Microgrid Control and Grid Interconnection

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***Abstract*— Defined as a group of distributed energy resources forming between them an independent subsystem capable of operating interconnected to the main grid or autonomously, microgrids are becoming a real solution to face the continuous expansion needs related to the distribution grid. Environmental concerns, the ample supply of renewable energy, the advent of powerful storage equipment, the availability of reliable inexpensive communication systems and the development of powerful algorithms for control and scheduling have made the concept of microgrid increasingly interesting. Yet, for economic reasons and for the sake of security of supply, a microgrid benefits from its connection to the main grid.**

The presented work aims to approach, through detailed and concise simulations, control strategies implemented in the microgrid scope, focusing the study in the stability of the system's controllable variables, frequency and voltage, in the moments immediately after the occurrence of a disturbance caused by an islanding process. For such purpose, a simulation platform was developed composed by two distinct microgeneration sources, namely the photovoltaic panel and the fuel cell, both modeled and simulated, storage units, conversion equipment and fixed loads. It is shown a detailed approach to the control strategies applied by the inverters, and two different modes of operation were evaluated and compared. The simulations are made based on four different scenarios, in way that illustrates clearly the dynamic stability processes that occur in a microgrid and, by that, allowing to draw some major conclusions regarding the variables behavior and the time that they take before restoring process is completed.

Through the obtained results it's possible to analyze the feasibility of the system's operation based on the set of characteristics that support the microgrid concept, from a point of view focused exclusively on the dynamic behavior control.

***Keywords*—Microgrid, Microsources, Control, Islanding, Stability**

I. INTRODUCTION

Over the years, electricity supply has been made, mainly, based on large power plants that, with the help of long transmission lines, take power to the places of consumption. However, issues such as environmental concerns, the emergence of renewables and the rapid development of storage equipment, have raised interest in the microgrid concept. Microgrid can be defined as a set of geographically close distributed energy resources, such as generation, storage and loads, that together form an autonomous unit with its own control system within the main grid. It has the possibility of operation in two different modes: interconnected with the main grid or isolated (or, as often called, island mode).

One of the main attraction points of the microgrid study is the possibility that it offers of a larger penetration of renewable energy in the distribution grid, making use of small scale generation units that allows the increasing of production efficiency and decreasing of CO_2 emission levels when compared to large power plants [1]. However, it is necessary to consider the intermittence of renewable resources, thus making essential the use of some storage equipment ensuring that the available energy is sufficient to satisfy the consumption. The storage unit will store the surplus of production when the consumption is less than the generation or, in turn, will supply the loads when the consumption exceeds the generation. There is also the possibility, in the case where the production exceeds the consumption and the storage unit is fully charged, to sale the surplus to the main grid.

Another matter of fundamental interest is the use of power electronic devices, as some of the generation sources and storage units have a DC characteristic and cannot be directly connected to the AC microgrid without the use of a proper DC/AC inverter. Also, in a microgrid without any synchronous generator operating in island mode, the inverters are essential for control purposes, as responsible for regulation of frequency and voltage within the system. When operating interconnected mode, the microgrid sees the main grid as an infinite power source, thus being in charge of voltage and frequency control. This will be discussed further.

The microgrid concept and its applications have been extensively studied in recent decades, but there is still a vast potential to be explored in technical, economic and regulatory issues. This local small-scale production paradigm is seen as an effective solution to tackle the environmental impact of energy production and to face the distribution grid's continuous expansion needs. Its considered as important step towards the creation of small, self-sufficient communities that uses exclusively the local resources available to generate all the energy consumed, thus creating small local economies and contributing for the sustainability of the planet.

The paper is organised in folowing order: Section I – Introduction; Section II – Microgrids and state-of-the-art; Section III – Dynamic Modelling; Section IV – Control Strategies; Section V – Simulation and Results; Section V – Conclusion and future work.

II. MICROGRIDS AND STATE-OF-THE-ART

Although a widely discussed subject, a clear and globally accepted definition on what it is and what it is not a microgrid is yet to be achieved. When trying to define it, some relevant questions appear. Do microgrids need to incorporate renewables? Should microgrids have smart meters? Should a microgrid be obliged to connect and disconnect from the main grid? All of these are still open questions [2]. Despite the scarcity of a formal definition, several identities have their own definition on what they comprehend to be a microgrid. The U.S. Department of Energy defines it as a set of distributed energy resources and loads with electric limits clearly defined that acts as a controllable unit and may operate connected or disconnected to the main grid [3]. The International Council on Large Electric Systems, CIGRÉ, defines it as a distributed electric system containing loads and distributed energy resources that may operate in a controlled and coordinated way if connected to the main grid or if in island operation [4]. The E.U. Research Projects defines it as a LV distribution system with distributed energy resources, storage devices and controllable loads that may operate in non-autonomous mode if connected to the main grid or, in an autonomous way if disconnected [5]. From this set of conclusions some conclusions can be drawn:

- It is a localized set of distributed energy resources, storage units and loads;
- Can operate connected or disconnected to the main grid;
- Plan, manage and coordinate all its operation, thus forming a unique and controllable unit.

These points, are common to all definitions and intend to give an, as clear as possible, idea on what is the main idea behind the microgrid concept.

Microgrids can be classified based on different market segments where its use is presented as a solution [1]:

- Campus/Institutional: aggregation of local existent generation and localized loads (industrial parks);
- Remote: never connect to the main grid (small villages or islands);
- Military: focused on the physical security of military bases;
- Commercial/Industrial: not yet fully standardized, which leads to limitations on its implementation;
- Community: cannot operate disconnected to the main grid.

