

Droop Controller to Power Sharing among Inverters in Distributed Generation Microgrids in Distributed Generation Microgrids

Deboub Raouf¹, Meziane Salima², Toufouti Riad³

¹Oum El Bouaghi University, Algeria, ²Laboratory of Electrical and Renewable Energies, Souk Ahras University, Algeria, ³Laboratory of Electrical and Renewable Energies, Souk Ahras University, Algeria.

Abstract - In last years, several countries have shown massive interest in Micro Grid technology, In order to meet the demand for electricity due to the development of the population by integrating renewable energy and reducing the greenhouse gas emission. When we integrate renewable energies into smart grids, the idea of a micro grid (MG) becomes real, The micro-grid is a sophisticated, intellectual, local and small network that can be separated from the central network and operates autonomously but the integration of distributed renewable energy generations is expecting frequency and voltage droop due to increasing demand of PV and load. To permit zero net-energy consumption and best power management for future smart city or buildings, this paper discusses the (DC) voltage and frequency regulation approach to address the rise/drop of voltage in a Microgrid, equipped with a residential Photovoltaic (PV) system, storage battery (SB), residential load and Smart Control Strategies (SCS) of parallel operated voltage source inverter (VSI). Voltage and frequency can be regulated by controlling the active and reactive power. The effectiveness of the proposed Droop Controller is verified by numerical simulation. A Simulation result of (MG) is given to demonstrate the effectiveness of the proposed approach.

Keywords: Droop control, micro grid, hierarchical control, photovoltaic system, voltage source inverter (VSI).

1. Introduction

Electric energy represents an important need for every country, because it has a primordial role in its economic and social development. Until now, a significant part of energy production has depended heavily on fossil fuels, namely: natural gas and coal. On the other hand, the large increase in energy consumption to create a gap between energy production and demand [1]. More than a billion people are expected to be added, bringing the world's population to around 10 billion by 2040. The energy consumption is expected to increase by 40% through 2040. Almost one third of the predictable increase in energy consumption will be the result of the rapid growth of the world population and the world economy. The trend towards over-reliance on conventional energy production threatens the sustainability of life itself. In addition to the unequal distribution of fossil fuels and their rapidly depleting, these sources also change the ecological balance necessary for existence. Energy security as well as climate change have become essential concerns. Henceforth it is well accepted that unless far-reaching measures are taken to appease global warming, economic development will slow down and the world could evolve into a man-made environmental catastrophe [2]. Since engineers and scientists are aware that the reserves of conventional (fossil) energy sources are limited and can have negative consequences on the environment, they seek to find and use alternative energy sources. For isolated and remote sites where the possibility of accessing electricity grids is almost nil due to the very high cost and also to technical constraints, renewable energies are considered a pleasant choice and preferred in many regions. [3]. The growth of wind and

Photovoltaic power, and other renewable technologies, has augmented very rapidly. Renewable energies accounted for almost a 30% rate of recently built power generation capacity.

Solar power generators decrease greenhouse gas emissions which harm the environment. Photovoltaic and solar thermal farms can meet most of the world's electricity demand and can become the source capital of electricity. Renewable energy technologies have become increasingly less expensive, due to technological change and mass production as well as market competition [4]. Recently, the use of renewable energy sources has become more pleasant, profitable and meaningful. However, as renewable energy sources are variable and discontinuous, it is essential to have a storage system with a back-up source to guarantee the continuity of supply.

But if these energy sources are renewable, this hybrid system can be considered a hybrid renewable energy system.

When hybrid systems work efficiently, they increase the overall efficiency of the system and become a more credible source of energy. In addition, hybrid systems can greatly reduce production costs and harmful effects on the environment. The use of hybrid systems that include renewable sources, backup sources and energy storage minimizes the limits of renewable sources and opens up horizons for investments that would not exist [5]. Electricity grids have a capacity to be more dispatching the electric power with intelligent and flexible. New electronic power equipment will control the electrical network for the next few years. The goal of this electrical power network is to become more distributed, so the areas of energy production and consumption cannot be designed independently. However, electrical power network has to face a new plane in which small distributed electric power generators and energy storage system have to be installed together in the grid.

The advanced power grid, called the Smart Grid (SG), will deliver electricity produced to consumers by using digital technology to control household appliances to save energy,

Thereby lowering costs and increasing reliability and clarity. To this end, the entire expected energy system will be more interactive, intelligent and distributed [6]. The Smart Grid is a perfect technology of a complex electric power system. Considered as the evolution of the current electricity grid, the vision we can have of the Smart Grid is that of a complex network where the two-way flows of information and electricity allow real-time adjustment of demand, supply, distribution and transport [7].

The micro-grid is an electrical system that includes consumers, distributed resources and energy storage systems that can operate in isolated mode or connected to the grid [8]. Several proposals on the stability of network microphones which operate in isolated mode have been proposed. We can find some control techniques based on if the communication network breaks down we lose the means of control, which makes this technique highly dependent on the communication network and this represents a major drawback. Other techniques based on the control of active and reactive power known as local control techniques without communication are also used. The droop control technique uses this feature [9].

This paper discusses the (DC) voltage and frequency regulation approach to address the rise/drop of voltage in a Micro grid, equipped with a local Photovoltaic (PV) system, storage battery (SB), local load and Smart Control Strategies (SCS) of parallel VSI. Voltage and frequency can be regulated by controlling the active power injection into the system. The effectiveness of the proposed Droop Control is verified by simulation results in the Matlab/Simulink environment. A detailed investigation of voltage regulation of a local Micro-Grid (MG) is given to demonstrate the effectiveness of the proposed approach.

2. SMART GRID

The term smart grid brings together several realities depending on the country, the actors and the networks. It is therefore difficult to give a precise definition of what smart grids are and will be [14]. Although there is no single definition of smart grid, at least one thing is certain: more and more new applications (renewable energy production, distributed production, large-scale storage, plug-in hybrid electric vehicles, smart devices, etc.) will be added to the existing electricity grid, and the smart grid includes all enabling technologies that will make these new applications conveniently connected / integrated into the grid [11]. A common interpretation of the

smart grid is that it is the combination of electric power and communication infrastructure, characterized by two-way communication and two-way energy flow [11]. The term smart grid as introduced by Amin and Wollenberg (2005), generally covers the entire spectrum of the electricity system, from transmission and distribution to delivery (see figure 1). In common with the previous definitions, it contains two key elements: digital data processing and communication networks [10].

After having presented various visions concerning the smart grid namely that of EPRI's, US Department of Energy (DOE), ABB's, European Union (EU)'s, Electricite de France

(EDF)'s, Hydro Quebec's, General Electric's, IESO's, Ofgem's and OECD's, In [10] the author confirms that the term "smart grid" is generally used to describe an electrical network whose operation has developed from 20th century analog technology to digital technology for communications and surveillance. In [13], the authors define the smart grid as much as a network that can have a two-way flow of electricity and information, while advancing the reliability, safety and efficiency of all the electricity grid. Namely production, transport and distribution. It is justified by the obligation to have a more powerful, flexible and at the same time strong electrical system to meet the growing demand for electricity, the relief of greenhouse gas emissions, and the depletion of energy resources.



