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Hybrid AC/DC Microgrids for Rural Electrification

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Abstract

Microgrids are one of the most suitable solutions to fight against the energy poverty, existent in developing countries with a strong rural presence. The inclusion of the renewable energy as a way of energy generation is essential in these places, taking advantage of the high quantity of natural resources present there.

This dissertation elaborates the basic concepts of a microgrid, where it is pretended to make an upgrade of this grid, consisting in a union between AC and DC grids (a hybrid microgrid). In other words, the main idea is the exploration of the microgrid as a solution to support the electrification of remote areas, by exploring the endogenous resources, hence building a scalable solution that can emerge from a DC grid and, then, join to an AC grid.

The dissertation structure is in the direction of an hybrid solution, through the different explications about the basic concepts of the different types of existing MGs (AC and DC MGs); on how the MG can be controlled and can maintain its own stability and on how both types of MGs can interconnect between each other. This theorical strand is, then, transformed into a practical one, where the controls and the simulations to study will be applied.

It is noteworthy that, by recurring to the *MATLAB Simulink* Software, it will be possible to implement the design of the models to consider in each type of MG and their controls. These controls are defined by mathematical expressions that depend on the main role of each specific unit. This program allows the hybrid system, built in the end of this document, to be simulated in real-time, in order to perform the last conclusions and, consequently, the practical benefits, when applying these solutions in grids of the modern electric sector. Also, this work addresses the identification of technical requirements in the constitution of the hybrid microgrid and these requirements are validated by a symmetrical simulation, implying the development of models and a simulation platform, as referred before.

Keywords: AC, Control, DC, Electrification, Hybrid**,** Microgrid, Real-Time, Rural, Simulation, Software *MATLAB Simulink*, Units.

Resumo

As micro redes são uma das soluções mais adequadas para combater a pobreza energética nos países em desenvolvimento com forte presença rural. A inclusão da energia renovável como meio de geração de energia é essencial nestes meios, aproveitando a elevada quantidade de recursos naturais aí existentes.

Esta tese elabora os conceitos básicos de uma micro rede, onde é pretendido efetuar um *upgrade* da mesma, consistindo numa união entre a energia AC e a energia DC (i.e., uma micro rede híbrida). Por outras palavras, a ideia fundamental é a exploração da micro rede como solução técnica para suportar a eletrificação de zonas remotas a partir da exploração de recursos endógenos, contruindo uma solução escalável que pode emergir a partir de uma rede DC e, posteriormente, integrar-se numa rede AC.

A dissertação estrutura-se em direção a uma solução híbrida, através de explicações acerca dos conceitos básicos dos diferentes tipos de micro redes existentes (micro redes AC e DC); de como uma micro rede é controlada e mantém a sua estabilidade e de como ambos os tipos de micro redes se relacionam, com o intuito de as juntar. Esta vertente teórica é, logo de seguida, transformada numa vertente prática, onde são aplicados os controlos e as simulações a estudar.

É de salientar que, recorrendo ao Software *MATLAB Simulink*, será possível implementar o *design* dos modelos a considerar em cada uma das redes e os seus controlos definidos por expressões matemáticas dependentes do papel de cada unidade específica. Este programa permite ao sistema híbrido, construído no final deste documento, ser simulado em tempo real, de forma a retirar das últimas análises os resultados finais e, consequentemente, os seus benefícios práticos, ao aplicar estas soluções nas redes do setor elétrico atual. Este trabalho também endereça a identificação de requisitos técnicos na constituição da micro rede hibrida e, estes, são validados através de uma simulação simétrica, implicando o desenvolvimento de modelos e de uma plataforma de simulação, tal como referido anteriormente.

Palavra-Chave: AC, Controlo, DC, Eletrificação, Híbrida**,** Meios Rurais, Micro rede, Simulação, Software *MATLAB Simulink*, Tempo Real, Unidades.

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Thank you all,
Gonçalo Tovar

“Let everything happen to you: beauty and terror.
Just keep going. No feeling is final.”

Rainer Maria Rilke

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Abbreviations and Symbols

AC	Alternate Current
AG	Induction Generator
CAMC	Central Autonomous Management Controller
CERTS	Consortium for Electrical Technology Solution
DC	Direct Current
DER	Distributed Energy Resources
DG	Distributed Generation
DMS	Distributed Management System
DSO	Distributed System Operator
EMS	Energy Management System
HT	Hydro Turbine
HV	High Voltage
LV	Low Voltage
MG	Microgrid
MGCC	Microgrid Central Controller
MMG	Multi-Microgrid
MS	Micro Source
MV	Medium Voltage
PCC	Point of Common Coupling
PV	Photovoltaic
RES	Renewable Energy Source
RTU	Remote Terminal Unit
SG	Smart Grid
SM	Synchronous Machine
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
WG	Wind Generator
WT	Wind Turbine

Chapter 1

Introduction

This chapter addresses the global organization of this dissertation, on what are the main objective and purposes of this work. It also reinforces all the benefits that the hybrid micro-grids will offer for the future of power systems and energy in rural areas.

1.1. Motivation

Electricity, nowadays, has a very important role in the society and in the lives of every person, but energy poverty is a real issue, where around 70% of the rural areas, globally, are not prepared to electrification through grid extension [1]. One of the many reasons is the usage of non-renewable energy as a generation, for example, fuel fossils, because, not only, of the high costs spent but also due to the limitations and dangers it causes to the environment. In order to contradict these disadvantages, the usage of renewable energy on the power system and microgrids are becoming more popular through the years.

There are also big problems in the world of renewable energy. The weak reliability is a great example of a major disadvantage in the renewable energy's world. In these remote areas the endogenous resources can be better exploited, in order to find better technical solutions to support the electrification and to satisfy the low power in these areas. There are many existing solutions, for example, the grid extension, stand-alone systems, AC and DC microgrids, but due to the high costs of investment, these solutions are not very well accepted in these communities.

It is possible to contradict some of these disadvantages by implementing in these microgrids the concept of hybrid microgrid. These hybrid microgrids combines two different kinds of power generation technologies: AC and DC generation. These systems can distribute energy, through an independent grid, to a variety of customers and, their autonomous functionalities can provide the same qualities and services as the national grid to rural communities. These developing countries, without these systems, have a less reliable and cost-effective service. A hybrid microgrid is supplied by a mix of renewable energy sources (generation that can produce AC or DC energy), back-up batteries and, sometimes, a back-up genset (usually diesel generation) [3] [4]. It is important to add that the DC systems are easier to explore in these environments where there is need of low power consumption.

This document focuses primarily on analysing how the hybrid microgrids work, by joining small DC systems to an AC microgrid.

1.2. Main Objectives

The main objectives of this dissertation are:

- To understand the basic concepts of microgrids.

- To develop suitable models for AC/DC and hybrid microgrid systems.
- To identify control solutions for power conversion stages, in order to make possible the integration of DC and AC systems.
- To find a set of solutions and ideas for future and reliable work in the area.

1.3. Dissertation

This dissertation is divided into five chapters, where the first one, the Introduction, explains the contributions, the motivation and how the dissertation is organized.

The second chapter, the State of Art, reports the basic concepts of electricity in rural areas, how the microgrids and hybrid microgrids work, its architecture, models, electrical implementations, applications and the importance of these grids in places that are located far away from the big cities and the main grids.

In chapter 3, it is stated a more succinct explanation about how the models are design for the grids proposed and how the control functions, implemented in each unit, operate.

The fourth one starts by explaining how the simulation and tests will be performed, the parametrization of each models, the different scenarios considered and the implementation of the AC and DC microgrids that are being studied. At the end of this chapter, the results of the simulation for each scenario are analysed and studied.

The last chapter represents all the main conclusions taken from this dissertation.

Chapter 2

State of Art

This chapter summarizes the main difficulties of the electrification in rural areas, why microgrids is one of the main solutions to that problem and why the use of hybrid MG is a good alternative to solve the lack of robust solutions with a sound of acceptance. All the basic concepts used in this work are also addressed in this chapter and applied in future ones.

2.1. Electrification in Rural Areas

2.1.1. Limitations of the Rural Areas

As referred before, there is a large amount of population living in rural communities that do not have any access to electricity. The main reasons behind this is that the grid extension to these areas is a highly costly and not convenient in rural areas and these communities are completely isolated from the urban cities or villages [3]. For example, in Sub-Saharan Africa, the energy poverty problem affects 588 million people, leaving these citizens without the basic needs for lighting their houses [2].

2.1.2. Solutions and main advantages

There is a big set of solutions that can revert and help decrease this big problem, by helping to achieve the main goal of the SE4ALL (Sustainable Energy for All) initiative: universal access to electrification to all by 2030 [1].

Also, there is a large interest by many developing countries about these solutions that can improve, not only the quality of life, but also their local economies [6].

The main solutions (Figure 2.1) for this big problem are [1] [2]:

- Micro standalone power generation systems like for example solar home systems that supply power to small equipment (small televisions, stereo systems, mobile phone chargers):
    - These systems have usually a DC nature of power supply.
    - The size capacity of these systems varies between 1 and 100 W.
    - If the nature of the power supply in the system is AC, the capacity may vary between 50 and 500 W and the main targets are institutions, the tourism sector, rural lodges and hotels in the villages that aren't connected to any grid or microgrid.

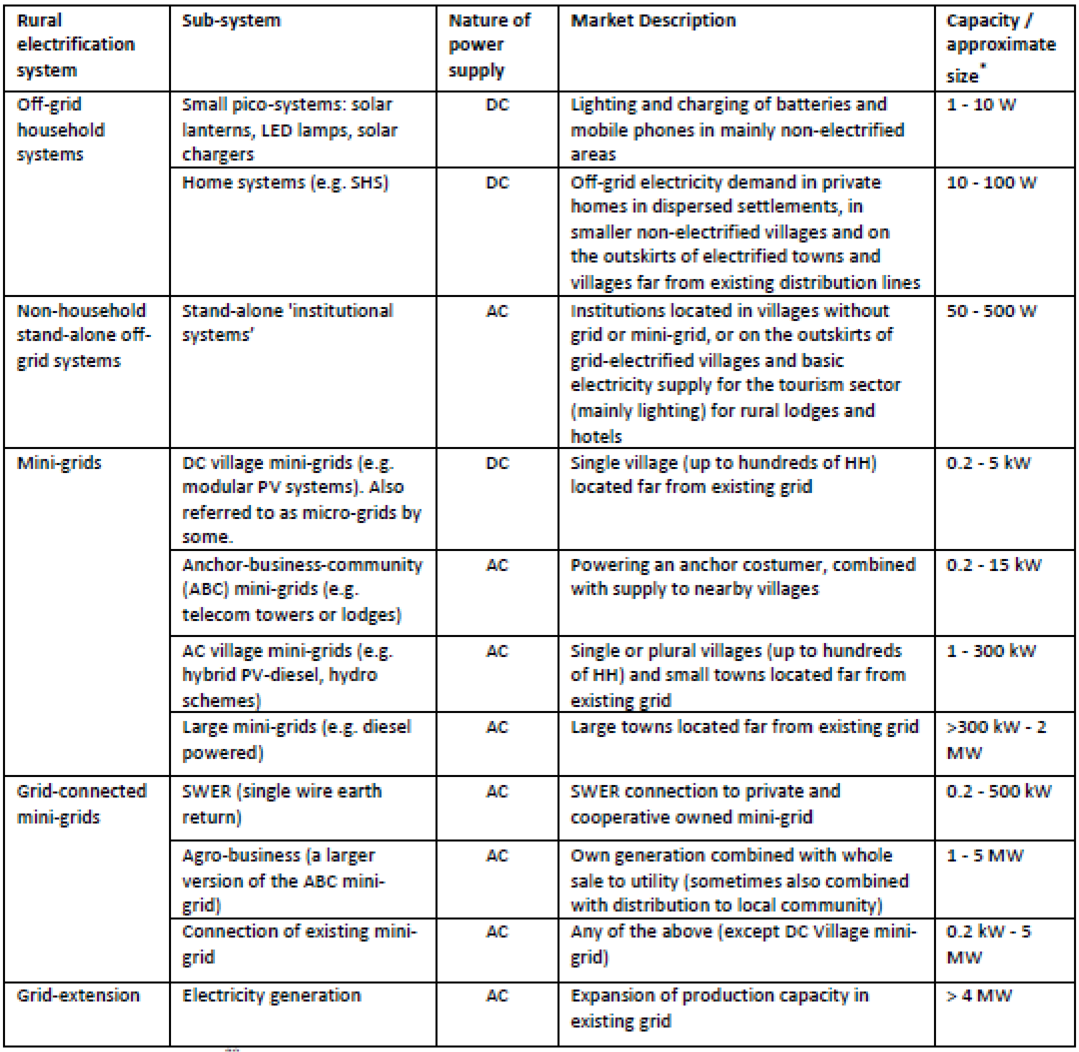
- Through the extension of grids that already exist near those areas.

  - Grid-extension expands the production capacity in an existing grid.
  - The size capacity is usually higher than 4 MW.

- Though mini grids and micro grids:

  - The nature of the power of a micro grid can be DC, AC or a mix of the two (hybrid micro grid).
  - The DC village micro grids usually vary between 0.2 and 5 kW in capacity and are used to power a single rural village that is far away from the main grid.
  - There are more AC micro grids, due to its power capacity size and the concept is already well established, primarily in the distribution grid, comparatively to the DC ones.
  - The AC village micro grids can vary, in capacity, between 0.2 and 300 kW. These grids supply single, multiple villages or even towns that are far from the main grid.
  - There are also larger AC mini grids that are implemented in bigger towns.

Table 2.1 - Solutions for rural electrification [1]



Rural electrification system	Sub-system	Nature of power supply	Market Description	Capacity / approximate size*
Off-grid household systems	Small pico-systems: solar lanterns, LED lamps, solar chargers	DC	Lighting and charging of batteries and mobile phones in mainly non-electrified areas	1 - 10 W
	Home systems (e.g. SHS)	DC	Off-grid electricity demand in private homes in dispersed settlements, in smaller non-electrified villages and on the outskirts of electrified towns and villages far from existing distribution lines	10 - 100 W
Non-household stand-alone off-grid systems	Stand-alone 'institutional systems'	AC	Institutions located in villages without grid or mini-grid, or on the outskirts of grid-electrified villages and basic electricity supply for the tourism sector (mainly lighting) for rural lodges and hotels	50 - 500 W
Mini-grids	DC village mini-grids (e.g. modular PV systems). Also referred to as micro-grids by some.	DC	Single village (up to hundreds of HH) located far from existing grid	0.2 - 5 kW
	Anchor-business-community (ABC) mini-grids (e.g. telecom towers or lodges)	AC	Powering an anchor costumer, combined with supply to nearby villages	0.2 - 15 kW
	AC village mini-grids (e.g. hybrid PV-diesel, hydro schemes)	AC	Single or plural villages (up to hundreds of HH) and small towns located far from existing grid	1 - 300 kW
	Large mini-grids (e.g. diesel powered)	AC	Large towns located far from existing grid	>300 kW - 2 MW
Grid-connected mini-grids	SWER (single wire earth return)	AC	SWER connection to private and cooperative owned mini-grid	0.2 - 500 kW
	Agro-business (a larger version of the ABC mini-grid)	AC	Own generation combined with whole sale to utility (sometimes also combined with distribution to local community)	1 - 5 MW
	Connection of existing mini-grid	AC	Any of the above (except DC Village mini-grid)	0.2 kW - 5 MW
Grid-extension	Electricity generation	AC	Expansion of production capacity in existing grid	> 4 MW

2.2. Microgrids

The concept of the term “Microgrid” or “Minigrid” vary from paper to paper. In other words, this term is a highly popular notion in the whole world, but its conceptualization has many different meanings applied in the vast variety of systems and grids that already exist. For example, some of the definitions of “Microgrid” do not define the capacity that the grid should have, but define some characteristics, like being an off-grid distribution and generation system. Other papers report that the capacity size of these grids must vary between 5 and 200 kW or even 300kW, meaning that there are different viewpoints in many projects [1].

2.2.1. Concept and History

Firstly, the CERTS (Consortium for Electrical Reliability Technology Solutions), over the years, have been researching and developing new equipment technologies and methods, in order to help protect and enhance the electricals’ system reliability in the United States. [7]

This group was formed in the year 1999 and developed a microgrid concept in 2002. This was a time where a lot of power outage was occurring in the western of the United States. Their main objective was to develop a solution more reliable and cost efficient to help the difficult situation occurring at the time [7].

For the CERTS, a microgrid could be characterized as a set of controllable loads and micro-sources that supplies and provides power and heat to a local area and operates as a single controllable system [7].

As referred on the last paragraph and shown in Figure 2.1, the proposed control strategy, made by this group, was to make a system that can operate while connected to a upstream grid and, also, when the system is disconnected from the main grid. In order to achieve this function, the system needs a PCC (Point of Common Coupling), to define the boundary between the main grid and the microgrid. In grid-tied mode, if the microgrid system has a shortage in power, it is necessary for the main grid to import that energy, otherwise, it is necessary to export the energy in excess, where the voltage and frequency in the system are defined by the main grid [7]. In Island mode, it is necessary for the power generation to be higher than the main or critical loads present in the system, where the DERs define the system’s frequency and voltage.

It is also necessary to use a converter that controls the voltage and the power flow of the micro source of the system; some protection devices that can protect the system, having set-points that can change, depending on the mode of operation and ensure the selectivity. A coordinator device is also important for the control of these systems because these devices will certify if the generation is in the necessary limits and if the power losses are in the pretended minimum value [7].

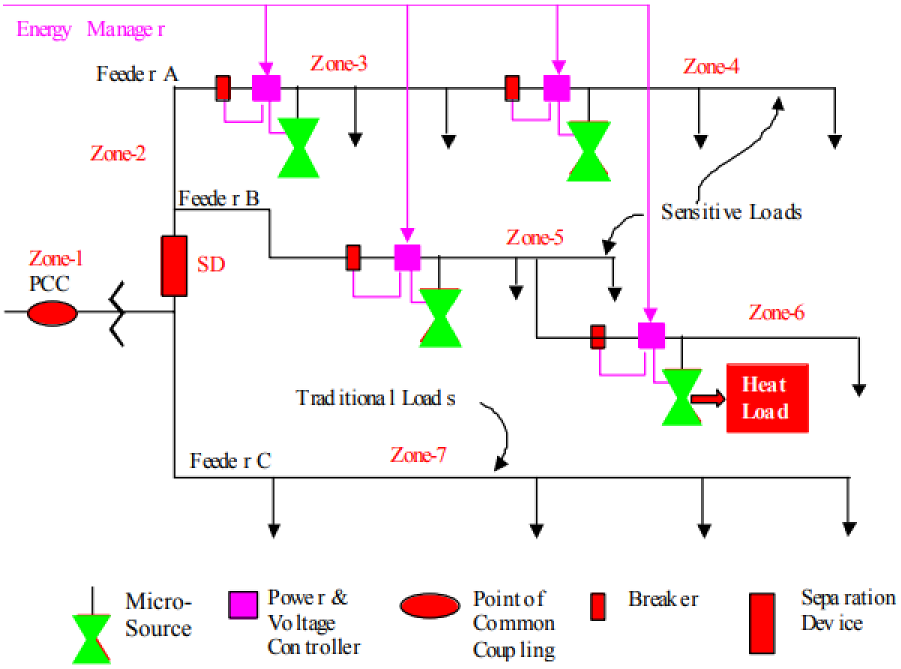


Figure 2.1 - Concept of microgrid by CERTS [7]

For the European Union Fifth's Framework Program 'MICROGRIDS', as depicted in Figure 2.2, the main objective of building a microgrid was, not only to improve the reliability of the system, but also to provide a solution for improving observability and controllability of the distribution grid, aiming to facilitate the integration of renewable energy sources as well as the exploitation of the flexibility of some [8].

Their definition of microgrids is that these systems are LV (Low Voltage) distribution systems that contain distributed energy sources and storage systems. These systems can be autonomous, if operating in island mode, or non-autonomous, if connected with the higher voltage grid [8].

Similar to the CERTS project, it is important to have converters that connect the small generators to the feeders and that also can control the voltage and frequency of the sources, in order to control these grids. Load Controllers are also used to help the load shedding and observer functionalities in the loads. The Microgrid Central Controller can control these two controllers, increasing the quality of operation and coordination, by sending set-points and commands to the system [8].

It is possible to conclude that these two concepts have their own differences. The first one does not define the type of operations that the MGs can function, neither define the type of system (LV, MV or HV), but mentions that the MGs should provide power and heat. The second one specifies that the microgrids is a LV system and has storage systems implemented in the grid but does not reference the supply as form of heat.

Despite these contrasts, these two concepts were really important for the future work in this domain, because they established the basic fundamentals of a MG.

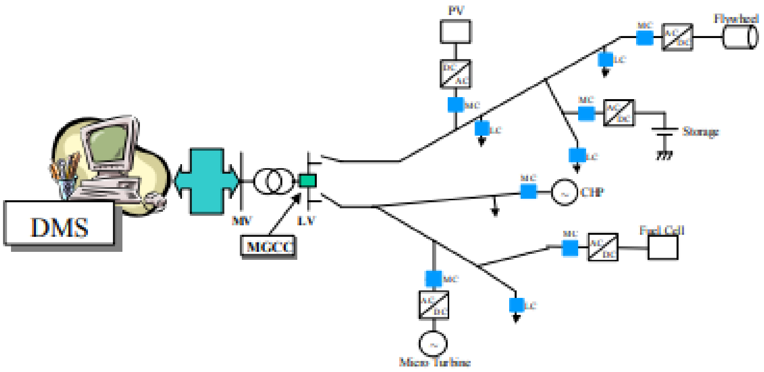


Figure 2.2 – Concept of microgrids by the European Union fifth’s framework program [8]

Finally, in 2011, the US Department of Energy’s Microgrid Initiative defined the concept of MGs as a “a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid” and “can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode” [9].

2.2.2. Benefits

Through the years, customers all around the planet have been more motivated on using the help of renewable energy as a solution. These consumers are more self-aware of the benefits of using renewable energy: the increase of resilience and reliability in a system, while having reduced environmental pollution and energy costs [7].

There are many benefits in the use of MGs, in order to deliver energy to these remote areas [1]:

- The implementation of RES in MGs helps the environment, by reducing the pollution emitted by other sources that, are supplied by diesel fuel, gas, or coal, depending on the central. In other words, microgrids will help the future of the electrical systems to turn into a healthier and viable one.

- The reduction of energy losses due to the DG existent in the grid. This type of generators is implemented near the loads of the system, compared to the conventional equipment distance from the distributed sources.

- The use of renewable energy will not only improve the health of the environment, but also reduce the prices of energy, due to the use of the natural resources as an energy supply. These natural resources are abundant in the rural areas, which is easier to implement this type of generation and grids.

