel can share active and reactive power in proportion to their ratings without requiring real-time communication.

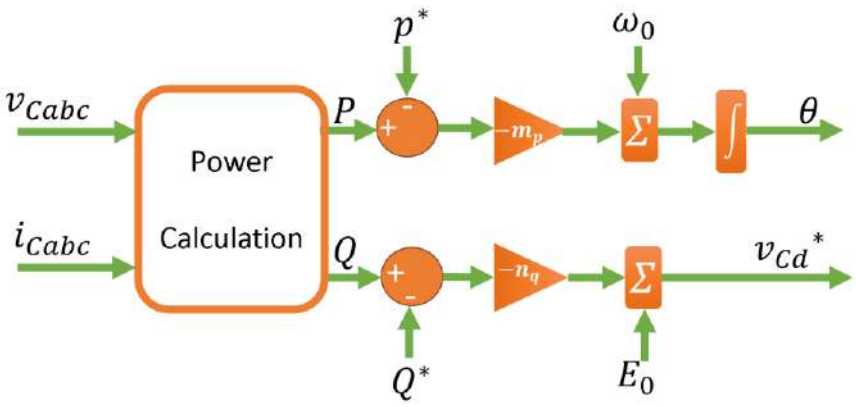


Fig 3.2 Block diagram of conventional droop control

Conventional droop law are expressed below:

3.3.2 Power Measurement and Filtering

In practice, inverters do not measure instantaneous active and reactive power directly, as such signals contain oscillations at double the fundamental frequency. Instead, low-pass filters are applied to extract the average power values used in the droop laws:

$$P(s) = \frac{\omega_c}{s + \omega_c}\,\tilde{p}(s) \tag{3.15}$$

$$Q(s) = \frac{\omega_c}{s + \omega_c}\,\tilde{q}(s) \tag{3.16}$$

where $\tilde{p}, \tilde{q}$ are instantaneous powers, and ω_c is the filter cutoff frequency.

The cutoff frequency must be carefully selected:

- A low value ensures smooth signals but slows down response.
- A high value improves dynamic response but allows oscillations to propagate into the control.

The filter thus represents a trade-off between stability and response time.

3.3.3 Selection of Droop Coefficients

A critical design task in Conventional Droop Control is tuning the coefficients m_p and n_q.

- The **frequency droop coefficient** m_p defines how much frequency deviation is tolerated for a given change in active power. Smaller m_p values improve frequency stability but reduce power-sharing accuracy [123].
- The **voltage droop coefficient** n_q dictates the trade-off between reactive power sharing and voltage regulation [124].

For example, if an inverter is rated at P_{rated} and a maximum frequency deviation of Δf_{max} is permitted, then:

$$m_q = \frac{\Delta \omega_{max}}{P_{rated}} \tag{3.17}$$

Similarly, for reactive power and voltage:

$$n_q = \frac{\Delta V_{max}}{Q_{rated}} \tag{3.18}$$

The choice of these coefficients must balance accuracy, stability, and compliance with standards.

3.3.4 Advantages of Conventional Droop Control

Conventional Droop Control remains the most widely adopted grid-forming strategy in both academic research and industrial practice, owing to several advantages:

Decentralized operation – No need for communication links; each inverter operates autonomously.

Scalability – Additional DG units can be integrated without redesigning the system.

Simplicity – Straightforward implementation with low computational requirements.

Robustness – Works under both grid-connected and islanded modes.

These properties make it highly suitable for microgrids deployed in remote areas, rural electrification projects, and renewable-dominated power systems.

3.3.5 Limitations of Conventional Droop Control

Despite its simplicity and success, Conventional Droop Control is not without limitations:

Steady-state deviations: Because frequency and voltage are intentionally allowed to vary with power, droop-controlled microgrids often operate outside nominal values. Secondary control layers are typically needed to restore them.

Coupling between P and Q: In low-voltage microgrids where resistive effects are non-negligible, the decoupling between active power–frequency and reactive power–voltage becomes imperfect.

Slow dynamic response: The use of low-pass filters and static droop equations leads to sluggish performance under sudden load changes.

Poor sharing accuracy: Small parameter mismatches among inverters can lead to uneven power distribution and circulating currents.

These drawbacks have motivated the development of advanced variants such as Transient Droop Control and Droop with Two Integrators, which attempt to overcome specific weaknesses while preserving the decentralized nature of the approach [125].

Conventional Droop Control provides the fundamental mechanism that enables decentralized power sharing in grid-forming inverters. It mimics the natural behavior of synchronous machines through simple linear laws relating power to frequency and voltage. While highly effective in many applications, its inherent limitations necessitate the development of more advanced strategies. The following sections build upon this foundation by introducing modifications that improve transient stability and eliminate steady-state deviations [126].

3.4 Transient Droop Control

3.4.1 Motivation and Concept

Although Conventional Droop Control is widely implemented in inverter-based microgrids, it suffers from two critical drawbacks:

1. Poor transient response – Under sudden load variations, the static droop law reacts slowly due to low-pass filtering of power signals. This can cause frequency overshoot or voltage sags.

2. Limited stability margin – In systems with high penetration of renewable energy, fast fluctuations in power can destabilize the inverter control loop if not properly damped.

To address these challenges, researchers have introduced Transient Droop Control (TDC). This strategy introduces dynamic terms into the droop law, thereby improving both stability during rapid transients and power-sharing accuracy. The modification adds a virtual inertia element that emulates the inertial response of synchronous machines, which is absent in static inverter-based systems [91] [127], [128].

3.4.2 Mathematical Formulation of Transient Droop Control

The conventional droop equations (recalled here) are:

$$\omega = \omega_0 - m_p(P - P^*) \tag{3.13}$$

$$v_{cd}^* = E_0 - n_q(Q - Q^*) \tag{3.14}$$

In the transient droop formulation, the frequency reference is modified by incorporating time constants $T_a$and T_b, which act as lead–lag compensators to simulate virtual inertia and damping. The modified equation is:

$$\omega = \frac{1 + sT_a}{1 + sT_b}(\omega_n - m_p P) \tag{3.19}$$

where:

- T_a: time constant associated with the numerator (virtual inertia),
- T_b: time constant associated with the denominator (damping),
- s: Laplace variable.

Equation (3.19) shows that the frequency dynamics are no longer purely static but evolve with time, creating a more realistic inertial response similar to synchronous machines.

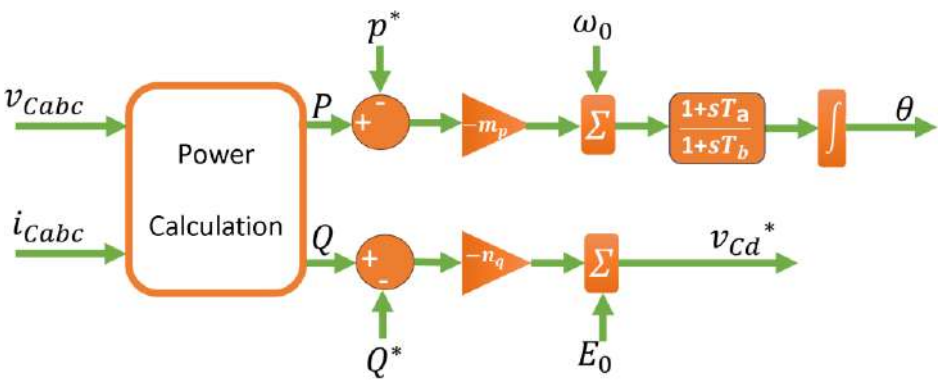


Fig 3.3 Block diagram of Transient droop control

3.4.3 Role of Virtual Inertia in Microgrids

In synchronous generators, the kinetic energy stored in the rotating mass provides inertia, which naturally resists sudden changes in frequency. Inverters, however, have no mechanical parts and thus no inherent inertia.

By introducing T_a and T_b, transient droop artificially embeds a virtual inertia response into the inverter dynamics:

Thus, transient droop makes inverter-based resources behave more like conventional machines, ensuring smoother transitions during load steps, connection/disconnection of DGs, and fault recovery [129]..

3.4.4 Parameter Selection

The performance of transient droop strongly depends on the choice of parameters T_a, T_b, m_p, n_q, and the PI gains.

- **Frequency droop coefficient** m_p ensures proportional load sharing.
- **Voltage droop coefficient** n_q maintains reactive power balance.
- **Time constants** T_a, T_b shape the transient dynamics.

3.4.5 Advantages of Transient Droop Control

Compared to conventional droop, transient droop offers:

1. **Improved transient response** – Rapid frequency stabilization during load changes.
2. **Virtual inertia** – Mimics synchronous machine behavior, improving resilience to disturbances.
3. **Reduced oscillations** – The lead–lag compensator adds damping and prevents instability.
4. **Enhanced power-sharing accuracy** – Better balance between DGs under dynamic scenarios.

3.4.6 Limitations and Challenges

Despite its advantages, transient droop still faces limitations:

- Parameter sensitivity – Performance is highly for choice of T_a, T_b. Poor tuning can result in instability.
- Steady-state deviations – Like conventional droop, it still requires secondary control for frequency/voltage restoration.
- Complexity – More parameters to tune compared to static droop.

3.5 Droop Control with Two Integrators

3.5.1 Motivation

While Conventional Droop Control provides a simple and decentralized solution for power sharing, it suffers from steady-state errors in reactive power and voltage regulation. Similarly, Transient Droop Control improves dynamic performance by introducing virtual inertia but does not inherently eliminate long-term steady-state deviations.

To overcome these limitations, researchers have introduced Droop Control with Two Integrators (DC2I), which incorporates an additional integral state in the voltage loop of the droop law. This modification enhances the steady-state accuracy of voltage regulation and improves reactive power distribution among inverters, while still maintaining the droop philosophy of decentralized control [92], [129], [130].

3.5.2 Mathematical Formulation

In the Droop Control with Two Integrators, the steady-state performance is improved by modifying the voltage–reactive power droop law. Specifically, an integrator is introduced in the voltage loop, yielding the following equations:

$$\omega = \omega_n - m_p P \tag{3.20}$$

$$\dot{V}_{cd}^* = K(E_0 - V_{Cd}) - n_q Q, V_{cq}^* = V_{cq} = 0 \tag{3.21}$$

where:

- $V_{cd}^{*}$is the reference voltage along the d-axis,
- $V_{Cd}, V_{Cq}$are the Capacitor voltage,
- $K$is the integrator gain,

Equation (3.21) clearly shows the additional integral action: instead of directly setting the voltage reference, the derivative of $V_{cd}^{*}$is defined, ensuring that any error between nominal and measured voltage is corrected over time.

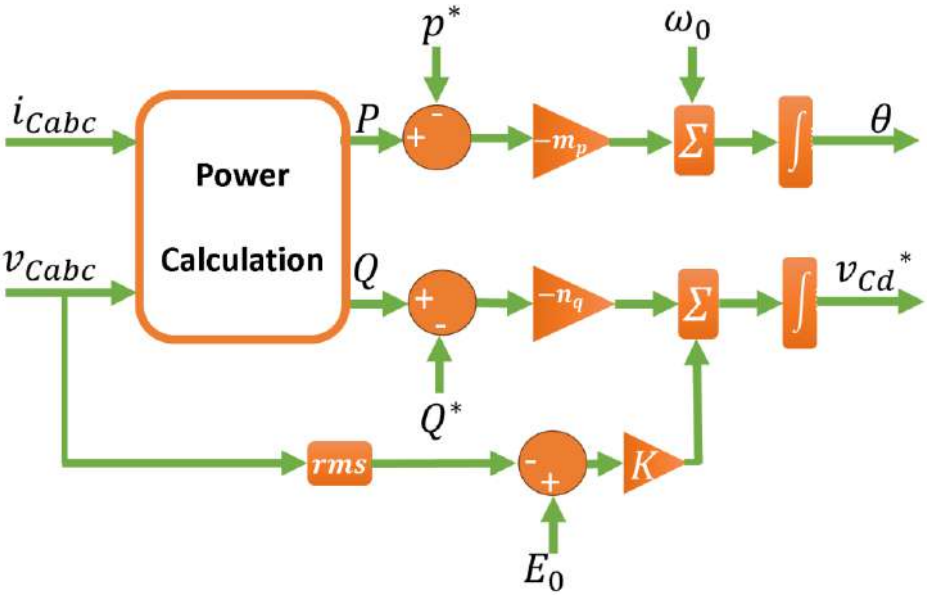


Fig 3.4 Block diagram of Droop control with two integrators

3.5.3 Advantages of Droop with Two Integrators

Compared to conventional droop and transient droop, the DC2I strategy provides:

1. **Superior steady-state accuracy** – Eliminates long-term voltage deviations by correcting errors through integral action.
2. **Improved reactive power sharing** – Ensures more accurate distribution of Qbetween parallel inverters.
3. **Adaptability to nonlinear loads** – Maintains voltage waveform quality even under distorted current conditions.
4. **Compatibility with PI loops** – Can be integrated with conventional inner-loop PI controllers without adding major complexity.