Nowadays, the majority of microgrids installations are presented in the Campus/Institutional and in Community classes. Nonetheless, recently the Military class has seen an increased investment, as the military bases depend highly on the main grid and in some scenarios that may be not adequate, so to prevent it, military identities have been using PV panels or wind turbines to increase the energy feasibility.

A. Control Architecture

In Figure 1 is presented the simplified microgrid operational architecture diagram as studied by the EU R&D Microgrids Project. The architecture is composed by the LV grid, loads, controllable and uncontrollable micro sources, storage equipment and a control scheme supported by a communications infrastructure used to monitor and control the system [6]. The control system is composed by the Microgrid Central Controller (MGCC), the Microsource Controllers (MC) and the Load Controllers (LC).

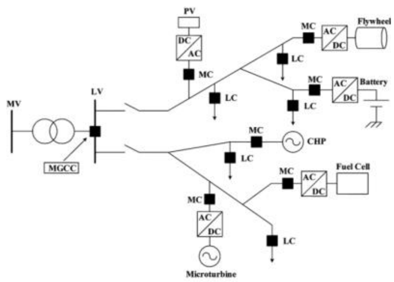


Figure 1 – Microgrid control architecture diagram [6]

The microgrid is centrally controlled and managed by the MGCC installed in the MV/LV substation, being the interface between the microgrid and other actors, and performing key functions such as economic management and control functions. The LCs are in the loads serving as interface through the implementation of load shedding functions. The MCs are in the micro sources and control the active and reactive powers injected in the system by the respective source. These LCs and MCs exchange information with the MGCC by planning and managing the microgrid through the provision of set-points of operation, requesting information regarding active and reactive powers or voltage levels and control messages of the microgrid switches.

B. Potential Benefits

Identifying the benefits associated with the use of microgrid a multi-objective and multi-stakeholder coordination task. The scale and type of benefits obtained are dependent on the design and planning circumstances implemented.

From an economical perspective, microgrids can:

- Reduce energy costs;
- Sell the surplus to the main grid;
- Avoid/reduce grid investments.

From an energy quality perspective, microgrids can:

- Reduce energy outages;
- Improve energy quality;

From an environmental perspective, microgrids can:

- Reduce CO_2 emissions;
- Reduce atmospheric pollutants;

All these points are detailed in [8].

C. Technologies implemented in the microgrid scope

The study of microgrids are based on the assumption of making the most of the use of distributed generation resources and storage equipment. Regarding the usually called microsources, the main technologies implemented are photovoltaic panels, small-scale wind turbines, fuel cells and microturbines. In the storage units field, the usually implemented technologies are batteries, flywheels and supercapacitors.

Photovoltaic technology is the interface that converts energy from solar radiation into electricity. This technology is particularly attractive from the point of view of microgrids because it can be installed on top of buildings and thus solving installation problems in small areas

Wind technology makes it possible to take advantage of kinetic energy from the wind and through wind turbines transform it into mechanical energy and consequently into electrical energy. The adaptation of wind technology to the micro-networks requires the use of these turbines on a small scale so that they can be arranged in areas close to the consumers.

Fuel cells are devices that convert chemical energy directly into electrical energy through an electrochemical reaction between hydrogen and oxygen. Its operation is similar to batteries. This is a suitable and recommended technology to be used in distributed generation due to its high efficiency, scaling, modulation and practically negligible emission levels harmful to the environment.

Microturbines are small combustion turbines used as local or mobile generation sources or in mechanical drive applications. Microturbines offer a vast amount of potential advantages as reduced number of moving parts, compact size, light weight, better efficiencies, low pollutant emissions, low electricity costs, and the opportunity to re-use wasted heat.

Batteries are devices composed of one or more electrochemical cells that store electrical energy in the form of chemical energy. There are different types of batteries with different characteristics depending on their constituent chemicals.

Flywheels are systems that base their operation on the storage of kinetic energy in a rotational mass. This energy can then be converted into electricity through a generator. Flywheels have a very short response time and can deliver high energy levels which makes them useful for critical load protection.

Supercapacitors are a new and emerging technology with potential to provide important advances in the field of energy storage. The principle of operation of this technology follows the same fundamental principle of conventional capacitors, however using an electrode with larger contact areas and finer dielectric to obtain higher capacitances.

III. DYNAMIC MODELLING

A. Photovoltaic Panel

In this work the modeling of the photovoltaic panel was carried out through the adoption of the simplified model described in [9] and its *Simulink* interface is illustrated in Figure 2

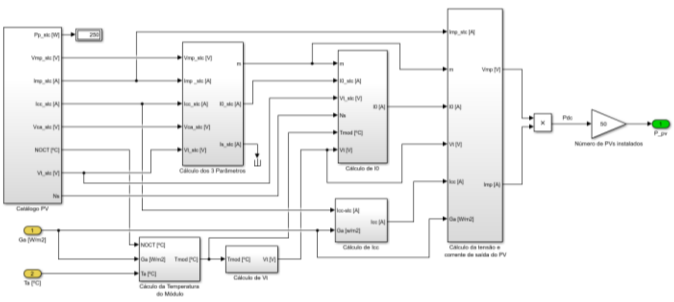


Figure 2 – PV Simulink Interface

This model is based on three parameters obtained exclusively from values supplied by the datasheet and defined by the following equations:

$$m = \frac{V_{MP}^{stc} - V_{ca}^{stc}}{V_t^{stc} \ln\left(1 - \frac{I_{MP}^{stc}}{I_{cc}^{stc}}\right)} \tag{1}$$

$$I_0^{stc} = \frac{I_{cc}^{stc}}{e^{\frac{V_{ca}^{stc}}{mV_t^{stc}}} - 1} \tag{2}$$

