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THEME

Control of an inverter-based Microgrid in islanded operation

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Abstract

Nowadays, there is increasing attention on the generation, distribution, and consumption of electricity, and microgrids are emerging as a viable a practical solution. This dissertation aims to explore hierarchical control techniques for two parallel inverter configurations: forming-forming and forming-following. The control process involves multiple levels, beginning with individual voltage or current control for each inverter, techniques such as Droop control are employed to ensure power-sharing between the inverters. Finally, the Droop control method is further enhanced with voltage amplitude and frequency restoration implementation.

Keywords: Microgrids, parallel inverter, forming-microgrid, following-microgrid, Droop control, power-sharing.

ملخص

في الوقت الحاضر، يتزايد الاهتمام بإنتاج وتوزيع واستهلاك الكهرباء، وتعد الشبكات مصغرة حلاً عمليًا. تهدف هذه الأطروحة إلى استكشاف تقنيات التحكم الهرمية لتكوينين للعواكس المتوازية: تشكيل وتشكيل، تشكيل و متابعة. تشمل عملية التحكم مستويات عدة، تبدأ بالتحكم في الجهد أو التيار لكل محول، وتستخدم تقنيات مثل التحكم بالتدلي لضمان تقاسم الطاقة بين المحولات. وأخيرًا، يتم تعزيز طريقة التحكم بالتدلي بتنفيذ استعادة الجهد وتردد الجهد.

الكلمات المفتاحية: الشبكات مصغرة، العاكس المتوازي، تشكيل الشبكات مصغرة ، متابعة الشبكات مصغرة ، التحكم بالتدلي، تقاسم الطاقة

Résumé

De nos jours, on accorde de plus en plus d'attention à la production, à la distribution et à la consommation d'électricité, et les micro-réseaux apparaissent comme une solution viable et pratique. Cette thèse vise à explorer les techniques de commande hiérarchique pour deux configurations d'onduleurs parallèles : formage-formage et formage-suivi. Le processus de contrôle implique plusieurs niveaux, en commençant par le contrôle individuel de la tension ou du courant pour chaque onduleur, des techniques telles que le contrôle Droop sont utilisées pour assurer le partage de puissance entre les onduleurs. Enfin, la méthode de contrôle Droop est encore améliorée avec la mise en œuvre de la restauration de l'amplitude et de la fréquence de la tension.

Mots-clés : micro-réseaux, onduleur parallèle, formage micro-réseau, suivi micro-réseau, contrôle Droop, partage de puissance.

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Dedication

ALHAMDULILLAH who gave me the courage and patience, to complete this work despite the difficult circumstances.

I dedicate this work:

To my parents who always pray for me, encourage me, and push me to succeed. To my sweet sisters **HAFSA**, and **ASMAA**, for their support during this journey.

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BENRAHAL Zineb

Dedication

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BENAMAR Meriem

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Acronyms

MG: Microgrid

DERs: Distributed Energy Resources

PCC: Point of Common Coupling

DC: Direct Current

AC : Alternative Current

VSI : Voltage Source Inverter

DG: Distributed Generation

MGCC: Microgrid Central Controller

LCs: Local Controllers

DNO: Distribution Network Operator

DPGS: Distributed Power Generation Systems

PWM: Pulse Width Modulation

THD: Total Harmonic Distortion

Symbols

L_f: Inductor

C_f: Capacitor

R_F: Resistor

V : voltage

I : current

W: Angular frequency

***E*:** amplitude

m & n: droop coefficients

P &Q: active and reactive power

S_1, S_2, S_3, S_4, S_5, S_6: The switches

General Introduction

In recent years, there has been a growing awareness of the environmental impact associated with fossil fuels and the urgent need to address climate change. Simultaneously, modern electric power systems have implemented stringent regulations to minimize electricity outages and enhance grid resilience. These dual pressures have compelled the power industry to redirect its focus towards distributed power generation on the users' side, leading to increased investment in this area. This strategic shift holds the potential to yield multiple benefits, including reduced generation costs, decreased power loss, and heightened overall system reliability.

The concept at the heart of this transformation is the microgrid (MG), which enables localized generation and distribution of electricity. By integrating various sources of energy, such as renewable resources like solar, wind, and hydropower, alongside localized generators powered by natural gas or other fuels, microgrids provide a flexible and sustainable approach to meeting energy needs. [1].

A Microgrid is an advanced and versatile energy system that encompasses a cohesive group of Distributed Energy Resources (DERs), comprising various Renewable Energy Sources (RES) and Energy Storage Systems (ESS). Together with local loads, these components function as a unified and controllable entity, operating autonomously or in conjunction with the main power grid.

At the core of a Microgrid are the Distributed Energy Resources (DERs). These resources can encompass a range of renewable energy technologies, including solar photovoltaic (PV) panels, wind turbines, biomass generators, and small-scale hydroelectric systems. By harnessing these clean and sustainable energy sources, Microgrids offer a pathway towards reducing greenhouse gas emissions and mitigating the environmental impact associated with traditional fossil fuel-based power generation. [2].

The utilization of parallel inverters has become widespread in various applications, driven by their numerous advantages, including expandable output power and enhanced reliability. However, to ensure optimal and desirable operation of paralleled inverters, the implementation of an efficient control approach is crucial.

Parallel inverters offer the ability to combine the output power of multiple inverters, thereby increasing the overall power capacity. This scalability makes parallel inverters an attractive solution for applications that require higher power levels, such as renewable energy systems, microgrids, and uninterruptible power supplies (UPS). By paralleling inverters, the system can meet increasing power demands without the need for a complete overhaul or replacement of existing equipment [3].

Our study is focused on microgrids where our objective is controlling islanded AC microgrids based on two or three parallel inverters. This dissertation was made in the Master's degree in automatics and systems, at **LACOSERE** laboratory at **Amar Telidji Laghouat University**. This work includes three chapters:

The first chapter presents a thorough overview of microgrids, the utilization of three-phase voltage source inverters (VSI), and control methods that can be employed to regulate inverters within a microgrid.

The second chapter focuses on the modeling of an inverter bridge and an LC filter, and it delves into the primary control strategy. This strategy employs a cascade loop with a PI controller and incorporates droop control. Additionally, the chapter discusses secondary control, which involves frequency and voltage restoration.

The third chapter focuses on the implementation of two methods: forming-norming and forming-following. We also present the simulation results using MATLAB obtained from each method.

In the final section, we provide a concise conclusion that summarizes our work and discusses potential avenues for future research.

CHAPTER I

OVERVIEW ON MICROGRID

I.1 Introduction

In recent times, the topic of green and eco-friendly energy has gained widespread attention from both political and scientific perspectives due to pressing environmental concerns. As a result, it has become a prominent issue among audiences globally.

Microgrids offer a practical and dependable solution for the challenging task of addressing electricity shortages while simultaneously transitioning toward renewable energy. According to the International Energy Forum, microgrids have proven to be an effective means of eliminating electricity shortages and promoting the adoption of green energy. Additionally, microgrids are an affordable option for achieving these objectives.

This chapter aims to provide a comprehensive overview of microgrids, including their basic concepts, benefits, drawbacks, and operating modes. Additionally, we will examine the three-phase voltage source inverters (VSI), and their association with micro-grids. Finally, the chapter will cover a range of control strategies that can be employed to regulate inverters within a microgrid.

I.2 Microgrids

A microgrid can be defined as a power system that comprises multiple interconnected sources and loads, which can operate independently or in coordination with the main power grid. The sources in an MG can include distributed energy resources (DERs), such as solar panels, wind turbines, fuel cells, and generators, as well as energy storage devices, such as batteries and flywheels, The structure of MG is shown in Figure I.1, The loads in a MG can include homes, businesses, and other facilities that require electric power. The interconnected sources and loads in an MG are typically managed by a control system, which optimizes their operation based on various factors, such as energy demand, available resources, and energy prices.

microgrids are characterized by their ability to provide reliable and high-quality power to their local area, while also integrating renewable energy sources and energy storage, and improving overall energy efficiency. There are several types of MG, which can be classified based on factors such as their energy sources, size, application, and level of connectivity with the main power grid.

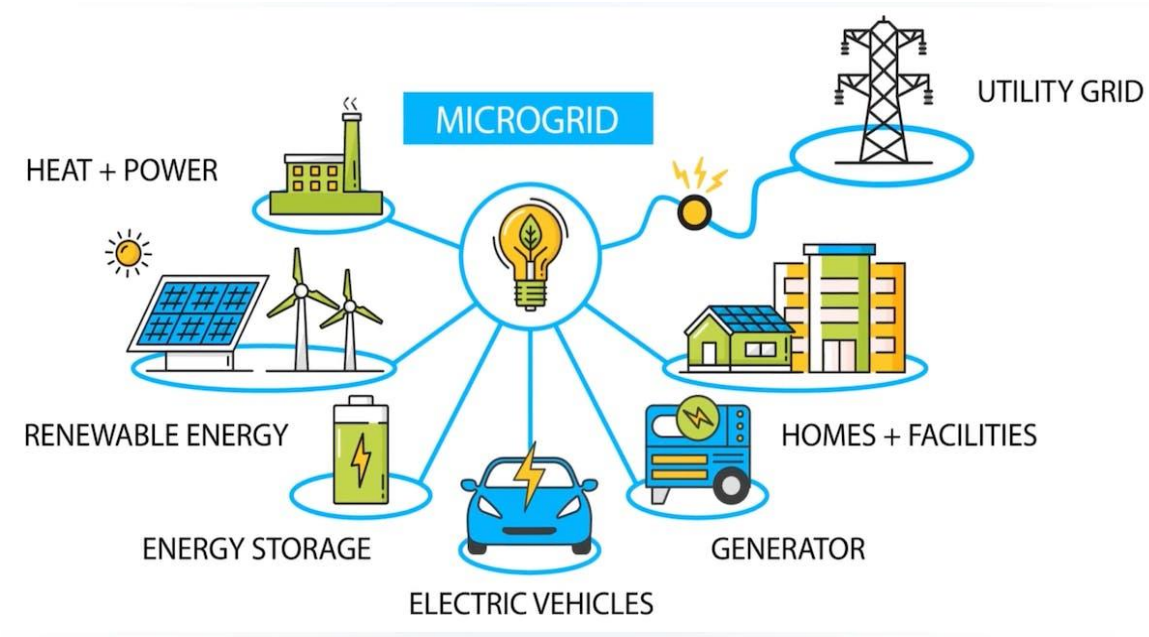


Fig I.1 Structure of microgrid

I.3 Different Types of Microgrids

- **Islanded**

islanded mode refers to the state of operation of a microgrid when it is disconnected from the main utility grid and is operating in a self-contained manner. In this mode, the MG relies on its DERs such as solar panels, wind turbines, and batteries to generate and store power. The intelligent control system of the MG manages the flow of power between the energy sources and the loads within the MG, ensuring that the energy demand is met even when the main grid is down.

islanded mode is beneficial for remote areas or regions where the traditional power infrastructure is not available or is too expensive to connect to the larger power grid. Islanded microgrids can provide reliable power to local communities, promote energy independence and resiliency, and reduce carbon emissions by using renewable energy sources.

- **Grid-connected**

Grid-connected refers to a power system that is directly connected to the main utility grid, enabling it to import or export electricity from and to the grid as needed. In a grid-connected system, the main utility grid serves as the primary source of power for the

connected loads, while also providing backup power in case of power outages or emergencies.

Opposed to the first type, these micro-grids have the option of connecting to the grid using a switching mechanism at the Point of Common Coupling (PCC), they also have the option of working in island mode as well. In connected mode, they can provide grid services to the main or utility grid such as frequency and voltage regulation, real and reactive power support, and power quality improvement [4]. As illustrated in Figure (I.2)

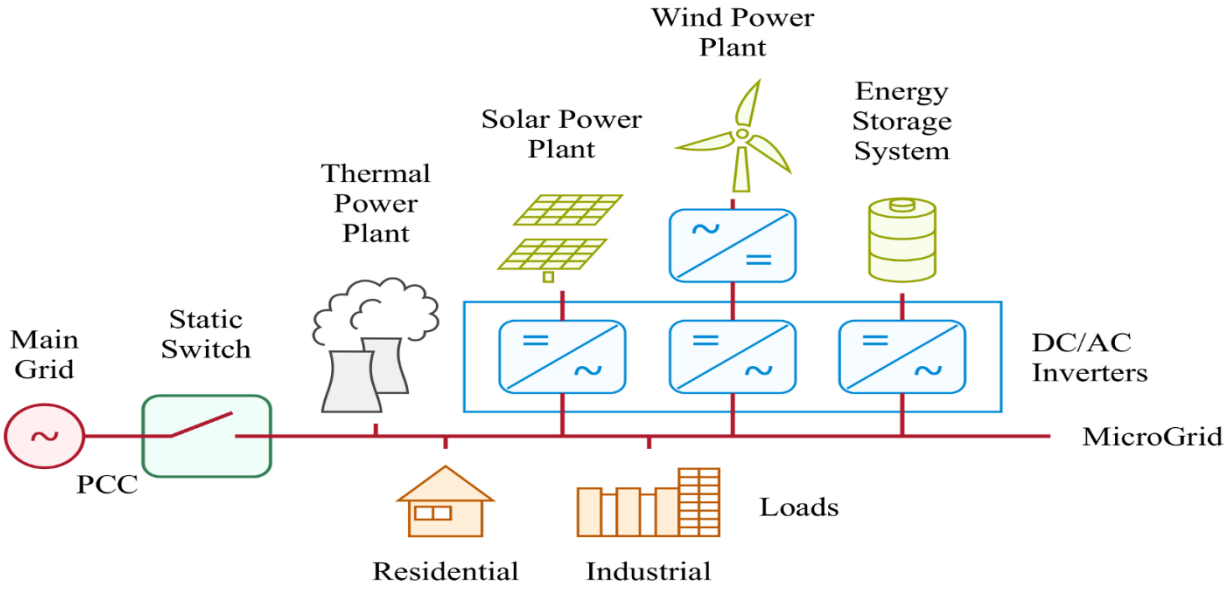


Fig I.2 The model of connected/islanded mode MG

- **DC microgrids**

A DC microgrid maintains a DC bus, which feeds DC loads connected to it. Normally, DC loads are low-power rating electronic devices such as laptops, cell phones, wireless phones, DVD players, battery-powered, vacuum cleaners, and Internet routers…etc. In DC micro-grid structure, sources with DC output are connected to the DC bus directly, whereas sources with AC output are interfaced to the DC bus through AC/DC converter [5]. Figure.I.3 presents the schematic diagram of AC and DC microgrids.