3.5.4 Challenges and Limitations

Despite its strengths, DC2I also presents challenges:

- **Parameter tuning** – the selection of *K*and PI gains requires careful optimization to avoid instability.

3.6 Simulation Studies

To validate the effectiveness of the three grid-forming droop control strategies, detailed simulations were conducted in MATLAB/Simulink. This section discusses a system that includes DC sources, two inverters in parallel with LC filters, and 3 loads. as seen in Figure (3.5) An impedance transmission line connects them. In this study utilized a three phase, 50 Hz. In this system, a control makes it possible to regulate the voltage at the output of each DG and to adjust the power sharing between the DGs, these operate using a droop control for standalone mode of operation. with modifications in the voltage and current control that based on PI control. The internal model of each DG is based on the relations between current and voltage equations across the filter, which can be described in abc frame.v_{Cabci} is shown as the voltage at the capacitor, and i_{Labci} is the three-phase current at the point of common coupling (PCC), where v_{abci} and i_{abci} are the voltage and the current at the output of the inverter, respectively. where (*i*) represents the number of the inverter.

$$L\frac{di_{abci}}{dt} = v_{abci} - v_{Cabci} \tag{3.22}$$

$$C\frac{dv_{abci}}{dt} = i_{abci} - i_{Labci} \tag{3.23}$$

transformed into the synchronously rotating frame (SRF)

$$L\frac{di_{di}}{dt} = L_i\,\omega_i\,i_{qi} + v_{di} - v_{Cdi} \tag{3.24}$$

$$L\frac{di_{qi}}{dt} = v_{qi} - L_i\,\omega_i\,i_{di} - v_{Cqi} \tag{3.25}$$

$$C\frac{dv_{Cd}}{dt} = i_{di} - i_{Ldi} + C_i\,\omega_i\,v_{Cqi} \tag{3.26}$$

$$C\frac{dv_{Cq}}{dt} = i_{qi} - i_{Lqi} - C_i\,\omega_i\,v_{Cdi} \tag{3.27}$$

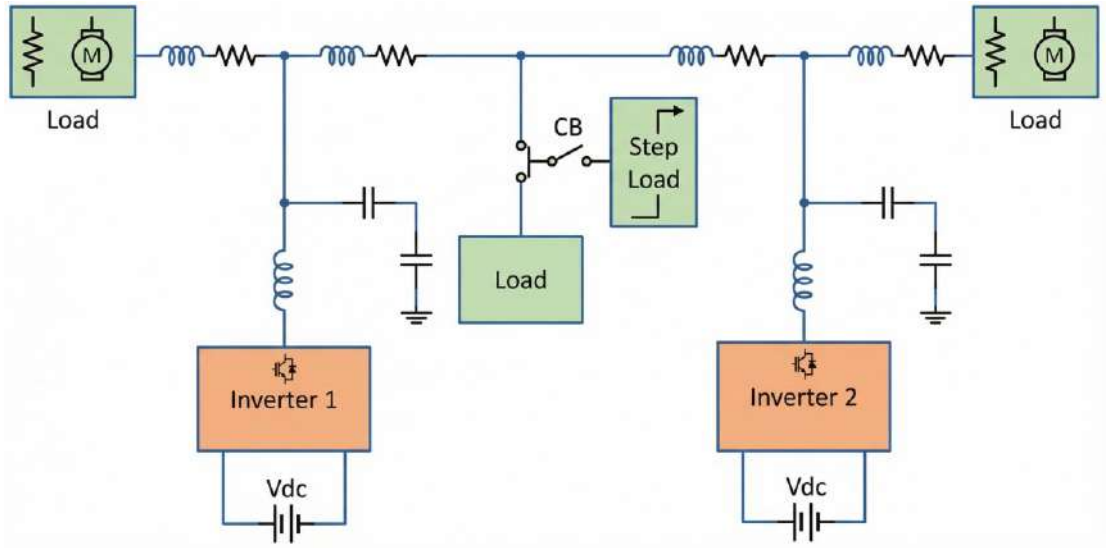


Fig 3.5 Main circuit schematic diagram.

3.6.1 Inverter Controls

In this chapter, we have already developed and analyzed three main types of primary control strategies—each defining how the inverter interacts with the microgrid in terms of power sharing and voltage–frequency regulation.

Now, to complete the overall system architecture, we move to the design of the internal control. This control aims to keep a sinusoidal voltage wave at each distributed generation unit's output. It guarantees system stability, removes the static error, and ignores disruptions. These performance requirements must be met while adhering to the rules and regulations that govern the electrical network. The literature suggests several methodologies and control schemes to drive each dispersed generation unit separately to ensure optimal performance. Depending on how many control loops are employed, whether the control is linear or non-linear, and other factors, such as the proportional integral PI controller.

$$i^*_d = P_v(s)\left(v^*_{cd} - v_{cd}\right) + i_{ld} \; - C\omega v_{cq} \tag{3.28}$$

$$i^*_q = P_v(s)\left(v^*_{cq} - v_{cq}\right) + i_{lq} + C\omega v_{cd} \tag{3.29}$$

$$v^*_d = P_c(s)\left(i^*_d - i_d\right) - L\omega i_q + v^*_{cd} \tag{3.30}$$

$$v^*_q = P_c(s)\left(i^*_q - i_q\right) + L\omega i_d + v^*_{cq} \tag{3.31}$$

Where $P_v(s)=K_{Pv}+\frac{K_{Iv}}{s}$ and $P_c(s)=K_{Pc}+\frac{K_{Ic}}{s}$ represent the transfer functions of the PI Controller for the voltage loop and the current loop, respectively.

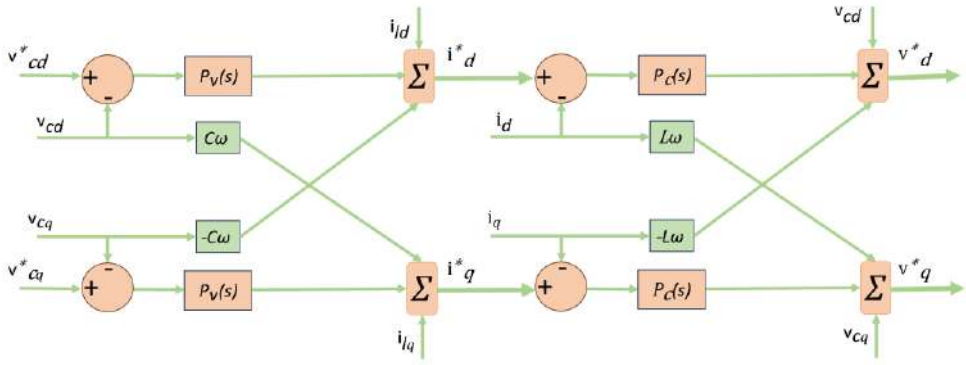


Fig 3.6 Block diagram of internal control based on PI

3.6.2 Simulation result

This study compares conventional, transient droop, and droop control with two integrator which include voltage and current controls containing PI. Both inverters will have the same control structures, and we can obtain 3 uniform or similar control combinations, as shown in the table below.

Table 3.1 Various cases study for power sharing controls.

Case	Droop control	Voltage and current control
(a)	Conventional droop	PI
(b)	Transient droop	PI
(d)	Droop with two integrators	PI

The two inverters are considered identical. The controls have the same values. A model microgrid system was tested in two steps, from 0 to 0.5 seconds for one inverter, then for two inverters. They are connected with balanced load, unbalanced load, and nonlinear load. In addition, the step load can be controlled with a circuit breaker for 0.2 to 0.3 seconds for one inverter and 0.7 to 0.8 seconds for two inverters. A simulation was carried out by building a microgrid model in MATLAB Simulink to confirm the suggested strategy's viability and efficacy. Where balanced Load1 is: P=64 Kw, Q=200 Var; Unbalanced Load2 is: L_1=1mH r_1=100Ω, L_2=10mH r_2=150Ω, L_3=200mH r_3=250Ω; nonlinear Load3 is: a Full bridge rectifier with RC load in parallel, C_4=3.25µF r_4=200Ω and Step Load is: P= 25 Kw, Q=200 Var.

The main system parameters are summarized in Table 3.1.

Table 3.2: Microgrid System Parameters

Parameter	**Symbol**	**Value**
DC-link voltage	V_{dc}	400 V
Nominal line-to-line RMS voltage	V_n	150 V
Nominal frequency	f_n	50 Hz
Switching frequency	f_{sw}	10 kHz
Filter inductor	L	1.53 mH
Filter capacitor	C	50 µF
Cut-off frequency (LPF)	ω_c	31.41 rad/s
Frequency droop coefficient	m_p	7×10^{-5}rad/(W·s)
Voltage droop coefficient	n_q	13×10^{-4}V/var
Time constants	T_a; T_b	0.03 Sec ; 0.0006 Sec
Gain of Current (PI)	K_{Iv}; K_{Ic}	189.345 ; 1005.310
Gain of Voltage (PI)	K_{Pv}; K_{Pc}	0.1682 ; 13.5716
Gain of the integrator	K	10