- Higher reliability in the system, due to the system’s independency. For example, when working in Island mode the system does not depend on the main grids, leading to less outages in the system.

- The businesses and industries will gain more profit, with less power failures in the system.

- The DGs can support and supply reactive power and improve the quality of voltage, throughout the system.

2.2.3. Difficulties

Besides all the benefits that MGs can bring, there are also many difficulties in the implementation of these grids in the rural areas [1] [2]:

- The lack of literature about rural electrification in these rural areas. For example, in the East of Africa, the projects and reports they have been more general than in Asia, where they have a more specific and advanced library about the topic.

- Besides the lower cost in energy, the investment in renewable energy sources and technology is still too expensive for the budget expected in these locals.

- Some of these villages are located far away from other grids, being more difficult to implement these grids.

- The lack of standardization. With the existence of new projects every year, it is important to define some new standards, by researching and testing the systems and how they perform.

- The control of the frequency and voltage needs advanced engineering, due to the fluctuations that exist in the system.

- The charging and discharging regulation of electrical cars is still very new in micro grids and its implementation needs more research.

- The adherence of the concept of microgrid to the necessity of electrification. In other words, the MG was not conceptualized to the purpose of electrification.

2.2.4. Architectures Control

The control of a microgrid is a very important feature because it is with this control that the grid can read all the measurements and automatically respond and take the right decisions when an event happens in the grid. This control can be defined in many different ways, but two of the main ways of control are a hierarchical control or a distributed control [11]. The first one is the most common to use and it is divided into 3 layers: the primary control, the secondary control, and the tertiary control, as shown in Figure 2.3 [11].

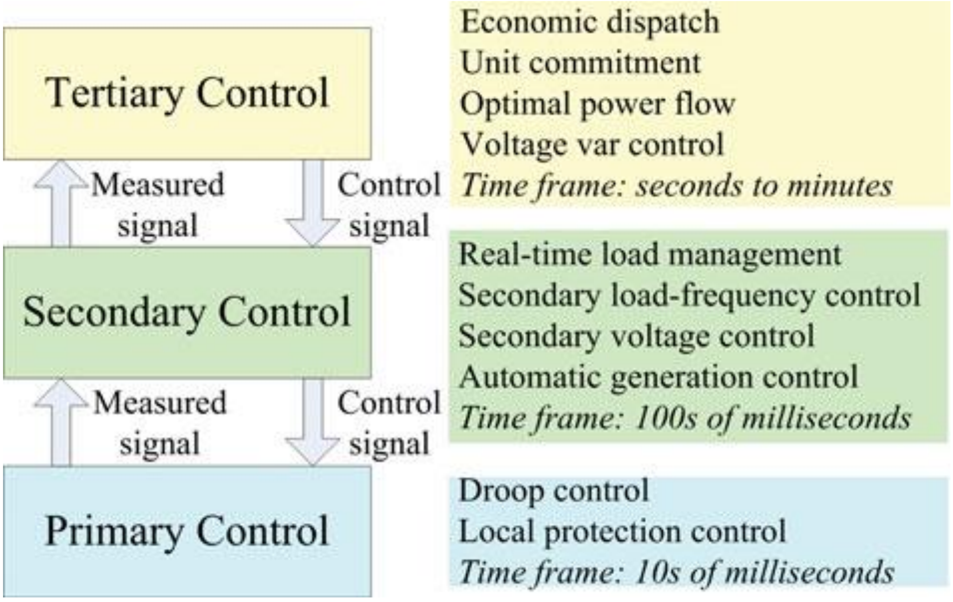


Figure 2.3 – Hierarchical control in microgrids [11]

2.2.4.1. Primary control

This is the first layer of the control hierarchy and has the fastest response.

Its main objective is to assure the stability of the system using power balancing and power sharing. This control is usually done with the help of a droop-based P and Q control, where the frequency and voltage amplitude are adjusted [10].

This droop is based on Equation (2.1) and Equation (2.2) and the representation of these two equations are in Figure 2.4.

$$\omega = \omega_{ref} - kp * (P_{ref} - P) \tag{2.1}$$

$$V = V_{ref} - kq * (Q_{ref} - Q) \tag{2.2}$$

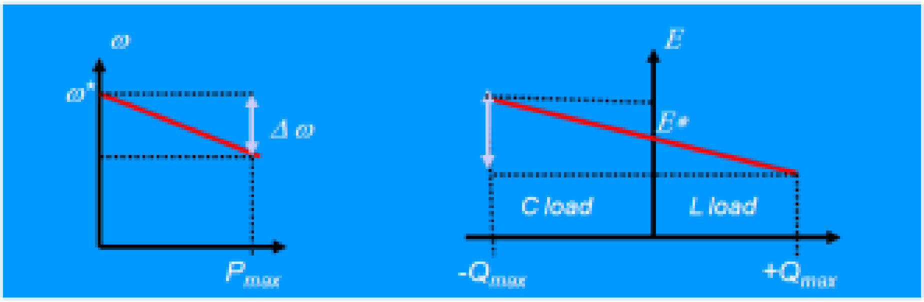


Figure 2.4 – Droop functions representation [10]

In Equation (2.1), ω and ω_{ref} correspond to the frequency and its reference (Hz), respectively. P and P_{ref} are the active power and its reference (W) respectively and kp is the primary droop coefficient correspondent to the active power. In Equation (2.2) V and V_{ref} represent the voltage (V) and its reference, respectively. Q and Q_{ref} are the reactive power (var) and its reference respectively and kq is the primary droop coefficient for the reactive power.

Despite all the advantages of using this type of control, there are some problems that need to be corrected like: some variation in frequency and voltage; the power charging is not that accurate among DER units in the systems, due to uncertainties of the output impedance; the output power of the DERs have fluctuations and still aren't capable to connect nonlinear loads, due to the harmonics [12].

An alternative to droop control is communication-based control techniques. This type of control, contrary to the droop-based one, does not require a secondary control, because the voltage and the frequency are usually close to their necessary values. However, the reliability of the system can be lower, due to interference when the distances between the communication lines are long. Also, these communication lines are needed between each module, which make the cost of investment very high [12].

2.2.4.2. Secondary Control

The secondary layer of the hierarchy control is very important for the correction of some problems presented in the droop-based control, for example, the variation of the frequency that happens when the system switches modes of operation.

Comparing to the previous control, it has a slower response and one of the main necessities of this control is to compensate the variations of the frequency and voltage. The main theory behind this control is that the error between the measured values of the voltage amplitude and frequency (V and ω, respectively) and their references (V_{ref} and ω_{ref}) is calculated, processed through compensators and stored in the units δ_V and δ_ω, in order to restore the voltage and frequency outputs, as shown in Figure 2.5 [10] [13].

The value of these two constants (δ_V and δ_ω) can be either positive or negative, depending on which case the grid is being studies. If there is more power generation than load capacity in the system, there will be a downwards effect to maintain the frequency of the system stable. Otherwise, when the load capacity is higher than the power generation it will make an upwards effect in order to stabilize the frequency.

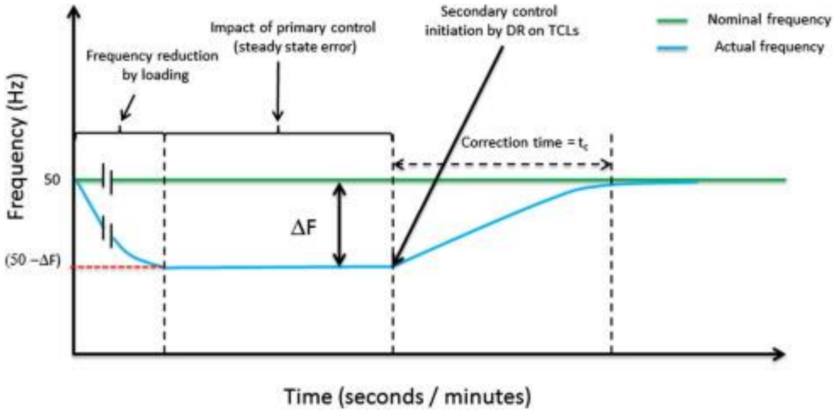


Figure 2.5 – Secondary Control → Restoration of the system's frequency [12]

The Equations (2.3) and (2.4) represent the correction done to the primary control.

$$\omega = \omega_{ref} - kp * P + \delta_\omega \tag{2.3}$$

$$V = V_{ref} - kq * Q + \delta_V \tag{2.4}$$

Where ω and ω_{ref} are the frequency and its reference, respectively; P is the output active power; kp the primary droop coefficient for active power and δ_ω the secondary droop coefficient for frequency. V and V_{ref} represent the amplitude of the voltage and its reference, respectively; Q is the output reactive power; kq is the primary droop constant of reactive power and δ_V is the secondary droop coefficient for voltage amplitude.

This stage of control has different configurations and topology.

The most usual one to use in a microgrid is the Centralized Controller. This type of controller uses a MGCC to send all the data and calculations measured, in order to communicate all the necessary actions that the sources controllers, throughout the system, should do. It is located near the control bus PCC and computes these measurements and calculations (the secondary droop coefficients) using the Equations (2.5) and (2.6) [10].

$$\delta_\omega = k_{p\omega}\left(\omega_{ref} - \omega\right) + k_{iw}\int\left(\omega_{ref} - \omega\right)dt \tag{2.5}$$

$$\delta_V = k_{pV}\left(V_{ref} - V\right) + k_{iV}\int\left(V_{ref} - V\right)dt \tag{2.6}$$

Where $k_{p\omega}$, k_{iw}, k_{pV} and k_{iV} are the terms of the secondary control compensator. ω and ω_{ref} are the frequency and its reference of the whole microgrid, respectively. V and V_{ref} correspond to the voltage amplitude and its reference of the whole microgrid, respectively.

The microgrid is controlled as if it was a single unit, making it an easy and very practical model to implement (Figure 2.6).

Despite all the great advantages, this topology requires high costs, due to the communication system used, it does not have plug-and-play capabilities and it also doesn't have backups in case of a single unit failing.

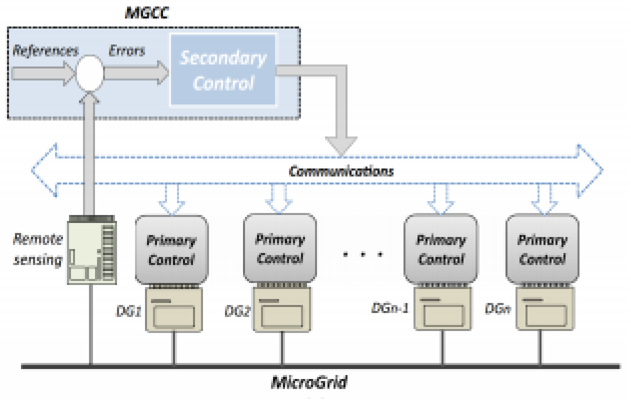


Figure 2.6 – Centralized secondary control [12]

It is important to salient that researchers have been studying a way of implementing a distributed secondary control. In other words, every DER in the system has its own secondary control equipped, helping the primary control with more precise results (Figure 2.7) [13].

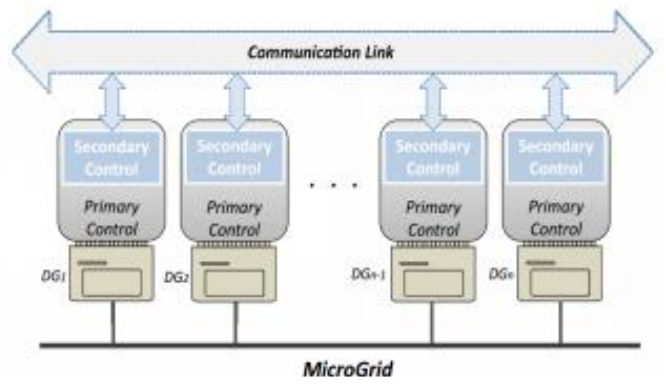


Figure 2.7 – Distributed secondary control [12]

2.2.4.3. Tertiary control

The tertiary control, as shown in Figure 2.8, is made, not only for one general microgrid, but also for set of several multi-grids, in order to help the costumers, by achieving an economic improvement globally [12].

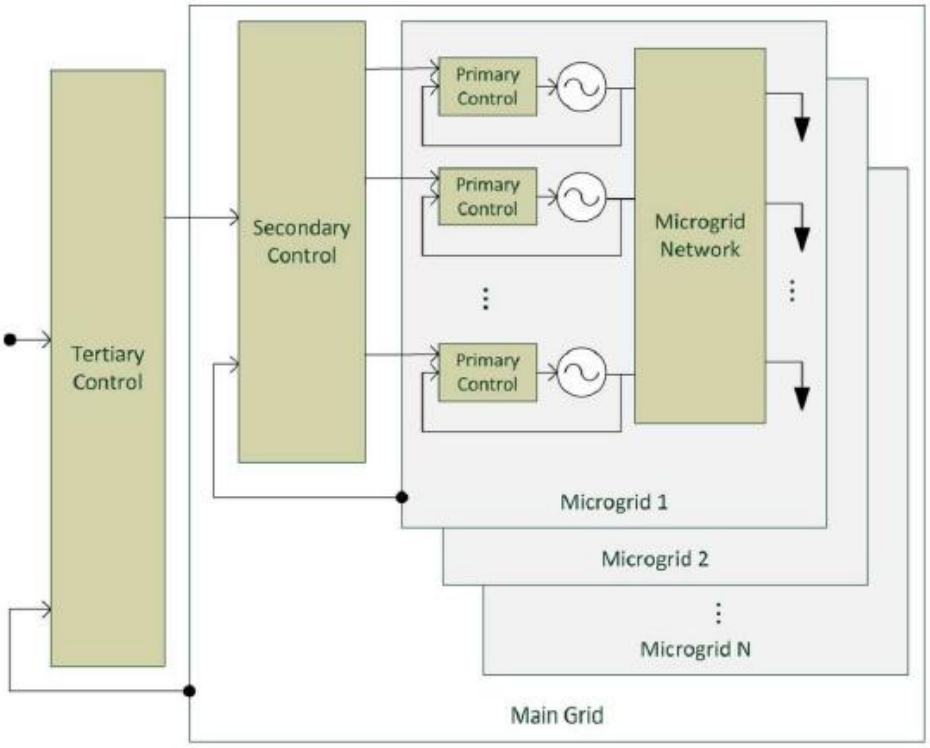


Figure 2.8 – Tertiary control [12]

Compared to the primary and secondary controls, this one as the longest response. The main objective is to optimize the system, in terms of energy prices, losses in power flow, reduction of pollution, operational and maintenance costs, using the help of RES technology [11] [12].

These objectives are achieved by using functions such as state estimation, EMS, Q-V control, and thermal system management. The EMS is one of the main functions of the tertiary level, where it receives a large amount of data and information about the whole grid (for example: the state of the system; market and operational costs; state of the loads and generators; power quality) and calculates, in small interludes, the actions to take, in terms of load shedding, imports and exports of energy and generator activation [12].

2.2.5. Multi-Micro Grid

As seen in Figure 2.9, an MMG is a grid that is formed at the MV level and, then various LV microgrids and DG technologies are connected to the feeders of the MV level [14].

A new control strategy and architecture needs to be implemented with this new concept, where multiple microgrids are agglomerated. The main strategy adopted for this new control was, as seen before, the hierarchical control architecture, where the CAMC (Central Autonomous Management Controller) is installed in the HV/MV substation and will be entrusted by a System Operator (DSO). This controller is an intermediate controller and oversees the whole MMG system. The Distribution Management System will also help and control the distribution network in the different operating modes. The CAMC will help the DMS to interface with other controllers of lower level and will also interact with the MGCC. The MGCC is installed in a lower level substation (MV/LV substation) and controls the loads and micro sources [15].

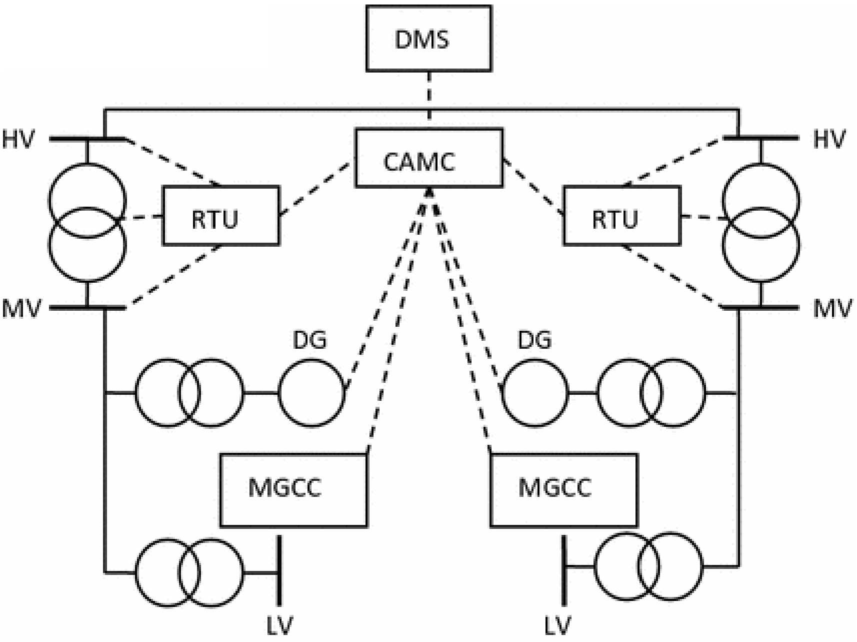


Figure 2.9 – Multi-Microgrid control [18]

A communication infrastructure is needed, in order to monitor the voltage in every LV grid.

Overall, only one more control was added at the HV/MV level. Besides this new control implemented, there are still a lot of similarities with the control of a normal microgrid. For example, the control functions used are still disposed by the same three-levels (primary level, secondary level, and tertiary level) and it can operate in islanded mode and in grid-tied mode [14].

2.2.6. Hybrid MG

These MGs and MMGs can be represented as AC Microgrids, DC Microgrids or even have a hybrid power (AC and DC power) in the same grid.

2.2.6.1. AC Microgrids

An AC microgrid is the most common to use, due to the originality of the microgrid architecture being defined and created as an AC power-based grid. These grids have AC loads, buses and mostly AC generation, like wind turbines and micro-hydro power generation. But some AC grids can also have DC generation associated (batteries or PV generation), with the help of AC/DC converters, as shown in Figure 2.10.

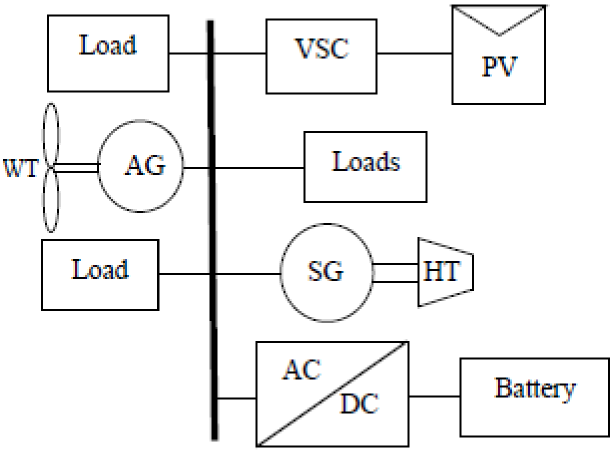


Figure 2.10 – AC Microgrid model [4]

2.2.6.2. DC Microgrids

DC microgrids are important systems, especially for rural electrification, because of the power loss advantages and the capital cost spent in this grid, compared to AC microgrids.

The main technical advantages of these grids are: being less difficult to implement and having less stability problems; the use of DC loads has been more popular over the years, making the use of AC/DC converters to be reduced and, as result, less losses and less costs in manutention and investment; the control of the DGs is easier, because it is based on the DC voltage and not in the synchronization. These factors may not seem a huge change, but these reductions in cost and in power losses are very useful for consumers living in developing countries, where the energy is scarcer and the poverty more abundant [6].

Comparing AC power based microgrids to DC microgrids, these last ones can save up to 33 % of energy, due to the avoidance of AC/DC converters and to the use of DC-technology instead of AC [2].

The main problem with this type of LV DC systems is that there is a huge lack of standardizations. The economy, the geographical limitations and the lack of population also make the extension of the grid a less sustainable investment [6].

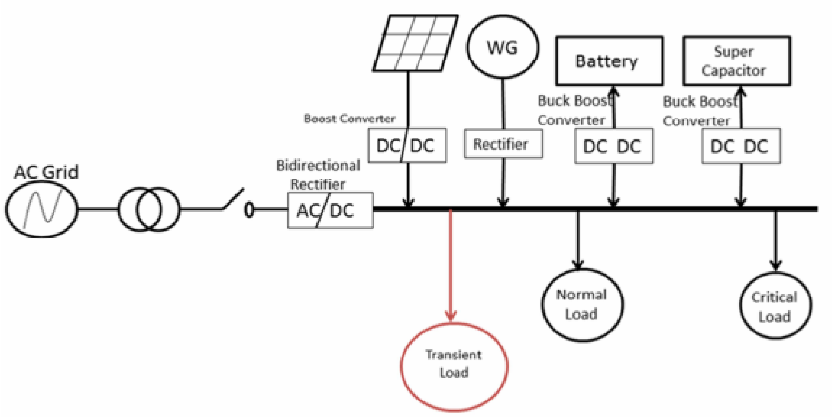


Figure 2.11 – DC Microgrid model [17]

2.2.6.3. AC/DC Hybrid Microgrids

As shown in Figure 2.12, the hybrid microgrid is a combination of the two types of power (AC and DC) as well a mix of their main advantages. But, in order to allow the integration of AC and DC power grids in the same grid, it is necessary to have a lot of researches and studies of some aspects, for example, the models and designs configuration, the architecture control to use and the parametrization of the models. These characteristics and configurations will depend on the environment and on the applications of the grid [16].

In order to integrate the AC microgrid it is solely used a transformer that reduces the voltage level and provide galvanic isolation to the microgrid. This transformer is implemented in between the hybrid microgrid and the main electrical grid, uniting them [16].

For the DC microgrid, it is necessary the addition of a bidirectional converter, to convert the power from AC to DC and vice-versa. These hybrid MGs can also manage these bidirectional converters connected to the DC microgrid and to the batteries installed [16].

