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Voltage and Reactive Power Control in Autonomous Microgrids

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Resumo

O conceito de micro-rede surgiu nos Estados Unidos, em virtude de políticas implementadas pelo Departamento de Energia que pretendiam proteger e melhorar a fiabilidade do sistema elétrico do seu país, permitindo também potenciar a eficiência dos seus mercados de energia elétrica mais competitivos [1]. Paralelamente, este conceito tem vindo a ser desenvolvido no continente europeu e asiático, particularmente no Japão, com o intuito de promover pesquisa, desenvolvimento, demonstração e implantação do conceito de micro-rede [2] [3]. Atualmente, a necessidade de promover políticas que atenuem a dependência das centrais ditas clássicas que, tipicamente, consomem grandes quantidades de combustíveis fósseis e, consequentemente, contribuem para a emissão de gases de efeito de estufa, intensifica o interesse de implementar e alargar a aplicação deste conceito.

Uma micro-rede é composta por uma **rede de distribuição**, tipicamente de baixa tensão, na qual são interligadas pequenas unidades de produção de energia elétrica, denominadas de **micro-fontes**, juntamente com **cargas controláveis** e **dispositivos de armazenamento de energia**. Por último, são incluídos sistemas de gestão e controlo suportados por uma infra-estrutura de comunicações que permite um modo de operação coordenado e controlado e por último, capacidade de operação em dois modos distintos: operação em modo **interligado** com a rede de distribuição de média tensão local ou, por outro lado, operação em modo **autónomo**, desligada da rede de média tensão. A operação de uma micro-rede em modo autónomo é dominada por **inversores** que têm a responsabilidade de controlar os valores da frequência e da tensão, garantindo que os valores estão inseridos dentro de gamas admissíveis de funcionamento, garantindo também pontos de funcionamento que se traduzam em maior eficiância e fiabilidade do sistema elétrico. Acresce ainda, tal como referido anteriormente, o facto de estas redes estarem estabelecidas em baixa tensão e como tal os cabos elétricos que as constituem apresentaram uma predominância da resistência face à reactância, levando a que o trânsito de potência ativa influencie de forma significativa o perfil das tensões enquanto que a potência reactiva, por outro lado, é incapaz de controlar os perfis de tensão. Ao longo desta dissertação será então considerado um controlo dos **VSI** (*Voltage Source Inverters*) com base na manipulação dos seus **droops potência reactiva/tensão** e **droops potência ativa/frequência** com o objetivo de apresentar, implementar e avaliar estratégias para a operação e manutenção de uma micro-rede em modo isolado, garantido condições apropriadas para manutenção dos níveis de tensão e despacho de potência reativa favoráveis mediante diferentes cenários de operação. Será então definida e desenvolvida uma metodologia baseada em controlo de droop dos inversores, sendo que as estratégia de controlo irá correr ao nível do controlador central da micro-rede (**MGCC**), responsável pela definição dos ajustes de controlo de tensão.

Palavras-chave: baixa tensão, controlo de tensão, controlo droop, despacho de potência reativa, inversor de fonte de tensão, micro-rede, modo autónomo, produção dispersa.

Abstract

The MicroGrid (MG) emerged in the United States due to the support provided by the Department of Energy that intended not only to protect and enhance the reliability of the United States electric power system, but also to improve the efficiency of competitive markets [1]. Similarly, Europe and Asia, in particular Japan, are walking in the same path, actively promoting research, development, demonstration and deployment of the MG [2] [3]. Nowadays, the need to promote policies that reduce the dependence from fossil fuelled generation plants that contribute significantly to the emission of Greenhouse Gases, intensifies the interest in implementing and generalizing the application of the MicroGrid concept.

A MicroGrid is composed by a **distribution network**, typically set at low voltage, with distributed energy sources, known as **MicroSources** (MS), together with **controllable loads** and **storage devices**. Lastly, management and control systems supported by a communication infrastructure are included, allowing an operation in a controlled and coordinated way in two different operation modes: **interconnected** with the upstream Medium Voltage distribution network and, on the other hand in **standalone/islanded** mode, disconnected from the upstream medium voltage distribution network. The operation of a MG in islanded mode is dominated by **inverters** that have the responsibility to control frequency and voltage profiles, ensuring that their values are within acceptable ranges while also present set-points that translate in higher levels of efficiency and reliability of the electric power system. Moreover, these networks are typically set at low voltage, where electrical cables existent possess a predominance of the resistance over the reactance ($X \ll R$) which on its turn causes the active power flow to significantly influence voltage profiles as it exists a direct coupling between active power and voltage and additionally, reactive power is not able to control voltage. Throughout this dissertation it will be considered a control based on Voltage Source Inverters (**VSI**) based on the manipulation of its reactive power/voltage, **Q/V**, and active power/frequency, **P/f**, **droops** aiming to present, implement and evaluate control strategies for the operation of a MicroGrid in islanded mode, guaranteeing appropriate conditions for voltage control and reactive power dispatch upon different operating scenarios. By defining a methodology for the modelling approach of a MG with droop controlled converters and setting possible strategies for voltage/reactive power problem, the strategies may run at the MGCC level, thus constituting a secondary voltage control mechanism.

Keywords: distributed generation, droop control, islanded mode, low voltage, microgrid, reactive power dispatch, voltage control, voltage source inverter.

Acknowledgments

Now it is time to sing my song. This thesis culminates my academic journey and now that I am about to reach the finish line I can finally look back and properly evaluate what I accomplished. It was a journey filled with ups and downs and I clearly had a false start. Luckily, I have a family that I can always rely on, since they always supported me believing I would find my path no matter what. Timed passed by and I slowly started to gain interest on renewables and started seeing light at the end of the tunnel. As a result my will to succeed appeared and despite the fact that it was a marathon with an awful start, as they usually say, it does not matter how you start it is how you finish. So, first and foremost I would like to highlight the role played by my family, especially my parents and no words can express my gratitude over your continuous support, care and sacrifices you have been through so that I could have the best tools in order to properly succeed.

I would also like to thank my friends who helped to continue, pushed and supported me so that I could reach for a better outcome. A word of appreciation as well to the professors I had the privilege to meet and who maneged to adequately share its passion and knowledge in their subjects and allowed me to feel excited and inspired.

Finally, I would like to leave a special acknowledgment towards my supervisor, Professor Carlos Moreira. I "chose" him because of the high level of knowledge demonstrated in the classes I had the opportunity to assist under his responsibility. Besides, it was a professor that rarely answered directly to my questions but instead, usually guided me so that I could think properly for myself and develop my critical thinking and in the end find the solution to my question, properly understanding the subjects and mechanics involved. Over this period I would like to commend him for his skilled guidance, constant support and swift feedback received whenever needed. Thank you for presenting me a challenge that fulfilled me and I hope I have not disappointed you.

Last but by no means least, I would like to dedicate this thesis to my grandfather, Gualter Nascimento, and my grandmother, Zulmira Afonso, who I lost throughout this journey. Wherever they are I am sure they would be extremely proud of his grandson small achievement.

Ivan Nascimento

“It is paradoxical, yet true, to say, that the more we know, the more ignorant we become in the absolute sense, for it is only through enlightenment that we become conscious of our limitations.

Nikola Tesla

Contents

List of Figures

List of Tables

List of Abbreviations and Symbols

BS	Black Start
CERTS	Consortium for Electric Reliability Technologic Solutions
AFC	Alkaline Fuel Cell
BDFIG	Brushless Doubly Fed Induction Generator
CHP	Combined Heat and Power
CPV	Concentrator Photovoltaics
DDSG	Direct Drive Synchronous Generator
DER	Distributed Energy Resources
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DMFC	Direct Methanol Fuel Cell
DMS	Distributed Management System
DSM	Demand Side Management
DNO	Distributed Network Operator
EMS	Energy Management System
EP	Evolutionary Programming
EPSO	Evolutionary Particle Swarm Optimization
FRT	Fault Ride Through
GHG	Greenhouse Gases
HAN	Home Area Network
HV	High Voltage
LC	Load Controller
LV	Low Voltage
MCFC	Molten Carbonate Fuel Cell
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
MSE	Mean Square Error
MV	Medium Voltage
MG	MicroGrid
MGCC	MicroGrid Central Controller
MS	MicroSource
MC	Microsource Controller
MMO	Multi Master Operation
OLTC	On Load Tap Changer
PAFC	Phosphoric Acid Fuel Cell
PV	Photovoltaic
PCC	Point of Common Coupling
PLC	Power Line Communication

PI	Proportional Integral
PEMFC	Proton Exchange Membrane Fuel Cell
PMSG	Permanent Magnet Synchronous Generator
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
RMSE	Root Mean Square Error
SMO	Single Master Operation
SCADA	Supervisory Control and Data Acquisition
SCIG	Squirrel Cage Induction Generator Wind System
SOFC	Solid Oxide Fuel Cell
SRG	System Reluctance Generator
SSMT	Single Shaft Micro Turbine
UNFCCC	United Nations Framework Convention on Climate Change
V2G	Vehicle to Grid
VSI	Voltage Source Inverter
WWW	*World Wide Web*

Chapter 1

Introduction

This chapter intends to present a succinct contextualization of the topic addressed within the scope of this dissertation. The development of the Electrical Power System, planet's sustainability and environmental awareness that led to the development of Renewable Energy Resources and Distributed Generation (DG) are briefly addressed. Afterwards it is introduced the MicroGrid (MG) concept and subsequent issues that arise and serve as a motivation of the dissertation. The next sections outline the objectives that are proposed to be obtained in this dissertation and the structure of the dissertation.

1.1 Motivation of the dissertation

Historical development of Electrical Power Systems had inherent constraints related to the technologies and resources available. Consequently, countries had commonly installed large scale generation power plants such as hydro, fossil fueled and nuclear power plants that were located in remote places. Therefore, the energy was transmitted over long distances until reaching its final consumer. Additionally, it led to an electrical energy chain that was highly reliant on imported fossil and nuclear fuels in each country. Furthermore, the energy demand continued to raise and the increased dependence on imported fossil fuels deepened international political instability that affected the primary energy resources prices. Additionally, the planet's sustainability started being questioned and environmental concerns and climate change issues started gaining a lot of importance and the typical Electrical Power System arrangement was targeted. The Consortium for Electric Reliability Technology Solutions, CERTS, found in 1999, is an example of this shift as its creation intended to research and develop methods and technologies that could improve not only the efficiency, but also the reliability of the United States Electric power system [1].

Since energy is the basis of economic development, energy policies were created in order to assure a continuous and sustainable economic growth that could increase energy efficiency and increase renewable energy resources integration in order to diminish climate changes, particularly global warming. Kyoto's protocol [6] which was created in 1997 and signed by 59 countries is an example of environmental awareness, as it set goals that aimed to be reached by the year of 2020:

- 20% reduction on Greenhouse Gases (GHG);
- 20% improvement in energy efficiency;
- 20% increase in the share of renewable energy.

More recently, in December 2015, the Paris Agreement [7], set a new global agreement to combat climate change, adopted under the United Nations Framework Convention on Climate Change (UNFCCC). Countries submitted national plans listing their intentions for addressing the climate change challenge after 2020. As a result, the Paris Climate Agreement intended to combat climate change and adapt to its effects, strengthening the global response upon the temperature rise, tracing a new course in the global climate effort. The Agreement was signed by 197 states and 122 of those parties have ratified or acceded to the Agreement, most notably China, the United States and India, the countries with three of the largest greenhouse gas emissions.

The policies introduced empower even further the development of Renewable Energy Sources (RES) and Distributed Generation (DG) in order to achieve the affirmed climate goals. Nowadays, technologies such as photovoltaic cells, wind generators, microturbines and fuel cells can be used nearer the final consumer. These technologies, which will be explained in further detail in Chapter 2, are becoming increasingly deployed in the electrical networks, enlarging the energy generation portfolio and creating a paradigm shift in the electric sector, since the electric generation is no longer predominantly centralized. This paradigm shift will also be discussed in Chapter 2.

It is undeniable that the exploitation of DG capabilities can offer advantages to system operators such as the postponement of investments on transmission/distribution systems and reduction of losses in the distribution system much due to the fact that energy production is now nearer the final consumption spot when considering relatively low levels of DG penetration. In [8] it is listed the main drivers to the adoption of DG into electric power systems, stating environmental, political and economical reasons.

While the advantages related to the integration of low levels of DG units are appraised, when facing a massive integration of these type of units in distribution networks, various technical issues start to arise and must be tackled because there is a risk of negating some of the aforementioned benefits since, for example, the losses in the distribution system may raise for high levels of DG integration. Typically, DG connection has been following a purely passive approach commonly known as "fit and forget", and such policy may cause problems such as voltage profiles and congestion levels. Consequently, it is urgent to develop coordinated strategies for the operation and control of DG sources, loads, and storage devices that may allow a massification of DG deployment. This requirements and hurdles led to the development of the MicroGrid concept. Summarily, a MG is composed with small modular generation technologies, known as microsources (MS), controllable loads and storage devices, embedded in a low voltage distributed system. The defining characteristic of this type of grids is the fact that they can be operated while being connected to the main power network, or alternatively, in an islanded mode, through a controlled and coordinated way.

MG can be seen as the next step forwards towards a further decentralization of decision makers, by allowing the costumer to actively participate in the electricity market. This next step needs to be supported by an institutional restructuring of the electricity supply industry and alteration in the scale and location of electricity production in order to smooth the transition.

An operation of a MG requires an approach that faces technical and non-technical issues, most notably, the study of a MG design and operation, so that the level of penetration of RES and other MS is as high as possible and development and demonstration of control strategies that allow a proper operation and management of a MG, which means that technical constraints associated to frequency and voltage values are within acceptable ranges, meeting not only safety but also customer requirements.

Considering the operation of a MG with several Voltage Source Inverters (VSI) and resorting to droop characteristics, namely P/f and V/Q droops it is possible to establish a similar concept associated to conventional power system where synchronous generator provide active power/frequency and reactive power/voltage control capabilities. Nevertheless, solving the power flow for a MG cannot be done through conventional approaches, such as Newton Raphson, because in islanded mode there is no slack bus and frequency is not constant, like in grid connected mode. Additionally, there is a direct dependence of the power on frequency due to the droop characteristics. Moreover, given the specific nature of a MG, some issues need to be tackled. The resistive nature of a LV system means that voltage profile is severely influenced by the active power flow. Additionally, voltage and reactive power control needs to take into consideration that voltage has local characteristics and network cable impedances prevent precise reactive power sharing among VSI.

As a result, it is necessary to define and develop strategies for the operation and management of a MG in standalone mode, assuming a droop controllable approach, ensuring appropriate conditions for voltage control and reactive power dispatch.

1.2 Objectives of the dissertation

As previously referred, a successful design and operation of a MG is the key to further promote the growth of DG that, between many other advantages already stated, present practically non-existent emissions and will augment the contribution to lessen the global warming phenomenon. The operation of a MG, particularly when considering an islanded operation mode, exhibit unique features. Most of the MS considered, such as photovoltaic panels, microturbines and fuel cells resort to power electronic interfaces in order to provide an adequate flexibility and controllability. This type of power system naturally differs from a conventional system that utilizes synchronous generators which leads to different characteristics:

- Altered dynamic behaviour due to very low global inertia;
- Slow responses to control signals from controllable MS such as Fuell Cells.

Additionally, in low voltage (LV) MG, the high resistance compared to the reactance of LV lines requests specific strategies for voltage and frequency control. Consequently, this dissertation will be focusing on demonstrate the feasibility of the MG concept taking into consideration the following aspects:

- Develop an **adequate framework for islanded MG** and its implementation in ***Matlab/Simulink*** platform;
- Identification of **voltage control and reactive power sharing issues** during **MG autonomous operation**;
- Identification of **voltage/reactive power sharing control mechanisms in autonomous MG**;
- Comparison between the identified **voltage control and reactive power dispatch strategies** and identification of **resulting impacts**.

1.3 Structure of the dissertation

This section intends to briefly portray the structure outlined for the dissertation. Apart from this introductory chapter, the work developed within the scope of this dissertation contains four (4) more chapters and three (3) appendixes.

In chapter 2, state of the art, it is introduced the Distributed Generation topic. This chapter also provides a detailed characterization of the MicroGrid concept and associated MicroSources technologies.

In Chapter 3 it is addressed the MicroGrid control related to islanding operation mode. It is identified the power electronics converters commonly existent in the grid, possible operation modes, namely Single Master and Multi Master Operation. Lastly, it is issued in detail the frequency and voltage control regarding MicroGrids under islanded mode operation. It should be stated that the chapter's principles considered here also serve as foundations to the simulation platforms developed. It is addressed the issue of LV cables that have a high resistance in comparison to its reactance and the inability of reactive power injection to control voltage profiles. Limitations caused by a reactive power/voltage and active power/frequency droop control approach are addressed, as well as how it is dealt with the fact that power flows in islanded MG can not be solved in conventional modes, since there is no compensator/reference bus.

Chapter 4 presents, through illustrative examples, the effectiveness of the proposed control strategies under different scenarios and then proceed to compare the proposed voltage control / reactive power dispatch strategies.

Chapter 5 conducts the main conclusions of this dissertation and also suggestions and perspectives for future paths to explore.

In Appendix A it is presented an explanation of the EPSO (Evolutionary Particle Swarm Optimization) evolutionary algorithm applied under the *Matlab*® /*Simulink*® simulation process. In Appendix B it is illustrated the MicroGrids dynamic simulation platform, detailing the models adopted and its control parameters. Finally, in Appendix C is presented the article written within the scope of this dissertation, containing an overview of the topic addressed, as well as some of the results obtained through the developed of the two different strategies.

Chapter 2

State of the art

This chapter addresses the Distributed Generation (DG) subject and the change of paradigm that electric industry sector is facing when considering the integration of DG into the distribution system. It is also presented the general characteristics of different types of DG technologies and main applications such as Photovoltaic Panels (PV) Micro wind generators, single shaft microturbines (SSMT), fuel cells and storage devices. Last, it is discussed the MicroGrid (MG) concept, explaining its operational control architecture and modes of operation, while also mentioning some of the contribution to the distribution system, particularly its contribute to service restoration.

2.1 Introduction

Conventional power systems are facing numerous challenges because environmental awareness and technological developments are forcing the boundaries and putting in question a model based on a vertically integrated structure and heading towards a deregulated environment with open access to the distribution network, something that could favour the development of DG [9]. As a result, the continuous growth on the interest in connecting generation plants to the distribution network gained a lot of momentum, altering electrical power system operators and planers challenges. Simultaneously, policies have been implemented to further develop DG technologies and respective application in order to achieve environmental goals. As a result, from the technical point of view, while a low level of DG penetration poses no major concerns, the tendency to increasingly augment DG implementation in electrical distribution systems causes a major revolution and several issues arise [10]:

- voltage profile modification;
- global system stability;
- harmonic distortion levels increase;
- islanded mode operation capabilities.

These issues, mainly caused by power injection in the distribution network, must be tackled in order to ensure a positive shift in the electrical power system actual configuration.

2.2 Distributed Generation

Distributed Generation, also known as Embedded Generation, still lacks an universal and formal definition widely accepted. Several authors [11] [12] [13] [14] try to elaborate DG definitions that diverge, mostly due to the size of the DG units, but allow different generation schemes such as small-scale generation units connected to the distribution network up to solutions that include large scale wind farms. Nevertheless, within the scope of this dissertation, given such wide range of definitions, the DG concept is assumed to be related to the electricity generation activity regarding the lower voltage level of the electric power system. In terms of technologies, which will be further explained in section 2.4, the DG units size has ratings that vary between few tens of kilowatts given the Low Voltage (LV) grid technical limitation to receive high injection powers. These smaller scale DG units are also commonly known as MicroSources (MS).

2.2.1 The paradigm shift in the Electrical Power System

Electrical Power Systems, when first designed, had an hierarchical structure well defined, as seen in Figure 2.1 [4]. They were composed of 3 levels: **generation**, **transmission** and **distribution**. In the upper level, energy was produced in large scale through generation units that fed the transmission system, allowing the transport of energy to substations located near consumption zones. This energy was then extracted and distributed along different stages of voltage being subsequently stepped down from High Voltage (HV), Medium Voltage (MV) until Low Voltage (LV) levels, reaching every consumer according to their level of demand.

From a technical point of view, this arrangement lead to unidirectional power flows. Conventional power system possess some advantages in terms of operation and management simplicity because the interconnected system allows the transport of bulk power over large distant with reduced losses, while bulk power system interconnection and large scale generation units improve overall system stability. Additionally, since the power flows are unidirectional, the design and mode of operation at the distribution level is simpler. Finally, the electrical efficiency of large power plants is higher when compared with small scale generation units, assuming they have similar technological levels [15]. However, conventional power systems also have some disadvantages like the large distance existent between producer and consumer which increases the cost of the transmission network. Conventional generation units are starting to get outdated, with reduced efficiency especially when compared with the technology currently available. Additionally, their environmental impact is higher since their main source is fossil and nuclear fuels or coal. Lastly, while this classical structure was relatively simple to operate from the distribution network point of view, this hierarchical system has some reliability concerns since a problem affecting a high hierarchical level can significantly affect hierarchical levels below given the dependency established between different levels.

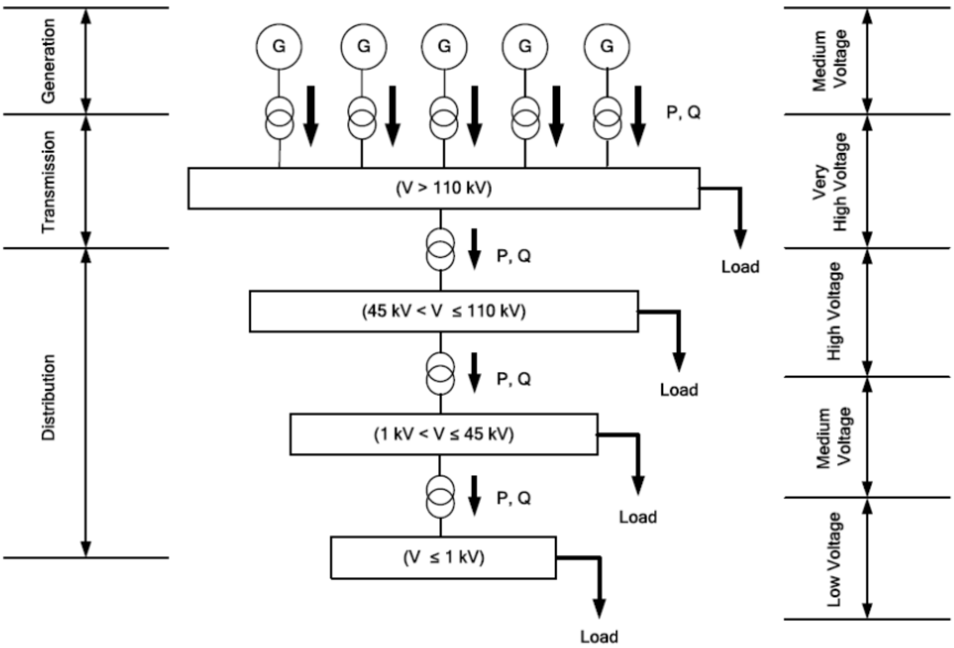

Figure 2.1: Conventional power system organization [4]

Over the recent years, however, with the increase in DG units being connected to the distribution network, the classical structure initially set is facing some challenges since this conventional electric power paradigm was not designed to accept power injections at distribution levels as the unidirectional power flow may no longer be true in some situations.