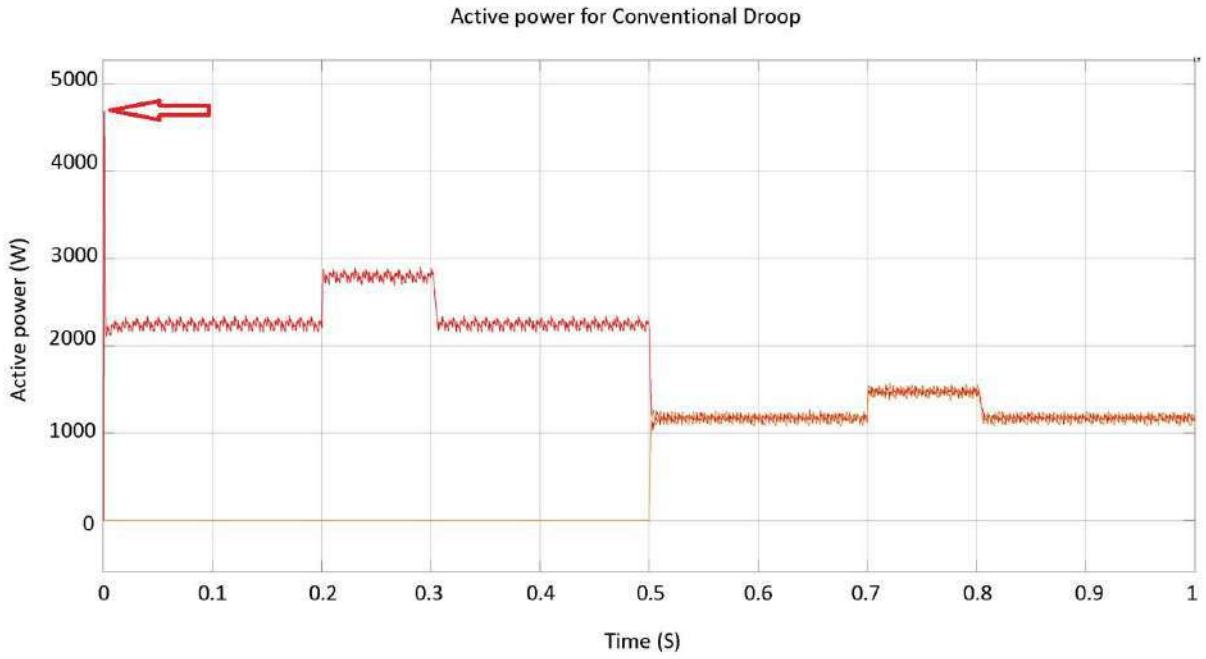


Fig 3.7 Active power output for Convetional droop control

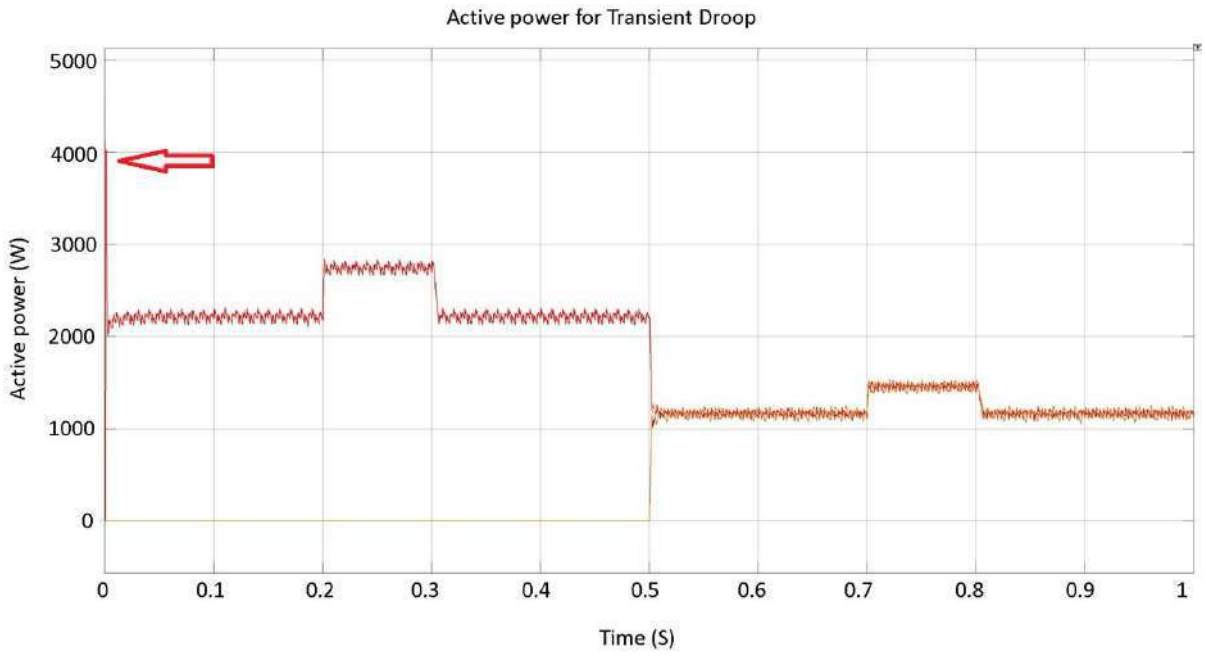


Fig 3.8 Active power output for Transient droop control

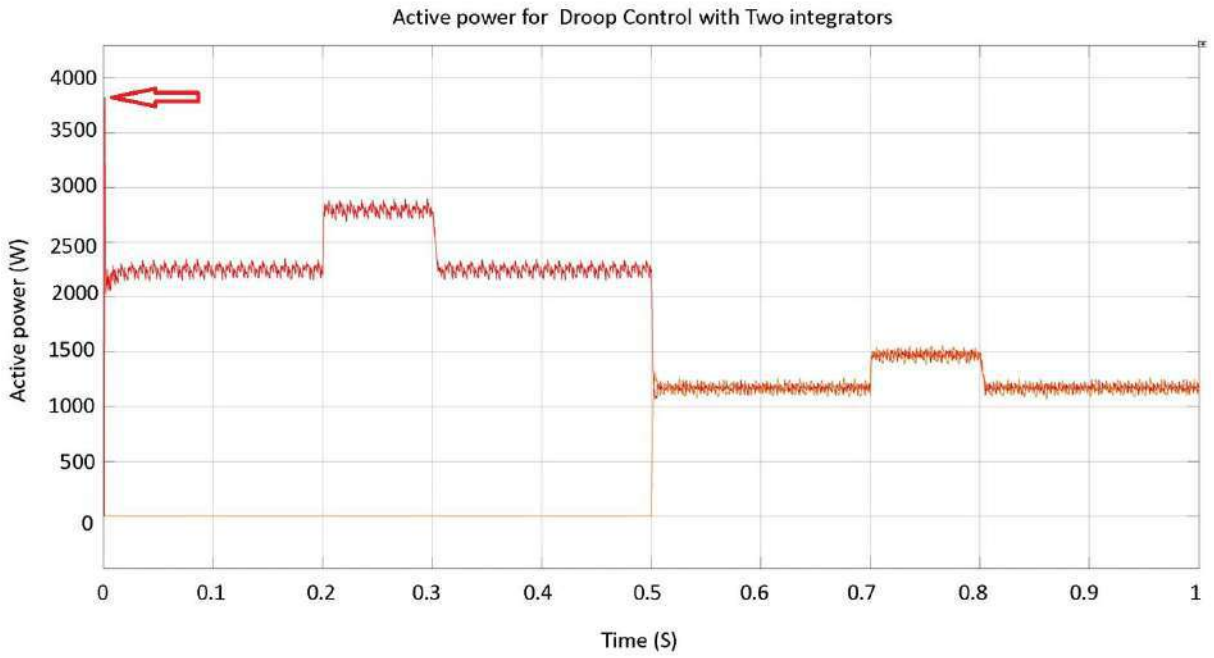


Fig 3.9 Active power output for droop control with two integrators

The diagrams above illustrate the active power outputs of two distributed generators (DGs), showing five transient events corresponding to the load connection and disconnection cycles, in addition to the moment when DG2 was connected.

At the beginning of the simulation, only one DG was operating, during which the conventional droop control exhibited a large overshoot exceeding 4000 W at startup. In contrast, the transient droop control remained close to 4000 W, while the droop control with two integrators demonstrated the best performance, maintaining its output slightly below this level.

These results confirm that the droop control with two integrators, combined with a PI regulator, ensures a faster dynamic response and effectively suppresses harmonics and disturbances.