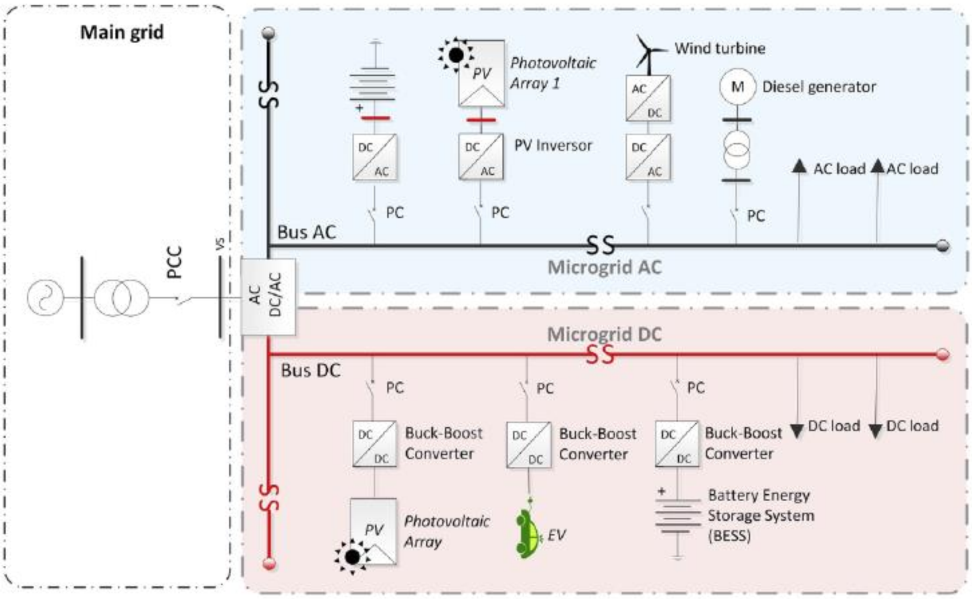


Figure 2.12 – Hybrid Microgrid model [16]

It is also very important to take into account some requirements, for example the hierarchical control; the existing natural resources in these rural areas; the use of batteries as a back-up, in case there’s a need of more power in the grid; the type configuration of the grid and the compensation of reactive power [16].

2.2.7. Operational Modes

The main operational modes that the grid usually works are:

- The Grid-Tied mode: The grid behaves as a semi-autonomous system that is linked with the main grid. In case of an excess of power generation in the microgrid, the grid can deliver to the main grid this excess of power. Otherwise (microgrid needs more power in order to satisfy the loads capacity), the main grid will help transmitting the necessary power to the MG.

- The Islanded mode: The grid behaves autonomously without the help of the main grid. This is due to some incident that happened in the high-level grid. In this case, the batteries of the MG will discharge and charge, helping the stabilization of the system, only if the production generated by the micro sources is insufficient or excessive, respectively.

2.3. Smart Grids

The Smart Grid is a set of automations, controls, new equipment, computers, while working with the electrical grid. In other words, there is an exchange of electrical power data and information between the consumers and the electrical grid (Figure 2.13).

Many benefits can be provided by the implementation of the Smart Grid, but a lot of research, implementation of standards and rules and training for the consumers is necessary to happen. The main benefits are [19]:

- Reduced power costs, due to the less operations and management performed in the grid.

- A better security in the grid, due to less blackouts. The blackouts are reduced, because of an improvement in resiliency, resulting in a forecast of emergencies. Also, the SG can detect and isolate small outages, before they transform into blackouts, using automatic rerouting.

- Improve in the health of the environment, with the integration of RES.

- Use of controls that can quickly restore the systems, after a disturbance occurs.

- Efficiency in energy transmission.

- During emergencies, some consumers can help generating energy from their homes to the community, through consumer-own power generation.

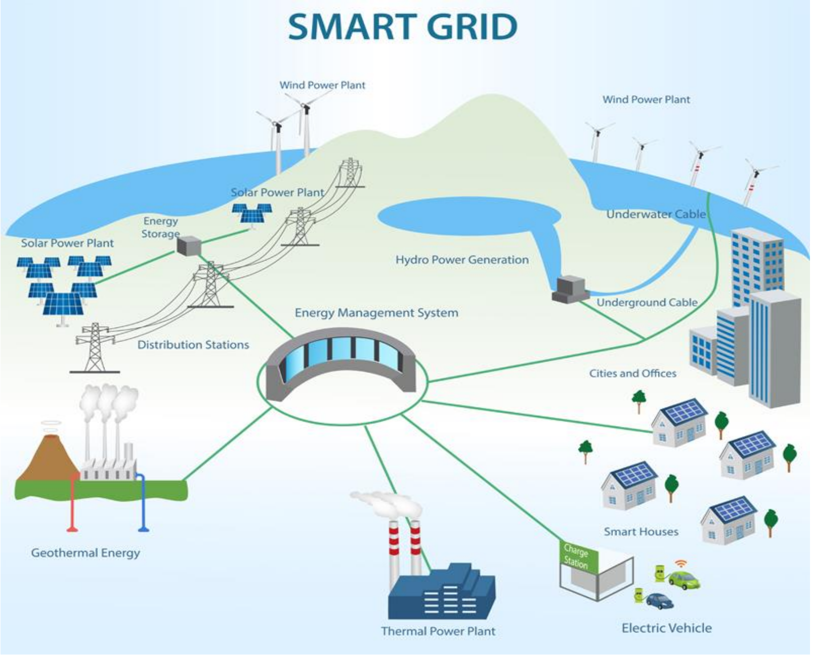


Figure 2.13 – Smart Grid structure [20]

As seen before, this type of grids is not only about the new technology, but about the consumers and about the future of the electrical grids. Having the consumers participating in the grid, by producing energy from their own homes, by making choices and helping them in how to make use of their energy and efficient way to save it. The mechanisms used in SG, like Smart Meters, will help the consumers to read how much energy is being used and how much money is spent in energy, giving them some notion about how the consumers should save [19].

2.4. Main Conclusions

As seen in this chapter, there are many different solutions, in order to help the problem of electrification in remote areas. One of the main solutions is the use and the implementation of microgrids.

These microgrids can have different types of configuration, for example the MGs can be AC, DC, multi-microgrids or hybrid AC/DC microgrids and, between the same type or different types, their modelling, design and control functions implemented are not the same.

Chapter 3 of this dissertation will focus on the modelling and design of the components of the hybrid microgrid and their control functions.

Chapter 3

Hybrid Microgrid Modelling and Control

This chapter is a very important part of this dissertation, where an explanation about how the models of the DC Microgrid and the AC Microgrid are defined and designed and how their control functions are implemented.

3.1. Global Overview of the Control Strategy

3.1.1. DC Microgrid

This section includes the basic ideas for the DC systems and its own operation, as well the perspective of the connection between the DC grid to the AC one. In other words, the hybridization and what it implies.

As well as the AC microgrid, where the frequency and the voltage are the main variables of control in function of the active and reactive power, respectively, the DC microgrid has the voltage and the active power as variables to control and directly related between each other, given that in DC there is only resistances and there aren't any reactances.

Besides that, by having renewable sources and loads to supply, something needs to be responsible for the constant balance between the production and the consumption of the system, there is a necessity of a buffer of energy. That unit needed is one or more batteries that guarantee that necessity.

There are basically two options to control the voltage in the DC system:

- By maintaining the voltage constant in a point associated with one of these buffers of energy → batteries and every single unit that adjust the power injected.

- By doing a distributed control of the voltage and, therefore, shared between various buffers of energy, in case of having more than one battery in the system.

This last solution is more robust and reliable, because if one of the batteries doesn't work, the others can support the system (something that doesn't happen in the first solution). This solution leads to the necessity of implementing a droop P-V control function in the battery. This control function is also needed in the perspective of subsequently interconnecting the DC system with the AC one. This means that the AC/DC converter will have this buffer function (the AC system is far bigger than the DC MG and, hence, has clearance for such).

From this organization of ideas, all the control requirements for the DC system and the AC/DC converter appeared.

3.1.2. AC Microgrid

In the AC microgrids there are implemented converters due to the MSs (Micro Source) added to this system. If the MS is DC, the power converter needs to be DC/AC and if the MS is AC, the power converter can be an AC/AC converter, in order to regulate the voltage values, the frequency or/and to implement other control functions.

For the AC microgrid there are 2 main control strategies for the inverters connected to the micro-sources of the system:

- The first one is the VSI (Voltage Source Inverter) control: This inverter has already the values of frequency and voltage defined beforehand and can be modelled as a voltage source. Also, the output voltage can be regulated with the help of the P-Q measurements on the loads [21].

- The second one is the PQ inverter control: This inverter, with the help of a current control loop, has as a goal to maintain the PQ reference and can be modelled as a current source (simpler than the VSI control). This inverter has the values of the active and the reactive power defined beforehand.

These controls can be implemented, or separately in each inverter, depending on the type of the MS the inverter is connected to; or with both control strategies in the same inverter, where there is a switch command between the two controls.

For example, if the grid is operating in grid tied mode, the frequency regulation is ensured by the main grid and the inverters work with the PQ inverter control, in order to draw out the maximum power of the sources connected to the respective inverters.

If the grid is operating in island mode, the VSI control is applied only to highly controllable equipment (diesel engines, batteries, flywheels), due to most of the MSs in the system that produce unreliable energy through the help of natural resources (RES) and can’t maintain constant operation values. In this case, the VSI control will help the critical loads of the system to receive the minimum power necessary to supply them. The VSI can operate as a single master operation, where the MG will operate with a single VSI control and the sources from the system are controlled by the PQ inverters, or as a multi-master control, where the MG will operate with more than one VSI control. The PQ inverters control is connected after the system stabilizes.

3.2. Models Implemented in Simulink

In order to make the simulation and the hybrid model work, it is needed to implement mathematical equations and functions into each unit of this microgrid. There are different ways of controlling and designing each model, depending on the type of grid they are constructed in (DC and AC).

3.2.1. DC Microgrid

3.2.1.1. Solar PV

The solar PV is the easiest unit to model and design in Simulink. This unit does not produce reactive energy and does not depend on the frequency, because it is a DC unit. This component works as a power injector, due to the small time of simulation, where the variation of irradiation is really low. As seen in Equation (3.1) and in Figures 3.1 and 3.2, it injects a current that is dependent of the output voltage (V_{DC_PV}) and the output power (P_{PV}) (both already known).

In other words, the solar PV can be represented as a current source in parallel with a capacitor.

$$I_{PV} = \frac{P_{PV}}{V_{DC\_PV}} \tag{3.1}$$

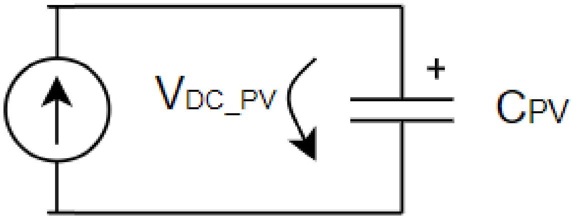


Figure 3.1 – Simplified model of the solar PV

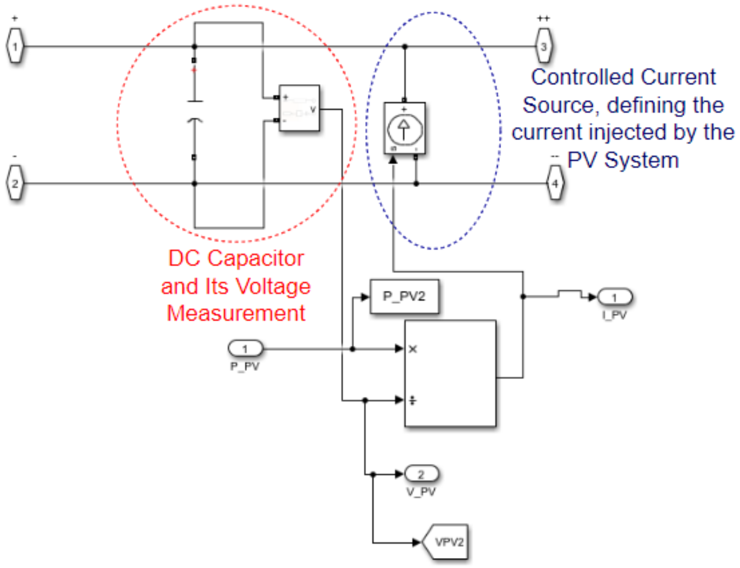


Figure 3.2 – Solar PV implementation in *MATLAB Simulink*

3.2.1.2. Battery

Both the battery and the AC/DC Converter have similar characteristics when it comes to the control of these units. The battery serves as a back-up unit for the system, where its bidirectional (can charge or discharge, depending, or not, on the need of more energy for the DC system).

This unit also behaves as a current source and it will depend on the output of active power and on the output voltage (Equation (3.2)).

The control function used was based on the droop P-V (Equation (3.3)), where the active power will depend on the voltage output [22].

$$I_{BAT} = \frac{P_{BAT}}{V_{BAT}} \tag{3.2}$$

$$P_{BAT} = P_0 - k * (V_{BAT\_ref} - V_{BAT}) \tag{3.3}$$

Where I_{BAT}, P_{BAT} and V_{BAT} are the current, active power and voltage output of the battery, respectively. k is the drop of active power. V_{BAT_ref} corresponds to the reference of the voltage output and P_0 to the reference of active power output.

Figures 3.3 and 3.4 represent the model's representation and the Simulink implementation, respectively.

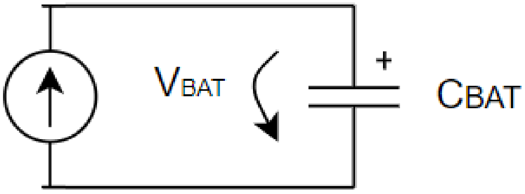


Figure 3.3 – Simplified model of the battery

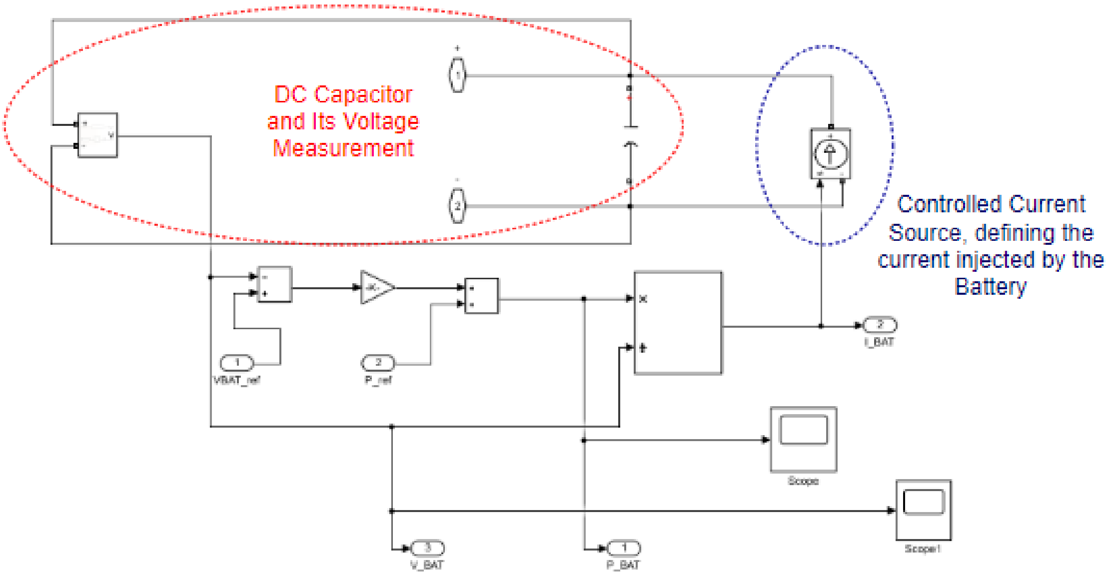


Figure 3.4 – Battery implementation in *MATLAB Simulink*

3.2.1.3. AC/DC Converter

When the DC MG is connected to the AC MG (to form the Hybrid Microgrid), it is necessary to use an AC/DC converter. This converter is a bidirectional unit and it can control the power flow between the AC and the DC grid. If the value of the active power that goes through the converter is positive, the energy will be transferred from the AC side to the DC one. Otherwise, the DC MG will deliver the energy to the AC MG (Figure 3.5).

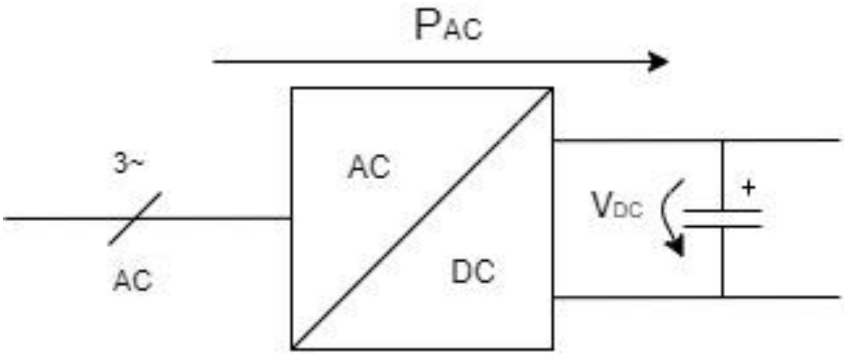


Figure 3.5 – AC/DC converter

Similar to the battery unit installed in the DC MG, Equation (3.4) and (3.5) represent the droop control P-V used in this type of converter and shows that the power that comes from the AC grid will depend on the voltage output at the terminals of the converter [22].

As referred before, the converters and generators are represented as current sources (Figure 3.6) that are dependent of the voltage output and the active power that comes from the AC grid.

$$I = \frac{P_{AC}}{V_{DC}} \tag{3.4}$$

$$P_{AC} = P_0 - k * (V_{DCref} - V_{DC}) \tag{3.5}$$

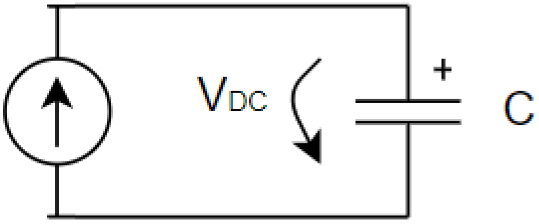


Figure 3.6 – Simplified model of the AC/DC converter

Where I, P_{AC} and V_{DC} are the current output, the active power that goes through the converter and the voltage output of the converter, respectively. k is the droop of active power of the converter. P_0 and V_{DCref} correspond to the references of the active power and DC voltage output, respectively.

When the AC/DC converter is connected to the AC grid, it is necessary to have into account first the bidirectional flow. By adding the block Three-Phase Dynamic Load with a negative PQ reference, the DC grid can cooperate with the AC MMG as a load or as a generator (Figure 3.7).

The converter can be used or not for the share of the regulation services between grids. That is, the power can be constant or adjustable, depending on what is happening in the AC microgrid. In order to do that, the frequency of the AC system was taken into account. In other words, P_{AC} will not only be dependent on the voltage output of the converter, but also on the frequency of the AC grid as seen in Equation (3.6).

$$P_{AC} = P_0 - k * \left(V_{DCref} - V_{DC}\right) + P(f) \tag{3.6}$$

Where $P(f)$, is the droop control function implemented. This control will depend on the derivative of the frequency and on the gain applied to it.

On the AC side of the grid, it can be used to adjust the reactive power, despite that function not being used in this dissertation.

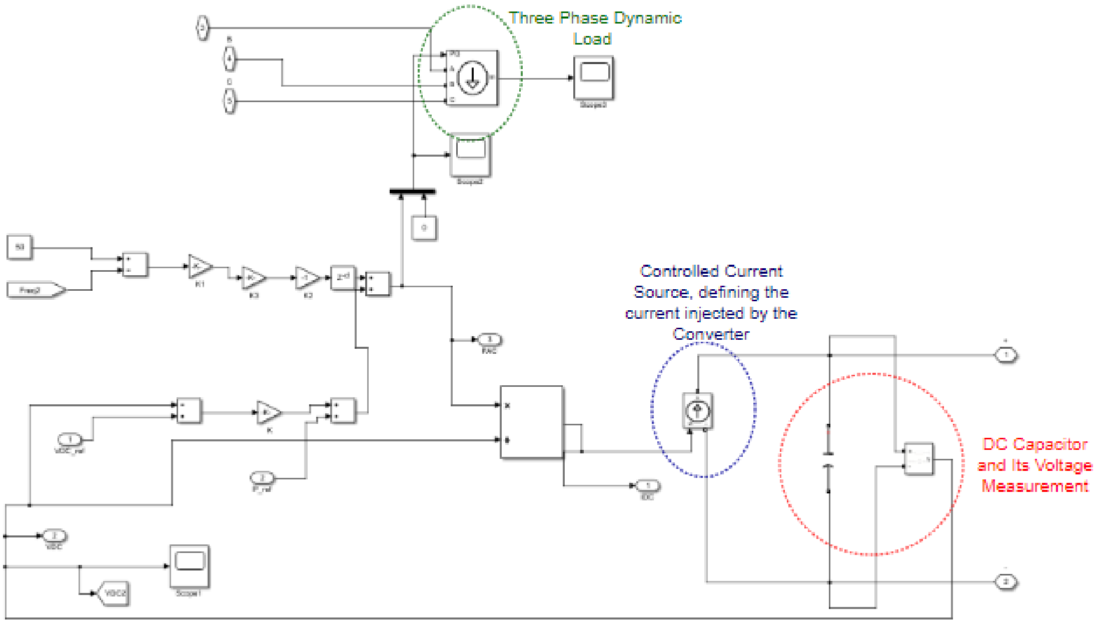


Figure 3.7 – AC/DC converter implementation in *MATLAB Simulink*

3.2.1.4. DC Loads and DC Lines

As said before, in the DC systems there are no reactances, and only resistances. The loads and the lines in these systems are represented as only resistances, as seen in Figures 3.8 and 3.9.

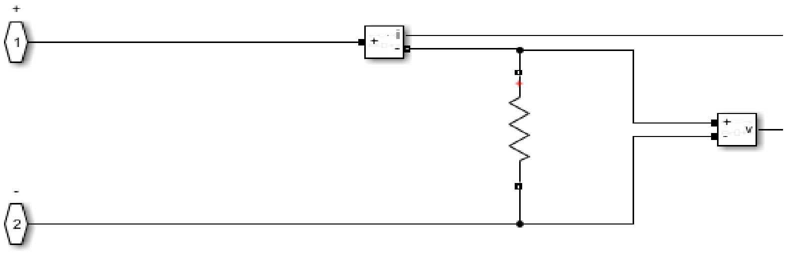


Figure 3.8 – Load implementation in *MATLAB Simulink*

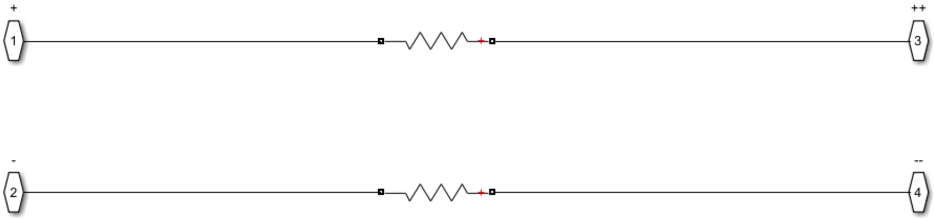


Figure 3.9 – Line implementation in *MATLAB Simulink*

3.2.2. AC Microgrid

3.2.2.1. Voltage Source Inverter (VSI)

Due to the time of the simulation being short, the models will be easier to implement. This includes the battery banks connected to the VSI. These storage systems can be represented as constants DC voltages and, as a result the VSI also can be represented as a Synchronous Machine (SM). This SM will contain governors that control the mechanical power, allowing the VSI to have variations in frequency [5].