In a wider context, DG can also be seen as a more complex concept, since it is also necessary to consider new devices that start to be connected to the system, such as energy storage devices and controllable loads, as seen in [8] which are referred as Distributed Energy Resources (DER). Additionally, a "fit and forget" policy towards DG installation must be taken aside and they will have to start participating actively in the supply chain, offering additional services to the electricity network and improving increased reliability, flexibility and lower prices which will also allow the connection to the system of more DG units. This new concept is based on a full exploitation of all resources available, adopting and improving the active management of the distribution grids [8] in order to improve system efficiency and its operating conditions, ensuring higher standards for electricity supply.

The restructuring process that has been taking place in the electricity industry is leading to the functional separation of the vertically integrated utilities that once existed into well defined activities: generation, transmission and distribution. This eases the access to the networks, which contributes to increase the competitiveness of the market, deepening the participation of customers, since they can actively participate and look for the best suited service.

2.3 Microsources technologies

This section describes some of the technologies that can be found within every MS available in MG. Among the renewable technologies, photovoltaic and wind generator systems are detailed, while microturbines, fuel cells and storage devices are also briefly addressed.

2.3.1 Photovoltaic panels

Photovoltaic (PV) panels are the most common technology in LV distribution network and its high power capacity per unit weight is one of the biggest selling points. Additionally, photovoltaic technology can also power remote and underdeveloped places that do not have electrical systems and, in industrialized countries, they can also provide grid support applications.

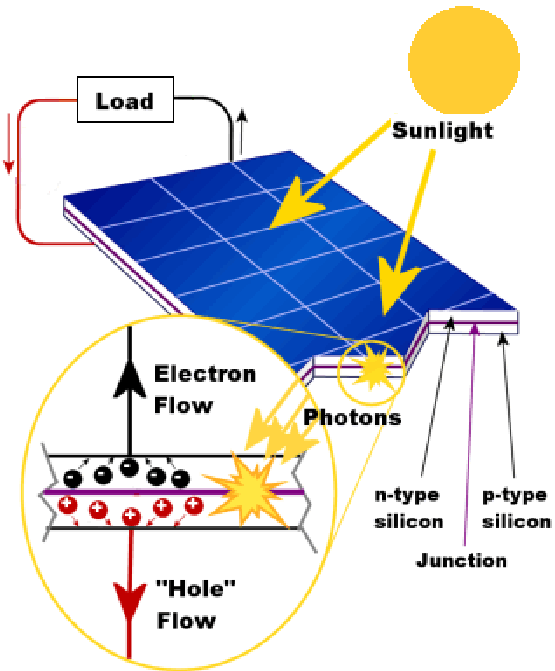

Figure 2.2: Photovoltaic effect

The basic building block of a PV panel is a solar cell, which is a semiconductor, usually made of silicon, that converts sunlight directly in electricity, as illustrated in figure 2.2. This process of conversion is called photovoltaic effect [16]. Typically, the front of the silicon cell is doped with phosphorous to give it a negative character (n-type silicon) while the rest is doped with a small quantity of boron to give it a positive character (p-type silicon). The interface between the layers, junction, contains electric field.

When photons hit the semiconductor materials, they transmit their energy to the valence electrons of the semiconductor, breaking the link that maintains them attached to the atoms. Each broken link origins a free circulating electron inside the solid which on its turn origins a gap, the lack of an electron in the broken link. Since electric field exists between the two layers (junction), electrons and gaps circulate in opposite directions creating an electric current that flows in the direction of the electric field. Finally, through an external circuit it is possible to deliver the energy supplied by photons when the electric-gap core is formed.

Given the fact that a solar cell is only capable of generating very low voltage/current characteristics that are not suited for most of applications, in order to overcome this problem, solar cells are connected in series and/or parallel, creating a module that can present usable voltage and current values, as in figure 2.2. Depending on the requirement of the application these modules can be combined even further in series and/or parallel. These group "modules" formed are known as a PV arrays.

The PV array can not operate autonomously since it needs a system to conduct, control, convert, distribute and in some cases store the produced energy. Consequently, the electric energy produced needs to be converted to AC power, something that is done by a power electronic device (inverter). If storage is also a requirement, it is necessary to utilize battery banks and controllers. Besides, the solar cell V-I characteristic is nonlinear and varies with irradiation and temperature. Generally, there is a single point on the V-I or V-P curve, called the Maximum Power Point (MPP), at which the entire PV system operates with maximum efficiency, producing its maximum output power. The location of the MPP is not known, but can be located, either through calculation models or by search algorithms. Therefore Maximum Power Point Tracking (MPPT) is required in a PV system, allowing the PV to maintain the operating point at its MPP [17] [18] [19].

The development in solar PV technology is growing very fast in recent years due to technological improvement, cost reductions in materials and policies that support renewable energy based electricity production. In [20], for example, it is shown that Photovoltaic is one of the fastest growing industries, with annual growth rates at a rate of 35–40%.

In short, PV technologies comprise 4 generations:

- Fist Generation: Crystalline Silicon Cells with approximately 90% of the current market;
- Second Generation: Fine Film Technologies on Rigid Substrates (glass or ceramic) with approximately 10% of the current market;
- Third Generation: Nanotechnologies for the formation of thin films on Flexible substrates. Better use of all Solar spectrum (multijunction cells with the use of concentration);
- Fourth Generation: Concentrator Photovoltaics (CPV).

The efficiency of the solar cell is one of the main concerns in the market and, for example, nowadays it has values of approximately 28% for monocrystalline silicon solar cells. The growth in solar photovoltaic technologies, specially through different materials for solar cells that can positively improve the efficiency of a PV module is crucial so, third and fourth generation can see an increase of its share in the market, diminishing the "reliance" on first generation technologies.

2.3.2 Micro wind generators

Wind energy is the most mature of the renewable energy technologies apart from hydro [21]. Wind energy is a result of kinetic energy existing in a moving mass of air. Movement of air happens because irradiance from the sun heats up the air, leading to pressure differences in the atmosphere and forcing the air to rise. Conversely, where temperatures fall, a low pressure zone develops and winds balance out the differences. Wind turbines capture the air flow by converting it into a rotational movement, which subsequently drives a conventional generator for electricity.

Assuming air mass flows through the blades of a wind turbine with *v(t)* speed, the power of that air movement at t time can be obtained through the following equation:

$$P(t) = \frac{1}{2} \times C_p \times \rho \times A \times v(t)^3 \tag{2.1}$$

Where:

- C_p (adimensional): turbine power coefficient ;
- ρ (kg/m^3): density of the air;
- A (m^2): area swept by the wind turbine blades;
- *v(t) (m/s)*: wind speed.

The aforementioned turbine power coefficient, was first introduced by a German physicist *Albert Betz* who, in 1919, concluded that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. To this day, this is known as the Betz Limit or Betz' Law [22]. The theoretical maximum power efficiency of any design of wind turbine is 0.59, or in other terms, no more than 59% of the energy carried by the wind can be extracted by a wind turbine. This is called the "power coefficient" and is defined as: $C_{p,max}$ = 0.59. Nevertheless, wind turbines cannot operate at this maximum limit. The C_p value is unique to each turbine type and it is a function of wind speed that the turbine is operating in. Once it is incorporated the engineering requirements of a wind turbine, strength and durability in particular, the real world limit is below the *Betz* limit with values ranging from 0.35 up to 0.45. This coefficient that measures wind turbine efficiency, is often used by the wind power industry since it represents the ratio of actual electric power produced by the wind turbine divided by the total wind power flowing into the turbine blades at a specific wind speed.

Regarding a wind generator system in itself, its main component is the turbine nacelle, as illustrated in figure 2.3 [5], which accommodates the mechanisms, generator, power electronics, and control cabinet. The mechanisms, including yaw systems, shaft, and gear box, facilitate mechanical support to various dynamic behavior of the turbine. The generator is dedicated to the conversion between mechanical energy, which is captured by turbine rotor, and electrical energy. Lastly, the electrical energy generated needs to be regulated and conditioned in order to be connected to the power grid. In [23], for example, it was shown the operating ability in standalone grid-connected mode of a small wind turbine.

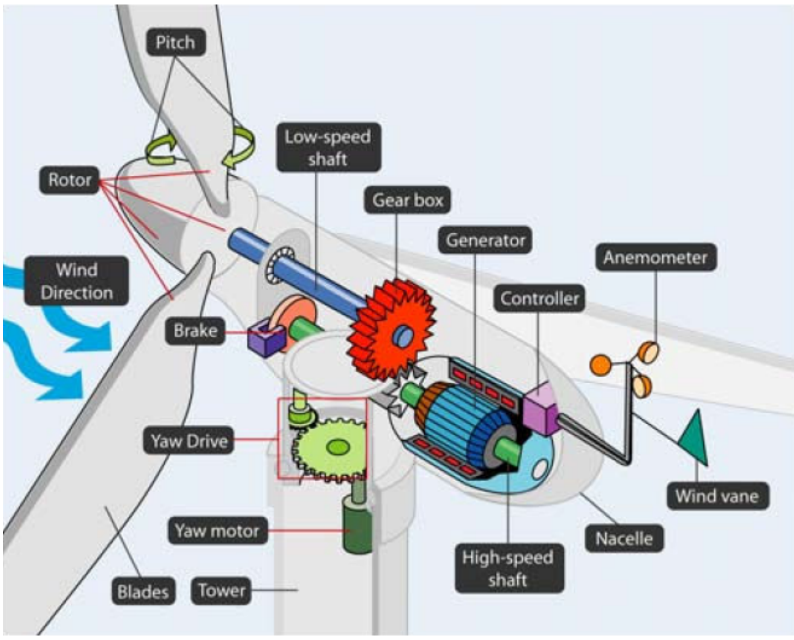

Figure 2.3: Wind power system nacelle [5]

Since the main goal of this dissertation is not particularly concerned in providing a deep view of MS technologies, it will only be listed the most "popular" options of the generators used:

- SCIG: Squirrel Cage Induction Generator wind system;
- DFIG: Doubly Fed Induction Generator wind system;
- PMSG: Permanent Magnet Synchronous Generator wind system.

While the aforementioned generator wind systems are more oriented for higher rated power wind turbines and installation in higher voltage levels, other technologies are best suited when considering micro wind turbines in a low voltage MG such as:

- **BDFIG** (brushless DFIGs);
- **DDSG** (system direct-drive synchronous generator);
- **SRG** (System Switched Reluctance Generator system);
- **Multiple-stage geared SCIG system**;
- **Radial/axial/transversal-flux PM generator** systems.

These solutions generally require relatively complex operation principle and equipment assembly.

Regarding induction generator wind systems, they can be divided in three groups, according to the operations of induction generator speed:

- Fixed-speed;
- Limited-variable-speed;
- Variable-speed wind systems.

Table 2.1 enumerates the disadvantages among different wind power systems [5].

Table 2.1: Advantages vs. Disadvantages between different wind power systems

	Advantages	**Disadvantages**
Fixed-speed system	a. Simple construction and robust b. Low cost and maintenance c. Easy control	a. Not optimal operation, thus low efficiency b. Easy power fluctuation caused by wind speed and tower pressure c. External reactive power compensation is needed d. Weak capability of FRT
Limited-speed system	a. Limited speed variation is implemented b. The slip ring may be replaced by optical coupling	a. Speed variation range depends on the size of the variable rotor resistance (<10%) b. The controlled rotor power must be dissipated by heat in the resistor c. Still need reactive power compensation and cannot support the grid alone
Variable-speed system	a. Large range of speed variation b. Appropriate control enables optimal operation for maximum power extraction c. No external power compensation is needed and is able to support the grid d. High FRT capability e. Suitable and commonly used for large-scale wind farms	a. Relatively complicated control system b. Higher converters and control costs c. May need a multistage gearbox and slip ring in DFIG system d. May need expensive PM material and large diameter design in direct drive

The introduction of power electronic devices in the systems enabled them to perform total or partial decoupling between the generator and the grid frequency, allowing more efficient extraction of the available power. It also allows the control of the active and reactive power injected, which further improve operation and control capabilities of the electrical grid.

Regarding the axis orientation of the wind turbine, there are two different types that can be used for electric power generation [24]:

- Vertical axis turbine;

- Horizontal axis turbine.

While the horizontal axis is the most common, it presents some disadvantages, particularly in situations of more turbulent wind flows where vertical axis wind turbines perform better, such as urban areas.

Last, despite the fact that it is one of the most mature renewable energy technology (apart from hydro), as mentioned above, its implementation is not as high as one would expect because the cost per unit of turbines with lower power ratings is higher when compared to higher power turbines installed in wind farms. Additionally, the natural resources available vary from country to country and some situations the weather and geographic conditions may not be favourable.

2.3.3 Single shaft microturbines

Microturbines, particularly those with a single shaft design[1], are mechanically simple devices, having high operation speed, in the range of 50.000rpm up to 100.000rpm. Their design combines the reliability of commercial aircraft auxiliary power units with the low cost of automotive turbochargers. Despite their mechanical simplicity, microturbines rely on power electronics to interface with the grid. Their primary fuel is natural gas, although they may also burn propane or liquid fuels in some applications, allowing clean combustion with low particulates emissions. This type of microturbines is particularly interesting in CHP (Combined Heat and Power) as it improves overall system efficiency.

Compared with the other DG technologies, microturbine has the advantages of lower initial investment and maintenance costs, low emission, higher reliability and relatively noise level [25]. In

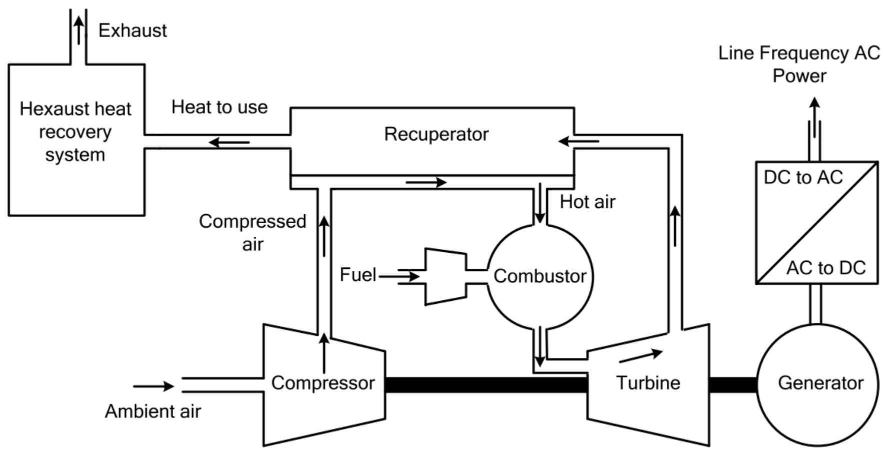

Figure 2.4: SSMT system scheme [4]

figure 2.4 taken from [4], it is illustrated the scheme of a SSMT, based on Brayton thermodynamic cycle. The most distinctive feature is the "Recuperator" as it increases overall system efficiency by

[1] split shaft is not discussed in this dissertation

pre-heating the air. The first step of this cycle is the compression and, as referred, the pre-heating of the ambient air. When the air enters in the combustor, it is mixed with fuel and then ignited and the resulting gas flow is expanded over the turbine, turning the shaft and ultimately, producing energy that is properly conditioned through a AC/DC/AC inverter in order to be connected to the grid.

2.3.4 Fuel cells

The fuel cell principle was first discovered 150 years ago but material problems prohibited its commercialization during a long time. However, in the last 30, some technological developments led to two types of fuel cell technologies: low and high temperature operation cells.

Table 2.2 enumerates the different cell types and its main characteristics [26].

Table 2.2: Data of types of fuel cells

Fuel cell type	**Mobile ion**	**Operating temperature**	**Applications and notes**
Alkaline (AFC)	OH^-	50–200°C	Used in space vehicles, e.g. Apollo, Shuttle.
Proton exchange membrane (PEMFC)	H^+	30–100°C	Vehicles and mobile applications, and for lower power CHP systems.
Direct methanol (DMFC)	H^+	20–90°C	Suitable for portable electronic systems of low power, running for long times
Phosphoric acid (PAFC)	H^+	220°C	Large numbers of 200-kW CHP systems in use.
Molten carbonate (MCFC)	CO_3^{2-}	650°C	Suitable for medium- to large-scale CHP systems, up to MW capacity
Solid oxide (SOFC)	O^{2-}	500–1000°C	Suitable for all sizes of CHP systems, 2 kW to multi-MW.

Fuel cells, also suited for distributed generation applications, offer high efficiency and low levels of emissions but, despite current technological advances, are still relatively expensive. These electrochemical devices convert the chemical energy contained in some fuels into electricity. Some power generation technologies add an intermediate step to generate electricity as the production of heat from fuels followed by its conversion into mechanical energy that is used to drive an electrical generator [27].

Phosphoric acid cells are commercially available in the 200kW range, and high temperature solid-oxide and molten-carbonate cells could be promising for MG application. The main focus in development made by automotive companies is considering the possibility of using on-board reforming of gasoline or other common fuels to hydrogen, to be used in low temperature proton exchange membrane (PEM) fuel cells. Fuel cell engine designs are being considered, as they promise high efficiency without significantly polluting emissions associated with internal combustion engines. Higher temperature PEMs are also under development, being particularly interesting for CHP applications.

The fuel cell will continue to play a very particular role, since hydrogen is not easy to store and to transport. The more promising target is the utilization of liquid methanol.

2.3.5 Storage devices

Energy storage technologies do not represent energy sources but they provide added benefits to improve system stability, power quality and reliability of supply. Storage devices such as batteries and ultracapacitors are important components of a MG since storage on the microsource dc bus provides ride-through capabilities during system changes. Storage systems have become more versatile as they can provide high levels of power with short time responses. Energy storage can also boost the output of a DG unit so it can meet brief but high "needle peak loads" that sometimes occur. Energy storage systems can be used to follow the net load changes, stabilize voltage and frequency, manage peak loads and improve power quality. They can support renewable integration since Renewable Energy Sources (RES) may be problematic due to their variable and intermittent nature. In addition, wind fluctuations, lightning strikes, sudden change of a load, or the occurrence of a line fault can cause sudden momentary dips in system voltage [28].

There is a wide range of solutions currently available, depending on the application intended [15]:

- Batteries;
- Capacitor Storage;
- Superconducting magnetic energy storage;
- Mechanical storage: flywheels; pumped and compressed fluids.

Energy storage can be defined as the conversion of electrical energy from a power network into a form in which it can be stored (chemical, thermal or mechanical) until converted back to electrical energy [29] [30]. The only exception is the capacitor storage. Additionally, energy storage systems can be divided into four categories, according to the type of energy storage system and specificity of the application for which it is planned [31]:

- Low power applications in isolated areas (emergency terminals support);
- Medium power applications in isolated areas (individual electric systems or town supply);
- Network connection with peak levelling
- Power quality control applications.

Within the scope of this dissertation, the technologies that are most relevant in the intended MG application are batteries, supercapacitors and flywheels, technologies that are briefly described in the following sections. Further information regarding the other technologies mentioned can be found in [31].

2.3.5.1 Batteries

A number of different battery technologies exist for use as utility-scale energy storage facilities. Primarily, these have been lead-acid, but other battery technologies like sodium-sulfur (NaS), lithium-ion (Li-ion) and hybrid lithium-ion, and nickel-cadmium are also commercially available [15].

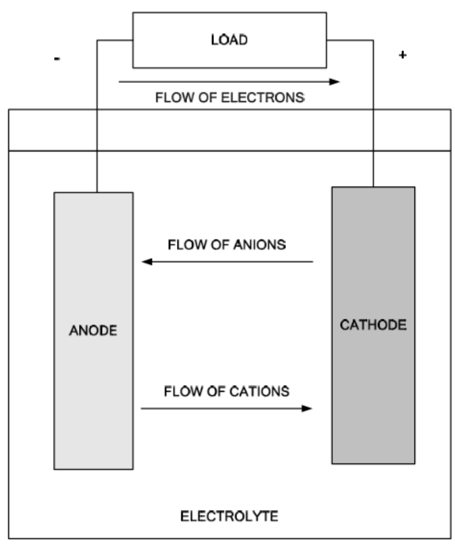

Figure 2.5: Discharge mode: electrochemical operation of a cell [4]

All batteries are electrochemical cells composed of two electrodes separated by an electrolyte so, despite being commonly known as "batteries", they are actually a "cell", the basic electrochemical unit, that can be combined in series and/or parallel with more cells depending on the intended output capacity in terms of voltage and current. A battery converts chemical energy into electric energy through an oxidation-reduction reaction, where electrons from one material are transferred to another by means of an electric surface. As a result, during discharge, ions from the anode (first electrode) are released into the solution (electrolyte) and deposit oxides on the cathode (second electrode) as seen in figure 2.5 [4]. Reversing the electrical charge through the system recharges the battery. When the cell is being recharged, as illustrated in figure 2.6 [4], the chemical reactions are reversed, restoring the battery to its original condition.

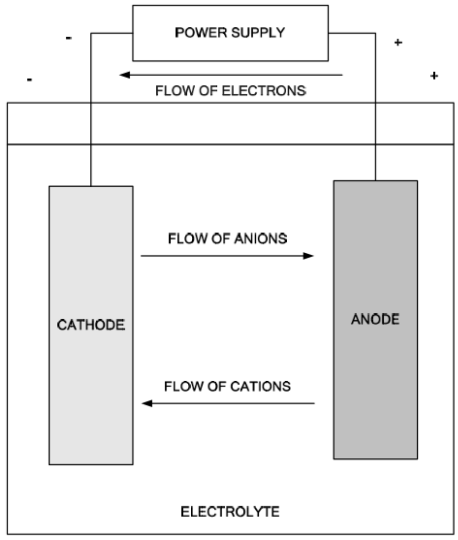

Figure 2.6: Charge mode: electrochemical operation of a cell [4]

Batteries are an adequate option for storing small to medium quantities of electricity. However, its utilization should take into account the charge and discharge cycles, since it can affect the battery lifetime. Since batteries gradually suffer from degradation of their storage characteristics after repeated charge/discharge cycles, it is recommended to submit them to no more than half, or less, charge/discharge cycles. This is due to the fact that the chemical reaction involved in the discharge cycle is not completely reversed during the charge cycle, contaminating the electrolyte, damaging the electrodes and in severe cases permanent molecular damages on components [15] [32].