Fig.1 Smart grid structure.

Smart Grid is a vision for the future of the electrical system. There are many ways to see this future which are perhaps mainly summed up by US Secretary of Energy Steven Chu who says that the Smart Grid is the main trigger for: integrating renewables into the electricity grid [15]. According to [16], the smart grid delivers electricity from generators to consumers using technologies developed to control consumer devices to improve energy efficiency, reduce costs and increase reliability. To this end, a key feature of the smart grid is the automation technology that allows the electric utility to control each device from a central location [4]. The control of smart grid is much more complicated than the conventional power grid and to be operated some special components such as computers, sensors, remote-controlled switching devices, as well as communication networks are required [10]

2.1. Objectives of smart grids

The smart grid uses innovative products and services as well as intelligent technologies for monitoring, control, communication and self-healing to:

- (1) Facilitate the connection and operation of generators with different sizes and technologies.
- (2) Allow consumers to have a role in improving the functioning of the system.
- (3) Offer consumers more information and a greater choice of reserves.
- (4) Significantly reduce the environmental effects of the entire system.
- (5) Improve the reliability and security of supply [16].

2.2. Advantages of smart grids

- (1) The expected benefits and requirements of Smart Grid are as follows.
- (2) Improve the credibility and quality of the power supply
- (3) Improve the use of facilities and avoid the building of emergency power stations (for peak load hours).
- (4) Improve the capacity and efficiency of existing electricity networks.
- (5) Activate maintenance forecasts and self-healing responses to system upheavals.
- (6) Facilitate the development of renewable energy sources.
- (7) Integrate distributed energy sources.
- (8) Developed maintenance and operation.
- (9) Reduce greenhouse gas emissions.
- (10) Present offers to improve network security.
- (11) Allow the switch to rechargeable electric vehicles and new energy storage options.
- (12) Offers more choice to the consumer.
- (13) Offers new products, services and markets [17].

3. HIERARCHICAL CONTROL

For electrical systems, two distinct control methods can be determined, namely centralized and decentralized control strategies. Centralized control method is based completely on data collection in a typical central controller that does the necessary calculations and orders control actions for all units. Centralized control method requires expensive communication between the central controller and the other controlled units, which limits the reliability and the flexibility of the system.

On the other hand, in a decentralized control method, any unit is controlled by its own local controller, which receives only local information and has no knowledge of the variables and functions of other controllers, removing the communication link makes this more attractive method. In addition, a completely decentralized method is impractical. An intermediary solution between centralized and decentralized control methods can be achieved through a structured control scheme which includes three levels of control (see figure 2) [3][21].

The first level, which is called tertiary control, ensures an optimal operation of the system as well as the control of the power flow mainly in grid-connected mode. The second control level, called secondary control is dedicated to restore the voltage and the frequency as well as the synchronization between the micro-grid and the main network, the last control which is the primary control must ensure the stability of the voltage and the frequency and detect the passage in isolated mode [18]. The authors in [19] propose a hierarchical control

composed of five levels of control ranging from level zero to level four. In the first level, which is the internal control loop, the identification of the type of control is taken into account from the physical system of the micro-grid. The second level which is the primary control concerns the change of the real power demand at any point of the network by a change of frequency, in this level, the control loops of all the production units respond in a few seconds. The third level called secondary control is necessary because the primary control action is usually not sufficient to restore the frequency of the system, especially in an interconnected power grid.

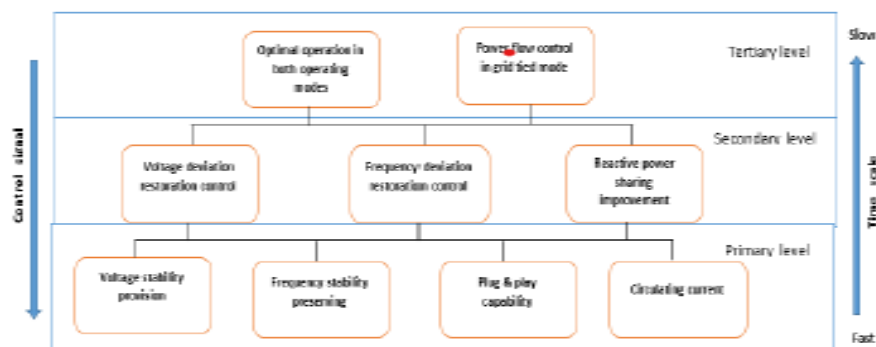


Fig. 2 Hierarchical control structure.

Therefore, the purpose of secondary control is to restore voltage, frequency and compensate for the frequency deviation. The fourth level which is tertiary control concerns the economic issues in the optimal functioning of the microgrid, and controls the flow of energy between the microgrid and the main network by adjusting the frequency and amplitude of the voltage inside the microgrid. Finally a last level which is the emergency control concerns the appearance of an abnormal condition, the emergency command must be used to reduce the risk of cascade failures, an immediate change in the power control of the microgrid gateway must take place. In [6] the authors proposed a hierarchical control of four levels, namely tertiary control, secondary control, main control, internal control loops, on the other hand in [20] they proposed only three levels of control (tertiary control was suspended), although in [21, 22] the authors propose a three-level hierarchical control without the inner loop.

4. DROOP CONTROL

The general structure of micro grid controlled by droop controller is given by figure.3. The purpose of basic control in a micro-grid operating in isolated mode is to have an accurate division of power while maintaining good control of the amplitude and frequency of the voltage at the present time, parallel operation of inverters can be divided into two types:

- (1) Communication-based control (wired methods): Based on the gathering of information in a typical central controller which performs the necessary calculations and orders the acts of control for all the units in a central point, making it an easy business to carry out, Nevertheless, once having an interruption at the level control center of the micro-grid or a problem with the lines, the whole parallel control system destroys itself, which reduces reliability.
- (2) Non communication based control (wireless methods): In order to overcome the problem of low reliability of centralized control, the theory of decentralized control can be used, the communication system is not necessary and the absence of the source reference increases the system reliability [23-24-25].

One of the solutions for wireless technology is to use droop control, which is widely used in conventional power generation systems. It works without communication for the distribution of power. Usually, the operation without communication link is decisive to connect remote inverters, likewise, without communication, connects systems thanks to the plug and play function of the modules, which allows us to replace defective units without any downtime of the system. Droop control techniques can be implemented to have good power sharing and to protect all inverters against overloads. In this case, no external communication mechanism is required between the inverter, which is a great advantage.

However, communication still exists between each unit and the central supervisory controller. This gives us good linear and / or non-linear load sharing. Moreover, its ease of start-up, based simply on local voltage and current information, enables plug and play operation [23 26-27-28].

