ABSTRACT

This Thesis presents the development of the MicroGrid concept, together with the identification of the required functionalities in order to operate this new type of power system. The MicroGrid concept consists on a low voltage distribution network with distributed energy sources (the microsources), together with storage devices and controllable loads, operating in a controlled coordinated way through the use of advanced management and control systems supported by a communication infrastructure.

The MicroGrid distinguishing characteristic is the ability to be operated as a coordinated entity, both in interconnected or islanded mode. In order to deal with MicroGrid islanded operation, an emergency operation mode must be envisaged. Therefore, this Thesis presents the possible control strategies to be adopted in order to operate a MicroGrid under islanding conditions. The proposed MicroGrid control strategies consider different inverter control modes together with voltage and frequency emergency control functionalities in order to achieve robustness of operation and to not jeopardize power quality during islanded operation. The development of the emergency control functionalities takes into account MicroGrid specific characteristics, namely in terms of the response of each type of microsource.

Concepts for exploiting MicroGrid generation capabilities in order to provide fast black start functionalities at the low voltage level were also developed and tested in this research. Such an approach will enable fast restoration times to final consumers, which contributes to reliability improvement at the distribution level and to reduce customer interruption times. The development of the MicroGrid restoration procedure required the identification of a sequence of actions and conditions to be checked during the restoration stage. Voltage and frequency control approaches, and the need of storage devices are specific issues that were considered in order to ensure system stability and achieve robustness of operation during service restoration in the low voltage area.

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List of Abbreviations

AFC	Alkaline Fuel Cell
AI	Artificial Intelligence
ANN	Artificial Neural Network
BoP	Balance of Plant
BS	Black Start
BTU	British Thermal Unit
CHP	Combined Heat and Power
CERTS	Consortium for Electric Reliability and Technology Solutions
CPM	Critical Path Method
DSM	Demand Side Management
DMFC	Direct Methanol Fuel Cell
DER	Distributed Energy Resources
DG	Distributed Generation
DMS	Distribution Management System
DNO	Distribution Network Operator
emf	electromotive force
EMS	Energy Management System
EU	European Commission
FP	Framework Program
GAST	GAS Turbine
GHG	Greenhouse Gases
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
CIRED	International Conference on Electricity Distribution
LC	Load Controller
LV	Low Voltage
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracker
MSE	Mean Squared Error

MV	Medium Voltage
MG	MicroGrid
MGCC	MicroGrid Central Controller
MS	MicroSource
MC	Microsource Controller
MCFC	Molten Carbonate Fuel Cell
MMO	Multi Master Operation
OLTC	On Load Tap Changer
OECD	Organisation for Economic Cooperation and Development
PMSG	Permanent Magnet Synchronous Generator
PAFC	Phosphoric Acid Fuel Cell
PV	Photovoltaic
PCC	Point of Common Coupling
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PLC	Power Line Communication
PERT	Program Evaluation and Review Technique
PI	Proportional Integral
PWM	Pulse With Modulation
RE	Relative Mean Squared Error
RES	Renewable Energy Sources
RMSE	Root Mean Squared Error
SRC	Silicon Controlled Rectifier
SMO	Single Master Operation
SOFC	Solid Oxide Fuel Cell
SCADA	Supervisory Control And Data Acquisition
V2G	Vehicle To Grid
VSI	Voltage Source Inverter

Chapter 1

INTRODUCTION

1.1 BACKGROUND AND MOTIVATIONS OF THE THESIS

The actual Electrical Power Systems generation portfolio was developed over more than five decades according to economy of scale concepts. It is based on large scale central generation (hydro power plants, fossil fuelled power plants and/or nuclear power plants), being the energy transmitted over long distances up to the final consumers. Consequently, the electrical energy chain in each country is largely dependent on imported fossil and/or nuclear fuels. According to the United States Government official energy statistics, a scenario where the current energy policies remain unchanged in the coming years will lead to the increase by 50% of the world marketed energy consumption in the period 2005–2030. Total world energy use will rise from 462 quadrillion British Thermal Units (BTU) in 2005 to 563 quadrillion BTU in 2015 and to 695 quadrillion BTU in 2030. For the same reference scenario, the world net electricity generation nearly doubles from about 17.3 trillion kWh in 2005 to 24.4 trillion kWh in 2015 and 33.3 trillion kWh in 2030. It is also expected that the total electricity generation in countries not belonging to the Organisation for Economic Cooperation and Development (OECD) will increase by an average of 4% per year from 2005 to 2030, as compared with a projected average increase of 1.3% per year for OECD countries [1]. Concerning the European Union (EU), as energy demand continues to grow, the EU dependence on imported fuels could increase from 50% to 70% in the next 25 years, or even less [2].

The increasing nations dependence on imported fossil fuels, the international political instability that have been affecting the primary energy resources prices and the security of supply, together with environmental concerns and climate change issues are compromising the current energy paradigm. In fact, energy is the basis of the economic development and these shortcomings can significantly affect the economic growth and the well being of millions of citizens worldwide. Therefore, issues related with security of supply of fossil and nuclear fuels, sustainable economic development and climate changes are the main drivers for the definition of ambitious energy policies. In particular, by focusing on these issues, the EU defined a set of very ambitious targets [3]:

- Reducing Greenhouse Gases (GHG) emissions at least 20% by 2020;
- Improve energy efficiency by 20% by 2020;
- Raising the share of renewable energy to 20% by 2020.

The development of Distributed Generation (DG) and renewable electricity generation technologies are essential means in order to achieve the proposed goals. DG and Renewable Energy Sources (RES) cover a wide range of technologies (wind generators, photovoltaic panels, fuel cells and microturbines – just to mention a few examples) that are suitable for supplying power at customers sites. However, in order to achieve such ambitious goals, the electric networks must be prepared for the large scale deployment and integration of these emerging technologies. Large scale DG deployment will transform the energy generation portfolio from a system dominated by the centralized generation to a new one in which environmentally friendly technologies will be largely adopted. This new scenario corresponds to a significant change of paradigm in the electric sector, where the electric generation portfolio will no longer be predominantly centralized. Under this emerging paradigm, the proper exploitation of DG sources can offer additional advantages to system operators since it can contribute for [4]:

- Deferral of investments on transmission and distribution systems;
- Reduction of losses in the distribution system;
- Provision of network support services or ancillary services.

In the last years, Electric Power Systems has been facing the connection of large amounts of DG sources to Medium Voltage (MV) distribution networks. Recent technological developments allowed the consolidation of DG solutions with very specific characteristics that make them suitable to be connected to the Low Voltage (LV) distribution grids. These DG units are small modular generation devices, also denominated as MicroSources (MS), with electrical power ratings of less than 100 kWe, most of them with power electronic interfaces, and making use either of RES or fossil fuel in high efficiency local Combined Heat and Power (CHP) applications. The types of MS suitable to be used are: microturbines, fuel cells, photovoltaic panels small and micro wind generators, together with storage devices such as batteries, flywheels or supercapacitors.

Considering a scenario characterized by a massive integration of DG in distribution networks, several technical issues need to be tackled, namely in what concerns the control of voltage profiles, the evaluation of congestion levels in steady state conditions, the evaluation of short-circuit currents and the network protection schemes, the assessment of network stability issues and the possibility of islanding operation [4]. In order to face these challenges and to realize the potential benefits of a massive DG deployment, it is imperative to develop a coordinated strategy for the operation and control of DG sources, electrical loads and storage devices. A possible approach in order to face the challenge imposed by the paradigm shift may consist on the development of the MicroGrid (MG) concept. In this sense, a MG comprise a LV distributed system with small modular generation technologies (the MS), storage devices and controllable loads, being operated connected to the main power network or islanded, in a controlled coordinated way.

Regarding the 5th and 6th EU Framework Programs (FP), active research was envisaged in what concerns the definition of new system architectures for the future European electricity networks based on a large share of Distributed Energy Sources (DER), while maintaining or even increasing the actual reliability and power quality levels of present networks. The research projects successfully developed under the Target Action "*Integration of Renewable Energies and Distributed Generation in European Electricity Networks*" in the 5th FP can be considered as the start point for the development of the first generation of new architectures for electricity grids [5]. The MICROGRIDS project, *MicroGrids: Large scale integration of MicroGeneration to Low Voltage Grids*, Contract no. ENK5-CT-2002-00610, is one of them and was the first attempt at EU level to deal in-depth with MG [6].

The MG concept is a natural evolution of simple distribution networks with high amounts of MS. The current industry restructuring that is in progress worldwide requires the functional separation of the past vertically integrated utilities into its generation, transmission and distribution functions, in order to ensure open competitive access to the transmission system by the competing generators. MG represents the next step because it leads to a further decentralization of decision making, by bringing the customer explicitly into the electricity market. This stage involves not only institutional restructuring of the electricity supply industry, but also physical changes in the scale, location and ownership of the electricity production. Therefore, the formation of active LV networks through the exploitation of the MG concept can potentially provide a large number of benefits to the Distribution Network Operator (DNO) and to the end-user, namely [6]:

- The operation of MG is based on DG and RES that are characterised by very low emissions, which, in combination with the reduction of distribution network losses, will contribute to a drastic reduction in GHG emissions.

- Microturbines and fuel cell systems in a MG will be used in high efficiency CHP applications. Exploiting renewable energy sources and CHP applications will contribute for reducing the dependence on imported fossil fuel and hence increase energy security.

- MG make possible the widespread application of CHP, thus significantly raising the energy efficiency to levels far beyond what is possible with central power stations. MG will allow the customer to act as both a buyer and seller of heat energy and electrical energy. This flexibility potentially allows the development of a more efficient generation system that has the ability to be responsive to customer needs.

- At the consumer level, separating the MG from the distribution network in case of external disturbances and allowing its operation in islanded mode can dramatically increase reliability levels.

The successful design and operation of a MG requires the solution of a number of demanding technical and non-technical issues, in particular related to their operation, control and safety issues. Therefore, the MICROGRIDS project aimed to address these issues, trough the development of the follwing topics [6]:

- Study of MG design and operation, so that increased penetration of renewable energies and other MS can be achieved;

- Development and demonstration of control strategies that will ensure the operation and management of MG is able to meet the customer requirements and technical constraints (regarding voltage and frequency) and to deliver power in the most efficient, reliable and economic way;

- Determination of the economic benefits of MG operation and proposal of systematic methods and tools in order to quantify these benefits in order to identify appropriate regulatory policies;

- Definition of appropriate protection (relaying) and earthing (grounding) schemes that will assure safety of operation and capability of fault detection, isolation and islanding operation;

- Identification of MG requirements in terms of telecommunication infrastructures and communication protocols;

- Simulation and demonstration of MG operation concepts on laboratory models;

- Projection of MG development on actual distribution feeders.

Contrary to the conventional “fit and forget” policy to connect DG units do distribution systems, MG envisage active DG integration policies aiming the exploitation of DG potential benefits in a controlled and coordinated way. Therefore, low voltage MG offers the possibility of fully profiting form active management strategies applied in systems with large scale integration of DG units. Following the adoption of active management strategies in distribution networks, the EU focused the energy theme in the 7th FP on “*Smart Energy Networks*” as the natural evolution of both past and current research and technological development activities on DER integration [7]. Thus, the objective of this area is to increase the efficiency and reliability of the European electricity networks by transforming them into an interactive (customers/operators) service network, and to remove the technical barriers to the large scale deployment and effective integration of DER.

1.2 OBJECTIVES OF THE THESIS

The successful design and operation of a MG, especially when the possibility of exploiting islanding operation is envisaged, requires the identification and development of specific control functionalities. The presence of power electronic interfaces in fuel cells, photovoltaic panels, microturbines or storage devices characterize a new type of power system when compared with conventional systems using synchronous generators. The dynamic behaviour of a system with very low global inertia, comprising some MS with slow responses to control signals, is also quite different from traditional power systems. Aiming to demonstrate the feasibility of the MG concept, namely in terms of islanding operation, the main objectives of this dissertation were defined as:

- **Development and selection of adequate models for simulating the operation of different types of MS and storage devices**, including the corresponding power electronic interfaces. The understanding of the dynamic behavior or MS and storage devices is crucial to identify the right decentralized control strategies to be installed in the system in order to assure a seamless transition to islanding operation.

- **Development of MG emergency control functionalities for islanding operation:** during MG islanding operation, load-tracking problems arise since some micro generators have slow response to control signals and are inertia-less. A system with clusters of MS designed to operate in an island mode requires some form of storage to ensure initial energy balance. The control strategy to be developed has to combine the fast response of storage devices, load shedding mechanisms and secondary frequency control functionalities to be installed in controllable MS.

- **Development of Black Start functionalities:** If a system disturbance provokes a general blackout such that the MG was not able to separate and continue in islanding mode, and if the MV system is unable to restore operation in a specified time, a first step in system recovery will be a local Black Start. The strategy to be followed will involve the MG operation structure in order to exploit the local generation capabilities and ensure a fast system restart.

- **Development of a MG robustness evaluation tool:** the ability of the local generation resources to provide the dynamic response in order to keep the islanded

> MG in synchronism depends on the MG load and generation profile prior to islanding. In these conditions, it might be necessary to make use of intelligent load or generation curtailment functionalities in order to ensure MG survival in the moments subsequent to islanding.

For the connection of DG to the grid a “fit and forget” policy has mainly been followed by distribution companies during the last years. However, a true DG integration policy is needed, through which a system perspective is used to capture the potential benefits that may arise to customers and to utilities form the increasing DG penetration levels. Therefore, the MG concept is explored within this dissertation as an advanced approach aiming to exploit the benefits DG units may provide to distribution systems. Within this dissertation, the MG is regarded as a set of distributed resources (MS and controllable loads) that can be operated connected to or separate from the main electricity grid. One of the key functionalities of the MG is related with the possibility to allow a seamless separation from a normal utility interconnected state to islanding operation, serving a set of critical loads until utility service is restored. Following system disturbances, DG and electrical loads can automatically separate from the main power system, therefore isolating the MG from the disturbance affecting the system.

1.3 OUTLINE OF THE THESIS

The research work developed within the scope of this dissertation is organized in 7 Chapters and 2 Appendixes.

The first chapter provides a contextualization of the problem under investigation and presents the main objectives this dissertation aims to achieve.

In Chapter 2 is introduced the DG concept, together with the main drivers that are contributing to a massive DG adoption. Concerning the types of MS to be installed a MG, this chapter provides also a brief characterization of different MS technologies. The technical challenges arising in electrical power systems due to DG adoption are also briefly addressed.

Chapter 3 presents the MG concept and its control architecture. The detailed dynamic models of the different MS technologies together with the dynamic models of power electronic interfaces are also presented and discussed. This chapter is the basis for the development of a simulation platform that will support the identification of the control strategies to be adopted in order to allow a seamless transition to islanding operation.

In Chapter 4 are presented and discussed the specific operation and control problems in the moments subsequent to MG islanding. Taking into account MG specificities, the control strategies that are able to run the MG under islanded conditions are identified and discussed. The control strategies to be adopted for MG black start and subsequent islanded operation as well as the identification of the set of rules and conditions to be checked during the restoration stage are also presented.

Chapter 5 presents a detailed evaluation of the performance of the proposed control strategies through extensive numerical simulations in different MG operating conditions.

Chapter 6 concerns the development of a MG robustness evaluation tool in order to ensure MG survival in the moments subsequent to islanding.

In Chapter 7 are presented the main contribution of this dissertation, as well as general conclusions and perspectives of future works.

In Appendix A are presented the electrical data of the test system used in this dissertation and the parameters of the dynamic models of the different microgeneration technologies. In Appendix B is presented a brief description of the MG dynamic simulation platform, which was developed under the *MatLab®/Simulink®* environment.

Chapter 2

THE DISTRIBUTED GENERATION PARADIGM

2.1 INTRODUCTION

In the last decades, the development, design and operation of electrical power systems followed a hierarchical arrangement. Within this paradigm, the energy always flows from an upper to a lower level, as it is illustrated in Figure 2-1. Electrical energy is produced in large central generation units feeding an interconnected transmission system, which transports the energy to substations near the consumption centres. The energy is then extracted from the transmission network and passed down through distribution transformers. High voltage lines distribute the electrical energy to the consumption centres, where the high voltage substations are located. In the high voltage substations, the voltage is stepped down to Medium Voltage (MV) levels and electrical energy is distributed to urban and rural areas via MV lines. Finally, in the distribution substations, electrical energy is stepped down to Low Voltage (LV) levels and it is distributed to small customers.

The conventional power system paradigm briefly described above present several advantages, such as [8]:

- **Efficiency of large power plants:** the electrical efficiency of the conversion process is always pending for the side of large central generation units. However, many of the existing large scale generation units are older than 20 years and have efficiencies ranging from 28% to 35%. By contrast, recent small scale generation units present efficiencies in the range of 40% to 55%. Nevertheless, this comparison is not reasonable because the technological level in both cases is significantly different. If a comparison is made between large and small scale generation plants with similar technological levels, size will be favouring the larger generator [9].

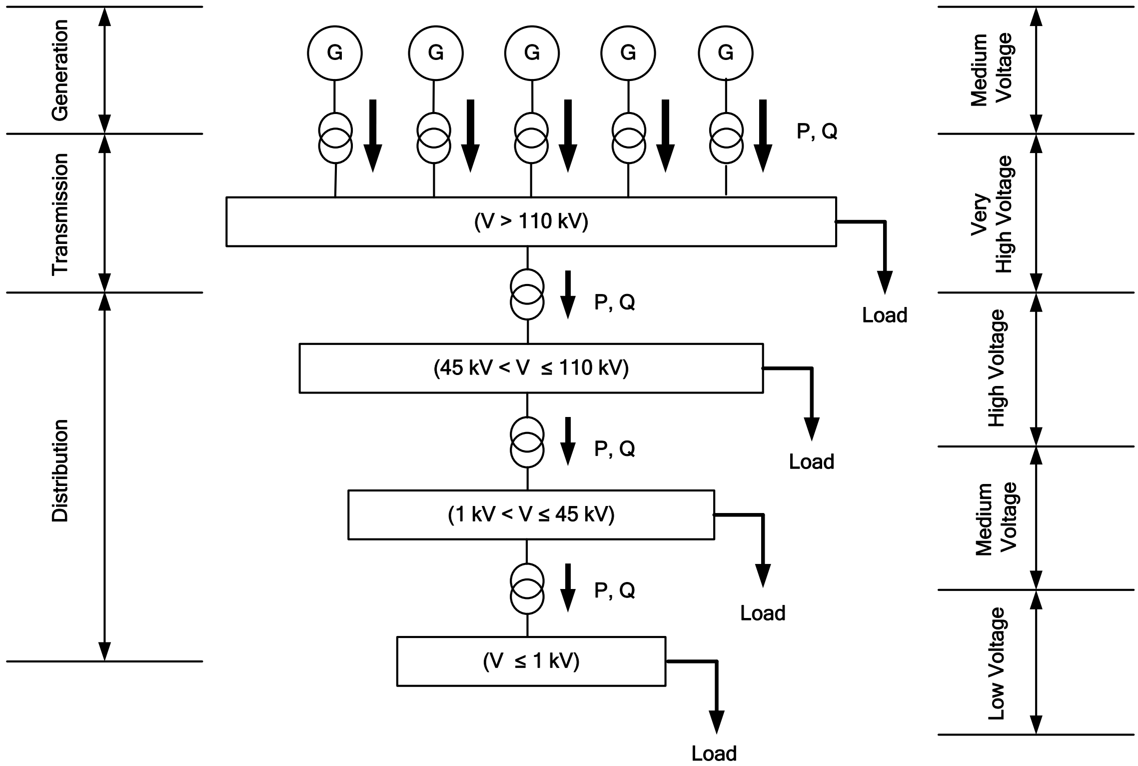


Figure 2-1: Organization of the conventional power systems

- **Operation and management:** the interconnected transmission system allows the transport of bulk power over large distances with reduced losses. Additionally, the trend on the interconnection practices of bulk transmission systems reduces the reserve requirements and guarantees the cheaper generating unit to be dispatched at any time. Also, large generation units and bulk power system interconnection contribute to enhance the overall system stability.