2.3.5.2 Supercapacitor

Supercapacitors offer high power density, fast transient response, low volume and low internal resistance, making them suitable for pulsed load applications [33]. Supercapacitors merge some of the characteristics of capacitors and electrochemical batteries, except that there is no chemical reaction, increasing its cycling capacity. Energy storage in supercapacitors is done in the form of an electric field between two electrodes. The energy/volume obtained is superior to that of capacitors at very high cost but with better discharge time constancy due to the slow displacement of ions in the electrolyte [31]. Supercapacitors are durable (8–10 years), presenting a 95% efficiency and 5% per day self-discharge, meaning that the stored energy must be used quickly.

In figure 2.7 [4] it is represented the conventional arrangement of a supercapacitor, where it can be identified two capacitors, one at each carbon electrode, connected in series and the electrolyte serve as a link between the two capacitors [34]. So, technologically, it is an electrochemical device similarly constructed to batteries since it has two porous electrodes immersed in an electrolyte solution flowing into and around the porous electrode plates that, as mentioned, are made of activated carbon whereas the electrolyte solution is usually potassium hydroxide ($NaOH$) or sulphuric acid (H_2SO_4). The use of porous materials in the electrodes and, simultaneously, a liquid electrolyte solution, can be translated in high capacitance values, particularly when compared to conventional capacitors.

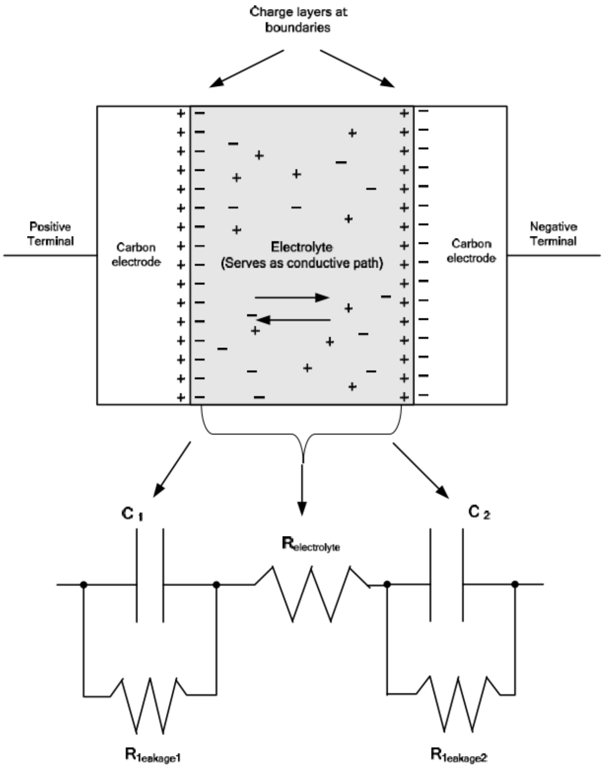

Figure 2.7: Electrochemical supercapacitor [4]

Electrochemical batteries have been used for different energy storage applications since they can store large amounts of energy and provide high power levels in a relatively small weight/volume ratio. However, batteries have many limitations like low power density, poor temperature performance, charge and discharge cycles are somewhat limiting and it requires repeated replacements throughout the life of system [33]. Additionally, this type of technology raises environmental concerns since they use chemicals to power their reactions. Some of these chemicals, such as nickel and cadmium are extremely toxic and can endanger humans and the environment. Nevertheless, this technology is still very popular, mainly due to low cost and sometimes a lack of an efficient alternative. In this regard, supercapacitors can provide a simple solution to improve performance and reliability and provide burst of power over many hundreds of thousands of cycles. They also have much higher power density, extremely longer cycle life, wide temperature range (-40^{o}C to +65^{o}C) but low energy density. It can also back up short term power mismatches between power available and power required with reduced system size and cost [35] [36] [37].

2.3.5.3 Flywheels

Traditionally, flywheels were used to achieve smooth operation of machines. The early systems were purely mechanical, consisting of only a wheel attached to an axle. Nowadays, flywheels are complex constructions where energy is stored mechanically and transferred to and from the flywheel by an integrated motor/generator and possibly power electronics [38]. A flywheel stores energy by accelerating a rotor up to a high rate of speed and maintaining the energy in the system as inertial energy. The energy is stored in the rotor proportionally to its momentum, but the square of the angular momentum. The flywheel releases the energy by reversing the process and using the motor as a generator. As the flywheel releases its stored energy, the flywheel's rotor slows until it is fully discharged [39]. Although most of the flywheel technology was developed in the auto and aerospace industry, flywheels are targeted for power delivery capabilities in the 150 kW up to 1MW range. These systems are compact and have lower maintenance costs and requirements when compared to battery systems. The main concern for development of this technology has been the power quality and reliability market.

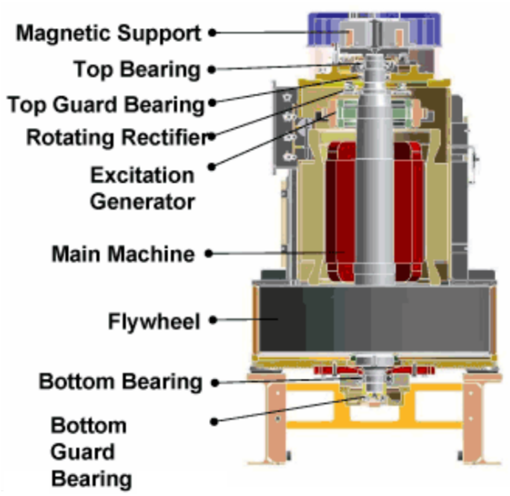

Figure 2.8: Components of a flywheel

Figure 2.8 shows the general components of the flywheel energy storage system. The kinetic energy stored in a flywheel is proportional to the inertia of the rotating mass and to the square of its angular speed speed as described:

$$E = \frac{1}{2} J \omega^2 \tag{2.2}$$

Where:

- E: kinetic energy (J);
- J: inertia of the rotating body ($kg.m^2$);
- ω: angular velocity ($rad.s^{-1}$).

Modern flywheels main parts are a power converter, a controller, a stator, bearings and a rotor. The rotor includes the rotating part of the motor/generator and the flywheel proper [40]. The inclusion of a rectifier and a converter to the generator allowed to increase the delivered amount of kinetic energy stored in the wheel, further increasing ride-through capability. Power electronics also allow the operation of flywheels at higher speeds, increasing stored kinetic energy in the rotating mass, achieving higher levels of energy and power densities [38].

In a flywheel, the rotating body that stores kinetic energy is connected to a variable speed Permanent Magnet Synchronous Generator, PMSG, that can operate as motor by accelerating the rotating body or as a generator by using the stored kinetic energy and convert it to variable frequency AC power [38]. In the charging state, storage of kinetic energy, power is absorbed from the grid and then converted into an appropriate form to drive the PMSG as a motor, which speeds up the flywheel. In the discharging state, the kinetic energy stored in the flywheel is converted to electricity by the motor which acts as a generator and the flywheel reduces its speed.

Flywheels, in terms of power quality applications, are appropriate to support the load throughout most of events, standing for less than a second, such as voltage sags and they can also provide power in order to support a system load during a few tens second while a standby generator is bought on-line. These sort functions were usually performed by chemical batteries but flywheels can compete with them since there is no capacity degradation and the lifetime of the flywheel is almost independent from the depth of charge and discharge cycles. Additionally, determining the state of charge in batteries is somewhat difficult, while in flywheels its state of charge depends on the rotational speed [41]. Last, it should be noted that flywheels are not suitable for low power applications (less than 100kW) since they present high power and energy densities and also high self-discharge rates. In this case, supercapacitors prove to be the cost-effective solution [42].

2.4 MicroGrid in depth

The massive adoption of DG resources throughout the electric system, supported by a maturation of some DG technologies, raises several technical issues that need to be tackled. As a result, in order to overcome these challenges and to maximize the potential benefits associated to DG resources, it is crucial to develop a coordinated strategy for its operation and control, while also taking into consideration electric loads and storage devices. A possible solution is the development of the MicroGrid (MG) concept. The development of this concept can be seen as an evolution of simple distribution networks with high levels of DG units where the formation of active LV networks can benefit the Distribution Network Operator (DNO) and the end user. From the grid's perspective, the advantage of considering a MG is the fact that it can be seen as a controlled entity within the power system with the possibility to be operated as a single aggregated load. From a customer point of view, the existence of a MG can benefit them them, since the consumer is able to act both as a buyer or seller of thermal and electrical energy, in a *prosumer* ("producer" + "consumer") attitude, while also providing uninterruptible power, enhance local reliability, reduce feeder losses, and support local voltages/correct voltage sag. Additionally, the pattern of exchange of energy services between the MG and the bulk power provider grid is determined by prevailing economic conditions.

However, it is necessary to achieve a coordinated control of the MG cell, in order to get the flexibility of operation required. To achieve that, it is necessary to develop an hierarchical control structure, developed according to the MG requirements and based on a network of controllers with local intelligence.

Since MGs are a future power system configuration that provides economic and environmental benefits while raising numerous economic, commercial and technical challenges that need to be addressed, United States, Europe, Japan and Canada are working in this sense, providing efficient solutions and trying to demonstrate MG operating concepts in laboratories and pilot installations.

The MG concept was first introduced in the United States by The Consortium for Electric Reliability Technology Solutions (CERTS) [1], established in 1999 to explore implications for power system reliability of emerging technological, economic, regulatory–institutional and environmental influences. From the inception of CERTS, the likely emergence of DG was recognized as an important factor, and it has been a focus of the CERTS. The specific concept of the CERTS Microgrid (CM) was fully developed by 2002.

In the European Union, the promotion and deployment of DER is expected to benefit energy consumers, energy system and the environment through optimization of the value chain from energy suppliers to end users. MG are considered a basic feature of future active distribution networks, able to take full advantage of DER, if coordinated and operated efficiently. They have been studied in a number of research and development projects, forming a key component in the Strategic Research Agenda for Europe's Electricity Networks of the Future [43].

Japan is the current world leader in MG demonstration projects. The Japanese government set ambitious targets for increasing the contribution of RES, such as wind turbines and PV panels, but the fluctuating power of RES could degrade the country's outstanding power quality reliability [3].

MG related research and development activities in Canada are focused on MV. Most were initiated in universities or as part of the Decentralized Energy Production program managed by the Canada Centre for Mineral and Energy Technology (CANMET). Research and development projects in Canada are mostly carried out in collaboration with the electric utility industry, manufacturers, and other stakeholders in DER integration and utilization.

2.4.1 MicroGrid Operational Control Architecture

Typically, a MG can be defined as a LV network that contains:

- **Feeders** that supply electric loads;
- **Microgeneration systems** based on Renewable Energy Sources (RES);

- **Storage devices**;
- **Hierarchical management and control scheme** that guarantees that all elements of the MG are aggregated in a single cell interfaced to the electrical power system.

Figure 2.9 [4], [44] properly illustrates the composition aforementioned. Microgeneration systems previously stated can be seen as energy sources such as photovoltaic panels, micro wind generator and microturbines whose technologies have already been described in previous sections and can either be controllable or non-controllable.

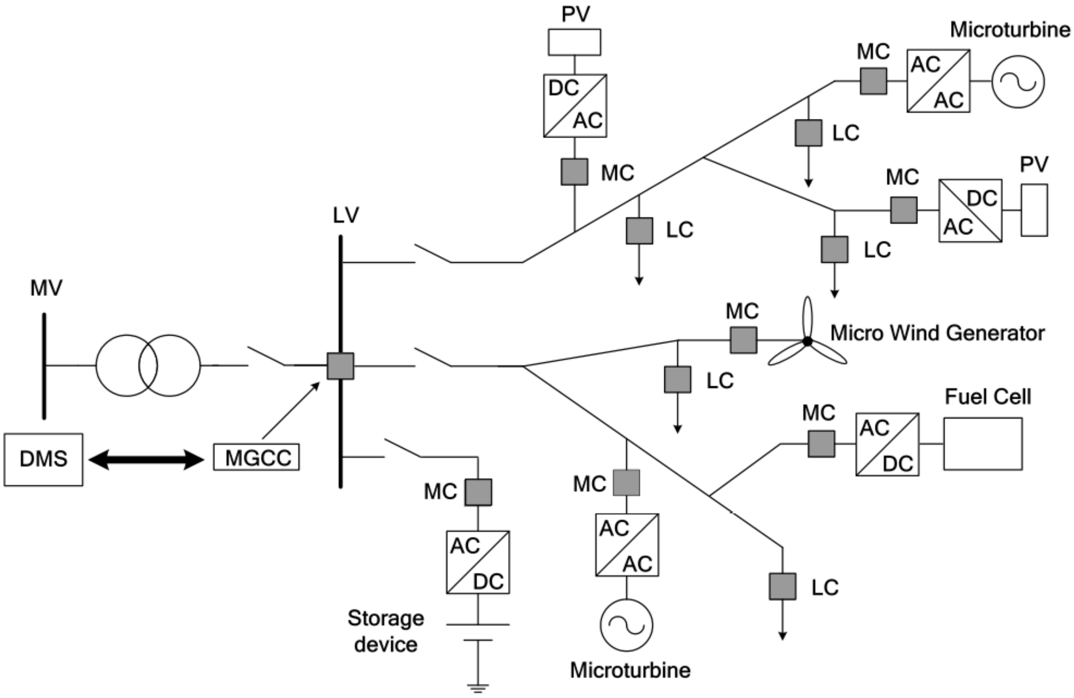

Figure 2.9: MG architecture [4]

Given the fact that a MG requires high levels of flexibility, the system is centrally controlled and managed by the **MicroGrid Central Controller** (MGCC), which is installed in the LV side of the MV/LV distribution transformer, as seen in Figure 2.9, allowing to communicate with controllers located at a lower hierarchical level. This second hierarchical level is composed by **Microsource Controllers** (MC) that control MS and storage devices at a local level and **Load Controllers** (LC) that manage electric loads.

The operation and control of the entire system is possible since it exists communication and interaction between the aforementioned hierarchical control levels. LC and MC serve as interfaces to control loads and MS active and reactive power management. The MGCC, being a central controller, ensures an adequate technical and economical management of the MG, providing set-points to MC and LC.

In order to actively contribute to enhance the management and operation of the MV distribution system, the MGCC should be able to communicate with the **Distribution Management System**

(DMS) which is located upstream, in the distribution network. DMS is responsible for monitoring, controlling and optimizing the distribution network operation network, being supported by a **SCADA** (Supervisory Control and Data Acquisition).

A SCADA allows:

- Data Acquisition through RTU (Remote Terminal Units);
- Alarm monitoring and processing;
- Manual/Automatic Control;
- Data Storage, event log, report creation and analysis.

A MG has the ability to operate in two different modes, either connected, or isolated from the upstream MV network. Such operation modes can be defined as [44]:

- **Interconnected Mode**: the MG is connected to the MV network and can be totally or partially supplied by it, while in some cases it can also inject power into the main system.
- **Emergency Mode**: the MG has the ability to move to islanded mode following a failure in the upstream network or due to planned action, such as maintenance procedures. Additionally, in case of a general blackout, it can locally perform a service restoration procedure. Both cases result in an autonomous operation from the MG, similar to physical islands electric power systems.

2.4.2 Microgrid communication infrastructure

Given the architecture previously described, it is necessary to grant communication capabilities between the MGCC and local controls in order to perform an optimized control and operation of the system. The data to be exchanged between network controllers includes:

- Set-points to LC and MC;
- Active and reactive powers, voltage levels and messages to control MG switches. This information is requested by MGCC to LC and MC.

In order to reduce telecommunication infrastructures costs, given the short geographical span of the MG, it could be exploited the concept of Power Line Communication technology) since the connectivity characteristics of the power grid provide the appropriate physical link between the different elements of the MG control system.

For a small MG, an Home Area Network (HAN) and a Neighborhood Area Network (NAN) [45] [46] are enough to operate a smart power system. Additionally, applications used in MG may affect the determination of communication technologies. SCADA system, for example, collects data at every few seconds or every minute. As a result, the requirement for data transmission rate and latency is not too high.

2.4.3 Low voltage microgrids and contribute to service restoration

MicroGrids feature several advantages being the most notable ones the deferral of investments in both transmission and distribution systems and last, the ability to reduce of losses in the distribution system. Nevertheless, MG can also contribute for power system restoration further improving overall system's reliability. Traditionally, restoration procedures focus on the restoration of bulk power transmission systems and its loads while DG is located at the bottom of the hierarchy, being reconnected when the system is energized and with stable values of voltage and frequency, based on the principle that its integration should not jeopardize the power system.

Conventional power system restoration plan is defined step-by-step, using predefined guidelines and operating procedures, recurring to decision support tools that assist system operators. The main focus is the plant preparation for restart, followed by network energizing and system rebuilding. MG, in this regard, besides allowing a reduction on interruption times at LV levels by operating in an islanded mode, can also provide faster Black Start (BS) fully exploiting its generation and control capabilities. A BS or service restoration consists in a process where, following a complete blackout, a system is restarted and a reconstruction of its networks and restoration of its service takes place without relying on other systems, fully depending on its self-starting units [47].

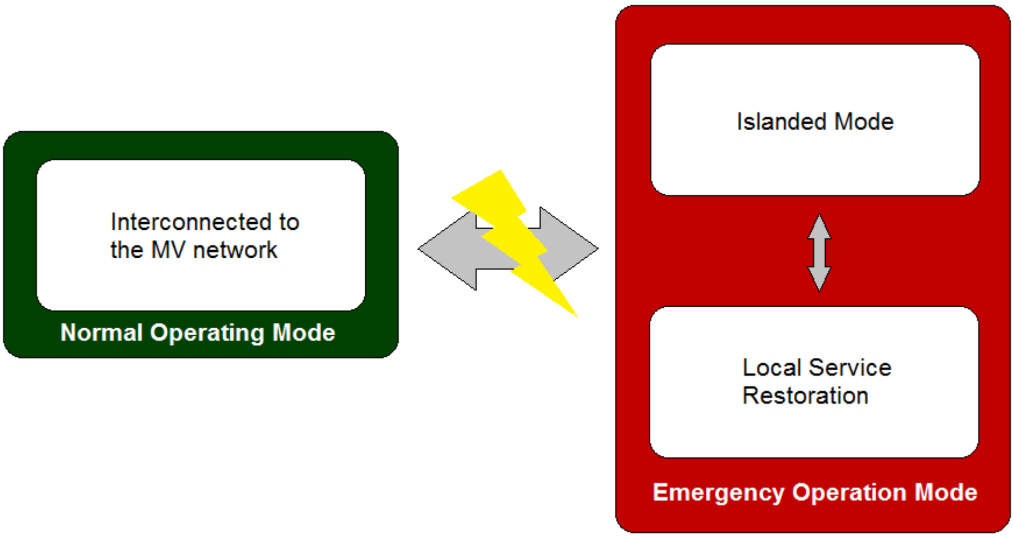

Figure 2.10: Schematization of the modes of operation that can be performed by a MicroGrid

An innovative approach in order to achieve system recovery following a general/local blackout that prevents a MG to shift into an islanded mode operation, consists in a local BS in the LV grid that is followed by the MG synchronization with the MV grid, which can be seen as a bottom-up strategy. This can result in a restoration service within each MG area of influence that when merged with the traditional top down strategy can allow to further reduce restoration times and unserved electricity during failures [48]. Since there are several issues related not only with conventional power system restoration but also MG restoration it is needed to define specific restoration strategies, as seen in [4]. The MS that are present in the MG make use of power electronic interfaces that allow the connection to the LV grid. Besides, MS operation has specific restrains, related to the slow response of the control signals and during transients, power balance is guaranteed by storage devices since there are no synchronous machines connected to the grid.

Summarily, the coordination of the MG resources allows it to operate not only in "normal" mode, connected to the upstream MV network, but also in emergency mode, as illustrated in figure 2.10.

2.5 Summary and conclusions

This chapter presented a general overview regarding the paradigm shift in the electric power system motivated by the increasing integration of DG in the system that is questioning the "validity" of vertically integrated utilities, since DG units can reduce transmission and distribution costs while also lessen the environmental impacts caused by promoting technologies that can produce energy with reduced levels of carbon dioxide and other GHG emissions.

While the development and increased DG deployment is a positive happening, its connection to the distribution network also needs another "paradigm shift" in the sense that DG integration needs to actively contribute to the management of the distribution grids, instead of a pure passive approach, also known as "fit and forget". This contribution can lead to a fully active distribution network, where DG, responsive loads and storage devices capabilities can be fully explored in order to further improve the system reliability and efficiency, operating conditions and quality of electricity supply.

Regarding MS technologies, it should be noted that in some cases, the lack of power electronics minimizes their role in a MG as they do not provide the required flexibility to ensure operation as a single aggregated system.

The MicroGrid structure assumes an aggregation of loads and microsources operating as a single system providing both power and heat. The majority of the microsources must be power electronic based to provide the required flexibility to insure controlled operation as a single aggregated system. This control flexibility allows the MicroGrid to present itself to the bulk power system as a single controlled unit, have plug-and-play simplicity for each microsource, and meet the customers' local needs. These needs include increased local reliability and security.

While a MicroGrid presents several advantages, it also raises some issues namely voltage control, power flow control, load sharing during islanding, protection, stability and overall operation.

The ability of the MicroGrid to operate connected to the grid as well as smooth transition to and from the island mode is another important function. While this issue is not debated in this dissertation, in [4] some strategies are suggested to overcome this problem.

Chapter 3

Microgrid control during islanding operation

The following chapter intends to give an insight on the main control strategies for grid inverters that allow the operation of a MicroGrid (MG) connected to the upstream Medium Voltage (MV) distribution network or isolated from the main grid.

Lastly, this chapter explains not only primary and secondary frequency control, but also also voltage control, topics that are crucial to understand the principles applied within the scope of this dissertation and that allow a successful operation of a MG in islanded mode.

3.1 Power electronics embedded in the grid

One of the key features that enables a MG application is the power electronics, control, and communications capabilities that allow a MG to function as a semiautonomous power system. In fact, power electronics are one of the distinguishing features of any MG. The interest in power electronics is due to the fact that most of the Microsources (MS) currently available can not be directly connected to the Low Voltage (LV) grid due to the characteristics of the energy they produce, requiring a DC/AC or AC/DC/AC interface.

Contrarily to what is seen in a conventional power system, where it is common to find synchronous generators, a MG, on the other hand, as distinctive features as most of its MS have power electronic interfaces due to the characteristics of the energy produced that need to be conditioned in order to be connected to the LV grid. As a result, voltage and frequency control operation is very different and it is crucial to understand the inverter control mechanics in order to ensure stable operation towards any given scenario.

In short, while inverters try to replicate some of the functions performed by synchronous machines in conventional power systems, they still have different characteristics, which are listed in the table 3.1 below [49].