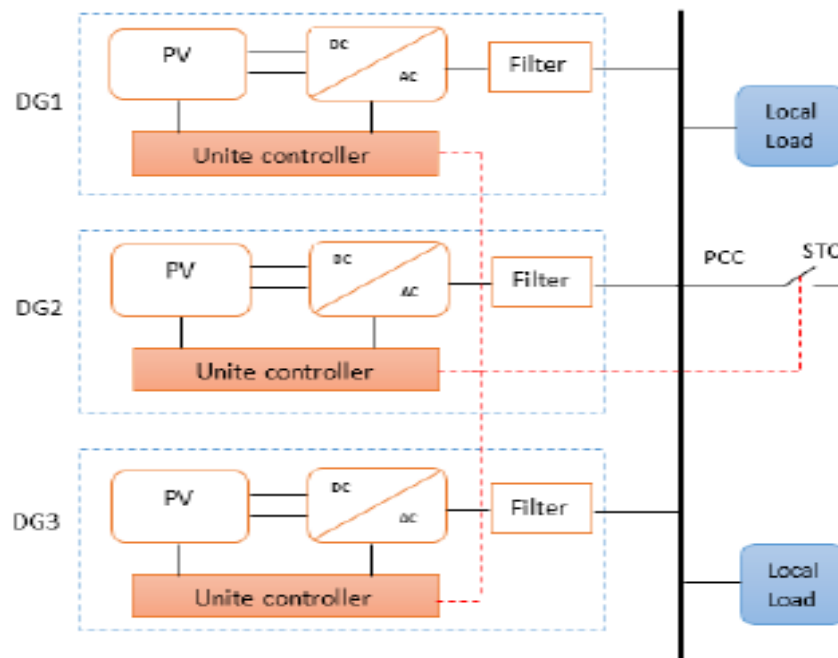


Fig. 3 Classic active and reactive power droops of a Micro-grid.

We assume a micro network that includes production sources connected to the PCC point. The circuit on the Figure 03 can be represented by the equivalent diagram given on figure 04. The power flow in a line at point A, is described as follows [29]:

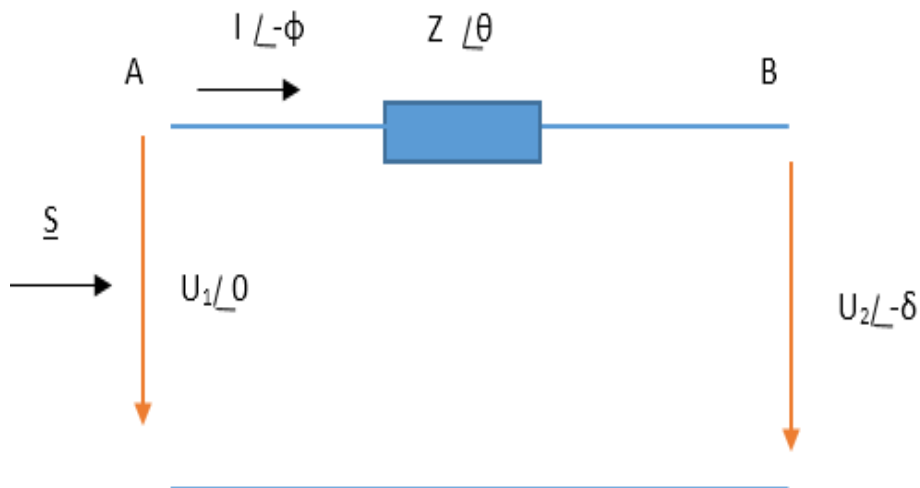


Fig. 4 Power flow through a line

$$\begin{aligned}
 P + jQ = \underline{S} &= \underline{U_1} \underline{I}^* = \underline{U_1} \left(\frac{\underline{U_1} - \underline{U_2}}{\underline{Z}} \right)^* \\
 &= \underline{U_1} \left(\frac{\underline{U_1} - \underline{U_2} e^{j\delta}}{\underline{Z} e^{-j\theta}} \right)
 \end{aligned} \tag{1}$$

$$= \frac{U_1^2}{Z} e^{J\theta} - \frac{U_1 U_2}{Z} e^{J(\theta+\delta)}$$

Thus, the active and reactive power flowing in the line is described as:

$$P = \frac{U_1^2}{Z} \cos \theta - \frac{U_1 U_2}{Z} \cos(\theta + \delta) \quad (2)$$

$$Q = \frac{U_1^2}{Z} \sin \theta - \frac{U_1 U_2}{Z} \sin(\theta + \delta) \quad (3)$$

With $Ze^{J\theta} = R + jX$ (2) and (3) becomes :

$$P = \frac{U_1}{R^2 + X^2} [R(U_1 - U_2 \cos \delta) + XU_2 \sin \delta] \quad (4)$$

$$Q = \frac{U_1}{R^2 + X^2} [-RU_2 \sin \delta + X(U_1 - U_2 \cos \delta)] \quad (5)$$

From where

$$U_2 \sin \delta = \frac{XP - RQ}{U_1} \quad (6)$$

$$U_1 - U_2 \cos \delta = \frac{RP + XQ}{U_1} \quad (7)$$

For overhead lines, $X \gg R$, which means that R can be neglected. If the power angle δ is also small, then $\sin \delta = \delta$ and $\cos \delta = 1$. Equations (6) and (7) then become:

$$\delta \cong \frac{XP}{U_1 U_2} \quad (8)$$

$$U_1 - U_2 \cong \frac{XQ}{U_1} \quad (9)$$

Equations (8) and (9), show that the power angle depends directly on active power P , On the other hand the voltage difference depends mainly on Q . Which shows the angle δ can be controlled by regulating the active power P .

On the other hand the output voltage of the voltage source inverter (VSI) U_1 is controllable directly the reactive power Q . Thus, by adjusting active and reactive powers P and Q individually, the frequency and voltage of the Micro grid is determined. These conclusions are the basis of the well-known regulation of frequency and voltage drops via active power and reactive power respectively:

$$f - f_0 = -K_p(P - P_0) \quad (10)$$

$$U_1 - U_0 = -K_q(Q - Q_0) \quad (11)$$

U_0 and f_0 are respectively the nominal voltage and frequency of the Micro Grid, and P_0 and Q_0 are the set points for the active and reactive power of VSI. K_p and K_q are the droop controller coefficients. The characteristics voltage and frequency droop control are shown graphically in Figure 5.