➢ **AC microgrids**

The operational principle of AC microgrids is quite similar to their DC counterparts. The main difference between them is the usage of an AC bus network for interconnection rather than the DC bus which interconnects the distributed generators and loads in the network. This output can be converted into AC through power electronic-based converters (inverters) that need control systems, which is the main topic treated in this work [6].

In addition to the various types of microgrids, there are also different advantages and disadvantages associated with their implementation.

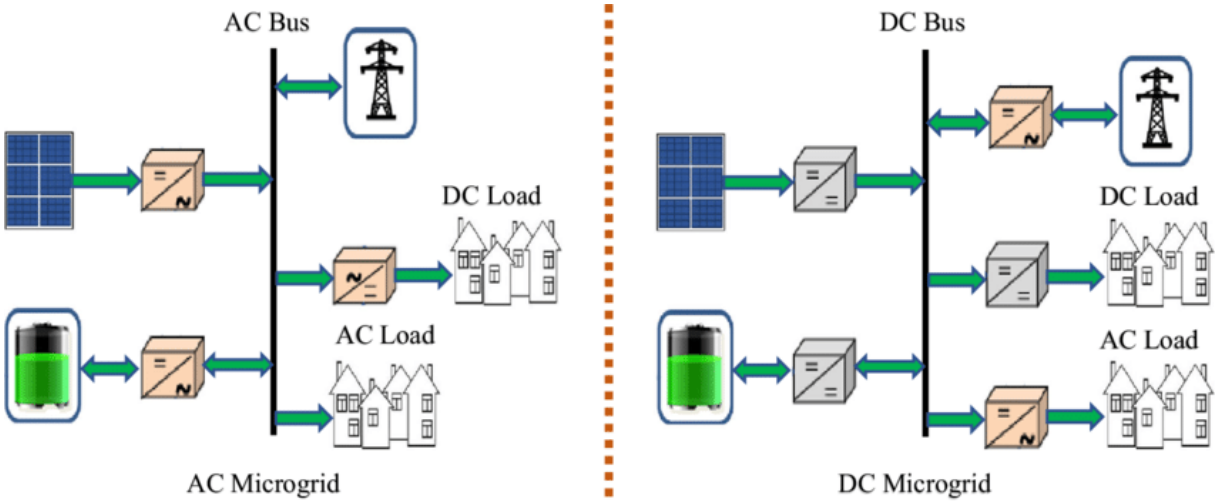


Fig I.3 Schematic diagram of AC and DC microgrid.

I.4 Advantages and disadvantages

➢ **Micro-grid Advantages**

- Microgrids have the ability during a utility grid disturbance to separate and isolate themselves from the utility seamlessly with little or no disruption to the loads within the Microgrid.

- In peak load periods micro-grid can prevent utility grid failure by reducing the load on the grid.

- Microgrids have environmental benefits made possible by the use of low or zero-emission generators.

- In a microgrid, maximizing energy efficiency involves allowing the utilization of both electricity and heat, enabling the generator to be closer to the end user.
- Microgrids can effectively mitigate electricity costs for their users by generating a portion or all of their electricity requirements [7].

➢ **Micro-grid Disadvantages**

- In a microgrid, it is essential to ensure and regulate voltage, frequency, and power quality parameters to meet acceptable standards, while maintaining a balance in power and energy.
- Electrical energy needs to be stored in battery banks thus requiring more space and maintenance.
- The difficulty of resynchronization with the utility grid.
- Microgrid protection is one of the most important challenges facing the implementation of Microgrids.
- Issues such as standby charges and net metering may pose obstacles for Microgrid [7]

I.5 Inverter

An inverter is an electronic device that converts direct current (DC) into alternating current (AC). Inverters are commonly used in applications where AC power is needed but the available power source is DC.

Inverters are the most common DC/AC interface proposed in the literature to transfer energy from renewable energy sources to the grid. For example, they are used for systems like photovoltaic applications, wind energy conversion systems, or fuel cell and battery associations [8].

I.5.1 Three-phase inverter

A three-phase inverter is a type of inverter that converts DC power into three-phase AC power. Three-phase AC power is commonly used in industrial and

commercial applications where high power is required for motors, pumps, and other equipment.

A three-phase inverter typically consists of six switches, with each pair of switches connected to a phase of the output AC power as depicted in Figure (I.4). The switches are controlled by electronic circuits that switch them on and off in a specific sequence to produce the desired output waveform.

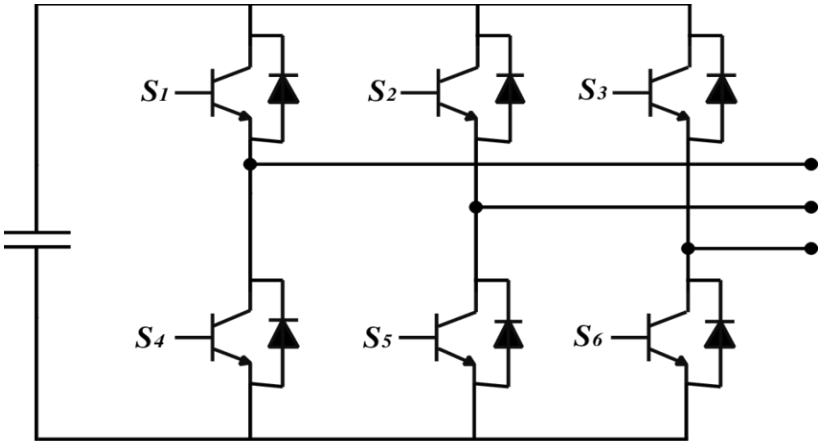


Fig I.4 Three-phase inverter circuit

The requirement for an inverter to be operated depends on the application and the nature of the power system used, in some applications where the inverter is used in an islanded or off-grid power system, a grid-forming capability may be necessary. In these systems, the inverter must establish its own voltage and frequency and operate independently of the utility grid.

I.5.2 The Significance of Parallel Inverters

Parallel-connected inverters are utilized extensively due to their advantages such as expandable output power and improved reliability. And those Power inverters can be utilized to connect resources to the network, power delivering through a single inverter may have some drawbacks including:

- Poor extensibility
- Poor reliability
- Poor flexibility and maintenance.

A parallel structure of inverters is one of the effective Solutions to overcome the aforementioned difficulties. Additionally, it helps to achieve a high-power rating as well as increase in system redundancy and reliability. However, parallel-operated.

inverters may be encountered some challenges such as the required control to achieve accurate load sharing and decline circulating current [9].

I.5.3 Grid-following inverter

Grid-following converters are widely used in micro-grids, because of their greatness when it comes to the point of controlling the micro-grid voltage and frequency. For grid-connected mode, many grid-following power converters are operated in parallel and they are controlled as current sources because they present a high parallel output impedance. In islanded mode operation, grid-feeding converters can be connected to the micro-grid if some other units are operating in grid-forming mode [10].

I.5.4 Grid-forming inverter

Grid-forming power converters are mostly connected in parallel to grid-following power converters in micro-grid, and the output of each grid-forming converter is considered to be the reference for the grid-following converter. The main purpose of those units is to form the micro-grid bus voltage and frequency. In general, grid-forming converters are controlled in a closed loop to work as an ideal ac voltage source. In this case, they present a low output impedance and an extremely accurate synchronization system is needed to be able to operate in parallel with other inverters. Thus, the power-sharing among the grid-forming converters is also a crucial function to be targeted [10].

The implementation of grid-forming systems should possess a significant energy potential. This is achieved through the utilization of droop control strategies, which involve voltage and frequency regulation. The determination of allowable output power is based on the characteristics of droop control parameters, as described in reference [7].

I.5.5 The difference between grid forming and grid following

Both grid forming and grid following have advantages and disadvantages. Grid-forming devices are more autonomous and can operate independently of the grid, which makes them useful for off-grid or isolated applications. However, they require more complex control systems and may be less stable than grid-following devices, which could cause issues during grid disturbances or unexpected events.

Grid-following devices are simpler and more reliable, and they can respond quickly to changes in the grid. They are designed to operate in parallel with the grid, so they don't require as much control as grid-forming devices. However, they rely on the stability of the grid and may not be able to operate during grid disturbances or blackouts, which could limit their usefulness in certain situations.

I.6 Strategies of control

Microgrids utilize an advanced control strategy that incorporates a hierarchical structure composed of four distinct levels of control. This hierarchical structure includes level-zero, primary, secondary, and tertiary control, as illustrated in Figure (I.5).

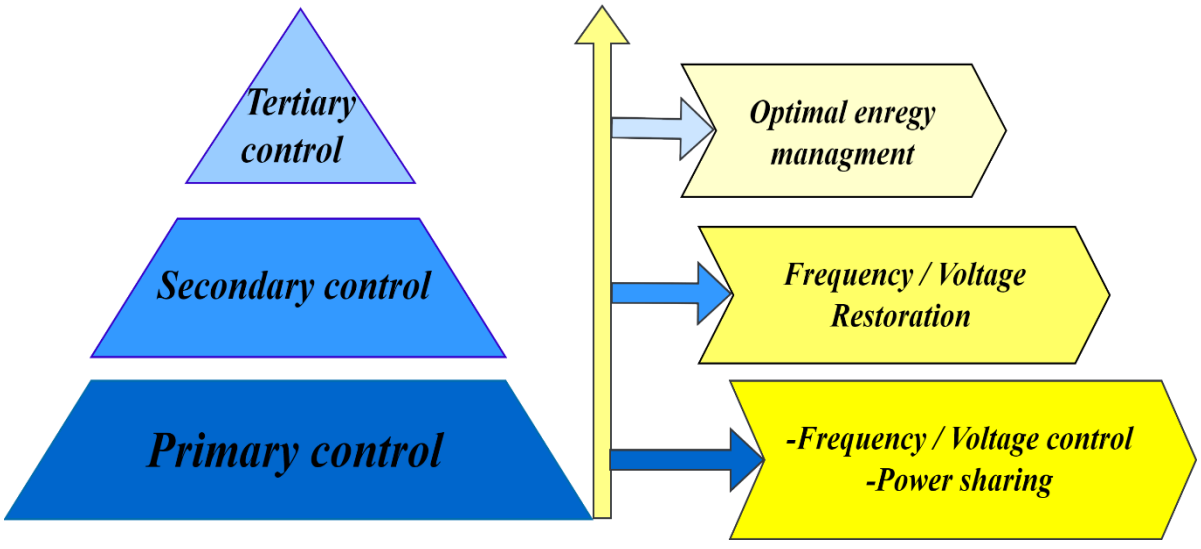


Fig.I.5 Hierarchical control strategy

I.6.1 Primary control

The primary control, also known as local control, is the lowest level in the hierarchy. Its response relies solely on local measurements, without any need for communication.

As basic level control, it has the fastest response to share the load among the paralleled dispatchable units based on their rated power. Furthermore, it has to have islanding detection capability and is also responsible for the improvement of voltage stability and for the reduction of circulating currents that may occur when the converters are connected in parallel [11].

The primary control methods for microgrids can vary depending on the specific configuration and control strategy employed. Here are a few commonly used primary control methods for microgrids.

a) Centralized Control

Micro-grid can be controlled in a centralized way. In most cases, centralized control is used for islanded micro-grid with fixed infrastructures, where the communication network and decision-making hierarchy are simple. When a centralized control is implemented, the central master controller that connects to each DG in the microgrid collects information from all DGs, then runs the voltage and frequency stability logic, and thereafter based on the results it issues appropriate primary control commands. Furthermore, in the centralized control system, the microgrid central controller (MGCC) will maintain the lookup table with updated information related to DGs status and types, generation capacity, voltage and current levels, operation mode, and demand.

The centralized control method has some drawbacks in its operation. If a master central controller fails, control commands are interrupted and not available to DGs and other microgrid assets. Second, the power system and the MG infrastructures in general are rapidly developing and new advanced configurations are needed. Therefore, it is challenging to modify the already in-place central master controller configurations and settings. Another issue, the centralized control method requires a dense communication structure and is not suitable for large-area control [10].

b) Decentralized control

The decentralized control structure consists of local controllers (LCs), MGCC, and distribution network operator (DNO). It is considered to be a possible solution for integrating as much as possible DGs in a microgrid because within this control scheme, each inverter-coupled DG is controlled freely and various service providers can own the DGs. The LC's responsibilities are much more in a decentralized control than in a centralized control method. However, the main grid manages the voltage and the frequency when the MG is operating in grid-connected mode. In such a case, the DGs are equipped with frequency droop features for sharing the active power, and voltage droop features for sharing the reactive power to the microgrid. When the MG is operating in islanded mode, one of the DGs takes responsibility to govern the microgrid's voltage and frequency.

Decentralized control can use a peer-to-peer communication network between the DGs. In this case, a secondary control layer is present at each DG to collect all measurement information from the DG which is used to produce new appropriate control commands to be sent to the primary control layer which resolves the steady-state errors in voltage and frequency. Moreover, the decentralized control with its distributed structure offers a high level of redundancy and improves the overall secondary control reliability, for example when one unit fails, it can be excluded from the network and the rest will continue to operate with adequate primary and secondary controls in place [10].