$$I_{cc}^{stc} = I_s^{stc} \tag{3}$$

where m is the diode ideality factor, I_0^{stc} is the diode's saturation current, I_s^{stc} is source's current, V_{MP}^{stc} is the output voltage, V_{ca}^{stc} is the open circuit voltage, V_t^{stc} is the thermal potential, I_{MP}^{stc} is the output current, and $I_{cc}^{stc}$is the short circuit current. STC index means that the value is obtained under Standard Test Conditions. From the values obtained it is possible to compute I_0 and I_{cc} for any value of temperature or irradiation:

$$I_0 = I_0^{stc}\left(\frac{T}{T^{stc}}\right)^3 e^{\frac{\varepsilon}{m'}\left(\frac{1}{V_t^{stc}} - \frac{1}{V_t}\right)} \tag{4}$$

$$I_{CC} = I_{cc}^{stc}\frac{G}{G^{stc}} \tag{5}$$

where T is the module temperature, G is the solar irradiation, ε is silicon hiatus (1,12 eV) and m' is computed by:

$$m' = \frac{m}{N_s} \tag{6}$$

where N_s is the number of cells connected in series. It is necessary to introduce the relation between the module temperature and the ambient temperature, computed by:

$$T = T^a + \frac{G(NOCT - 20)}{800} \tag{7}$$

where T^a is the ambient temperature and $NOCT$ is the normal operating cell given in the datasheet. The output voltage at any input conditions is computed through the Gauss-Seidel iterative method:

$$V_{MP}^{(k+1)} = mV_t \ln\left(\frac{\frac{I_{cc}}{I_0} + 1}{\frac{V_{MP}^{(k)}}{mV_t} + 1}\right) \tag{8}$$

The computation should continue as long as the difference between two iterations is as close as desired. The output current is the computed by:

$$I_{MP} = I_{cc} - I_0\left(e^{\frac{V}{mV_t}} - 1\right) \tag{9}$$

Finally, the output power of the model can be computed by:

$$P_{max} = V_{MP} I_{MP} \tag{10}$$

B. Fuel Cell

The adopted model was validated by the Microgrids project [10] and corresponds to the Solid Oxide Fuel Cell modeling. Its Simulink interface is present in Figure 3.

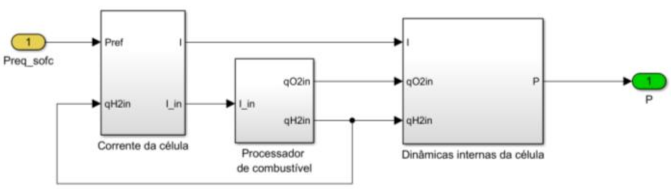


Figure 3 - SOFC Simulink interface

In order to describe the main electrochemical reactions occurring in the SOFC, one begins by assuming that the anode is fed only by hydrogen, H2, while the cathode is only supplied by oxygen, O2, so that the only reaction to occur in the cell is as described in (11).

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{11}$$

This establishes a potential difference between the anode and the cathode that can be calculated by combining the Nernst equation and the Ohm law by:

$$V_{fc}^{r} = N_0\left[E_o + \frac{RT}{2F}\left(\ln\frac{p_{H_2}p_{O_2}^{\frac{1}{2}}}{p_{H_2O}}\right)\right] - rI_{fc}^{r} \tag{12}$$

Where E_o represents the voltage associated with the free energy of Gibbs, p_{H_2}, p_{O2} and p_{H_2o} are the partial pressures of each component, N_0 represents the number of cells, r represents the electric resistance of the cell, I_{fc}^{r} is the output current, R is the universal gas constant, T is the channel temperature and F is the Faraday constant. The partial pressures of each component are given by:

$$p_{H_2} = \frac{\frac{1}{K_{H_2}}}{1+\tau_{H_2}s}\left(q_{H_2}^{in} - 2K_rI_{fc}^{r}\right) \tag{13}$$

$$p_{O_2} = \frac{\frac{1}{K_{O_2}}}{1+\tau_{O_2}s}\left(q_{O_2}^{in} - K_rI_{fc}^{r}\right) \tag{14}$$

$$p_{H_2O} = \frac{\frac{1}{K_{H_2O}}}{1+\tau_{H_2O}s}2K_rI_{fc}^{r} \tag{15}$$

In the cell there are two distinct currents: the input currentI_{fc}^{in}, and the output current, I_{fc}^{r}. The input current is obtained by the required power, through equation (16).

$$I_{fc}^{in} = \frac{P_{req}}{V_{fc}^{in}} \tag{16}$$

On the other hand, the output current is obtained considering the safety limits that allow the cell to function properly. To guarantee these limits a usage factor is defined as the ratio between the flow that reacts and the flow that enters the cell.

$$U_f = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} = \frac{2K_rI_{fc}^{r}}{q_{H_2}^{in}} \tag{17}$$

Assuming for a given hydrogen flow the typical value for the utilization factor should vary from 80% to 90% to avoid any kind of damage to the cell. If it exceeds 90%, irreversible damage caused by lack of sufficient fuel may occur, whereas if the factor is less than 80%, excessively high voltages may occur in the cell. The current in the cell shall be equal to the input current provided it is limited to the following range:

$$\frac{0{,}8q_{H_2}^{in}}{2K_r} \leq I_{fc}^{r} \leq \frac{0{,}9q_{H_2}^{in}}{2K_r} \tag{18}$$

In addition to this condition, the output current of the cell is still affected by the time constant associated with the electrical component of the cell. The electric response dynamics is relatively fast and is modeled by a first order transfer function with time constant Te (s), which usually has values that are around 0.8 s. The fuel processor allows regulating the incoming flows of the reactants. An optimum utilization factor (U_{f_opt}) of 85% is assumed, which allows controlling the input flow by measuring the output current of the cell, such that:

$$q_{H_2}^{in} = \frac{2K_rI_{fc}^{in}}{0{,}85} \tag{19}$$

The molecular ratio of hydrogen to oxygen, RH-O, is two to one, however, the entry of excess oxygen is always allowed to maximize its reaction with hydrogen. Under normal operating conditions this ratio should be 1,145 to ensure that the cell pressure difference does not exceed 4 kPa. At this point, it is also necessary to consider the response dynamics of the part corresponding to the chemical reactions that occur in the cell. This response is slower compared to the electric response, and is also modeled by a first-order transfer function with a time constant Tf (s), which in this case is around 5 s.