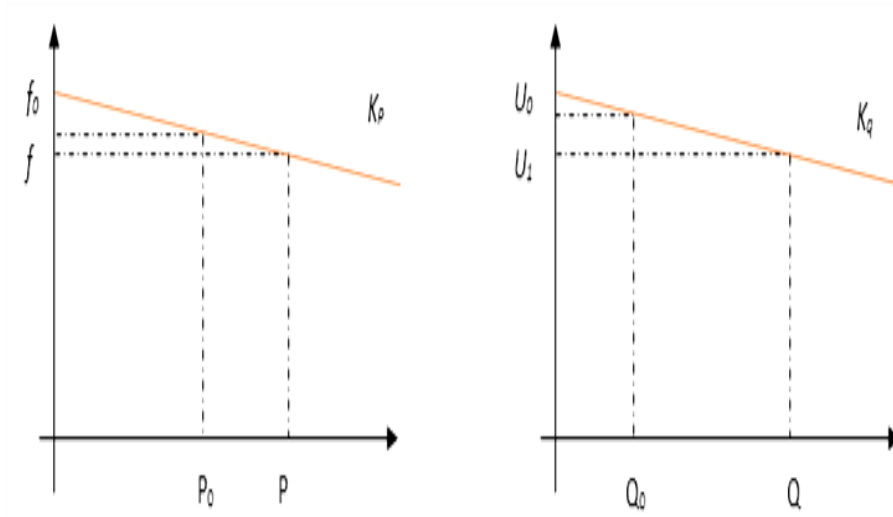


Fig. 5 Characteristic of the Droop Control

Figure 06 shows the principle of classic droop control, using the voltage and current which are measured using the voltage and current sensors. The first block calculates the active and reactive power (P , Q); then using the equations of the control droop given in (10) and (11), the second block produces the frequency values of the reference voltage.

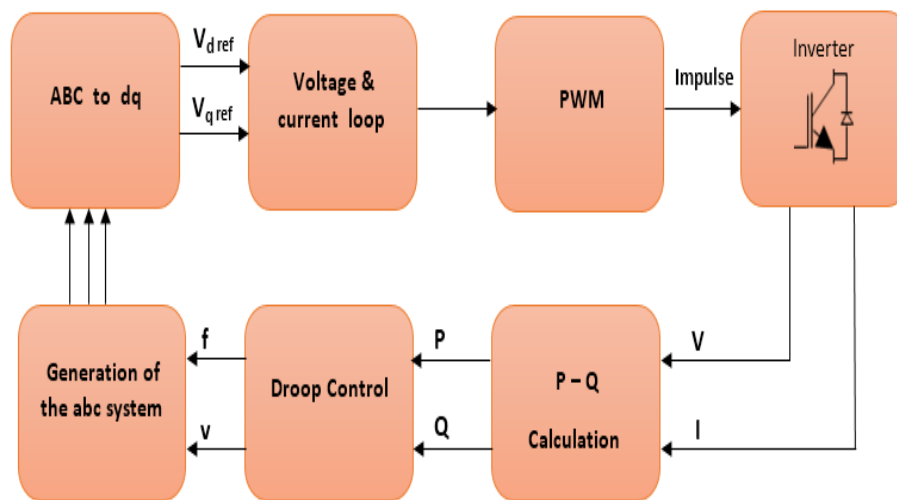


Fig. 6 Simplified diagram of the classic power controller

Subsequently, a new block generates three sinusoidal signals which will be transformed into two voltages two-phase reference, V_{dref} and V_{qref} which will be introduced into the control unit which has four loops; two for

voltage regulation and the two others for current regulation. Afterwards, we switch to three-phase to have the three sinusoidal reference signals.

These latter voltages are compared with a triangular signal in the PWM block (sine-triangular) to generate the trigger pulses of the inverter. In this way, the active power of each source can be controlled by varying the frequency (phase angle) of the output voltage of the inverter and on the other hand, the reactive power can be regulated by varying the amplitude of the output voltage. The detail of droop control block is given by the figure 7, it has three internal blocks: Calculation of active and reactive powers, Power loop (classic Droop control loop) Voltage loop and control loop current.

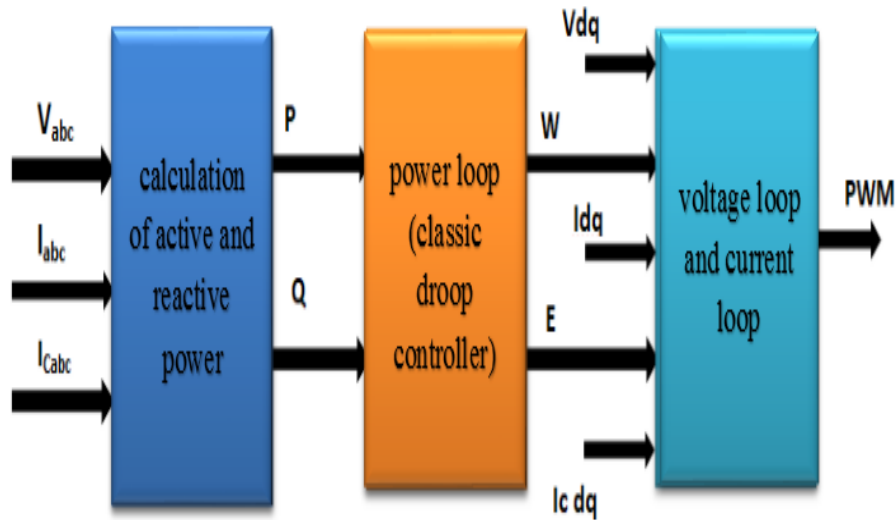


Fig. 7 Principle of the droop control

✓ *Active and reactive power calculation block*

The active and reactive power calculation block diagram is given in the figure below.

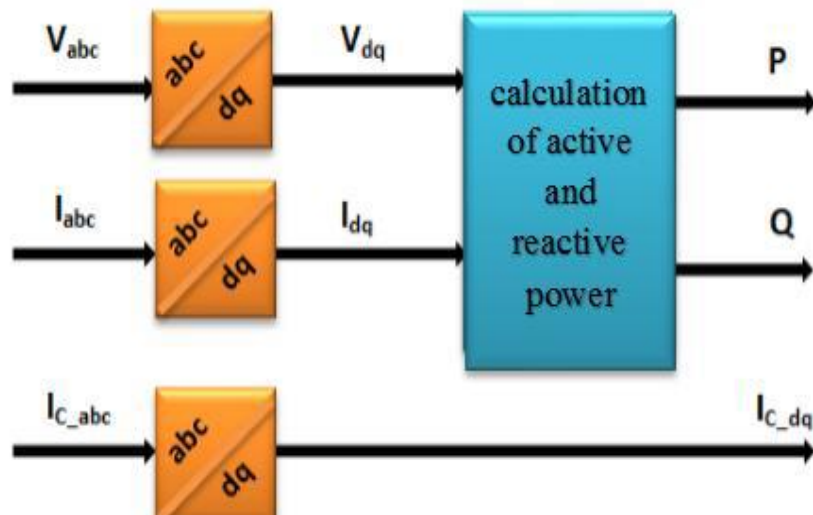


Fig. 8The active and reactive power calculation block structure

The calculation of the active and reactive powers is based on the measurement of the voltages and currents at the output of the LC filter and after a three-phase two-phase transformation according to the following equations

$$\begin{cases} P = V_d I_d + V_q I_q \\ Q = V_d I_q - V_q I_d \end{cases} \quad (12)$$

✓ **Frequency and voltage calculation block (classic droop)**

The active and reactive power loops of the classic droop control are given by figure 9, which allows to give us the frequency and the voltage respectively from an active power loop and a reactive power loop, which is given by the following equations.

$$\begin{cases} f = f_n - K_p (P - P_n) \\ V = V_n - K_Q (Q - Q_n) \end{cases} \quad (13)$$