In other words, as seen in Equation (3.7), in these type of inverters the relationship between the variations of active power (ΔP) and angular velocity ($\Delta\omega$), will depend, not only on the active power droop (kp), but also on the primary control actuation delay (TdP) [24].

$$\frac{\Delta\omega}{\Delta P} = \frac{kp}{TdPs+1} \Rightarrow \frac{1}{\frac{TdP}{kp}s+\frac{1}{kp}} \tag{3.7}$$

Comparing to a synchronous machine, the use of Laplace domain ($\frac{\Delta\omega}{\Delta P} = \frac{1}{2Hs}$) and considering a direct feedback action through a seep-droop function of a SM (R), it is possible to achieve the Equation (3.8) [23].

$$\Delta\omega = \frac{1}{2\mathrm{Hs}}\left(\Delta\mathrm{P} - \frac{1}{\mathrm{R}}\Delta\omega\right) \Rightarrow \frac{\Delta\omega}{\Delta\mathrm{P}} = \frac{1}{2\mathrm{Hs}+\frac{1}{\mathrm{R}}} \tag{3.8}$$

Where H is the emulated machine inertia and it can be defined as the relation between the kinetic energy and the nominal power rating [23].

It is possible to conclude that both equations have similarities, where H can be $\frac{TdP}{2kp}$ and R can be equal to kp.

The implementation in *MATLAB Simulink* was very similar to the theory discussed before, where with the help of the block denominated “Simplified Synchronous Machine”. This block can have a relationship between H and the droop control parameters for active power of the VSI.

As referred before, the VSI will simulate the governors equipped in the SM, controlling the mechanical power input, resulting in variations of the frequency of the VSI. These governors contain three different types of delay, two for the primary control (actuation and observer delay) and another one for the secondary control (integral control). In the delays of the primary control, the observer is not considered, because, compared to TdP, it is very small. The integral control (TdI) is responsible for the restoration of the VSI frequency variations and a low passive filter was also installed [25].

Focussing, now, in the Q-V droop functions. These functions are very similar to the ones before as seen in Equation (3.9). There is only one delay considered in these functions, which is the decoupling delay of reactive power.

$$\frac{\Delta V}{\Delta Q} = \frac{kQ}{TdQs + 1} \tag{3.9}$$

Where V is the internal voltage of the machine, Q is the reactive power output and kQ the primary droop of reactive energy.

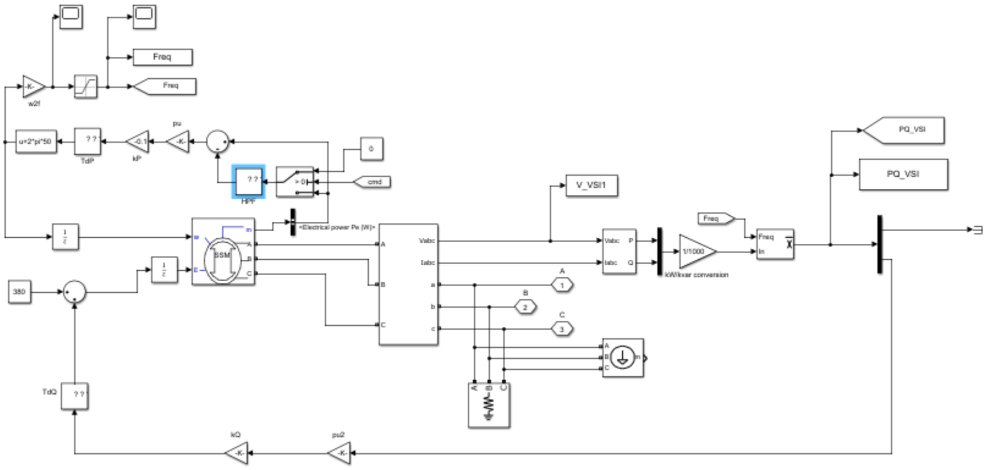


Figure 3.10 – VSI implementation in *MATLAB Simulink* [5]

The control of the frequency and voltage is very important, because it makes the AC system stable. There are 5 variables that can control both the frequency and the voltage of the system.

TdQ and kQ are two of those variables, but can have any value associated with them, because of the small values of reactive energy, comparing to the active power, cannot do a big effect on system’s voltage. So, the considered values for these parameters are TdQ=0.1 and kQ=5%.

The first variable to take into account is kp. It can control the amplitude of the frequency’s variation, at the moment the grid starts operating in island mode. As demonstrated in equation (ds), the droop of active power is the relation between the variation of active power and frequency, that is for the same active power variation, the amplitude of the variation is even lower, when its droop is gets lower. In order to choose the right kp, some tests were performed. As seen in Figures 3.11, 3.12 and 3.13, the kp chosen to use for the rest of the dissertation was with the value of 5%, because the amplitude of the frequency is a little lower than the minimum limits (49 Hz) and some of the objectives are to see how it's possible to correct this problem. When kp has a bigger value (20 % in this case), the frequency goes far below the limits, and when it has a smaller value (1% in this case) the frequency is in the limits.

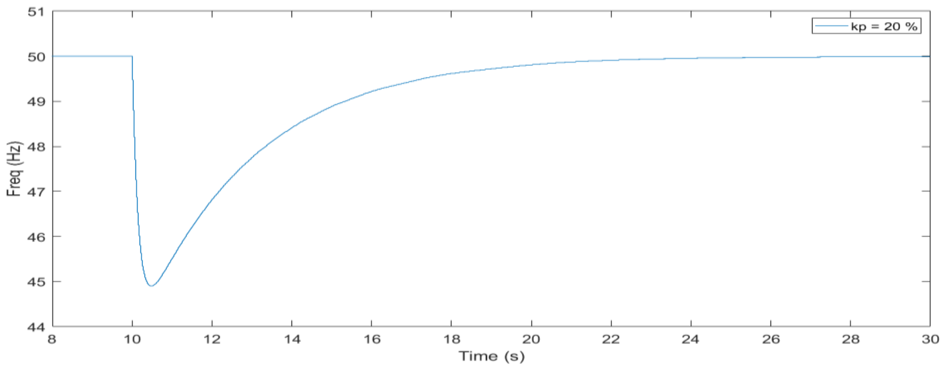


Figure 3.11 – Control of the frequency's amplitude using kp (kp = 20 %)

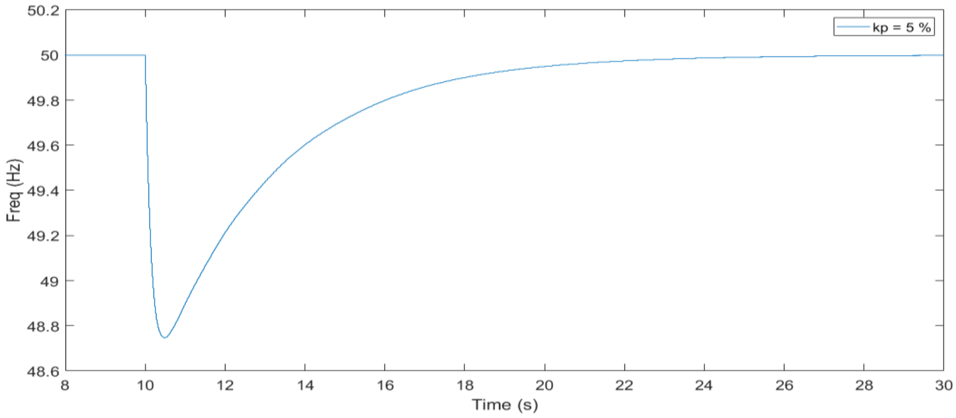


Figure 3.12 – Control of the frequency's amplitude using kp (kp = 5 %)

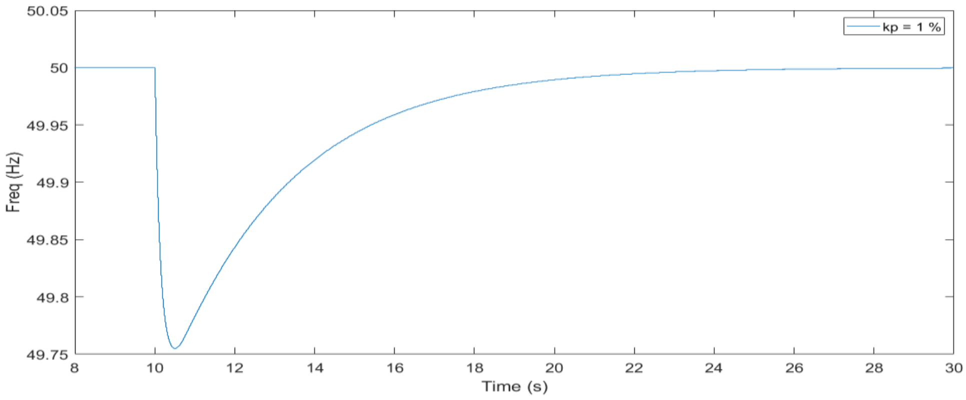


Figure 3.13 – Control of the frequency's amplitude using kp (kp = 1 %)

The second variable into matter is TdP and controls the time that the frequency takes to achieve its minimum value, since the grid suffers a perturbation. This delay control is very important, because if there are multiple VSI in the system, the one that activates first, in case of a big variation in the energy of the system and in case the VSI that activates first doesn't have de capacity to handle these variations, the system could collapse. This delay will give the other VSI time to activate and serve as a back up to the first inverter. The TdP chosen was 0.15s, because a time higher takes too much time, as proven by the Figure 3.14, 3.15 and 3.16. The virtual inertia of the system (H) is equal to 1.5 s.

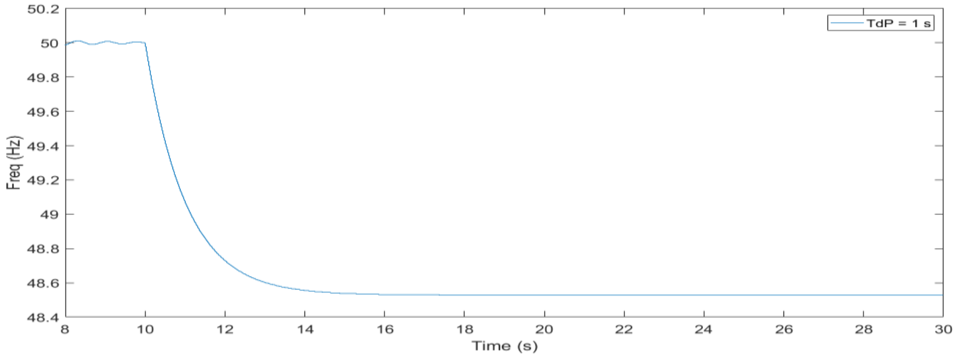


Figure 3.14 – Actuation delay control TdP (TdP = 1 s)

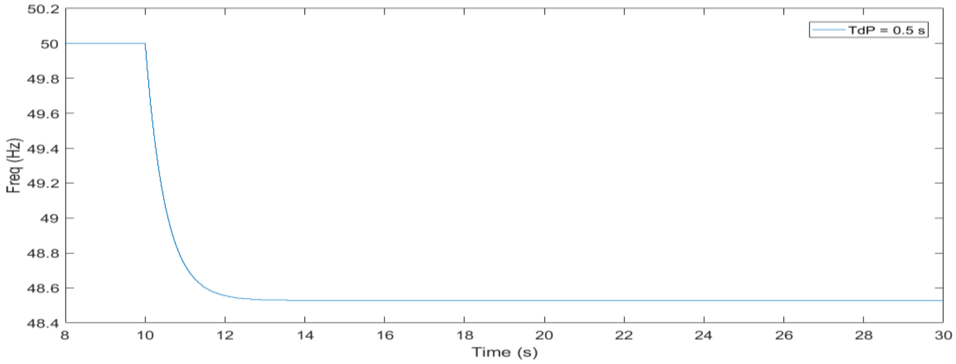


Figure 3.15 – Actuation delay control TdP (TdP = 0.5 s)

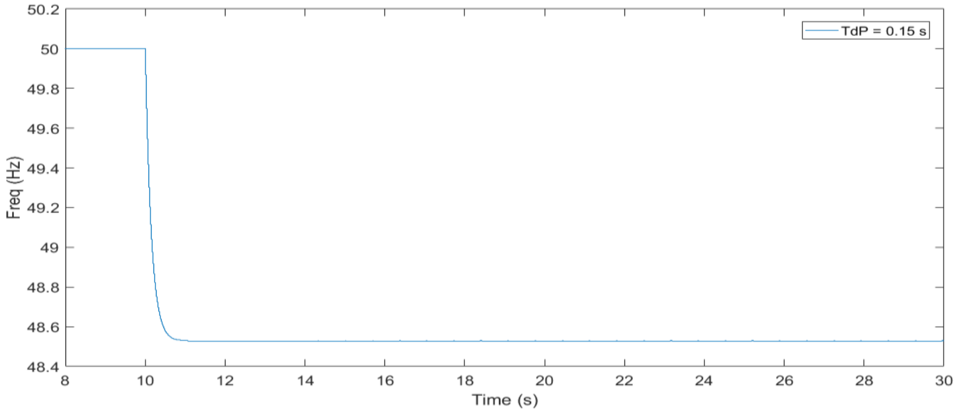


Figure 3.16 – Actuation delay control TdP (TdP = 0.15 s)

The last variable to be considered is the TdI and focuses on the time delay that the variation of the frequency takes until it is restored. The value chosen for this time delay was 1.5 s. A value lower can overlap the delays in the primary control and higher can take too much time, as seen in Figures 3.17, 3.18 and 3.19.

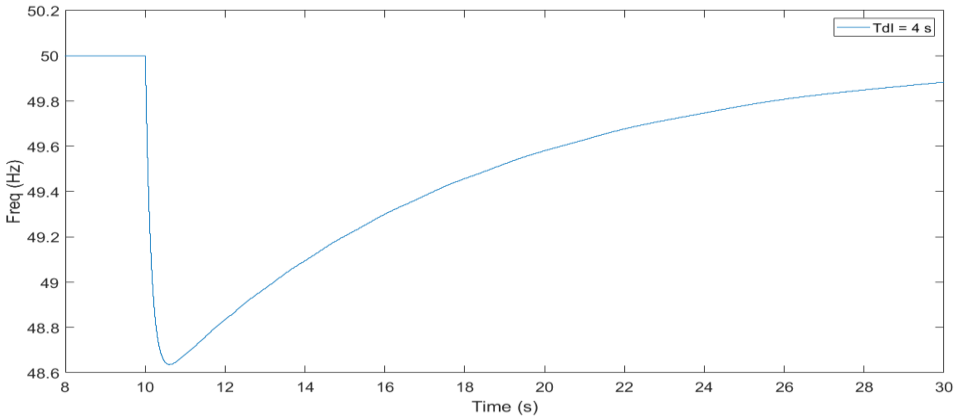


Figure 3.17 – Integral delay control TdI (TdI = 4 s)

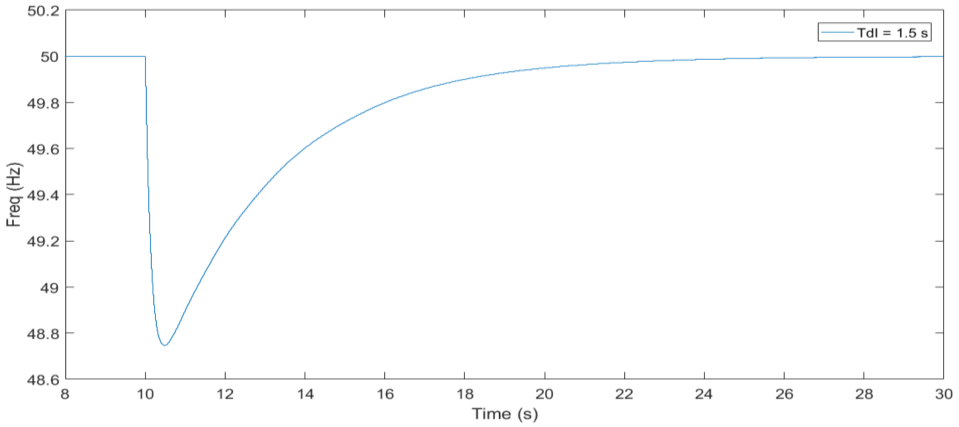


Figure 3.18 – Integral delay control TdI (TdI = 1.5 s)

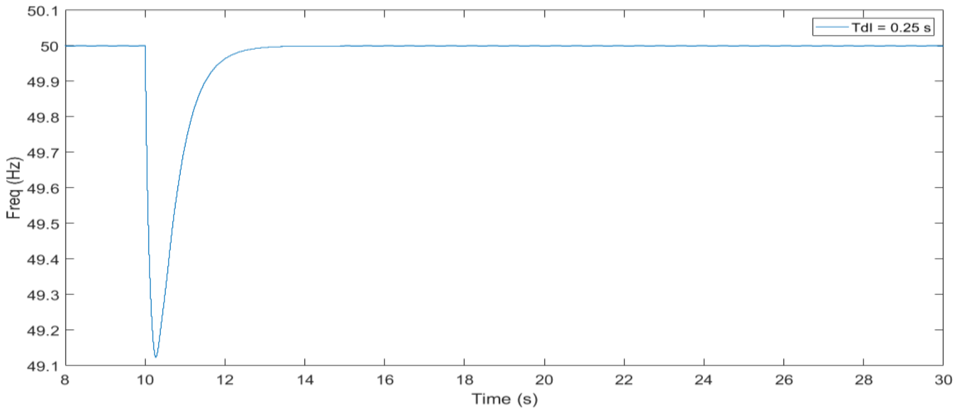


Figure 3.19 – Integral delay control TdI (TdI = 0.25 s)

3.2.2.2. PV Sources

The PV Sources are controlled with the help of PQ inverters. The solar irradiation does not vary too much, due to the short time of simulation. Hence, the inverters can act as constant current sources.

As seen in Figure 3.20, the implementation of these generators in *MATLAB Simulink* was done with the help of a block named Three-Phase Dynamic Load with a negative PQ reference. This unit, as it is connected to the AC MMG, is dependent of the frequency. In other words, every time that the frequency suffers some sort of variation, the active power alters too, with the help of the P-f droop control. The regulation of Europe compels all the generators connected to the AC grid to have some functions sensitive to the frequency of the grid (Limited Frequency Sensitive Mode).

Also, the block Three-Phase Dynamic Load receives 90% of the nominal power. This happens, because if the grid is under 50 HZ, the active power being generated by the PV sources can augment until more 10 % and if the frequency is over the 50 Hz the active power can decrease 100 % of its value. The droops are equal to 5% and TdP is equal to 0.25 s.

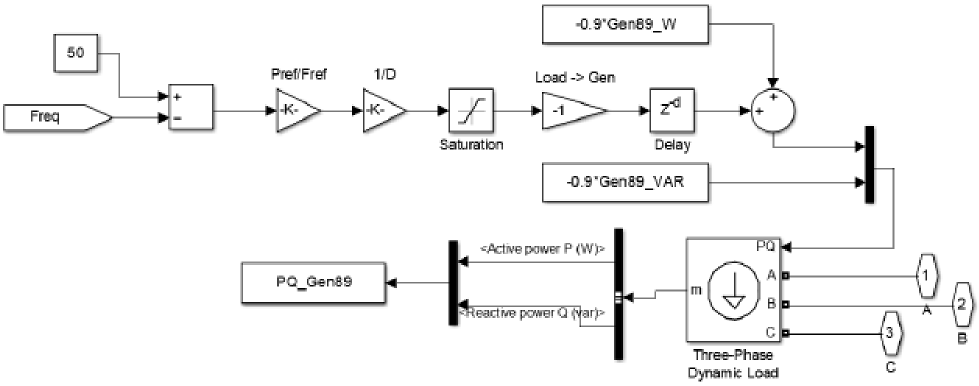


Figure 3.20 – PV sources implementation in *MATLAB Simulink* [5]

3.2.3. Additional Models

There were some models that were not used in this document, but are also important to refer, due to their help in maintaining the stability of the hybrid system. These models are the Batterie units that can be added to the AC grid and the Load Shedding.

The battery can be represented as a constant voltage source, because of the short time intervals of simulation. The block Three-Phase Dynamic Load would be also used in this scenario, as well the P-f control and a dead-band, as shown in Figure 3.21.

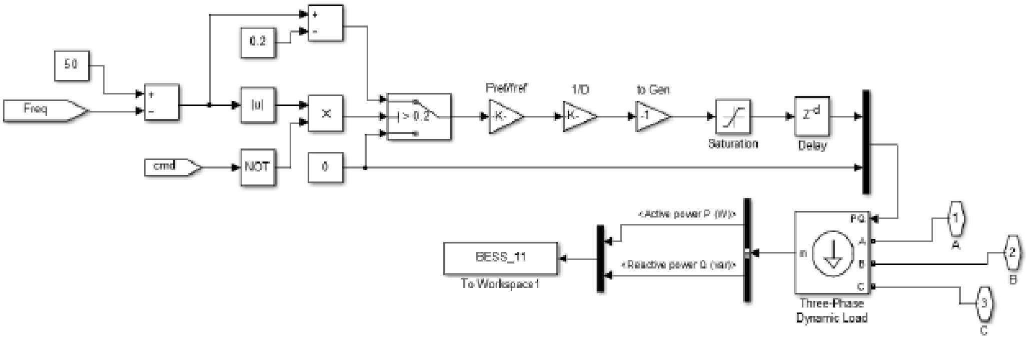


Figure 3.21 – Model of the batteries equipped to AC MMG in *MATLAB Simulink* [5]

The Load Shedding would help the system's frequency not to go below its limits, by implementing, to some loads, relays that provide these capabilities. These relays will act when the frequency is secured above 49 Hz. Appendix C.1 and C.2 show how the Load Shedding control can be represented.