- **Simplicity of operation at the distribution level:** the unidirectional power flows from the high voltage substations up to the medium and low voltage substations simplifies the design and operation of distribution networks.

Nevertheless, the conventional power system paradigm presents also some disadvantages, being possible to point out the following ones [8]:

- **Distance between production and consumptions centres:** in the conventional power system paradigm, large distances usually separate the production and consumption centres, thus requiring the construction of large and expensive transmission networks. In addition, the growing distance for transporting energy increases bulk transmission network losses.

- **Environmental impacts:** conventional generation units usually create significant environmental impacts due to the massive use of coal and nuclear or fossil fuels. However, these generation technologies have been progressively replaced by other ones with less aggressive environmental profiles, such as the combined cycle gas turbines.

- **System reliability:** in a hierarchical system, the existence of regulatory or economic problems of structural nature might create difficulties for the development of investments in new generation plants or in the transmission network. The resulting impact has strong effects on the entire system: any problem disturbing a higher hierarchical level can affect a large number of elements in the lower hierarchical levels.

Since the beginning of the 1990's, the conventional power system paradigm is facing several challenges. An interesting challenge results from a substantial growth on the interest of connecting generation plants to the distribution network, usually denominated as Distributed Generation (DG) units (a brief discussion on this topic is provided in Section 2.2). DG is calling the attention of electrical power system operators and planers, potential developers and policy makers. A key contribution for the recent interest on DG applications is the emphasis Governments have been putting on DG promotion in order to achieve ambitious programs for the reduction of CO_2 emissions and the need of diversifying the energy sources mix.

The current electric industry restructuring that is in progress worldwide leads to the functional separation of the past vertically integrated utilities into its generation, transmission and distribution activities, favouring the open access to the networks and contributing to the creation of competitive market niches, where customers look for the best suited electricity service. The current evolution towards a liberalized market, together with potential benefits

DG may have in distribution systems lead Governments to actively promote DG adoption, as it is discussed in Section 2.3.

The recent technological developments have been also contributing for the development of well suited applications in the DG field such as microturbines and fuel cells, which are solutions with high potential to be adopted by end-users for on-site power generation. A brief technological characterization of emergent small scale DG technologies is also presented in Section 2.4.

From the technical point of view, the increasing DG penetration levels in electrical distribution systems has strong implications, such as: modifications in the voltage profile, increases in the short-circuit power, possibility of augmented harmonic distortion levels, stability of operation, security of the maintenance personnel and possibility of islanding operation. These types of problems are a result of power injection at the distribution networks levels and are addressed in Section 2.5. When the DG installed capacity is quite small, the resulting impact in distribution networks do not deserve much attention from distribution companies. However, the DG growth in the last years leads distribution companies to be more aware about the new situation and they are starting the study of the resulting phenomena.

2.2 THE DISTRIBUTED GENERATION CONCEPT

Although Distributed Generation (also know as Embedded Generation or Dispersed Generation) has been an increasing phenomenon in the electrical power systems industry, there is yet no agreed universal and formal definition for the concept. A CIRED questionnaire dated from 1999 [10] illustrates precisely the inexistence of a general consensus concerning the DG definition. According to that questionnaire, some countries define DG on the basis of voltage level, whereas others establishes that DG comprises the generation sources connected to electrical circuits from which consumer loads are directly supplied. Other countries define DG based on some particular characteristics, such as electricity production from renewable energy sources, co-generation or being not dispatched or centrally planned. A literature survey illustrates the different DG definitions:

- Dondi *et al.* [11] define DG as a small scale power generation facility or storage device with power ratings typically ranging from less then a kW to tens of MW, closely located to the electrical loads and being not a part of central generation. The authors also explicitly present the classes of generating devices that makes part of their DG concept: biomass based generators, combustion turbines, concentrating solar power and photovoltaic systems, fuel cells, wind turbines, microturbines, engine/generator sets, small hydro plants and storage technologies. It is also assume by the authors that the generators can be interconnected with the electrical grid or operated autonomously of the grid.

- Ackerman *et al.* [12] propose a DG definition based on several topics that, in the authors perspective, should be considered in order to establish a more precise explanation of the DG concept. The proposed topics the authors identify for the DG definition are: purpose of DG, location, rating, power delivery area, technology, environmental impact, operation mode, ownership and the DG penetration level. However, these authors state that only the first two aspects are of utmost importance for the DG definition. In this sense, the authors present the DG purpose as the provision of active power, without the need of supplying reactive power. Concerning DG location, the authors consider DG as the electrical power generation units directly connected to the distribution network or connected to the network on the customer site of the meter, being the definition of "distribution network" to be issued by the competent entities of each country. The DG rating is not considered as a relevant parameter for DG definition, since the maximum rating of the DG units that can be connected to the distribution system depends on the characteristics of the electrical power system. Nevertheless, a simple classification based on the DG rating (S_n) is proposed:

    - Micro DG: 1 W < S_n < 5 kW;
    - Small DG: 5 kW ≤ S_n < 5 MW;
    - Medium DG: 5 MW ≤ S_n < 50 MW;
    - Large DG: 50 MW ≤ S_n < 300 MW.

- Willis & Scott [9] define DG as small generators typically ranging from 15 kW to 10 MW, that are spread throughout the electrical power system. Following Dondi *et* *al*. definition [11], these authors consider that the generators can be connected to the electrical power system (located in the utility system or at the facilities of an utility customer) or operated isolated from the power grid. In addition, the authors use the *Dispersed Generation* concept when referring to very small electrical generators to be used on residential applications or small business, with power ratings ranging from 10 kW to 250 kW.

- Jenkins *et al.* [4] propose a DG definition which does not focus the size of the electrical generators, the voltage level of the connection point or the DG technology. Instead, the authors define some general characteristics that should be fulfilled in order to classify a power source as a DG unit. Those characteristics are:
    - Not centrally planned by the utility;
    - Not centrally dispatched;
    - Usually smaller than 50 – 100 MW;
    - Usually connected to the distribution system.
- The International Energy Agency [13] defines DG as a generating power plant that serves on-site customers or provides support to a distribution network, connected to the electrical grid at the distribution level. Additionally, the definition specifies the types of DG units, as in [11].

From the literature survey on the DG definition, the larger divergences found among the definitions is related to the size of the DG units. Nevertheless, the wide range of definitions allows a broad range of possible generation schemes. Some definitions even allow the inclusion of large scale wind farms connected to the transmission network to be considered as DG; conversely, other definitions are focused on small-scale generation units connected to the distribution network. Electric power generation at customer facilities is usually considered as distributed generation, which is a broader criterion of the definition, allowing large scale generators owned by consumers connected to the transmission network to be considered as DG.

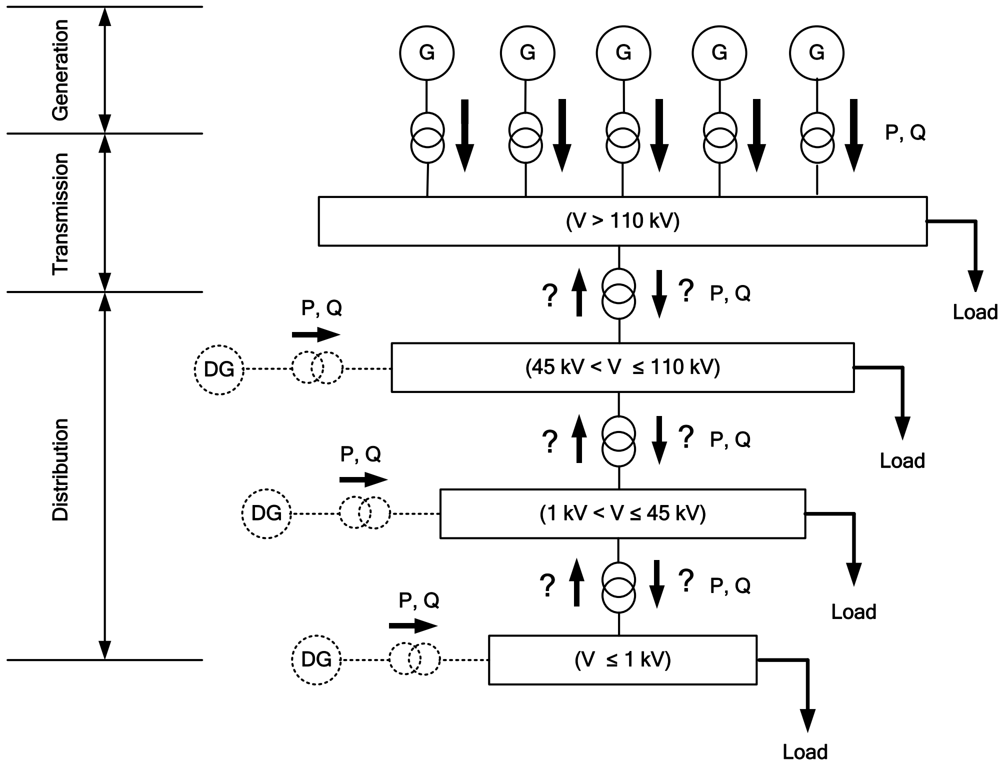


Figure 2-2: DG integration into electrical power systems

According to the definitions presented above, the conventional electrical power system scheme previously shown in Figure 2-1 is now being modified in order to consider the integration of DG units, and it is presented in Figure 2-2**.** The main impact in the conventional electric power paradigm is the emergence of generation units in places that were not planned to accepted power injections. Indeed, distribution networks were not initially designed to host generation. In particular, they were usually operated with energy flowing in only one direction, namely from the substation to the customers, which may no longer be true with the advent of DG units.

Within this dissertation, the DG concept refers to the electricity generation activity in lower voltages levels of the electric power systems, more specifically, at the LV distribution grids. This definition is quite broad in terms of technologies that can be connected to the grid; nevertheless, the size of the DG units are generally below a few tens of kW due to the technical limitations of LV grids to accommodate high power injections. In accordance with the small size of DG units to be connected to LV grids, they are usually designated as MicroSources (MS) or microgenerators, whose general characteristics will be described in Section 2.4.

2.2.1 THE CHANGE OF PARADIGM IN THE ELECTRICAL POWER SYSTEMS

In the previous section it was briefly addressed the integration of DG sources into electrical power systems. Nevertheless, in the recent times the trend is not to consider DG alone, but in a wider context, which includes the use of energy storage devices and responsive and/or controllable loads [14]. This new concept is usually referred as Distributed Energy Resources (DER). DER will inevitably change future electricity companies portfolio. Additionally, future electrical networks are required to provide reliable, flexible and cost-effective power supply, fully exploiting the use of both large centralised generators and DER. The continuous trend followed in the last years, where DG is connected to the grid in a purely passive way, that is, without offering other services to the electricity network than uncontrolled energy generation, creates serious problems and considerably limits the amounts of DG that can be connected to the system. The existing connection practice for DG units is largely based on a “fit and forget” policy, treating them as passive elements of the electricity supply chain. However, the electrical distribution network of the future will involve more than just massive integration of DG units into the grids. It will require the adoption of more ambitious concepts related to active management of the distribution grids, where loads, storage devices and DG can be used together to improve the overall system efficiency, the quality of electricity supply and the overall operating conditions, leading to a fully active distribution network.

The cost effective integration of DG into electrical distribution systems depends greatly from the deployment of active management strategies in the planning and operation activities, deeply contrasting with the current connect and forget policies. The intensive use of active management techniques enable the Distribution Network Operator (DNO) to maximise the use of the existing circuits by taking full advantage of a significant number of control variables, which are not monitorable nor controllable in their current operation and planning philosophies. By exploiting DER, it is possible to implement several functionalities such as Demand Side Management (DSM) policies, DG active and reactive power dispatch, control of transformer taps, voltage regulation and system reconfiguration in an integrated manner [14]. In the future, Distribution Management Systems (DMS) could provide real-time network monitoring and control at key network nodes by communicating with generator controls, loads and controllable network devices, such as reactive compensators, voltage regulators and on-load tap changing transformers. Throughout the realization of generalized strategies aiming the implementation of active management concepts, it will be possible to increase the amount of DG that can be integrated into distribution networks without significant reinforcement investments. The key issues for a costly and effectively DG integration in distribution networks requires the massive adoption of new operation and management philosophies aiming to exploit all the available resources [15].

2.2.2 Distributed Generation and the Formation of Autonomous and Non-Autonomous MicroGrids

The continuous trend of connecting DG to distribution networks will allow a certain customer or group of customers to have the option of providing their own power needs by exploiting the available DG resources or even sell the power surplus to the grid under normal operating conditions. In this sense, a MicroGrid (MG) can be generally defined as a small scale power network plus its loads and several DG units connected to it, together with the appropriate management and control functionalities supported by a communication infra-infrastructure [16-20]. The expression "small scale power network" corresponds intrinsically to a very wide context, especially if the reference taken for comparison purposes is the large interconnected power systems.

Under certain conditions, DG units can be used in order to allow MG autonomous operation, that is, MG separation from the main power system and continuing the operation under islanded conditions, in a similar way to what happens in physical islands (Figure 2-3). The idea is to provide the separation of a pre-defined distribution area from the upstream network in certain conditions (for example, following the occurrence of disturbances or due to some planned maintenance actions to be taken in the upstream networks). The promotion of islanding operation and the MG concept are emerging concepts in the electrical power systems domain and therefore are not yet clearly established among the scientific community. There are authors considering that a MG can be established at the MV level [17, 18]**,** while others define a MG at the LV level, with total power and generation levels below 1 MW [16, 19]. The formation of an autonomous MG by exploring the MS generating capabilities installed at a certain LV area is the seminal concept that is explored within this thesis, being clearly defined and detailed in Chapter 3. The distinguishing characteristic of LV distribution networks with DG is their ability to be a coordinated entity operating both in interconnected or islanded mode. This concept is a natural evolution resulting from the integration of large amounts of DG in distribution networks, which is suggested to be complemented with very innovative control structures intrinsically related to active management strategies in order to present advantages for global system operation and to increase the reliability at the consumer level.

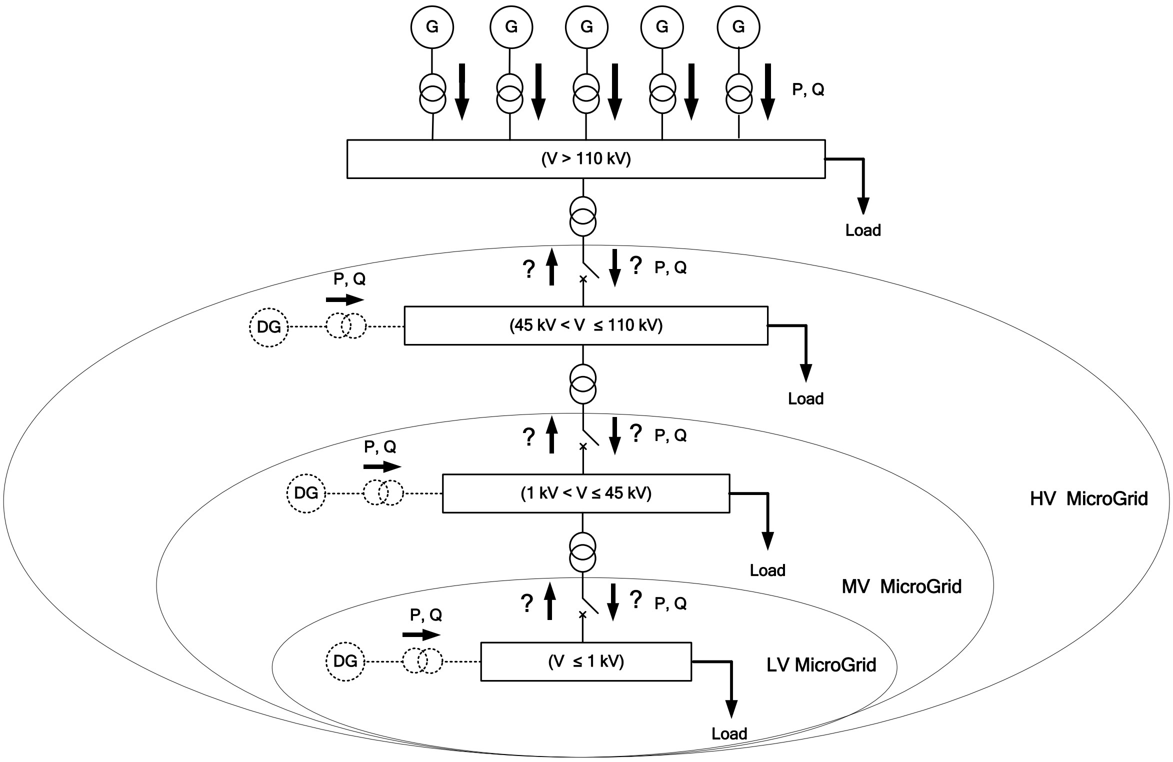


Figure 2-3: DG and the formation of autonomous MG

2.3 THE LEADING DRIVERS FOR DG GROWTH

According to a CIRED survey to its member countries dated from 1999 [10], the advent of DG is being pushed forward by several reasons, including commercial factors, competition policies and government initiatives encouraging the use of renewable energy sources in a supporting action to a growing environmental awareness. The referred survey concludes also the presently growing interest on the development of DG applications is not directly linked with any kind of interest or requirement from distribution network companies. However, a true realization of an alternative policy to distribution networks encourages the electric sector stakeholders for the exploitation of the potential impacts DG may have in several fields, which are discussed in the next subsections [14].

2.3.1 ENVIRONMENTAL CONCERNS

Nowadays, the society is much more awared about the environmental impacts resulting from industrial activities, namely from the electrical power system sector. Following the Kyoto Protocol, governments are more conscious regarding the adoption of environmental friendly policies in order to contribute to the reduction of Green House Gas (GHG) emissions. Therefore, the look for cleaner and cost-efficient solutions for the energy use is being an important driver in terms of the definition of new energy polices [21]. A massive DG adoption in electrical power systems reduces the capacity necessary to be provided by conventional power plants since the real power generation in DG units directly reduces the conventional generator output requirements. Additionally, loss reduction provided by DG, as will be discussed later, will further reduce the output requirements from conventional generators. These two factors, allied to the adoption of DG technologies with less pollutant emissions per MWh than conventional generators, contribute for the reduction of the global emissions accounted to the electric industry sector. It is therefore imperative to adopt technologies with less environmental impact such as renewable energy sources (e.g. wind, sun, biomass, landfill, mini-hydro, etc.) or with higher efficiencies like the Combined Heat and Power (CHP) applications.