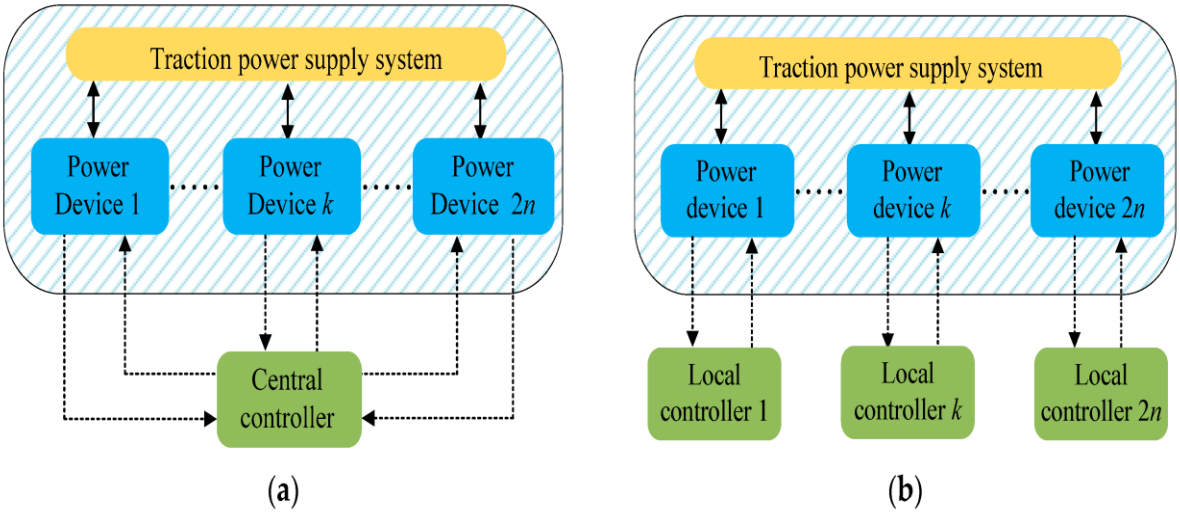


Fig I.6 (a) Centralized control model. (b) Decentralized control mode

c) Droop control

Droop control refers to a method of simulating the drooping characteristics of a traditional generator set. This control method is generally applicable to occasions where multiple communication line-free inverters are connected in parallel. The working principle is as follows: each inverter self-detects its own output power and then adjusts the same against the reference output voltage amplitude and the frequency obtained by carrying out droop control, so as to realize reasonable allocation of active power and reactive power of the system. This control method is also applicable to microgrid connections. In case of voltage and frequency changes in the grid, each distributed resource is able to adjust the output active power and reactive power automatically and participates in the regulation of grid voltage and frequency [11].

Concept of droop control

The droop control idea has been employed by the inverter parallel operations because of the power system inertia, and the frequency decreases with an increase in load. In the micro-grid operation renewable energy sources are directly connected through the power electronic elements, therefore the system inertia has been neglected. Introducing a droop control technique will imitate the inertia of the voltage source inverter within the synchronous.

When more number of Distributed Power Generation Systems (DPGSs) units are connected to parallel inverters, the power-sharing of load depends on the droop characteristics. The concept of the droop characteristics is when the load increases, then the reference frequency could be decreased [12]. Fig.I.7 shows the characteristics of droop control.

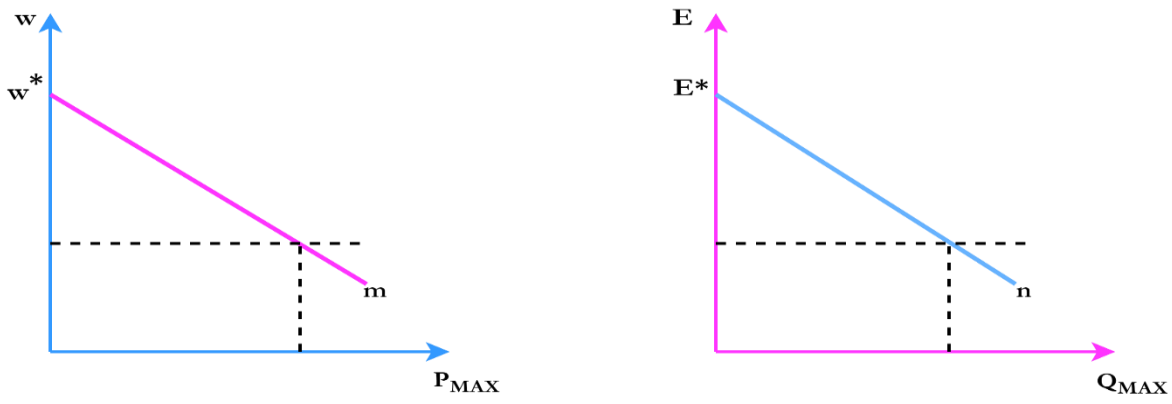


Fig I.7 *P/Q* Droop characteristic

The droop control introduces the droops in the amplitude *E* and the frequency ω of the inverter; they can be expressed as (Fig I.7)

$$W = W^* - m\,(P - P^*) \qquad E = E^* - n\,(Q - Q^*)$$

Where:

W: the angular frequency of the output voltage

W^*: the nominal frequency of the system

E: the amplitude of the output voltage

E^*: the nominal voltage of the system

m and n: coefficients that define the corresponding slopes for the frequency and amplitude, respectively

P^* and Q^*: the active and reactive power references

P and Q: the nominal active and reactive power values of the system.

Droop control is an important method used in power systems engineering to regulate the frequency of generators. However, droop control problems can arise when a power system is unbalanced, leading to over- or under-frequency conditions that may cause instability or damage to the system. Over-frequency can cause damage to the equipment, while under-frequency can lead to instability in the system. To avoid these problems, it's crucial to ensure that power systems are properly balanced and the Restoration of droop control can be added to the list of corrective actions to restore the balance of the system and stabilize the frequency and power output of the generators.

Advantages of droop control

1. Enables effective load sharing among generators or inverters.
2. Maintains system stability by preventing overpowering.
3. Scalable and flexible for easy addition or removal of units.
4. Enhances fault tolerance and system reliability.
5. Optimizes energy efficiency by operating units at efficient levels.
6. Simplifies control requirements, reducing complexity and costs.

I.6.2 Secondary control

The secondary control operates with a lower bandwidth compared to the primary control. This design choice serves two purposes: first, to decouple the two dynamics, and second, to reduce communication speed while allowing sufficient time for all calculations to be performed. The secondary control restores the voltage and frequency deviations induced by the primary control, and it also facilitates grid synchronization. [13].

Restoration

When droop control is applied, the frequency and voltage may deviate from their desired values. Therefore, frequency and voltage restoration after applying droop control is necessary.

The restoration is a process of returning a system after it has been altered or disrupted. Restoration involves adjusting the system parameters to bring the frequency and voltage back to their desired values after droop control has been applied. This entails modifying system parameters and implementing secondary control systems to restore stability and ensure consistent power output. The primary objective of restoration is to achieve the desired state of the system, even in the presence of fluctuations or disturbances.

I.6.3 Tertiary control

The last, and also the slowest level of control is the tertiary control. Indeed, its control actions take place in the range of minutes. This level performs the power regulation when the Microgrid is connected to the grid. Furthermore, the power references given to the second control can be calculated based on an optimal analysis focused on the market prices, the weather forecasting (when sources with stochastic behavior are employed, e.g., PVs), and on the agreement between the customer and the grid operator [13].

I.7 Conclusion

Throughout this chapter, we have familiarized ourselves with the concept of microgrids, various types of microgrids, methods of application, and the pivotal role played by inverters. Furthermore, we have delved into the importance of parallel inverters and their control within microgrid systems. Lastly, we have conducted a comprehensive examination of the different stages and strategies involved in the efficient management and control of microgrids.

In the upcoming chapter, our attention will shift towards the practical implementation of the cascaded loop dangling technique utilizing a PI controller. Additionally, we will explore the application of droop control within our system.

CHAPTER II

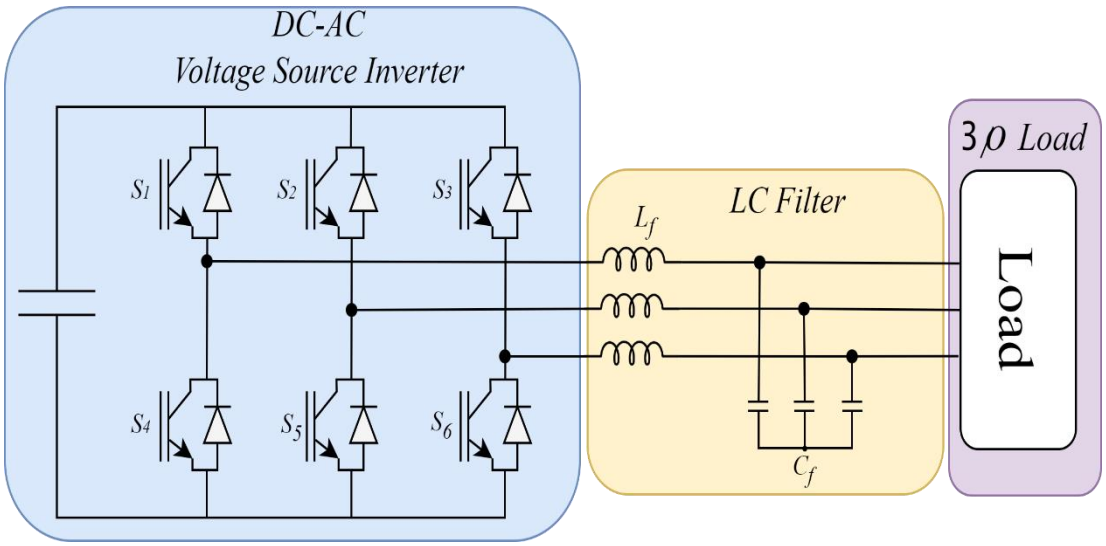
MODELLING AND CONTROL OF MICROGRIDS

II.1 Introduction

The control of microgrids holds immense significance, emploing variouse methods to ensure system stability and promote optimal power flow. Through, implementing various control mechanisms. This chapter focuses on system modeling and the application of control methods, outlining the steps involved in implementing our control techniques.

II.2 Modelling

The following model presents a three-phase inverter connected to the LC filter as shown in Figure II.1, From this model we have two parts, (Inverter and filter part) of the system each one possesses its mathematical model, which defines the relationship between the inputs and outputs for that particular part.



FigII.1 Inverter's bridge and LC filter

II.2.1 inverter's model

The primary function of this type of inverter is to convert the DC input into a three-phase AC output as depicted in Figure II.2. In a basic three-phase inverter there are three legs where each has two switches, the six switches indicated are S1, S2, S3, S4, S5, and S6. Each key is associated with a load station. The states of these switches can be either on or off. It is worth noting that any two switches in the system share a

common "leg" and cannot be simultaneously opened or closed. As illustrated in Figure II.2, let's consider the example of switches S1 and S4.

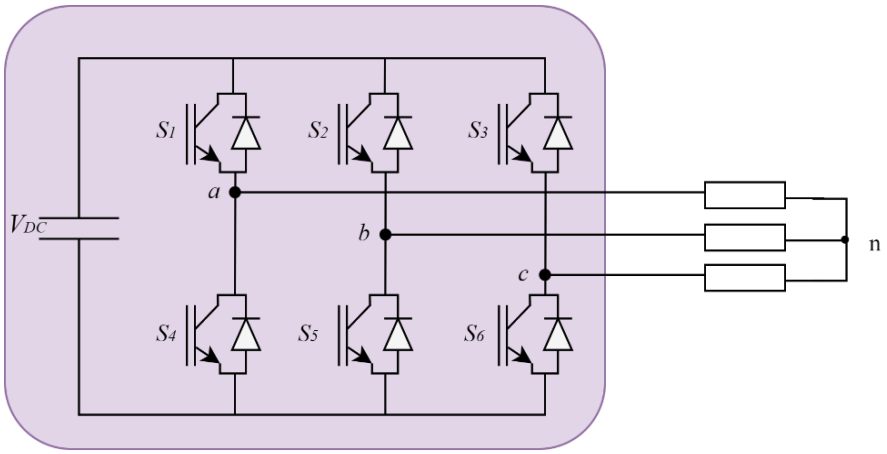


Fig II.2 Inverter's bridge

After applying Kirchhoff's laws to our system, The relationship between the phase-to-neutral voltages (V_{an}, V_{bn}, V_{cn}) and the upper switches (S_1, S_2, S_3) can be expressed by modeling the voltage inverter, where the voltage inverter can be modeled by the matrix $[T]$ ensuring the transition from continuous to alternating (DC-AC).

$$T = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \quad \text{(II.1)}$$

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = \frac{1}{3} v_{dc} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} . \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad \text{(II.2)}$$

The specific patterns of switching states are determined by the desired waveform and operation mode of the inverter. One common approach is to use pulse width modulation (PWM) techniques to control the switching states. By varying the switching states and the duration of ON and OFF periods, PWM allows for the generation of desired AC waveforms with adjustable frequency, amplitude, and harmonic content. The figure II.3 illustrates the operational principle of PWM.

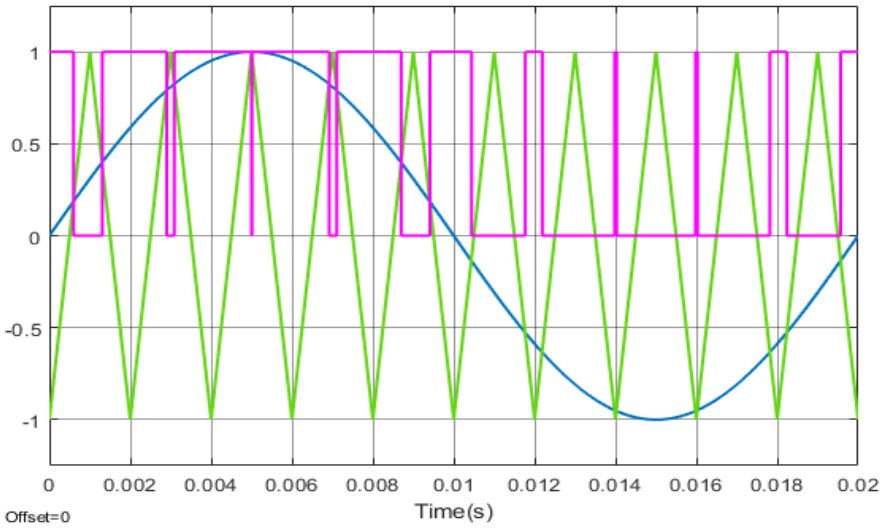


Fig II.3 Pulse width modulation

PWM switching in an inverter involves the rapid switching of power devices to convert a DC input into a high-frequency square wave. This square wave is then filtered to generate a smooth AC waveform with an adjustable magnitude, achieved through manipulation of the duty cycle of the PWM signal.