3.3. Main Conclusions

It is possible to conclude that:

- There are 3 main components modelled in this dissertation, in the DC microgrid: the battery, the solar PV and the AC/DC converter.
- There are 2 main components designed in the AC microgrid: the VSI and the PV generators.
- The control functions used in the AC side of the grid are not the same, comparing to the DC side.
- The AC/DC converter connects the AC MG to the DC MG, enables a bidirectional power flow between the two grids.
- The Battery functions as a backup unit in the DC MG, helping the DC loads of the system being supplied.
- The Solar PV connected in the DC system work as a power injector, due to the small variation of radiation in a small period of simulation.
- The VSI control functions will help the systems frequency and voltage stability when the system starts operating in island mode.
- The PV systems installed in the AC system are controlled by PQ inverters.

Chapter 4 will explain the overall models of the DC and AC microgrids used, as well as the hybrid model being simulated in that same chapter.

Chapter 4

Final Results

This chapter focuses on the whole structure of the hybrid AC/DC microgrid and the different scenarios used to test the grid, including all the parametrization used in each scenario. The results of each test, performed in the Software *MATLAB Simulink,* are also analysed.

4.1. Case Study

The implemented hybrid AC/DC model is divided into two microgrids: a DC microgrid and an AC multi-microgrid model. The Simulink model is presented in Appendix A.1.

4.1.1. DC Microgrid

In Chapter 3, the main units of the DC grid were described and as shown in Figure 4.1, the model of the grid with all those components is shown. The full DC MG implemented in the *Software MATLAB Simulink* is represented in Appendix A.2.

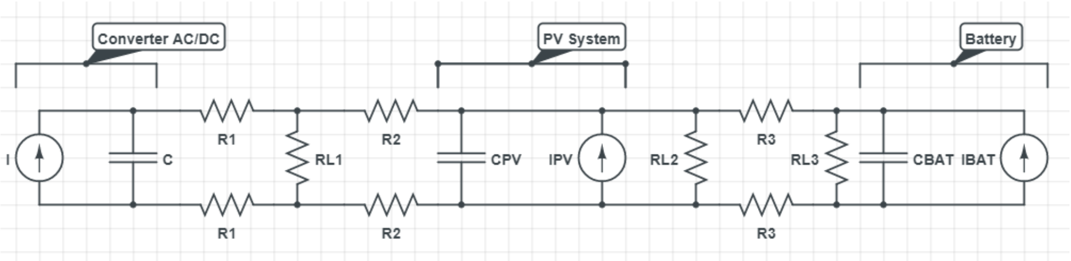


Figure 4.1 – Model of the DC microgrid with the converter being tested

It is possible to see that the DC microgrid contains:

- 3 resistive loads: RL1, RL2 and RL3.
- 3 resistive lines: R1, R2 and R3.
- 1 AC/DC converter.
- 1 Battery.
- 1 Solar

The parametrization of the resistances in the lines, the capacitors implemented in each unit and the droop of active power (kp) (for both the converter and the battery) are present in Appendix D.1. These values never change throughout the rest of the dissertation.

The characteristics and parameters of all these components will be explained when the DC grid is joined to the AC microgrid.

4.1.2. AC Multi Microgrid

This grid was implemented based on a rural network in Spain, named the MERGE project (Appendix B.1). This decision was made due to the big amount of information that INESC TEC had. As seen in Figure 4.2, the model was changed, where the microgrid was divided into two microgrids and the buses were distributed between the microgrids, maintaining the same 13 buses from the MERGE project, resulting in an easy computational system and having different power flows in the microgrid [5].

These were not the only changes made: The reactive power generation is 20% of its active power generated(the typical value to use in coupled PVs); the load system and the generation system are 3-phase balanced; the nominal power of loads and distributed generators was reduced by 50%, due to high voltages drops in the power lines and all this generators were considered PVs systems due to being easier to implement in the software *MATLAB Simulink* [5].

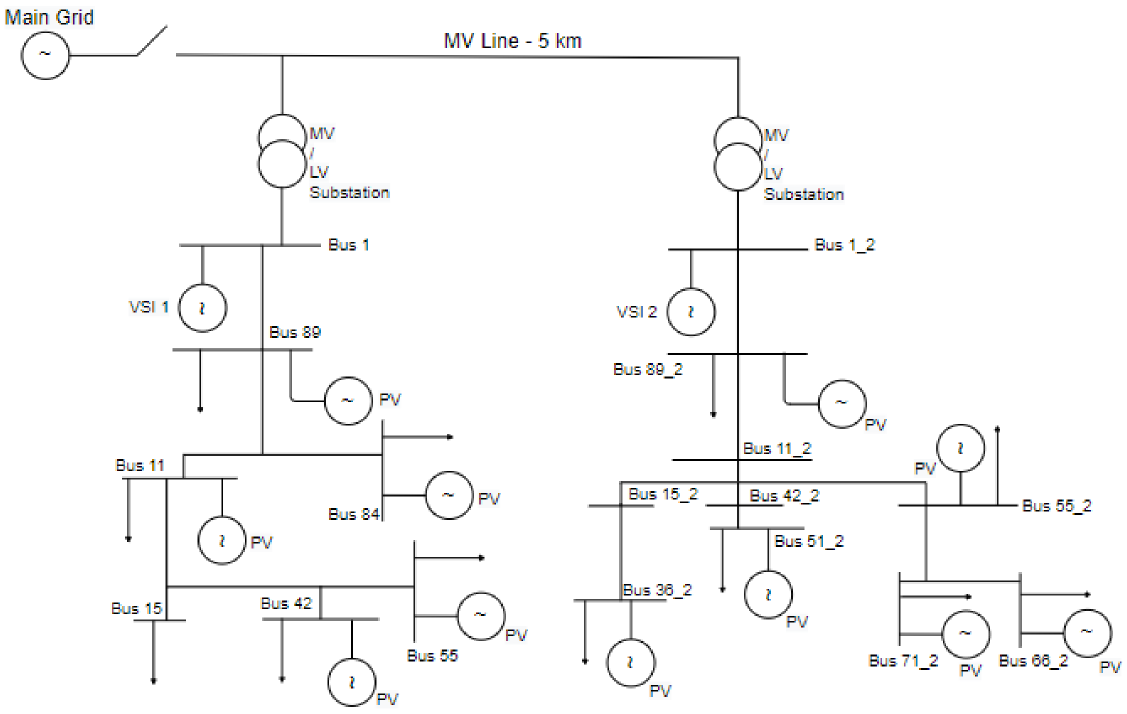


Figure 4.2 – Model of the AC MMG being tested

The main characteristics of this AC MMG are:

- The grid is divided into two LV microgrids associated with the main grid.
- The MV line connecting the two microgrids to the higher-level grid has 5 km.

- Each microgrid has a MV/LV substation and connected to the LV side, there is a 150 kW battery unit. These batteries are connected and controlled by the VSI, in order for the grid to operate in an autonomous way, when it is in the island mode.

- The DGs and loads (100 kW peak load) are spread throughout the buses.

- Both LV microgrids are 3-phase system.

- The nominal voltage of the microgrids are 380 V.

- The configuration of the grids is radial.

- In a rural network, the LV feeder have higher resistances than the reactance. The resistance and reactance used in each LV line is represented in Appendix D.2 and the impedances used in the MV lines are in Appendix D.3.

- The VSI is controlled with the help of the primary droop control (P-f and Q-V droop functions) and the secondary control (restoration of frequency).

- The limits of the frequency is between 49 and 51 Hz and for the voltage is 0.9 p.u and 1.1 p.u.

4.1.3. Hybrid Microgrid

After defining both grids separately, it is time to join them through the AC/DC converters.

Two DC microgrids were added to the AC MMG, one of them is connected to the bus 42 and another one is linked to bus 1_2 as seen in Figure 4.3.

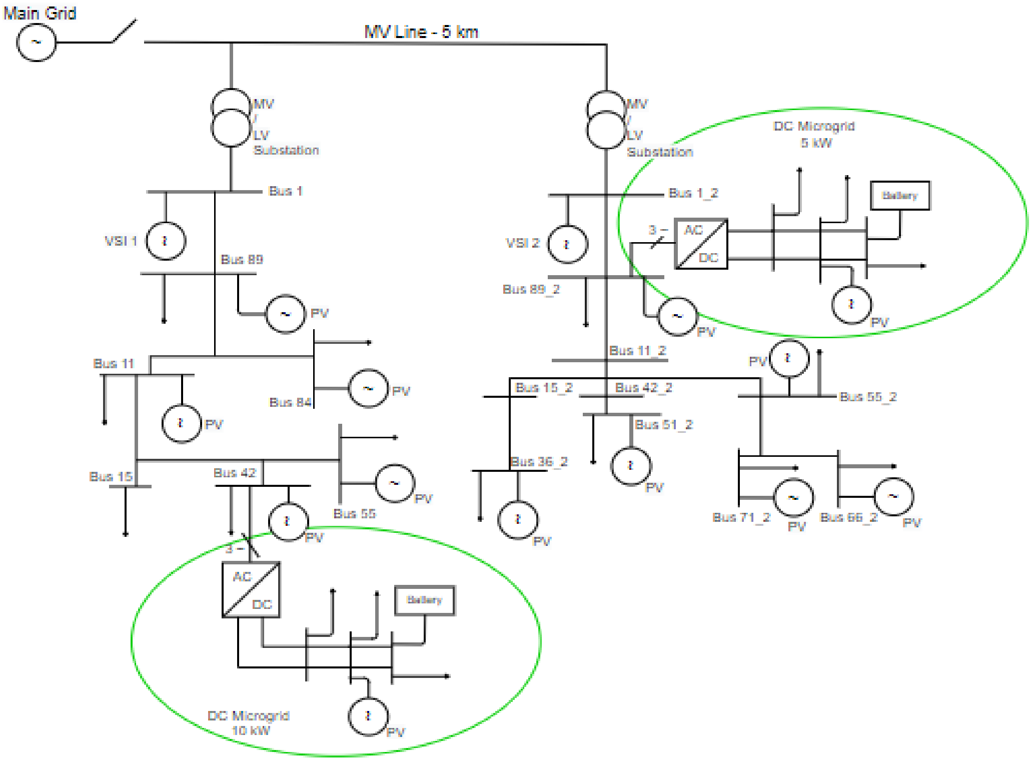


Figure 4.3 – Model of the Hybrid microgrid being tested

The DC grid connected to the bus 42 has a load peak capacity of 10 kW. It has a bidirectional AC/DC converter that interconnects the AC grid with the DC grid. This converter has as 10 kW of nominal active power and can deliver the energy from the AC grid or can send some active power to the AC grid, only in case the power generated by the DC grid is higher than the total capacity of the DC loads. The MG has a length of 1.5 km and as a battery and a solar PV implemented. The battery has a nominal power of 3 kW and is used as a back up to the DC grid.

Similar to the previous grid, the other DC grid has the same length and units installed, but the peak capacity of the loads is equal to 5 kW. The converter and battery's nominal power is equal to 5kW and 2kW, respectively.

The nominal voltage of both DC grids is 230 V and the models have a two-pole system (positive and negative pole). The limits of the voltage of the DC system should vary between 207 V and 253 V (0.9 p.u. to 1.1 p.u.).

4.2. Scenarios and Parametrization

The simulations performed in the Software *MATLAB Simulink* consist in 4 scenarios. These scenarios have a series of tests, in order to study the behaviour of the hybrid AC/DC microgrid (Figure 4.4).

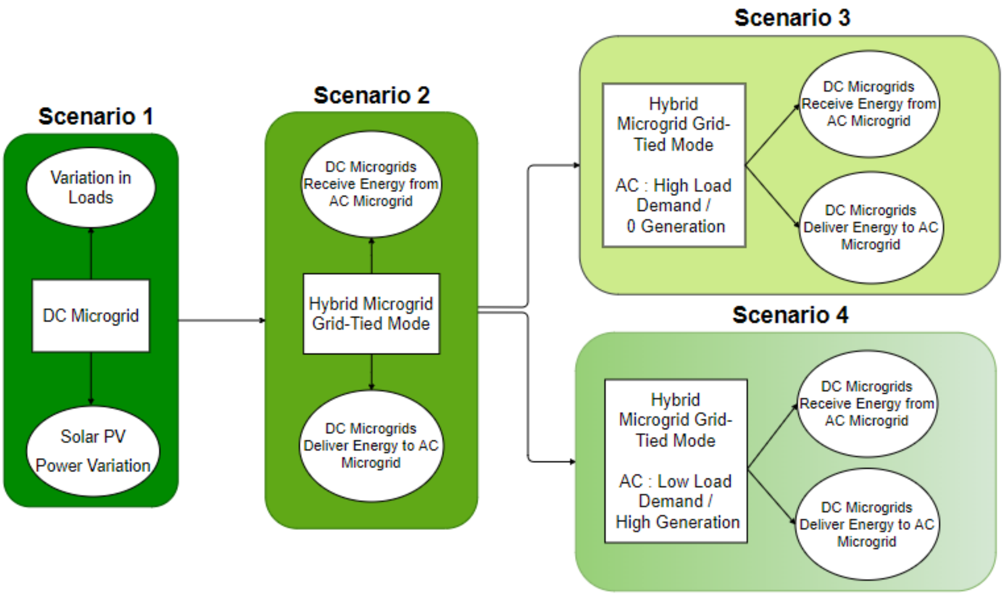


Figure 4.4 – Tree scheme of all the scenarios and tests performed

4.2.1. Scenario 1

The first scenario consists in a situation where the DC microgrid works independently of the rest of the hybrid grid, without the help of the AC grid and without a converter. This means that only the battery guaranties the control of the DC system. The original parameters used for this scenario are in Table 4.1 and the tests simulated consist in variations of the loads of the system and in the Solar PV power generation:

- Test 1: The power generated by the battery and the PV are equal between each other (2 kW each), meaning the total capacity of the loads is 4 kW. There is a balance between the power generation and the total load capacity.

- Test 2: At 7 seconds of the simulation, a load with capacity equal to 2kW is added in parallel with one of the loads of the system.

- Test 3: At 7 seconds, the power generated by the Solar PV is decreased from 2 kW to 200W. There is no variation in the load’s capacity.

- Test 4: At 7 seconds, the power generated by the Solar PV is increased from 2 kW to 3,8 kW. There is no variation in the load’s capacity.

- Test 5: A reduction in the power generation of the Solar PV is made at the 6 seconds of the simulation (2000 W→ 200 W) and, after 2 seconds of this variation, an increase in load is done. In other words, a mix of Test 2 and 3.

- Test 6: This is the final test to study in this scenario. The power generated by the PV Solar is sufficient to supply all the loads in the system, giving the opportunity for the battery to storage some energy.

Table 4.1 – Scenario 1 → DC microgrid parametrization

Values used for Scenario 1 (4 kW DC MG)			
Solar PV	P_PV	2000	W
Converter AC/DC	P_0	0	W
	V_{ref}	0	V
Battery	P_0	2000	W
	V_{ref}	230	V
Loads	L1	2000	W
	L2	1000	W
	L3	1000	W

4.2.2. Scenario 2

In the second scenario, two of these DC grids (one with 5kW and another with 10 kW peak load capacity) are connected to the AC MMG. The hybrid grid is operating in grid-tied mode and the tests performed were:

- Test 7: Both DC MG connected to the AC MMG are operating with high load capacity and low PV generation. The AC/DC converter will help the DC grid, by transmitting active power from the AC grid to the DC grid. The values used for this test are in Tables 4.2, 4.3 and 4.4.

- Test 8: Both DC MGs connected to the AC MMG are operating with low load capacity and high PV generation. The AC/DC converter will deliver the excess of active power to the AC grid. Using the same values for the AC grid, the parametrization of the DC MG used in this test is defined in Tables 4.5 and 4.6.

Table 4.2 and Table 4.3 – Test 7, 9 and 11 - 5 kW DC (left) and 10 kW DC (right) microgrids parametrization

Values used for Tests 7, 9 and 11 (5 kW DC MG)			
Solar PV	P_PV	1000	W
Converter AC/DC	P_0	2000	W
	V_{ref}	230	V
Battery	P_0	2000	W
	V_{ref}	230	V
Loads	L1	2000	W
	L2	1000	W
	L3	2000	W

Values used for Tests 7, 9 and 11 (10 kW DC MG)			
Solar PV	P_PV	2000	W
Converter AC/DC	P_0	5000	W
	V_{ref}	230	V
Battery	P_0	3000	W
	V_{ref}	230	V
Loads	L1	5000	W
	L2	2000	W
	L3	3000	W

Table 4.4 – Scenario 2 (Tests 7, 8, 11 and 12)→ AC MMG parametrization [5]

Scenario 2 and 3: AC High Load Demand and 0 Generation									
Left AC Microgrid					**Right AC Microgrid**				
	Generation		**Loads**			**Generation**		**Loads**	
Buses	**P (kW)**	**Q (kvar)**	**P (kW)**	**Q (kvar)**	**Buses**	**P (kW)**	**Q (kvar)**	**P (kW)**	**Q (var)**
89	0	0	12,1	2,5	**89_2**	0	0	12,1	2,5
84	0	0	12,8	3,9	**55_2**	0	0	6,4	1,6
11	0	0	20,2	4,1	**51_2**	0	0	4,3	0,9
55	0	0	6,4	1,6	**36_2**	0	0	8,1	2,4
42	0	0	3,2	0,9	**71_2**	0	0	3,2	0,6
15	0	0	1,1	0,2	**66_2**	0	0	10,5	2,1
Total	0	0	55,7	13,1	**Total**	0	0	44,6	10,1

Table 4.5 and Table 4.6 – Tests 8, 10 and 12 - 5 kW DC (left) and 10 kW DC (right) microgrids parametrization

Values used for Tests 8, 10 and 12 (5 kW DC MG)			
Solar PV	P_PV	1900	W
Converter AC/DC	P_0	2000	W
	V_{ref}	230	V
Battery	P_0	2000	W
	V_{ref}	230	V
Loads	L1	200	W
	L2	100	W
	L3	200	W

Values used for Tests 8, 10 and 12 (10 kW DC MG)			
Solar PV	P_PV	3800	W
Converter AC/DC	P_0	5000	W
	V_{ref}	230	V
Battery	P_0	3000	W
	V_{ref}	230	V
Loads	L1	500	W
	L2	200	W
	L3	300	W

4.2.3. Scenario 3

The third scenario focuses on the Hybrid MG working in island operating mode. At 10 seconds of the simulation, the grid will disconnect from the main grid and start working autonomously. Also, before the grid opened, the AC MMG was receiving energy from the main grid, meaning that there was more load capacity than power being generated in the AC grid. Table 4.4 shows the values of the AC MMG loads capacity used in this scenario. The tests performed in this scenario were:

- Test 9: The DC MGs implemented in the system receive energy from the AC MMG. As before, the generation in the DC MG cannot supply alone the loads in the system, needing help from the AC MMG (Tables 4.2 and 4.3).

- Test 10: The DC MGs delivers energy to the AC grid. The excess of energy produced in the DC MG is delivered to the AC MMG (Tables 4.5 and 4.6).

Table 4.7 – Scenario 3 (Test 9 and 10)→ AC MMG parametrization [5]

Scenario 4: AC Low Load Demand and High Generation									
Left AC Microgrid					Right AC Microgrid				
	Generation		Loads			Generation		Loads	
Buses	P (kW)	Q (kvar)	P (kW)	Q (kvar)	Buses	P (kW)	Q (kvar)	P (kW)	Q (var)
89	12,3	2,5	3,0	0,6	**89_2**	12,3	2,5	3,0	0,6
84	7,8	1,6	3,2	1,0	**55_2**	11,2	2,2	1,6	0,4
11	9,1	1,8	5,0	1,0	**51_2**	6,4	1,3	1,1	0,2
55	11,2	2,2	1,6	0,4	**36_2**	3,8	0,8	2,0	0,6
42	3,1	0,6	0,8	0,2	**71_2**	13,5	2,7	0,8	0.2
15	0,0	0,0	0,3	0,0	**66_2**	7,3	1,5	2,6	0,5
Total	43,4	8,7	13,9	3,3	**Total**	54,4	10,9	11,1	2,5

4.2.4. Scenario 4

In the last scenario studied, contrary to the one before, the AC MMG has more power being generated than the total capacity of the loads, delivering the excessed energy to the main grid. Table 4.7 represents the values used for this scenario in the AC MMG. The tests done to the grid were the same two tests done in scenario 3.

4.3. Results

4.3.1. Scenario 1

4.3.1.1. Test 1

This first test focuses on the grid working in a balanced environment. Figure 4.5 shows that the active power generated by the Solar PV and the Battery are constant throughout the simulation with a value around 2 kW, to supply the 4 kW loads in the system.

The voltage output of both units is also constant, around the 230 V_{DC} (Figure 4.6).

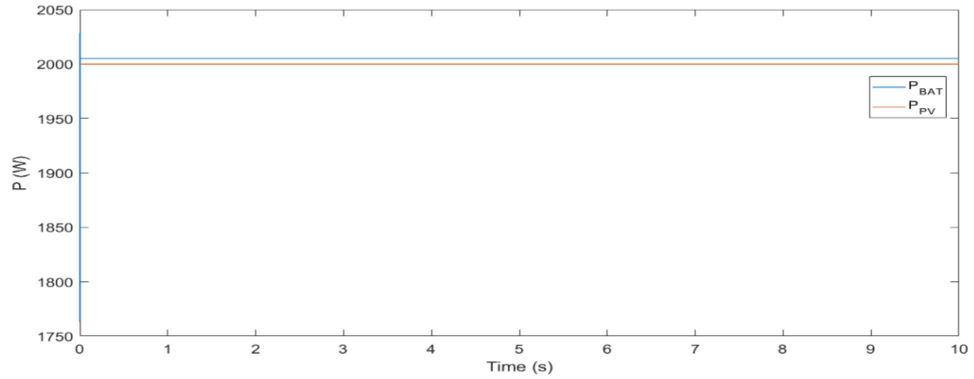


Figure 4.5 – Active power generated by the Battery and the Solar PV, without variation of load and generation

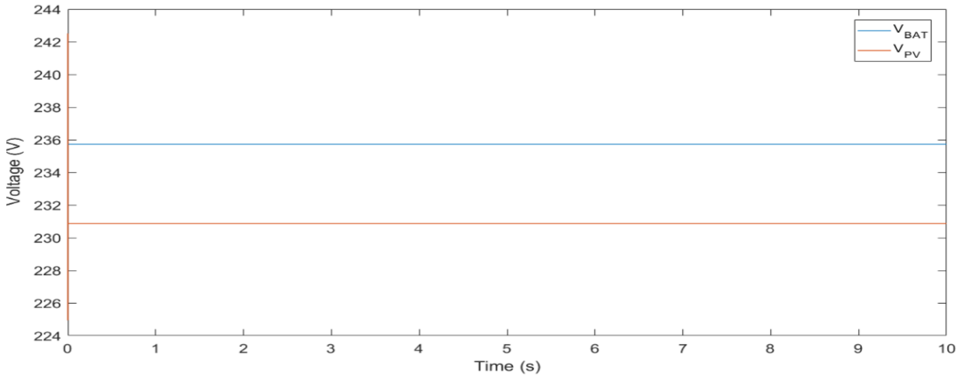


Figure 4.6 – Voltage output of Battery and Solar PV, without variation of load and generation

4.3.1.2. Test 2

With the addition of a 2 kW load at 7 seconds, there is a necessity of more power in the system. As seen in Figure 4.7, as soon the load is added to the system, the battery will produce the necessary power to help supply the increase in capacity of the system.