DG can also be a key element for industries where, in addition to its electrical needs, heat loads are a relevant part of its working appliances. By using the waste heat of thermal generating units, CHP applications for industrial or space heating purposes, are a well known method for increasing the global efficiency of the overall energetic process. When comparing the efficiency of using electrical energy from fossil fuelled central generation plants or the local use of fossil fired processes in CHP applications at the customer site for the sole purpose of satisfying his heating demands, the first option is less efficient than the second one [13].

In order to face the increasing demand for electricity, generation capacity and transmission and distribution infrastructures need to be reinforced. However, the construction of large power plants or transmission lines faces strong oppositions from environmental associations and also from the society in general. Concerning this adverse scenario in terms of public opinion, DG can be a possible alternative to investments on the construction of new equipments: by providing power closer to the loads, DG contributes for the reduction of branches congestion and central generation power outputs [22].

2.3.2 COMMERCIAL AND ECONOMIC ISSUES

In the last years the electrical industry have been witnessing a trend of moving from a vertically integrated structure to a deregulated environment with an open access to the distribution network, which is expected to favour the development of DG applications [4]. Additionally, in a highly competitive market, customers will search for an electricity supply service that is best suited to its own needs. At the same time, the technological developments in the last few years were responsible for enabling the commercialization of power generation technologies until then under development. Examples of such generation technologies are fuel cells and microturbines. Due to its characteristics, these types of generation sources are well suited for DG applications, contributing to enlarge the spectrum of available choices that fulfil specific customers needs. Hence, DG can be seen as a tool with high potential to be easily exploited by market players and to be adapted to market niches, searching for a balance between risk and promising opportunities in highly changeable market environments. In fact, there are many cases where DG applications provide high flexibility of adaptation to changing market conditions due to their quite reduced construction times and reduced financial risk when compared to conventional generation plants [13, 14, 20]. The valuation of such market niches, which comprise benefits resulting from DG integration in the electrical power system, is of utmost importance for utilities, consumers and regulators. In an open market environment, the incentives for DG should be based on the real value induced by the connection of a certain DG unit and not on the form of general government incentives or subsidies [22]. Some examples of potential aspects that can be exploited in an open market for an effective deployment of DG applications are:

- **Improvement of reliability:** the number of consumers which are very demanding in terms of reliability of power supply is growing fast, especially in the high-tech customer classes, where the effect of power outages can be a source of extremely high financial losses. Additionally, events like rolling blackouts in California during the 2000 and 2001 electricity crisis has contributed to stimulate the value of DG as a mean to increase power supply reliability [8]. DG benefits can come from the reduction of interruption times and energy not supplied, specially if DG is able to operate autonomously in face of network outages [23-25]. The possibility offered by DG to be operated under islanded conditions present benefits to consumers, to the DG owner and to the distribution network operator. The potential benefits to consumers arise due to the possibility of being supplied after an outage of the main power system. The DG owner benefits from the extra revenue for the additional energy sold during islanded operation, especially if specific tariffs are arranged in order to valuate the energy sold during islanded operation. The potential benefits for the distribution network operator arise from the improvement on the global system reliability indexes and the consequent reduction of penalties paid to consumers when regulated standard quality of service indexes are not met.

- **Standby capacity and peak shaving:** emergency generators installed in many buildings are not operated in parallel with the main grid. However, if parallel operation is allowed, especially during peak hours, power injection into the main grid will represent a significant percentage of total peak demand [26, 27]. The existence of these power source is gaining attention in the United States, where increasing demand growth is leading to tighter capacity margins, making the system susceptible for rolling blackouts. A possible option to be envisaged consists on exploiting the flexibility of many DG technologies in order to react against price strikes during peak hours and favouring congestion management in distribution networks [28]. Although DG units may not be as efficient and economical as central generating units, they are closer to the customer. This strategically position of DG units has the advantage of avoiding the cost of using the transmission and distribution networks, which are a very significant part of the total electricity cost. Therefore, by avoiding the transmission and distribution costs and the reliability bottlenecks of the distribution system, DG can provide better quality of service at a lower cost [9].

- **Alternative for the expansion/reinforcement of the electrical infrastructure:** instead of expanding existing transmission lines, building new substations or new central generation plants, DG can be used in order to accommodate load growth and eventually relief overloaded components [22, 29, 30]. The DG paradigm calls upon an integrated methodology where, in addition to the conventional options for network capacity expansion, a new alternative must be considered – the exploitation of DG sources. As an illustrative example, in [22] is presented a methodology for the quantification of DG deferral value. The benefit obtained by the utility is accounted by the time value of the money. The authors conclude that the most important deferral benefits are achieved when DG is connected near the loads located at the end of long feeders.

- **Provision of ancillary services:** the safe, secure and reliable operation of the electric power system as a whole requires the provision of ancillary services, which were and are still mainly provided by central power plants connected to the high voltage transmission network. With the advent of DG on distribution networks, it is imperative to develop mechanisms in order to include its participation on ancillary service provision. If one continues to adopt an approach where DG integration only displaces the energy produced by central generation without any other control possibilities, it will lead to an increase of the overall cost for operating the entire system. Additionally, DG participation in ancillary services will also contribute for the improvement of the economic viability of some DG projects. Regarding DG contribution for ancillary services, it may include reactive power support and voltage control, the capability of power generation on demand (of the network operator), the participation in frequency regulation and the contribution for the improvement of power quality (voltage flicker, active filtering and voltage sags compensation resulting from faults) [14, 28, 31].

- **Wholesale electricity market price reduction**: the extensive use of DG units may also have an impact on the wholesale electricity prices, which are determined by the total system demand and by the bids submitted to the market operator by the entities owning the electricity generation facilities. In [27] the authors propose an extensive use of customer owned backup reciprocating units, by means of a utility centrally controlled aggregation program (for utility energy management purposes). The objective is to complement the utility supply portfolio with additional resources, while bringing new benefits and new market opportunities both for the utility and for the backup reciprocating unit owner. One of the items analysed by the authors is the impact of such a program on the electricity prices reduction. By analysing the Ontario electricity market, the authors found that 100 MW of backup reciprocating units participating in such a program can achieve hourly wholesale savings up to 60000 $ at peak hours; the reduction on the wholesale market prices is up to 2.7 cent$/MWh at peak hours.

- **Energy distribution losses reduction provided by DG:** the impact of DG on distribution system losses has been addressed by several authors [30, 32-34]. Regulatory entities implement policies that incentive distribution companies to be economically efficient and reduce their energy losses. Usually, the incentives for distribution companies losses reduction is the cost difference between real and standard losses defined by regulatory entities through benchmark models. If real losses are lower than the standard ones, the utility obtains a profit [30, 33]. For example, in Spain, distribution companies buy the energy losses in the wholesale market. The energy losses are obtained as the difference between the energy injected in their networks and the energy sold to consumers. Consumers pay to the distribution company the energy they consume times a standard loss coefficient set by the regulatory entity. Therefore, the distribution companies buy their energy losses in the wholesale market but receive only for an amount of standard losses. As DG connection to distribution networks impacts system losses, a direct consequence is transmitted to the distribution companies profit [33]. For that reason, in a DG customer adoption model, the derivation of methodologies for loss allocation as in [35, 36] allows the implementation of incentives to DG owners through a different valuation of DG units according to their impacts on distribution network losses.

2.3.3 NATIONAL / REGULATORY ISSUES

Environmental protection, social development and economic prosperity are the basic components of a sustainable development. In order to achieve such goals, a reliable supply energy system is of utmost importance. Assuring energy sustainability and security will require a set of coordinated actions based on public support in order to explore paths for increasing the efficiency of energy use and to develop and deploy new energy sources. The oil crisis that happened in the last decades and the expectable depletion of this resource lead governments to adopt policies aiming the reduction of the dependency on external resources. The envisaged policies seek the diversification of primary energy resources by creating specific regulatory acts to promote renewable energy sources in order to achieve a sustainable and more secure energy mix. DG can be an effective mean for the realization of an energy policy focused on security and sustainability, due to the following specificities [14]:

- **The DG intrinsic nature is to be dispersed around the network:** as DG sources are located near customers, they contribute to increase the overall system reliability and security, since the failure of a small power station has a residual impact in the electrical power system when compared to the failure of a large conventional power plant or bulk electricity transmission facility.

- **Diverse technologies and primary energy sources:** nowadays, bulk fossil fuel reserves are located in regions facing high political instability, thus contributing to a potential unpredictable control of those resources. Consequently, a high risk is added to the electricity markets players. The use of renewable energy sources contributes to the reduction of nations external dependency on fossil fuels and to the control over the nations energy portfolio [28].

2.4 The Different Types of Micro Distributed Generation Technologies

In the previous sections it was briefly discussed the change of paradigm faced by the electric industry sector resulting from the integration of DG into the system; it were also discussed the DG concept, the possibility of forming autonomous and non-autonomous MG and the main factors contributing to the increasing interest in DG integration in the electrical power system. This section aims to present the general characteristics of different types of DG technologies and its main applications. Within the available DG technologies, it is possible to find a set of *conventional* DG units such as reciprocating engines, gas or steam turbines, mini-hydrous and wind generators. These kinds of technologies are used in a relatively large scale production of electrical energy and are usually connected to the MV distribution network, or even to the high voltage system. As the scope of this dissertation concerns small scale DG technologies to be connected to the LV grid, *conventional* DG units are not considered. Nevertheless, additional information on this type of DG sources can be found in [8, 9, 37].

The recent technological advances are contributing to the development of a new set of DG technologies – the MicroSources – such as fuel cells, microturbines, micro wind generators and photovoltaic panels. This kind of energy conversion technologies are usually available in power units with less then 100 kWe and are potentially adequate to be connected to LV distribution grids. In addition to this type of MS, energy storage devices can be used to support DG applications. The need of use of storage devices in the scope of this dissertation is related to dynamic phenomena. Energy storage is a mean of providing some form of temporary power buffering, as it will be explained in Chapter 4. A brief characterization of the different types of microgeneration technologies is presented in the next sections.

2.4.1 FUEL CELLS

Fuel cells are electrochemical devices that convert the chemical energy contained in a wide variety of fuels directly into electric energy. Other common power generation technologies involve an intermediate step to generate electricity: the production of heat from fuels followed by its conversion into mechanical energy used to drive an electrical generator. Regarding efficiency, fuel cells systems can achieve electrical operating efficiencies approaching 60%, a value that is nearly twice the efficiency of conventional internal combustion engines [38, 39]. In terms of part-load performance, fuel cells systems present also superior qualities when compared with other conventional technologies. In fact, their efficiency increases at part load conditions, unlike gas and steam turbines. A fuel cell system is therefore able to follow changes in the load without economic penalties due to its relatively flat efficiency-load curve [40]. However, the electrochemical processes of fuel cells lead to a quite slow electrical response to load transients. Hence, fuel cell systems are not very likely for responding to frequent load transients. Conversely, they present very good performances when operating under steady state conditions. Finally, fuel cells can use many different types of fuels such as natural gas, propane, landfill gas, diesel, methanol and hydrogen. This versatility ensures that fuel cells will not become obsolete due to unavailability of certain fuels.

Despite the wide range of fuel cell system advantages, some serious shortcomings can be referred. The very high initial cost of fuel cells, ranging from two to ten times the cost of other fossil fuelled DG technologies hinders its wide adoption [9]. Additionally, fuel cells systems are not a mature and proved technology and do not have a long history of commercial usage: many of the systems being used are in a demonstration phase. Lifetime performance degradation is also a key performance parameter in a fuel cell, but the causes of degradation are not yet fully understood [38]. While other DG technologies are almost insensitive to fuel impurities, fuel cells systems require a certain level of purity in their supplied fuel, making necessary the use of cleaners and filters to achieve the entailed fuel purity. Also, the maintenance of fuel cells systems requires highly qualified personal, which is not wildly available, and contributes to the increase in the operation costs [9].

2.4.1.1 Fuel Cells Systems

The basic element of a fuel cell is a unit cell, as shown in Figure 2-4 [38, 41]. These basic elements convert the chemical energy contained in fuels directly into electric energy. Each basic fuel cell unit consists of a cathode (positively charged electrode), an anode (negatively charged electrode) and an electrolyte layer. The anode provides an interface between the fuel and the electrolyte, catalyzes the fuel reaction, and provides a path through which free electrons are conduct to the load via the external circuit. The overall fuel cell reactions occur in two steps: the oxidation reaction at the anode and the reduction reaction at the cathode. The oxidation reaction is the dissociation of hydrogen atoms into protons and electrons. The reduction reaction occurs when the oxygen atoms dissociate and bond with the protons coming through the membrane and the electrons from the external circuit, forming water.

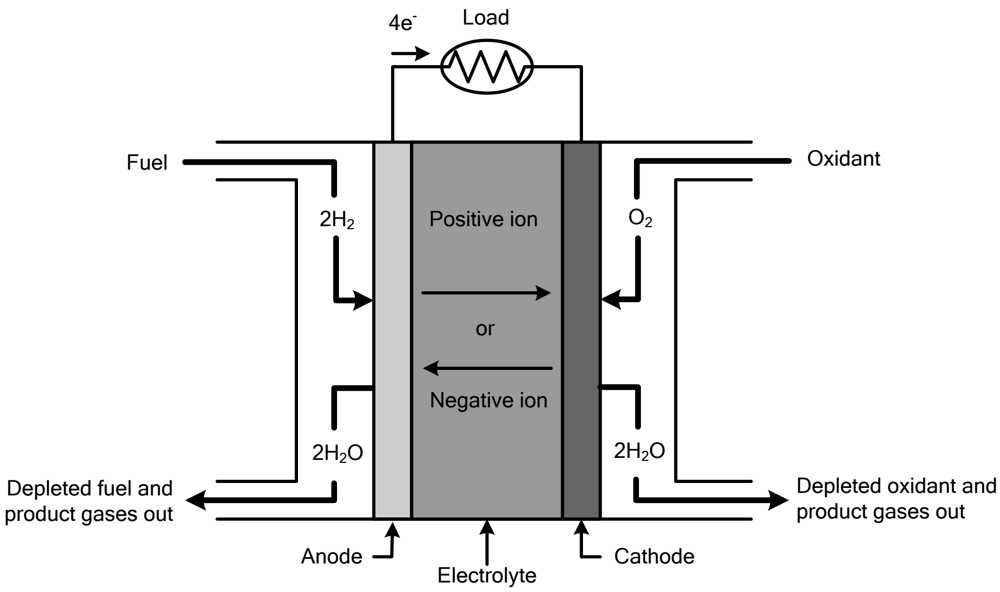


Figure 2-4: Schematic diagram of a basic fuel cell unit

The cathode provides an interface between the oxygen and the electrolyte, catalyzes the oxygen reaction and provides a path through which free electrons are conducted from the load to the oxygen electrode via the external circuit. The electrolyte, an ionic conductive medium (non-electrically conductive), acts as the separator between hydrogen and oxygen to prevent mixing and the resultant direct combustion. It completes the electrical circuit of transporting ions between the electrodes.

When generating power, electrons flow through an external circuit, ions flow through the electrolyte layer and chemicals flow into and out of the electrodes. Each process has natural resistances that reduce the operational cell voltage below the theoretical potential. Consequently, some of the chemical potential energy is converted into heat, which can be used in CHP applications.

Due to the very low power output of a basic fuel cell unit, the development of practical fuel cells systems requires staking of basic fuel cell units in order to achieve the adequate voltage and power levels for each specific application. In addition to the stack, practical fuel cells systems require other sub-systems and components, which are usually called the Balance of Plant (BoP), as in Figure 2-5 [38, 41]. Since fuel cells need to be supplied with hydrogen fuel, a gas not widely available, fuel cell systems must incorporate fuel processing devices in order to prepare the fuel to be used (convert the source fuel in a hydrogen rich fuel stream), usually removing impurities and providing thermal conditioning. The air supply system is critical, since air is provided to the cell stack as an oxidant. The air system includes air compressor or blowers, as well as filters. In order to obtain the adequate air pressure, it is necessary to have in consideration that higher air pressures usually increases fuel cell efficiency; however, the power required for the compressor reduces the net available power of the fuel cell system. Furthermore, compressors performances are low at low loads. Fuel cells systems releases thermal energy as a result of chemical reactions that take place in the stack. Thermal management involves a careful control of the stack temperature, as well as the use of the thermal energy that is released for a variety of purposes within the fuel cell system, as illustrated in Figure 2-5. Water is also required in some parts of the fuel cell, while overall water is a reaction product. In order to avoid having to feed additional water to the fuel cell, and to ensure smooth operation, water management is required in most fuel cell systems. And finally, since fuel cell stacks provide a DC power output, electric power conditioning systems are required for its connection to the utility grid.

2.4.1.2 Types of Fuel Cells

There are five basic types of fuel cells under consideration for distributed generation applications, each having different electrolytes which define the basic cell type, and a characteristic operating temperature [38, 41, 42]. Two of these fuel cell types, Polymer Electrolyte Membrane Fuel Cell (PEMFC) and Phosphoric Acid Fuel Cell (PAFC) have acidic electrolytes and rely on the transport of H^+ ions. Therefore, they are classified as proton-conducting fuel cells. Direct Methanol Fuel Cells (DMFC) make also part of this group, since it is basically a PEMFC in which methanol or another alcohol is directly used. Two others types, Alkaline Fuel Cell (AFC) and Molten Carbonate Fuel Cell (MCFC) have basic electrolytes that rely on the transport of OH^- and CO_3^{2-} ions, respectively. The fifth type, Solid Oxide Fuel Cell (SOFC) is based on a solid-state ceramic electrolyte in which oxygen ions (O^{2-}) are the conductive transport ion. The later three types are classified as anion conducting fuel cells. In Table 2-1 is presented a brief overview of the existing fuel cell types [43]. Additional information on each type of fuel cell can be found in [38].