C. Storage Units

Storage devices in a microgrid are essential to ensure uninterrupted power supply and must be able to provide the necessary active and reactive powers ensuring the balance of the system in cases of disturbance or load variation. From the control point, the modeling of these devices is done through the respective inverter that serves as interface with the grid. This strategy allows storage devices to function as controllable and rapidly responsive AC voltage sources for load changes or disturbances. In addition, and only for modeling purposes because, in reality, this is not the case, storage devices act as unlimited sources of storage capacity. The active power required to balance the generation and consumption within the microgrid is injected by the storage devices according to the control strategy implemented by the respective inverter. These investor control strategies will be introduced in the next section and will be further explored in Chapter 4.

D. Inverters

In a conventional power system, synchronous machines are usually responsible for voltage and frequency control, however, in a microgrid it is not common to find such devices. Understanding the control strategies of the inverters is fundamental to guarantee the stability of the system when in the presence of variations of generation or consumption. The investor control strategies adopted can be divided into two types:

- PQ control: the inverter has the function of supplying a given active and reactive power value according to a previously defined set point. The inverter operates in an interconnected mode with the grid, injecting into the network the power it has available to its terminals.

- VSI control: the inverter operates as a voltage source controlled to provide the loads with predefined voltage and frequency values. The active and reactive power supplied by the inverter is dependent on the load and not on set-points as in the case of the PQ control. The inverter is responsible for establishing the voltage wave with desired amplitude and frequency values.

The model presented here is made from an exclusive control point of view, so related aspects such as transients, harmonics or losses in the inverters were not taken into account in the behavior analysis. In chapter 4 the control strategies presented here will be studied in detail.

E. Load

All loads used throughout the work were modeled following a constant power characteristic, which means that the active and reactive powers consumed have a fixed and unchanged value during the time period of the simulation. It was also considered that the network where the simulations are carried out is three-phase and always in balanced operation.

IV. CONTROL STRATEGIES

Microgrids are extremely flexible systems when implemented in the conventional distribution grid due to their ability to operate autonomously over any other power system. However, this is only possible if the micro-network operates under appropriate control and management strategies. Microgrids can be classified as [11]:

- Grid forming unit: it defines the voltage and the reference frequency, ensuring the rapid response and correct balance between generation and consumption in the microgrid;
- Grid support unit: components whose active and reactive power is determined/modified according to the voltage and frequency characteristics of the system;
- Grid parallel unit: non-controllable components, whose function is to inject as much power into the network as possible.

Table 1 - Components control category

Categories	**Component**
Grid Forming	Storage Unit
Grid Support	Fuel Cell Microturbine
Grid Parallel	Photovoltaic Wind Turbine

Table 2 - Control strategy association

Inverter Control	Categories
VSI	Grid Forming
PQ	Grid Support Grid Parallel

A. PQ Control

The inverters controlled by PQ have two fundamental control functions in their operation: active and reactive power injection in the microgrid through a stipulated set-point and DC-link voltage control. The adopted model is presented in [11]. DC voltage is controlled by a proportional-integral controller (PI) that corrects the voltage error that arises on the DC stage by adjusting the magnitude of the active current injected as illustrated in Figure 4

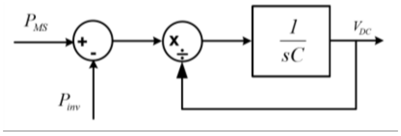


Figure 4 - DC-link model [11].

The full control scheme of PQ inverters is shown in Figure 5. The control system has the inputs: measured DC voltage, reactive power measured at the output of the converter and the quadrature and direct current components injected by the inverter into the microgrid, id and iq. The latter are obtained using the transformation matrix dq0 as presented in [12]. The reference DC voltage values and reference reactive power are defined by the MGCC and supplied to the MCs of the respective micro-source. The error in the DC voltage is corrected through a PI controller whose output is used in order to generate the direct current reference component, id. The power variations cause deviations in the DC voltage that are controlled by adjusting the magnitude of the direct current component delivered to the microgrid by the respective microsource. On the other hand, the error obtained by the difference between the reference reactive power value and the reactive value injected by the inverter in the microgrid is corrected through another PI controller whose output is used in order to generate the reference quadrature component of the current, iq. Any error in the reactive power is controlled by adjusting the magnitude of the quadrature component of the current injected into the micro-network by the respective micro-source [11]. Then these components of the current pass through a control loop composed of two PI controllers to generate the direct and quadrature voltage components, vd and vq, which will subsequently be subjected to the reverse dq0 transformation and thus serving voltage reference to the inverter. The voltage obtained at va*, vb* and vc* are the desired voltage values at the output of the inverter.