Hence, the voltage output of these units suffer a slight variation (decrease in this case), respecting the limits defined (Figure 4.8). This has to do with the power flow that establishes in the grid and with the power being sent from the battery, being this one operated in P-V droop (if the active power increases, the voltage will decrease).

It is also important to refer that the active power in the terminals of the loads of the DC MG is not always the same, due to these small variations of voltage in the grid. In other words, as the loads in the DC system are solely resistive, the active power can be represented by Equation (4.1). If there is variation in the voltage, there will be a variation in active power too.

$$P_{res} = \frac{V^2}{R} \tag{4.1}$$

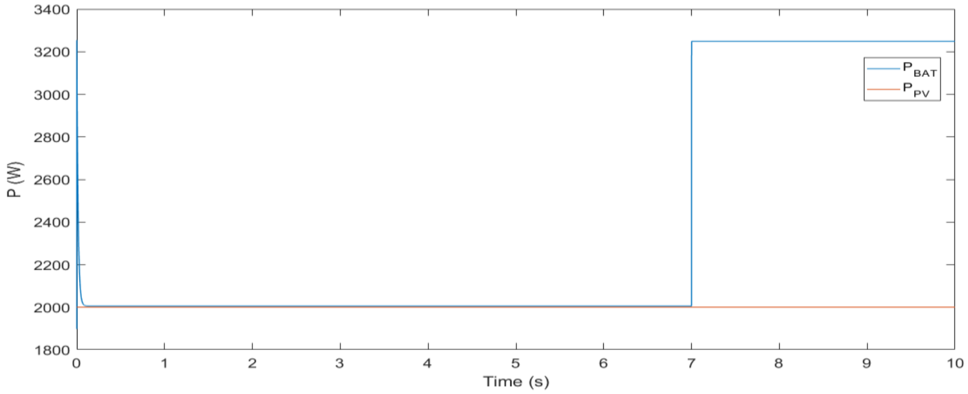


Figure 4.7 – Active power generated by the Battery and the Solar PV, with variation of load (+ 2 kW) and without change in PV generation

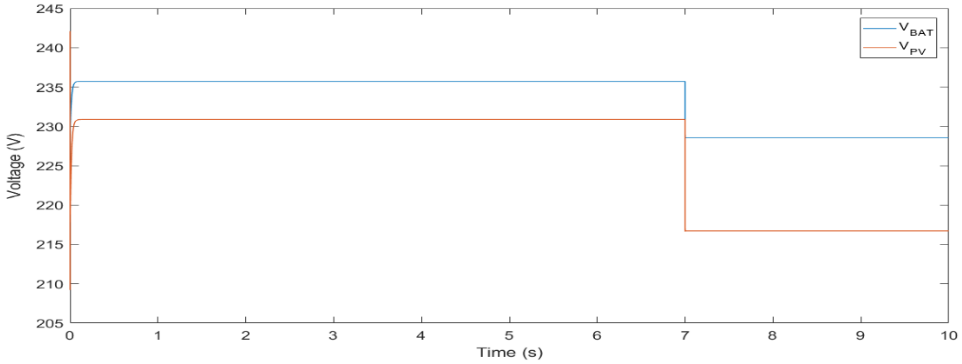


Figure 4.8 – Voltage output of Battery and Solar PV, with variation of load (+ 2 kW) and without change in PV generation

4.3.1.3. Tests 3 and 4

Both tests 3 and 4 simulate the variation of the power generated by the Solar PV.

Test 3 focuses on a decrease of 90% (2000 W → 200 W) of the power generated. Figure 4.9 shows that the battery will augment its discharge, in order to maintain the loads in the system supplied. This decrease in generation of the Solar PV will make decrease the voltage output from the units of the system, due to the increase of power generated by the battery (Figure 4.10).

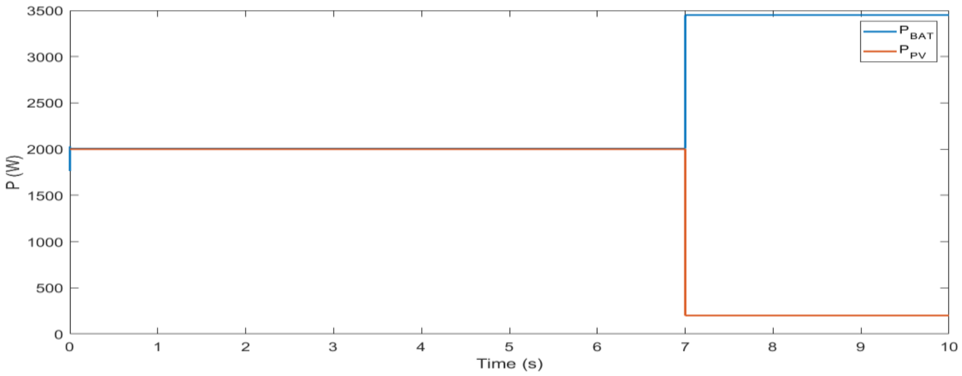


Figure 4.9 – Active power generated by the Battery and the Solar PV, without variation of load and with change in PV generation (2 kW→ 200 W)

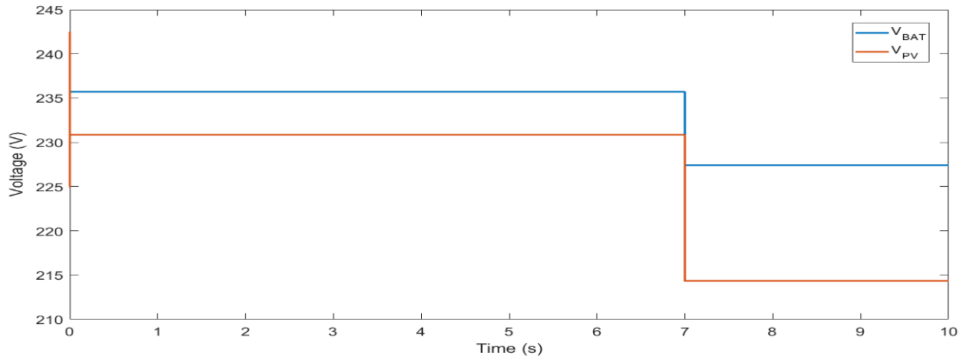


Figure 4.10 – Voltage output of Battery and Solar PV, without variation of load and with change in PV generation (2 kW→ 200 W)

As seen in Figure 4.11 and 4.12, test 4 is exactly the opposite from what happened in the previous test. By increasing the power generated by the Solar PV 90% (2000 W → 3800 W), the battery supplies less energy than before and, due to that, the voltage increases, instead of decreasing.

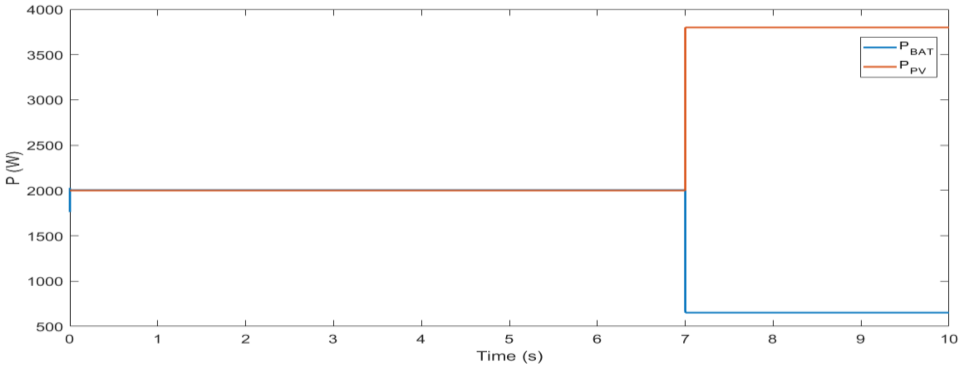


Figure 4.11 – Active power generated by the Battery and the Solar PV, without variation of load and with change in PV generation (2 kW→ 3800 W)

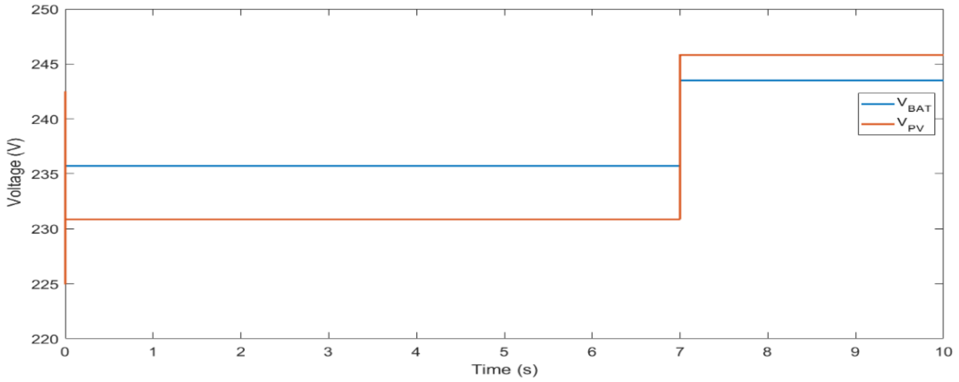


Figure 4.12 – Voltage output of Battery and Solar PV, without variation of load and with change in PV generation (2 kW→ 3800 W)

4.3.1.4. Test 5

In this test, there is a variation in the load capacity and in the power generated by the solar PV. The battery can help the system capability to deliver the necessary energy to the loads present in the system.

In this case the power delivered by the battery is increased when the active power generated by the Solar PV is reduced and, right after the addition of the load, the battery needs to increase the generation even further (Figure 4.13).

The effects in the voltage are the same as before. Every time there is an increase in the generation of the battery, the voltage output of both units decreases its value (Figure 4.14).

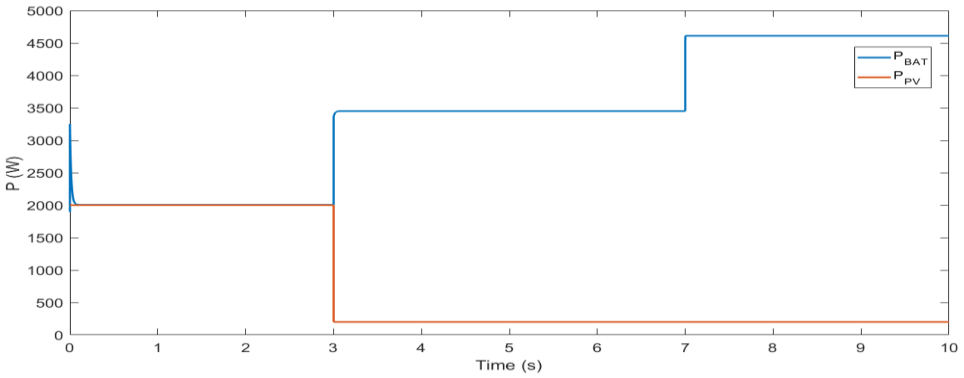


Figure 4.13 – Active power generated by the Battery and the Solar PV, with variation of load (+ 2 kW) and with change in PV generation (2 kW→ 200 W)

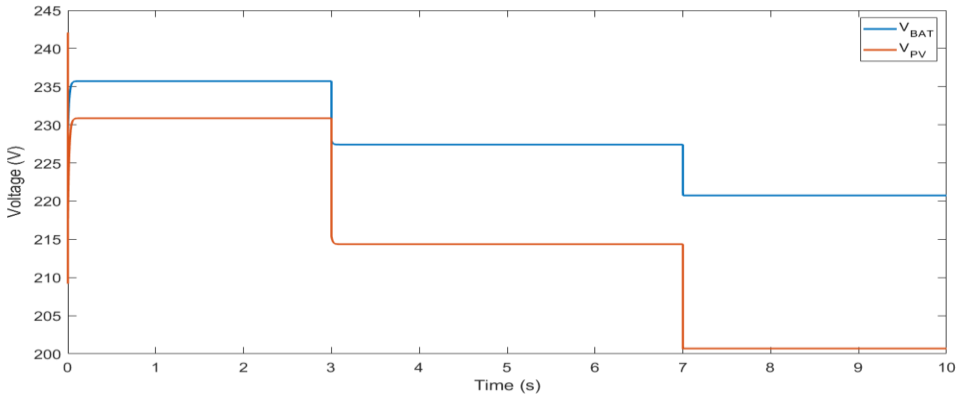


Figure 4.14 – Voltage output of Battery and Solar PV, with variation of load (+ 2 kW) and with change in PV generation (2 kW→ 200 W)

4.3.1.5. Test 6

In the previous tests, it was considered that the battery was fully charged and that it would help the system by discharging energy.

This test focuses on the Solar PV being able to supply all the loads by itself and letting the battery charge the energy generated in excess.

In Figure 4.15, it is possible to see that the battery is charging almost 1.5 kW. The capacity of the system was decreased to 500 W and the solar PV is producing 2 kW of active power, where this power is divided to supply the loads and to the battery charging. Consequently, the voltage output in each unit suffered a big increase (Figure 4.16).

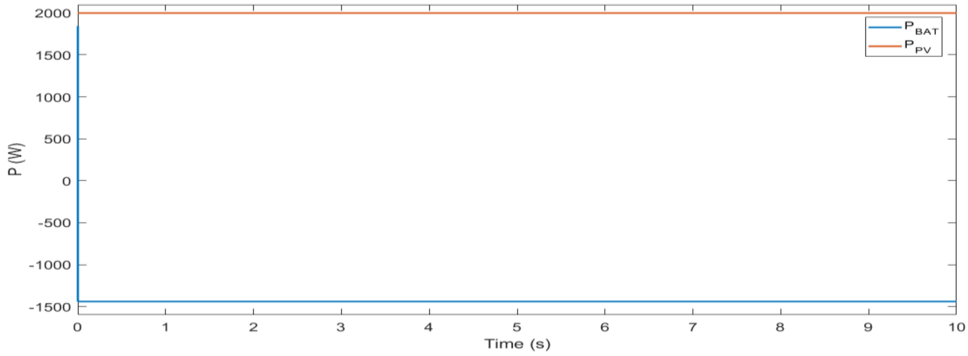


Figure 4.15 – Active power generated by the Battery and the Solar PV, with the Solar PV supplying the loads. Battery charging.

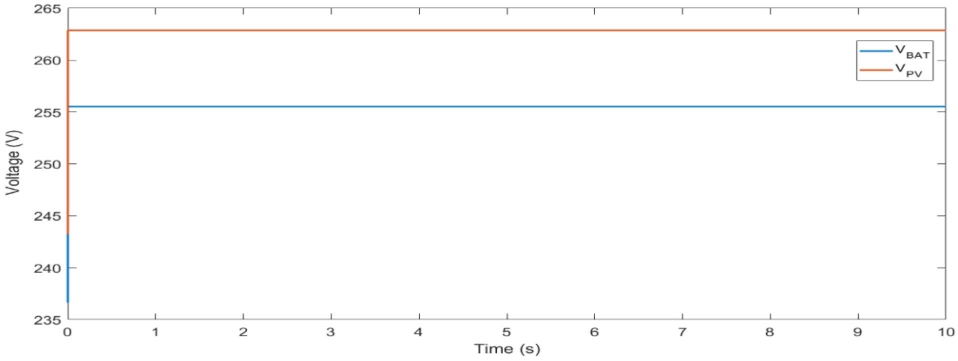


Figure 4.16 – Voltage output of Battery and Solar PV, with the Solar PV supplying the loads. Battery charging

4.3.2. Scenario 2

After adding the two DC grids to the AC multi microgrid, it is possible to see that, while the hybrid microgrid is operating in grid-tied mode, the frequency of the system and the voltage in each bus are constant through the time. In other words, the main grid will help the stability of the microgrid (Figures 4.17 and 4.18).

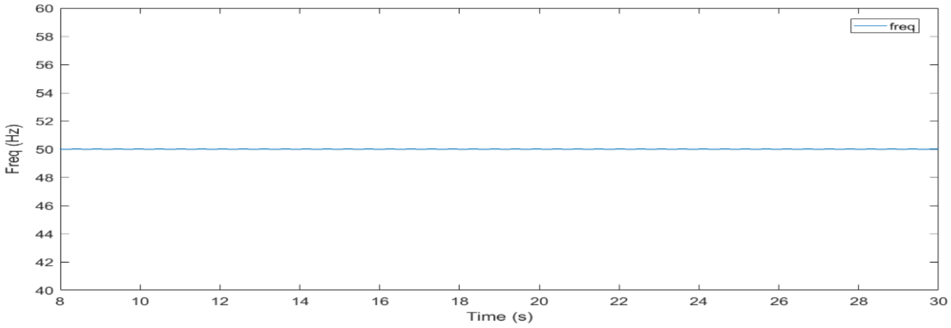


Figure 4.17 – Frequency of the system, when microgrid is operating in grid-tied mode.

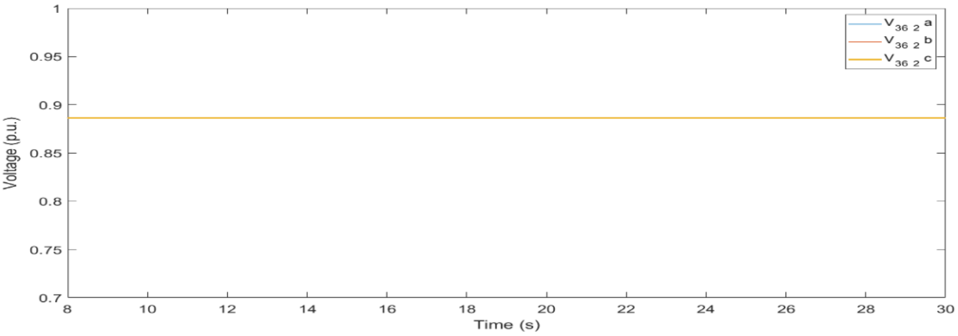


Figure 4.18 – Voltage of one of the buses (36_2), when microgrid is operating in grid-tied mode.

4.3.2.1. Test 7

In this test, the DC microgrids are being helped by the AC microgrid, in order to help supply the loads in the system. In other words, these two microgrids act like loads of the AC system.

The grid with a capacity of 5 kW is receiving from the AC grid around 1.5 kW and the battery is supplying around 2.5 kW. The voltage output in each unit of the DC MG (Converter, Battery, and Solar PV) is constant throughout the simulation (Figures 4.19 and 4.20).

The 10 kW DC microgrid acts in a similar way as the other DC microgrid. The voltage output of the units is constant. The AC MG will supply with 3.5 kW and the battery will discharge 4 kW (Figures 4.21 and 4.22).

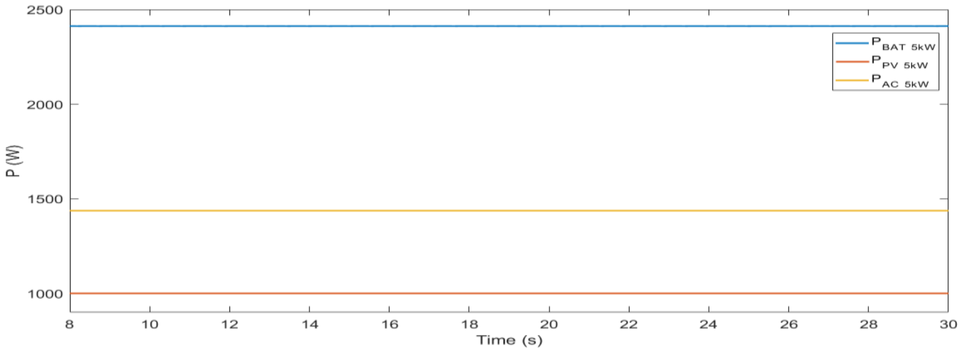


Figure 4.19 – Active power generated by the Battery, the Solar PV and supplied by the AC grid. (5 kW Capacity DC Microgrid)

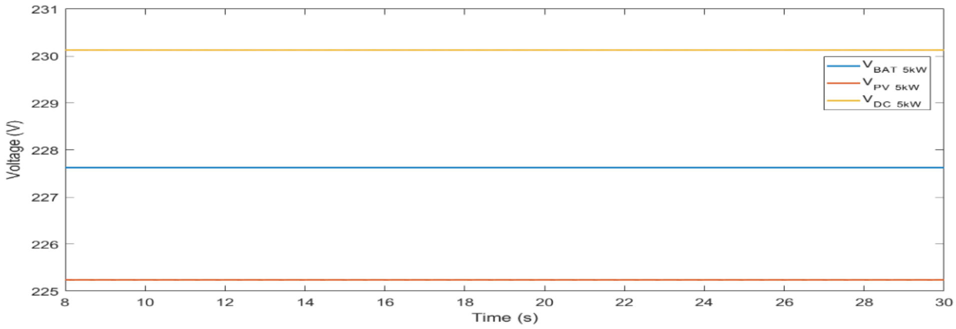


Figure 4.20 – Voltage output of Battery, Solar PV and Converter, while receiving energy from the AC Grid. (5 kW Capacity DC Microgrid)

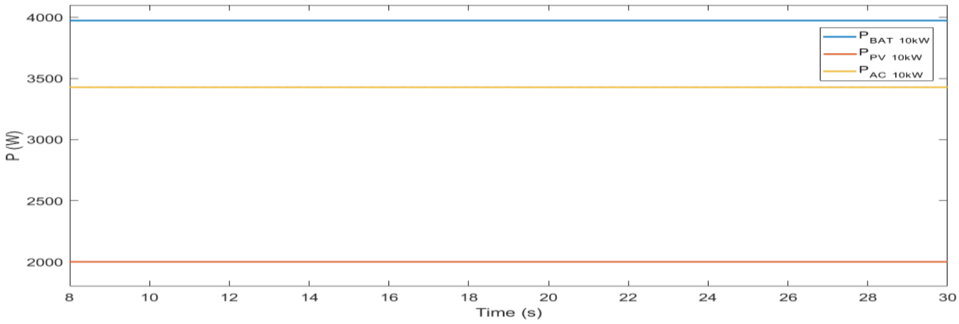


Figure 4.21 – Active power generated by the Battery, the Solar PV and supplied by the AC grid. (10 kW Capacity DC Microgrid)

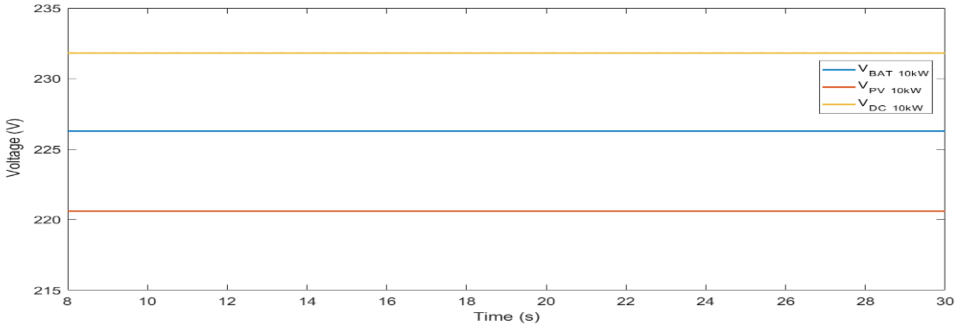


Figure 4.22 – Voltage output of Battery, Solar PV and Converter, while receiving energy from the AC Grid. (10 kW Capacity DC Microgrid)

4.3.2.2. Test 8

The main difference between this test and the previous one is that the DC microgrids are acting like generators of the AC MG. These microgrids have less capacity, meaning that the excess of energy produced in the grid is being sent to the AC grid.