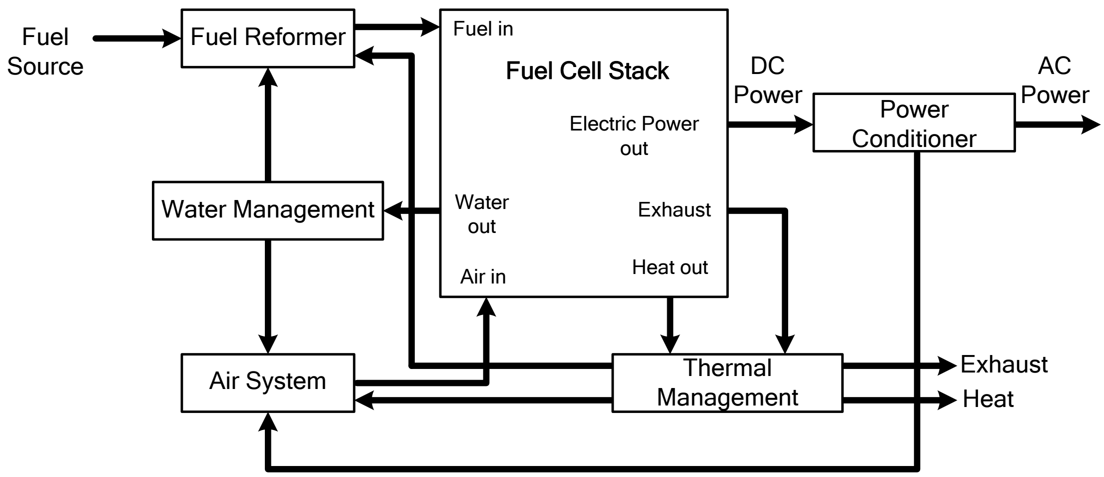


Figure 2-5: Basic processes in a fuel cell power plant

Table 2-1: Overview and brief description of the existing fuel cell types

Temperature	Stack Type	Description
Low Temperature Fuel Cells	AFC	**Alkaline Fuel Cell** **AFC is the first fuel cell to be widely used for space applications. Its electrolyte consists of potassium hydroxide at different concentrations and different temperatures. It should be fuelled by pure hydrogen and the working temperature is in the range of 65ºC to 220ºC.**
	PEMFC	**Proton Exchange Membrane Fuel Cell** **PEMFC contain an electrolyte that is a layer of solid polymer. The polymer electrolyte allows protons to be transported from one half cell to the other. PEMFC require a limited operating temperature and an accurate control of fuel cell humidity. They are mainly supported by the transportation sector. Because of the intrinsic nature of the materials used, the polymer membrane fuel cell operates at temperatures less than 100ºC, typically in the 40 – 80°C range.**
	DMFC	**Direct Methanol Fuel Cell** **DMFC are PEMFC for which the fuel is methanol instead of hydrogen. Methanol delivers directly hydrogen ions on the anode and these protons transfer through the PEM electrolyte towards the cathode. Improvements in solid polymer electrolyte materials have extended the operating temperature of direct methanol PEMFC from 60°C to almost 120ºC.**
	PAFC	**Phosphoric Acid Fuel Cell** **PAFC is the most mature fuel cell technology. It uses a 100% concentrated phosphoric acid electrolyte retained on a silicon carbide matrix. PAFC can be used for co-generation due to their higher operating temperature (150ºC to 220 ºC typically).**
High Temperature Fuel Cells	MCFC	**Molten Carbonate Fuel Cell** **MCFC operate at high temperature (650ºC) where the alkali carbonates from a highly conductive molten salt with carbonate ions (CO_3^{2-}) provide ionic conduction through the electrolyte matrix. MCFC exhibit higher efficiency and grater fuel flexibility that make them a good candidate for combined heat and power applications.**
	SOFC	**Solid Oxide Fuel Cell** **SOFC operate at high temperatures (typically in the 600 – 1000ºC range) with a ceramic electrolyte (e.g. zircon oxide). It can be fuelled with a variety of gases. Like MCFC, SOFC require high operating temperatures, and their most common application is in stationary power plants. The high operating temperatures of the cell open the opportunity for combined heat and power applications, using waste heat to generate steam for space heating,**

		industrial processing, or in a steam turbine to generate more electricity.

2.4.2 MICROTURBINES

The development of microturbines technology in the recent years is the result of intensive research and development in the field of small stationary and automotive gas turbines, reliable auxiliary systems used on board commercial aircraft and turbochargers, which started its development in the 1950s. Decades of experience with these applications provide the basis for the engineering and manufacturing technology of emerging microturbine components.

2.4.2.1 Microturbines Technological Description and Applications

Microturbines are small gas turbines with electrical output power of approximately 30 kW to 400 kW, burning gaseous or liquid fuels [44, 45]. There are two typical configurations for microturbines: the single shaft and the split shaft designs. In the single shaft design (Figure 2-6), the compressor, the expansion turbine and the electrical generator shares a common shaft rotating at very high speeds. The typical microturbine rotation speeds is variable (in the range of 50000 rpm to 120000 rpm) in order to accommodate varying load profiles, while maintaining high efficiencies and optimum long term reliability. The electrical generator is usually a variable speed Permanent Magnet Synchronous Generator (PMSG) that produces high-frequency AC power, being converter to line frequency AC power through a power electronic stage. When the Single Shaft Microturbine (SSMT) is started-up, the electrical generator acts as a motor, turning the turbine-compressor shaft until sufficient speed is achieved to start and sustain the combustion process. If the system is operated independently from the electrical grid, power storage units such as batteries are required to power the generator during the start-up process [46].

Two-shaft microturbine models comprise two turbines: a turbine for driving the compressor in one shaft and another separate shaft where a second turbine drives the electrical generator. The exhaust gases from the compressor turbine are used to power the generator turbine. The exhaust gas is used in a recuperator to pre-heat the air flowing out of the compressor. The two shaft microturbines can run at lower speeds. The power turbine can be connected to a conventional generator via a gear box to produce line frequency AC power [45, 47].

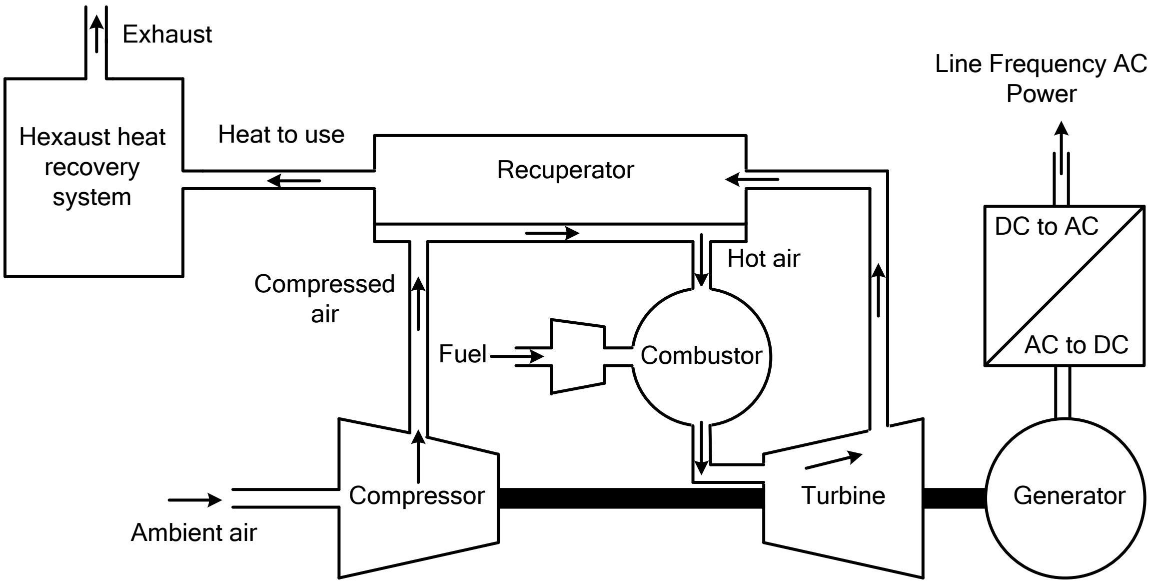


Figure 2-6: Single-shaft microturbine system

Microturbines operation is based on the thermodynamic Brayton cycle, which is illustrated in Figure 2-6. The ambient air is compressed and heated at constant pressure in the recuperator chamber by transferring heat from turbine exhaust gas to the inlet air before it enters the combustor. The compressed and heated air enters the combustion chamber where it is mixed in convenient proportions with fuel. The mixture is ignited and the resulting gas flow is expanded over the turbine, turning the shaft that powers the compressor and the electric generator. It is a common option to include a recuperator in order to increase the overall system efficiency by using the heat available in the turbine exhaust gas to pre-heat the air before it enters the combustion chamber [45, 46]. Without using a recuperator, microturbines present efficiencies around 15%, which is lower than similarly sized internal combustion engines. The addition of the recuperator allows doubling microturbine efficiency. Although this component is quite expensive, its use is fully justified by the significant improvement achieved in terms of global microturbine efficiency [46].

Microturbines commercially available from several manufactures are able to operate on a variety of fuel types: natural gas, biogas, diesel fuel, kerosene or propane. The use of very innovative combustion schemes, relatively low turbine inlet temperatures and low fuel-to air ratios result in low NO_x emissions and inherently low CO and unburned hydrocarbon emissions, especially when running on natural gas. From the mechanical point of view, microturbines do not have reciprocating parts that require frequent change of lubricants. Instead, it is common that microturbines utilize air bearings and air-cooling, thereby completely eliminating the need for hazardous liquid lubricants and coolants and requiring very minimal scheduled maintenance [44, 46].

Regarding microturbines applications, they are a versatile and reliable power and heat generation source suitable for a wide range of applications due to its potential for low emissions and to the reduce maintenance requirements. Furthermore, they are quit flexible in connection methods and are able to be stacked in parallel to serve large thermal and/or electrical loads. Microturbines found interesting applications such as peak shaving, provision of premium power or grid support and powering remote electrical installations. In addition to applications oriented only for the electrical utilization, CHP applications are also very promising. In commercial, industrial or residential facilities, the need of electricity can be combined with and efficient use of clean hot exhaust gases for heating, absorption cooling, dehumidification, baking or drying [44].

2.4.3 PHOTOVOLTAIC PANELS

Solar cells technology found its initial application within the United States space programs because of its high power capacity per unit weight. Since then, PhotoVoltaic (PV) energy conversion has been an important source of power for satellites. Nowadays PV technology is being widely used in terrestrial applications, ranging from powering remote sites to feeding utility distribution systems: PV technology is providing power to many people throughout the world who live without electrical service, for applications such as health care facilities, community centres and water delivery or purification systems. In industrialized countries, grid-connected PV systems applications are being deployed in great numbers for residential, commercial and utility grid support applications [48].

2.4.3.1 Basic Operating Principles

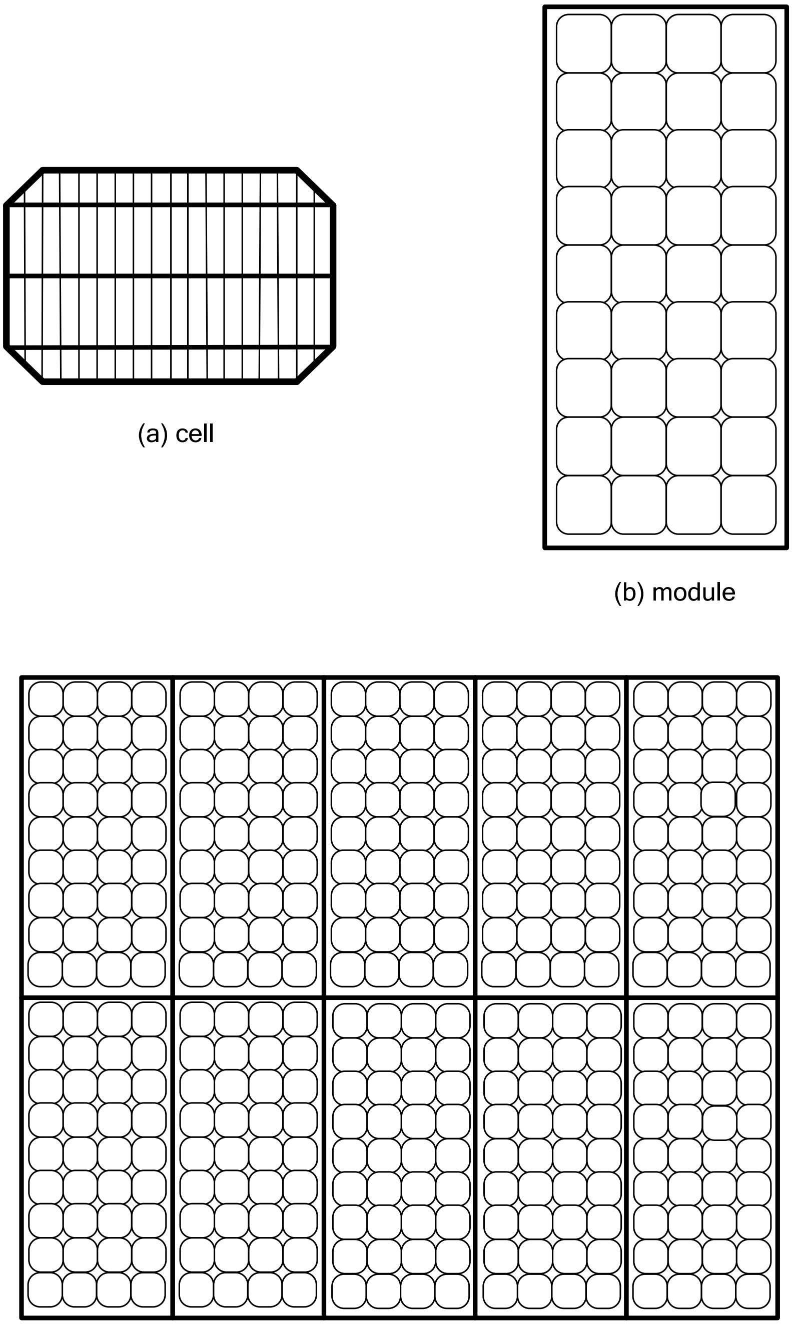
A photovoltaic device, generally called solar cell, is a semiconductor device that converts sunlight directly into electricity. They are usually made of silicon and consist of semiconductor material layers with different electronic properties. In a typical silicon cell, the bulk of the material is silicon doped with a small quantity of boron to give it a positive or p-type character. A thin layer on the front of the cell is doped with phosphorous to give it a negative or n-type character. The interface between these two layers contains an electric field and is called a junction. When light, which consists of particles called photons, hits the semiconductor materials, the photons are capable of transmitting their energy to the valence electrons of the semiconductor, causing the break of the link that keeps them attached to the atoms. For each broken link, there is a free electron circulating inside the solid. The lack of an electron in the broken link, called gap, can also circulate freely inside the solid, transferring from a free atom to another due to the displacement of the rest of the electrons of the links. The circulation of electrons and gaps in opposite directions creates an electric current inside the semiconductor, capable of circulating through an external circuit and of liberating in it the energy supplied by the photons when creating the electron-gap pairs. The electric field created in the union of two regions of a semiconductor crystal is used to split electrons from gaps and avoid them restoring the broken links, causing electrons and gaps to circulate in opposite directions and so creating an electric current in the direction of the electric field [48, 49].

2.4.3.2 Photovoltaic Modules and Arrays

The basic building block of a PV system is the solar cell. When charged by the sunlight, the solar cell is capable of generating an open circuit terminal voltage in the range of 0.5 – 1 V and a short-circuit current of a few tens of milliamps per cm^2. These voltage/current characteristics are not reasonable for being used in most applications. Therefore, the solar cells are connected in series and parallel and encapsulated in a module in order to obtain usable voltage and current levels **(**Figure 2-7**)**. These modules can be combined further in series and parallel in order to obtain larger voltages and current levels that match each specific application requirements. This arrangement of solar modules is usually denominated as a PV array or PV generator or panel [48]. Finally, the DC electric energy produced in the photovoltaic systems is converter into AC power by means of a power electronic interface module.

2.4.3.3 Photovoltaic Systems Architecture

In addition to an array of PV modules, a number of other components are required in any PV system to conduct, control, convert, distribute, and/or store the energy produced by the array. The specific components required depends on the functional and operational requirements for the system, and may include major components such as a DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and sometimes the specific electrical load.



(c) array

Figure 2-7: Grouping PV cells to build modules and arrays

PV systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and/or electrical loads. Two main classifications are usually defined: grid-connected and standalone systems [50]. Standalone PV systems are not within the scope of this dissertation; this type of PV systems are designed to operate independent of the electric utility grid, and sized to supply certain DC and/or AC electrical loads.

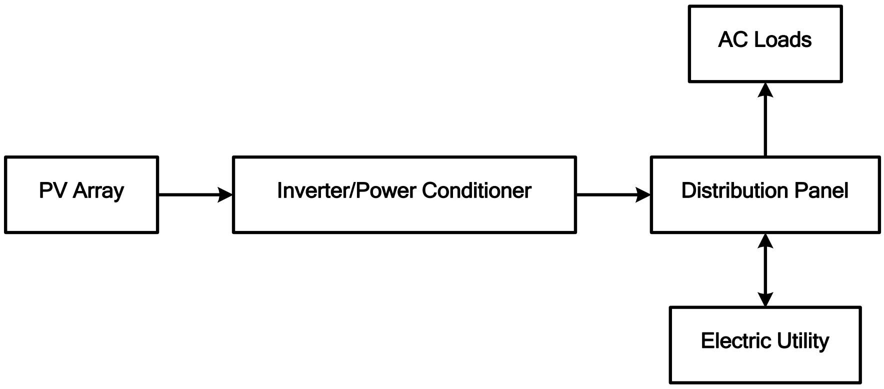


Figure 2-8: Block diagram of a grid-connected PV system

Grid-connected PV systems are designed to operate interconnected with the electric utility grid, as shown in Figure 2-8. A bi-directional interface is made between the PV system output circuits and the electric utility network, typically at an on site distribution panel or service entrance. This allows the AC power produced by the PV system to either supply on site electrical loads, or to back feed the grid when the PV system output is greater than the on site load demand [50].

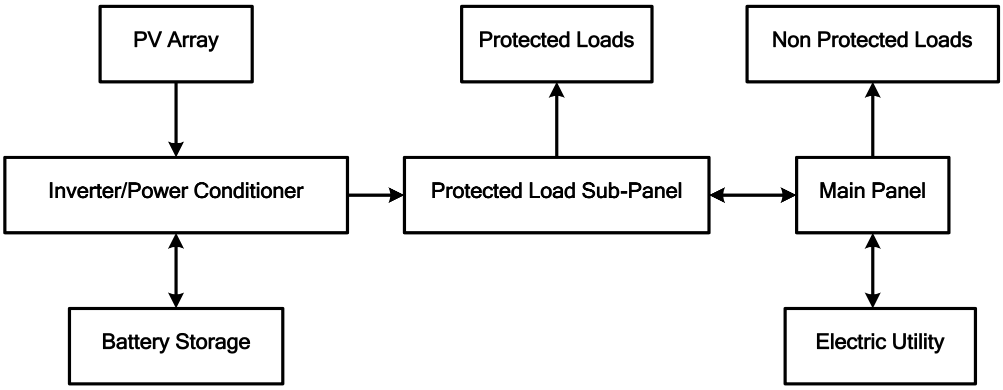


Figure 2-9: Block diagram of grid-connected power supply system with energy storage and protected loads

If battery storage is used, the PV system can operate in grid-connected mode and still operate critical loads during an outage of the utility grid (Figure 2-9) Under normal circumstances, the system operates in grid-connected mode, serving the on site loads or sending excess of power back onto the grid, while keeping the battery fully charged. In the event the grid becomes de-energized, control circuitry in the inverter opens the connection with the utility through a bus transfer mechanism and operates the inverter from the battery to supply power to the protected loads only. In this configuration, the critical loads must be supplied from a dedicated sub-panel [50].