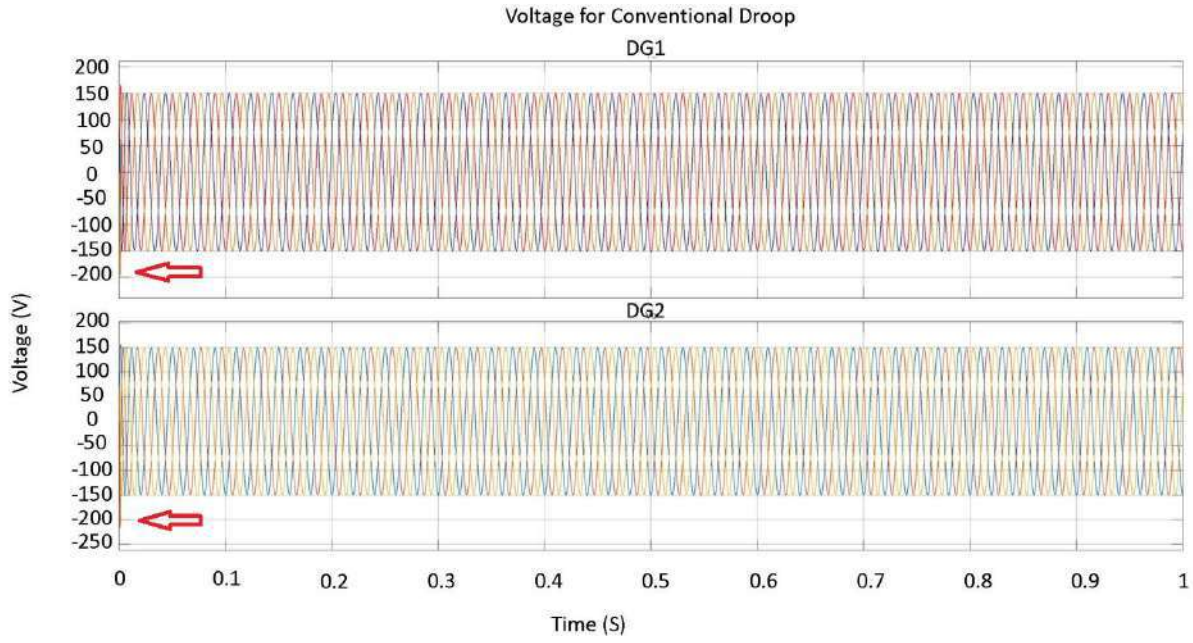


Fig 3.10 Voltage output for Conational droop control

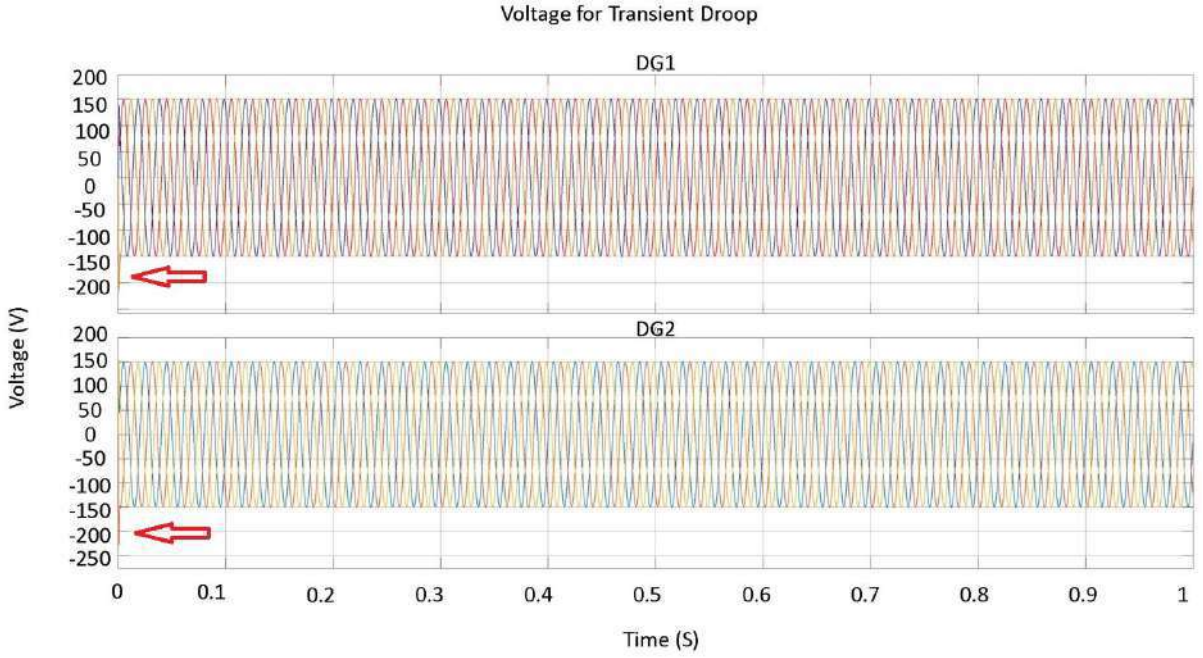


Fig 3.11 Voltage output for Transient droop control

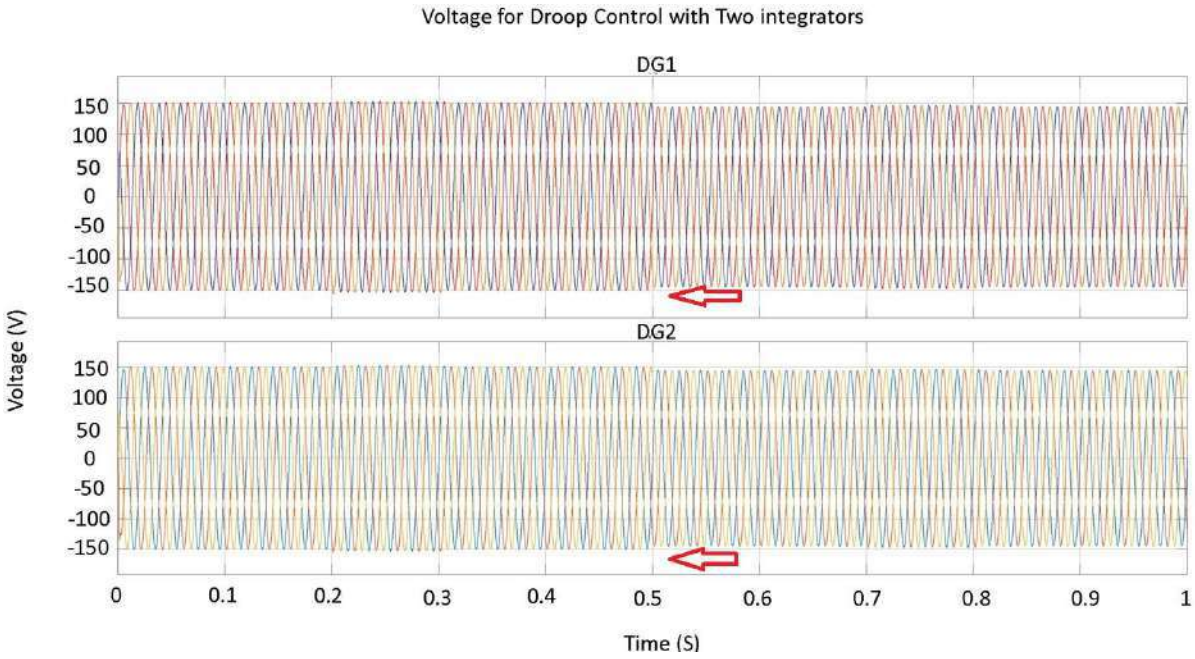


Fig 3.12 Voltage output for droop control with two integrators

In terms of voltage performance, the transient droop control method demonstrated the best behavior, maintaining a stable voltage level despite system variations and load disturbances. Conversely, the droop control with two integrators method exhibited the weakest voltage regulation performance, even though it achieved the best results in active power control.

This observation is clearly illustrated in the figures above.

3.7 Conclusion

This chapter presented a comprehensive comparative analysis of three grid-forming control strategies for inverter-based microgrids: Conventional Droop Control, Transient Droop Control, and Droop Control with Two Integrators, all implemented with PI internal regulation loops. The results confirmed that the control approach strongly influences both transient behavior and steady-state performance.

Overall, the droop control with two integrators provided the most accurate power-sharing and improved steady-state precision, while the transient droop control achieved superior voltage stability and smoother dynamic response under load disturbances. The conventional droop, though simple, exhibited limited damping and higher steady-state errors.

These findings highlight that no single method is universally optimal; instead, controller selection depends on system requirements—whether the priority is fast response, voltage regulation, or power accuracy. The next chapter extends this investigation by developing advanced droop control enhancements, integrating damping and energy-based methods to further improve stability and dynamic performance in autonomous microgrids.

CHAPTER IV:

Proposed Control Strategy

Chapter 4 – Proposed Control Strategy

4.1 Introduction

In this chapter, a new and detailed internal and primary controllers is developed for inverter-based distributed generators operating in an microgrid. The proposed approach is based on the Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC) method, which provides a systematic way to reshape the system energy and assign damping to ensure stability and robustness. This controller is designed to overcome the limitations observed in the previous control strategies presented in the earlier chapters—particularly the conventional droop control and its advanced variants such as droop with two integrators and transient droop control. These earlier methods showed good power-sharing capability but suffered from voltage deviations, slow transient responses, and sensitivity to network variations.

The IDA-PBC-based internal and primary controls proposed here offers a modular interpretable solution. It guarantees voltage and current stabilization, proper power distribution, and plug-and-play operation of multiple distributed generators. At the end of this chapter, the performance of the proposed control will be compared with the previous controllers under identical simulation conditions, showing its effectiveness in improving voltage regulation, dynamic behavior, and system robustness.

4.2 Principles of Modular Modeling

In decentralized and autonomous power systems, one of the most desired properties is Plug-and-Play (PnP) capability, which allows the flexible connection or disconnection of distributed generators (DGs) and loads without compromising system stability. To achieve this level of flexibility, the control architecture must be modular, enabling each subsystem to be modeled, controlled, and analyzed independently while ensuring global coordination at the network level [131], [132].

The modular approach provides a unified way to model several DG units operating in parallel, facilitating the design of a global control structure that guarantees both stability and scalability of the entire microgrid. In this context, the IDA-PBC (Interconnection and Damping Assignment Passivity-Based Control) method is particularly well suited because it allows the energy of each subsystem to be explicitly represented through a port-Hamiltonian model, which naturally preserves passivity and modularity properties [133], [134].

4.2.1 Global Hamiltonian Representation

The starting point of the modular modeling process is the representation of the overall system in a Port-Controlled Hamiltonian (PCH) form [93]. [135].
The general structure of such a system can be expressed as:

$$\dot{x} = [\mathcal{J}(x) - \mathcal{R}(x)]\nabla H(x) + g(x)u + d \tag{4.1}$$

where:

- $x \in \mathbb{R}^{n_g}$ is the global state vector of the system,
- $u \in \mathbb{R}^{n_g}$ is the control input vector,
- $g(x)$ is the input matrix defining the control interconnection,
- $H(x)$ is the Hamiltonian (energy) function representing the total stored energy,
- d denotes external disturbances or load variations,
- $\mathcal{J}(x) = -\mathcal{J}^T(x)$ is the interconnection matrix,
- $\mathcal{R}(x) = \mathcal{R}^T(x) \geq 0$ is the damping matrix.

This compact form captures both the dynamic and energetic interactions within the system. The antisymmetric nature of $\mathcal{J}(x)$ ensures power-conserving interconnections between states, while the symmetric positive-semidefinite property of $\mathcal{R}(x)$ ensures energy dissipation, contributing to the system's passivity and stability [136].

4.2.2 Modular Decomposition

For a system composed of n_g distributed generators operating in parallel, the global state can be decomposed into a block-diagonal modular structure as follows:

$$x = \begin{bmatrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_{n_g} \end{bmatrix}, \quad u = \begin{bmatrix} u_1 \\ \vdots \\ u_i \\ \vdots \\ u_{n_g} \end{bmatrix}, \quad d = \begin{bmatrix} d_1 \\ \vdots \\ d_i \\ \vdots \\ d_{n_g} \end{bmatrix} \tag{4.2}$$

And

$$\mathcal{J}(x)=\begin{bmatrix} \mathcal{J}_1(x_1) & 0 & \cdots & 0 \\ 0 & \ddots & \cdots & 0 \\ \vdots & & \mathcal{J}_i(x_i) & \vdots \\ 0 & \cdots & 0 & \mathcal{J}_{n_g}(x_{n_g}) \end{bmatrix},\quad \mathcal{R}(x)=\begin{bmatrix} \mathcal{R}_1(x_1) & 0 & \cdots & 0 \\ 0 & \ddots & \cdots & 0 \\ \vdots & & \mathcal{R}_i(x_i) & \vdots \\ 0 & \cdots & 0 & \mathcal{R}_{n_g}(x_{n_g}) \end{bmatrix} \tag{4.3}$$

Each subsystem i corresponds to a DG unit with its own local Hamiltonian $H_i(x_i)$, interconnection matrix $\mathcal{J}_i(x_i)$, damping matrix $\mathcal{R}_i(x_i)$, and control input u_i.
The global Hamiltonian of the system can then be expressed as the sum of individual energy functions:

$$H(x)=\begin{bmatrix} H_1 & 0 & \cdots & 0 \\ 0 & \ddots & \cdots & 0 \\ \vdots & & H_i & \vdots \\ 0 & \cdots & 0 & H_{n_g} \end{bmatrix} \quad \text{with} \quad H_i=\frac{1}{2}x_i^T Q_i^{-1} x_i \tag{4.4}$$

This block-diagonal decomposition preserves the passivity and structural properties of the overall system while allowing local controllers to be designed independently for each DG unit.

4.2.3 Modular Passivity and Plug-and-Play Property

The modular Hamiltonian formulation provides a natural foundation for Plug-and-Play operation. When a new generator $DG_{n+1}$is added or an existing one is disconnected, only the corresponding block in the matrices $\mathcal{J}(x)$, $\mathcal{R}(x)$, and $H(x)$changes. The other subsystems remain unaffected, which means that local stability and control parameters are invariant to network reconfiguration [137], [138]..

This property can be formally justified by considering the total energy balance of the modular system.
Let the stored energy be $H(x) = \sum_{i=1}^{n_g} H_i(x_i)$.
Differentiating with respect to time and using (4.1), we obtain:

$$\dot{H}(x) = -\sum_{i=1}^{n_g} (\nabla H_i)^T \mathcal{R}_i(x_i) \nabla H_i + \sum_{i=1}^{n_g} (\nabla H_i)^T g_i(x_i) u_i \tag{4.5}$$

Since each $\mathcal{R}_i(x_i)$is symmetric positive semidefinite, the first term on the right-hand side is non-positive, confirming that the overall system remains passive and dissipative. The second term represents the power supplied or absorbed by the control inputs u_i, ensuring that the interconnection of passive modules remains globally passive.

This modular passivity property is the key enabler for a decentralized IDA-PBC control design.
It ensures that local controllers can be developed and tuned individually, while the composite system maintains its stability and energy balance even under structural changes or disturbances [139].

4.3 IDA-PBC Control Synthesis Methodology

4.3.1 Conceptual Overview

The Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC) method is a nonlinear control framework derived from energy-based modeling principles. Unlike conventional control strategies that rely on linearization or small-signal approximations, IDA-PBC explicitly uses the physical energy balance of the system to define the control law. The objective is to reshape the energy function and assign desired damping so that the closed-loop system behaves according to a new, stable Hamiltonian structure [140].

The key idea is to design the control input $u$such that the closed-loop dynamics take the form:

$$\dot{x} = [\mathcal{J}_d(x) - \mathcal{R}_d(x)]\nabla H_d(x) \qquad (4.6)$$

where:

- $\mathcal{J}_d(x)$and $\mathcal{R}_d(x)$are the desired interconnection and damping matrices, and
- $H_d(x)$is the desired Hamiltonian, representing the energy of the controlled system.

This transformation is known as the energy-shaping process, because it modifies the original system energy $H(x)$into a new energy function $H_d(x) = H(x) + H_a(x)$, where $H_a(x)$is an auxiliary term representing the control contribution.
By properly designing $H_a(x)$and $\mathcal{R}_d(x)$, the system trajectories are forced to converge toward the equilibrium point that minimizes $H_d(x)$.

In the context of microgrids, this method is particularly powerful because:

- it provides intrinsic stability.
- it preserves the physical interpretation of energy exchange between inverters.
- it supports modular and decentralized implementation.

Furthermore, since each Distributed Generator (DG) is represented by a port-Hamiltonian subsystem, the IDA-PBC approach can be applied locally to each module, while ensuring global passivity and stability of the interconnected network [141], [142].

4.3.2 Desired Closed-Loop Energy Shaping

Starting from the general Hamiltonian form given in (4.1):

$$\dot{x} = [\mathcal{J}(x) - \mathcal{R}(x)]\nabla H(x) + g(x)u + d \tag{4.7}$$

the objective of the IDA-PBC design is to determine a control input u such that the closed-loop system takes the desired structure (4.6).
To achieve this, we impose the matching condition between the open-loop and desired dynamics as follows:

$$[\mathcal{J}_i(x_i) - \mathcal{R}_i(x_i)]\nabla H_i(x_i) + g_i u_i + d_i = [\mathcal{J}_{d_i}(x_i) - \mathcal{R}_{d_i}(x_i)]\nabla H_{d_i}(x_i) \tag{4.8}$$

This equation represents the core of the IDA-PBC synthesis.
The control input u must be found such that the above identity holds for all system states in a neighborhood of the equilibrium [143].

The desired Hamiltonian is defined as:

$$H_d(x) = H(x) + H_a(x) \tag{4.9}$$

where $H_a(x)$is an assignable energy function chosen to modify the system potential energy and to stabilize the equilibrium point.

Similarly, the desired damping and interconnection matrices are expressed as:

$$\mathcal{R}_d(x) = \mathcal{R}(x) + \mathcal{R}_a(x), \mathcal{J}_d(x) = \mathcal{J}(x) + \mathcal{J}_a(x) \tag{4.10}$$

where $\mathcal{R}_a(x) \geq 0$and $\mathcal{J}_a(x) = -\mathcal{J}_a^T(x)$are the additional damping and interconnection components introduced by the control action.