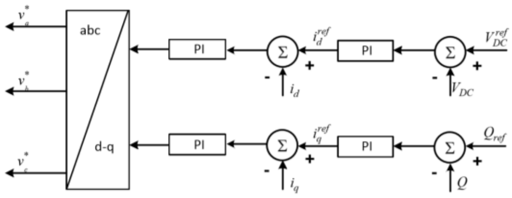


Figure 5 - PQ control model [11]

B. VSI Control

The inverters controlled by VSI have the function of emulating the behavior of synchronous generators of conventional power systems by changing the values of frequency and voltage through respective variations of active and reactive power. These inverters are usually associated with storage systems. The adopted VSI control model is also described in [11]. The control principle is defined by the following droop equations:

$$\omega = \omega_0 - k_P \cdot P$$
$$V = V_0 - k_Q \cdot Q \quad (20)$$

where P e Q are the inverter active and reactive output powers, k_P e k_Q are the droop coefficients and ω_0 e V_0 are the frequency and voltage reference values. The full control scheme is shown in **Erro! A origem da referência não foi encontrada.**. The model is based on three control steps: power calculation injected by the inverter, application of droop characteristics and obtaining the reference signal. The output voltage and current of the inverter are measured to calculate the active and reactive powers injected by the inverter into the system. This calculation step introduces into the system a time delay defined by the constants TdP and TdQ. Using the measured active power value, the inverter output voltage frequency is determined by the droop characteristic associated with the coefficient kp. Similarly, the measured reactive power determines the magnitude of the inverter output voltage through the droop characteristic associated with the coefficient kq.

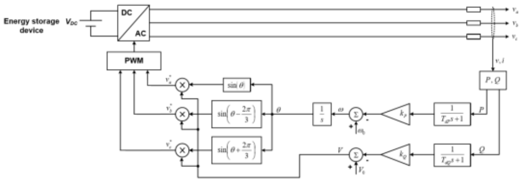


Figure 6 - VSI control model [11]

C. Single-Master Operation

Single-Master operation consists of the use of several inverters controlled by PQ and only a single inverter controlled by VSI with the function of supplying the voltage and frequency references to the system when it is in island mode. The Single-Master strategy implemented was studied in [13]. VSI control system responds to load variations in the microgrid according exclusively to the information available at its terminals. Considering only one VSI in operation, any active or reactive power variation will lead to a frequency and voltage variation, respectively, determined by the droop characteristic of the inverter, hence:

$$\begin{aligned} \Delta\omega = \omega_{pré} - \omega_{pós} &= \omega_0 - k_P \cdot P \\ &- [\omega_0 - k_P \cdot (P + \Delta P)] \\ &= k_P \cdot \Delta P \\ \Delta V = \omega_{pré} - V_{pós} &= V_0 - k_Q \cdot Q \\ &- [V_0 - k_Q \cdot (Q + \Delta Q)] \\ &= k_Q \cdot \Delta Q \end{aligned} \quad (21)$$

where $\omega_{pré}$ and $\omega_{pré}$ represent the frequency and voltage before the power variation and $\omega_{pós}$ and $V_{pós}$ represents the frequency value resulting from the power variation. The internal communication system of the microgrid makes the exchange of information between its components, allowing the MGCC to receive information from the local controllers of the microgrid, thus being responsible for updating the set-points of each PQ inverter associated with controllable sources to ensure normal system operation during the disturbance.

D. Milti-Master Operation

Multi-Master operation consists of the use of several inverters controlled by VSI and possibly other inverters controlled by PQ. Multi-Master strategy adopted here is presented in [13] and complemented with information contained in [14]. In this type of operation, power variation is shared between all VSIs to ensure that there are no components operating at different frequencies. In a system with n VSI, the power variation caused by a load increase is given by:

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \quad (22)$$

The frequency of the system can be obtained through:

$$\begin{aligned} \Delta\omega = \omega_{pré} - \omega_{pós} &= \omega_0 - k_{P_i} \cdot P_i \\ &- [\omega_0 - k_{P_i} \cdot (P_i + \Delta P_i)] \\ &= k_{P_i} \cdot \Delta P_i \end{aligned} \quad (23)$$

As can be observed, the frequency variation depends on the power variation in each VSI and not on the total variation, which allows to conclude that the use of more than one VSI in the system reduces the frequency deviation from the reference value. If there are two VSIs in the system, the power sharing must be processed in such a way that the frequency variation imposed by each VSI is equal, therefore:

$$\Delta\omega = k_{P_1} \cdot \Delta P_1 = k_{P_2} \cdot \Delta P_2 \quad (24)$$

It is also known that the coefficients of droop, kp1 and kp2, are known values imposed by the controller and that the sum of the power variations in each VSI is necessarily equal to the total power variation, so solving the system of equations (25) it is possible to calculate the power variation to be supported by each of the VSIs.

$$\begin{cases} k_{P_2} \cdot \Delta P_1 = k_{P_2} \cdot \Delta P_2 \\ \Delta P_1 + \Delta P_2 = \Delta P \end{cases} \quad (25)$$

This method holds true for whatever is the VSI number in the system. It is possible to repeat the process for the case of voltage/reactive droop control, however, in the Low Voltage networks the distribution cable impedances do not allow an accurate reactive power sharing between VSI [13].

E. Secondary Control

The control presented in the previous sections, commonly referred to as the primary control, allows the microgrid to be stabilized after a load variation, but does not allow it to return to the voltage and frequency nominal values checked prior to the disturbance. That being so, the use of a secondary control becomes critical to restore the values back to their nominal conditions. The implementation of this type of control is done through a PI controller. The operation of the secondary control is the responsibility of the MGCC, so when the microgrid is in interconnection with the distribution grid, the MGCC inactivates the secondary control and the distribution network is responsible for the balance of the system. In case of island operation, the MGCC is responsible for regulating the secondary control associated with each micro-source.

The secondary frequency control is active whenever, operating in island mode, a variation of power in the microgrid is detected which consequently causes frequency deviations from its nominal value of 50 Hz. The error between the nominal value and the measured value is corrected through a PI controller. Thereafter, the correction value is added to the set point established before the disturbance, thereby generating a new active power reference to be provided locally to the controllable micro-source associated with the secondary controller in question.