This chapter will be focusing on giving an insight of the two main control strategies for grid inverters [44] [50] [51]:

Table 3.1: Synchronous machine vs. Inverter

Synchronous machine	**Inverter**
Voltage source operation with controlled magnitude through the use of excitation systems.	Voltage source (although current source versions are known) with nearly independent magnitude control in each phase.
Sine-wave voltage output is taken into account during the machine design/construction phase.	Sine-wave can be achieved through the use a suitable modulator and reference waveform. Nevertheless, any shape can be achieved as desired.
High short-circuit current due to low internal impedances.	Potential short-circuit current is high but protection against it must be provided in the form of current limiting functions.
Current rating defined by the winding insulation temperature rise. The thermal time constant of the winding and surrounding material is large and a useful short term over-rating is available. Large thermal time constants allow large fault currents for several main cycles.	Current rating defined by the temperature rise of the semiconductors, which have very low thermal time constants. Large currents cause semiconductor failure in less than 1 ms. The cooling system has also low thermal time constants, limiting the over-rating capabilities. Inverter over-rating is necessary to accommodate over-currents.
Real power exchange is dictated by the torque applied to the shaft. Power sharing is based on the use of control systems as a function of system frequency.	Real power exchange is dictated by the references applied to the control system, subjected to the DC-link capacity to sink the requested power.

- **PQ inverter control**: also known as grid tied inverters, they are responsible for exporting a controlled amounts of active and reactive power, acting like a current-controlled voltage source and operating in grid-connected mode [49] [52] ;

- **VSI inverter control**: Voltage Source Inverters (VSI) have the ability to control the frequency and magnitude of its output voltage [49] [52], behaving like a voltage source.

Since in a MG there are no synchronous machines that guarantee the balance between demand and supply through frequency control, inverters take this responsibility during islanded operation mode. When the MG is connected to the MV network, all inverters can operate in PQ mode since voltage and frequency are defined by the main system. However, when considering an islanded mode scenario, the disconnection of the main power supply leads to the loss of the MG, as it is no longer possible to maintain balance between load and generation and for an instance, frequency and voltage control [4]. In order to overcome this critical situation, VSI have a crucial role in MG operation as they can operate in parallel with other voltage sources [44]. Therefore, it is possible to migrate and operate in islanded mode since it provides references for voltage and frequency without needing to change the control mode.

3.1.1 PQ inverter control

This type of control mechanism for power converters, also know as the control of a grid tied converter, is based on the fact that they synchronize with an existing grid, injecting to it given amounts of active and reactive power. Its two main functions can be enlisted as follows:

- Grid-connection operation;
- Meet active and reactive set-points.

In addition to the aforementioned functions, it is also responsible for controlling the DC-link voltage of the cascading DC/AC/DC system [53].

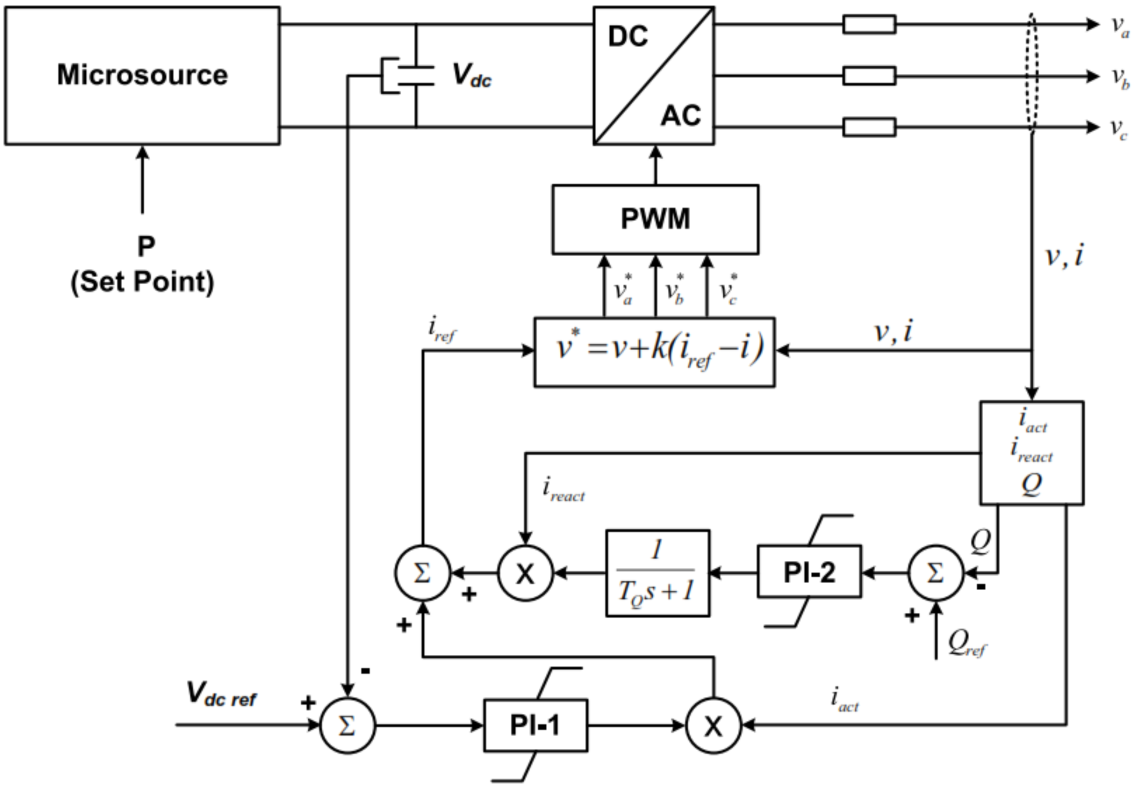

Figure 3.1: PQ inverter control [4]

The implementation of a PQ inverter control intends to act as a current-controlled voltage source, as it is illustrated in Figure 3.1 [4], [44] and it can be operated with a unit power factor or receive a set-point for the output reactive power, either locally or either from the MicroGrid Central Controller (MGCC). Power calculation is obtained by considering current components in phase and quadrature, i_{act} and i_{react} respectively, with the inverter terminal voltage. The control system has two cascade loops. The inner control loop adjusts the inverter internal voltage, $v*$, to meet a desired current, i_{ref}, while the outer loop comprises active and reactive power regulators. PI-1 and PI-2 regulators also seen in figure 3.1 allow to set active and reactive power output values. PI-1 regulator adjusts the active current output to be delivered to the grid, correcting power variations in the MS that induce a DC-link voltage deviation. PI-2 regulator enables the control of reactive power by adjustment of the magnitude of the inverter reactive current output.

3.1.2 Voltage Source inverter control

A Voltage Source Inverter (VSI) is designed through appropriated control mechanisms so that it emulates the behaviour of a synchronous machine by controlling voltage and frequency on an AC system [49] [52] [54] and, simultaneously, enabling parallel operation of variable frequency AC voltage sources. In conventional power systems the load variation is shared among synchronous generators according to their droop characteristics. As a result, in a situation where load increase occurs, synchronous generators react by decreasing the frequency according to their droop value. Conversely, when load decrease occurs, frequency increases accordingly to their droop value. Finally, reactive power sharing is done by introducing a droop characteristic in the voltage magnitude. Ultimately, a VSI can be seen as a voltage source since the magnitude and the frequency of its output voltage can be controlled through droops as seen in equation 3.1 and equation 3.2.

$$\omega = \omega_0 - k_P \times P \tag{3.1}$$

$$V = V_0 - k_Q \times Q \tag{3.2}$$

Where:

- P - inverter active power output;
- Q - inverter reactive power output;
- k_Q, k_P - droop slope (positive) values;
- ω_0 - angular frequency idle value of the inverter at no load condition;
- V_0 - voltage idle value of the inverter at no load condition.

In figure 3.2 [4], [55] it is presented the control scheme principle of a VSI. The basic idea of the model is based on equation 3.1 and equation 3.2, which requires the computation of output active and reactive power, whose computation is based on voltage and current measurement. After the measurement process, it is introduced a delay in order to allow decoupling between active and reactive power (identified as "*Decoupling*" set of blocks). In one dimension, by resorting to the reactive power/voltage droop, k_Q, the reactive power defines the magnitude of the output voltage. In another dimension the active power/frequency droop, k_P, determines the frequency of the output voltage. Additionally, in this loop, it is included a phase feed-forward gain, k_{ff}, for stability purposes. Lastly, in the "*Three-phase voltage computation*" set of blocks it is generated a three-phase set of voltages that ultimately lead to voltages v_a^*, v_b^* and v_c^* which serve as reference signals to control the VSI switching sequence through the Power Width Modulation (PWM) block, ensuring a correct implementation of a three-phase balanced model of the VSI.

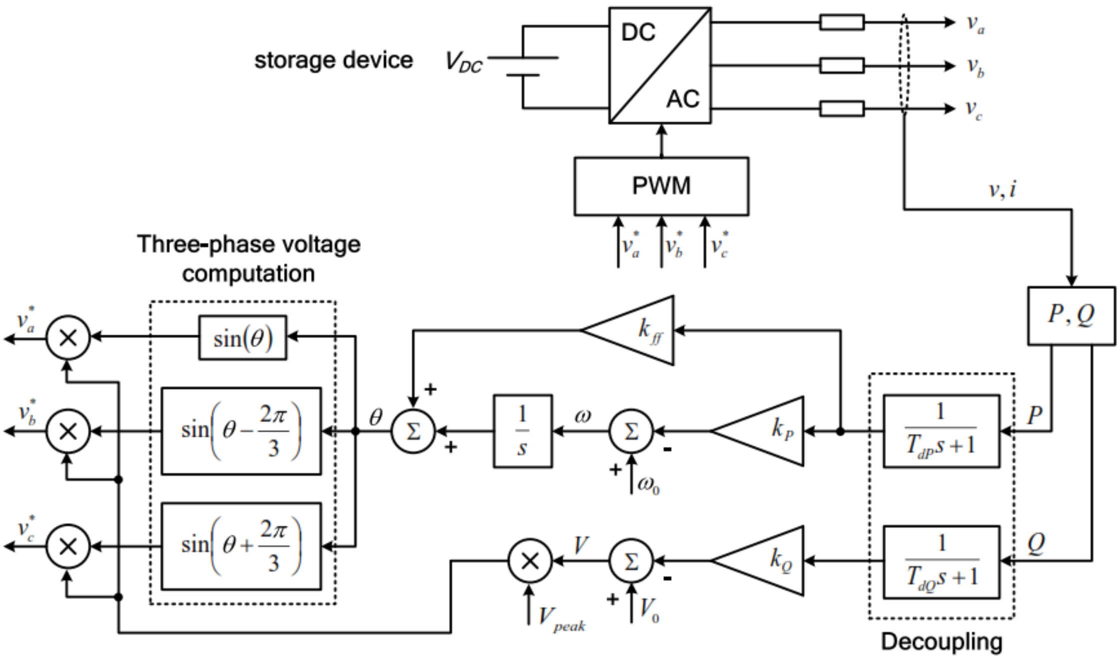

Figure 3.2: Voltage source inverter control [4]

A VSI, when interconnected with a stiff AC system with a ω_{grid} frequency and V_{grid} voltage, the voltage and frequency references of the VSI are externally imposed, as described in [56]. Additionally, as seen in figure 3.3 and equation 3.3 and 3.4, active and reactive output power, P_1 and Q_1 respectively, can be obtained in the VSI output by adjusting the idle values of the angular frequency ω_{01} and voltage V_{01}.

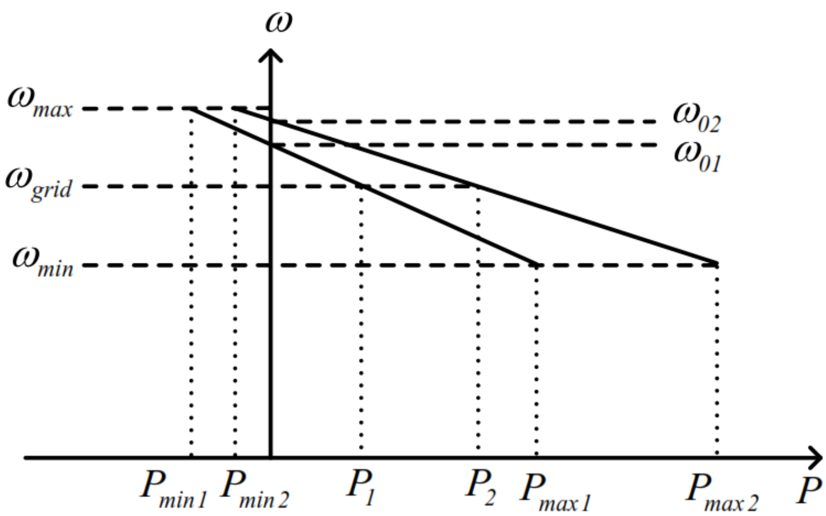

Figure 3.3: Frequency versus active power droop [4]

$$\omega_{01} = \omega_{grid} - k_P \times P_1 \tag{3.3}$$

$$V_{01} = V_{grid} - k_Q \times Q_1 \tag{3.4}$$

If a cluster of VSI operate in a standalone AC system, power sharing occurs when frequency variation takes place. As a result, ΔP, which represents the total power variation, has the following equation that is valid for a system considering a Multi Master Operation[1] with n VSI:

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \tag{3.5}$$

Regarding frequency control, which will be further detailed in section 3.4, in short therms, the frequency variation can be mathematically described as:

$$\Delta\omega = \omega_0 - k_P \times P - [\omega_0 - k_P \times (P + \Delta P)] = k_P \times \Delta P \tag{3.6}$$

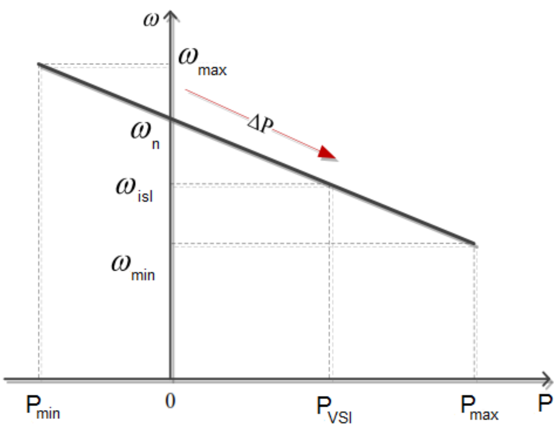

Figure 3.4: P-f droop

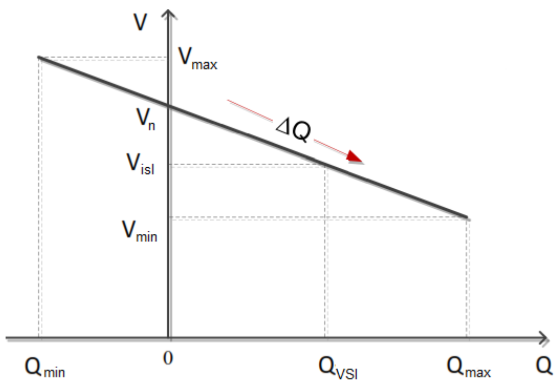

Figure 3.5: Q-V droop

Regarding voltage/reactive power control capabilities of a VSI, its control can also be based on droops, as demonstrated in [52]. However, voltage has local characteristics because the impedances of the network cables do not allow precise sharing of reactive power among VSI.

Analyzing figures 3.4 and 3.5 that are related to equations 3.1 and 3.2 and correspond to P-f and Q-V characteristic droops of any given VSI, it can also be stated that the greater the slope of one VSI in comparison to the nominal slope, the smaller the share of that unit [57].

3.2 Single Master Operation

Operating a MG with a single VSI and several PQ controllers is the definition of a Single Master (SMO) control strategy, as illustrated in figure 3.6 [4], [44]. When operating in islanded mode,

[1] Multi and Single Master Operation strategies are presented in the following sections

VSI sets the voltage and the frequency reference that allow the operation of the PQ controlled inverters. Additionally, the VSI also ensures fast load tracking during transients.

Conversely, MGCC uses the information received from MG local controllers and performs load control actions and defines the VSI droop settings, while it also updates each PQ inverter set-point to achieve an optimal operation configuration taking into account voltage levels, active power dispatch and reactive power flows.

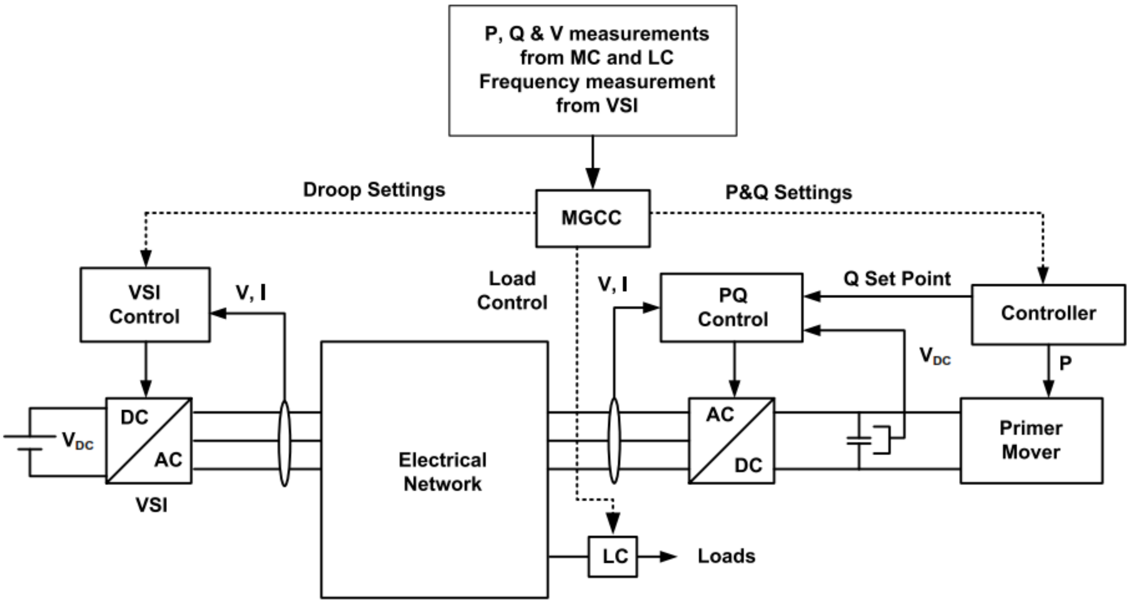

Figure 3.6: Single master Operation scheme [4]

3.3 Multi Master Operation

In the section above, a single VSI was responsible for providing voltage and frequency reference when in islanded mode. However, as illustrated in figure 3.7 [4], [44], [51], in a Multi Master operation (MMO), several VSI operate an isolated network in a similar way as conventional power systems who possess synchronous generators that control active power/frequency and reactive power/voltage. While the mode of operation is similar, in a MG this is performed by resorting to frequency/active power and voltage/reactive power droops instead of conventional voltage and speed governors. In short, by using additional VSI in parallel, redundancy in grids can be achieved. This solution avoids the master/slave operation meaning, in fact, that all VSI form the grid.

While it is not the objective of this dissertation, MMO as it was demonstrated in [48], can be seen as the best option (when compared to a SMO) to implement a BS strategy.

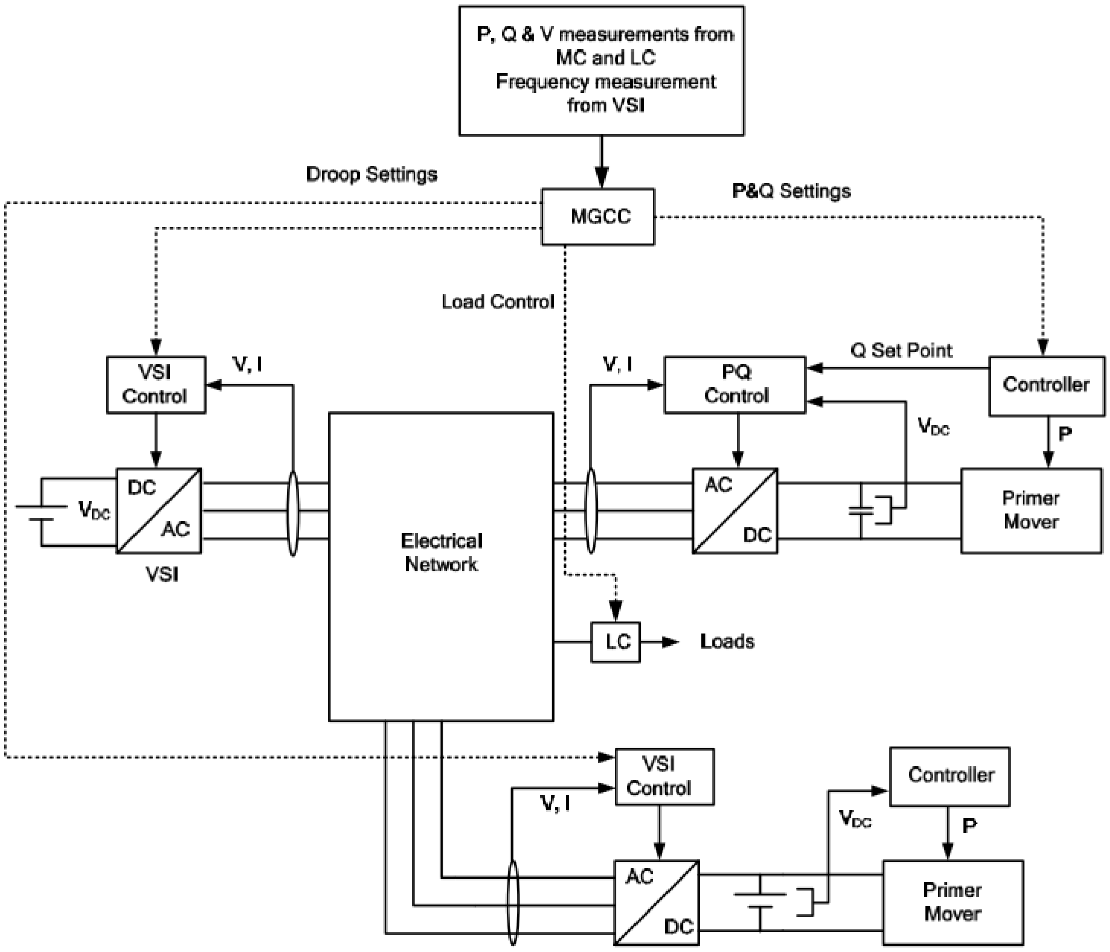

Figure 3.7: Multi master Operation scheme [4]

3.4 Frequency Control

MicroGrids can provide premium power functions using control techniques where the MG can perform in islanded mode and automatically reconnect to the bulk power system if needed.

When considering an interconnected operation mode, the frequency of the LV grid is set by the external grid. Additionally, its loads receive power both from the grid and from local MS. However, if the grid power is lost, the MG can shift to island mode operation, leading to voltage phase angles alterations at each MS in the MG, resulting in an apparent reduction in local frequency. This frequency reduction combined with a power increase allows for each MS to provide its proportional share of load without immediate new power dispatch from the MGCC. As a result, in islanded mode, some problems must be tackled such as small errors in frequency generation at each inverter and the necessity to alter power operating set-points in order to match load variations. Power versus frequency droop functions at each MS can address these problems without needing to rely on a complex communication network, while the overall system moves to a new operation point both in voltage and in frequency, dependant on the local load. After that, it is needed to restore the nominal value of the frequency by changing the idle frequency value of each inverter, while maintaining the output power constant which makes it possible to change the frequency of the MG without altering the output power of the VSI.