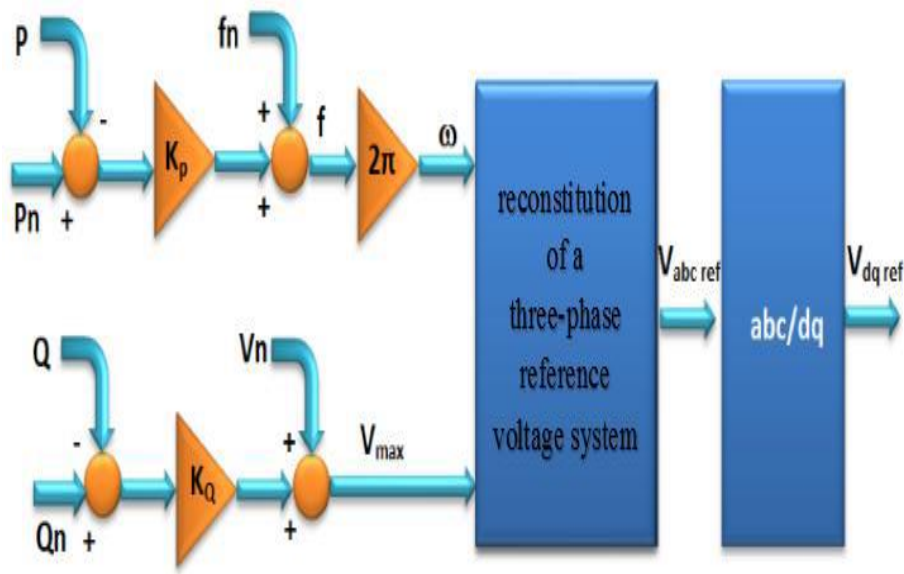


Fig. 9 The structure of frequency and voltage calculation block

From the voltage and frequency generated by the active and reactive power loops, we can reconstitute a system of three three-phase reference voltages V_{abc} , which are transformed into two-phase reference voltage V_{dq} . From the voltage and frequency generated by the active and reactive power loops, we can reconstitute a system of three three-phase reference voltages V_{abc} , which are transformed into two-phase reference voltage V_{dq} .

$$\begin{cases} V_a(t) = V_{\max} * \sin(\omega t) \\ V_b(t) = V_{\max} * \sin(\omega t - \frac{2\pi}{3}) \\ V_c(t) = V_{\max} * \sin(\omega t + \frac{2\pi}{3}) \end{cases} \quad (14)$$

✓ **Voltage and current controller block:**

The third block has two voltage and current controllers; the internal structure is given by the following figure:

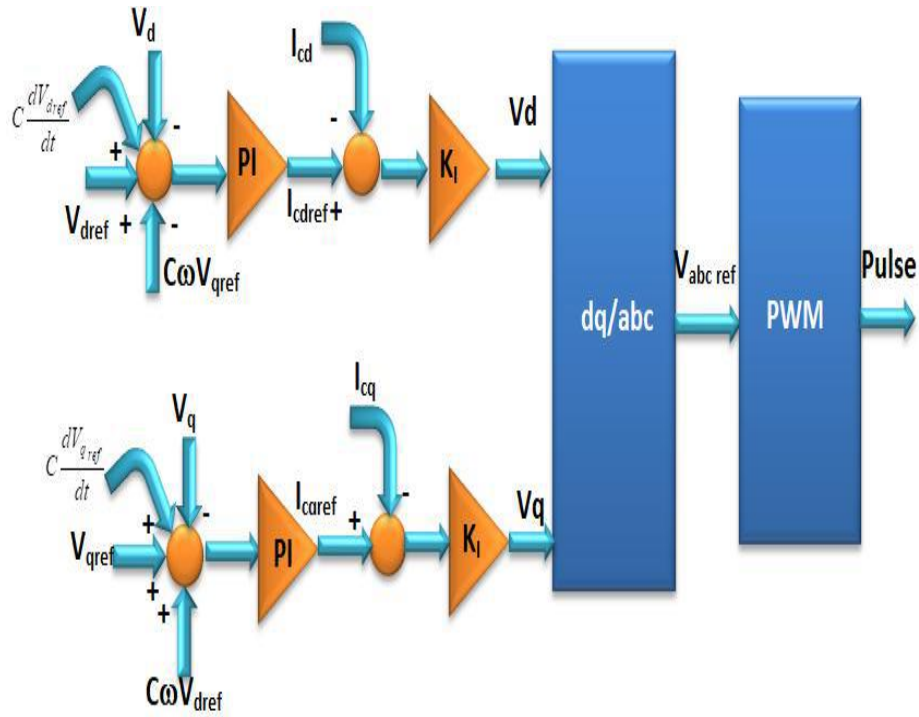


Fig. 10 The block diagram of the voltage and current controller

The reference voltages V_{dref} and V_{qref} are compared with the voltages at the output of the filter V_d and V_q , in order to determine the reference currents I_{cdref} and I_{cqref} at the filter placed at the output of the inverter. The reference currents I_{cdref} and I_{cqref} are given by the following equations:

$$\begin{cases} I_{dref} = K_p(V_{dref} - V_d) + K_i \int (V_{dref} - V_d) + C \frac{dV_{dref}}{dt} - C\omega V_{qref} \\ I_{qref} = K_p(V_{qref} - V_q) + K_i \int (V_{qref} - V_q) + C \frac{dV_{qref}}{dt} + C\omega V_{dref} \end{cases} \quad (15)$$

The reference currents I_{cdref} and I_{cqref} are then compared with the measured currents of the filter capacitor at the output of the inverter I_{cd} and I_{cq} . The output of the comparator is amplified with a gain K_i in order to generate the reference voltages V_{dref} and V_{qref} at the output of the current controller, the two-phase three-phase transformation of these voltages which gives the reference voltages V_{abc} which are compared with a triangular signal of high frequency (PWM triangular sine principle) to generate the pulses of the switches of the inverter

5. SIMULATION RESULT

In This section we present the simulation of the micro grid in island mode, includes two loads a primary permanent load with 30Kw active power of 0 Var reactive powers, at the moment 0.4s we insert the secondary load with 45Kw active power and of 1000 Var, reactive power. For the droop control we impose a reference maximum voltage of $U_{ref} = 311$ and a reference frequency $f_{ref} = 50\text{Hz}$. The DC bus voltage in the input inverter uses batteries with $V_{dc}=700\text{V}$. The general structure of the proposed micro grid is shown in figure.11.