Replacing (4.9)–(4.10) into (4.8) yields the matching equation:

$$[\mathcal{J}(x) - \mathcal{R}(x)]\nabla H(x) + g(x)u\,(x) + d = [\mathcal{J}(x) + \mathcal{J}_a(x) - \mathcal{R}(x) - \mathcal{R}_a(x)][\nabla H(x) + \nabla H_a(x)] \quad (4.11)$$

Solving this partial differential equation for $u(x)$provides the required control law.
The analytical derivation usually involves:

1. Selecting a desired equilibrium x^*.
2. Choosing $H_a(x)$such that $\nabla H_a(x^*) = 0$.
3. Assigning appropriate damping terms $\mathcal{R}_a(x)$to improve transient behavior.

When $H_d(x)$is positive definite around x^*, the closed-loop system is asymptotically stable in the sense of Lyapunov, since $\dot{H}_d(x) = -(\nabla H_d(x))^T \mathcal{R}_d(x)\nabla H_d(x) \leq 0$.

The Synthesis Steps

The overall synthesis of the IDA-PBC controller can be summarized in two main stages:

1. **Modeling:** Represent the microgrid system in port-Hamiltonian form to explicitly identify its energy and interconnection structure.
2. **Energy Shaping and Damping Assignment:** Solve the matching equation (4.11) to derive the control law that assigns desired energy and damping characteristics.

This methodology ensures that each DG can be controlled independently while the entire microgrid remains stable and balanced in terms of energy distribution and voltage regulation

4.4 Application to an Autonomous Microgrid

After establishing the theoretical framework of the modular IDA-PBC synthesis, this section applies the proposed methodology to an autonomous AC microgrid composed of multiple inverter-interfaced distributed generators (DGs) operating in parallel.
Each DG unit delivers its power through a filter and line impedance to a common Point of Common Coupling (PCC), supplying both linear and nonlinear loads.
The aim is to develop a complete Hamiltonian model that captures the energy interactions between the internal filter dynamics and the grid interconnections, enabling decentralized IDA-PBC control design [144], [145].

4.4.1 Description of the System Structure

The microgrid under consideration is conceptually illustrated in Figure 2.1 It consists of i distributed generators (DGs) connected in parallel to a common AC bus through individual line impedances. Each distributed generator DG_i is composed of:

- a DC-link source (typically interfaced with renewable energy such as photovoltaic or storage systems.
- a three-phase inverter
- an LC output filter followed by a line inductance L_{L_i}.

The line impedance represents the electrical connection between each inverter and the point of common coupling (PCC), while the LC filter provides harmonic attenuation and voltage regulation. Each inverter includes its own internal control loop, which will be redesigned using the Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC) approach [146].

Furthermore, the primary droop control with two integrators will also be developed based on the IDA-PBC framework, meaning that both the primary and internal control layers of the system will be fully governed by the passivity-based control design.

The system's architecture naturally lends itself to a modular representation, where each DG can be viewed as an energy port connected to the common AC bus. This configuration is particularly well-suited for decentralized passivity-based control, allowing each DG to independently regulate its local variables while collectively ensuring power balance and voltage synchronization at the PCC [147].

4.4.2 Dynamic Model of DGs

Each DG unit is modeled in the dq rotating reference frame synchronized to its local voltage. The LC filter dynamics are described by the current and voltage equations:

$$
\begin{aligned}
L_i \frac{di_{d_i}}{dt} &= +L_i \omega_i i_{q_i} + v_{d_i} - v_{C_{d_i}} \\
L_{\mathrm{i}} \frac{di_{q_i}}{dt} &= -L_{\mathrm{i}} \omega_i i_{d_i} + v_{q_i} - v_{C_{q_i}} \\
C_{\mathrm{i}} \frac{dv_{C_{d_i}}}{dt} &= i_{d_i} - i_{L_{d_i}} + C_{\mathrm{i}} \omega_i v_{C_{q_i}} \\
C_{\mathrm{i}} \frac{dv_{C_{q_i}}}{dt} &= i_{q_i} - i_{L_{q_i}} - C_{\mathrm{i}} \omega_i v_{C_{d_i}}
\end{aligned}
\tag{4.12}
$$

where:

- i_{d_i}, i_{q_i} dq-axis filter currents
- $v_{C_{d_i}}, v_{C_{q_i}}$ dq-axis capacitor voltages
- $i_{L_{d_i}}, i_{L_{q_i}}$ dq-axis load (line) currents
- v_{d_i}, v_{q_i} inverter output voltages
- $L_{f_i}, R_{f_i}, C_{f_i}$ filter inductance, resistance, and capacitance
- ω_i local angular frequency of the DG_i

The AC line connecting each DG to the PCC can also be represented by an inductance $L_{L_i}$and resistance R_{L_i}, which couple the DGs through the shared bus voltage v_{PCC}. These line dynamics can be appended to (4.14) to form the complete electrical model.

4.4.3 Port-Hamiltonian Representation of the System

Step 1: The Port-Hamiltonian (PH) model, specific to our system, is presented below and decomposed into two subsystems: the first for internal control dynamics, while the second represents the primary control layer.

$$
\frac{d(x)}{dt} = \left[J(x) - R(x)\right]\nabla H(x) + g(x)u + d \tag{4.13}
$$

a- Internal Control based on the PH

The internal control, which encompasses both voltage and current regulation, generates the reference inverter voltages required for distributed generation. Both control loops are designed to attenuate the output filter dynamics and ensure stable operation.

$$\begin{bmatrix} L_i \frac{di_{di}}{dt} \\ L_i \frac{di_{qi}}{dt} \\ C_i \frac{dv_{cdi}}{dt} \\ C_i \frac{dv_{cqi}}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \omega_i L_i & -1 & 0 \\ -\omega_i L_i & 0 & 0 & -1 \\ 1 & 0 & 0 & \omega_i C_i \\ 0 & 1 & -\omega_i C & 0 \end{bmatrix} \begin{bmatrix} i_{di} \\ i_{qi} \\ v_{cdi} \\ v_{cqi} \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0_i & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} v_{di} \\ v_{qi} \\ i_{ldi} \\ i_{lqi} \end{bmatrix} \tag{4.14}$$

b- Primary Control based on the PH

We adopt the droop control with two integrators as the primary control strategy, and in this section, it will be formulated within the Port-Hamiltonian (PH) framework, where:

$$V_n = E_i; V_{ld} = E_0; a_0 = 1; a_1 = 1/K$$

$$\begin{bmatrix} a_0 \frac{d\omega_i}{dt} \\ 1/K \frac{dE_i}{dt} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \omega_i \\ E_i \end{bmatrix} + \begin{bmatrix} -m_{pi} & 0 \\ 0 & -n_{qi}/K_i \end{bmatrix} \begin{bmatrix} P_i \\ Q_i \end{bmatrix} + \begin{bmatrix} 0 \\ E_0 \end{bmatrix} \tag{4.15}$$

The Hamiltonian function representing the total energy of the system can be formulated as:

$$x_i = \begin{bmatrix} x_{1i} & x_{2i} & x_{3i} & x_{4i} & x_{5i} \end{bmatrix} = \begin{bmatrix} i_{di} & i_{qi} & v_{cdi} & v_{cqi} & E_i \end{bmatrix} \tag{4.16}$$

And Q_i is given by:

$$Q_i = diag\{L_i \quad L_i \quad C_i \quad C_i \quad a_1\}$$

$$H_i(x_i) = \frac{1}{2L_i} x_{1i}^{\ 2} + \frac{1}{2L_i} x_{2i}^{\ 2} + \frac{1}{C_i} x_{3i}^{\ 2} + \frac{1}{C_i} x_{4i}^{\ 2} + \frac{1}{a_{1i}} x_{5i}^{\ 2} \tag{4.17}$$

$$H_i(x_i) = \frac{1}{2} L_i i_{di}^2 + \frac{1}{2} L_i i_{qi}^2 + \frac{1}{2} C_i v_{cdi}^2 + \frac{1}{2} C_i v_{cqi}^2 + \frac{1}{2} a_{1i} E_i^2 \tag{4.18}$$

4.4.4 Model for Closed-Loop System Based on IDA-PBC

Step Two: The IDA-PBC control law is then derived and implemented. This framework provides a systematic approach for synthesizing control laws that guarantee system stability. The closed-loop formulation of the IDA-PBC approach is expressed as follows:

$$\frac{d(x)}{dt} = \left[J_d(x) - R_d(x)\right]\nabla H_d(x) \tag{4.19}$$

The essential components of the structure's preservation and integrability to meet the condition of stability are shown below:

$$R_{di}(x_i) = R^T{}_{di}(x_i) = \begin{bmatrix} A_1 & 0 & 0 & 0 & 0 \\ 0 & A_2 & 0 & 0 & 0 \\ 0 & 0 & A_3 & 0 & 0 \\ 0 & 0 & 0 & A_4 & 0 \\ 0 & 0 & 0 & 0 & A_5 \end{bmatrix} \tag{4.20}$$

$$J_{di}(x_i) = -J^T{}_{di}(x_i) = \begin{bmatrix} 0 & 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{4.21}$$

$$\nabla H_d(x) = \begin{bmatrix} i_{di} - i_{di}^* \\ i_{qi} - i_{qi}^* \\ v_{cdi} - v_{cdi}^* \\ v_{cqi} - v_{cqi}^* \\ E_i - E_i^* \end{bmatrix} \tag{4.22}$$

The objective of the proposed control is to design a state-feedback law that ensures the closed-loop system dynamics retain the Port-Hamiltonian (PH) structure while stabilizing the system around the desired equilibrium point x^*. This is accomplished by defining a desired closed-loop energy function H_d and appropriately modifying the interconnection and damping matrices .where $e_i = x_i - x_i^*$.

The control variables considered in this context for tracking the error are defined as follows:

$$H_{di}(x_i^*, x_i) = \frac{1}{2L_i}(x_{1i} - x_{1i}^*)^2 + \frac{1}{2L_i}(x_{2i} - x_{2i}^*)^2 + \frac{1}{C_i}(x_{3i} - x_{3i}^*)^2 + \frac{1}{C_i}(x_{4i} - x_{4i}^*)^2 + \frac{1}{a_{1i}}(x_{5i} - x_{5i}^*)^2 \tag{4.23}$$

$$H_{di}(x_i^*, x_i) = \frac{1}{2}L_i(i_{di} - i_{di}^*)^2 + \frac{1}{2}L_i(i_{qi} - i_{qi}^*)^2 + \frac{1}{2}C_i(v_{cdi} - v_{cdi}^*)^2 + \frac{1}{2}C_i(v_{cqi} - v_{cqi}^*)^2 + \frac{1}{2}a_{1i}(E_i - E_i^*)^2 \tag{4.24}$$

The objective is to drive these variables to their prescribed set points, ensuring that the tracking error eventually converges to zero.

Through the process of matching or comparing these two equations, an observation will be made:

$$\left[J(x)-R(x)\right]\nabla H(x)+g(x)u+d=\left[J_d(x)-R_d(x)\right]\nabla H_d(x) \tag{4.25}$$

$$A_1(i_{di}-i^*_{di})-(v_{cdi}-v^*_{cdi})=L_i\omega_i i_{qi}+v_{di}-v_{Cdi} \tag{4.26}$$

$$A_2(i_{qi}-i^*_{qi})-(v_{cqi}-v^*_{cqi})=-L_i\omega_i i_{qi}+v_{qi}-v_{Cqi} \tag{4.27}$$

$$A_3(v_{cdi}-v^*_{cdi})+(i_{di}-i^*_{di})=C_i\omega_i v_{cqi}+i_{di}-i_{Ldi} \tag{4.28}$$

$$A_4(v_{cqi}-v^*_{cqi})+(i_{qi}-i^*_{qi})=-C_i\omega_i v_{cdi}+i_{qi}-i_{Lqi} \tag{4.29}$$

$$A_5(E_i-E^*_i)=-E_i+E_0-\frac{n_{qi}}{K}Q_i \tag{4.30}$$

The IDA-PBC equations are defined as follows:

$$i^*_{di}=A_3(v^*_{vdi}-v_{vdi})+i_{Ldi}+C_i\omega_i v_{cqi} \tag{4.31}$$

$$i^*_{qi}=A_4(v^*_{cqi}-v_{vqi})+i_{Lqi}+C_i\omega_i v_{cdi} \tag{4.32}$$

$$v^*_d=A_1(i^*_{di}-i_{di})+v^*_{cdi}+L_i\omega_i i_{di} \tag{4.33}$$

$$v^*_{qi}=A_2(i^*_{qi}-i_{qi})+v^*_{cqi}-L_i\omega_i i_{qi} \tag{4.34}$$

Equations (4.31) to (4.34) represent internal control, specifically addressing voltage and current to ensure high-quality voltage.