3.4.1 Primary Frequency control

The following equations reflect the proportional relation existent between the VSI active power output and the frequency deviation of a MG:

$$\Delta\omega = \omega_0 - k_P \times P - [\omega_0 - k_P \times (P + \Delta P)] = k_P \times \Delta P \tag{3.7}$$

$$\Delta V = V_0 - k_Q \times Q - [V_0 - k_Q \times (Q + \Delta Q)] = k_Q \times \Delta Q \tag{3.8}$$

Due to the fact that the storage devices that are coupled with the VSI have fast response capabilities, these devices are responsible for reacting in situations where load/power variations occur and also the moments subsequent to MG islanding meaning that they have high impact on primary frequency control. As illustrated in figure 3.8 [4], [51], when the VSI increases its output power, the MG decreases in accordance to the active power/frequency droop meaning that the value of this droops affects the slope of the correlation seen in the aforementioned figure. This situation happens since the VSI, as already mentioned in previous sections, acts as a voltage source and when power imbalances occur due to disturbances, it demands large currents from the VSI, forcing it to increase their output power.

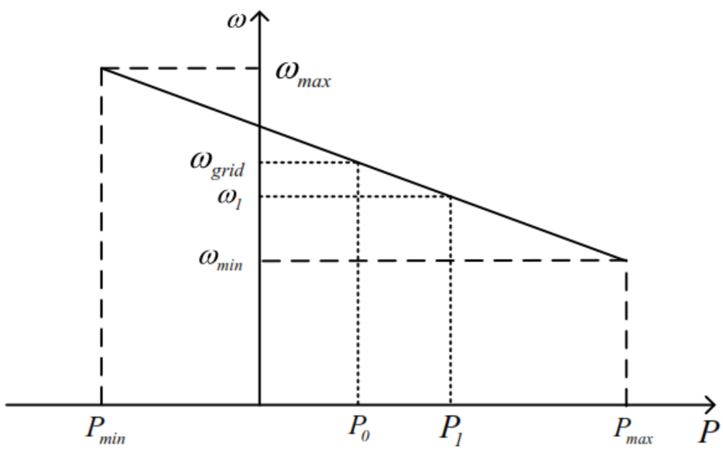

Figure 3.8: Correlation between frequency and active power variation [4]

The VSI action behaviour following disturbances also needs to take into account the type of operation chosen, which means that a SMO or MMO, described in the previous sections, lead to different mechanics. As a result, when considering a SMO mode where the MG is interconnected with the upstream MV network and it is injecting a certain amount of active power, P_0, in the moments subsequent to MG islanding, the frequency shifts to a new value, ω_1, while the active power increases to a new value as seen in figure 3.8, P_1. The difference between P_1 and P_0, ΔP, (representing the power imbalance between MG local load and generation and generation following islanding) corresponds to the amount of power absorbed from the upstream MV network if considering an interconnected operation mode. In this strategy, the single VSI existent act as the "*maestro*" and the frequency is determined by its P-f droop function. On another perspective, when considering a MMO mode, with n VSI operating in parallel and standalone AC system, a power variation ΔP in the system, forces the equation 3.5 in section 3.1.2 (Voltage Source Inverter Control) to be fulfilled, ensuring that the power variation in the system is properly shared within the existent VSI.

Through the following matrix equation 3.9, by combining every droop characteristic of the VSI present in the MG in a MMO mode, the steady state power variation in each VSI, ΔP_n, and the system frequency, ω_{grid}, enables to determine MG frequency deviation and the power sharing among the VSI following variations in generation/load during islanded mode.

$$\begin{bmatrix} 1 & k_{P1} & 0 & 0 & \dots & 0 \\ 1 & 0 & k_{P2} & 0 & \dots & 0 \\ 1 & 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & 0 & \ddots & \vdots \\ 1 & 0 & 0 & 0 & \dots & k_{P1} \\ 0 & 1 & 1 & 0 & \dots & 1 \end{bmatrix} \times \begin{bmatrix} \omega' \\ \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \\ \vdots \\ \Delta P_n \end{bmatrix} = \begin{bmatrix} \omega_{grid} \\ \omega_{grid} \\ \omega_{grid} \\ \vdots \\ \Delta P \\ \omega_{grid} \end{bmatrix} \tag{3.9}$$

Where:

- ω' corresponds to the post-disturbance angular frequency of the MG;
- ω_{grid} is the pre-disturbance MG angular frequency of the *i-th* VSI: $\omega_{grid} = \omega_{0i} - k_i \times P_i$.

3.4.2 Secondary Frequency control

As seen in the previous section, during islanded mode operation, the frequency of the MG deviates from its nominal value when facing power or load variations. Consequently, in situations where the MG frequency value stabilizes in a number different to the nominal one, storage devices, theoretically would keep injecting or absorbing active power until frequency deviation is equal to zero. In practice, due to the fact that storage devices have high capabilities for injecting power only during small periods of time, its storage capacity is finite and should restrict their actuation only during transient situations, preventing to run out of energy. As a result, it is necessary to include a control feature that corrects permanent frequency deviations in a MG during islanded mode for any operation scenario, relieving the dependence and restrains associated to the storage devices, namely the small time period of actuation capability.

Figure 3.9 [4], [44] properly illustrates the issue previously mentioned since whenever a frequency deviation occurs, power injection/absorption from the storage devices that are coupled

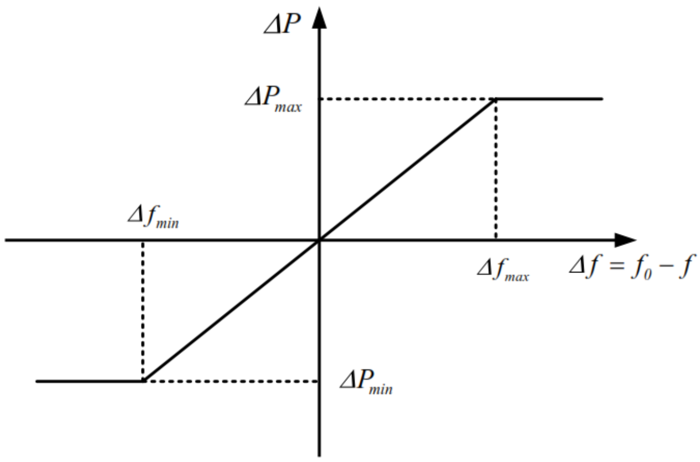

Figure 3.9: VSI power injection/absorption vs. MG frequency deviation [4]

with the VSI takes place, exhibiting a proportional relationship between frequency deviation and power injection/absorption and also restrains associated to the power ratings of the storage device, since after a certain frequency deviation, the storage device is incapable of injecting more power.

The control feature needed, which is actually a secondary frequency control, aims to restore the frequency to the nominal value, in this case 50Hz, following any power imbalance. There are two main strategies: local secondary control and centralized secondary control. The local secondary control uses a Proportional-Integral (PI) in each controllable MS as seen in figure 3.10 [4], [44]. In short terms, when considering a VSI controlled inverter, the frequency error is the input of the PI controller that determines the new ω_0 value. If considering a PQ controlled inverter, the frequency error is also the input of the PI controller that, instead, allows to determine the new active power reference point, P_{ref}. Centralized secondary control, on the other hand, is performed by the MGCC through algorithms implemented in the software. Both strategies use the frequency deviation error to set the values for active power output of the MS.

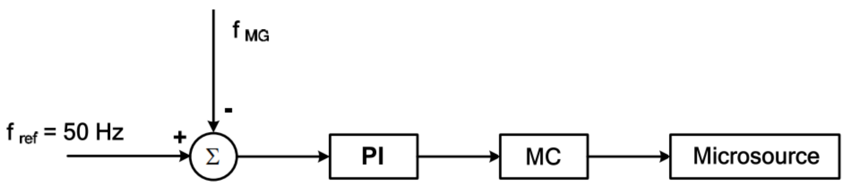

Figure 3.10: Local secondary control using a Proportional-Integral controller [4]

Within the scope of this dissertation, it will be considered the local frequency control. While in SMO strategy the target value is an active power set-point for a controllable MS, in a MMO strategy the target value is directly an active power set-point of a controllable MS connected to a PQ inverter or, additionally, a new value for the idle frequency of a VSI connected to a MS that comprises storage devices in the DC-link.

3.5 Voltage Control

LV distribution systems differ from the MV distribution systems in the sense that the cables have a high resistive nature in comparison with its reactance. While working well in a power grid with mainly inductive line impedances, the traditional decoupling principles (where the line resistance is neglected) leads to a concern when implemented on a LV MG, where the feeder impedance is not inductive and the line resistance, R_C cannot be neglected.

Figure 3.11 [4] illustrates a VSI and its respective inductance, L_{coupl}, and a LV cable, represented by R_C, connecting the VSI to the stiff AC power source, V_{grid}.

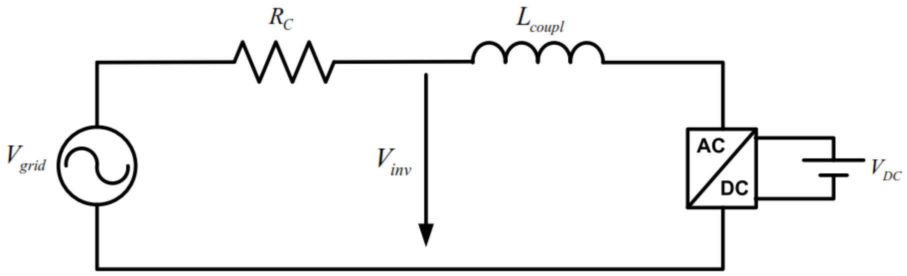

Figure 3.11: VSI and stiff AC power source connected through a LV cable [4]

Active and reactive power of the inverter can be determined through the following equations:

$$P_{inv} = \frac{V_{inv}}{R_C^2 + X_C^2}[R_C(V_{inv} - V_{grid}\cos(\delta)) + X_C V_{grid}\sin(\delta)] \tag{3.10}$$

$$Q_{inv} = \frac{V_{inv}}{R_C^2 + X_C^2}[R_C(V_{grid}\sin(\delta) + X_C(V_{inv} - V_{grid}\cos(\delta)] \tag{3.11}$$

Since X_C, as mentioned is admitted to being equal to zero (X_C=0), the aforementioned equations can be rearranged as follows:

$$P_{inv} = \frac{V_{inv}^2}{R_C} - \frac{V_{inv}V_{grid}}{R_C}\cos(\delta) \tag{3.12}$$

$$Q_{inv} = \frac{V_{inv}V_{grid}}{R_C}\sin(\delta) \tag{3.13}$$

Previous equations 3.12 and 3.13 indicate that active power flow is mainly related to the voltage magnitude and the reactive power to the phase difference between voltage sources. In this specific case, a possible approach could consist on using reverse droop concepts. Besides, in this case, it will not be possible to establish an effective power dispatch, since each load will tend to be fully supplied by the nearest generator. Due to the resistive nature of LV distribution networks, reactive power injection is unable to control voltage magnitude. In that sense, the MGCC, being a central controller, could perform reactive power set-point for each MS through, for example, a dedicated software in order to promote adequate technical and economical management policies.

To avoid P–Q coupling, virtual active and reactive powers can be used, while being decoupled through frame transformations with the line impedance angle information [58]. Despite being effective for power control in grid-connected mode, this method is unable to directly share the actual active and reactive powers between the DG units in MG islanding operation mode. Another way to decouple the powers with direct power control is to employ the virtual voltage and frequency control frame as demonstrated in [59]. However, these frame transformation methods are prone to the accuracy of the power control due to unequal impedance voltage drops. In [60] the DG interfacing inverter is controlled with a virtual output inductor that introduces a predominantly inductive impedance without the need of line impedance information in a order to control the decoupled active and reactive power flows in a similar manner as the conventional power system with a high X/R ratio.

Therefore reactive power injection cannot properly control voltage profiles. In fact, active power flow is linked to the voltage magnitude and the reactive power flow related to the phase difference between voltage sources. Within the scope of this dissertation voltage control is made through VSI where the manipulation of the reactive power/voltage droops (Q-V) can cause current circulation among VSI. They depend on the dispatched active power assigned to the inverter and on the VSI idle voltage.

Within the scope of this dissertation, since it is assumed a reactive power/voltage and active power/frequency droop control approach, some issues need to be addressed, particularly the fact that a droop based strategy prevents the classical formulation of a power flow since it is not possible to define the classical voltage controlled buses, as well as the reference and compensator bus.

3.5.1 Solving a power flow in islanded MicroGrid

Solving the power flow for a MicroGrid can not be done through conventional approaches, recurring to methods like Newton Raphson because, in islanded mode, there is no slack bus and the frequency is not constant, like in a grid connected mode. Additionally, there is a direct dependence of the power on frequency due to the droop characteristics. In [61] it is proposed a modified Newton Raphson method that bypasses the absence of slack bus and formulates the generator bus as a droop bus. Moreover, the bus at which the DG is connected either can not be classified as slack, PV or PQ bus in a power flow because the active and reactive powers, voltage magnitude and angle of the droop bus are not pre-specified, being dependent on the system parameters meaning that conventional approaches can not be considered in case islanded micrograms.

Typically, power flow models have three types of buses: slack bus, generating bus and load bus. Considering a generating bus, the active power and voltage magnitude may be specified by varying the mechanical torque and generator field current. All other buses specify real and reactive power. Generally all real power values at all the buses cannot be specified independently because power balance needs to be validated. The power at the slack bus is left open to, as the name suggests, take up the slack and balance the change in real power and provide a reference to the rest of the generators in the system. However, slack bus is not viable since in a standalone operation mode any change in power requirements needs to be evenly distributed among the VSI.

The changing frequency will influence the power flow solution and ultimately, a varying frequency will influence the voltage magnitude and angle.

Given the difficulties of having an expedite tool capable of providing a solution for the power flow probe in droop controlled autonomous MG, it was decided to explore an alternative solution based on the simulation models available in the Matlab/Simulink libraries.

First, it is necessary to take into consideration the VSI inverter model presented earlier in this chapter, in section 3.1.2 (figure 3.2). The initial step is to implement not only the k_P (P-f) but also the k_Q (Q-V) droop mechanisms in a synchronous machine model available in Matlab/Simulink library while still guaranteeing the equivalency of the droop controlled VSI mechanism.

In a VSI, the basic relation between the active power variations and angular variations is given in figure 3.12 through a linear transfer function, as follows:

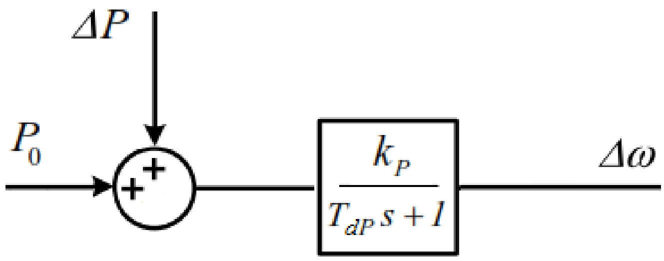

Figure 3.12: Voltage Source Inverter transfer function

As a result, VSI transfer function $\Delta\omega/\Delta P$ can be presented in the given form:

$$\frac{\Delta\omega}{\Delta P} = \frac{k_P}{T_{dP}s+1} = \frac{1}{\frac{T_{dP}}{k_P}s+\frac{1}{k_P}} \tag{3.14}$$

For this machine, represented as a constant voltage source behind an internal reactance, the classic swing equation [62] in the Laplace domain (considering small frequency variation) can be mathematically represented as follows:

$$\frac{\Delta\omega}{\Delta P} = \frac{1}{2Hs} \tag{3.15}$$

Additionally, if we consider that a fast control mechanism is added to the simplified model of the synchronous machine, its model can be represented as illustrated in figure 3.13. The $\Delta\omega/\Delta P$ transfer function of the figure is given by:

$$\Delta\omega = \frac{1}{2Hs}(\Delta P - \frac{1}{R}\Delta\omega) \Leftrightarrow \frac{\Delta\omega}{\Delta P} = \frac{1}{2Hs+\frac{1}{R}} \tag{3.16}$$

It is now possible to observe that equation 3.14 and equation 3.16 have an equivalent arrangement, allowing to define the following equivalences:

$$H \Leftrightarrow \frac{T_{dP}s}{2k_P} \tag{3.17}$$

$$\frac{1}{k_P} \Leftrightarrow \frac{1}{R} \tag{3.18}$$

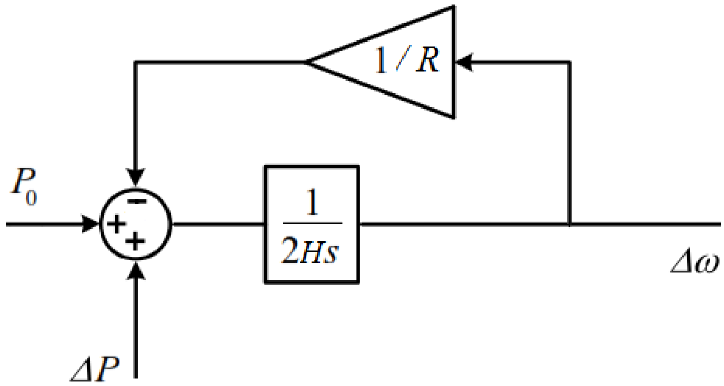

Figure 3.13: Synchronous machine transfer function

This means that in the simplified model available in the Matlab/Simulink for synchronous machines, there is a link between the machine inertia (H) and the control parameters of the active power droop of a VSI ($T_{dP}s$, active power decoupling delay and k_P, active power droop).

Taking now into consideration the VSI model with respect to the reactive power droop, we can also define the same characteristic for the simplified synchronous machine model in *Matlab/Simulink*.

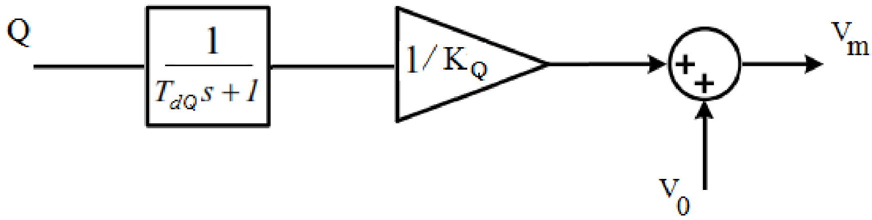

Figure 3.14: *VSI k_Q droop control based on a SSM*

Where:

- V: internal voltage of the simplified synchronous machine.
- Q: reactive power output of the machine model.

Finally, the simulation model to implement in *Matlab/Simulink* is depicted below, figure 3.15, having the key advantage of of running in the "phasor simulation mode", thus providing the necessary simulation speed while keeping the equivalency to the droop controlled VSI.

Where:

- X: internal reactance of the synchronous machine (being equal to the coupling reactance of the VSI for equivalency purposes) as illustrated in figure 3.15.

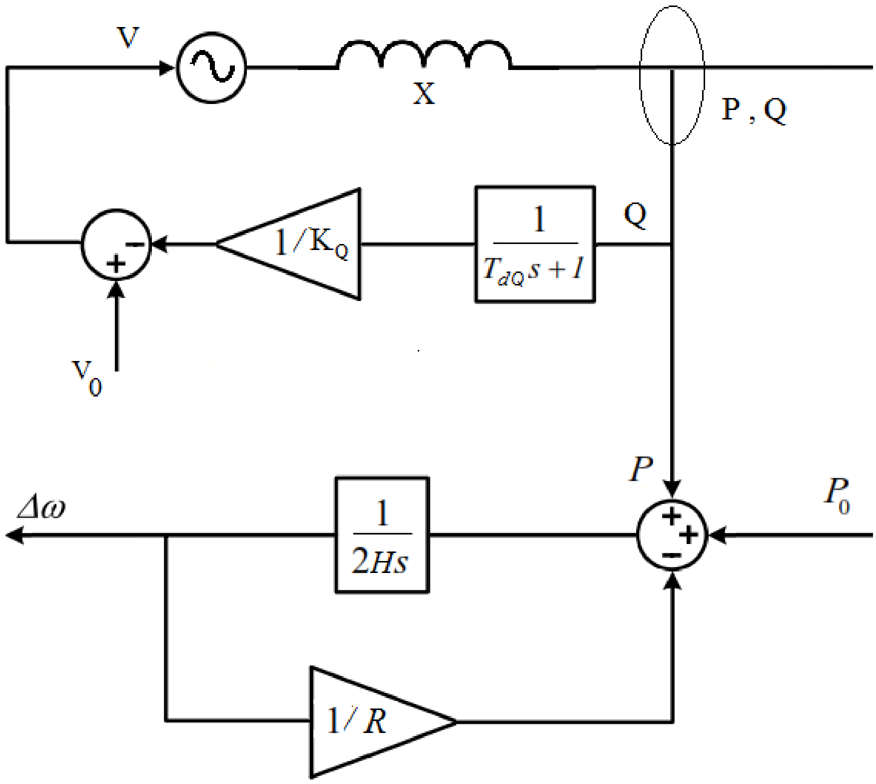

Figure 3.15: *Integrated equivalent model of VSI with droop control based on a SSM*

3.5.2 Voltage control: formulation of the problem

Having defined a methodology for the modelling approach of a MG with droop-controllable converts where the primary voltage control mechanism is assumed by the Q-V droop implemented in the VSI, it is now necessary to define possible strategies for the voltage/reactive power control problem. This strategies will run at the MGCC level, thus constituting a secondary voltage control mechanism that will run periodically. The voltage control problem can be generally defined as follows:

$$minOF(X,u) \tag{3.19}$$

Subject to:

- g(X,u) = 0
- $V_i^{min} \leq V_i \leq V_i^{max}$
- $Q_i^{min} \leq Q_i \leq Q_i^{max}$

Where:

- X is the MG state vector corresponding to the node voltages and phase angles;
- u is the control vector, corresponding to the idle voltages V_{0i} of the Q-V droop function of each VSI;
- g(X,u) stand for equality constraints, representing the power flow balance in the autonomous MG;
- V_i is the voltage at each bus i (i = 1...n);
- V_i^{min}, V_i^{max} are the minimum and maximum voltages admissible at bus i;
- Q_i^{min}, Q_i^{max} are the minimum and maximum reactive powers of each VSI.

With respect to the objective function (OF), it is proposed two alternatives/strategies:

1. **Minimization of the voltage magnitude deviation with respect to the nominal value**:

$$OF_1(X,u) = \sum_{i=1}^{n} (V_i - 1)^2$$

2. **Minimization of the active power losses in the autonomous MG**:

$$OF_2(X,u) = P_{losses}(X,u)$$

Both strategies are treated with respect to their performance and impact in MG operation in the next chapter

3.6 3-phase load and network modelling considerations

The feasibility of islanded mode operation was performed through the analysis of the LV network dynamic behaviour considering only three-phase balanced operation, despite the fact that it is not the most common situation in LV distribution networks. Two load types were considered: constant impedance loads (dependent on frequency and voltage) and motor loads. Load characteristics greatly influence the dynamic behaviour of the MG.