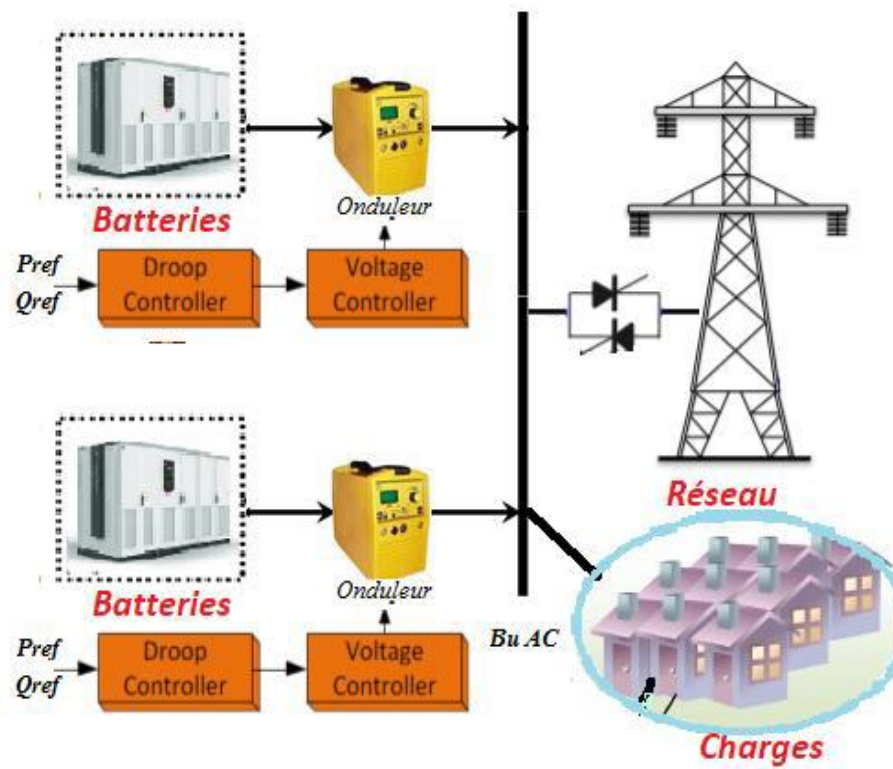


Fig. 11 Proposed micro grid [28]

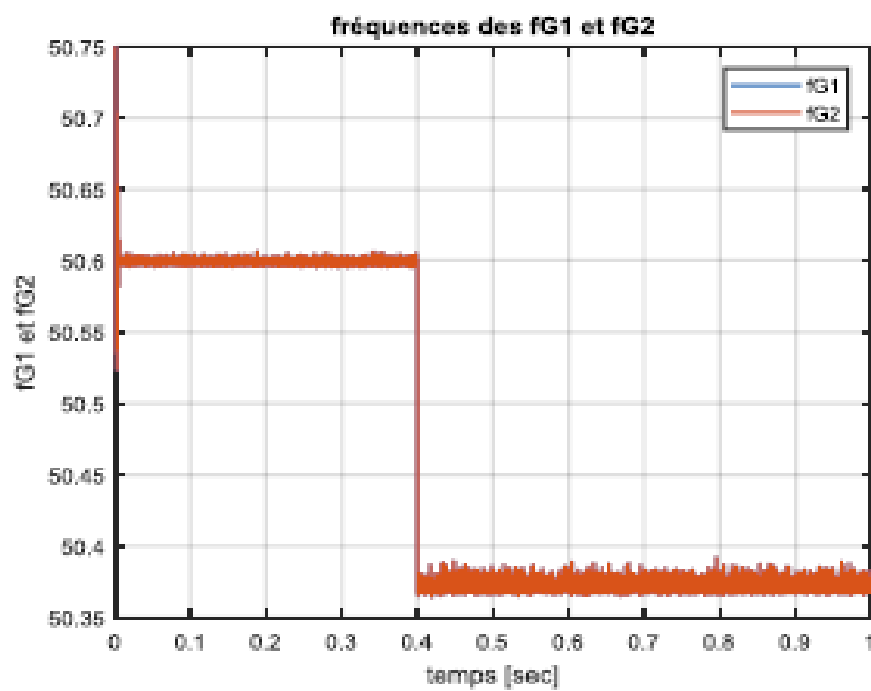


Fig. 12 Frequency of two VSI

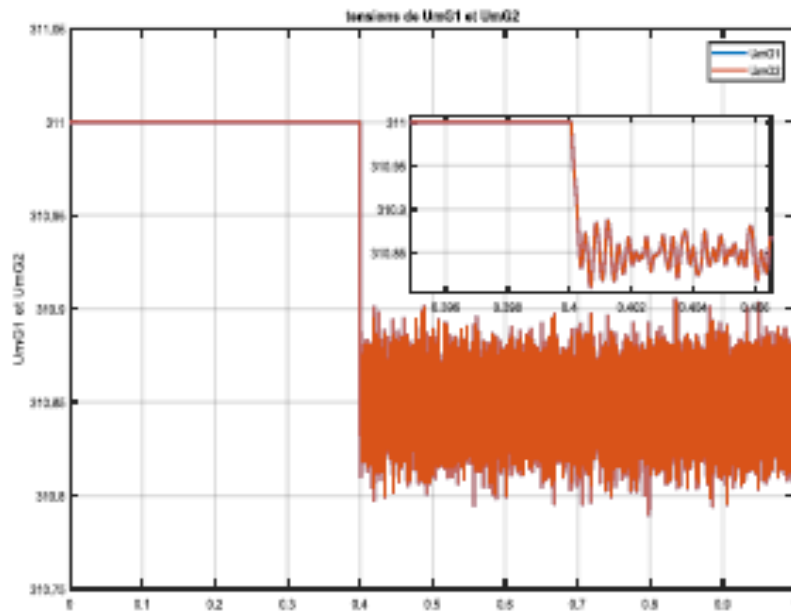


Fig. 13 Magnitude of output voltage of two VSI

From figure.12 we observe that the frequency of the voltage generated by the two inverters has remained stable around the reference frequency 50 Hz, with a difference between the frequency of the voltage generated by each inverter and the nominal frequency of 0.6Hz in the first mode (30kW load) but once the second load was inserted the deviation decreased to a value of 0.36Hz in the second mode (load $P = 75\text{kW}$, $Q = 1000\text{var}$).

In Figure 13, we notice that the value of the maximum voltages generated by the two inverters has remained stable around the maximum reference voltage 311V, hence the difference between the voltage generated by each inverter and the nominal value is zero for the 1st load mode 30kW, on the other hand for the 2nd load mode 75kW the voltage has decreased to a value of 310.85 V with a difference of 0.15 V, either a rate of 0.04%, this shows that the control of proposed droop is valid for maintaining frequency and voltage