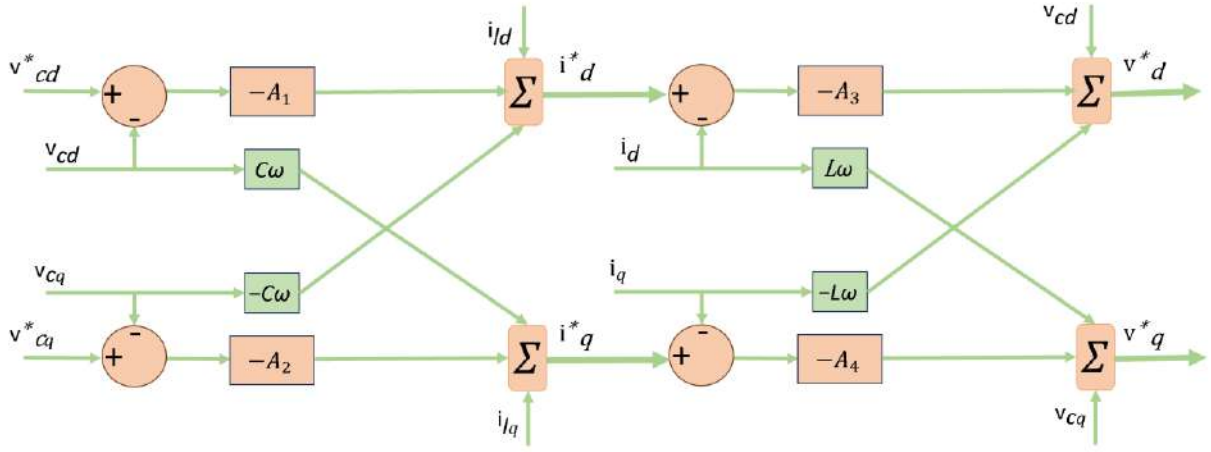


Fig 4.1 Block Diagram of Internal Control Based On IDA-PBC.

$$\omega_i^* = \omega_0 - m_{pi} P_{fi} \tag{4.35}$$

$$E_i^* = E_i - \frac{1}{A_5} E_i + \frac{1}{A_5} E_0 + \frac{n_{qi}}{KA_5} Q_i \tag{4.36}$$

Equations (4.35) and (4.36) are dedicated to primary control objectives, including frequency synchronization, voltage regulation, and power-sharing. where : $E_i = V_n; E_0 = V_{cd}$.

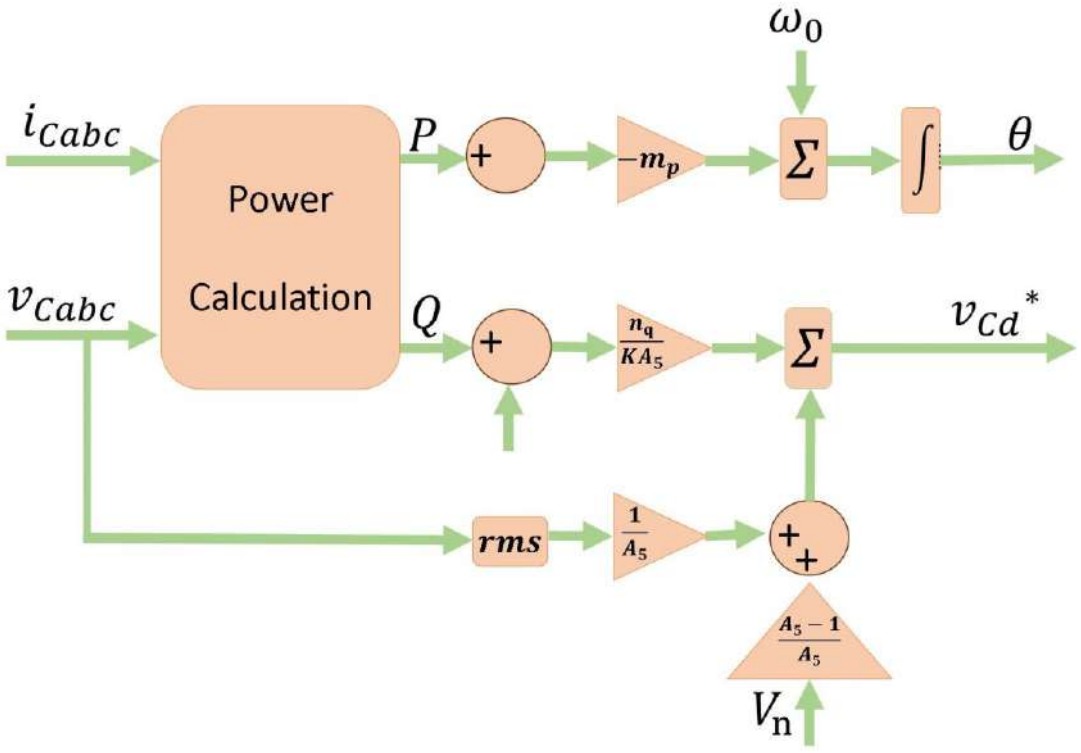


Fig 4.2 Block Diagram of Primary Control Based on IDA-PBC.

4.4.5 Stability Verification

Hd(x) should have a minimum at equilibrium point x* to achieve closed-loop stability and convergence under three conditions [148].:

$$\begin{aligned}\frac{\partial H_{ai}(x_i^*, x_i)}{\partial x_i} &= \frac{\partial (H_{ai}(x_i^*, x_i) - H_i(x_i^*))}{\partial x_i} \\ &= [-\frac{1}{L_i} x_{1i}^*, -\frac{1}{L_i} x_{2i}^*, -\frac{1}{C_i} x_{3i}^*, -\frac{1}{C_i} x_{4i}^*, -\frac{1}{a_{1i}} x_{5i}^*]^T\end{aligned} \tag{4.37}$$

$\partial H_{ai}(x_i^*, x_i)$ denotes the energy stored within the error terms of the controller.

$$\begin{aligned}\nabla H_i(x_i^*) &= \frac{\partial H_i(x_i^*)}{\partial x_i} \\ &= [\frac{1}{L_i} x_{1i}^*, \frac{1}{L_i} x_{2i}^*, \frac{1}{C_i} x_{3i}^*, \frac{1}{C_i} x_{4i}^*, \frac{1}{a_{1i}} x_{5i}^*]^T\end{aligned} \tag{4.38}$$

$$\begin{aligned}\frac{\partial H_{di}(x_i^*)}{\partial x_i} &= \frac{\partial H_{ai}(x_i^*, x_i)}{\partial x_i} + \frac{\partial H_i(x_i^*)}{\partial x_i} \\ &= [0, 0, 0, 0, 0]\end{aligned} \tag{4.39}$$

Condition 2:

$$\frac{\partial^2 H_{di}(x_i^*)}{\partial x_i^2} = [\frac{2}{L_i} + \frac{2}{C_i} + \frac{1}{a_{1i}}] > 0 \tag{4.40}$$

Condition 3:

$$-\left[\frac{\partial H_{di}(x_i^*)}{\partial x_i}\right]^T R_{di} \frac{\partial H_{di}(x_i^*)}{\partial x_i} = \begin{bmatrix} -\frac{a_{11}}{L_i}(x_{1i} - x_{1i}^*)^2 \\ -\frac{a_{22}}{L_i}(x_{2i} - x_{2i}^*)^2 \\ -\frac{a_{33}}{C_i}(x_3 i - x_{3i}^*)^2 \\ -\frac{a_{44}}{C_i}(x_4 i - x_{4i}^*)^2 \\ -\frac{a_{55}}{a_{1i}}(x_5 i - x_{5i}^*)^2 \end{bmatrix} \tag{4.41}$$

The condition is verified when $a_{ii} \geq 0$

This study fulfilled all three conditions.

4.4.6 Modular Aggregation of Multiple DG Units

The total microgrid model is obtained by stacking the individual port-Hamiltonian subsystems:

$$\dot{x} = [\mathcal{J}(x) - \mathcal{R}(x)]\nabla H(x) + g(x)u + d \qquad (4.42)$$

with block-diagonal matrices:

$$\mathcal{J}(x) = \text{diag}\{\mathcal{J}_1, \mathcal{J}_2, \dots, \mathcal{J}_{n_g}\}, \mathcal{R}(x) = \text{diag}\{\mathcal{R}_1, \mathcal{R}_2, \dots, \mathcal{R}_{n_g}\} \qquad (4.43)$$

and total Hamiltonian $H(x) = \sum_{i=1}^{n_g} H_i(x_i)$.

This modular structure ensures that adding or removing a DG affects only its corresponding block, thus preserving the Plug-and-Play property discussed in Section 4.2.

4.4.7 Control Objectives

For each DG unit, the Proposed control based on IDA-PBC aims to:

1. Regulate the capacitor voltage $v_{C_i}$to its reference $v_{C_i}^*$.
2. Ensure accurate current tracking through appropriate damping assignment.
3. Provide energy sharing between DGs via the droop characteristics embedded in the outer power-control loop.
4. Maintain passivity and stability under load variations and dynamic disturbances.

In the following sections, the simulation study and comparative analysis will demonstrate that the proposed control achieves these objectives more efficiently than previous control.

4.5 Simulation and Discussion

4.5.1 Simulation Framework and Objectives

To evaluate the effectiveness of the proposed IDA-PBC-based control, extensive simulations were conducted using MATLAB/Simulink.

The study focuses on islanded microgrid consisting of two inverter-interfaced Distributed

Generators (DGs) connected in parallel to a common bus supplying linear and nonlinear loads.

The main objectives of the simulation are:

1. To validate the ability of the proposed controller to regulate the output voltage under different operating conditions.
2. To verify active power sharing between DGs without communication links.
3. To assess the dynamic behavior during load perturbations and plug-in/out operations.
4. To compare the performance of the proposed control with conventional droop, droop with two integrators, and transient droop controllers.

4.5.2 Simulation Analysis

To compare the proposed control with previous controllers, the same microgrid system described in Chapter 3 was implemented. The two inverters were assumed to be identical and operated using the same control parameters. As presented in Table 3.2 (Microgrid System Parameters) of Chapter 3, the exact same parameters are reused in this chapter to ensure a fair comparison. The only additional parameters introduced for the IDA-PBC controller are $A_1, A_2 = 50$ - $A_3, A_4 = 0.8$ and $, A_5 = 1$, which correspond to the damping and energy-shaping gains required by the proposed control strategy.

The performance of all controllers was tested under the following scenarios:

1. **Load Step Variation:**
   At $t = 0.2$ s,
   The controller's response in terms of voltage regulation and active/reactive power recovery is evaluated.
2. **Load Shedding:**
   At $t = 0.3$ s, part of the load is disconnected.
   The controllers' ability to suppress overvoltage and stabilize the system is compared.
3. **DG Plug-and-Play Test:**
   At t=0.5 s, The second DG unit is reconnected.

The goal is to verify that the modular control structure allows smooth reconfiguration without system instability or retuning.

4. **Nonlinear Load Test:**

   At t=0.7 s, A rectifier-type load is connected to assess harmonic distortion and current tracking performance.

5. **Nominal Operation:**

   At t=0.8 s, Both DGs supply the load at rated conditions.