2.4.4 Small and Micro Wind Generators

Wind energy development has been gaining a lot of notoriety in large wind farms (utility-size projects), where wind generators with power ratings ranging from a few hundreds of kW up to 5 MW are frequently installed. Additional information on the different types of large wind generators and available control techniques can be found in [51]. Nevertheless, small wind turbines (less than 100 kW) and micro wind turbines (less than 5 kW) have been installed for decades, making very important contributions in terms of off-grid electricity supply in isolated areas and also on grid-connected areas [52]. Together with the PV systems, small and micro wind turbines are another option for customers aiming to pledge the mitigation of climate changes and the reduction of the national dependence on fossil and nuclear fuels. The turbines are usually chosen to meet the energy requirements, given the available wind resource: turbines with power ratings from 1 kW up to 25 kW are usually the option to be installed in a home or a farm.

Many micro wind turbines are designed to be roof-mounted, requiring very specify characteristics that must satisfy customers and planers expectations. Some key issues that must be tackled are: noise levels, reliable operation, minimal visual impact and compliance with safety requirements (structural and electrical). Mounting the turbines at high points on buildings may provide a great opportunity for onsite electrical generation, since wind speeds increase with the distance to the ground. However, urban environments usually introduce high turbulence in wind flow when compared to open spaces. The turbulence introduced in the built environment has negative impacts on micro wind turbines, requiring a careful design and installations planning. Following these general principles, different designs are being evaluated in order to develop a technology that can be widely accepted in accordance with the referred aspects. The currently available wind turbine designs can be organized in three main categories [53]:

- **Horizontal axis wind turbines:** in this case, the turbine blades rotate around a horizontal axis like in the traditional windmills. Currently, the horizontal axis wind turbine is the most commonly available design.

- **Vertical axis wind turbines:** the turbine is designed in order to rotate around a vertical axis. There are some results suggesting this design is better suited to be used in the built environment than horizontal axis wind turbines due to the better performance in turbulent wind flow.

- **Building augmented wind turbines:** this design is specially derived in order to make use of the buildings as a concentrator of the wind.

2.4.4.1 Horizontal Axis Wind Turbines

Being the most common design in small and micro wind turbines, the horizontal axis design is the one to be considered in this dissertation. It generally consists of a rotor where the turbine is solidly fixed, an electrical generator, a mainframe and a tail. The turbine usually consists of two or three blades. A three-blade design can be a little more efficient and run smother than a two blade turbine [52, 54]. The blades are usually made from fibber glass with the appropriated strength.

The electrical generator is specifically designed for the wind turbine. Permanent magnet generators are popular since they do not require the need of brushes as in direct current machines and in some conventional synchronous generators with separate excitation systems. In most small and micro wind turbine designs, the rotor is connected directly to the shaft of the permanent magnet generator, thus creating variable frequency and voltage AC power, according to the wind speed. The output power is then rectified to DC to either charge batteries or feed a grid-synchronous inverter. In the designs with a direct coupling between the turbine and the generator, high reliability and lower cost is achieved since the design eliminates the additional maintenance of gears and the relatively low reliability indexes of these devices. In systems with higher power ratings, a gearbox is used to increase generator speed from a slower turning rotor. Nevertheless, both systems can be found in the micro and small wind turbines power range.

The blades of the turbine must be oriented perpendicularly to the wind direction in order to maximize the wind energy extraction. A yaw bearing is needed, allowing the wind turbine to track the winds as they shift direction [54]. The mechanism consists of a tail that directs the rotor into the wind. Governing systems are also included in order to limit the rotation peed as well as generator output to protect the turbine from high winds. A shut down mechanism is also useful to stop the machine when necessary, as during extreme storms, or when maintenance actions are necessary to be performed.

2.4.5 Storage Devices

The use of energy storage technologies combined with DG units is a natural evolution resulting from the inability of many DG sources to deliver power in coordination with consumption and network requirements. Energy storage is also used in other applications in order to increasing the quality of service, allowing critical loads to run through outages or to improve the power quality supplied to sensitive loads (voltage sag compensation, etc.). Regarding energy storage technologies, it is possible to choose among a wide range of available solutions, which depend on the application for which it is intended [9]:

- Batteries;
- Capacitor storage;
- Superconducting magnetic energy storage;
- Mechanical storage:
    - Flywheels;
    - Pumped and compressed fluids.

Excepting the capacitor storage, which directly stores electric energy, the available technologies for energy storage encompasses a transformation of the electric energy into another form (chemical, thermal or mechanical) to be transformed back when required.

Depending on the type of energy storage system, and the specificity of the application for which it is intended for, they can be divided into four categories [55]:

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

The small scale power range storage in the first two categories can be performed by means of kinetic energy storage in flywheels, chemical energy in batteries, compressed air systems, supercapacitors or hydrogen storage to be used in fuel cells. Additional information on the other categories can be found in [55]. For the purpose of low scale short term energy storage, as in a MG application developed within this dissertation, technologies with major interest are batteries, supercapacitors and flywheels energy storage systems, which are briefly described in the next sections.

2.4.5.1 Batteries

Currently available batteries include lead-acid, nickel-cadmium, nickel-metal hybrid, lithium-ion and sodium-sulphur, whose general characteristics can be found in [9]. Although the term “battery” is often used, the correct designation of a basic electrochemical unit is the “cell”. A battery consists of one or more of these cells, connected in series or parallel, or both, depending on the desired output capacity in terms of voltage and current. A battery is a device that converts the chemical energy contained in its active materials directly into electric energy by means of an electrochemical oxidation-reduction (redox) reaction. This type of reaction involves the transfer of electrons from one material to another through an electric circuit. Concerning the chemical reactions, the basic elements of a battery cell consist of three major components, as shown in Figure 2-10 [43]:

- **The anode** or negative electrode, which gives up electrons to the external circuit and is oxidised during the electrochemical reaction;

- **The cathode** or positive electrode, which accepts electrons from the external circuit and is reduced during the electrochemical reaction;

- **The electrolyte**, which provides the medium for transfer of electrons, as ions, inside the cell between the anode and cathode.

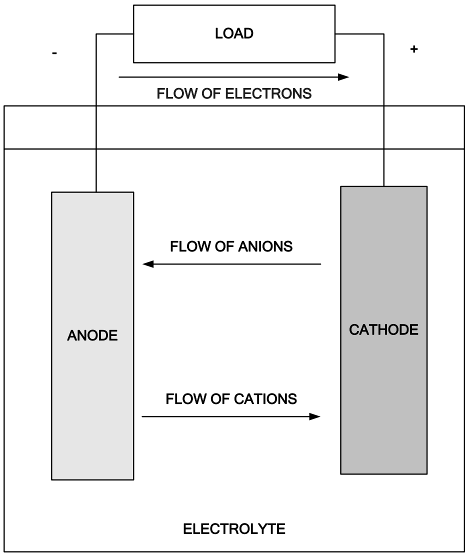


Figure 2-10: Electrochemical operation of a cell – discharge mode

When the cell is connected to an external load (discharge operation, as in Figure 2-10), electrons flow from the anode (anode oxidization) through the external load to the cathode, where the electrons are accepted and the cathode material is reduced. The electric circuit is completed in the electrolyte by the flow of anions (negative ions) and cations (positive ions) to the anode and cathode, respectively. During the recharge of a rechargeable or secondary battery, the current flow is reversed and oxidation takes place at the positive electrode and reduction at the negative electrode, as shown in Figure 2-11.

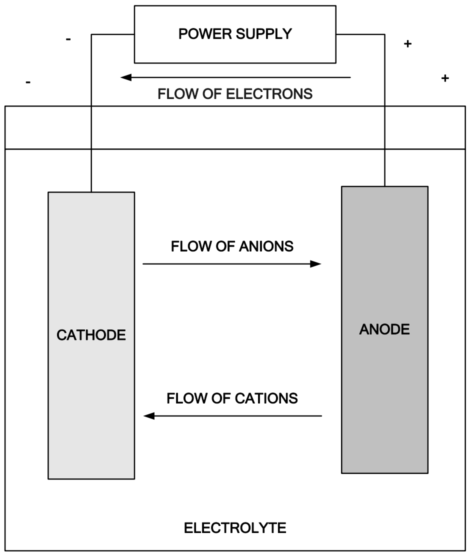


Figure 2-11: Electrochemical operation of a cell – charge mode

A major concern in all types of batteries is the impact of charge and discharge cycles on battery lifetime. The reason is batteries gradually suffer from degradation of their storage characteristics following repeated charge and discharge cycles. The chemical reaction involved in the discharge cycle are not completely reversed during the charge cycle, thus contributing to the poisoning of the electrolyte, damaging in the electrodes or even to permanent molecular damages of some components [9, 56]. Additionally, batteries lifetime is even more reduced is they often suffer full charge and discharge cycles. As an example, typical lead-acid batteries for industrial applications, designed to face deep charge and discharge cycles, do not withstand more than a few hundreds of deep cycles; nevertheless, their lifetime is considerably prolonged if they are submitted to no more than half or even less charge and discharge cycles.

2.4.5.2 Supercapacitors

From the technological point of view, the supercapacitor is an electrochemical device that is built similarly to batteries: it has two porous electrodes immersed in an electrolyte solution flowing into and around the porous electrode plates. The electrodes are made of activated carbon and the electrolyte solution is typically potassium hydroxide or sulphuric acid. By using a liquid electrolyte solution and porous materials in the electrodes, the effective surface area increases radically when compared to conventional capacitors, leading to a very high capacitance. Other technological solutions for building supercapacitors are possible and can be found in [57]. The conventional structure of a supercapacitor is represented in Figure 2-12. This arrangement effectively creates two capacitors, one at each carbon electrode, that are connected in series. The electrolyte is the conductive medium serving as a link between the two capacitors, while it serves also as an "effective conductive plate" for one side of each capacitors formed at the electrolyte/electrode interface [58].

Electrochemical batteries have been the leading technology for energy storage in many applications due to its ability for storing large amounts of energy and providing high power levels in a relatively small weight and volume. However, its cycle and shelf lifetime has been a major disadvantage in its application. Therefore, this weakness is assumed and tolerated in all the applications due to the leak of suitable alternatives in a technical and economic sense [58]. Certain applications such as the short time storage, requiring high power for a short time period, lead to the development of pulse batteries, sometimes reducing the energy density and cycle life. Nowadays, supercapacitors are being developed as an alternative to pulse batteries: these devices are demonstrating to have a much longer life and shelf cycle life than batteries and much high power density. Supercapacitors can be deep cycled at high rates for up to one million cycles with a relatively small change in its characteristics – up to 20% degradation in capacitance and internal resistance [57]. Additionally, supercapacitors can be charged in seconds or fractions of seconds with higher efficiency than batteries: a lead-acid battery can lose 20% to 30% of energy during the charge/discharge cycle (including inverter losses), while a supercapacitor system may lose only 10% of the energy. However, the relatively low energy density of supercapacitors when compared to batteries and its high initial cost are major shortcomings, limiting its use in applications with low requirements of energy [57, 58].

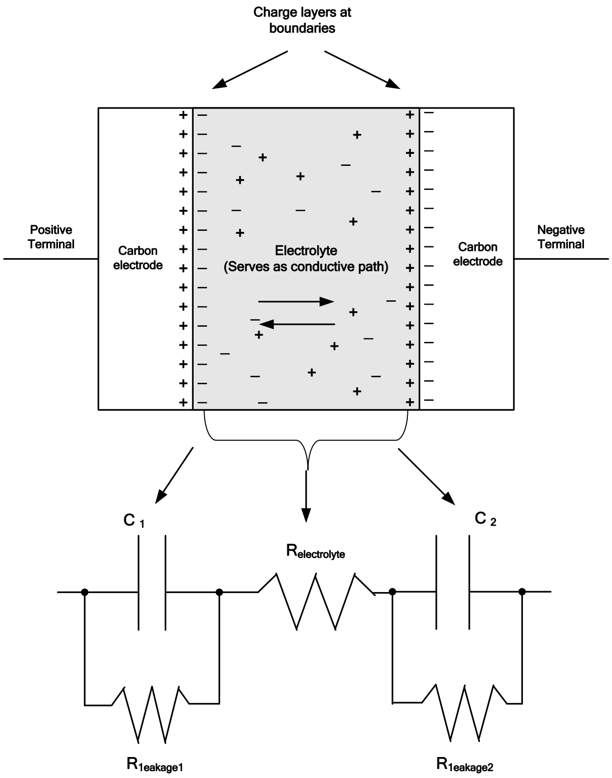


Figure 2-12: Electrochemical supercapacitor

Regarding short term energy storage applications, supercapacitors are well suited to be used for supporting fuel cells or microturbines during load changes in a time range of 10 to 30 seconds. In such applications, the supercapacitor is responsible for supporting the connection of a new load or for absorbing extra power if a load is disconnected, while the fuel cell or the microturbine is adjusted to a new operating point. Other applications may include uninterruptible power supply, in combination with a battery bank: the supercapacitor will respond to the pulse power occurring during voltage sags, or momentary interruptions, while batteries are used for long term load support [58].

2.4.5.3 Flywheels Energy Storage Systems

Flywheels store kinetic energy in a rotating mass, being the amount of the stored energy dependent on the mass and geometry (inertia) of the rotating body and on the rotational speed, according to the following equation:

$$E = \frac{1}{2} J \omega^2 \qquad (2\text{-}1)$$

where:

E : **kinetic energy (J)**

J : **inertia of the rotating body (kg.m^2)**

ω : **angular velocity (rad.s^{-1})**

Regarding the electric industry sector, and particularly, the early years of the power quality industry, flywheels systems based on steel wheels coupled to motor/generator sets where extensively used in order to increase system inertia and consequently allow a longer ride-through capability in case of utility interruptions. However, effective increase in the running time of such systems do not often exceed one second at rated load, which correspond to the delivery of about 5% of the kinetic energy stored in the wheel. Increased values of system running times were not possible, since the delivery of more kinetic energy reduces the rotational speed of the generator set, and consequently the output frequency, with the corresponding degradation on the power quality [59]. With the advent of power electronics, additional improvements were possible in such a system by adding a rectifier and a converter to the generator. In this case, it was possible to deliver around 75% of the kinetic energy stored in the wheel, with substantial gains in the ride-through times.

By taking advantage from the developments on composite material technology and power electronics, nowadays it is possible to operate flywheels at higher speeds, effectively increasing the kinetic energy stored in the rotating mass in order to achieve high energy and power densities [60]. Trough the use of composite material technology, it is possible to develop flywheels with rotational speeds around 60000 rpm. Such high speed flywheels are placed in a vacuum container in order to eliminate air friction losses. The use of mechanical bearings is not possible due to high friction losses resulting from high rotational speeds. The alternative is the use of magnetic bearing systems, which do not have any contact with the flywheel shaft, has no moving parts and require no lubrification. The magnetic bearings support the flywheel weight through magnetic repelling forces, which are controlled by sophisticated systems [60, 61].

In a flywheel, the rotating body that stores kinetic energy is connected to a variable speed PMSG, which can operate as a motor to accelerate the rotating body or as a generator by using the stored kinetic energy and convert it into variable frequency AC power [60, 61]. A general scheme of the system is shown in Figure 2-13. During the charging state, (storage of kinetic energy), power is absorbed from the grid, which is converted by the power electronic equipment into an appropriated form to drive the permanent magnet machine as a motor in order to speed up the flywheel. In a discharging state, the kinetic energy stored in the flywheel is converted to electric energy by the PMSG, acting as a generator, while the flywheel speeds down. The power electronic equipment converts the variable frequency output from the generator into the electric power required by the load or by the electric grid.

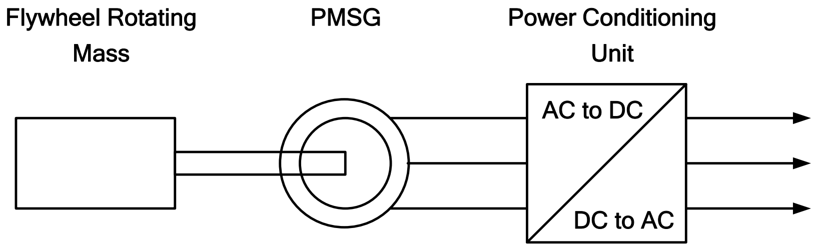


Figure 2-13: Flywheel energy storage system

Flywheel energy storage systems found application in the power quality industry and transportation, where frequent charge and discharge cycles are required. Applications on long term energy storage are yet not promising [59, 61]. Regarding power quality applications, flywheels are suitable to support the load during a vast majority of events standing for less than a second, such as voltage sags. They can also provide power to support a system load during a few tens of seconds, while a standby generator is bought on-line. Such applications have been primarily due to chemical batteries, against which flywheels are forceful competitors due to two main reasons. Firstly, flywheels life cycle is almost independent on the depth of discharge, which is a very demanding situation for chemical batteries. Secondly, the state of charge of flywheels depends only on its rotational speed and can be easily determined; however, determining the state of charge in batteries is more difficult [61]. When compared to supercapacitors, the main issues that can be identified are related to high power and energy densities that can be found in flywheels. Additionally, flywheels present very high self-discharge rates, being an import limitation unacceptable for low power applications (less then 100 kW), where supercapacitors demonstrate to be a cost-effective solution. In applications requiring high powers, the kinetic energy storage systems provide both high power and high energy and seem to be the most feasible technology [62].

2.5 TECHNICAL CHALLENGES FOR DISTRIBUTED GENERATION INTEGRATION IN DISTRIBUTION NETWORKS

The increasing trend of connecting DG to MV and LV grids has given rise to new and sometimes challenging problems. Indeed, these distribution networks were not initially designed to host generation. In particular, they were usually operated with energy flowing in only one direction, namely from the substation to the consumers, which might no longer be true with the presence of DG units. The impacts resulting from DG connection to distribution networks arise mainly due to the changes induced in the network power flows, affecting not only its magnitude but also its direction. In order to overcome the technical problems resulting from DG integration, several authors suggest advanced control techniques following the concept of active management strategies previously referred. Presently, the solutions reported in the literature are usually oriented to a specific technical problem at a time, not an integrated solution for all the aspects. The main technical aspects that need to be evaluated due to presence of DG units in the grid are:

- Voltage profile;
- Steady state and short-circuit currents;
- Distribution network protection schemes;
- Power quality;
- Stability;
- Network operation;
- Islanding and islanding operation.

2.5.1 VOLTAGE PROFILE

During normal (steady state) operating conditions, the voltage has to be maintained between upper and lower admissible values everywhere in the distribution grid. Figure 2-14 shows the typical voltage profile on a radial distribution feeder, where it is possible to observe that the adjustment of the MV/LV transformer ratio guarantees acceptable voltage levels in the remote customers, even during maximum loading conditions [4]. The points shown in the graphic of Figure 2-14 are:

- A: The voltage is kept constant by HV/MV distribution transformer tap-changer;
- A – B: Voltage drop in the MV feeder due to the loads;
- B – C: Tap-chargers in MV/LV distribution transformer boost voltage level;
- C – D: Voltage drop in the MV/LV distribution transformer;
- D – E: Voltage drops in the LV feeder due to the loads.

DG connection to distribution grids modifies the voltage profile due to power injections. The voltage rise ΔV in lightly loaded distribution circuits due to the connection of a DG is given in per unit by [4]:

$$\Delta V = \frac{PR + XQ}{V} \tag{2-2}$$

where:

V : **circuit nominal voltage**

P : **active power output of the DG unit**

Q : **reactive power output of the DG unit**

R : **resistance of the circuit**

X : **reactance of the circuit**

From Equation (2-2) it is possible to observe that both active and reactive power injections influence the voltage magnitude in the grid. The power injection from DG units into distribution networks causes an increase in the voltage profiles comparatively with the situation where no DG unit is connected to the grid. Such impact is due to a partial local supply of demand, which contributes to reduction of the voltage drop in the distribution network.