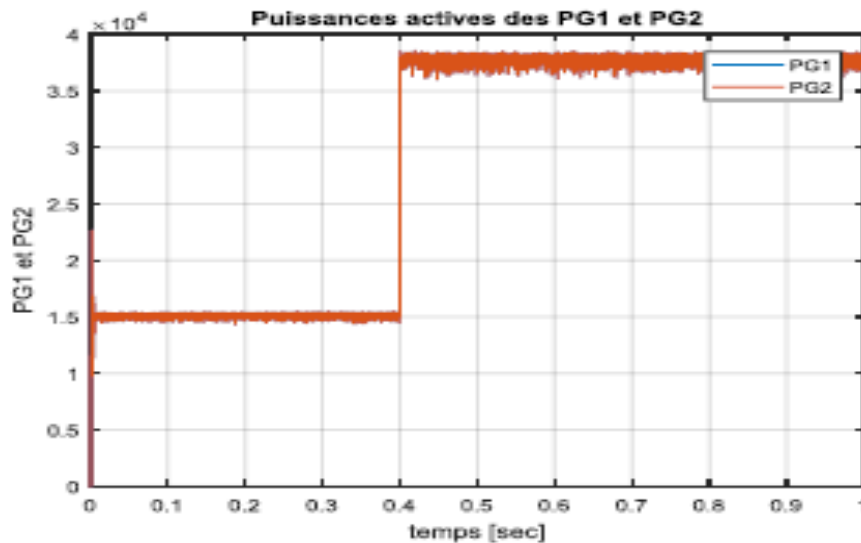


Fig.14 Active power PG1 and PG2

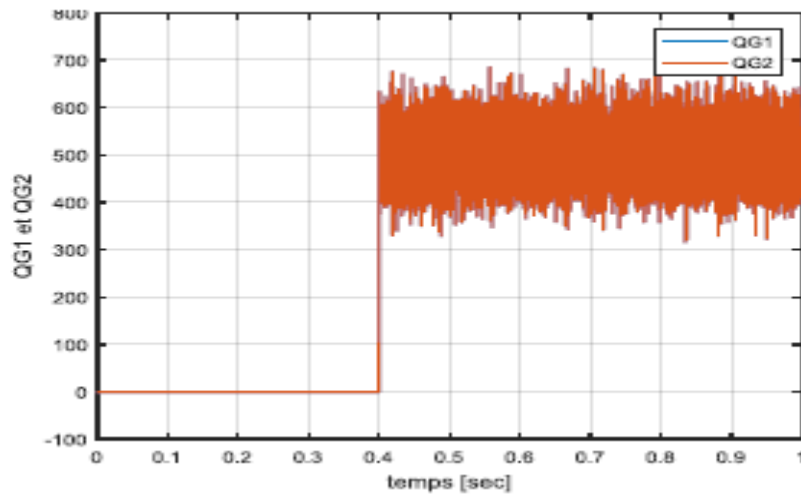


Fig. 15 Reactive power QG1 and QG2

According to the figure 14 which represents the evolution of the active powers of the two generators, one observes the good sharing of the active power of the load between the sources for the first mode (resistive load of $P = 30\text{kW}$), the load was distributed equitably by droop control between these two generators (15kW) for each generator and for the second mode (load $P = 75\text{kW} = 30\text{kW} + 45\text{kW}$ and $Q = 1000\text{Var}$ $0\text{Var} + 1000\text{Var}$), the load was distributed equitably between these two generators (37kW and $Q = 500\text{Var}$) for each generator we also note the good readback of the powers in transient state without peaks in the two transient and permanent states, with a very short readout time.

Same remark that can be noted for the sharing of the reactive power for a variation of the load from 0Var to 1000Var , according to figure 15 we observe the good sharing of the reactive power of the load between the sources ($Q = 1000\text{Var}$), the load was evenly distributed between these two generators ($Q = 500\text{Var}$) although large oscillations of the order of more or less 100 var are observed, the performance of the proposed power regulator is always maintained. It should be noted that increasing the reactive power leads to a decrease in voltage.

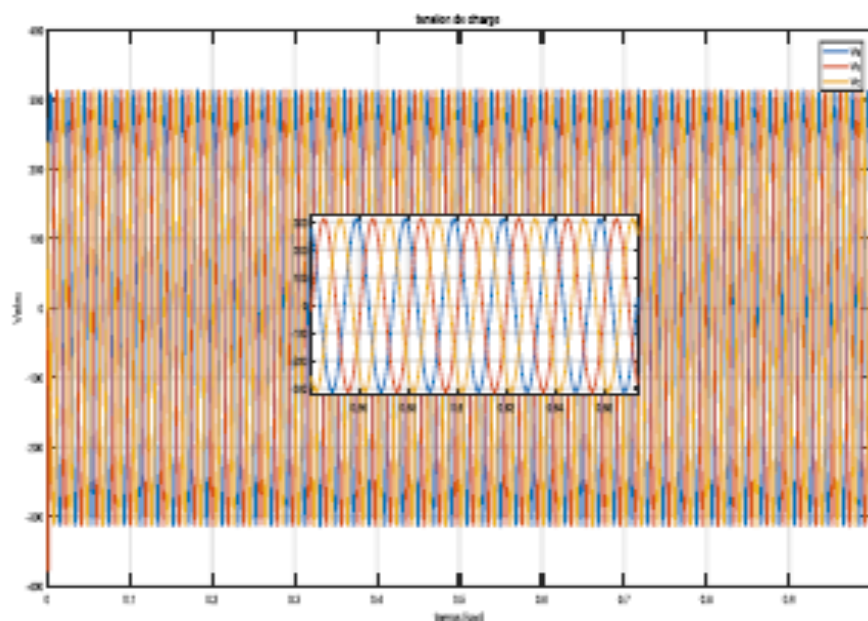


Fig. 16 Waveforms of the load voltage

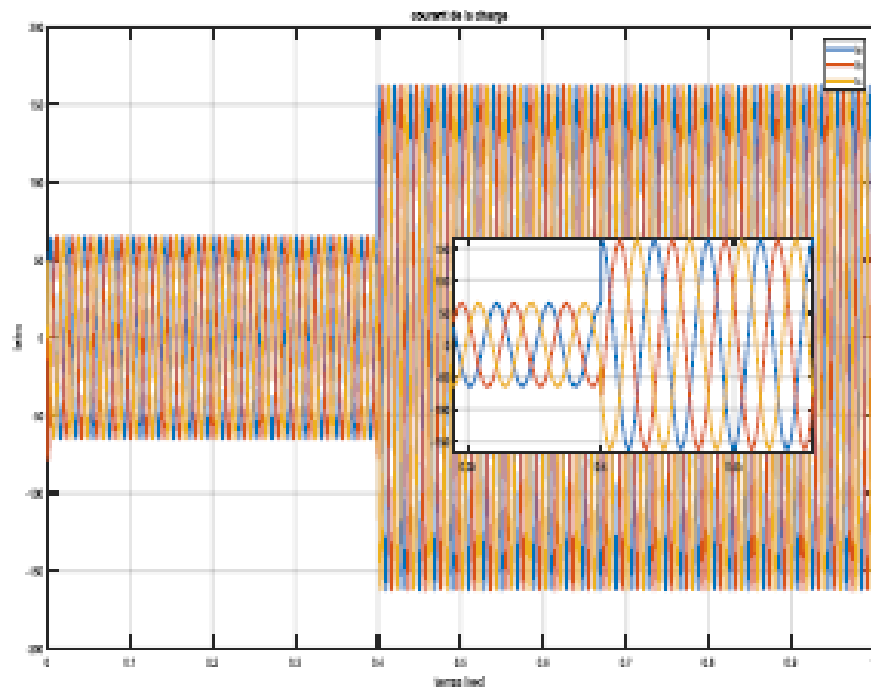


Fig.17 Waveforms of Load currents

From figure 16, we observe that the voltage at the terminals of the load has a purely sinusoidal shape and it is kept stable around the values of the reference voltage generated by the power regulator, even in the presence of a variation of the load the voltage keeps its sinusoidal shape with a maximum value of 311V.