II.2.1 LC Filter Modelling

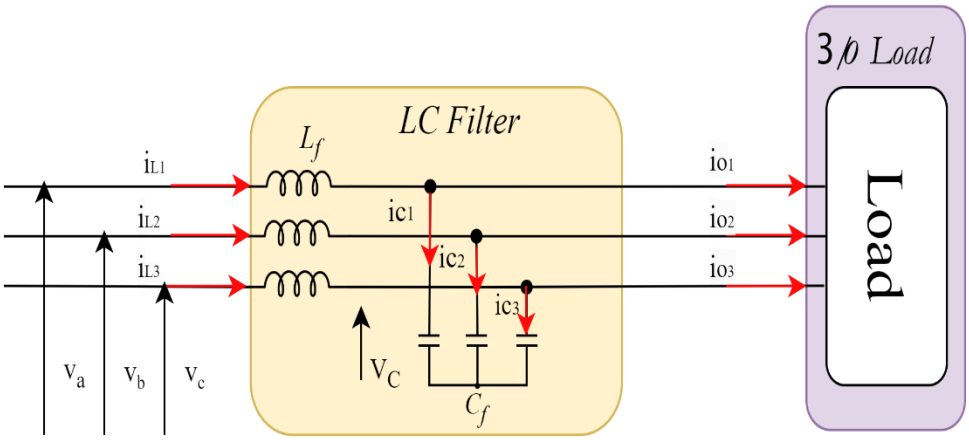


Fig II.4 *LC* filter

After Applying Kirchhoff's laws on A phase, we get:

$$v_a = v_{Lf1} + v_{C1} \quad \text{(II.3)}$$

And we know that:

$$v_{Lf} = L \frac{di_L}{dt} \quad \text{(II.4)}$$

From eq II.3 and eqII.4 we get:

$$L \frac{di_{L1}}{dt} = v_a - v_c \quad \text{(II.5)}$$

After applying the law of the nodes, we obtain:

$$i_{L1} = i_{c1} + i_{o1} \quad \text{(II.6)}$$

And we know that: $$i_{c1} = C \frac{dv_c}{dt} \quad \text{(II.7)}$$

From eqII.6 and eqII.7 we get:

$$C \frac{dv_c}{dt} = i_{L1} - i_{o1} \quad \text{(II.8)}$$

- **The current equations**

$$\begin{cases} \frac{di_{L1}}{dt} = \frac{1}{L}(v_a - v_{c1}) \\ \frac{di_{L2}}{dt} = \frac{1}{L}(v_b - v_{c2}) \\ \frac{di_{L3}}{dt} = \frac{1}{L}(v_c - v_{c3}) \end{cases} \quad \text{(II.9)}$$

- **The voltage equations**

$$\begin{cases} \frac{dV_{c1}}{dt} = \frac{1}{C}(i_{L1} - i_{o1}) \\ \frac{dV_{c2}}{dt} = \frac{1}{C}(i_{L2} - i_{o2}) \\ \frac{dV_{C3}}{dt} = \frac{1}{C}(i_{L3} - i_{o3}) \end{cases} \quad \text{(II.10)}$$

II.3 Park and Clark transformation

The Clarke-Park transformation is a mathematical transformation used in control systems to convert a three-phase coordinate system (ABC) to a two-phase rotating coordinate system (*dq*).

- The Clarke transformation converts the three-phase ABC quantities to the αβ stationary coordinate system.
- Park Transformation: After obtaining the αβ components, the Park transformation rotates these quantities to the *dq* rotating coordinate system. The rotation angle θ, is usually derived from the phase-locked loop (PLL) or other synchronization methods. The *dq* components represent the active (*d*-axis) and reactive (*q*-axis) power components of the microgrid.

This transformation converts vectors in the balanced two-phase orthogonal stationary system into orthogonal rotating reference frame. The three reference frames considered in this implementation are:

1. Three-phase reference frame, in which a, b, and c are co-planar three-phase quantities at an angle of 120 degrees to each other.

2. Orthogonal stationary reference frame, in which α (along α axis) and β (along β axis) are perpendicular to each other, but in the same plane as the three-phase reference frame.

3. Orthogonal rotating reference frame, in which *d* is at an angle θ (rotation angle) to α axis and *q* is perpendicular to *d* along the *q* axis.

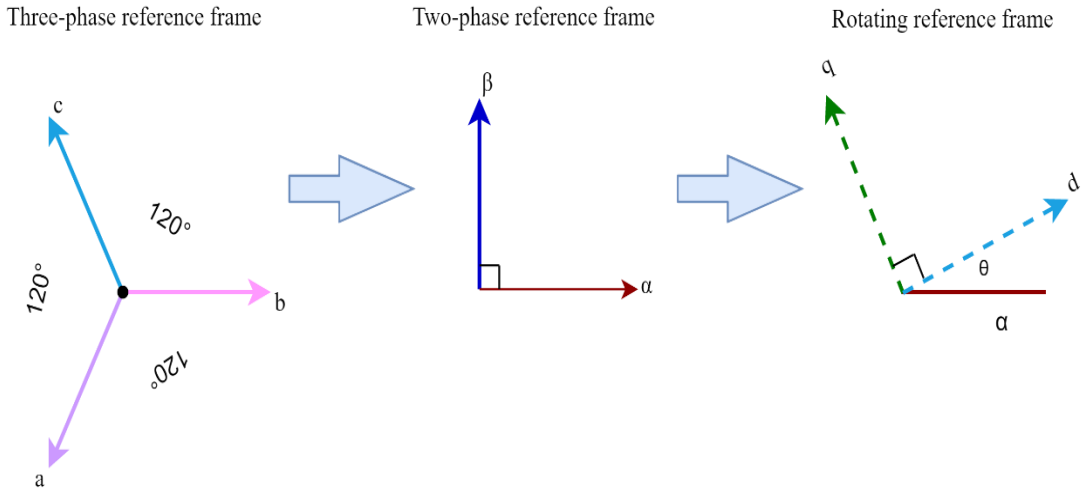


Fig II.5 Reference frames

II.3.1 Application in our system

We apply the transformation of Park by using the matrix *P*

$$P = \sqrt{\frac{2}{3}}\begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin\theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{bmatrix} \quad \text{(II.11)}$$

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = P\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \; ; \; \begin{bmatrix} v_{cd} \\ v_{cq} \end{bmatrix} = P\begin{bmatrix} v_{c1} \\ v_{c2} \\ v_{c3} \end{bmatrix} \quad \text{(II.12)}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = P\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \; ; \; \begin{bmatrix} i_d \\ i_q \end{bmatrix} = P\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad \text{(II.13)}$$

Current and voltage equations of the output *LC* filter are obtained in a synchronous *dq* reference frame after Park's transformation. According to Figure II.4, the state equation of the system can be defined as

From eqII.9 the current equation is rewritten as:

$$\begin{pmatrix} \frac{di_{Ld}}{dt} \\ \frac{di_{Lq}}{dt} \end{pmatrix} = \begin{bmatrix} 0 & -w \\ w & 0 \end{bmatrix}\begin{pmatrix} i_{Ld} \\ i_{Lq} \end{pmatrix} + \frac{1}{L_f}\begin{pmatrix} v_d - v_{cd} \\ v_q - v_{cq} \end{pmatrix} \quad \text{(II.14)}$$

$$\begin{cases} \frac{di_{Ld}}{dt} = -\omega i_{Lq} + \frac{1}{L_f}v_d - \frac{1}{L_f}v_{cd} \\ \frac{di_{Lq}}{dt} = \omega i_{Ld} + \frac{1}{L_f}v_q - \frac{1}{L_f}v_{cq} \end{cases} \quad \text{(II.15)}$$

From eqII.10 the voltage equation is rewritten as:

$$\begin{pmatrix} \frac{dVc_d}{dt} \\ \frac{dVc_q}{dt} \end{pmatrix} = \begin{bmatrix} 0 & -w \\ w & 0 \end{bmatrix}\begin{pmatrix} v_{cd} \\ v_{cq} \end{pmatrix} + \frac{1}{C_f}\begin{pmatrix} i_{Ld} - i_{od} \\ i_{Lq} - i_{oq} \end{pmatrix} \quad \text{(II.16)}$$

$$\begin{cases} \frac{dVc_d}{dt} = -\omega v_{cq} + \frac{1}{C_f}i_{Ld} - \frac{1}{C_f}i_{od} \\ \frac{dVc_q}{dt} = \omega v_{cd} + \frac{1}{C_f}i_{Lq} - \frac{1}{C_f}i_{oq} \end{cases} \quad \text{(II.17)}$$

II.4 PID controller

PID controllers have become widely used in industrial control applications due to their features like simple mathematical modeling, easy to operate, good robustness, high reliability, stabilization, and eliminating steady-state error. It consists of three terms P, I, and D, where the 'P' corresponds to the proportional term, 'I' for the integral term, and 'D' for the term derived from the command. A PID controller is an instrument widely used in industrial control applications.

To adapt and optimize the performance of a controller, the coefficients should be adjusted which are:

K_p: for proportional action.

K_i: for integral action.

K_d: for derivative action.

For our work, we use a PI (Proportional-Integral) as shown in Figuer II.6

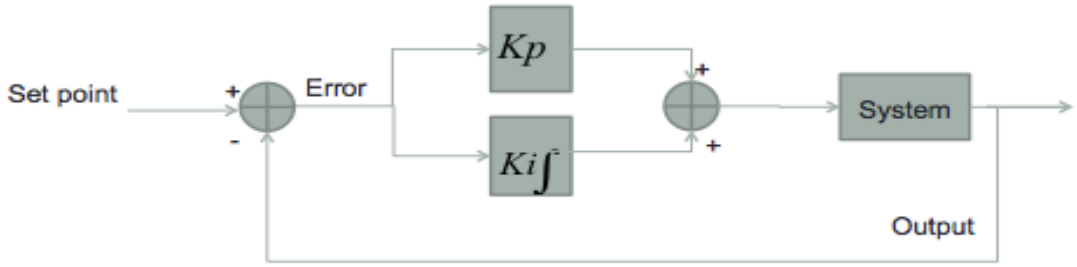


Fig II.6 PI controller structure

From the figure, the equation of the pi controller is as follows:

$$y(t) = k_P e(t) + k_i \int_0^t e(t)\, dt \qquad \text{(II.18)}$$

Tuning a controller involves employing various methods that have been developed to accommodate different control systems and performance requirements.

tuning include:

• Trial & error tuning method

• Pole placement tuning method

• Ziegler-Nichols tuning method

• Cohen-Coon tuning method

• PID Tuning Software Methods (MATLAB)

II.5 Cascade PI control

Cascade control is feedback combining method where the inner loop controller derives its set point from the outer-loop control. This control system involves two controllers, with the output of one controller serving as the input of the other. By utilizing the secondary loop alongside the primary controller, it enhances the control of the primary process variable, resulting in improved overall control performance. [14].

- **Current loop**

We equalize equation (II.9) with the controller PI to obtain the current loop as follows:

$$\begin{cases} \frac{di_{Ld}}{dt} = -\omega i_{Lq} + \frac{1}{L_f} v_d - \frac{1}{L_f} v_{cd} = k_P e_{id}(t) + k_i \int_0^t e_{id}(t)\, dt \\ \frac{di_{Lq}}{dt} = \omega i_{Ld} + \frac{1}{L_f} v_q - \frac{1}{L_f} v_{cq} = k_P e_{iq}(t) + k_i \int_0^t e_{iq}(t)\, dt \end{cases} \quad \text{(II.19)}$$

Where $e_{id} = i_{Ld}^* - i_{Ld}$ and $e_{iq} = i_{Lq}^* - i_{Lq}$

$$\begin{cases} v_d^* = k_{P_i} e_{id}(t) + k_{i_i} \int_0^t e_{id}(t)\, dt + \omega L_f i_{Lq} + v_{cd} \\ v_q^* = k_{P_i} e_{iq}(t) + k_{i_i} \int_0^t e_{iq}(t)\, dt - \omega L_f i_{Ld} + v_{cq} \end{cases} \quad \text{(II.20)}$$

- **Voltage loop**

From eq (II.10) we got the voltage loop as follows:

$$\begin{cases} \frac{dVc_d}{dt} = -\omega v_{cq} + \frac{1}{C_f} i_{Ld} - \frac{1}{C_f} i_{od} = k_P e_{vd}(t) + k_i \int_0^t e_{vd}(t)\, dt \\ \frac{dVc_q}{dt} = \omega v_{cd} + \frac{1}{C_f} i_{Lq} - \frac{1}{C_f} i_{oq} = k_P e_{vq}(t) + k_i \int_0^t e_{vq}(t)\, dt \end{cases} \quad \text{(II.21)}$$

Where $e_{vd} = V_{cd}^* - V_{cd}$ and $e_{vq} = V_{cq}^* - V_{cq}$

$$\begin{cases} i_{Ld}^* = k_{P_v} e_{vd}(t) + k_{i_v} \int_0^t e_{vd}(t)\, dt + \omega C_f v_{cq} + i_{od} \\ i_{Lq}^* = k_{P_v} e_{vq}(t) + k_{i_v} \int_0^t e_{vq}(t)\, dt - \omega C_f v_{cd} + i_{oq} \end{cases} \quad \text{(II.22)}$$

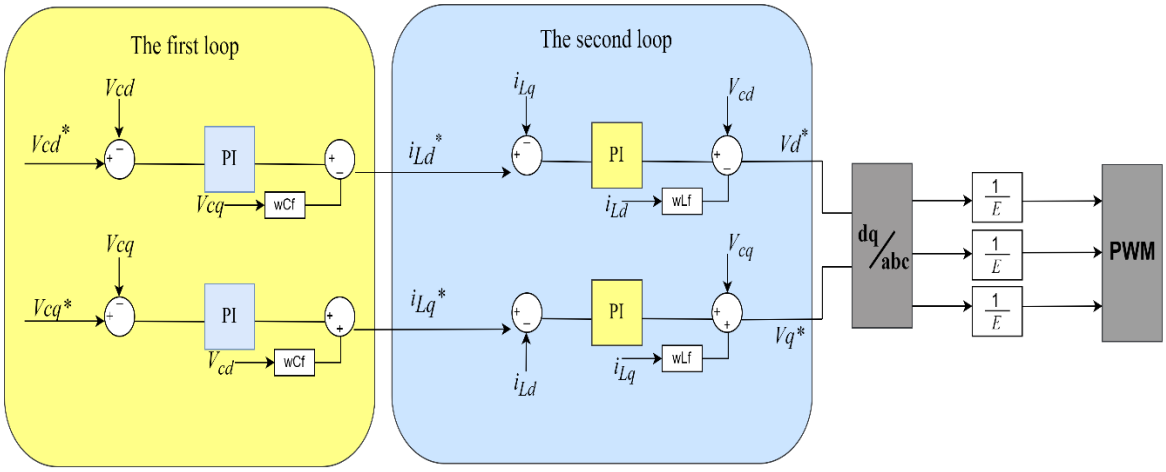


Fig II.7 Cascade PI control loop

As figure II.6 shows the application of the successive loop, as the main loop is the control loop of the current where we apply its outputs to the second loop to obtain the optimal voltage, then we convert it from *abc* to *dq*, then the voltage refence inserted to the PWM to obtain the switching states.