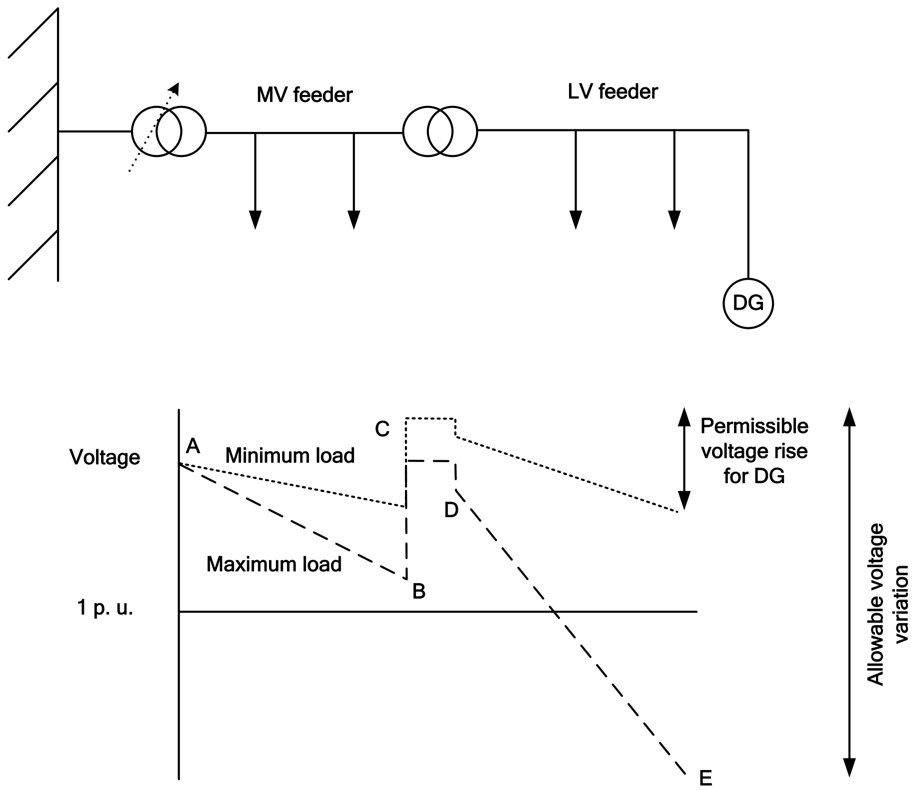


Figure 2-14: Voltage profile in radial distribution feeders

When the DG unit injects power into the distribution network, the resulting impact depends on:

- DG units supplying active and reactive power;
- DG supplying active power and absorbing reactive power from the grid;
- DG units supplying active power at unit power factor.

Voltage and reactive power control is an important issue for DNO, requiring the definition of technical conditions concerning the contribution of DG plants to the voltage or reactive power regulation in the distribution network. In fact, the voltage rise effect is usually a limiting factor for the connection of DG to the distribution network. The maximum allowable DG capacity connection is usually calculated based on deterministic procedures and assuming a worst case scenario: maximum substation voltage, minimum network loading conditions and maximum DG output power [63, 64]. The use of these deterministic based rules considerably limits the allowable capacity connection mainly for intermittent DG sources such as wind turbines. This approach relies on a purely passive operation methodology of the distribution system, where no actions are taken in order to control DG sources. However, the probability of simultaneous occurrence of the referred conditions is very low, being a strong bottleneck on the determination of the maximum allowable DG capacity connection. Therefore, the use of probabilistic techniques like the probabilistic load flow or the Monte Carlo simulation is proposed as a mean of avoiding extremely restrictive rules for assessing and determining DG integration effects [65]. An alternative to probabilistic analysis is the use of fuzzy logic concepts in order to model ill-defined situations, resulting from the integration of large number of DG units and to model other phenomena that can not be characterized in a complete way, namely due to lack of data. If that is the case, fuzzy sets correspond to a very flexible tool that can be used in several power systems domains [66]. Concerning the use of fuzzy logic concepts, the aim is to reflect the uncertainties present in the data in the traditional results of power flow studies (node voltages, active and reactive generations, active and reactive flows, currents and losses) and evaluate the possible impact in face of nodal data uncertainties.

Aiming to overcome the limitations of a passive operation philosophy followed by distribution network operators, several authors are proposing active management strategies in order to control the voltage rise effect in order to increase the maximum allowable DG connection capacity [63, 67]. In [63] the authors propose and compare three control alternatives in order to maximize the wind power generation in existing distribution networks. Following an increasing order of maximum penetration of wind power, the proposed alternatives are:

- Active power generation curtailment, mainly during low consumption periods.
- Absorbing reactive power by means of reactive power compensation devices: generation curtailment is applied only when the reactive power absorbed is not enough for maintaining the voltage within acceptable limits. In this approach it is assumed an increase in network losses due to the increased reactive power lows.
- On-Load Tap Changer (OLTC) co-ordinated voltage control strategy: voltage control is usually based on a simple constant voltage control strategy or on a scheme that takes into account circuit loading while determining the voltage set-point at the substation. These authors exploit the area-based voltage control (coordinated control

of OLTC and voltage control at the DG connection point) in order to maximize wind energy penetration in distribution networks.

Being in line with the co-ordinated voltage control strategy, in [67] the authors propose an automatic voltage controller for maximizing wind generation penetration. The controller is based on a statistical state estimator for the estimation of voltage magnitudes in network buses based on real time measurements from remote terminal units strategically placed on the distribution grid and on load profiles to build pseudo-measurements for unmeasured loads. The control algorithm alters the OLTC set-point according to the estimates of the node voltage magnitudes.

In addition to the limitations introduced by the voltage rise effect in the maximum allowable DG connection capacity to distribution networks, the possibility of using DG units for voltage support in distribution feeders is being also a matter of investigation [68, 69]. The use of DG units for voltage control and reactive power support according to the interests of the distribution network offers the possibility of supplying ancillary services at the distribution level. Such an approach is based on the assumption of having some communication capabilities established along the distribution network, moving in the direction of an active management philosophy of the distribution system. Making use of innovative controllers and strategies that coordinate the OLTC action at the HV/MV substation, the capacitor banks and the reactive power exchanges between DG units and the distribution grid, the authors demonstrate the potential DG benefits for voltage and reactive power control in distribution grids. These are quite innovative procedures which are far away from the current practice followed by distribution utilities. In fact, they recognize the potential benefits DG units have for voltage and reactive power support and try to define incentives or regulatory mechanisms leading to reactive power injection or absorption according to the needs of the grid. However, without an effective communication system, and a dedicated network of controllers, the adoption of these strategies is not possible [8].

2.5.2 Steady-State and Short-Circuit Currents

The power delivered by DG units may lead to an increase in the current flowing in the distribution grid, depending on DG connection point and on the size of the installation. This situation is contrary to the DG potential benefits regarding investments deferral, which was previously referred. In some cases, the accommodation of high DG levels requires extra investments for the upgrade of the distribution grid in order to accommodate DG power production.

In faulted situations, the DG also contributes to the fault currents in the network. The fault current value is often one of the impeding factors for the connection of large amounts of DG units to the existing distribution grids. The reason for such situation relies on the fact that, in many situations, the contribution of the upstream system is quite close to the maximum value used during the distribution network design phase. Therefore, even small amounts of DG units connection may lead to prohibitive values for the short-circuit current, which must be lower than the network design value under the most unfavourable conditions [70]. Knowing the value of short-circuit currents is very important for the correct sizing of several equipments (such as circuit breaker rating, thermal and mechanical endurance of transformers, bus bars and cables, etc.) and for determining the setting of protective relays or to verify the coordination among different protection systems.

DG contribution to the short-circuit current is dependent on the technology used and in particular on the "coupling system" used (e.g. rotating machine directly connected to the grid or coupling through power electronic converters). The contribution of synchronous or asynchronous machines to short-circuit currents is well defined throughout the literature. The contribution of synchronous generators to the short-circuit current depends on the pre-fault voltage, subtransient and transient reactances of the machine and on the excitation system characteristics. Induction generators can also contribute to short-circuit currents whenever they remain excited. Its contribution is limited to a few cycles and is dependent on the pre-fault voltage and the machine sub-transient reactance. However, the behaviour of power electronic interfaced DG units during short-circuit conditions is not straightforward due to its non-linear V-I characteristic in the 2 to 60 cycles time range. The exact behaviour of a power electronic interface depends on the control strategies implemented. Therefore, in [71] is proposed a dynamic simulation technique to analyse the impact in the short-circuit current resulting from DG units connected to the grid through power electronic interfaces. In [70, 72], the authors follows a simpler approach and consider that inverters contribution to short-circuits can be represented by a constant current source equal to k times the rated current, during a certain time interval before the DG unit is disconnected by its own internal protection systems. A typical value for the fault current may be k = 1.5 (over-current capability of the inverter), but values up to $k = 4$ are possible by a convenient inverter design; the time interval the short-circuit current is withstand by the inverter depends on the protection and fault ride through capability for which the inverter is designed.

2.5.3 Distribution Network Protection Schemes

The connection of DG in distribution networks may affect the proper operation of the protection system. Traditionally, distribution networks are radial circuits, enabling the use of over-current protection schemes, since the current flow is unidirectional. However, this is not always the rule due to DG connection. DG connections modify network power flows and require a deep verification of the protection coordination between the grid and the DG unit itself. In particular, the sensitivity and selectivity of the protection system as a whole may be affected. For instance, some faults may be undetected by the existing protection systems or their clearing may require the tripping of parts of the network larger than necessary. Besides, the presence of DG units must not lead to unwanted tripping of parts of the network (such as neighbouring feeders not affected by the fault) and it should not prevent the proper operation of automatic or manual reclosing schemes that may be implemented in the distribution network. Examples of potential problems in the case of generating plants connected to MV networks include non-detection of faults by feeder over-current protection, unwanted tripping of a healthy feeder, or disturbance of fault locators. Additional considerations on protection coordination aspects may be found in [73-75].

Detailed case by case studies are required in order to determine whether the protection system will still operate properly after the connection of the DG unit. If this is not the case, suitable measures have to be taken. At one hand the safety of the people and equipment is at stake and on the other, the quality of supply that cannot be degraded. Decoupling criteria are often defined in order to prevent DG to supply power in abnormal conditions. They generally consist of voltage and frequency criteria and may imply time delays. Additionally, the neutral grounding of the DG unit should be implemented in accordance with the grid protection scheme; otherwise earth faults may cause over-voltages that may damage utility or customer equipment [76].

Another aspect concerns the protection of the DG installation itself. The protection of DG plant must be ensured and generally requires the use of dedicated internal protection schemes. These schemes should be coordinated with the overall distribution grid protection system. The internal protections are used for DG protection against internal faults and for avoiding DG islanded operation (usually designated as the loss of mains protection), which is not allowed by technical, safety and regulatory issues [4]. For the first case, the current flowing from the grid to the faulted DG unit can be used for detecting the fault. Concerning the loss of mains protection, a critical factor for its unacceptability is the use of autoreclosure schemes in distribution networks. Therefore, the loss of mains protection requires the use of relays that trips the DG unit in the dead-time of any reclousure scheme in order to avoid out-of-phase reconnection. Techniques based on the maximum and minimum voltage and frequency relays, rate-of-change-of-frequency and voltage vector shift are widely used to implement the loss-of-mains protection [4, 75, 76].

2.5.4 Power Quality

The power quality issues comprise the continuity of power supply and the quality of the energy delivered to the consumers. The continuity of power supply is directly related to system reliability. As previously referred, DG units may have a positive impact in terms of reducing the number and duration of customer interruptions if DG units are able to supply the load during power outages or if islanded operation is allowed. Nevertheless, DG units may also have a negative impact on system reliability: for example, if an internal fault in a DG unit leads to network protection tripping and to the disconnection of a large number of consumers which are not directly related to the faulted installation.

The quality of the energy delivered to the consumers is related to the characteristics of the voltage wave form and to the perturbations it may suffer. Depending on the primary energy source and on the technology used for the energy conversion process, the connection of DG units to the grid may raise a certain number of problems which, if not properly addressed, may reduce the quality of supply on the network. The degradation of the power quality may affect the installations of the network users and prevent the network operator from meeting its obligations. The main problems that may be found are: voltage fluctuations, flicker, harmonic and inter-harmonic emissions [4, 76]. DG units are sources of harmonic and inter-harmonic pollution, especially when power electronic converters are used. However, most of the new inverters are being designed based on Insulated Gate Bipolar Transistors

(IGBT) switches; its application combined with appropriated control and filtering techniques is capable of producing very clean outputs [76].

The impact of these phenomena depends largely on the short-circuit power available at the connection point of the DG unit. On weak grids this may be one of the limiting factors for determining the number and size of DG units that can be connected. The impact also depends on the technology used, especially coupling interface with the grid: for instance, coupling systems making use of an electronic interface may help to limit or even to avoid voltage fluctuations or flicker [77].

The connection of certain types of DG units to the distribution grid may lead to the occurrence of voltage fluctuations due to different reasons. This is particularly true for renewable energy sources characterized by rather high generation variability and a stochastic nature (e.g. wind turbines). Additionally, fast voltage fluctuations or voltage step changes may be experienced at coupling and decoupling of the DG units (or their transformers) or at starting up or shut downs.

2.5.5 Stability

Stability of DG units and their capability to withstand disturbances become a more and more important issue as the DG penetration levels are growing. Following the occurrence of disturbances on the network (short-circuits, important line outages, voltage dips, loss of generation plants, or important load variations), the loss of DG plants results in a loss of generation and also on the support to the network. In this respect, the impact of DG in the network depends on several factors, such as:

- The size of the DG plant (the impact is larger for large DG plants), or for higher penetration levels;
- DG on the grid (large number of small units representing a significant total generation may have the same impact as large DG plants);
- The voltage level at the connection point and the network configuration;
- The characteristics of the connection and the DG technology used.

If DG represents an important share of the total generation in the electrical system, DG units tripping can have very negative impacts on system frequency and possibly leading the global system to an unstable operation point that results in a global collapse. Additionally, service restoration procedures of a section of a distribution network with DG require special attention. If the distribution system was relying on DG units to support the load, then, once the circuit is restored, the power demand will come up before DG units can be reconnected, which may cause significant overloads in the system [4].

In distribution grids connection criteria, requirements are already often specified concerning the capability of DG to operate under specific voltage and frequency ranges that can occur in degraded conditions. Resulting from the important developments in wind energy penetration levels, system operators now require fault ride through capabilities in order to ensure that the DG units will not disconnect in the case of voltage dips [51].

2.5.6 Network Operation

The current philosophy followed by distribution network operators relies on the least possible monitoring and control actions over the grid, usually designated as a “passive distribution network”. These networks were designed through deterministic procedures and considering the “worst case scenario” approach, which by itself tries to solve the critical cases in the planning phase [14]. The use of this philosophy relies on very well established principles of radial distribution systems such as the unidirectional behaviour of power flows. However, the increasing penetration levels of DG require a step ahead and a higher degree of control and coordination between the distribution network and DG units. Therefore, an immediate consequence resulting from the increasing DG penetration levels is the need of an active management of the distribution system. The active management system offers an effective capability of disposing from each resource according to the circumstances at a time [8].

Active management of distribution networks aims to solve some problems that currently are a bottleneck for DG integration. The concept subjacent to active management strategies is to allow the network operator to maximize the use of existing circuits through generator dispatching schemes, voltage and reactive power control (OLTC, capacitor banks, DG units reactive power production) and system reconfiguration in an integrated manner. The basic requisite for achieving the referred functionalities is the existence of a real time monitoring and control system, in a similar way to what take place in the transmission network. Distribution network state estimation and real time modelling of power capabilities, load flow, voltage monitoring, fault levels and security analysis could be used to make the right scheduling and/or constraining decisions at each moment in order to achieve an increased overall performance [14].

2.5.7 ISLANDING AND ISLANDING OPERATION

With the evolution of power systems and the advent of DG, many questions have been raised concerning islanding and possible islanded operation of DG in parts or sections of the distribution grid. The islanded operating conditions occurs when a portion of the utility system becomes electrically isolated from the remaining part of the power system and continues to be energized by DG units [76, 78]. As the distribution networks usually follow a radial topology, opening a circuit at an upstream level will leave the downstream portion of the system fed only by the connected DG units. Causes for circuit opening result from faults leading to the operation of circuit breakers, reclosers or fuses. Such an approach is contrary to the current practice followed by distribution network operators: in face of disturbances occurring in the grid, the DG protection functions should disconnect it promptly in order to avoid the possibility of islanding operation [76, 78, 79]. The protection devices required to be installed at the DG unit should detect the fault and trip it before an island can be formed.

An electrical island formed under these conditions should not last for a long time period, unless the aggregated active and reactive DG generation closely matches the load demand. Otherwise, voltage and frequency will change rapidly, which will be detected by voltage and frequency relays used for anti-islanding protection purposes. The referred anti-islanding detection methods are usually denominated as passive detection methods, since they rely only on local measurement of electrical quantities such as voltage. These methods are widely used since they are not costly, but their effectiveness is questionable due to the possibility of significant non-detection zones [80, 81]. Non-detection zones corresponds to sufficiently small active and reactive power mistakes leading to voltage and frequency variations not large enough for anti-islanding devices detect main grid disconnection. In order to minimize non-detection zones, active anti-islanding detection methods were created in order to accelerate the reach of voltage and frequency trip points. Active anti-islanding methods manipulate electrical quantities by introducing a positive feedback destabilizing control in the system that accelerates frequency and voltage deviation in an islanded system and accelerates the reaching of voltage and frequency tripping points. When the DG is connected to the utility grid, the stiffness of the external grid ensures system stability. Following islanding, the destabilizing control leads the system to a tripping point due to the induced instability control feedback [78].

Under the current distribution network operation philosophy, safety, power quality and system integrity issues are on the basis of the renitence of distribution utilities to not accept islanded operation practices. Inadvertent islanding conditions present serious problems to line workers safety once DG sources feed the system after the main energy source under network operator responsibility is disconnected. Additionally, islanded systems may be not properly grounded and the protections systems may be uncoordinated due to the significant changes observed in short-circuit power. In terms of power quality, the utility do not have control over voltage and frequency within an island. Therefore, power quality may be degraded and damage network or customers equipments. Also, reliability indexes may be affected since islanding may hinder service restoration by requiring line crews spending additional time to disable island conditions. Issues like automatic reclosure coordination are of utmost importance regarding the very short time island detection. After islanding, the island may quickly drift out of phase with the utility system. When a reclosure occurs, the utility will connect out of phase with the island, which can cause damages to utility equipment, to the DG units supporting the island or to customer loads [76, 78].