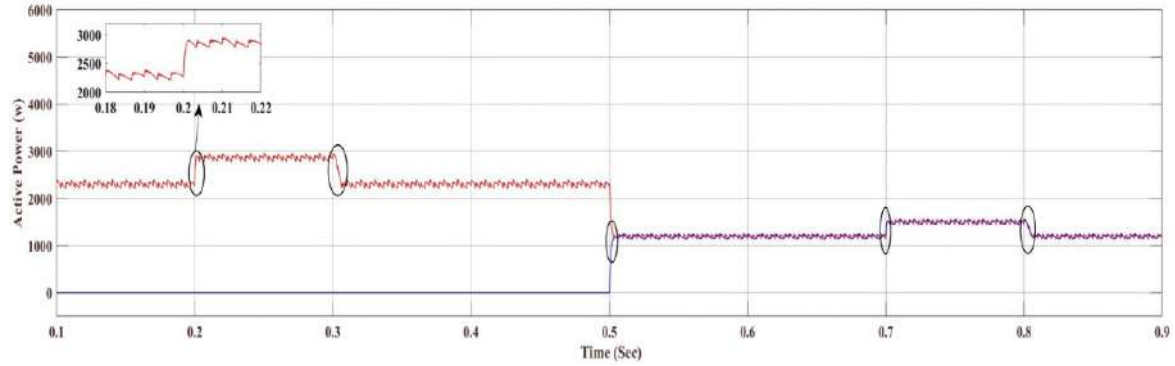
   The system voltage, current, and power-sharing behavior are observed.

- **Simulation 1**

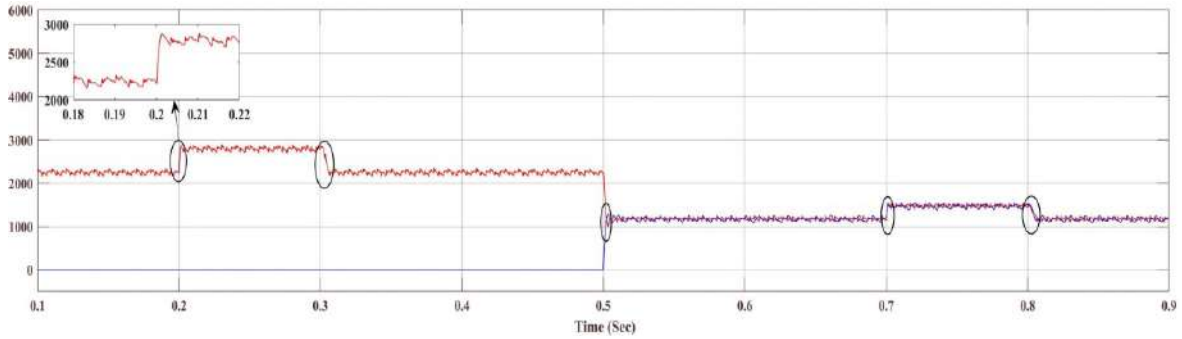
The performance of the internal control based on the IDA–PBC method is evaluated through four test scenarios, which are detailed in the table below.

Table 4.1 Various case studies on microgrid control strategies

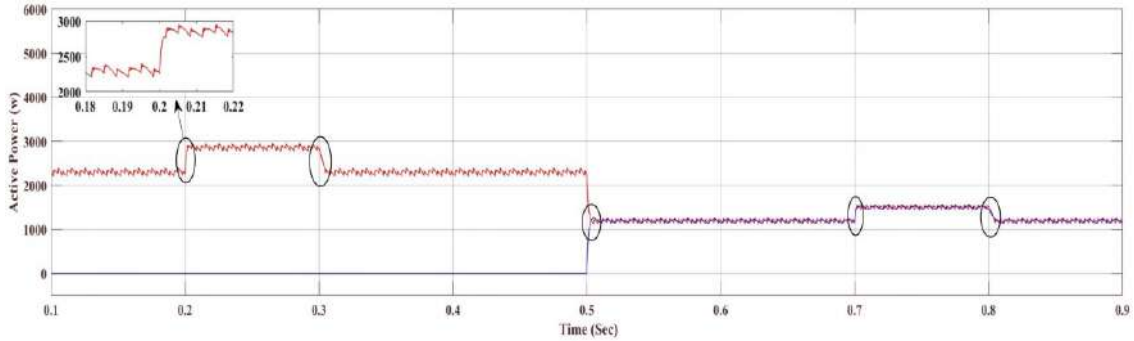
Case	Primary control	Internal control
(1)	Conventional droop	PI
(2)	Conventional droop	IDA-PBC
(3)	Transient droop	PI
(4)	Transient droop	IDA-PBC



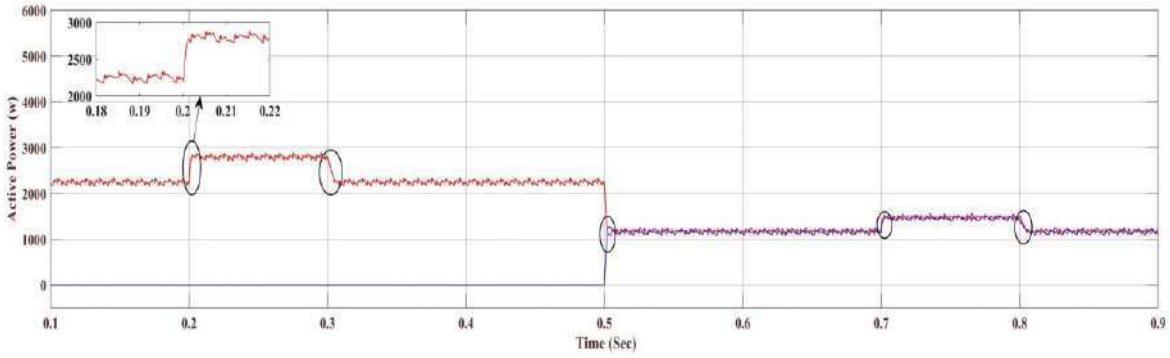
(1)



(2)



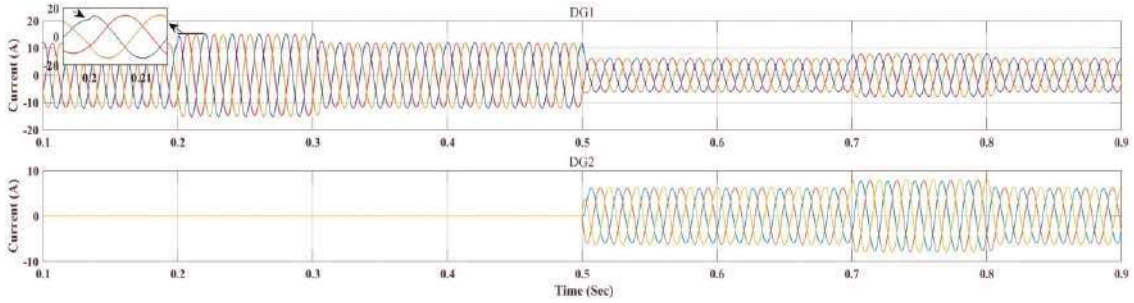
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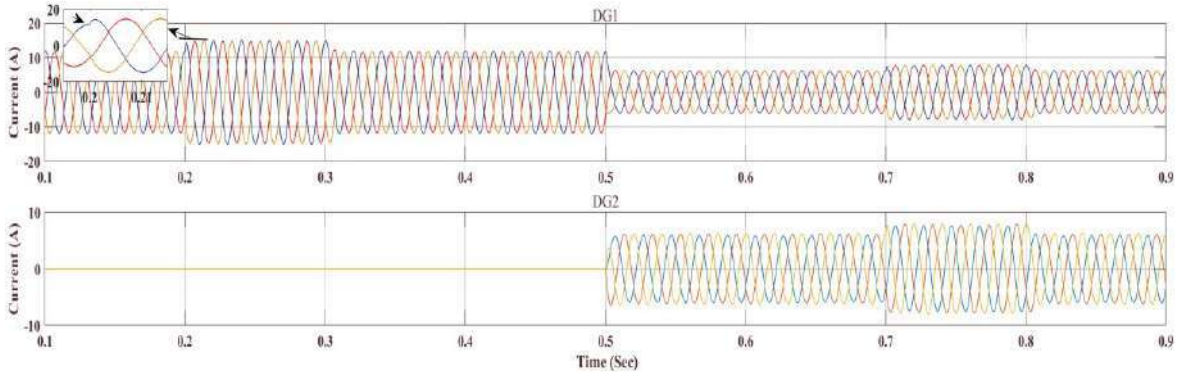
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Fig. 4.3 Active Power Response of Inverters under Different Test Cases

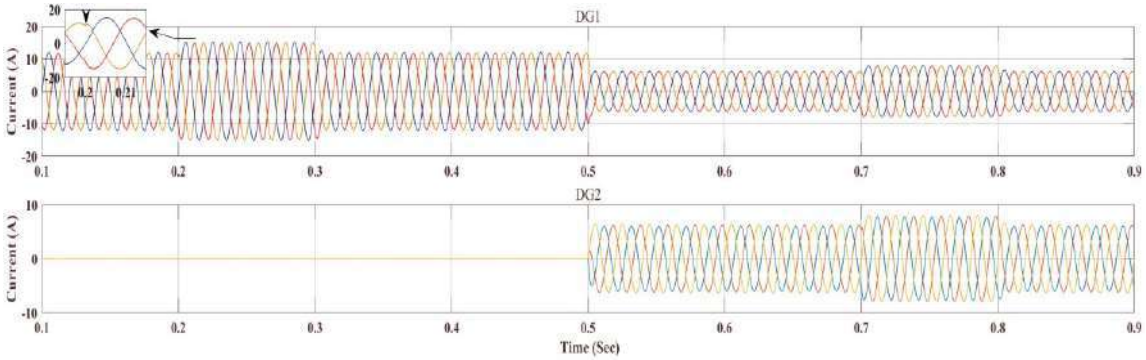
This simulation focuses solely on the stability and dynamic response of the system. The results confirm that the transient droop control, combined with the internal control based on the IDA–PBC approach, achieves a fast dynamic response while significantly reducing harmonics and disturbances. The voltage and current waveforms exhibit excellent performance — the voltage remains stable at 150 V, and the current varies smoothly according to power sharing and load variations.



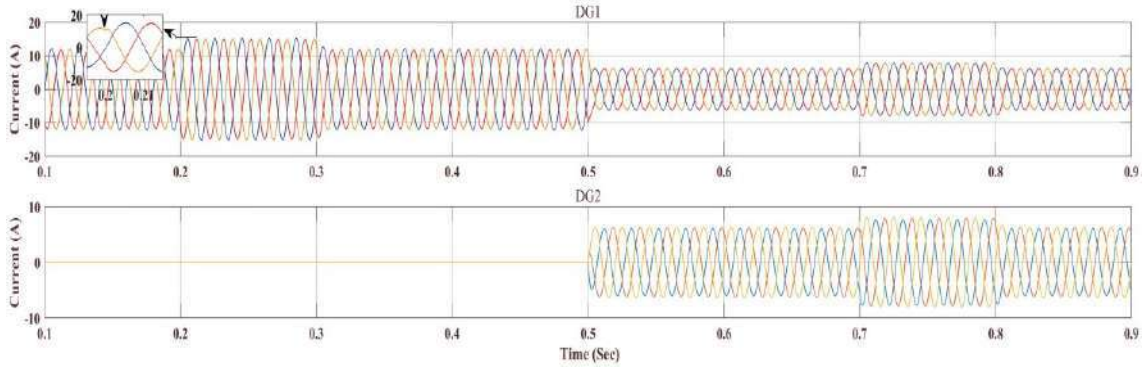
(1)



(2)



(3)



(4)

Fig 4.4 Current Response of Inverters under Different Test Cases.

These figures illustrate the variation in current output according to power sharing, highlighting slight differences that occur during load changes and when the second distributed generator becomes active. They also depict the distinct waveform shapes obtained under the different control strategies.

Based on the simulation results, the transient droop control combined with the internal control based on the IDA–PBC approach demonstrates superior stability compared to the internal control using a conventional proportional–integral (PI) structure. Although the conventional droop control achieves the fastest transient response, it exhibits a smaller stability margin.

- **Simulation 2**

This investigation aims to design a comprehensive control system capable of achieving both an optimal transient response and robust stability for various distributed generation sources operating in islanded mode—a topic that will be examined in this section.