II.6 Droop control

We applied the droop control on our system where the principle of the droop can be described as follows:

a) Principle of work

Each inverter in droop control self-detects its output power and adjusts it based on the reference output voltage amplitude and frequency obtained through droop control. This process enables the equitable allocation of active power and reactive power within the system by utilizing frequency and voltage as control parameters, droop control ensures that each inverter adjusts its power output to maintain system stability and proportional power sharing.

- **frequency equation**

$$\omega = \omega^* - m\,(P - P^*) \qquad \text{(II.23)}$$

We can say that the frequency is related to the active power where if the frequency decreases below the nominal value, the active power output increases; and if the frequency increases above the nominal value, the active power output decreases.

- The voltage equation

$$E = E^* - n\,(Q - Q^*) \qquad \text{(II.24)}$$

From the voltage equation, we can say the same thing the Voltage and the reactive power are related.

The droop gains ***m*** and ***n*** are calculated based on the changes in the specified frequency and voltage and the rated power as:

$$m = \frac{\Delta\omega}{\Delta p} \qquad \text{(II.25)}$$

$$n = \frac{\Delta E}{\Delta Q} \qquad \text{(II.26)}$$

We have applied the droop control in two closed-loop on our system the first is the frequency regulation and the second is the voltage regulation as shown in Figure II.7

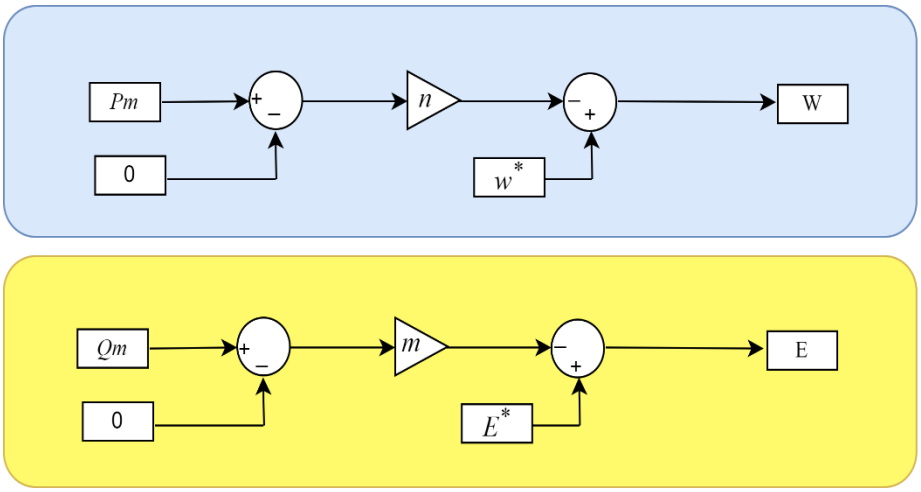


Fig II.8 Droop control regulation loop

II.7 Frequency and voltage restoration

The presented figure II.9 showcases the frequency effect following the implementation of droop control and subsequent restoration processes by examining the graph, one can gain insights into the impact of applying droop control and subsequent restoration measures on the overall stability of the frequency in the system.

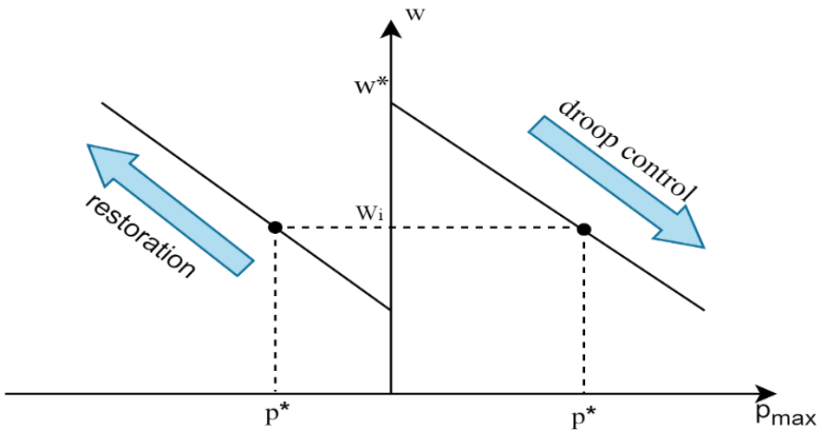


Fig II.9 Frequency regulation

Where:

P:* the nominal active power value

P_{max}*:* the maximum value of the active power

W:* the nominal frequency

Wi: frequency drop

The droop control presents weak performance due to the deviations in frequency and voltage caused by the loads, we can restore the frequency and voltage to their nominal values, by applying a locked loop using a PI controller.

- The Frequency voltage restoration loop:

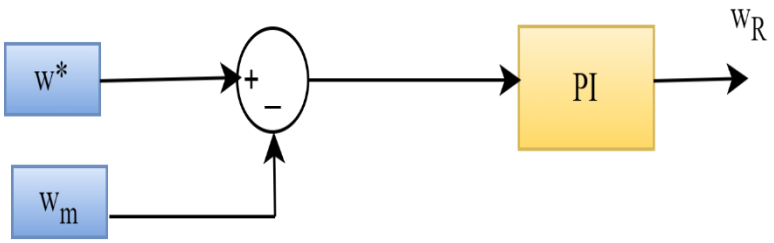


Fig II.10 Frequency restoration loop

Where:

W:* nominal angular frequency

W_m*:* measured angular frequency

W_R*:* optimal angular frequency

- The voltage restoration loop :

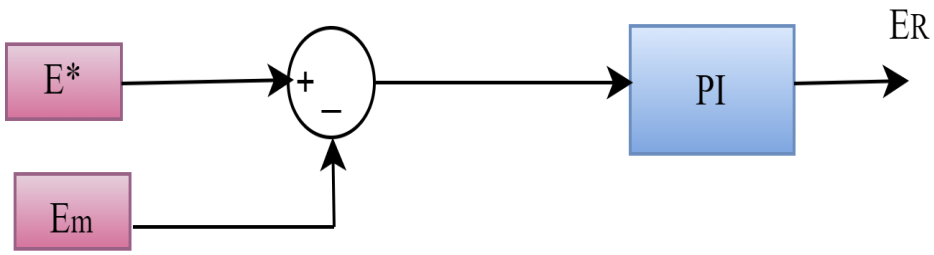


Fig II.11 Voltage restoration loop

Where:

E:* nominal voltage

E_m*:* measured voltage

E_R*:* optimal voltage

II.8 Conclusion

In this chapter, we explored the modeling of our system, consisting of an inverter bridge and an LC filter. We discussed the primary control, which utilizes a cascade loop incorporating a PI controller and droop control to regulate the output. Additionally, we delved into the secondary control, emphasizing the restoration of frequency and voltage values.

The upcoming chapter will delve deeper into the application of control techniques specific to our system. Furthermore, we will showcase the simulation results obtained, providing valuable insights into the performance and effectiveness of our control approach.

CHAPTER III

RESULTS AND DISCUSSION

III.1 Introduction

This chapter focuses on designing a small MG scale using two parallel inverters. We will compare the results of two different MG structures: Forming-Forming and Forming-Following. In the Forming-Forming structure, both inverters operate independently, while in the Forming-Following structure, one inverter acts as the master, and the other follows its references. We will analyze the performance of these structures in terms of power quality and system efficiency. Finally, will present the simulation results to evaluate voltage and frequency regulation, power sharing, and response to load variations.

III.2 Forming DG control

The control levels for a forming DG unit can be outlined as follows, the primary control initiates frequency and voltage regulation, while the droop control operates in tandem, facilitating load sharing among multiple DG units. The full structure of the system is depicted in figure III.1.

The secondary control comes into play for the restoration of frequency and voltage, where ***m*** and ***n*** are calculated as follows:

$$m = \frac{\omega_{max} - \omega_{min}}{P_{max} - P_{min}} \quad \text{(III.1)}$$

$$n = \frac{E_{max} - E_{min}}{Q_{max} - Q_{min}} \quad \text{(III.2)}$$

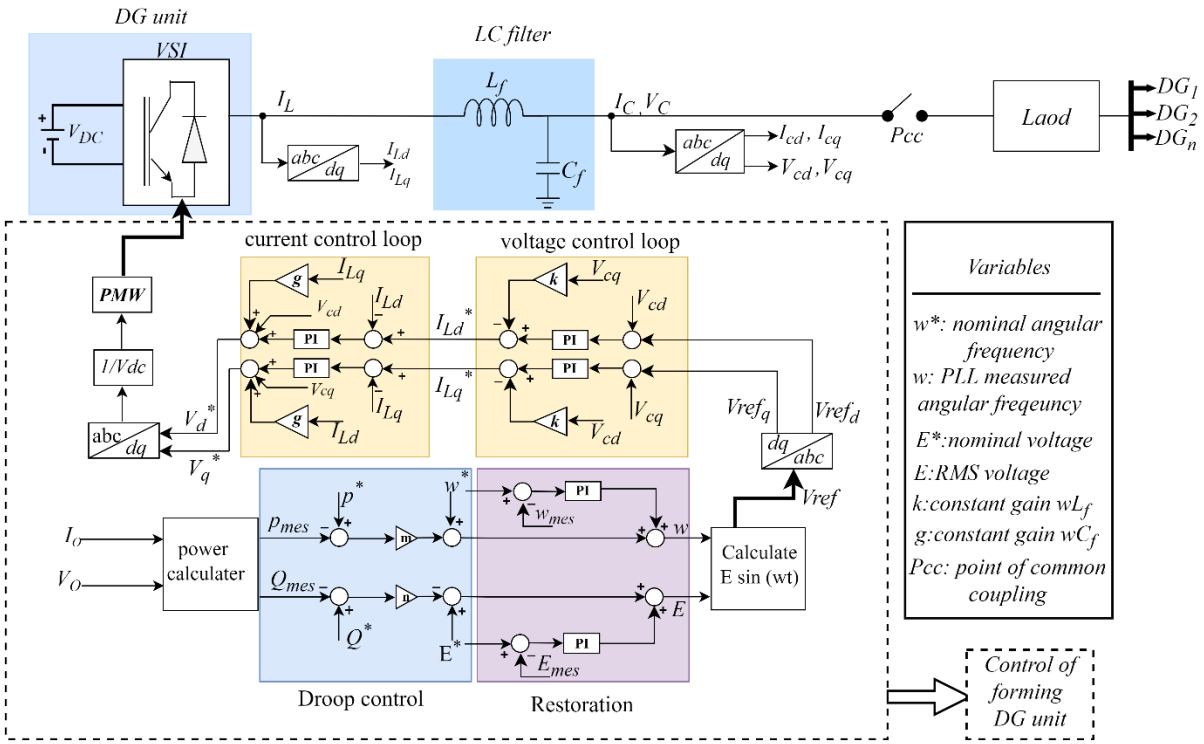


Fig III.1 Control levels for forming DG unit.

III.3 Following DG control

The voltage of the following inverter is synchronized with the main inverter's voltage. However, to control the current, a current loop is implemented using a PI controller. This current loop enables precise regulation of the current output. By decoupling the current control from the main inverter's voltage, independent control of the current is achieved while maintaining synchronization with the main inverter's voltage.

To determine the current reference amplitudeI^*, we can impose a percentage value of power that the slave inverter should create, the I^* can be calculated using the following equation:

$$I^* = \frac{P_L}{3}\% \frac{\sqrt{2}}{V_{nom}} \qquad \text{(III.3)}$$

Figure III.2 shows the control of the slave inverter, we use a current control loop using a PI controller. By regulating the current, the slave inverter can then fix the optimal voltage to control the pulse width modulation PWM.

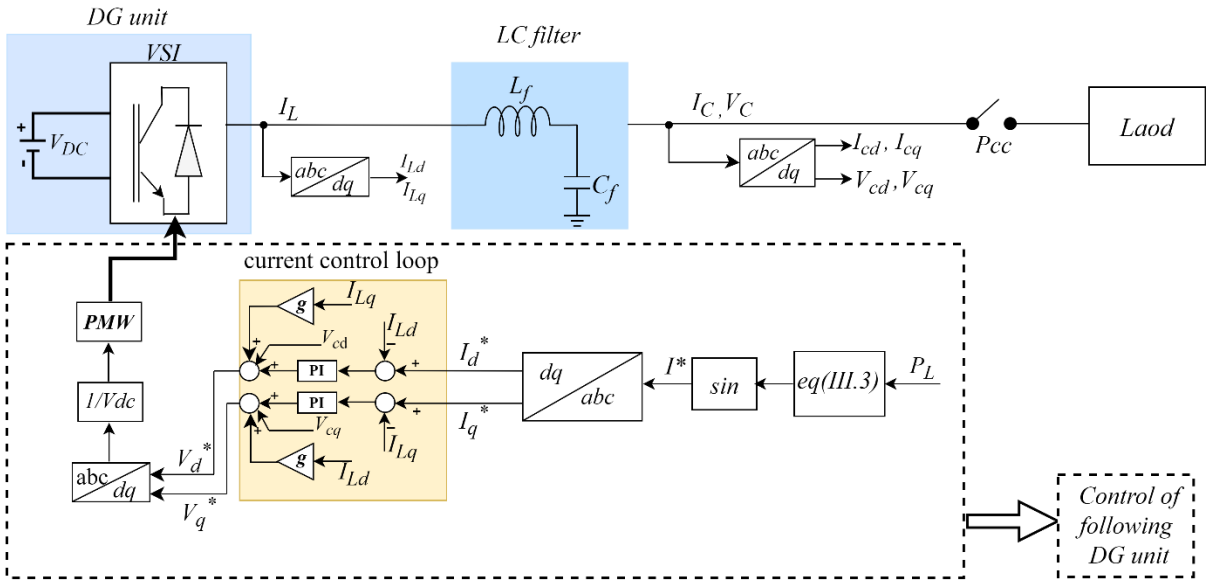


Fig III.2 Control of following DG unit.