As previously referred, DG units can contribute to increase system reliability, especially if certain conditions are verified in order to allows islanded operation. Otherwise, reliability levels are the same as it was before integrating DG units since those units are just injecting energy into the grid, but do not provide any other additional functionality. This is a radical change that needs to be assumed by DNO. Such an approach requires a careful coordination of protection equipments and the development of new functionalities and system studies in order to guarantee an effective islanded operation: identification of adequate protection schemes under islanded operation, power flow analysis and voltage and frequency control. When DG units are operating in parallel with the utility system, they are usually controlling the output power factor and providing energy support to the owner and/or to the grid. Voltage and frequency control modes are not the current practice for DG units operation in parallel with the stiff system. Technological advances are contributing to ease the installation of voltage and frequency control system in many DG units installed in the grid. In fact, the wide use of electronic control systems and communication modules allows the effective establishment of an interface between DG and network operators. The possibility that DG have to offer system services such as voltage and reactive control, in addition to the possibility of operating under islanding conditions for reliability increase may effectively contribute to decide upon the cost-effectiveness of installing the required regulation and communication systems.

Following these general guidelines, the use of DG units for supporting islanded operation of portions of the electrical system following unplanned disturbances is presently being under investigation by the scientific community. One of the first approaches dealing with islanding operation can be found in [82]. The authors undertake a study over the Finish power system, which is decentralized by nature: it relies on central generation units plus generation facilities in large cities (connected at the subtransmission network) and providing heat for space and water heating. When severe power disturbances occur in the system, a possible solution is the controlled breaking of some tie-lines in order to separate the grid into smaller islands. The authors clearly show the advantages of islanded operation by exploiting the decentralized generation system and present a set of requirements in terms of power balance within the island, load shedding mechanisms, voltage and frequency control and earthing and protection schemes to be used during islanding operation.

In [83], the authors describe how captive power plants in industrial facilities in India can contribute to enhance the reliability of supply. Captive power plants is the designation used for “a plant set up by any person to generate electricity primarily for his own use and includes a power plant set up by any cooperative society or association of persons for generating electricity primarily for use of members of such cooperative society or association” [84]. In other words, captive power plants are power plants commissioned by industries to meet self-consumption and are ultimately equivalent to DG units. The main driver for captive power plants installation in certain industries is the need of increasing the reliability of supply due to the low quality of supply provided by the Indian electric power system. The authors describe the use of several schemes, combined together in order to detect a disturbance, its severity and properly isolate the industrial facility from the grid. By using rate of change of frequency relays, underfrequency and undervoltage relays, reverse power relays, directional current relays and over-voltage relays combined with reactive power inflow, the authors state that the proposed protection systems achieve a high robustness to detect the majority of possible disturbances occurring in the grid and lead to system isolation. The use of under frequency load shedding schemes of less important loads is also used as a means of preventing islanded system collapse. Settings for under frequency load shedding able to guarantee system stabilization in the majority of cases were determined off-line by means of dynamic stability studies and considering different operating conditions.

Another contribution [85] addresses the operation of combined cycle power plants in islanding operation. Firstly, the authors focus the modelling of cogeneration plants for dynamic simulation purposes, as well as the turbine regulators. The developed models are then tested on a realistic industrial power plant, comprising two 25 MW gas turbines and two 3 MW steam turbines coupled to 40 MVA and 5 MVA synchronous generators respectively. The authors present the dynamic simulation results for system islanding following a three-phase fault in the main power system. Two scenarios were considered by the authors: the industrial power plant importing power from the upstream network and the industrial power plant exporting power for the upstream network. In both cases the authors show results demonstrating the effectiveness of the isochronous control used in one synchronous machine for frequency regulation purposes in the islanded system. Additionally, the authors use a load shedding mechanism as a mean for facing a generation capacity deficit in the scenario where the industrial power plant is importing power from the upstream network.

As previously stated, DG units operating in parallel with the stiff system usually provide active and reactive power support instead of voltage and frequency control. Therefore, if islanding operation is to be allowed following network disturbances, proper control functionalities are required in order to change the DG units control mode during and in the moments subsequent to the islanding process. In this case, voltage and frequency control are the key issues in order to assure local stability of operation. In [86], the authors focus on the development of a rule based control system in order to provide the necessary switching between the control strategies during parallel operation with the utility grid and when islanding occurs. A key issue defined by the authors is the development of a control system not requiring a communication infrastructure for detecting and changing between the control modes. Instead of using communications, the system relies on generator terminal measurements. During network disturbances, the control system switches the excitation control mode from power factor control to voltage control. The control system automatically switches to power factor control mode when normal gird-connected conditions are restored. During islanded operation, the DG unit governor is responsible for maintaining the frequency within a tight range. The possible use of load shedding strategies for accommodating islanding operation in the scenarios where load exceeds generation capacity is also proposed. The frequency control strategy is also automatically reset following normal grid-connected operation.

In the referred scientific works, the authors report the problem of intentional islanding of distribution networks following disturbances occurring in an upstream level. Therefore, islanding operation is presented as a result of an unplanned action and such a situation is possible if adequate separation and protection devices are installed in the system. However, islanding operation can also be effective as a result of pre-planned and deliberated switching events, resulting for example from the need of performing maintenance works in a certain area of the distribution system. In [87] it is presented a study on feasibility of adopting intentional (pre-planned) islanding operation in distribution networks with DG by studying the behaviour of different types of generating units and additional requirements, specially in terms of system protection settings. The study is based on a real 60 kV distribution network with large DG penetration levels (including hydro, wind and diesel generators) located in the north of Portugal. In order to succeed in the pre-planned islanding, the authors found that a simple procedure consisting on the reduction of the power flow in the interconnection point must be envisaged prior to separating the distribution grid from the transmission system. This reduction must be performed by disconnecting some load inside the island to be formed and/or increase local generation. Such a reduction in power flow is required in order to avoid protection tripping. It is important to notice that in Portugal DG units usually has interconnection protections set for instantaneous tripping, a situation that offers a significant limitation when islanding operation is to be envisaged. Therefore, in order to increase the success of islanding operation, a relaxation in the protection settings should be considered (by addressing interconnection relays and load shedding relays).

In [18] the authors address the planned and unplanned islanding issues of a distribution network with DG units, which is generally referred as a MG. Additionally, the authors evaluate the effects resulting from integrating dispatchable DG units with fast acting power electronic interfaces with adequate capacity to meet active and reactive power demands.

Islanding phenomena resulting from pre-planned switching events can be significantly smoothed since a proper load sharing can be performed among several DG units in order to minimize the power transfer with the upstream network. Even power quality levels can be maintained for sensitive loads during the pre-planned islanding transitions. Successful unplanned islanding resulting from faults in the upstream network is also demonstrated to be feasible; however, islanding detection is needed and also a change in the control strategy of DG units. In the moments subsequent to islanding, power swings and frequency variations occurs in the islanded system. By exploiting the fast acting capabilities of dispatchable DG units with power electronic interfaces, the authors show that it is possible to effectively damp such oscillations and ensures angle stability during autonomous operation.

In [17] the authors further exploit the work presented in [18], by proposing active and reactive power management strategies for DG units connected to the grid through power electronic interfaces. No communications are assumed to be available among the DG units. Therefore, the power management strategy is implemented based on measurements taken at DG units terminals. The proposed active and reactive power management strategies provide active and reactive power set-points for each DG unit in order to:

- Share active and reactive power among different DG units during autonomous operation;
- Achieve a fast response to disturbances and transients;
- Determine the final power generation set-points of the DG units to balance power and restore frequency to the nominal value;
- Allow the autonomous island to be re-synchronized with the utility system.

The power management strategy proposed by the authors comprises two parts: active power management and reactive power management. The active power management strategy determines the active power output of each DG unit based on frequency variations, as shown in the block diagram of Figure 2-15. The output of the control block is the d-axis current reference of the *n-th* unit $i^d_{ref\ n}$ corresponding to the real power reference of the unit ($P_{ref\ n}$), and is determined by

$$P_{ref\ n} = P_n^d + P_n^r \tag{2-3}$$

where P_n^d is the power variations due to frequency changes (determined by the frequency droop characteristic) and P_n^r is determined through the Proportional-Integral (PI) controller PI-1 in order to restore the nominal frequency of the system. The frequency droop characteristic is represented by

$$P_n^d = \frac{1}{k_n}\left(\omega_0 - \omega_n\right) + P_n^0 \tag{2-4}$$

where k_n is the droop characteristic for the *n-th* DG unit, ω_0 is the reference frequency of the islanded system and P_n^0 is the initial power generation assigned to the unit.

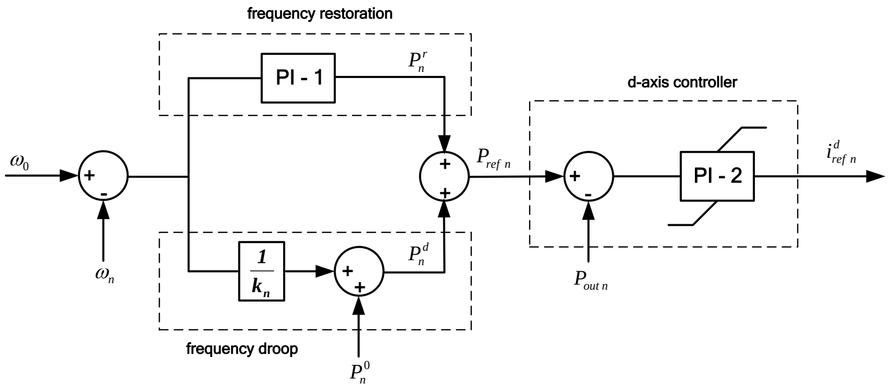


Figure 2-15: Active power controller for the *n-th* DG unit

For the reactive power management strategies, the authors proposed three possible schemes, which are illustrated through the block diagrams in Figure 2-16:

- **Voltage-droop characteristic:** the V-Q droop characteristic is used to determine the reactive power reference $Q_{ref\ n}$. A PI controller is then used to derive the q-axis current $i_{ref\ n}^q$ to adjust the reactive power output of the DG unit. Therefore, reactive power injection varies according to node voltage variations.

- **Voltage regulation:** in this case, reactive power injection is regulated in order to maintain the node voltage where the DG unit is connected at a certain level ($V_{ref\ n}$). Then, a PI controller is used for the same purposes described in the voltage-droop control scheme.

- **Load power factor correction:** in this case, the DG unit reactive power injection is controller in order to improve the power factor or to meet the reactive power requirements of the load connected to the same bus. The relation among the load power factor (pf_n^{l}), the desired power factor ($pf_n^{l\,c}$) and the compensation factor ($m_{pf\ n}$) is given by:

$$pf_n^{l\,c} = \frac{pf_n^{l}}{\sqrt{\left(pf_n^{l}\right)^2 + \left(1 - m_{pf\ n}\right)\left(1 - \left(pf_n^{l}\right)^2\right)}} \tag{2-5}$$

where $m_{pf\ n} = 1$ corresponds to a situation with a full compensation of the reactive load, while $m_{pf\ n} = 0$ corresponds to no reactive power compensation.

After discussing the power management strategies, the authors present a methodology for deriving the small signal model of a MG in order to evaluate its stability, design and optimize the different control parameters of the power management strategies and to investigate the impact of the proposed strategy on MG dynamics.

An impact study of intentional islanding of DG connected to the radial subtransmission system in the Thailand electric power system is presented in [88]. The system under study consists of a 115 kV network with two DG units with ratings of 90 MW and 50 MW. The authors consider that system islanding may occur due to faults in the upstream network or due to schedule maintenance activities. For both islanding conditions, detailed system studies are presented, considering different load scenarios. The use of load shedding mechanisms is also suggested, especially in heavy load scenarios, in order to maintain the system frequency and reach the steady state conditions quickly after islanding. Also, the coordination between load shedding mechanisms and under frequency protection relays of DG units is required in order to maintain stable system frequency. Considering islanding operation, the authors present also detailed studies for different operating conditions such as: load following and load rejection, large motor starting and faults occurring in the islanded system. The authors suggest also the use of adaptive protection schemes, since they allow changing the settings of protective devices from a normal operation state to islanding operation mode. This is important because, during islanding operation, the grid becomes weaker and protection settings need to be modified comparatively to the interconnected operation mode.

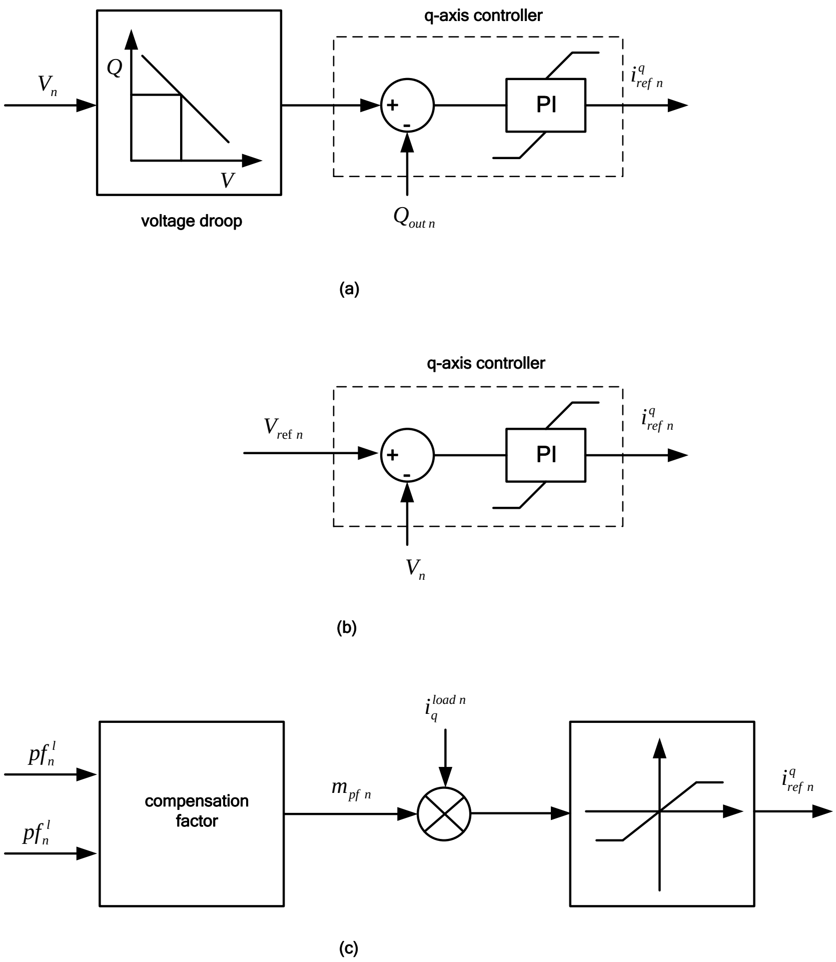


Figure 2-16: Possible reactive power controllers for the *n-th* DG unit. (a) voltage-droop characteristic; (b) voltage regulation; (c) reactive power compensation

In the referred works concerning the possibility of islanding operation of certain sections of the distribution network, the authors always assume the existence of at least one synchronous generator. This is the most well understood unit for voltage and frequency control procedures in power systems. A synchronous generator is intrinsically a voltage source that can be used for building up an electrical network, where it is possible to connect other types of generating units. With the advent of DG units such as fuel cells, microturbines or photovoltaic panels, the formation of distribution network islands feed solely through power electronic interfaces is a complex issue that need to be properly tackled.

In [89, 90] the authors focus on the investigation of the feasibility of islanding operation of distribution networks with DG units connected to the grid through power electronic interfaces. The authors provide an interesting overview about the control problems resulting from the use of DG units with power electronic interfaces, which will be discussed in deep detail in a later chapter within the scope of this dissertation. Conventional power systems intrinsically have kinetic energy storage in the rotating rotor of synchronous generators (inertial system). The system inertia is the source for ensuring power balance in the moments subsequent to changes in the power system operating conditions (load switching, generators outages, etc). The resulting consequence is a slight frequency variation. In the case where power electronic interfaced DG units are the dominant source of power, together with the fact that fuel cells and microturbines are inertia-less systems, new approaches for system control during islanding operation are required. In order to face this problem, it is essential to provide some form of energy storage to guarantee the initial energy balance following transients. This solution mimics the inertia contribution from synchronous machines for control in conventional power systems. Another issue that arise is the power sharing among DG units in islanding operation without relaying in communications. These can be achieved by means of frequency droop methods, since frequency is a global variable of the system. Therefore, it is proposed a frequency droop control method, which allows DG units to communicate without an explicit communication system, since frequency varies as a function of power demand.

In [91], the authors devote special attention to modelling of power electronic interfaces and its control requirements in the case where no synchronous generator is directly connected to the grid. Depending on the DG operation mode, two control strategies can be implemented for operating the inverter:

- **PQ control:** the inverter is controlled to meet a desired active and reactive power set-point;

- **Vf control:** the inverter control schemes allows an independent regulation of terminal voltage and frequency. In order to achieve these control characteristics, active power/frequency and reactive power/voltage droops are used.

In order to run the system into islanding operation, the control scheme of the power electronic interfaces must be switched from PQ control (used during the interconnected operation mode) to Vf control during autonomous operation. Such procedure requires the fast detection of the islanding conditions and a communication path to change the control modes of the inverters following the change of the operating conditions (system islanding or reconnection to the main grid).

Especially from [17, 18, 86, 89, 90], a key concern for distribution networks islanded operation is the development of control techniques for DG units not relying on fast communications: the control of DG units should be based on information available locally at its terminals, since the use of communication systems for an increasing number of DG units is impractical. The fundamental problem of a complex control and communication system is that a failure of a component will bring the system down. When switching to islanding operation following disturbances in the upstream system, the DG units should immediately change from a dispatched power mode to a voltage and frequency control mode. From a communication point of view, only the steady state power and voltages need to be dispatched and assigned to each DG unit for optimization purposes. However, this procedure runs in larger time frames (few minutes) and should not compromise system operation in the moments subsequent to system islanding and following transients that may happen during islanded operation.

The bibliography survey on islanding operation shows that islanded operation of distribution feeders would allow the supply of power to the customers until the system is restored. In certain areas where the transmission network is often subject to disturbances (e.g. strikes of lightning) and voltage dips, islanded operation may provide higher quality of supply.

Islanded operation of distribution grids is a very complex problem and the possibility of deliberate islanding must be very carefully planned in order to ensure a safe and reliable operation of the islanded network and to guarantee a sufficient level of quality of supply to the customers. The DG units need also to be equipped with suitable voltage and frequency regulation devices and modifications to the grid itself are generally required (e.g. concerning the protection scheme and protection coordination, installation of synchronization devices, etc.). However, this is presently not a trend in the power system industry, but it is expected to have high importance in a near future in order to increase power system security and reliability following the exploitation of DG units.

2.6 SUMMARY AND MAIN CONCLUSIONS

In this chapter a general overview about the paradigm change in the electric power system industry that results from a large scale integration of DG in the system is presented. DG is being promoted worldwide to a large extent as a mean of reducing energy costs and environmental burdens by limiting the emissions of GHG and reducing transmission and distribution costs. In the last years, this change of paradigm was more perceptible due to the connection of large amounts of DG sources at the MV distribution networks. However, the recent technological developments contribute to the development of DG units with very specific characteristics, which make them suitable to be connected to the LV distribution grids.