The secondary voltage control is implemented in the same process as the secondary frequency control, however the voltage is not such a sensitive variable, so to very small voltage variations, the operation of the secondary control is not necessary [14].

V. Simulation and Results

In this chapter, results of several simulations will be presented with the purpose of analyzing the performance of the control functions evidenced in the previous chapter.

The test system has capacity of 115 kW, consisting of three photovoltaic (30 kW, 30 kW and 20 kW) installations corresponding to 80 kW of nominal power and an installation composed of two fuel cells (20 kW and 15kW) totaling 35 kW of nominal power. The storage system is not counted because for the purposes of the study in question it is used only to inject/absorb power in the transients corresponding to islanding situations. The network is also composed of an MV/LV transformer. On the LV side of the transformer is the device responsible for separating the microgrid from the main grid. In the system there are four different blocks of loads distributed through the system. In Single-Master simulation is counted only one storage unit and VSI in the system, while in Multi-Master simulation another storage unit and VSI is added in parallel.

Four scenarios were simulated. Scenario A corresponds to a Single Master operation, with an islanding occurring while the microgrid was importing power from the main grid. Scenario B is the same as A but in Multi-Master operation. Scenario C corresponds to a Single Master operation, with an islanding occurring while the microgrid was exporting power from the main grid. Scenario D is the same as C but in Multi-Master operation

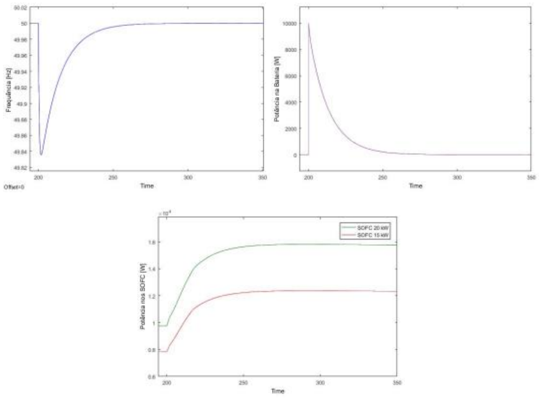
A. Scenario A: Importing Single-Master

In table 3 is illustrated the power balance. The microgrid is importing 10 kW from the main grid.

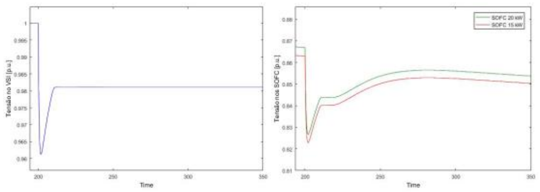
Table 3 - Scenario A and Scenario B Power Balance

	P [kW]	Q [kvar]
Generation	65,86	21
Load	75	24
Importing	10	3

The results from the simulation are presented in the following graphics.



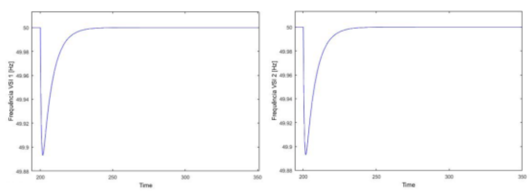
At t = 200s an islanding occurs, resulting in a deficit of 10 kW (a value that was previously being imported by the distribution network). At that same time the VSI and storage system act, compensating this deficit and consequently changing the frequency value of the system to 49.84 Hz. To reset the frequency value to its nominal value, the MGCC changes the power of fuel cells to compensate the deficit so far supported by the storage system. There is an increase of 5,714 kW in the nominal 20 kW fuel cell and an increase of 4,286 kW in the nominal 15 kW fuel cell. As the fuel cell model describes, it has in its dynamics time constants making it not instantaneous. As fuel cells increase their generated power, the storage system, per action of the secondary control decreases the power it injects into the microgrid and thus re-establishes the frequency value at its desired nominal value. The operation returns to stability past about 60 s after the islanding.

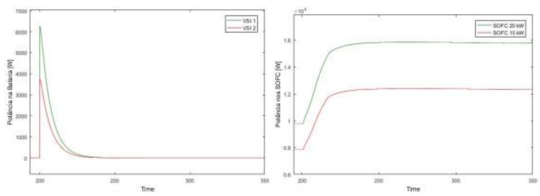


The system reference voltage decreases in t = 200 s due to the reactive power deficit caused by the islanding. The stabilization occurs about 15s after the islanding at 0.9811 p.u. The output voltages of the fuel cells decrease slightly as consequence of the decrease in the reference voltage amplitude value, stabilizing at 0.8541 p.u. in the nominal 20 kW fuel cell and in the 0.8502 p.u. in the nominal 15 kW fuel cell, about 100s after the islanding. The stabilization of the fuel cell voltage value is more time-consuming due to two factors: the already mentioned fuel cell time constants and the fact that the voltage is also influenced by the cell power variation occurring due to the frequency control dynamics mentioned above.

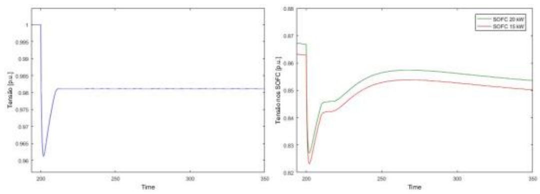
B. Scenario B: Importing Multi-Master

The power balance in the microgrid is the same as in the previous scenario. It is importing 10 kW from the main grid. The results from the simulation are presented in the following graphics.