The Figure 4.23 shows that the 5 kW DC grid will send around 1000 W to the AC grid and the battery is not charging, neither discharging.

The active power that the AC grid receives from the 10 kW microgrid is equal to 1 kW. Also, the battery implemented in this grid, at the same time, is charging another 1 kW (Figure 4.25).

The voltage output of the solar PV and the battery, in both DC MGs, is constant, because of the constant frequency in the AC side of the grid and the non-existing variation in the generation of active power in the units of the DC systems (Figures 4.24 and 4.26).

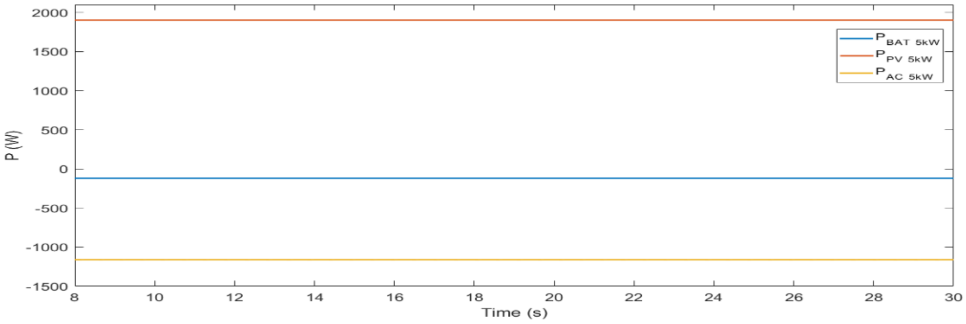


Figure 4.23 – Active power generated by the Battery, the Solar PV and given to the AC grid. (5 kW Capacity DC Microgrid)

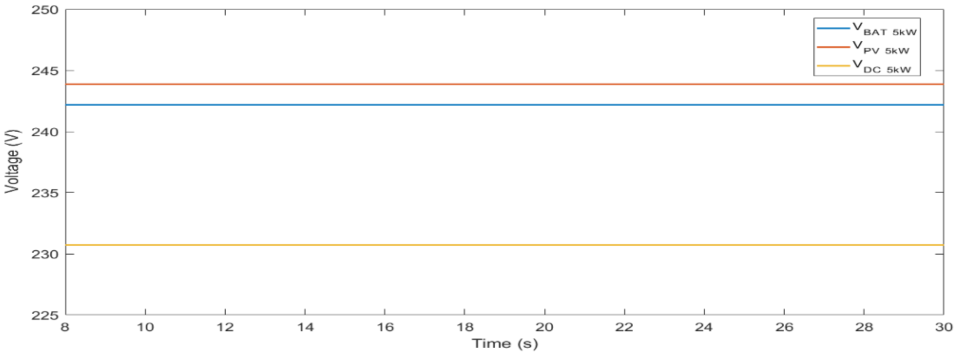


Figure 4.24 – Voltage output of Battery, Solar PV and Converter, while sending energy to the AC Grid. (5 kW Capacity DC Microgrid)

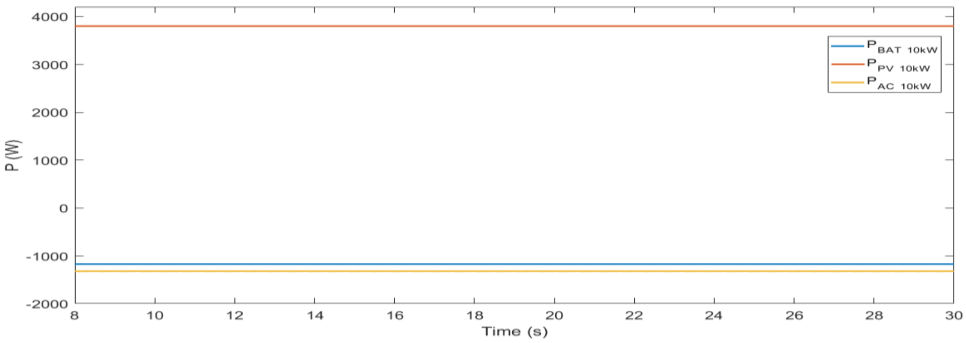


Figure 4.25 – Active power generated by the Battery, the Solar PV and given to the AC grid. (10 kW Capacity DC Microgrid)

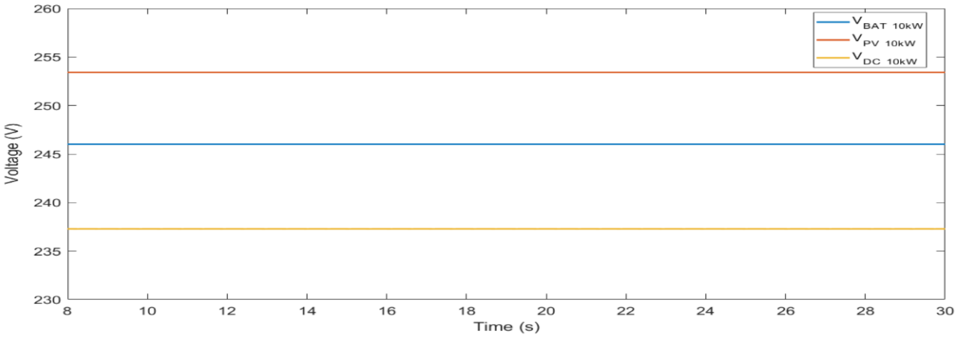


Figure 4.26 – Voltage output of Battery, Solar PV and Converter, while sending energy to the AC Grid. (10 kW Capacity DC Microgrid)

4.3.3. Scenario 3

In this scenario, while the grid is receiving energy from the main grid, due to the lack of generation in the MG, this hybrid grid starts operating in Island Mode, in an autonomous way, separated from the main grid.

4.3.3.1. Test 9

As seen in Figure 4.27, the DC MGs in the system are acting also as loads, due to the lack of power generated to fully supply the capacity inside them.

Hence, at the moment the grid starts operating in island mode, the frequency of the system suffers a variation, where its minimum point is below the accepted limits (48.7 Hz). The voltage in the buses of the system also suffers a small decrement, when the operation mode changes (Figure 4.28).

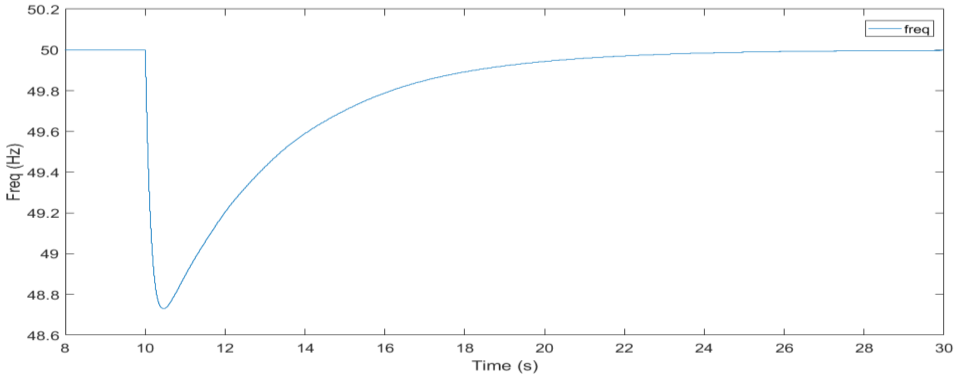


Figure 4.27 – Frequency of the system, when microgrid starts operating in island mode from the 10 seconds of operation. Hybrid microgrid has high load demand (including DC systems) and 0 generation.

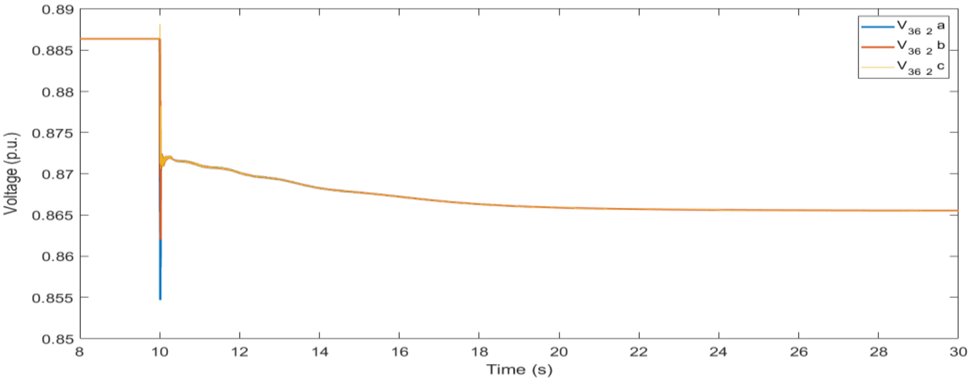


Figure 4.28 – Voltage of one of the buses (36_2), when microgrid starts operating in island mode from the 10 seconds of operation. Hybrid microgrid has high load demand (including the systems) and 0 generation.

Both DC MGs suffer from this change in frequency. The value of active power transmitted from the AC side to the DC changes according to the frequency, resulting in a variation of the output power generated by the battery and the voltage in the system.

Figure 4.29 shows this variation in the 5 kW capacity MG, where the active power that passes through the converter suffers a small variation, consequently making the battery to generate more power to compensate that drop of power. The voltage output in each unit varies according to the variation the active power in the DC system (Figure 4.30). When the frequency is restored, the active power and the voltage in these systems are also restored.

The same results happen in the other 10 kW DC microgrid.

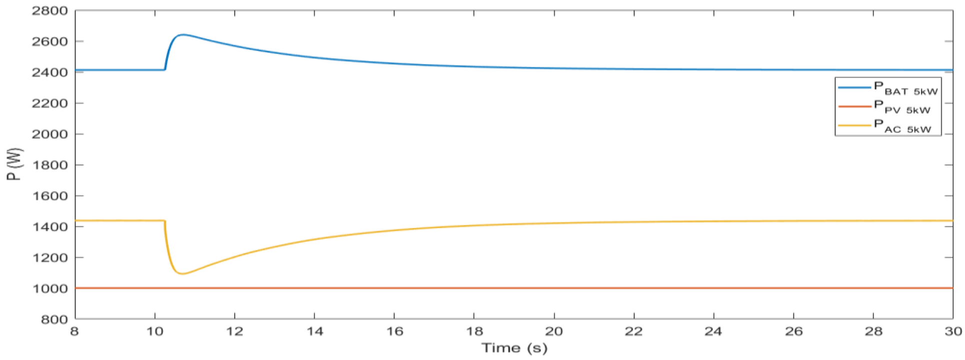


Figure 4.29 – Active power generated by the Battery, the Solar PV and given by the AC grid. (5 kW Capacity DC Microgrid)

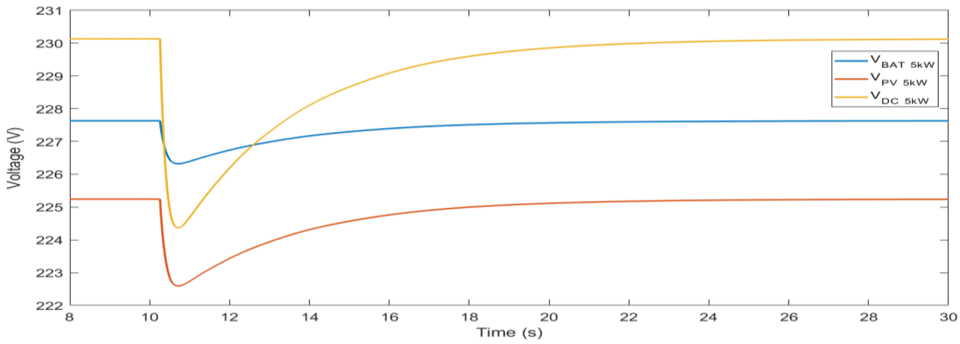


Figure 4.30 – Voltage output of Battery, Solar PV and Converter, while receiving energy from the AC Grid. (5 kW Capacity DC Microgrid)

4.3.3.2. Test 10

With the DC grids acting as generators of the AC MG (in this case the DC MGs are supplying the AC grid with the maximum active power 5 kW and 10 kW), the frequency drop is slightly improved where, in the previous tests was around 48.7 Hz and, in this test is around 48.9 Hz, getting closer to the limits (Figure 4.31).

The DC microgrids, as shown in Figure 4.32, have the same behaviour as before, where the active power and voltage present in the system changes with the frequency. The batteries in both systems are receiving energy, due to the big amount of energy that the solar PV is generating. The voltages in the DC systems have also higher values and vary accordingly with the active power (Figure 4.33).

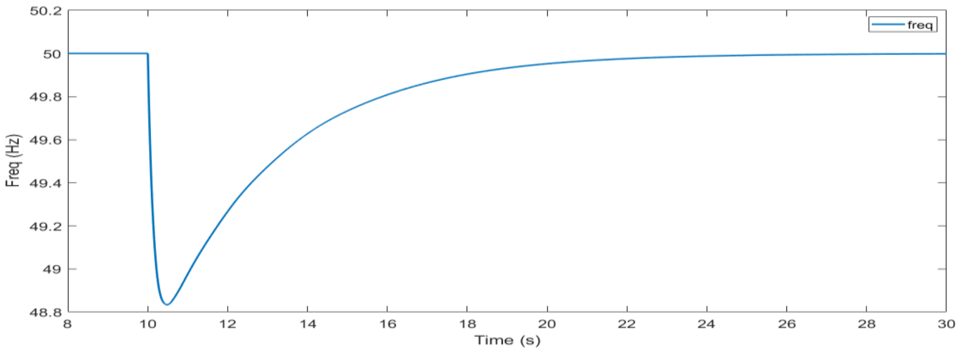


Figure 4.31 – Frequency of the system, when microgrid starts operating in island mode from the 10 seconds of operation. Hybrid microgrid has high load demand and supply from the DC Microgrids.

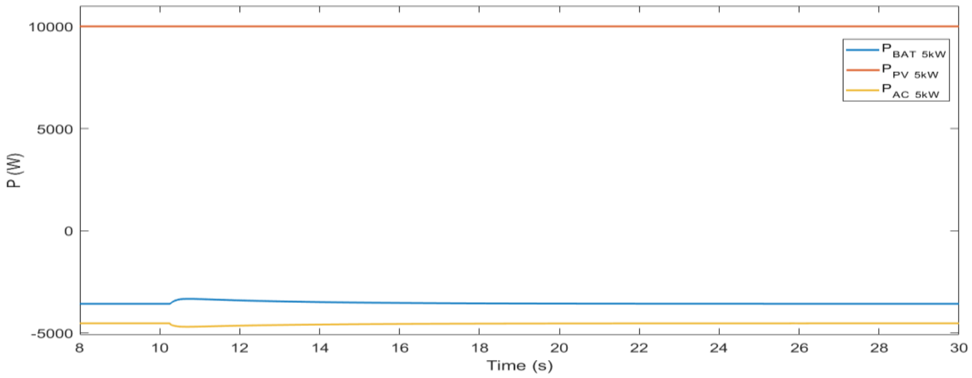


Figure 4.32 – Active power generated by the Solar PV, given to the AC grid, and charged by the Battery. (5 kW Capacity DC Microgrid)

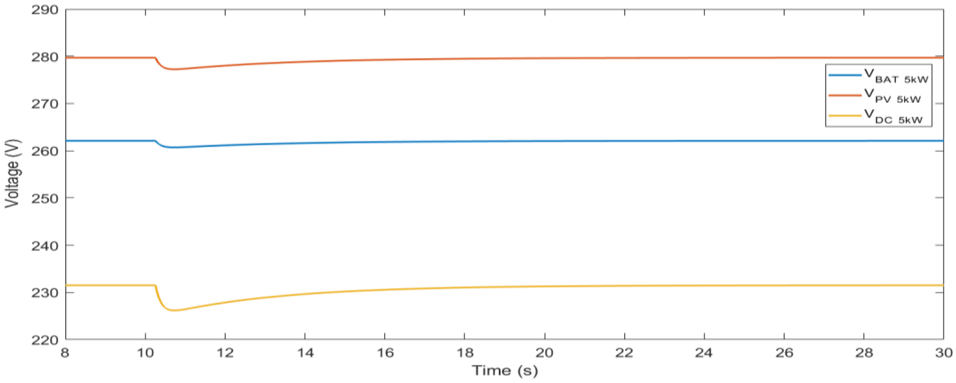


Figure 4.33 – Voltage output of Battery, Solar PV and Converter, while sending energy to the AC Grid. (5 kW Capacity DC Microgrid)

4.3.4. Scenario 4

In this last scenario, the hybrid microgrid will have a big amount of generated energy and a low capacity, supplying the excessed energy to the main grid. Then, this microgrid, at the 10 seconds of simulation, starts operating in island mode, working autonomously.

4.3.4.1. Test 11

The frequency of the microgrid, contrary to the scenario before, rises when it is operating in island mode. The voltage in the buses of the AC MG have a small variation, stabilizing with the restoration of the frequency (values near 1 p.u.) (Figures 4.34 and 4.35).

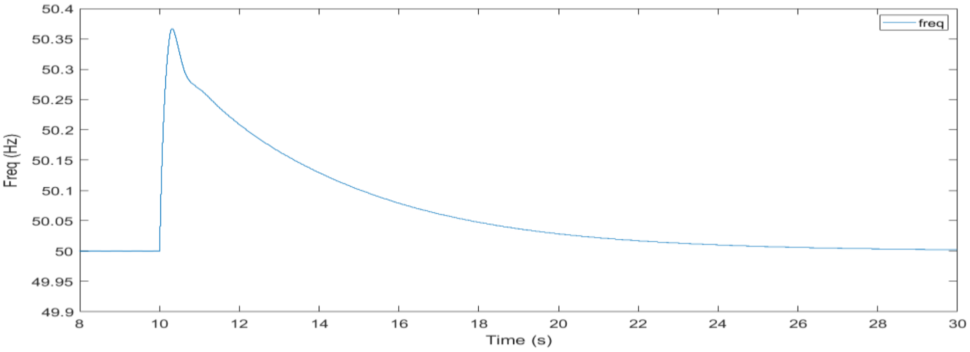


Figure 4.34 – Frequency of the system, when microgrid starts operating in island mode from the 10 seconds of operation. Hybrid microgrid has low load demand (including DC systems) and high generation (DERs in the System).

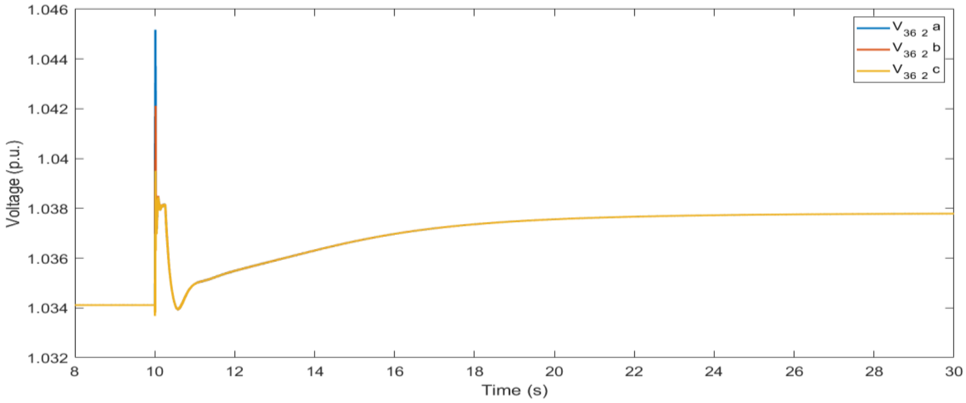


Figure 4.35 – Voltage of one of the buses (36_2), when microgrid starts operating in island mode from the 10 seconds of operation. Hybrid microgrid has low load demand (including DC systems) and high generation (DERs in the System).

As seen in previous scenarios, the active power received from the AC MGs react accordingly to the frequency. In the 5 kW microgrid, the DC microgrid is receiving 1.4 kW of active power from the AC side and, when the hybrid microgrid starts operating autonomously there is a small variation in that power, originating the battery to compensate that rise in power (Figure 4.36). The voltage output of each unit varies as the active power changes (Figure 4.37).

The exact same effect happens in the other DC microgrid implemented in the hybrid system.