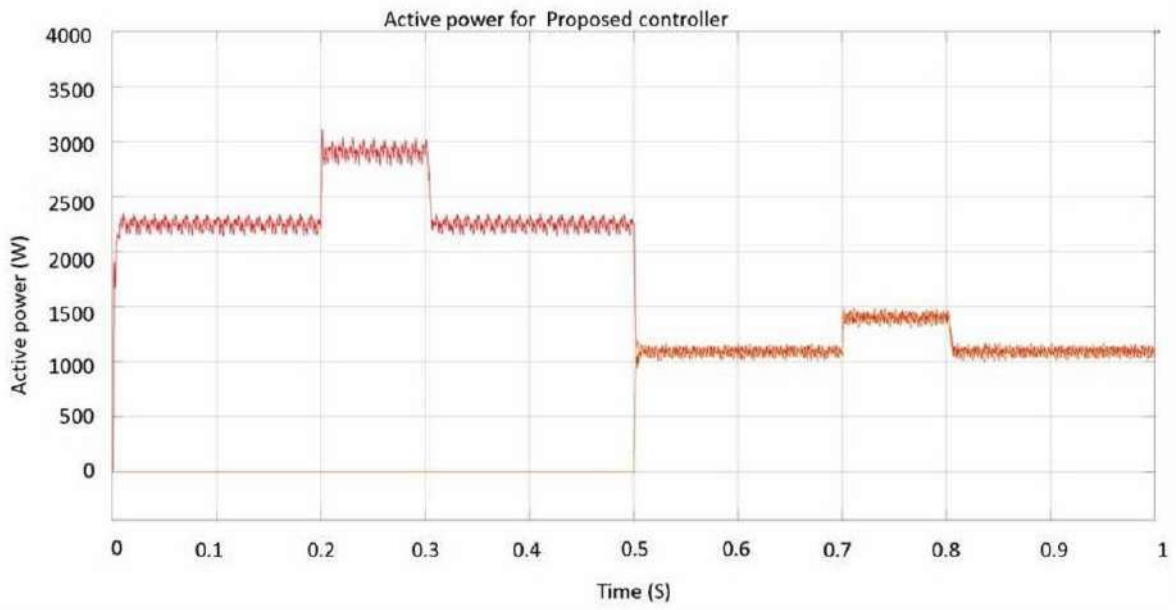


Fig 4.5 Active Power Response of DGs under the Proposed Controller.

As observed above, the system exhibits no transients, in contrast to the previous method. The figure below clearly shows that the voltage remains stable throughout the operation.

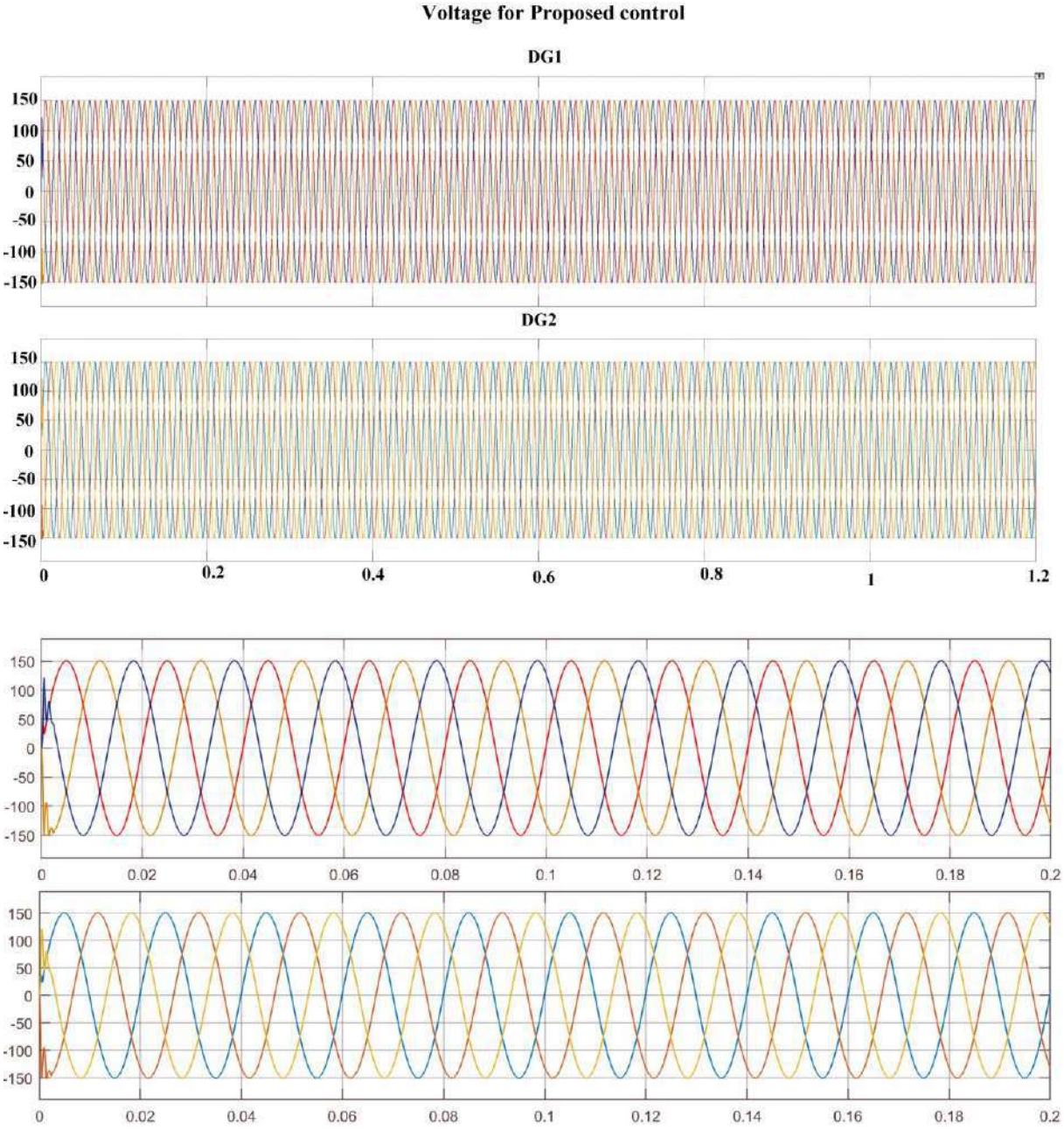


Fig 4.6 Voltage Response of DGs under the Proposed Controller

The simulation results demonstrate significant improvements in voltage stability, transient response, and power distribution using the proposed controller compared to conventional methods.

Under the plug-and-play test, the proposed controller-maintained synchronization and stability without any control retuning, confirming its modular and decentralized nature.

The transient droop controller required parameter readjustment, while the droop controller with two integrators failed to stabilize the PCC voltage after reconnection.

These results clearly show that the IDA-PBC architecture inherently supports Plug-and-Play integration of DGs.

4.5.3 Discussion of Results

1. Transient Dynamics

The proposed controller demonstrates the shortest settling time and minimal overshoot. This improvement results from explicit damping assignment within the control synthesis, which shapes the system's closed-loop energy landscape to achieve near-critical damping without sacrificing robustness. In contrast, the transient droop controller achieves partial damping through derivative compensation but lacks an explicit energy-based structure, limiting its performance under nonlinear conditions.

2. Power Sharing

The proposed method achieves the lowest Active Power Sharing Error, confirming accurate proportional sharing among DGs. This arises from the passivity-preserving interconnection, which inherently balances energy exchange between inverters through the PCC without requiring communication or synchronization channels.

3. Modularity and Plug-and-Play Capability

The modular structure of the IDA-PBC framework enables straightforward scalability. When an additional DG unit is connected or disconnected, the global Hamiltonian (energy) function automatically adjusts without requiring retuning of other controllers. This feature was experimentally validated during the plug-in/out scenario: the system remained stable, confirming that the closed-loop energy remains bounded and dissipative.

4.6 Conclusion

In this chapter, a comprehensive modeling and control framework based on the Interconnection and Damping Assignment – Passivity-Based Control (IDA-PBC) approach has been developed and applied to inverter-based distributed generators operating in an autonomous microgrid.

The study started with the formulation of a modular Hamiltonian representation, which allowed the microgrid to be modeled as an interconnection of energy-preserving subsystems.

This modular structure guaranteed the Plug-and-Play property, enabling flexible connection and disconnection of distributed generators without requiring retuning of the local controllers.

Building on this foundation, the IDA-PBC control synthesis methodology was derived through energy shaping and damping assignment principles.

The resulting control law ensures that the closed-loop system preserves a port-Hamiltonian structure, providing both stability and robust transient performance.

Extensive MATLAB/Simulink simulations were conducted to compare the proposed control with three established methods: conventional droop, droop with two integrators, and transient droop.

The comparison was performed under various operating conditions, including load variations, DG plug-and-play operations, and nonlinear load disturbances.

The results demonstrated that the proposed controller consistently outperforms the other methods in terms of:

- Voltage regulation (lowest deviation and zero steady-state error).
- Active and reactive power sharing (minimal mismatch and fast restoration).
- Transient dynamics (shortest settling time and lowest overshoot.

These results confirm that the proposed controller provides an energy-coherent and physically interpretable control mechanism that enhances both stability and performance in decentralized microgrids.

Furthermore, its inherent modularity ensures scalability, allowing new DGs to be added without reconfiguration or communication links.

General Conclusion

GENERAL CONCLUSION

This thesis has investigated advanced control strategies for inverter-based microgrids, with the overarching goal of achieving reliable, decentralized grid-forming operation. The study began by introducing the fundamental concepts of microgrids, including their architecture, principal components, and operational modes. Emphasis was placed on the importance of control hierarchies—particularly primary and internal control loops—in maintaining system stability and performance. To provide a clear analytical foundation, a simplified system model was presented. This model described DC sources, multiple inverters connected in parallel through LC filters, and their interconnection via an impedance transmission line. By defining key voltage and current variables at the inverter output and point of common coupling, the model established a consistent framework for evaluating and comparing control strategies.

The subsequent chapters explored droop-based primary control methods in depth. Conventional droop control was analyzed as the baseline strategy, offering simplicity and scalability but limited by steady-state deviations, poor reactive power sharing under impedance mismatches, and suboptimal transient performance. To address these challenges, two improved methods were considered. droop control with two integrators control introduced lead–lag compensation to improve damping and accelerate dynamic response, while Transient droop added integral action to reduce steady-state voltage and frequency errors without depending entirely on secondary control. These analyses revealed the inherent trade-offs between simplicity, transient response, and steady-state accuracy among the various droop-based approaches.

Building upon these insights, the thesis proposed a novel robust damping droop control strategy based on Interconnection and Damping Assignment Passivity-Based Control (IDA-PBC). This energy-based method reshaped the microgrid's Hamiltonian and assigned adaptive damping properties to enhance both stability and performance. By combining the well-established principles of droop control with the passivity framework, the proposed approach mitigates local oscillations, ensures accurate power sharing among distributed generators, and maintains voltage and frequency stability—without the need for centralized communication or complex coordination mechanisms.

Comprehensive simulations performed in MATLAB/Simulink validated the proposed strategy under a wide range of operating scenarios, including balanced and unbalanced load changes, line impedance mismatches, and plug-and-play events. The results consistently demonstrated that the

IDA-PBC-based controller outperformed conventional and transient droop methods in terms of voltage regulation, frequency stability, transient recovery speed, and harmonic suppression. These findings confirm that reshaping the system's energy dynamics offers a practical and effective path toward more robust primary control in inverter-dominated microgrids.

In summary, this work contributes to the field of microgrid control by bridging traditional droop-based methods and modern passivity-based techniques. The proposed robust damping droop controller not only addresses key limitations of conventional approaches but also preserves their decentralized, communication-free advantages. Future work should focus on experimental validation using hardware-in-the-loop or laboratory microgrid testbeds to confirm the controller's performance in real-world conditions. Further research could also explore integrating adaptive or machine learning-based tuning methods, extending the approach to hybrid AC/DC microgrids, and investigating fault-tolerant enhancements to improve resilience against component failures or cyber-physical disturbances. These directions will help ensure that microgrid technology remains a viable and flexible solution for future power systems with high renewable energy penetration.

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