At t = 200s the islanding occurs, resulting in a deficit of 10 kW (a value that was previously being imported by the distribution network). At that time, the storage systems act to compensate in a shared way the power deficit. Sharing is, as seen in Chapter 4, dependent on the respective droop coefficients imposed by its associated VSI and is done in such a way as to ensure that both VSIs always impose the same frequency value on the microgrid. The 10 kW deficit was shared as follows: VSI 1 assumed 6,252 kW of value and VSI 2 assumed 3,744 kW. This process has caused the system frequency to drop to 49.89 Hz. To reset the frequency value to its nominal value, the MGCC changes the required power values of the fuel cells so that they are compensated the deficit supported by the storage systems, increasing 5,714 kW in the nominal 20 kW fuel cell and increasing 4,286 kW in the nominal 15 kW fuel cell. Again, the model time constants of the fuel cell causes this increase not to be instantaneous, so that as the fuel cells increase their generated power. The storage system, by the action of the secondary control, decreases the power which injects into the microgrid and thus reestablishes the frequency value at its intended nominal value. The operation returns to stability past about 40 s after the islanding.



Regarding the voltage in the system, the respective graphs for the control in Single-Master, show no significant differences between the two. This is due to the fact that, as mentioned in Chapter 4, that in the low voltage networks, the impedance of the distribution cables does not allow a precise sharing of reactive power between VSI, so that the voltage/reactive power control function, even in operation in Multi-Master, it is only responsibility of one of the VSIs of the system.

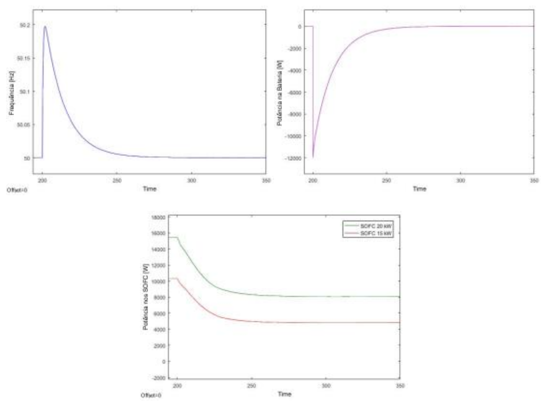
C. Scenario C: Exporting Single-Master

In table 4 is illustrated the power balance. The microgrid is exporting 10 kW from the main grid.

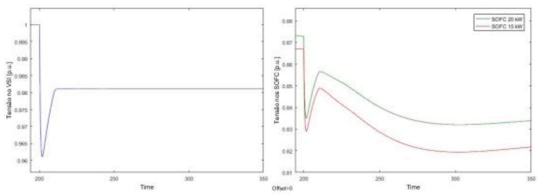
Table 4 - Scenario C and Scenario D Power Balance

	P [kW]	Q [kvar]
Generation	73,83	21
Load	61	24
Importing	12	3

The results from the simulation are presented in the following graphics.



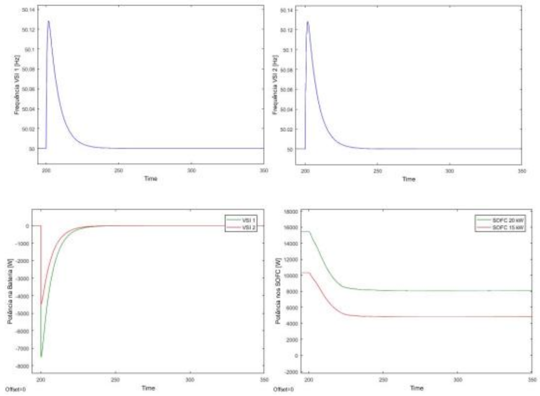
At t = 200s the islanding occurs, resulting in an excess of 12 kW (a value that was previously being exported to the distribution network). At that same time the VSI and storage system act by absorbing this excess, and consequently changing the frequency value of the system to 50.2 Hz. To reset the frequency value to its nominal value, the MGCC reduces the power of the fuel cells to decrease the internal generation in the microgrid. There is a decrease of 6,857 kW in the nominal 20 kW fuel cell and a decrease of 5,143 kW in the nominal 15 kW fuel cell. Again, the time constants of the fuel cell cause this decrease not to be instantaneous, so as the fuel cells decrease their generated power, it decreases the excess generation in the microgrid. The amount of power absorbed by the storage system (the storage system is absorbing the excess generation that is not compensated by the fuel cells) is also reduced by secondary control. This process lasts until the moment when the fuel cell set has decreased its combined output by 12 kW (original excess value) and, according to the power balance, there is no excess power in the micro-network. From the moment the storage system stops absorbing power the frequency value is reset to its nominal value. All this restoration takes about 60s.



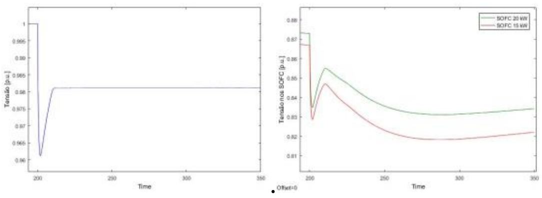
The system reference voltage decreases in t = 200 s due to the reactive power deficit caused by islanding. The stabilization of its value occurs about 15s after islanding at 0.9811 p.u. The fuel cell output voltages decrease slightly as a consequence of the decrease in reference voltage amplitude value, stabilizing at 0.8339 p.u. in the nominal 20 kW fuel cell and 0.8218 p.u. in the nominal 15 kW fuel cell, about 100s after the islanding. The voltage in the fuel cells shows a more pronounced decrease when compared to the same situation in case of importation, since the output voltage is directly related to the output power. In the export, after the islanding, the power of the fuel cells reduces and consequently the voltage decreases, while in the import the power increases and consequently tension also increases.