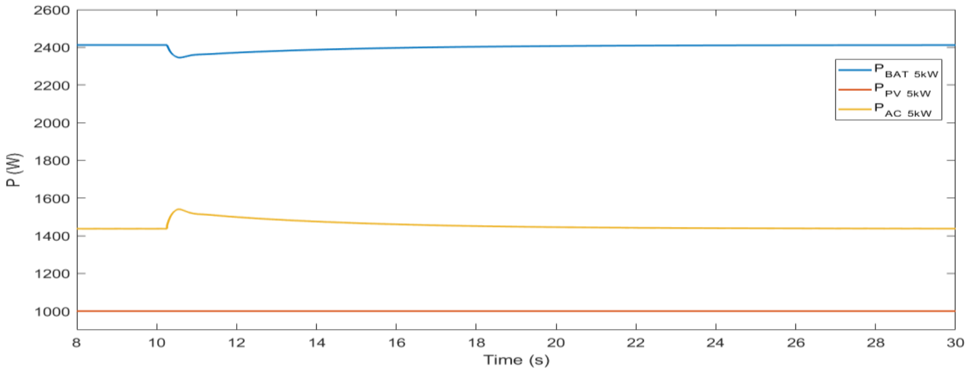


Figure 4.36 – Active power generated by the Solar PV, the Battery and given by the AC grid (5 kW Capacity DC Microgrid)

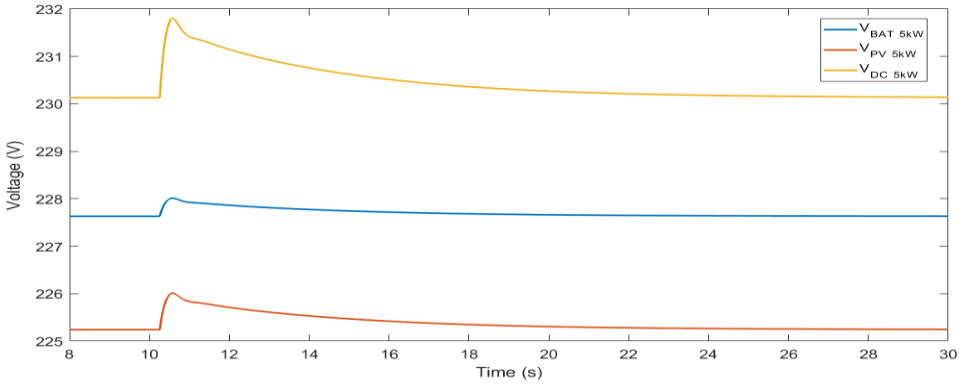


Figure 4.37 – Voltage output of Battery, Solar PV and Converter, while receiving energy from the AC Grid. (5 kW Capacity DC Microgrid)

4.3.4.2. Test 12

With an increase in the solar PV generation and a decrease in the load's capacity of the DC systems, it is possible to see that the frequency rise, when the operating modes change, is higher 0.1 Hz. This is due to the increase of generation in the system, that is, not only the DERs are producing energy to the grid, but the DC microgrids are supplying even more energy (Figure 4.38).

The DC microgrid (5 kW capacity peak load) is sending almost 5 kW to the AC grid and the battery is charging around 3500 W (Figure 4.39).

The other DC MG implemented in the system is supplying the AC grid with almost 10 kW and the battery is charging around 6 kW of energy.

The voltage, as seen before and in Figure 4.40, changes depending on the variation of the active power in the system.

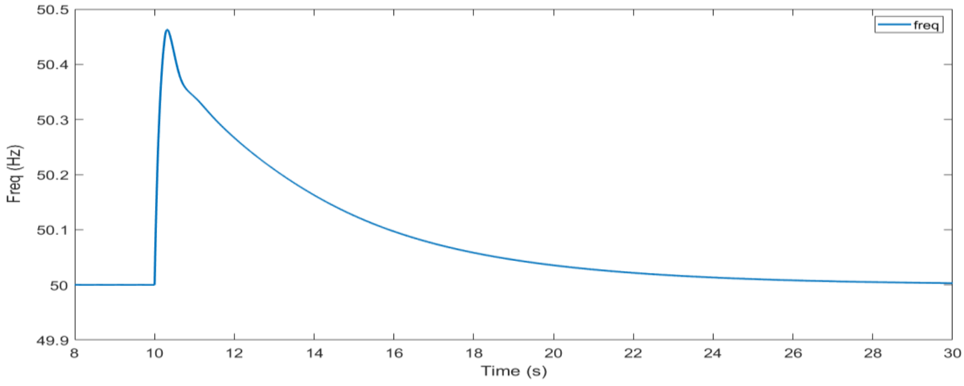


Figure 4.38 – Frequency of the system, when microgrid starts operating in island mode from the 10 seconds of operation. Hybrid microgrid has low load demand (including DC systems) and high generation (DERs in the System).

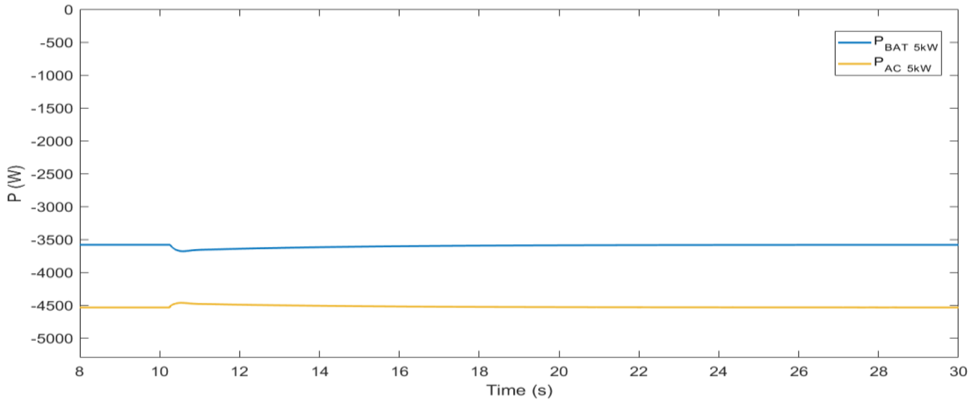


Figure 4.39 – Active power charged by the Battery and given to the AC grid (5 kW Capacity DC Microgrid)

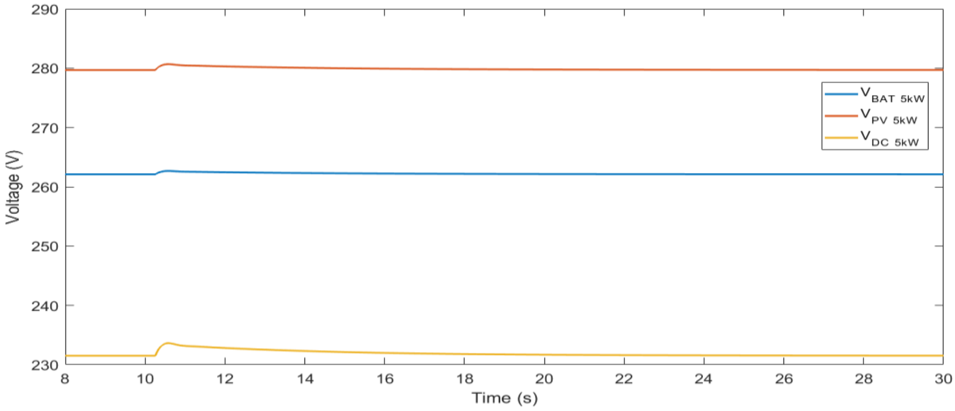


Figure 4.40 – Voltage output of Battery, Solar PV and Converter, while sending energy to the AC Grid. (5 kW Capacity DC Microgrid)

4.4. Main Conclusions

The main conclusions taken from the tests and simulations made are that:

- The first scenario demonstrates how the battery operates as a backup unit of the DC grid. When there is a lack in energy production and the battery is fully charged, this unit can act as a generator, by discharging some energy to the grid. When the energy generated by the Solar PV is big enough to supply all the loads, the excess of energy will help the battery to charge.

- In terms of the voltage in a DC grid, it changes depending on the battery power output. For example, with a small power output by the battery, the voltage has a higher value in the system. When added the converter and considering the power that comes from the AC MG, this situation maintains the same, that is the voltage on the system will still depend on the power output of the battery installed.

- The second scenario shows that the frequency and voltage in the hybrid system are stabilized, due to the connection with the main grid.

- The DC microgrids implemented have a bidirectional converter and can be supplied by the AC side of the MG or the opposite.

- When the operation mode changes in scenario 3 and 4, the hybrid microgrid suffers some variations in frequency and voltage, affecting, not only the AC side of the grid, as well the DC microgrids, due to the bidirectional power transferred between the two types of grid.

- The frequency variation is connected to how both AC and DC microgrids are behaving. For example, in scenario 3, the AC MG has a high load demand, leading to a drop in frequency when the hybrid MG is disconnected from the main grid. This drop gets lower if the DC MGs are acting as generators, by supplying the AC MG, helping the system to be more stable and reliable.

- In scenario 4, where the AC grid has a low load demand and a high generation, there is an increase of frequency in the system, when it starts working in island mode. The best-case scenario, for the frequency not to increase that much is to have the AC grid supply the DC MGs present in the system.

Chapter 5

Conclusions and Final Remarks

5.1. Summary

In the first two chapters of this work the basic concepts and definitions were presented, in order to comprehend and elaborate more project of AC/DC hybrid microgrids. It was important to make a small overview of some solutions to fight back the energy poverty around the world, where the microgrids is one of the biggest solutions to help this big problem.

The explanation of the base three phases of control in a microgrid was fundamental, because it is a key feature of the implemented AC/DC hybrid microgrid. In other words, the stability of the system depends on how these controls are set throughout the whole grid. The controls defined in chapter 3 for each unit have their similarities and their differences. It is essential to salient that the consideration of a droop control (where the bidirectional active power that travels through the AC/DC converter is dependant of the frequency of the AC system) was important for the interaction of both microgrids.

The tests and simulations performed in chapter 4 demonstrates how all these controls and units take action in different environments. It was possible to see the interaction between both types of grid and how the DC MGs contribute for the stability of the hybrid microgrid. All the conclusions of these obtained results are succinctly represented in the end of the fourth chapter.

5.2. Contributions and Future Remarks

The study of microgrids in general is essential for the future of energy, because with the growth of knowledge, papers, guidelines and standardization of this topic, it is possible to evolve and to fight against the energy poverty existent around the world. With this dissertation there are many contributions and guidelines that can be used for future work in the area and even for simulation in a laboratory:

- The basic concepts presented in the state-of-art will help new projects and researchers to understand how the organization of a hybrid microgrid is set; how it can contribute for the developing countries progress in electrification; what types of microgrid are used and how they can be controlled.

- Ideas for different ways of control in each unit implemented, from active power control, to frequency and voltage control and an idea of how to interact the two types of grids in the system (DC and AC microgrids).

- An understanding of how the units can be represented and modelled, in both AC and DC microgrids, when performing small timed simulations.

- The requirements for the AC/DC converter to support the interaction between the DC system and the AC system, through P-V and P-f droop controls.

- The obtained results can give an overall idea on how a DC microgrids work autonomously and in close correlation with the rest of the hybrid microgrid.

As said before, these achievements can help future work in the area, for example:

- By implementing more complex DC microgrids in the system. With more buses, more battery units, generation and loads, i

- By developing more controls in the system, in order to make the simulation even more near to the reality of a hybrid systems:

    - A control variant for the batteries and the Solar PV implemented in the DC MGs: when the battery is fully charged and there is an excess of energy in the system, the control makes an increase in the DC voltage output and the Solar PV will "feel it" and decrease the generation).
    - A secondary control for the DC system.
    - The connection of the DC system with the control system of the AC microgrid.

- The implementation of this type of grid, not only in the *MATLAB Simulink*, but also in a laboratory. There are laboratories around the world that can test this type of grids in a real-time type of simulation. Several studies already made studies of AC microgrids in these laboratories, but for the hybrid microgrids the case is not the same, due to the lack of equipment and components needed to simulate the DC microgrids together with the AC microgrids.

- A more detailed research about the opposite effects between the P-f control and the P-V control implemented in the AC/DC converter: the frequency of the AC system drops, demanding more power to the converter; hence, the DC voltage also drops and the P-V droop will try to reduce the power contribution of the coverter.

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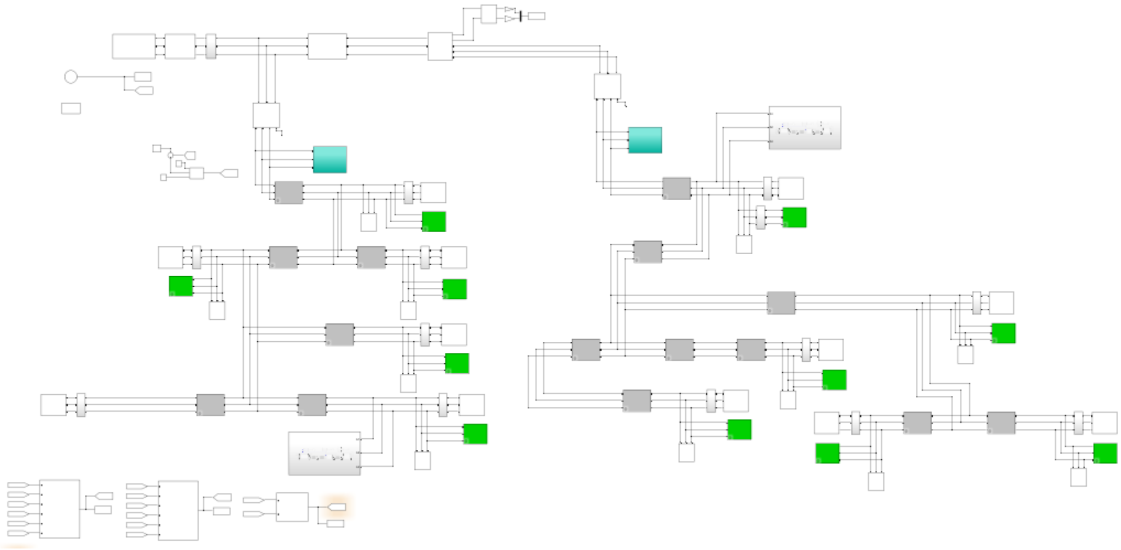
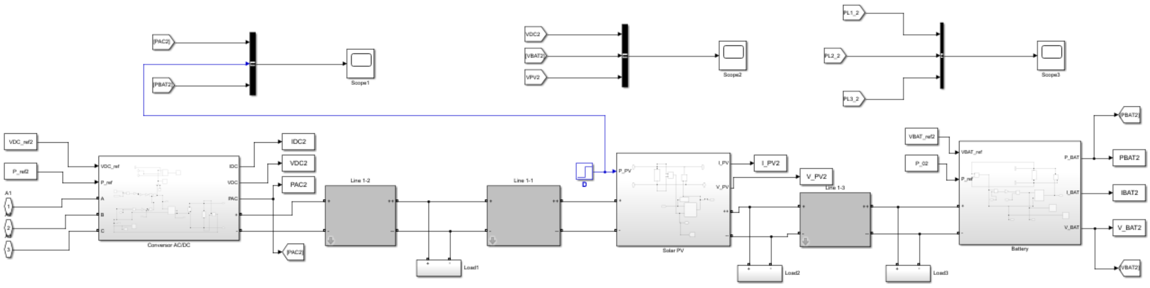
Appendix A

Model Implementation (Simulink)



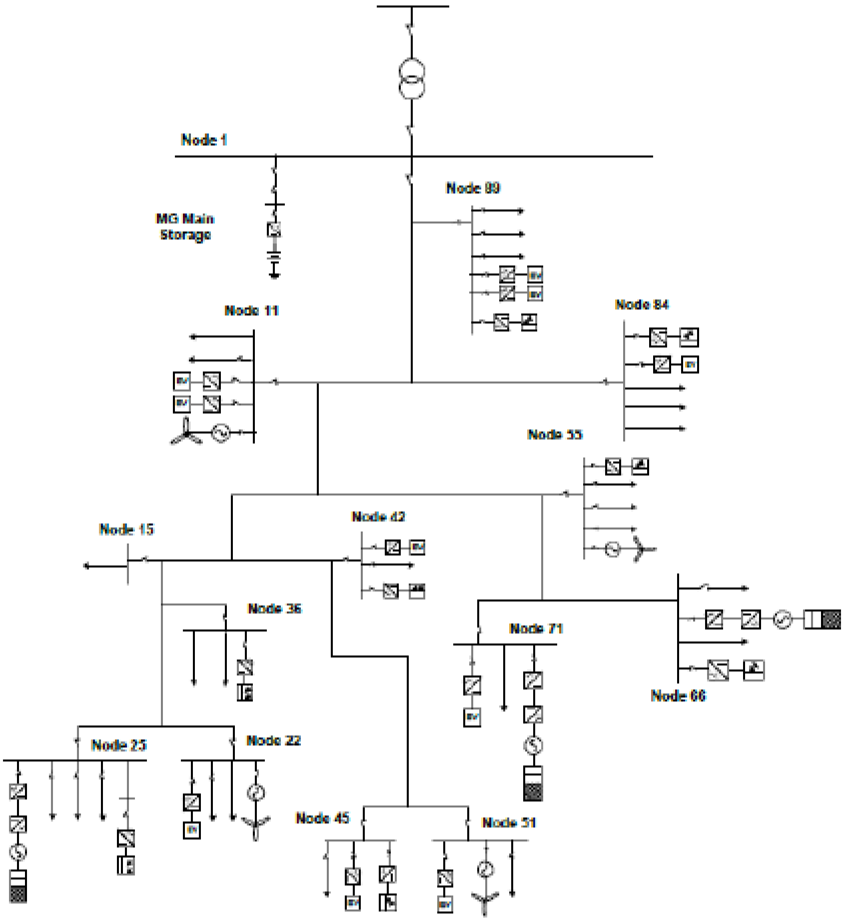
Appendix A.1 – AC/DC Hybrid Microgrid Implementation in MATLAB Simulink



Appendix A.2 – DC Microgrid Implementation in *MATLAB Simulink*

Appendix B

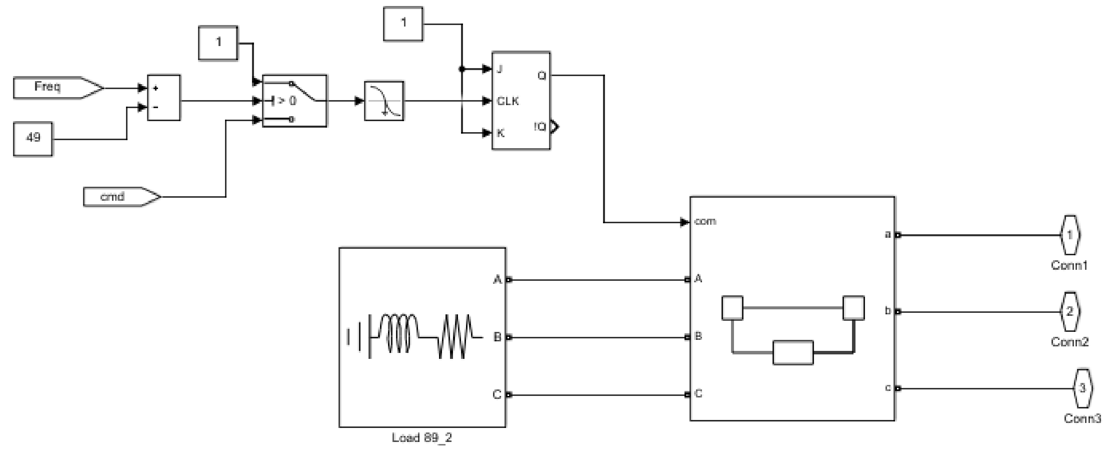
MERGE Project



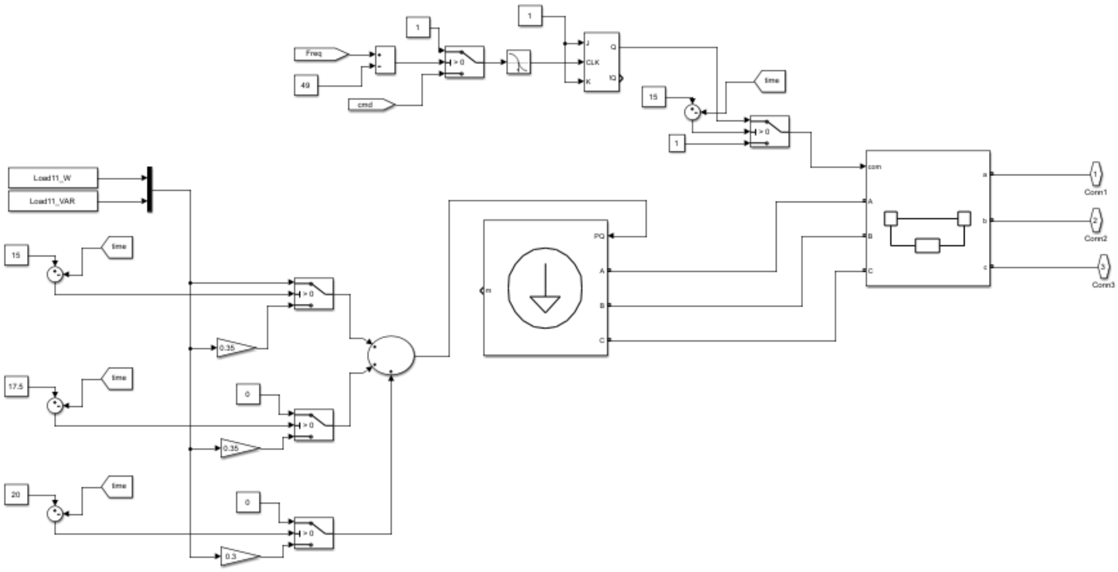
Appendix B.1 – MERGE Project

Appendix C

Load Sheading



Appendix C.1 – Implementation of Load Shedding (Load 89_2) in *MATLAB Simulink*



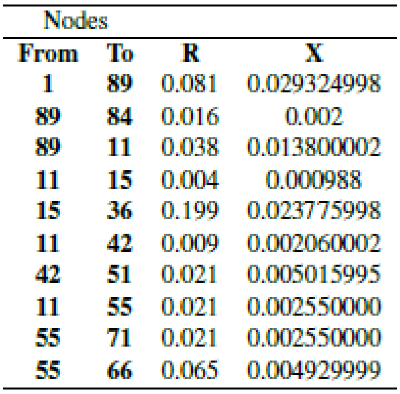
Appendix C.2 – Implementation of Load Shedding (Load 11) in *MATLAB Simulink*

Appendix D

Additional Parametrization

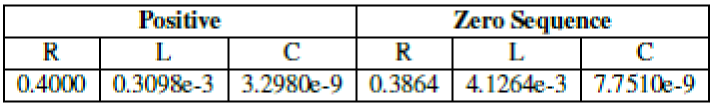
Parametrization			
Lines	Resistance	0.6	Ohms
Capacitors	Converter	5	mF
	Solar PV	5	uF
	Battery	50	uF
k_{bat} / $k_{AC/DC}$	k_{bat} / $k_{AC/DC}$	10	%

Appendix D.1 – Line Impedances in MV Side of the Grid



Nodes			
From	**To**	**R**	**X**
1	**89**	0.081	0.029324998
89	**84**	0.016	0.002
89	**11**	0.038	0.013800002
11	**15**	0.004	0.000988
15	**36**	0.199	0.023775998
11	**42**	0.009	0.002060002
42	**51**	0.021	0.005015995
11	**55**	0.021	0.002550000
55	**71**	0.021	0.002550000
55	**66**	0.065	0.004929999

Appendix D.2 – Line Impedances in LV Side of the Grid



Positive			**Zero Sequence**		
R	L	C	R	L	C
0.4000	0.3098e-3	3.2980e-9	0.3864	4.1264e-3	7.7510e-9

Appendix D.3 – Line Impedances in MV Side of the Grid