III.3 Simulation results

The simulations were conducted using MATLAB/Simulink (version R2021b) using the simulation solver ode8. Table III.1 illustrates the parameters employed in the simulation:

Table III.1 Simulation parameters

DC voltage	$V_{DC} = 1000V$
Inductor	$L_F = 10mH$
Capacitor	$C_F = 50\mu F$
Resistor	$R_F = 0.1\Omega$
Nominal phase-to-phase voltage	$V_{nom} = 220\sqrt{3}$
Nominal frequency	$F = 50\ Hz$
Switching frequency	$f_s = 10KHz$
The droop gain m	$m=0.001$
The droop gain n	$n=0.033$

III.3.1 Forming-forming micro-grid

We have implemented a forming-forming method with two inverters and three different loads. Figure III.3 illustrates the structure of our system.

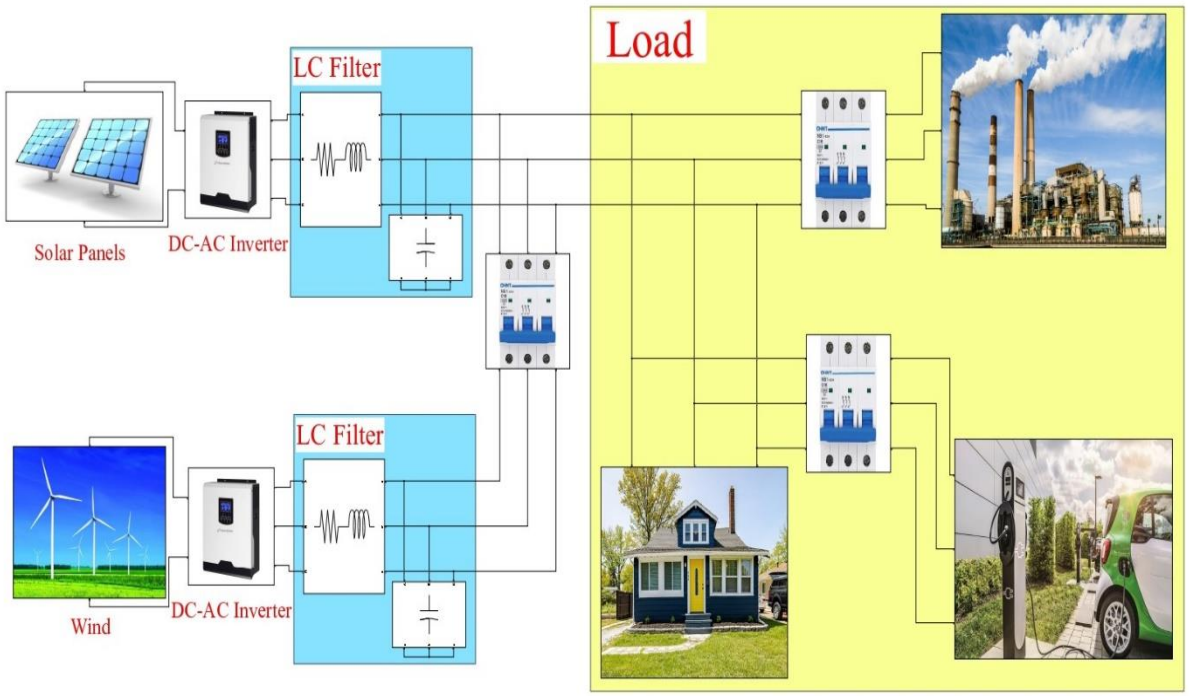


Fig III.3 Forming-Forming block diagram

As we can see from figure III.3, three different loads are implemented, where the first load starts at the beginning of the simulation, the second one is introduced at $t = 0.5s$, and the third load is connected at $t = 1s$, each load is characterized by specific parameters, which are represented in table III.2.

Table III.2 Load parameters

Load 1 active power	*2KW*
Load 2 active power	*1KW*
Load 3 active power	*1KW*
Load 1 reactive power	*0 VAR*
Load 2 reactive power	500VAR
Load 3 reactive power	300VAR

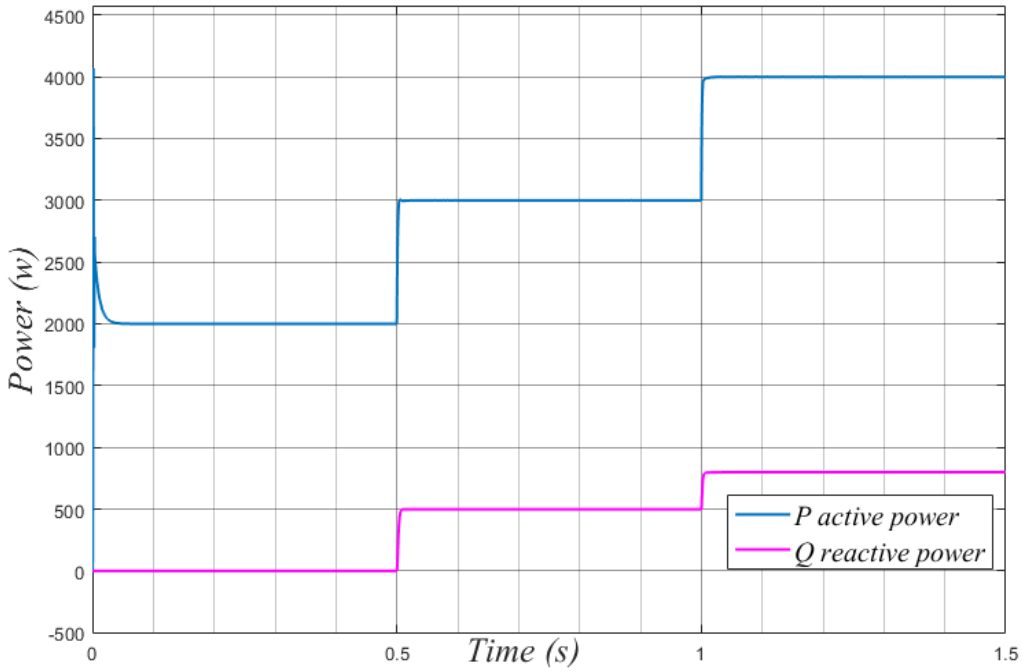


Fig III.4 Active and reactive power of three loads

Figure III.4 shows that our control is performing well, with each load receiving the required amount of active and reactive power.

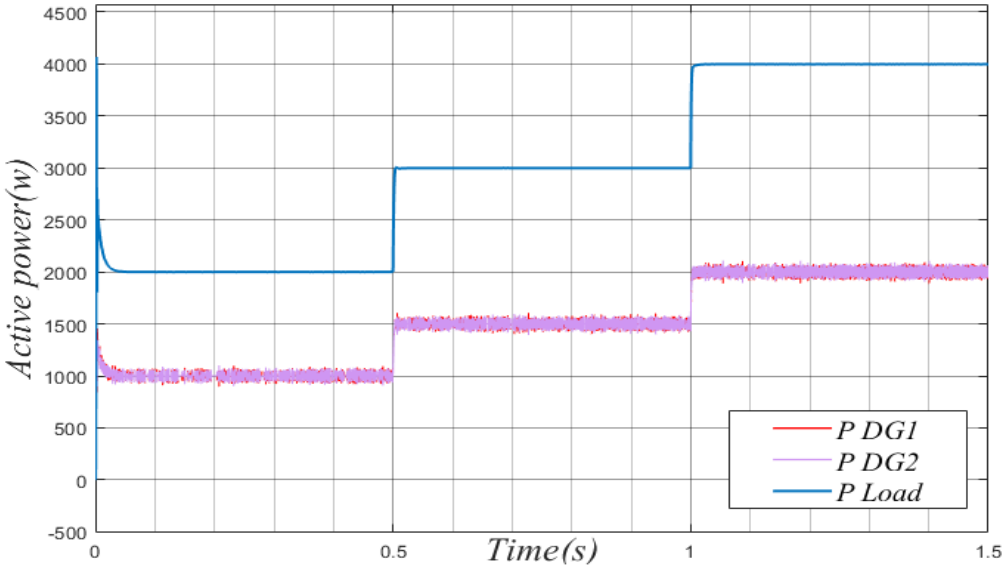


Fig III.5 Active power of two DG and three loads

The two forming inverters are working together, they evenly distribute the required energy production between them, where figure III.5 shows that the first DG produces 1kw while the second DG generate also1kw to supply the load demand, at

$t = 0.5s$ the second load is introduced, we can see that the two DG's raise their power production and equally share the load demand, The same scenario is happening when we introduce the third load at $t = 1s$.

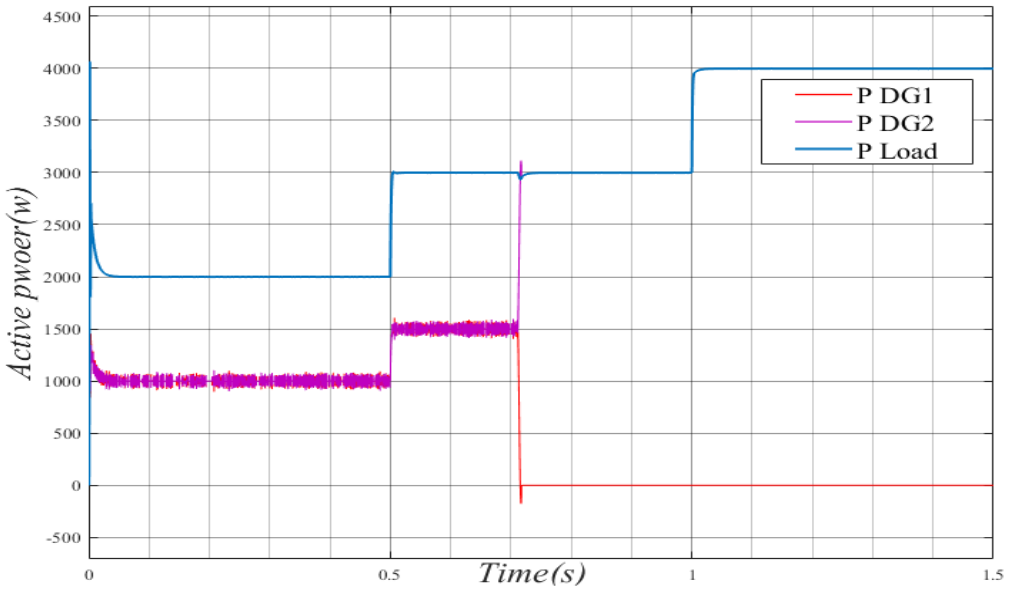


Fig III.6 The Impact of shutting down one DG inverter

To further investigate the robustness of our micro gird, we shut down one DG to see how the system will behave, at $t = 0.7s$ the lower DG is disconnected from the grid. It can be sees that tunning off one of the inverters the dose not impact the power circulating on the loads and that's because the working DG take place and generate all the required power of the load.

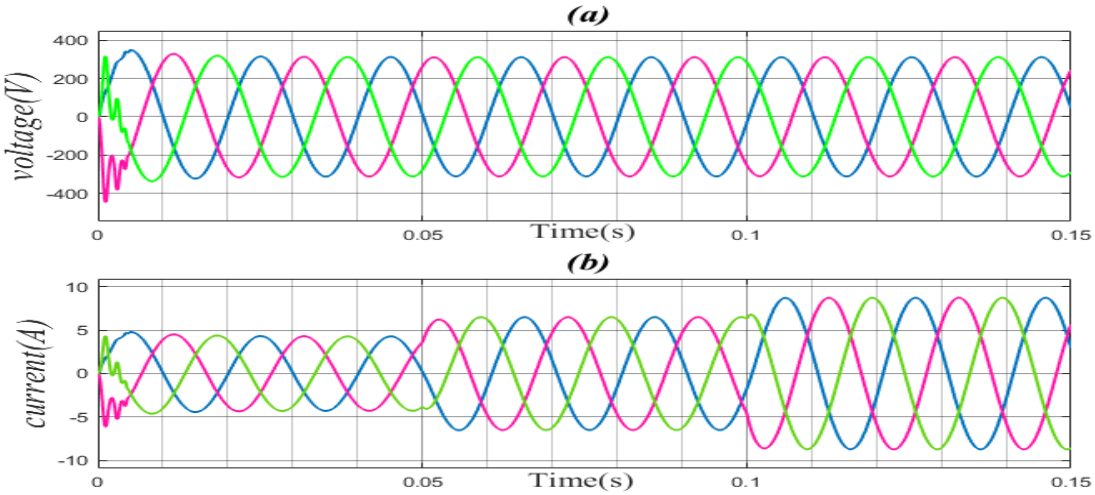


Fig III.7 (a) Load voltage, (b) Load current.

By observing Figure III.7, it becomes evident that an increase of the load consumption at t=0.5s and then at t=1s results in a corresponding increase in the current without any impact on the load voltage.