D. Scenario D: Exporting Multi-Master

The power balance in the microgrid is the same as in the previous scenario. It is exporting 1w kW to the main grid. The results from the simulation are presented in the following graphics.



At t=200s the islanding occurs, resulting in an excess of 12 kW (a value that was previously being exported to the distribution network). At that moment the storage systems act to absorb, in a shared way, the excess power. Sharing is dependent on the respective droop coefficients imposed by its associated VSI and is done in such a way as to ensure that both VSIs at all times impose the same frequency value on the microgrid. The excess 12 kW was shared as follows: VSI 1 absorbed 7.507 kW of value and VSI 2 absorbed 4.493 kW. This process has caused the system frequency to rise to 50.13 Hz. To reset the frequency value to its nominal value, the MGCC reduces the requested power values of the fuel cells in order to decrease the internal generation in the microgrid. There is a decrease of 6,857 kW in the nominal 20 kW fuel cell and an increase of 5,143 kW in the nominal 15 kW fuel cell. Again, due to the time constants of the fuel cell model this decrease is not instantaneous, so that as the fuel cells decrease their generated power, the excess generation in the microgrid decreases, and by the action of the secondary control also reduces the amount of power absorbed by the two storage systems. This process lasts until the moment when the fuel cell set has decreased its production in such a way that there is no more excess power in the micro-network. From the moment the storage system stops absorbing power the frequency value is reset to its nominal value. This operation lasts about 40s



Regarding the voltage in the system, there are no significant differences compared to the Single-Master operation, due to the fact that, as seen in the case of import, in the low voltage networks the impedances of the distribution cables do not allow a precise sharing of reactive power between VSI, so the reactive voltage/power control function, even in Multi-Master operation, is the responsibility of only one of the VSIs of the system.

E. Single-Master vs. Multi-Master Comparison

In table 5 are presented numerical results obtained in the simulations concerning the dynamics between frequency and active power. The data on the dynamics between voltage and reactive power are not presented.

Table 5 - Single-Master vs Multi Master performance

	Importing		Exporting	
	SM	MM	SM	MM
Storage Unit Power [kW]	10	6,252 +3,744	12	7,507 +4,993
Maximum Frequency Deviation [Hz]	0,16	0,11	0,20	0,13
Restoration Time [s]	60	40	60	40

Analyzing the results, we concluded that if the microgrid operates with Multi-Master control, since the deficit/excess is shared between the storage systems, it is possible to obtain smaller frequency deviations in relation to their nominal value and shorter restoration times. Therefore, from an exclusive control point of view, the operation in Multi-Master is preferable because it presents better results. However, implementing this type of control is costlier as it requires at least two power storage devices, thus increasing the investment in the system.

VI. Conclusion and future work

A. Conclusion

In the scope of the work, two microsources were modelled, the photovoltaic panel and the fuel cell. The main reason for choosing these two technologies relates to their distinct way of interacting with the system where they are inserted. Although both have the purpose of injecting power into the microgrid, the way they do it differs. In the case of the photovoltaic panel, this is a device that operates in parallel with the grid, so the power injected depends exclusively on the meteorological conditions. In the case of the fuel cell the injected power depends on the power requested at the entrance of the system, which allows it to assist in the variations of load and has a fundamental role in its control. Due to these features, the fuel cell is designated as a net support device.

From the control point of view, different control strategies implemented by conversion devices were studied, allowing to associate the type of microsource or storage system with the desired control function. The VSI controlled inverter was studied, which intends to emulate the control performed by the synchronous generators in the conventional energy systems through the implementation of droop characteristics, and thus to define the frequency and voltage reference values to be followed by the whole system in case disconnected from the distribution network. It was also studied the PQ controlled inverter that intends to regulate the values of active and reactive power that the device that is added to it injects in the system. A secondary control has been studied and implemented that allows the system to recover the operation to its nominal values at times consequent to an islanding of the system. Two strategies of microgrid configuration that directly influence its performance were discussed: Single-Master control strategy and Multi-Master control strategy. The Single-Master strategy consists of the presence of only one VSI-controlled converter in the system, which ensures that only one device uniquely defines the frequency and voltage references of the entire system. In turn, the control in Multi-Master consists of the presence of more than one VSI-controlled converter in the system, so they will have to operate together defining the references for the system.

Testing and simulations of the operation of a test micro-network were performed for two different islanding situations, one at an instant that imported active power from the distribution grid and another at an instant in which excess energy generated in the microgrid was exported to the distribution grid. It was concluded that both the Single-Master strategy and the Multi-Master strategy are effective in executing the purposed control. However, differences between the two methods were pointed out and an analysis of the results was concluded that the Multi-Master strategy presents a better performance, since it originates smaller peaks of variable variation, and in addition , has smaller reset times, meaning that the microgrid is in unstable operation, or at least outside the nominal operating values, for a shorter period of time compared to the Single-Master operation.

B. *Future Work*

Taking into account the study carried out, it is considered of special importance the future investigation of the implementation of a strategy of centralized control of reactive power that allows the management and tension control in the microgrid in operation in Multi-Master, in an identical way to that studied for the active power, and that in the case of the reactive power has limitations in the low voltage cables.

In the case of load variations that cause very high frequency variations, and which are not possible to mitigate through microsources of the microgrid, the implementation of load-shedding strategies must be studied, which enable non-essential loads to be disconnected from the system. In this way it is intended to reduce the load variation and consequently reduce the frequency variation, allowing its value to approach the nominal value.

It will be interesting and relevant to analyze the control strategies under unbalanced operating conditions, since small-scale micro-sources, such as the photovoltaic panel and wind turbine generators with nominal power of a few kW will be single-phase units, which can contribute to the imbalance of the system and may render the strategies studied here ineffective.

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