As a result it was chosen a Three-Phase Dynamic Load block since as the name suggest, implements a three-phase, three-wire dynamic load whose active power P and reactive power Q vary as function of positive-sequence voltage. Negative and zero-sequence currents are not simulated. The three load currents are therefore balanced, even under unbalanced load voltage conditions.

The parameters set are the following:

- Nominal L-L voltage and frequency: Specifies the nominal phase-to-phase voltage, in volts RMS, and nominal frequency, in hertz, of the load.
- Active and reactive power at initial voltage: Specifies the initial active power P_0, in watts, and initial reactive power Q_0, in vars, at the initial voltage V_0.
- Initial positive-sequence voltage V_0: Specifies the magnitude and phase of the initial positive-sequence voltage of the load.
- When using the Load Flow tool or the Machine Initialization tool of *Powergui* to initialize the dynamic load and start simulation in steady state, these two parameters are automatically updated according to values computed by the load flow.
- External control of PQ: It was considered, thus enabling active and reactive power of the load to be defined by an external *Simulink*® vector of two signals.

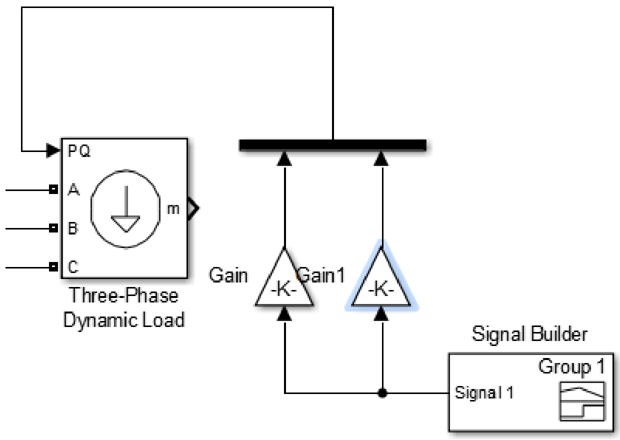

Figure 3.16: 3-phase Dynamic Load final aspect

3.7 Summary and conclusions

This chapter presented two inverter control strategies for power export to an AC system and two control strategies that can successfully exploit a MG in islanded mode. In that regard, it was also shown the need to establish control strategies within the MS in order to improve the MG capabilities and functionalities.

Frequency and voltage control are two of the main concerns when operating a MG, especially when considering islanded mode, as they need to be within certain limits and a MG as specific features, namely low global inertia and LV lines that present higher resistance when compared to its reactance. These points of operation are constantly changing, since power production and levels of consumption are being constantly changed as well. In that regard, the inverters existent in the MG allow stable frequency and voltage profiles. As a result, the specific nature inherent to a MG requires unique control strategies for frequency and voltage control.

The PQ inverter control is operated in grid connected mode, injecting a certain amount of active and reactive power set-point to the network. Regarding the VSI, its action during islanded mode can be seen as a frequency controller, playing a similar role of the synchronous generators present in conventional systems, which are responsible for controlling primary frequency. Summarily, VSI can be seen as a voltage source where the magnitude and frequency of the output voltage is controlled through droops.

Despite the fact that it was not addressed within this dissertation, load shedding can enhance some MG operating conditions, especially cases where load is greater than generation. This procedure is particularly useful since not only does it aid frequency restoration to its nominal value, but it can also prevent larger frequency amplitude deviation which is an important issue, since storage devices have finite storage capabilities.

This chapter also intended to give an insight regarding how the MG was built under a simulation environment. The main concern was to develop a VSI model that could actually present the features and type of responses in accordance to what was described in the previous chapter. In fact, modelling a VSI proved to be the most challenging device because there are no models available in the Simulink catalog. As a result, in order to overcome this aspect, it was proposed to use a simplified synchronous machine emulating the behaviour of a VSI. The swing equation allowed to establish a relation between synchronous machines and droop values of the inverter.

It was also addressed the implications of applying a droop control approach, since the formulation of classical power flows can no longer be applied since the slack bus cannot be considered in standalone operation mode

In short, the presented model allowed to implement a VSI based on droops, where the active power determines the output voltage frequency through the P-f droop, or k_P, while reactive power determines the magnitude of the output voltage through the Q-V droop, k_Q.

The next chapter demonstrates, in a simulation environment, the feasibility of the proposed control strategies in order to achieve improved MG operation conditions, particularly voltage profiles and reactive power flows.

Chapter 4

Evaluation of the performance of voltage and reactive power dispatch control strategies

This chapter intends to present, through illustrative examples, the effectiveness of the proposed control strategies that were applied in different operating scenarios of a MicroGrid (MG) test case. Simultaneously, the results obtained were compared with initial scenario, where there is not any voltage/reactive power sharing secondary control mechanisms actuating in the MG. Last, it is made a comparison between the proposed voltage control and reactive power dispatch strategies and enhancement of resulting impacts.

4.1 Introduction

As seen in Chapter 3, primary voltage/reactive power control mode based on droops for any given Voltage Source Inverter (VSI) raises some difficulties, particularly due to the fact that voltage has local characteristics due to the cable impedances of the network that prevent precise sharing of reactive power among VSI. Additionally, the operability of droops in inverters is a concept that derives from inductive coupled voltage sources. However this is not valid in Low Voltage (LV) lines due to its resistive predominance, meaning that reactive power is related with phase shift and active power with voltage. This particularity raises the need to develop specific control strategies for voltage and frequency.

This chapter's main focus is to present the obtained results from two different control strategies for voltage control and reactive power dispatch assuming different load scenarios and simultaneously, assuming a three-phase balanced model of the proposed load scenarios. As a result, it is admitted that the values of the loads are known and the inverters will establish the proposed strategies in steady-state conditions. Additionally, the load scenarios try to cover a wide range of situations, namely high imbalance between loads, balance between loads and high levels of load that pretend to simulate a peak scenario or a situation where load is close to generating capacity.

These load scenarios naturally lead to different scenarios mainly in terms of voltage and power flow profiles, which on its turn put to the test the robustness of the proposed control strategies. As mentioned in the introduction, simulations are performed by using *Matlab*® /*Simulink*® environment which will ultimately allow the evaluation and comparison between the proposed control strategies.

4.2 Case Study

The system that was subject to test in *Matlab*® /*Simulink*®environment is composed by two VSI connected by a cable typically seen in LV lines and two different loads, as illustrated in figure 4.1.

The arrangement of the simulation system tested under Matlab/Simulink platform can be seen in Appendix B or simply in figure 4.1.

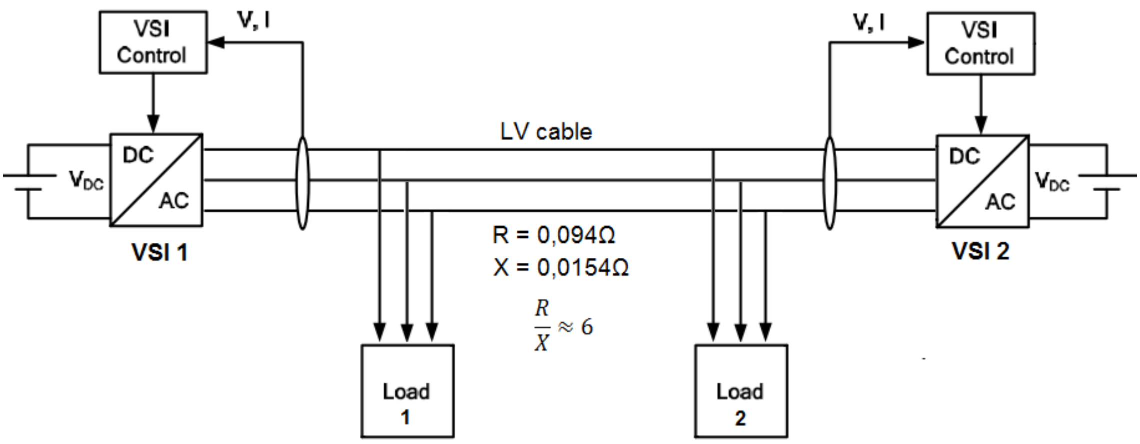

Figure 4.1: Case study system

Regarding the components considered under the simulation MG, the VSI characteristics can be seen in table 4.1. For the LV cable applied in the MG, it was considered a 200m long, $95mm^2$ aluminum cable, with a resistance of 0,094Ω and a reactance of 0,0154Ω (R/X=6).

The first step was to consider the VSI parameters presented in table 4.1 and apply them accordingly to the parameters requested (applying unit conversion equivalencies if necessary) in the equivalent model based on the *Matlab/Simulink* Simplified Synchronous Machine (SSM), as seen in table 4.2.

Last, rated power and power factor values considered for both VSI were:

- $P_n = 50$ kW
- $\cos\phi = 0.9$

The reactive power limit values are now determined:

$Q_{min} \leq Q \leq Q_{max} \Leftrightarrow -24.16kVar \leq Q \leq +24.16kVar$

Table 4.1: VSI parameters

Parameter	VSI 1	VSI 2	Units
Idle frequency, f_0	50	50	Hz
Idle voltage, V_0	1.0	1.0	p.u.
Active power decoupling delay, t_{dP}	0.6	0.6	s
Reactive power decoupling delay, T_{dQ}	0.6	0.6	s
Active power droop, k_P	-1.2566×10^{-4}	-1.2566×10^{-4}	$rad.s^{-1}.W^{-1}$
Reactive power droop, k_Q	-3.0×10^{-4}	-3.0×10^{-4}	V(p.u.).var^{-1}
Coupling inductance	0.5	0.5	mH

Taking into consideration the VSI parameters defined in table 4.1 and making use of the model equivalency between the VSI and the SSM as seen in equation 3.17 and 3.18 (Chapter 3), it is presented in table 4.2 the simulation parameters for the SSM. So, the values considered had to maintain the equivalency of a droop controlled VSI approach.

Table 4.2: SSM

Parameter		Value	Units
Nominal power		50×10^3	VA
Line-to-line voltage		400	Vrms
Nominal frequency		50	Hz
Inertia		$2 \times (\frac{0.6}{2 \times 1.2566 \times 10^{-4}})/(50\pi)$	$kg.m^2$
Damping factor		0	$\frac{pu_{of} torque}{pu_{of} speed}$
Internal	Resistance	10×10^{-6}	Ω
Impedance	Inductance	0.5×10^{-3}	H

For each scenario, it is also necessary to consider a strategy for the active power dispatch among the VSI, since it influences the voltage profile and consequently, reactive power. The dispatch can be done considering that in steady state the following equations hold:

$$\begin{cases} P_1 = P_{0_1} - \frac{1}{R_1}\Delta\omega \\ P_2 = P_{0_2} - \frac{1}{R_2}\Delta\omega \\ P = P_1 + P_2 \end{cases} \tag{4.1}$$

and $\Delta\omega = 2\pi \times 50 - \omega_{grid}$

Where:

- P_1, P_2: active power output from VSI 1 and VSI 2, respectively;
- P_{01}, P_{02}: reference active power for VSI 1 and VSI 2, respectively;
- $P = P_1 + P_2$: total active load in the system (losses negleted);
- $\Delta\omega$: frequency variation;
- ω_{grid}: frequency of the MG.

4.2.1 Definition of case study scenarios

As already mentioned, the main focus of this chapter is to present two different control strategies for voltage control and reactive power dispatch assuming different load scenarios that try to cover a wide range of situations. Consequently, three different scenarios were considered, as seen in table 4.3.

Table 4.3: Scenarios

	Active Power **Load 1 (kW)**	Reactive Power **Load 1 (kVar)**	Active Power **Load 2 (kW)**	Reactive Power **Load 2 (kVar)**
Scenario 1	85	15	15	10
Scenario 2	25	10	25	10
Scenario 3	25	10	60	15

Summarily, scenario 1 tries to replicate a case where there is a high imbalance between the two loads and the biggest load is requesting 85% of the sum o each VSI nominal power rating (since each VSI as a 50kW power rating). Scenario 2 considers a balanced situation between the active power demanded in load 1 and load 2, while the total amount of active power requested remains moderate. In the last scenario, while it is not as severe as scenario 1, the imbalance is the opposite since it is load 2 that is requesting most of the active power. Given the aforementioned scenarios, where in some situations there are high imbalances between load requests and high levels of load demand it is likely that the MicroGrid operation conditions without control are far from ideal and ultimately, it may occur violation of technical constrains such as overvoltage profiles, and extremely high imbalances between the levels of reactive power being produced by each VSI, as discussed in the following section.

4.3 Microgrid without secondary control

In order to fully understand the impact caused by the proposed strategies, it is first necessary to analyze the aforementioned study scenarios. The main concern is to verify the behaviour of voltage and reactive power flows observed in both inverters. Active power is not a relevant issue since both inverters have the same active power/frequency droop. This means they are intended to share active power in the exact same proportion. The following images (4.2, 4.3 and 4.4) illustrate the behaviour if the three different proposed scenarios without any control are applied.

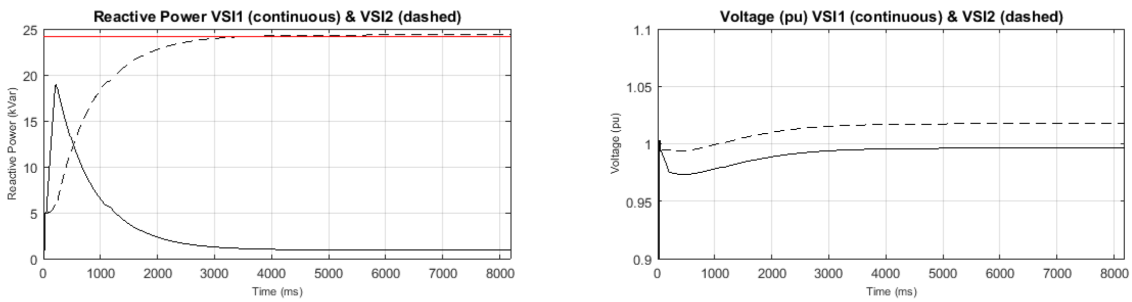

Figure 4.2: Scenario 1: VSI 1, VSI2 reactive power and voltage profiles

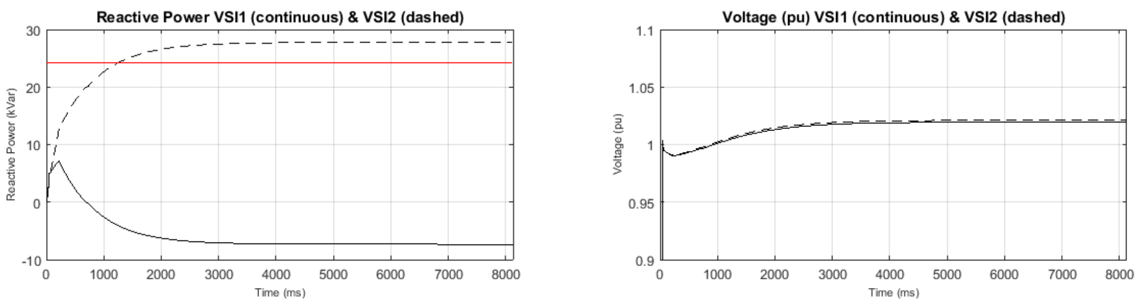

Figure 4.3: Scenario 2: VSI 1, VSI2 reactive power and voltage profiles

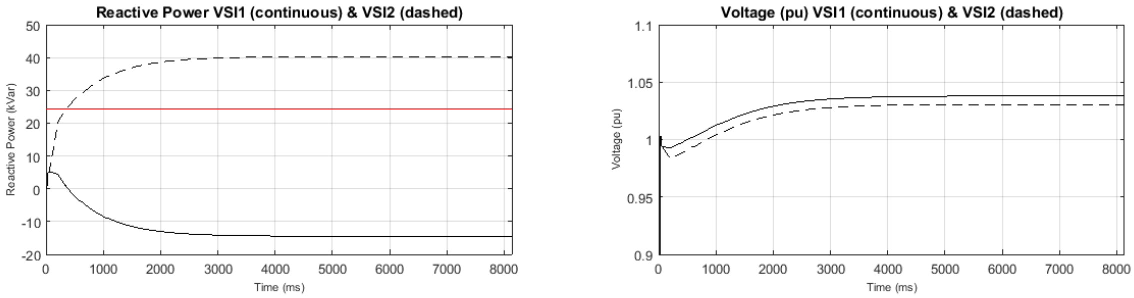

Figure 4.4: Scenario 3: VSI 1, VSI2 reactive power and voltage profiles

The first thing that can be quickly identified is that in all cases there is an high imbalance between reactive power flows. Additionally, in all scenarios, VSI 2 is injecting more reactive power than its maximum admissible value, as mentioned in section 4.2 ($Q_{max} = 24.16kVar$). In scenarios 2 and 3, VSI 1 is absorbing reactive reactive power. So, the question is: why do this issues occur? Analyzing scenario 3, for example, VSI 2 is injecting more than the totality of reactive power required by load 2. Terminal voltage of VSI 1 is higher than VSI 2 because the high resistive nature of LV networks means that in order to exist power flow from one side to another, VSI 1 needs to increase its voltage in order to supply load 2. So, voltage imbalances between inverters tend to be higher when the imbalances between loads are more severe. In scenario 2, for example, since loads 1 and 2 are approximately the same, its voltage is nearly identical.

In short, these scenarios demonstrate that while in some cases the operation could be somewhat feasible, they are extremely unreliable and in real conditions can not perform adequately. So, by implementing control features that allow a MG to operate in adequate conditions, it is possible to improve the system efficiency and quality of electricity supply.

4.4 Results and evaluation of control strategies applied

As seen in the previous section, reactive power flow imbalance is a serious concern. One approach could consist in altering the reactive power/voltage droop characteristics of the inverters. For example, in scenario 3, in order to reduce the reactive power absorption of VSI 1 its idle voltage could be increased up to values that can prevent this absorption. This could be done manually but it would be impractical, especially if considering a more complex MG with more VSI devices. So, the natural step would consist on establishing a control strategy that could be implemented as a software module in the MGCC (secondary control functionality), improving its technical and management capabilities.

The next sections present the obtained results from the proposed strategies compared and evaluated through analysis of the previous scenarios. This tests were once again conducted in Matlab/Simulink environment and using a program interface that automatically set the adjusting parameters. The results were obtained by recurring to the Evolutionary Particle Swarm Optimization (EPSO) algorithm. Besides, the fact that this algorithm can penalize and eliminate situations where technical restrains are not met is a very important feature that, despite the "quality" of the strategy to be applied is guaranteed to be feasible from a technical point of view. EPSO algorithm is properly explained in Appendix A. It is also important to mention that the main goal is to make a proof of concept of the proposed control management approach, rather than the development of an efficient and dedicated optimization tool for this specific application.

As mentioned and discussed in chapter 3, section 3.5.2 (voltage control: formulation of the problem), two strategies were considered, having the following objective:

- **Strategy 1**: minimization of the voltage deviation with respect to the nominal value (1p.u.).
- **Strategy 2**: minimization of the islanded MG active power losses.

The proposed optimization strategies were applied, for each of the defined scenarios, being the output the definition of the idle voltage of each VSI (V_{01} for VSI 1 and V_{02} for VSI 2).

4.4.1 Results and analysis of the control strategies: scenario 1

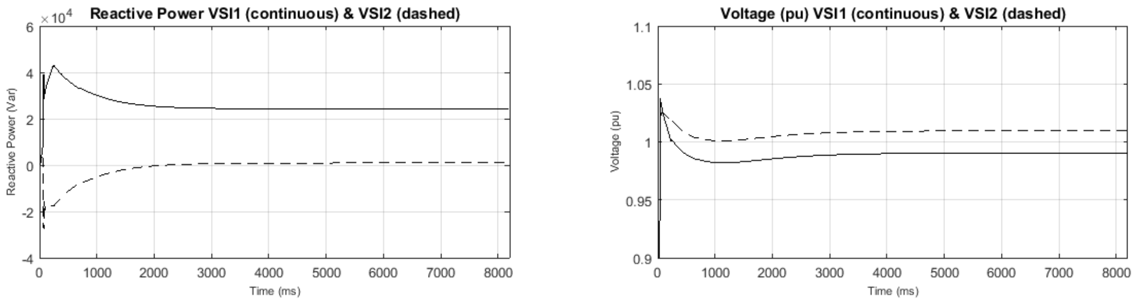

Figure 4.5: Strategy 1, Scenario 1 - VSI 1, VSI2 reactive power and voltage profiles

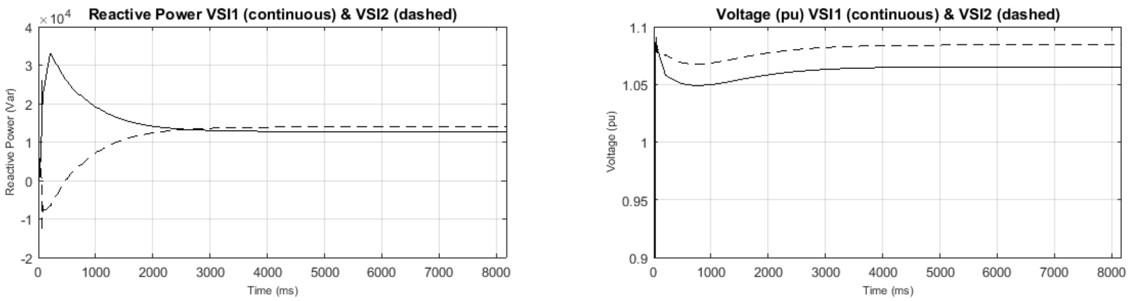

Figure 4.6: Strategy 2, Scenario 1 - VSI 1, VSI2 reactive power and voltage profiles

Considering strategy 1, when compared with the initial setup, reactive power profiles have been significantly modified since it is now VSI 1 the device injecting practically the totality of requested reactive power from both loads. So, this method, in this case, did not contribute to improve reactive power share between inverters and regarding voltages levels, they got closer to values of 1p.u.. Nevertheless it provided a solution that did not violate any technical restrains (admissible voltage and reactive power levels.

Strategy 2 shows almost ideal reactive power flow dispatch since each VSI is displaying values almost identical to the nearest load. Voltage profiles slightly increased and voltage on VSI 2 is greater than on VSI 1 because the biggest load power dispatch is load 1. Consequently, VSI 2 needs to raise its voltage in order to allow active power flow from VSI 2 to supply load 2. In this method, the idle voltage is at its maximum admissible value which can be explained as a mechanism that helps avoiding reactive power flow between inverters to happen.

In this scenario, characterized for a high imbalance between loads (L1 >> L2), strategy 2 achieves a satisfactory control management results, while strategy 1 did not show much improvements.