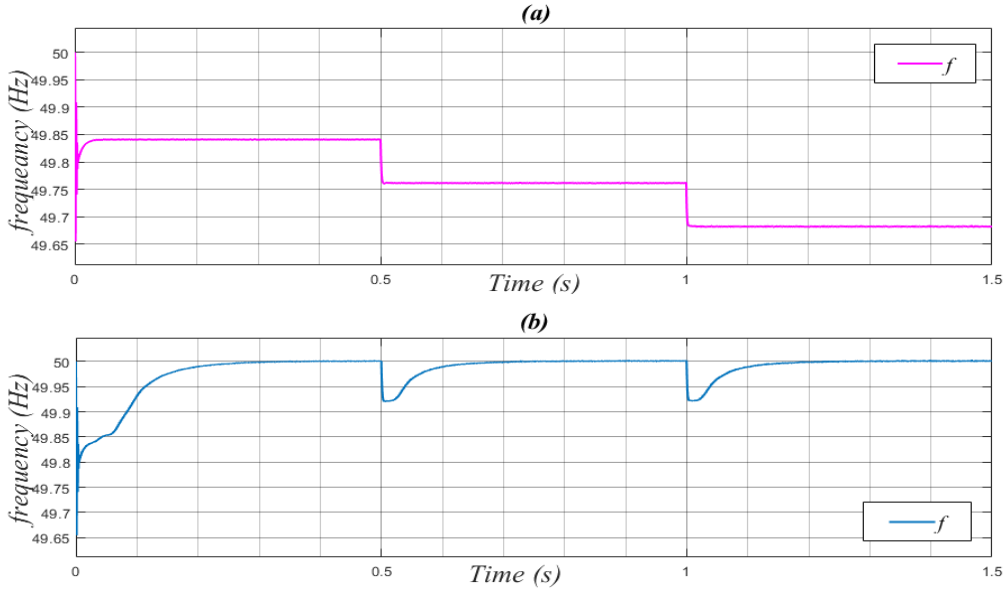


Fig III.8 Frequency (a) without restoration. (b) with restoration

Figure III.8 (a) shows the frequency. We see that the increase of the load consumption cause the frequency drop. However, when the restoration is introduced the frequency is steered back to its reference as it depicted in figure III.8(b).

The FFT analysis of the load voltage is presented in the figure. III.9. The load voltage THD is 2.69%.

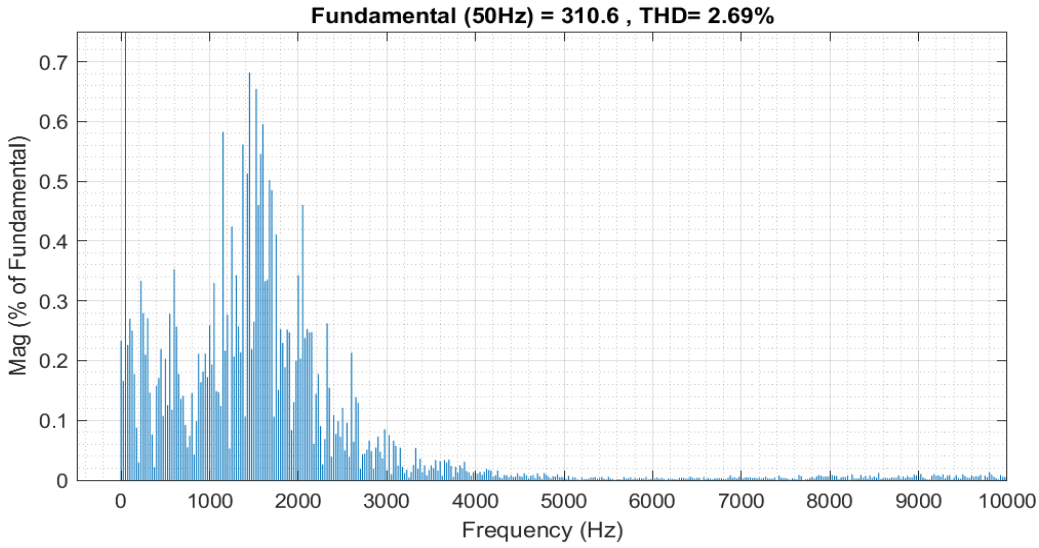


Fig III.9 THD of the load voltage for Forming-Forming structure.

III.3.2 Forming-following micro-grid (master/slave)

We have implemented a forming-following method by using a master inverter, two slave inverters, and three different loads, where the master inverter sets the output, and the slave inverters follow it, the figure III.10 illustrates the structure of the system.

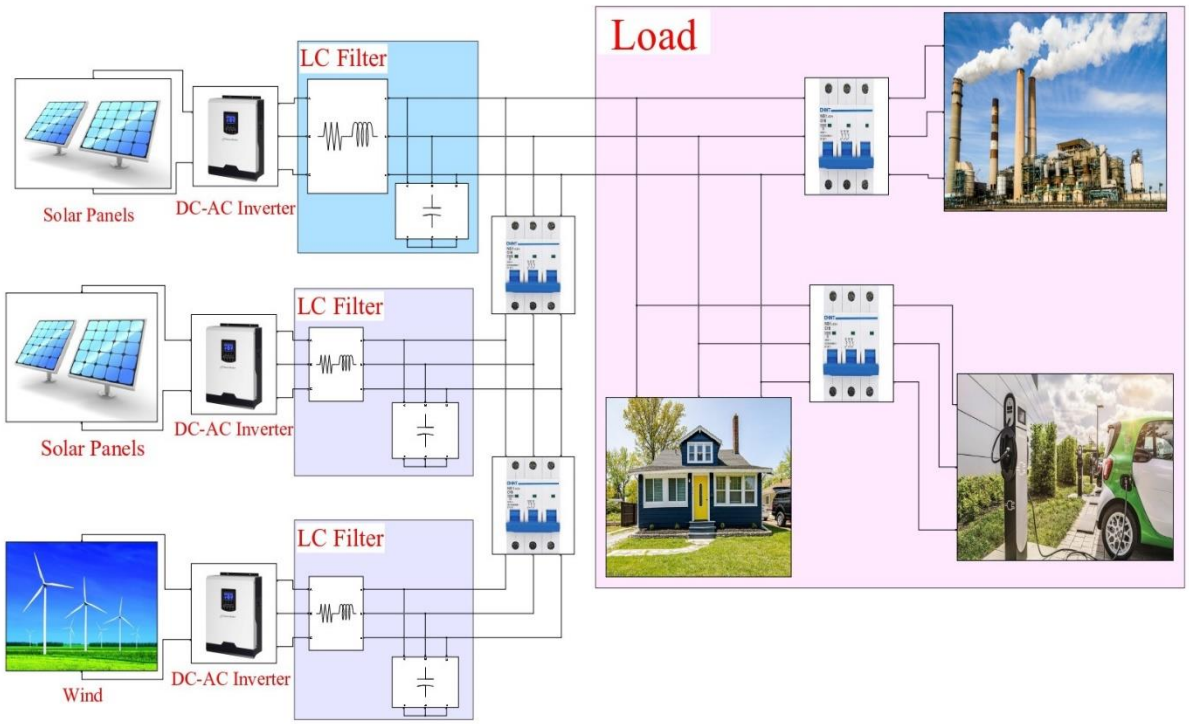


Fig III.10 Forming-Following block diagram

Our system consists of three inverters, as illustrated in the figure III.10. The first inverter acts as the master, while the other two serve as slaves. The power distribution is as follows: the second inverter generates 30% of the total power output, the third slave inverter contributes 20%, and the remaining power demand is fulfilled by the master DG. Moreover, the system incorporates three distinct loads. The first load becomes active at the system's initiation, the second load engages at t=0.5s, and the third load is activated at t=1s.

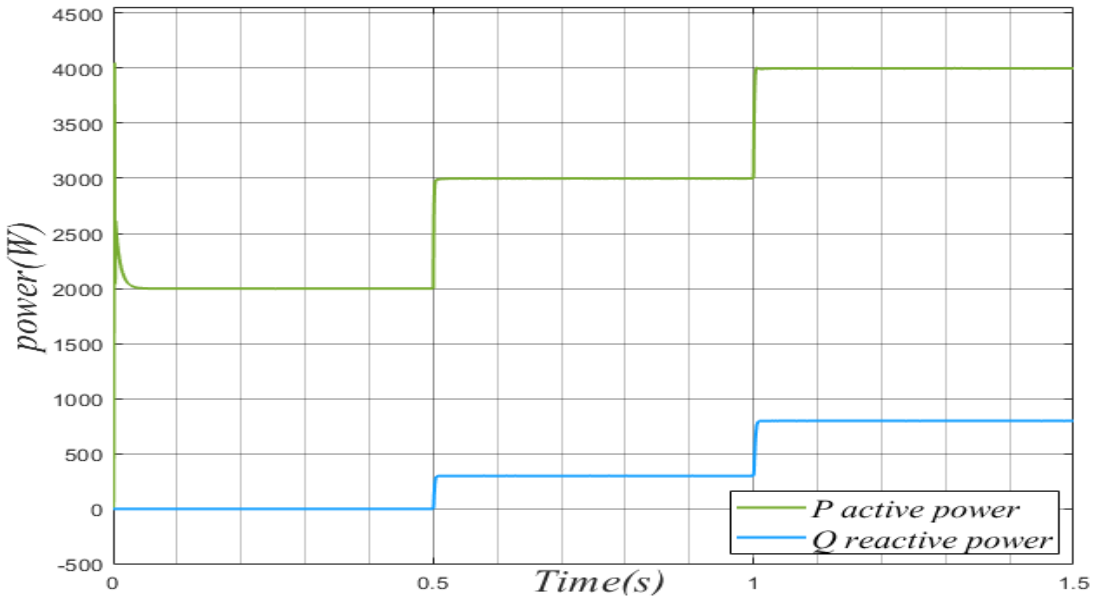


Fig III.111 Active and reactive power

Based on Figure III.11, it is evident that our system is operating optimally, effectively meeting the power demands of our load. The power allocation is precisely tailored to match the load's requirements, demonstrating successful synchronization between our system and the load.

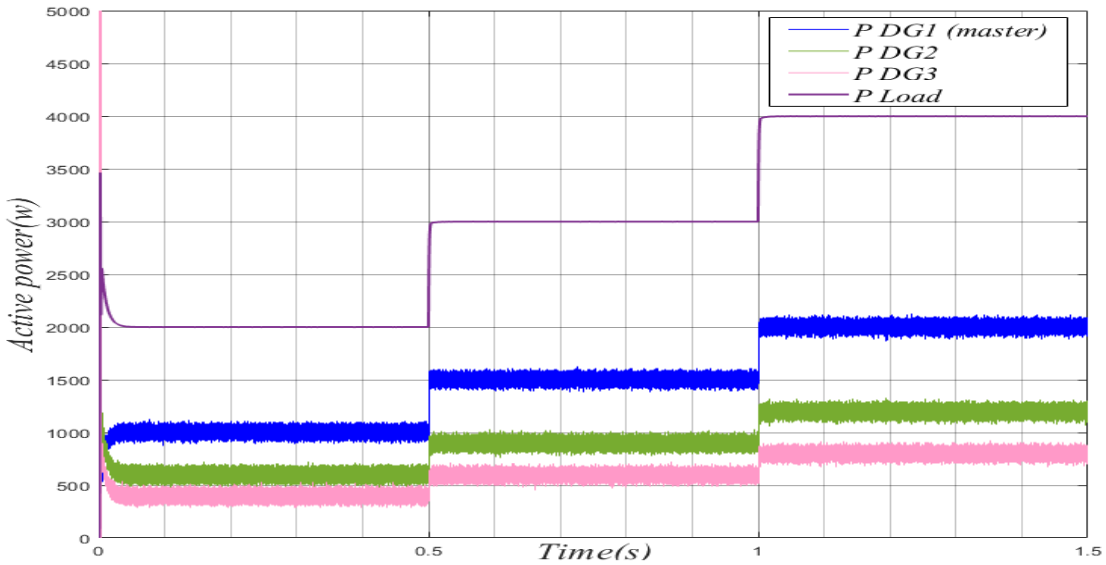


Fig III.12 Load active power DG's

In Figure III.12, the active power of the load and the three DG are depicted. It is evident that the load receives the required power, while the first slave inverter produces 400W, equivalent to 20% of the total power. The second slave inverter generates 600W, representing 30% of the total power. The master inverter generates

the remaining power to fulfill the load's requirements which represent 50% of the total power.

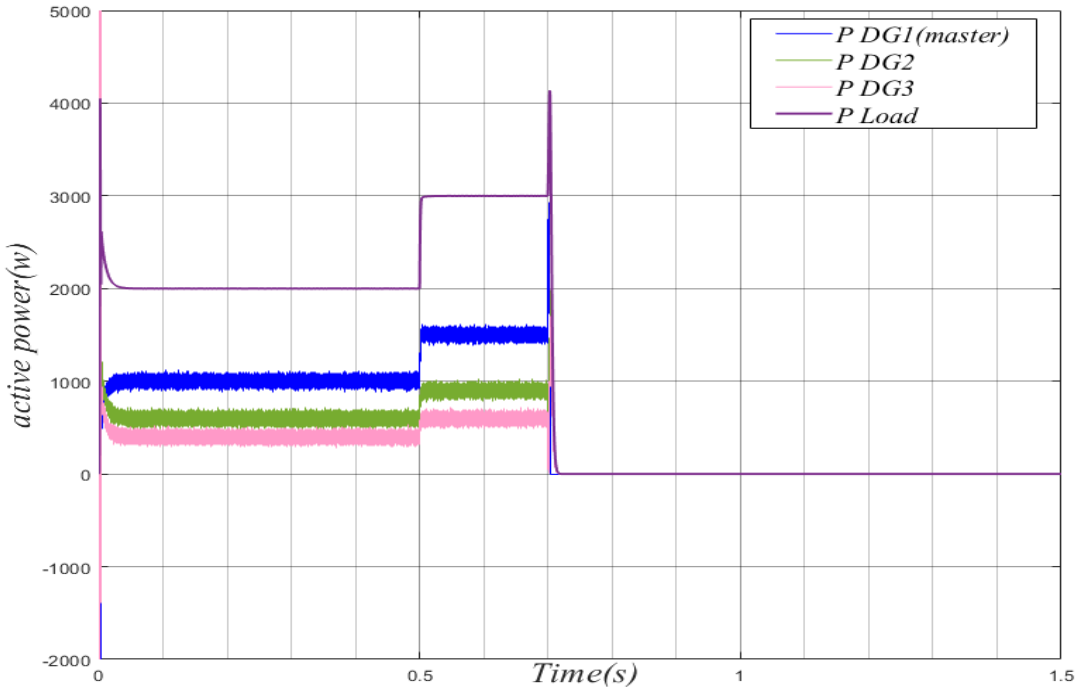


Fig III.13 Effects of the master inverter shutdown

To test the system when the master DG failure, we conducted an experiment where we intentionally turned off the master inverter at t=0.7s. In Figure III.13, it is evident that the entire system encountered a failure when the master inverter was halted. This outcome can be attributed to the interdependence between the slave inverters and the master inverter. As a result, when the master inverter ceases operation, all of the slave inverters also stop functioning, leading to a system crash.