From figure 17, it can be seen that the load current for the first mode (first load) takes the value 60A and in the second mode (second load inserted) the value of the current follows this variation in demand and increases to a value of 160A, we see that for both modes the form of the current is purely sinusoidal so with this control technique the quality of the energy is better

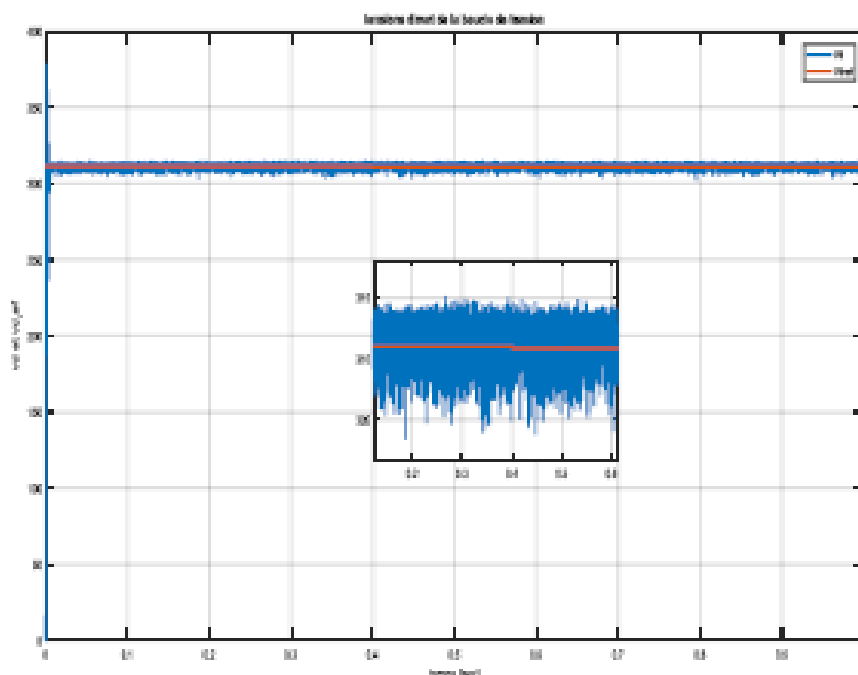
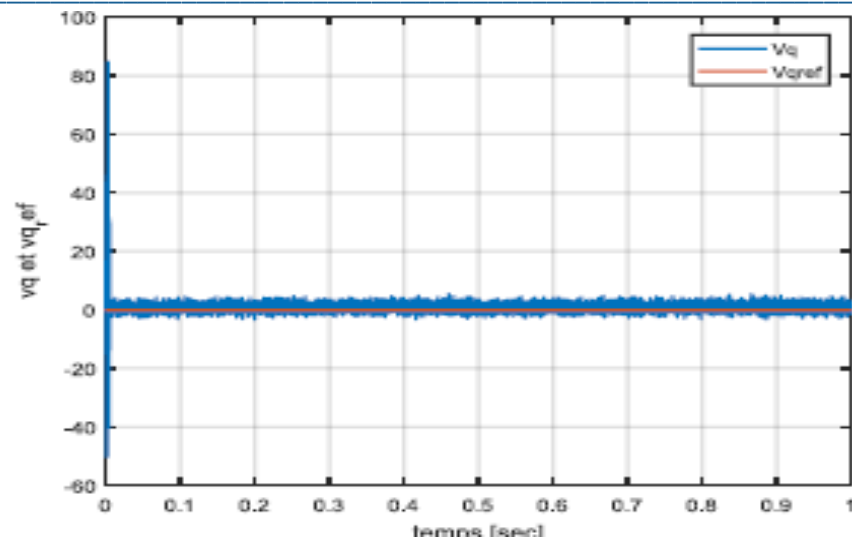
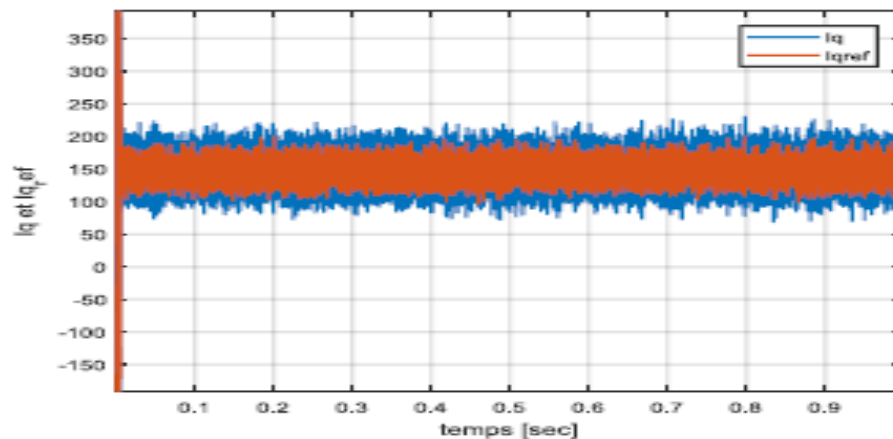


Fig.18 Direct outputs Voltages Vd Vdref

Fig. 20 Direct outputs current I_d I_{dref} Fig. 21 Inverse outputs currents I_d I_{dref}

6. CONCLUSION

In the first part of this article, a definition of the smart grid as well as these objectives and these advantages were presented. In the second part, the principle of the hierarchical control was also detailed then we started the study of the traditional control of the droop in the micro networks. Numerical simulations were presented to validate the qualities of the proposed active and reactive power controller (Droop Control).

The results obtained show the good sharing of the active and reactive powers while keeping the frequency and the voltage stable at the terminals of the load. It is obvious that a droop regulator giving a good sharing of active and reactive power is obtained at the expense of the degradation of the voltage regulation.

From the simulation results, we observe to a large extent the dynamics and stability of frequency and voltage source inverters in parallel operation. Although no external communication mechanism is required between the inverters, which allows good load sharing, in addition to the ease of implementation, based only on local voltage and current information, which replaces the need for communication especially in isolated mode, when all units must share power without the need to communicate with other units.

These drawbacks limit its applications; it has an inherent trade-off between load sharing accuracy and voltage regulation as it introduces frequency and voltage variations proportional to active and reactive output power.

Classical droop control uses an assumption of pure inductive or resistive output impedance, which is practically not the real case, the latter could be a complex impedance, and this is due to the nature of the distribution network.

In conclusion, using the usual droop method, the dynamics of the undulator cannot be controlled individually, which leads us to think about other perspectives that are necessary for the continuation of the work, namely the use of the droop control with smart new techniques.

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