4.4.2 Results and analysis of the control strategies: scenario 2

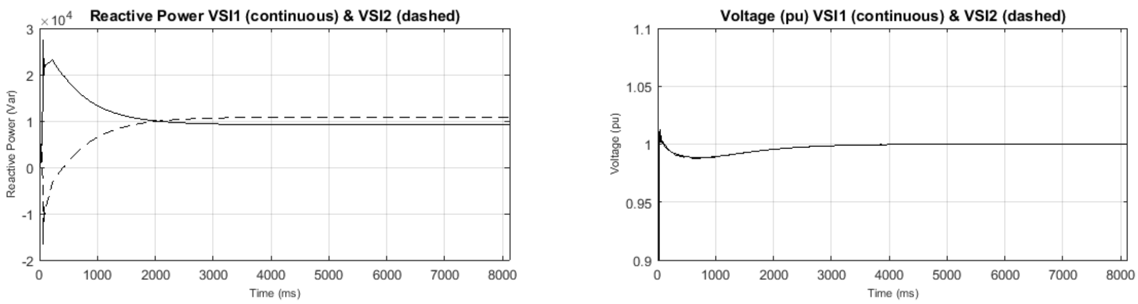

Figure 4.7: Strategy 1, Scenario 2 - VSI 1, VSI2 reactive power and voltage profiles

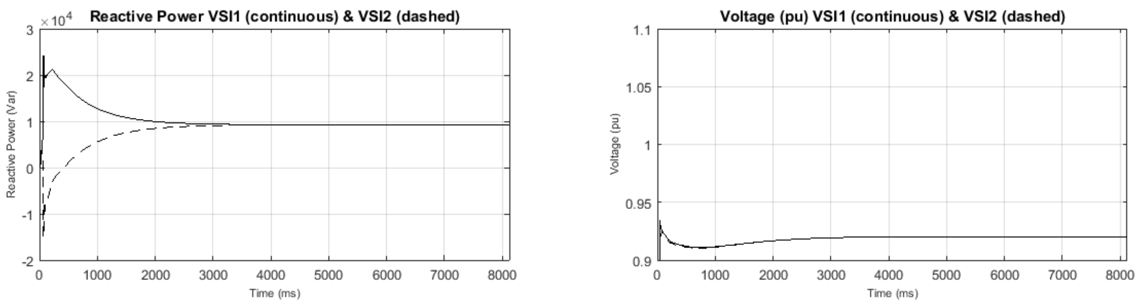

Figure 4.8: Strategy 2, Scenario 2 - VSI 1, VSI2 reactive power and voltage profiles

In scenario 2, the strategies applied show significant improvements over its initial setup and it can almost be considered an ideal situation. Regarding strategy 1, both voltages are exactly at 1p.u. and reactive power share is almost perfect. This may indicate that this control strategy could be suited for situations where the required load is similar in different places ($L1 \simeq L2$) something that despite not being common has its merits.

If the previous strategy already showed satisfactory results, the second strategy leads to a further optimized situation regarding reactive power share and voltage magnitude. First, by analyzing the objective function value obtained, which represents the active power losses is equal to zero and since the losses have a quadratic dependence on current, it is also safe to ensure that power flow is non-existent since the current is practically zero. So this configuration leads to a situation where each inverter supplies the nearest load.

4.4.3 Results and analysis of the control strategies: scenario 3

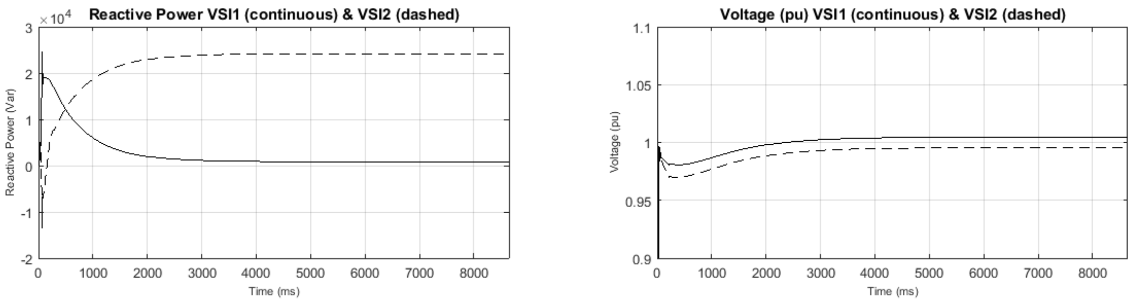

Figure 4.9: Strategy 1, Scenario 3 - VSI 1, VSI2 reactive power and voltage profiles

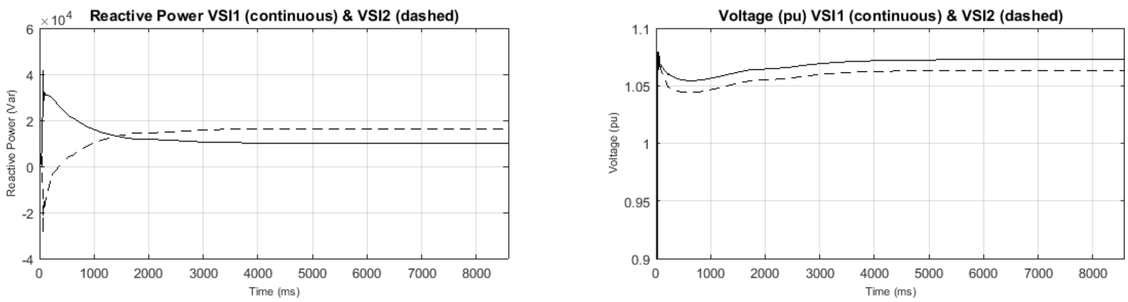

Figure 4.10: Strategy 2, Scenario 3 - VSI 1, VSI2 reactive power and voltage profiles

Finally, in scenario 3, the implementation of the control strategy 1 allowed VSI 1 to stop from absorbing reactive power since its idle voltage was slightly raised while on the other hand the idle voltage in VSI 2 was decreased, resulting in a lower reactive power imbalance. Regarding voltage levels, once again, they are much closer to 1p.u., since the objective function aims to minimize the deviation from that value.

Once again, despite a different scenario, the method proposed (strategy 2) shows very good results with moderate voltage levels and almost perfect reactive power share. Similarly to scenario 1, the solution presented is hindered by the fact that VSI 1 can not increase any further its idle voltage value in order to avoid reactive power flow between inverters. On a side note, it should be stated that in these types of situations, where maximum idle voltage value is reached, when applying the EPSO algorithm, the optimal solution is found in shorter number of iterations.

4.4.4 Evaluation of the control strategies: overview

While previous sections showed the behaviour of the MG for each scenario and comparing its "performance" regarding the two control strategies only in terms of reactive power and voltage profiles, this section intends to give more detailed view by also considering the losses for each case. As such, the obtained results are summarized in the following table:

Table 4.4: Summarized results

	Voltage (p.u.)		Reactive Power (kVar)		Idle Voltage (V)		P_{losses} (W)	
Scen	VSI 1	VSI 2	VSI 1	VSI 2	VSI 1	VSI 2		
1	1	1.02	0.9	24.3	400	400	1605	no control
	1	1.01	24.2	0.9	423	404	1499	strategy 1
	1.07	1.08	12.7	13.9	440	430	1220	strategy 2
2	1.02	1.02	-7.3	27.8	400	400	342	no control
	1	1	9.2	10.8	410	397	1	strategy 1
	0.92	0.92	9.2	9.2	379	366	0	strategy 2
3	1.04	1.03	-14.5	40.3	400	400	999	no control
	1.01	1	0.8	24.2	403	391	449	strategy 1
	1.07	1.06	10.0	16.4	440	420	307	strategy 2

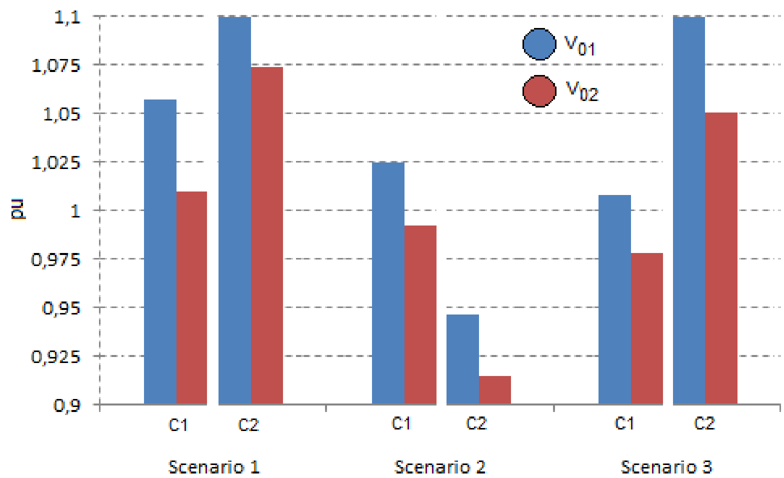

Figure 4.11: Strategy 1 vs. strategy 2: Comparison between idle voltages (V_{0_1} and V_{0_2})

Figures 4.12, 4.13 and 4.14 illustrate the impact caused on the MG active power losses which allows savings of:

For scenario 1:

- Strategy 1: 6,6%;
- Strategy 2: 24,0%.

For scenario 2:

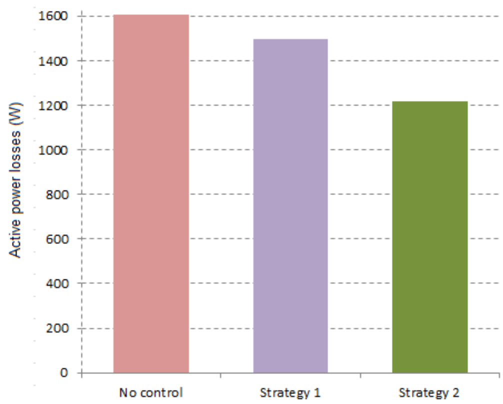

Figure 4.12: Active power losses for scenario 1

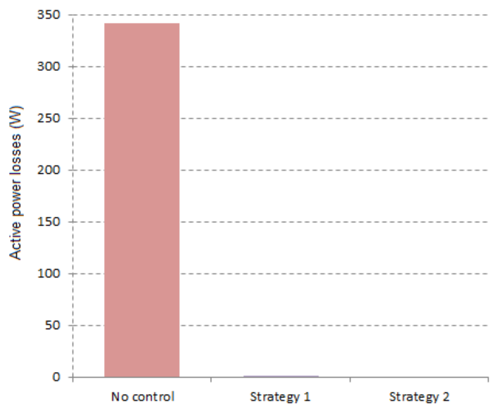

Figure 4.13: Active power losses for scenario 2

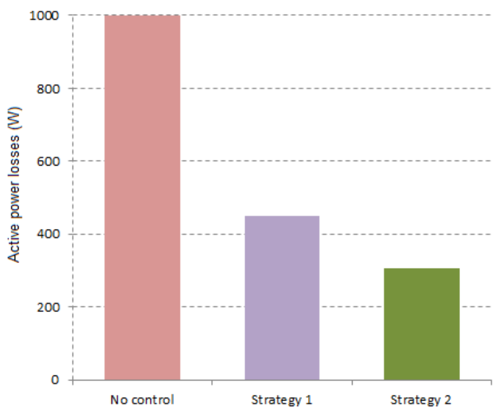

Figure 4.14: Active power losses for scenario 3

- Strategy 1: 99,8%;
- Strategy 2: 100%.

For scenario 3:

- Strategy 1: 55,1%;
- Strategy 2: 69,2%.

These savings take into comparison the initial setup. Once again these values demonstrate the necessity of implementing a secondary voltage control mechanism that allows the adjustment of the VSI idle values where strategy 2 allows enhanced reactive power sharing between inverters and also lower levels of active power losses.

4.5 Summary and conclusions

This chapter intended to present, test and evaluate two different strategies that allow an adequate voltage control and reactive power dispatch. In order to test this methods in the MG assembled, it was taken three different scenarios that tried to emulate distinctive scenarios.

Regarding the first strategy, its performance was dependant on the load conditions, providing an adequate control strategy in situations where there is a balance between loads. However, when load imbalance occurs, its performance is not reliable, since the reactive power sharing among VSI is no longer satisfactory. This control strategy ensures that the all VSI operate as near as possible from the 1p.u. voltage band.

The second strategy, which considers the minimization of active power losses, presented consistent results towards any given load scenario, contributing for an adequate reactive power sharing within the admissible limits of operation. While on the first strategy control the voltages had a tendency to be as near as possible from 1p.u., in this strategy, however, the voltage profile was much more variable but always within acceptable values.

Finally, the following tables summarize the idle voltage alteration of each VSI for each strategy, under the three load scenarios considered. It can be observed that the idle voltages have significant alterations especially when considering the loss minimization strategy. This may indicate that an operation of a MG without any control was far from ideal when considering the resultant power flows. Additionally it can be seen that in two situations VSI 1, scenario 1 and 3, where high imbalance load occurs, the inverter can no longer increase its idle voltage since it is at its maximum admissible value. Strategy 1, on the other hand, did not have such drastic alterations, because voltage profiles in the initial situation, where there was not any type of control, did not deviate very much from 1p.u. (in scenario 3 VSI 1 had the highest voltage value of 1.04p.u., corespondent to the highest voltage registered) and as a result is actuation was not as severe as when considering the second control strategy.

In general, the obtained results evidence that the different operational conditions in the MG demand for careful adjustments of the the VSI idle voltage.

Table 4.5: Control Variable values system active power losses obtained: strategy 1

	V_{0_1} **(V)**	V_{0_2} **(V)**	P_{losses} **(W)**
Scenario 1	423	404	1499
Scenario 2	410	396	1
Scenario 3	403	391	449

Table 4.6: Control Variable values system active power losses obtained: strategy 2

	V_{0_1} **(V)**	V_{0_2} **(V)**	P_{losses} **(W)**
Scenario 1	440.	429	1220
Scenario 2	379	366	0
Scenario 3	440	420	307

Chapter 5

Conclusions and future work

5.1 Conclusions

The paradigm shift that is affecting the electric power systems has been severely motivated by the massive penetration of Distributed Generation (DG) in the distribution network. A MicroGrid (MG), by having the ability to operate as an active cell of the distribution network with the ability the operate interconnected with the upstream network or in islanded mode, requires well defined modes of operation.

This dissertation focused on presenting voltage control and reactive power dispatch strategies for MG in islanded mode. Low voltage (LV) distribution systems possess cables with an high resistive nature and reactive power injection cannot control voltage magnitude profiles so, voltage control was performed by Voltage Source Inverters (VSI), recurring to reactive power/voltage droops under a Multi Master Operation (MMO) strategy.

First, in order to present strategies that could in fact control voltage, it was necessary to implement a MG in a simulation environment. The implementation took into account the features, capabilities of the inverters. When simulating and solving any given power flow, one must remember that there is no slack or voltage controlled bus in a MG so, conventional methods can not be applied as frequency is not constant and will influence the voltage magnitude and angle. Modelling a VSI also had to consider some constraints in the simulation platform and it was necessary to use a Simplified Synchronous Machine pre-built block while also guaranteeing equivalency between synchronous machine and a droop base inverter approach.

By successfully implementing a simulational MG that could replicate its behaviour in islanded mode, two different strategies were considered under three different power dispatch scenarios. One assumed the minimization of voltage magnitude deviation with respect to the nominal voltage and the other control assumed the minimization of the active power losses. The Evolutionary Particle Swarm Optimization (EPSO) algorithm was used to solve the proposed optimization problem, in order to sustain the importance and need of having secondary regulation functionalities for voltage and reactive power in a MG.

The first method was somehow unreliable because it was dependant on the load dispatch arrangement. So, in cases where imbalances in power dispatched loads were minor, each VSI idle voltage value was adjusted so that it could reach a magnitude as close as possible to 1p.u. and reactive power share was satisfactory. However, in cases where high load dispatched power imbalances occurred, the method did not obtain the same levels of performance. Nevertheless, this actuation always ensures that no technical restrains are violated.

Regarding the second proposed method, minimization of active power losses, since the losses have a quadratic correlation with current, it should be expected that the VSI manipulate its idle voltage value so that the reactive power flow is as little as possible. This was translated into satisfactory and consistent results regarding different scenarios, since reactive power was much more close to be perfectly shared among VSI. Some results went a little below the ideal operating scenario, simply because the idle voltage admissible band of values did not allow some VSI to adjust even further its point of operation.

5.2 Suggestions for future investigation work

Given the fact that the MG set of analysis performed in this dissertation assumed balanced conditions, LV distribution systems are in fact unbalanced systems, meaning that further analysis need to be made in order to validate the effectiveness of the proposed control strategies in such situations. Moreover, the unbalanced situation is worst when considering the fact that small scale MS are typically single phase units.

It would also be interesting to test the possibility of the proposed strategies being, in fact, performed at the MGCC level through algorithms implemented in the software and evaluate its performance and feasibility in real time, under constant alterations in the values of load/generation.

It is also necessary to take into consideration MG scenarios with integration of Renewable Energy Sources (RES), such as solar photovoltaic (PV), being necessary to include the control capabilities of their inverters in the proposed strategies. Furthermore, managing such a system will require a deeper approach in order to consider the energy/state of charge issues in VSI energy storage devices, thus leading to the implementation of multi-temporal approaches.

Appendix A

Applying an evolutionary algorithm to enhance voltage and reactive power dispatch control

Inspired in biology, EPSO (Evolutionary Particle Swarm Optimization) is one of the Evolutionary Computation algorithms existent and can be defined as an hybrid process. Its formulation is one of the most successful and it is a process that, when compared with other meta-heuristic models [63], displays overall better results and ability to solve problems with high optimization issues. Past studies and benchmarking demonstrate that EPSO has led, generally speaking, to better results than alternative methods [64], [65].

Applications of the EPSO algorithm have already been reported in many power systems problems where EPSO displayed faster convergence and better solutions when compared with other meta-heuristics. In [63], it successfully solved the optimization problem of voltage control and loss minimization in a conventional power system. In [66] and [67] it was also successfully validated EPSO algorithm in order to control voltage and reactive power on networks integrating microgrids in the interconnected mode.

A.1 *EPSO* in detail

EPSO present a set of solutions for each iteration, known as particles. In each iteration, each particle, X_i, moves according to the "movement rule" which will define the next position of the particle. Finally it should be noted that a particle can be interpreted as a potential solution for any given optimization problem. In this model each particle group sets vectors that define:

- **position**, represented by X_i;
- **speed**, represented by V_i;
- **best position occupied by the particle up until that exact moment**, represented by b_i;

- **cooperation**, represented by b_G.

The set of vectors identified allow the formulation of the **movement rule** which will determine the new position of each particle belonging to the solution swarm:

$$X_i^{new} = X_i + V_i^{new} \tag{A.1}$$

V_i can be defined as the speed of the particle X_i and obtained through the following equation:

$$V_i^{new} = W_{in_i}.V_i + Rnd().W_{m_i}(b_i - X_i) + Rnd().W_{e_i}(b_G - X_i).P \tag{A.2}$$

In equation A.2 the aforementioned factors can be properly identified:

- **inertia** represents the first term which tends to maintain particle's movement on the same direction presented before;
- **memory** is represented in the first term and is defined by the presence of the vector with the best fitness position that was reached up until that moment;
- **cooperation** which can be identified as the third term of the equation, stimulates the swarm's information exchange, attracting particles to the best point reached by the whole swarm.

The equation A.2 also introduces a set of W parameters that allow the occurrence of mutation processes within these strategic parameters. *in* index stand for the inertia, index *m* for memory weight and index *c* for the weight of the cooperation in a determined posterior position. *Rnd()* generates random numbers that belong to an uniform distribution included in the interval [0,1]. Finally, figure A.1 properly illustrates the movement of a given particle:

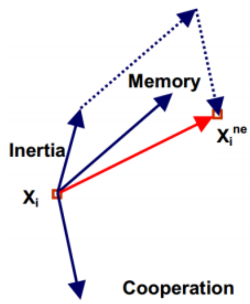

Figure A.1: Particle's movement: the influence of inertia, cooperation and memory.

A.2 Distinctive features of *EPSO*

One of the distinctive features of this method is the fact that it has auto-adaptive capabilities when solving any given problem since it can automatically adjust its parameters and behaviour, reacting to the way in which the problem process of solving is being developed. This type of auto-adaptive models require the algorithm to autonomously develop the ability to establish and modify its own behaviour according to the problem, avoiding dependencies on exterior parameters. As a result, it is possible to conceive an algorithm with not only learning ability but also with intelligent behaviour that allow an increased performance control on the algorithm itself.

A.3 EPSO's algorithm in depth

The EPSO, as initially mentioned, can be defined as an hybrid process since it merges the optimization abilities of particle swarms through information exchange during their movement, with techniques linked to the classical PSO (Particle Swarm Optimization). Moreover, it is also an auto-adaptive evolutionary algorithm that includes a mutation process. The algorithm is composed with the following stages:

1. **Replication**: Each particle X_i is replicated r times;
2. **Mutation**: Each particle X_i suffers a mutation of its parameters W;
3. **Reproduction**: Each mutated particle X_i generates a descendant according to the movement equation A.1;
4. **Evaluation**: The fitness of the new individual is calculated based on the new position taken in the dimensional space;
5. **Selection**: Through Stochastic Tournament Selection or other selection processes[1], the best particle survive and give origin to a new generation that is composed by all descendants selected from all particles of the previous generation.

With the algorithm previously described, it is possible to formulate an adequate process that helps solving the problem targeted in this dissertation. In figure A.2 it is represented a flowchart with the steps followed in order to obtain such results. The first step is to read the technical data necessary to produce a lognormal distribution. Simultaneously, it is defined the dimension of the population and maximum number of iterations to be considered. Next step consists in generating the first population with a size accordingly to what was initially set. After the creation of the population, the computation enters in a loop that will only end when the maximum number of iterations defined is obtained. The population (pop) is cloned and mutated (pop'), leading to a new population with double of its size (pop + pop'). After this process, it is applied the movement rule to every particle. All particles existent are tested in the Simulink model and then evaluated through the defined objective function. In the evaluation process, penalization are also applied in cases where restrictions are violated, such as situations where the solution produces overvoltages or any other type technical violation that turns the operation of the MicroGrid technically unfeasible. Finally, the selection process occurs and it is applied an elitist selection, meaning that only the best

[1]The simulations performed within the scope of this dissertation applied methods that selected particles that had the best fitness, known as elitist selection

individuals are selected, resulting in a population with half of its initial size, pop. The iteration ends and it is memorized the best position obtained so far by each particle and also the best position obtained by all set of particles. When the loop ends the results are saved and correspond to the best solution found that properly solves the optimization problem formulated.