In the second test, we conducted an experiment to assess the impact of turning off the slave inverters. Specifically, we switched off the first slave inverter at t=0.7s and the second slave inverter at t=1.2s. Our objective was to observe the effect on the active power. Figure III.14 illustrates the results.

Upon turning off the first slave inverter at t=0.7s, it is notable that the second slave inverter maintains its active power at 30%. Meanwhile, the master inverter compensates for the power deficit caused by the deactivated first slave inverter by increasing its output. Consequently, the master inverter ensures that the required power for the load is maintained.

Subsequently, when both slave inverters are turned off at t=1.2s, the master inverter takes full responsibility for generating the entire power necessary for the load. This outcome demonstrates the adaptive behavior of the master inverter in response to the changes in the system configuration.

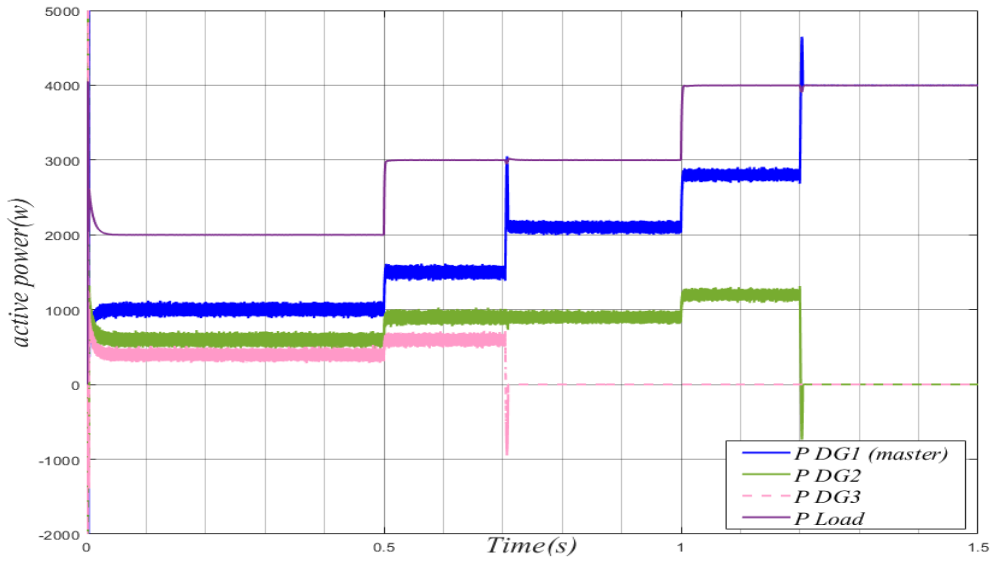


Fig III.14 Effects of the slave inverters shutdown

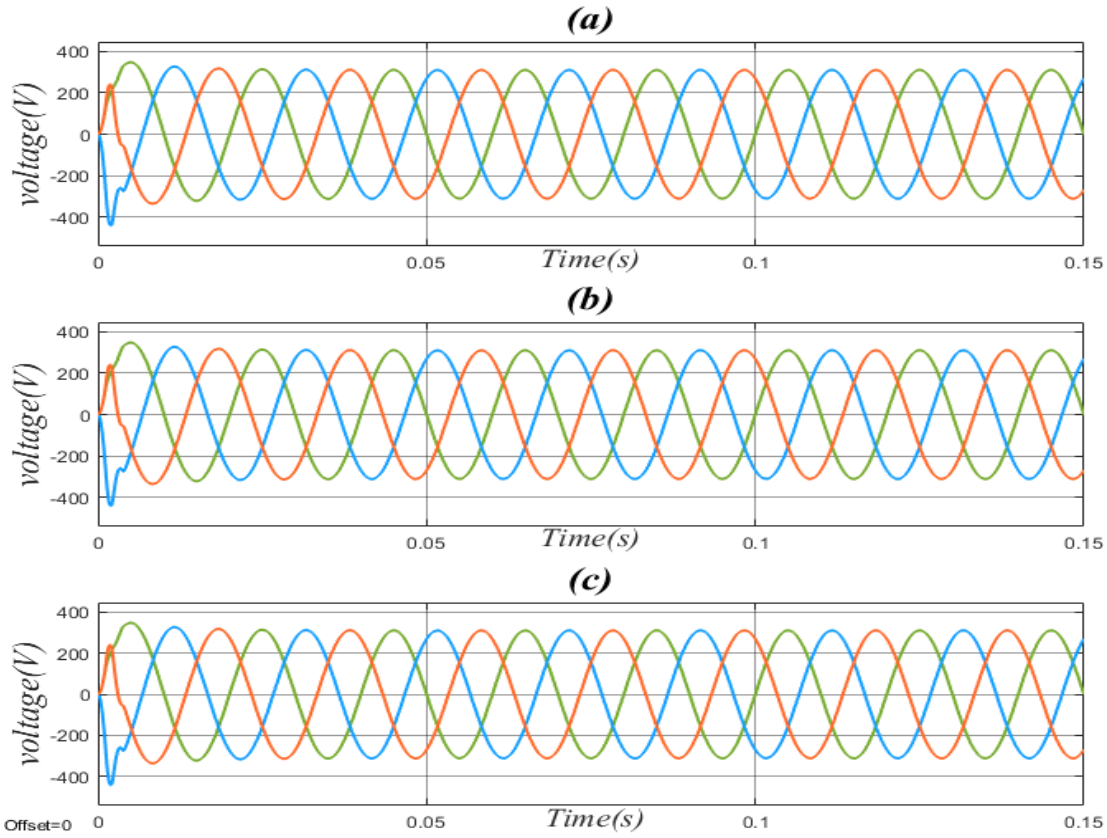


Fig III.15 The voltage of (a) first DG, (b) second DG (c) third DG

Figure III.15 we can notice that the voltage control is robust when we connected a second load at time t = 0.05s and the third load at t=0.1s, and it is evident that the two slave inverters closely track the voltage of the master inverter. This behavior indicates that the slave inverters are synchronized with the master inverter and adjust their voltage output accordingly.

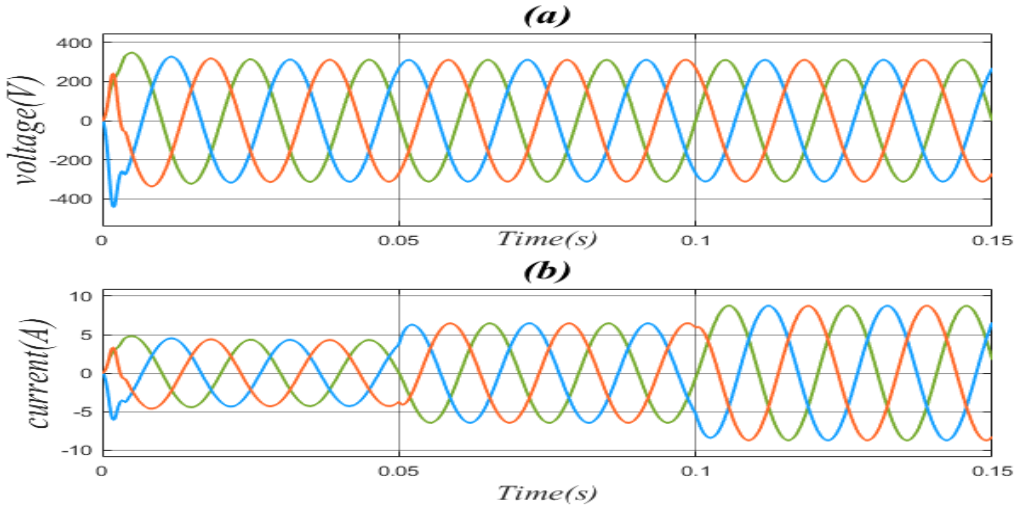


Fig III.16 (a) Load voltage (b) Load current

Figure III.16 presents the voltage and the current of the load. From this figure, we can notice that the voltage control is robust when we connected a second load at time t = 0.05s and a third load at t=0.1s.

The FFT analysis of the load voltage is presented in figure. III.17. The load voltage THD is 1.34%.

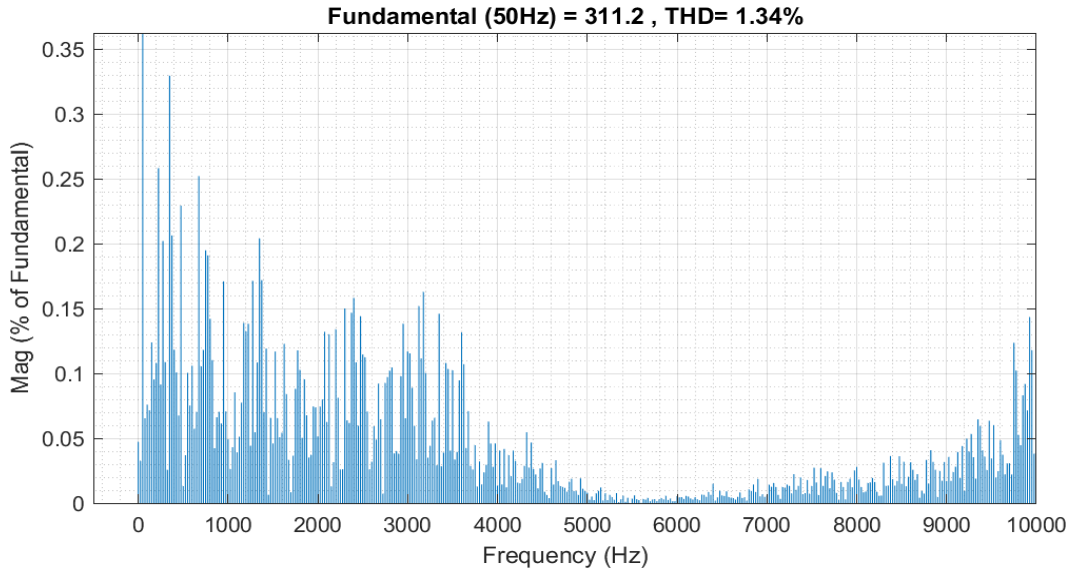


Fig III.17 THD of the load voltage for forming-following structure.

III.4 Results discussion

After conducting the tests and analyzing the results, we have compiled a detailed comparison table to assess the performance of different microgrid formations. The table below provides an overview of the key parameters for each formation:

Tabel.III.3 Performance Comparison between the Two Methods

Microgrid	Power Stability	Load Balancing	Resilience
Forming-Forming	High	Moderate	Low
Forming-Following	Moderate	High	High

In the forming-forming microgrid formation, power stability is achieved at a high level, indicating consistent power generation and supply. However, load balancing capabilities are only moderate, which means there may be slight imbalances in power distribution among the loads. Additionally, the resilience of this formation is relatively low, suggesting that it may be vulnerable to disruptions or failures in the system.

On the other hand, in the forming microgrid formation, power stability remains at a moderate level. While not as high as the forming-forming formation, it still ensures a reliable power supply. However, load balancing capabilities are significantly higher, ensuring an equitable distribution of power among the connected loads. Moreover, the forming microgrid formation exhibits a high level of resilience, indicating its ability to withstand and recover from system disruptions or failures.

This comparison allows us to evaluate the trade-offs between power stability, load balancing, and resilience in different microgrid formations. It is important to consider the specific requirements and priorities of the system when choosing the appropriate formation.

Finally, we present a comprehensive summary of the knowledge gained from this work in the following table. This table highlights the key findings and insights obtained throughout the study:

Tabel.III.4 Analysis of Features and Drawbacks

Method	Features	drawbacks
Forming-Forming	Reduced Dependence on External Signals: the MG can operate with minimal or no reliance on external communications. High Modularity, Flexibility, and Expandability. Virtual Inertial Emulation Capability.	The difficulty of the control. Reliance on communication links for synchronization. The independent operation of each DG may lead to challenges in maintaining system stability.
Forming-Following	Simple synchronization between the inverters. Generation and load disturbance can be compensated by the master inverter. Implementing the control system is relatively simple	If the master inverter is turned off, it can result in a complete system blackout. Lacks the ability to self-heal, it is unable to automatically recover or restore functionality in the event of a failure or disruption. Dependency On communication.

III.5 Conclusion

In this chapter, we have described the control system for both the single DG forming and single DG forming units. Subsequently, we presented the simulation results obtained for each method, namely forming-forming and forming-following, finally, we have provided a comprehensive discussion by comparing and analyzing the results of both methods to evaluate their respective performance in terms of power quality, and system efficiency.

General conclusion

The increasing global demand for electrical power and energy has led to ongoing research and development efforts focused on achieving more sustainable and renewable energy solutions. One area of particular interest is the implementation of microgrids, which can play a crucial role in providing efficient and reliable power distribution.

In the preceding chapters, a comprehensive exploration was conducted on various aspects of microgrids, with particular emphasis on the utilization of three-phase voltage source inverters and the control methods employed for regulating inverters within a microgrid.

The first chapter provided a thorough overview of microgrids, shedding light on their functioning and the significance of three-phase VSI in their operation. Additionally, it delved into the diverse control methods that can be utilized to ensure effective regulation of inverters within a microgrid.

Building upon the foundation laid in the first chapter, the second chapter focused on the modeling of an inverter bridge and an LC filter, presenting a detailed examination of the primary control strategy. This strategy employed a cascade loop incorporating a PI controller and integrated droop control techniques. Furthermore, secondary control strategies pertaining to frequency and voltage restoration were extensively discussed.

The third chapter placed emphasis on the implementation of two distinct methods: forming-forming and forming-following. These methods were carefully explained, and the chapter featured the presentation of simulation results obtained using MATLAB, which provided valuable insights and validation.

Concluding the study, the final section offered a concise summary of the work conducted, highlighting key findings and contributions.

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