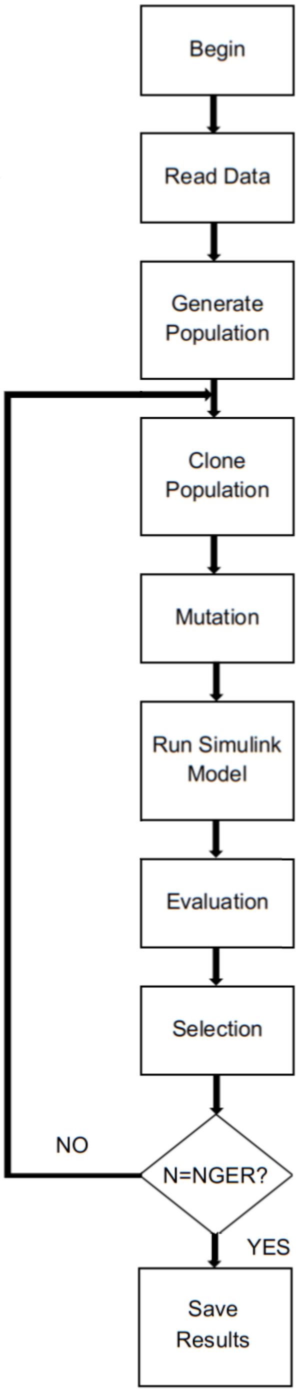

Figure A.2: Flowchart.

Appendix B

Dynamic Simulation Platform developed under the *Matlab*® */Simulink*® environment

This appendix illustrates the Microgrid (MG) dynamic simulation platform developed under the *Matlab/Simulink* environment, exploring the *SymPowerSystems* toolbox and illustrating the settings considered to implement an islanded MG. The simulation platform is built in a modular way, where the control parameters and models can be modified using the *mask* functionalities, providing user-friendly models on a graphical perspective.

B.1 Models' implementation scheme and parameters

B.1.1 Power flow settings

Powergui block is a particularly useful tool as it allows to solve the power flow of the circuit through different methods:

- Continuous, which uses a variable-step solver from Simulink;
- Ideal switching continuous;
- Discretization of the electrical system for a solution at fixed time steps;
- Phasor solution.

The method chosen was the phasor solution and the mask interface can be seen below. In this box, the only needed value to add is the phasor frequency, in this case 50Hz.

B.1.2 Simplified Synchronous Machine

The Simplified Synchronous Machine block models both the electrical and mechanical characteristics of a simple synchronous machine.

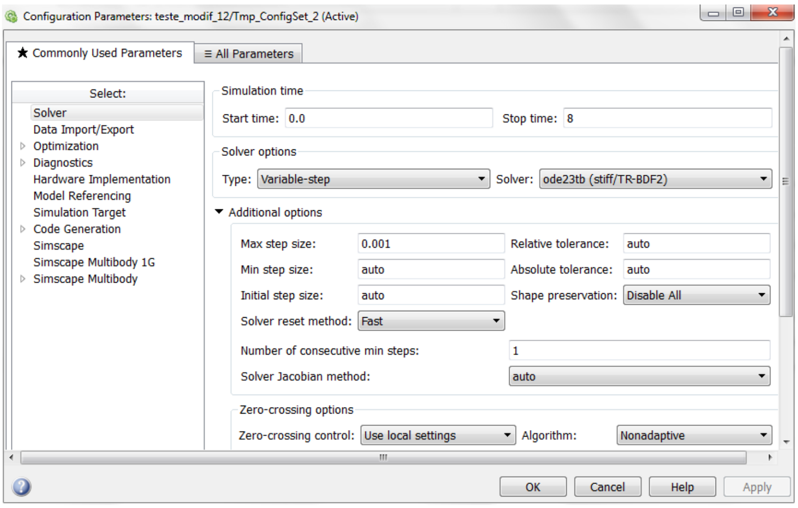

Figure B.1: Solver parameters

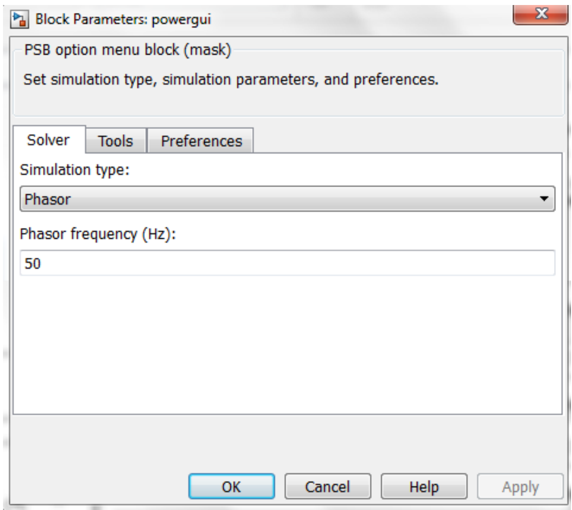

Figure B.2: Powergui parameters settings

The electrical system for each phase consists of a voltage source in series with an RL impedance, which implements the internal impedance of the machine.

- $\Delta\omega$: Speed variation with respect to speed of operation
- H: constant of inertia
- T_m: mechanical torque
- T_e: electromagnetic torque
- K_d: damping factor representing the effect of damper windings (equal to 0 given the fact it is being implemented a VSI model, inertia less)

- $\omega(t)$: mechanical speed of the rotor
- ω_0: speed of operation (1 p.u.)

Inputs and Outputs

- **Pm**: The mechanical power supplied to the machine, in watts. The input can be a constant signal or it can be connected to the output of the Hydraulic Turbine and Governor block. The frequency of the internal voltage sources depends on the mechanical speed of the machine.
- **w**: The alternative block input instead of Pm (depending on the value of the Mechanical input parameter) is the machine speed, in rad/s.
- **E**: The amplitude of the internal voltages of the block. It can be a constant signal or it can be connected to the output of a voltage regulator. If you use the SI units machine, this input must be in volts phase-to-phase RMS. If you use the pu units machine, it must be in pu.
- **m**: The Simulink output of the block is a vector containing measurement signals. You can demultiplex these signals by using the Bus Selector block provided in the Simulink library. Depending on the type of mask that you use, the units are in SI or in pu. It was considered: Rotor speed (rad/s), Electrical power Pe (W) and Internal voltage Ea (V)

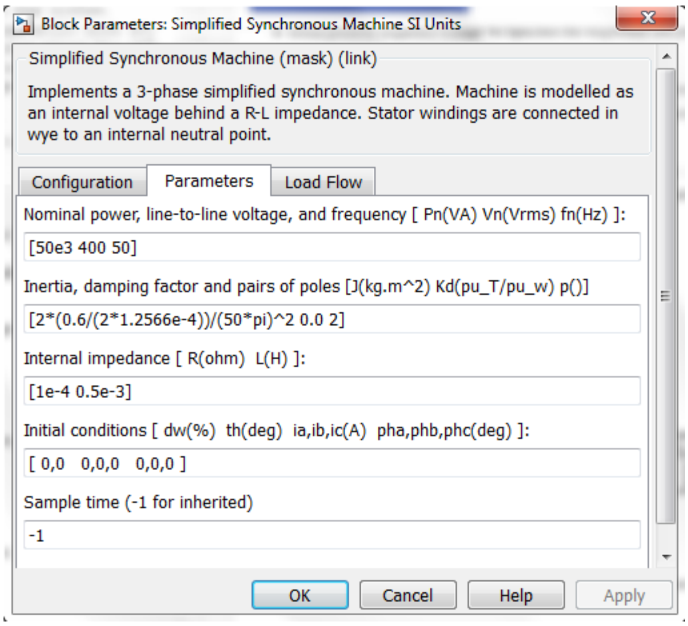

Figure B.3: SSM block parameters

B.1.3 MG full arangement under Matlab environment

Finally, the simulation platform obtained has the following structure:

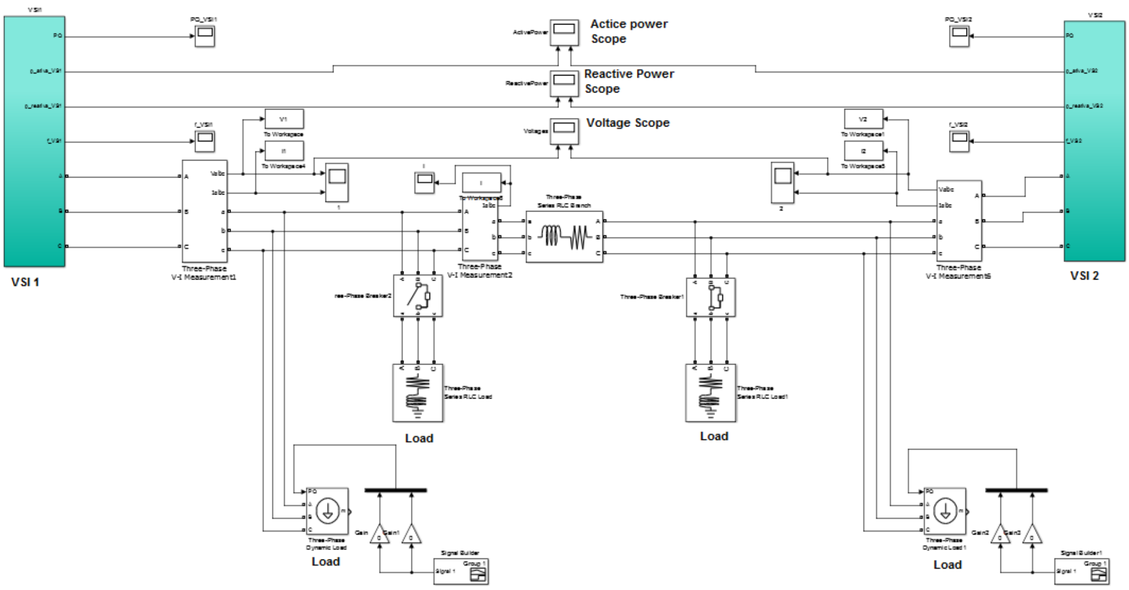

Figure B.4: Matlab/Simulink final simulation arrangement

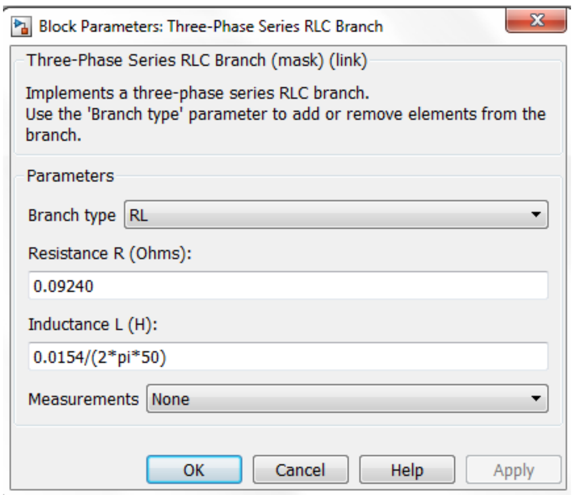

Figure B.5: LV cable parameters

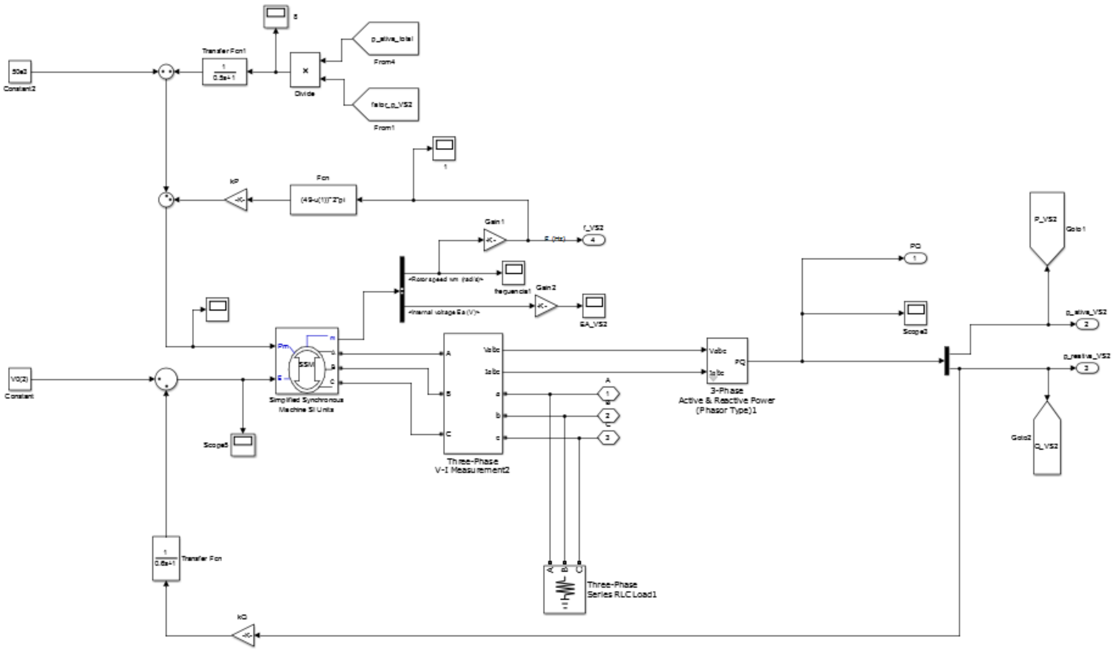

Figure B.6: VSI in blocks

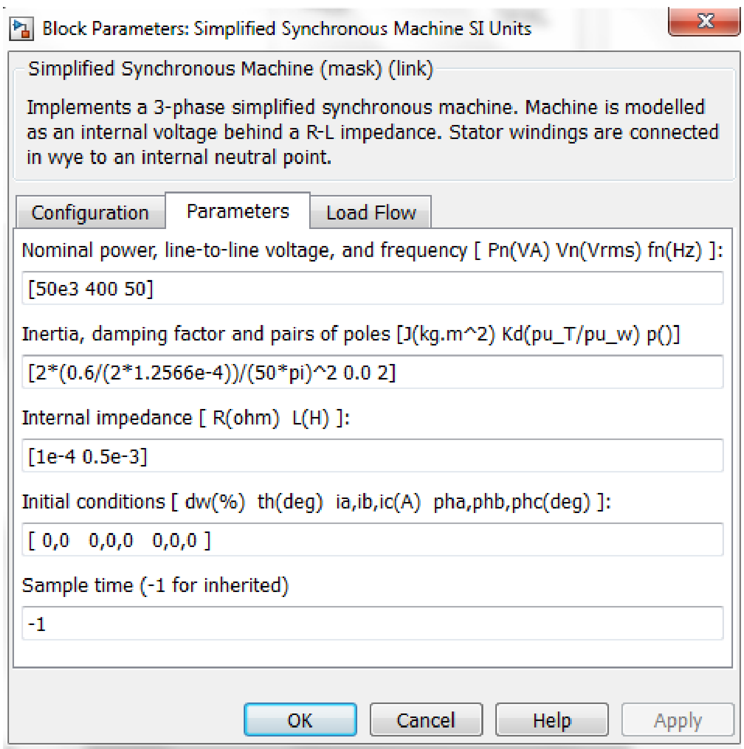

Figure B.7: SSM parameters

Appendix C

Article for submission

Voltage and Reactive Power Control in Autonomous MicroGrids

Ivan Nascimento*, C. L. Moreira†

***Abstract*—Microgrids have been receiving increasing interest due to the fact that they can operate autonomously following disturbances that may occur in the upstream network. Its operation in islanded mode is dominated by inverters that have the responsibility to control the frequency and voltage profiles within acceptable ranges. Typically set at low voltage, this type of networks present a resistive nature, which on its turn causes the active power flow to significantly influence voltage profiles.**

In this regard, this paper pretends to define and develop two strategies for the operation and management of a microgrid in standalone mode with droop controllable converters, ensuring appropriate conditions for voltage control and reactive power dispatch. The results were obtained under a tailor-made *Matlab/Simulink* platform.

***Index Terms*—Droop control, islanded operation, microgrid, reactive power dispatch, voltage control, voltage source inverter.**

I. INTRODUCTION

A Microgrid (MG) can be seen as a small scale power LV network that has Distributed Generation (DG) units, loads and storage devices connected to it while being supported by a communication infrastructure that enables appropriate management and control. A MG has the ability to operate in two modes: normal and emergency mode [1]. In normal mode both voltage and frequency are externally imposed by the stiff AC system. Conversely, in emergency mode, the previous assumption is invalid and some considerations need to be readjusted. Considering the operation of a MG with several Voltage Source Inverters (VSI) and resorting to droop characteristics, namely P/f and V/Q droops it is possible to establish a similar concept associated to conventional power system where synchronous generator provide active power/frequency and reactive power/voltage control capabilities. Nevertheless, solving the power flow for a MG cannot be done through conventional approaches, such as Newton Raphson, because in islanded mode there is no slack bus and frequency is not constant, like in a grid connected mode. Additionally, there is a direct dependence of the power on frequency due to the droop characteristics. Moreover, given the specific nature of a MG, some issues need to be tackled. The resistive nature of a LV system means that voltage profile is severely influenced by the active power flow. Additionally, voltage and reactive power control needs to take into consideration that voltage has local characteristics and network cable impedances prevent precise reactive power sharing among VSI.

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Given the difficulties of having an expedite tool capable of providing a solution for the powerflow probe in droop controlled autonomous MG, it was explored an alternative solution based on the Simplified Synchronous machine simulation model model available in the Matlab/Simulink library.

II. DROOP CONTROLLABLE VSI APPROACH

A. Modelling VSI with Simplified Synchronous Machine

Modelling a VSI had to take into consideration constraints related to the simulation platform and it was used a Simplified Synchronous Machine (SSM) pre-built block by proving the relation of the time constants on a synchronous machines and droop based inverters. For this machine (and adding a fast control mechanism), represented as a constant voltage source behind an internal reactance, the classic swing equation in the Laplace domain can be mathematically represented as follows:

$$\frac{\Delta\omega}{\Delta P} = \frac{1}{2Hs + \frac{1}{R}} \tag{1}$$

VSI transfer function $\Delta\omega/\Delta P$ can be presented in the given form:

$$\frac{\Delta\omega}{\Delta P} = \frac{k_P}{T_{dP}s + 1} = \frac{1}{\frac{T_{dP}}{k_P}s + \frac{1}{k_P}} \tag{2}$$

Equations 1 and 2 have an equivalent arrangement, allowing to define the following equivalences:

$$H \Leftrightarrow \frac{T_{dP}s}{2k_P} \tag{3}$$

$$\frac{1}{k_P} \Leftrightarrow \frac{1}{R} \tag{4}$$

P/V droop does not have any alteration relatively to VSI model because it sets the internal voltage of the SSM model.

B. Problem formulation

Having defined a methodology for the modelling approach of a MG with droop-controllable converts where the primary voltage control mechanism is assumed by the Q-V droop implemented in the VSI, its now necessary to define possible strategies for the voltage/reactive power control problem. This strategies will run at the MGCC level, thus constituting a secondary voltage control mechanism that will run periodically at the MGCC level. The control strategies applied made use of Evolutionary Particle Swarm (EPSO) algorithm [3] and can be defined as follows:

$$minOF(X, u) \tag{5}$$

Subject to:

- g(X,u) = 0
- $V_i^{min} \leq V_i \leq V_i^{max}$
- $Q_i^{min} \leq Q_i \leq Q_i^{max}$

Where:

- X is the MG state vector corresponding to the node voltages and phase angles
- *u* is the control vector, corresponding to the idle voltages V_{0i} of the Q-V droop function of each VSI
- g(X,u) stand for equality constraints, representing the power flow balance in the autonomous MG
- V_i is the voltage at each bus i (i = 1...n)
- V_i^{min}, V_i^{max} are the minimum and maximum voltages admissible at bus i
- Q_i^{min}, Q_i^{max} are the minimum and maximum reactive powers of each VSI

With respect to the objective function (OF), it is proposed two different strategies:

1. **Minimization of the voltage magnitude deviation with respect to the nominal value**:

$$OF_1(X,u) = \sum_{i=1}^{n} (V_i - 1)^2$$

2. **Minimization of the active power losses in the autonomous MG**:

$$OF_2(X,u) = P_{losses}(X,u)$$

III. Simulation Results and discussion

A. Test Network Characterization

The MG subject to test in *Matlab/Simulink* environment is composed by two VSI (VSI 1, VSI 2) connected by a cable typically seen in LV lines and two different 3-phase balanced loads (L1, L2) as illustrated in figure 1. It should be stated that there are no energy storage devices in the system since, it was assumed a steady-state period of time, where the values of load and generation were known. The LV cable applied in the MG was a $95mm^2$ aluminum cable, with a resistance of 94mΩ and a reactance of 15,4mΩ (R/X=6).

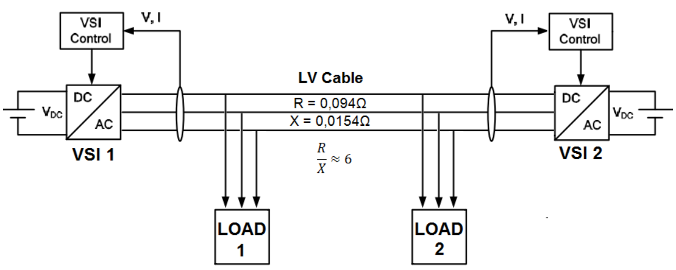

Figure 1. Microgrid for the Matlab Simulink simulation platform

The test complied 3 different scenarios as follows:

- Scenario 1: L1 = 85kW + 15kVar; L2 = 15kW + 10kVar;
- Scenario 2: L1 = 25kW + 10kVar; L2 = 25kW + 10kVar;
- Scenario 3: L1 = 25kW + 10kVar; L2 = 60kW + 15kVar

The synthesis of the obtained results is presented:

Table I

Summarized results: voltage, reactive power and active power losses)

	Voltage (p.u.)		Reactive Power (kVar)		Plosses (W)	
Scen	VSI 1	VSI 2	VSI 1	VSI 2		
1	1	1.02	0.9	24.3	1605	no control
	1	1.01	24.2	0.9	1499	strategy 1
	1.07	1.08	12.7	13.9	1220	strategy 2
2	1.02	1.02	-7.3	27.8	342	no control
	1	1	9.2	10.8	1	strategy 1
	0.92	0.92	9.2	9.2	0	strategy 2
3	1.04	1.03	-14.5	40.3	999	no control
	1.01	1	0.8	24.2	449	strategy 1
	1.07	1.06	10.0	16.4	307	strategy 2

IV. Conclusions

The results prove the importance of considering a strategy for applying secondary voltage control mechanisms, allowing the inverters to adjust its set-points according to the conditions of the MG, improving its efficiency.

The first method proved to be unreliable given its dependency on load dispatch arrangement. In cases where imbalances in power dispatched loads were minor, each VSI idle voltage value was adjusted so that it could reach a magnitude as close as possible to 1p.u. and reactive power share was satisfactory. However, in cases where high load dispatched power imbalances occurred, the method did not obtain the same levels of performance. Nevertheless, this actuation always ensures that no technical restrains are violated.

Regarding the second proposed method, minimization of active power losses the results were satisfactory and consistent regarding different scenarios, since reactive power was much more close to be perfectly shared among VSI, while minimizing system losses.

These strategies will run at the MGCC level, constituting a secondary voltage control mechanism.

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