From the utility point of view, DG deployment can potentially reduce the demand for distribution and transmission facilities. Clearly, distributed generation located close to the loads will reduce the flows in transmission and distribution circuits with two important effects: loss reduction and ability to potentially defer reinforcement or upgrade investment costs. Furthermore, the presence of generation close to the demand avoids the transmission and distribution costs, thus potentially contributing to reduce delivered energy costs. Also, a significant reduction on customer interruption times can be achieved is if islanded operation is allowed following disturbances in the upstream system.

The electrical distribution network of the future is, however, more than just massive integration of DG units into the grids. In fact, DG connection to distribution networks following a purely passive philosophy (fit and forget) may cause more problems than those it might solve. Costly and effectively DG integration involves the adoption of more ambitious concepts related to active management of the distribution grids, where responsive loads, storage devices and DG can be used together to improve the overall system efficiency, quality of electricity supply and operating conditions, leading to a fully active distribution network. Under this scenario, the possibility of forming autonomous or non-autonomous MG (distribution network islanding operation) is a promising solution that needs to be explored further in order to be considered as an effective way to increase power system security and reliability. The possibility of operating a MG as a single controlled entity that can offer services to the DNO in order to help solving stressing conditions is discussed in the next chapter of this dissertation.

Chapter 3

CONCEPTS AND MODELS FOR MICROGENERATION AND MICROGRIDS

3.1 INTRODUCTION

In the previous chapter were briefly presented and discussed the main factors leading to a massive adoption of Distributed Generation (DG) resources throughout the electric power system. In the last years, the change of paradigm was more perceptible due to the connection of large amounts of DG sources to Medium Voltage (MV) distribution networks. However, recent technological developments are contributing to the maturation of some DG technologies, such that they are becoming suitable to be connected to Low Voltage (LV) distribution grids. Regarding a scenario characterized by a massive integration of DG in the network, several technical issues need to be tackled. In order to face these challenges and to realize the potential benefits of DG resources, it is imperative to develop a coordinated strategy for its operation and control, together with electrical loads and storage devices. A possible approach is the development of the MicroGrid (MG) concept, as it was introduced in Section 2.2.2. Within the scope of this dissertation, a MG comprise a LV distributed system with small modular generation technologies, storage devices and controllable loads, being operated connected to the main power network or islanded, in a controlled coordinated way. The small modular generation technologies, also denominated by MicroSources (MS), are small units with electrical power ratings of less than 100 kWe, most of them with power electronic interfaces, and exploiting either Renewable Energy Sources (RES) or fossil fuels in high efficiency local Combined Heat and Power (CHP) applications. The types of MS suitable to be used in a MG are those listed in Section 2.4 and are: micro gas turbines, fuel cells (different types) photovoltaic panels, small and micro wind generators, together with storage devices such as batteries, flywheels or supercapacitors.

The MG concept is a natural evolution of simple distribution networks with high amounts of DG, since it offers considerable advantages for network operation due to its additional control capabilities. The formation of active LV networks through the exploitation of the MG concept can potentially provide a number of benefits to the Distribution Network Operator (DNO) and to the end-user. These benefits are in-line with the major factors (identified in Section 2.3) contributing to a massive adoption and deployment of DG technologies [6]:

- MG operation is based in a large extent on RES and MS characterised by zero or very low emissions. In addition, the reduction of distribution system losses resulting from DG integration contributes also for decreasing Greenhouse Gas GHG emissions.

- MG will exploit either RES or fossil fuels in high efficiency local micro-CHP applications. The intensive use of micro-CHP applications contributes to the raise of overall energy systems efficiency to levels far beyond what is possible to achieve with central power stations. On the other hand, the exploitation of local RES will contribute to the reduction of the dependence on imported fossil fuel and to increase energy security.

- A consumer integrated in a MG will be able to act both as a buyer or seller of thermal and electrical energy. This flexibility potentially allows the development of a generation system with a higher overall efficiency and being able to be more responsive to customer needs.

- A well designed MG is capable of enhancing power system reliability at the customer level, since two independent sources (the MV distribution grid and DG units) can be used to supply the electrical loads. Also, the transmission system dynamic stability can be improved under a scenario of provision of ancillary services by DG. Additional benefits such as voltage support or enhanced power quality can also be provided by MG.

- The installation of power generation closer to the loads lowers overall system Transmission and Distribution losses, and can be an interesting solution in order to face the growing power needs. In fact, DG can potentially prevent or defer the investments required for upgrading or building additional central power generation units or transmission and distribution infrastructures.

Achieving a coordinated control of the MG cell in order to provide the required flexibility of operation is a challenging task and can be realized only by means of the hierarchical control structure to be developed according to MG specific requirements. The exploitation of a centralized control strategy would require multiple high data rate bi-directional communication infrastructures, powerful central computing facilities and a set of coordinated control centres. Therefore, such an approach is not attractive for a practical realization due to the inherent high costs of a high data rate and extremely reliable telecommunication and control infrastructure. Additionally, and in order to guarantee an efficient and reliable control of the MG under abnormal operating conditions, the most practical approach should rely on a network of local controllers in order to handle the resulting transient phenomena and guarantee MG survival. Therefore, MG control strategies should be based on a network of controllers with local intelligence. The information to be exchanged should be limited to the minimum necessary to achieve the optimization of MG operation when the MG is connected to the main grid, to assure stable operation during islanding conditions and to implement local recovery functionalities after a general failure (local Black Start functionalities) [6]. The development of the MG operation and control architecture is discussed in Section 3.3.

Regarding MG operation and control specificities, they are inherently associated with a set of issues, including safety, reliability, voltage profile, power quality, protection, unbalance/asymmetry and non-autonomous/autonomous operation. In particular, the operation and control issues of a MG are challenging problems due to the very specific nature of the new electrical power system under consideration. Therefore, adequate modelling of MS, storage devices and power electronic interfaces is also addressed in this Chapter (Section 3.4), since it is the first step required in order to evaluate the dynamic interactions that may occur within a MG and to evaluate the feasibility of the control strategies to be derived (Chapter 4).

This Chapter contains therefore the presentation of the MG concept and its overall control and management architecture, together with the description of the models adopted to describe MS behaviour, taking into account the objectives of this dissertation. The appropriate MS control structures and their corresponding power electronic interfaces are also presented. Such modelling is of paramount importance for the success of the development of the research work of this dissertation.

3.2 THE FOUNDATION OF THE MICROGRID CONCEPT

Europe, North America and Japan are leading the revolution being faced in the conventional electric power systems operation paradigm, by actively promoting research, development, demonstration and deployment of MG. Additional information on international MG research activities and demonstration sites can be found in [92, 93]. The MG concept was originally introduced in the United States by the Department of Energy, who have actively supported considerable work in the area. More specifically, the Consortium for Electric Reliability Technology Solutions (CERTS) was founded in 1999 to research, develop and disseminate new methods, tools and technologies in order to protect and enhance the reliability of the United States electric power system and the efficiency of competitive electricity markets [94]. The CERTS electricity reliability research covers several areas, one of which is devoted to Distributed Energy Resources (DER) integration, by developing tools and techniques to maintain and enhance the reliability of electricity service through a cost-effective, decentralized electricity system based on high penetrations of DER.

Since the early beginnings, a “fit and forget” policy was followed by distribution companies when connecting DG to the system. However, a true integration policy is needed, through which a system perspective is used to capture the potential benefits that may arise to customers and to the utilities form increasing DG penetration levels. The CERTS MG concept is an advanced approach aiming to the effective large scale DG integration in distribution systems. The conventional approach for DER integration is focused on the impact resulting from the connection of a small number of DG to the grid, as it can be seen by analysing the IEEE P1547 standard (IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems) [79]. The focus of this standard is to assure DG is quickly disconnected following the event of grid disturbances. On the contrary, the MG is regarded as an aggregation of loads, MS and storage devices that can be operated connected to or separate from the main electricity grid. One of the key functionalities of the MG is to seamlessly separate from a normal utility interconnected state to islanding operation and serving the critical loads until utility service is restored. Following system disturbances, DG and electrical loads can automatically separate from the main power system, therefore isolating the MG from the disturbance affecting the system. The adoption of intentional islanding practices can contribute to increase local reliability indexes to levels higher than the ones ensured by the electric power system as a whole.

3.2.1 THE CERTS MICROGRID CONCEPT

The CERTS MG concept assumes an aggregation of loads and MS operating in a single system and providing both power and heat to local consumers. The majority of MS should be power electronic interfaced in order to provide the required flexibility, assure MG operation as a single aggregated system and to achieve a plug-and-play simplicity for each MS. From the bulk power system perspective, the MG can establish contractual agreements for energy and possibly other services in a similar way to what happens with ordinary consumers or power producers. From the technical point of view, MG connection to the distribution grid should satisfy at least minimum requirements that other conventional equipments are obliged to satisfy. However, the CERTS emphasizes MG flexibility should be explored further and should not be limited to not jeopardizing the surrounding electrical power system by behaving as a “good citizen” [95].

3.2.1.1 The CERTS MicroGrid Architecture

The CERTS MG exploits mainly DG technologies with power electronic interfaces in order to provide the required flexibility and controllability. In principle, no limitations are imposed to DG ratings; nevertheless, pragmatic reasons related to availability and controllability, lead to focusing the effort on LV grids to which microturbines with power ratings less then 500 kW are connected. Although it is not the case, other emerging MS technologies like fuel cells can also be considered as candidates to be integrated in the MG. The possibility of extending the MG concept to large systems is also referred. In case of large sites, it is suggested to divide the loads in many controllable units (buildings, industrial sites, etc.) and exploit the distribution system for the interconnection of several MG in order to supply the entire system [95].

The basic CERTS MG architecture is shown in Figure 3-1, where it is represented a typical LV distribution system with several radial feeders (in these case A, B and C). The LV side of the distribution transformer is the Point of Common Coupling (PCC) between the MG and the distribution system and it is used to define the boundary between both systems. At the PCC, the MG should comply with existing interface requirements (for example, the IEEE P1547 standard). As it shown in Figure 3-1, the key elements of the CERTS MG architecture are [19, 90, 95]:

- **Microsource Controller (Power and Voltage Controller):** the basic MG operation relies on the MS controller in order to perform the following actions: control feeder power flow according to pre-defined criteria, voltage control at the MS connection point, load sharing among MS following MG islanding and MG synchronization with the upstream MV network. The response time of the MS controller is very fast (in the order of milliseconds) and the control functions are performed using only measurements available locally at the controller connection point. Running in a larger time frame, the Energy Manager, a kind of central control system, defines operational strategies to achieve an optimal management of the entire MG. This requires a communication channel to be established between the Energy Manager and the MS controllers. The MG control architecture confers the plug-and-play characteristic to MS, that is: MS can be connected to the MG without requiring modification in the control and protection functions of the units already making part of the system.

- **Energy Manager:** the energy manager is responsible for managing the MG operational control, by periodically providing the adequate power and voltage dispatches to the MS controllers according to pre-defined criteria such as: reduction of MG losses, maximizing MS operation efficiency, satisfying the contractual agreements at the PCC, etc. The control functions in the Energy Manger are executed with a periodicity of a few minutes.

- **Protections:** the MG protection scheme should ensure an adequate response to faults occurring in the upstream MV network or in the MG itself in order to provide the required reliability levels to the critical loads or MG sections. The isolation speed is dependent on the specific customer loads on the MG (in some cases, voltage sag compensation can be used without separation from the distribution system in order to protect the critical loads). If the fault is located within the MG, the protection coordinator should isolate the smallest possible section of the radial feeder in order to eliminate the fault. The development of the protection system requires special attention due to the massive presence of power electronic converters, which have reduced capability to provide large fault currents. Eventually, it will be necessary to develop alternative methods to the conventional over-current protection schemes used in distribution systems.

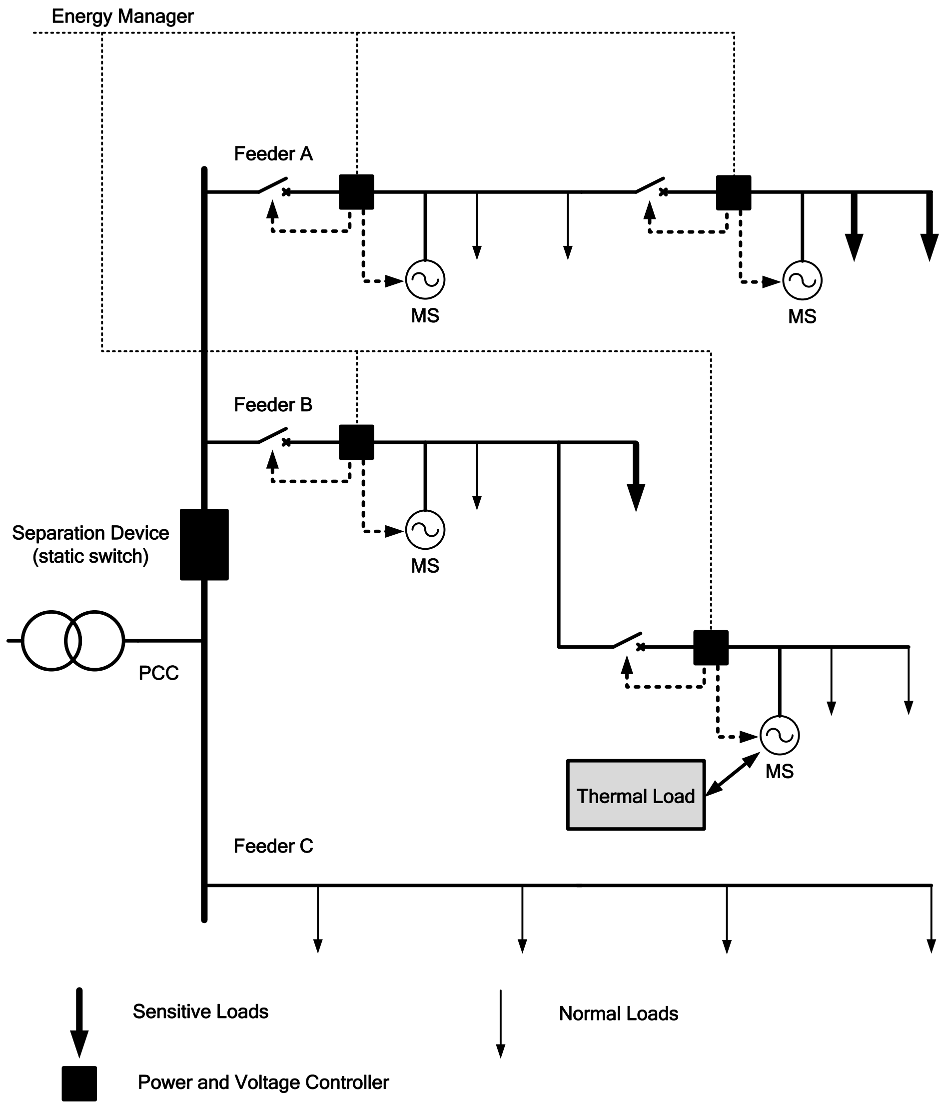


Figure 3-1: The CERTS MG architecture

In addition to MG islanding, the CERTS MG architecture allows the following operation modes when the MG is interconnected with the upstream system [90]:

- **Unit Power Control Configuration:** each MS control its own power injection and the voltage magnitude at the connection point. This operation mode is specially envisaged for MS associated to thermal loads, since electric power production is driven by thermal loads requirements.

- **Feeder Flow Control Configuration:** the MS are operated in order to control the voltage magnitude at the point of connection and to maintain a schedule power flow in strategic points of the feeder. In this case, load variations in the feeder are picked up by the MS.

- **Mixed Control Configuration:** in this case some MS regulate their output power, while others control feeder flows.

3.3 THE MICROGRID OPERATIONAL AND CONTROL ARCHITECTURE

In the European Union, the first major effort devoted to MG was initiated with the Fifth Framework Program (1998-2002), which funded the R&D project entitled "*MICROGRIDS – Large Scale Integration of Micro-Generation to Low Voltage Grids*" [16]. Within this project, a MG can be defined as a LV network (e.g., a small urban area, a shopping centre or an industrial park) plus its loads and several small modular generation systems connected to it, providing both power and heat to local loads. A MG may also include storage devices (such as batteries, flywheels or supercapacitors) and network control and management systems [6]. The MG concept developed within the MICROGRIDS project, and followed in this dissertation, is shown in Figure 3-2. The figure illustrates a typical LV distribution network connected to the secondary winding of a MV/LV distribution transformer. This MG example includes:

- Several feeders supplying electrical loads;

- Microgeneration systems based on renewable energy sources such as Photovoltaic (PV) or micro wind generators and fuel-based MS in CHP applications (a microturbine and a fuel cell);

- Storage devices;
- A hierarchical-type management and control scheme supported by a communication infrastructure, in order to ensure all the elements of MG are aggregated in a single cell that is interfaced to the electrical power system in a similar way as ordinary consumers or DG sources.

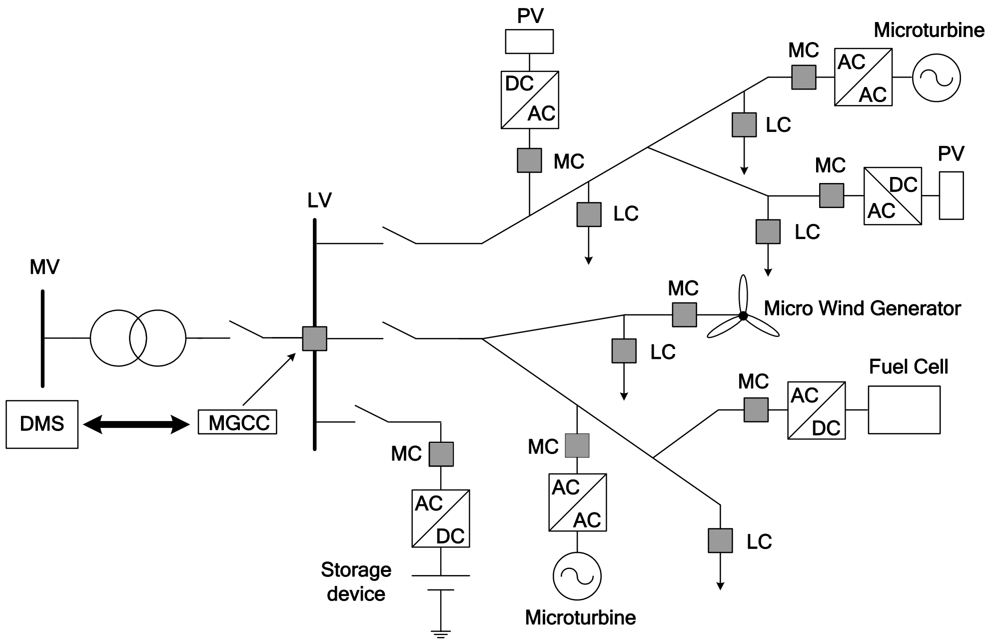


Figure 3-2: MG architecture, comprising MS, storage devices and a hierarchical control and management system

A MG cell is intended to operate connected to or isolated from the upstream MV network, allowing the definition of the following operation modes [96]:

- **Normal Interconnected Mode:** the MG is connected to the upstream MV network, either being totally or partially supplied by it (depending on the dispatching procedures used to operated the MS) or injecting some amount of power into the main system (in case the relation between the MS production level and the total MG consumption allows this type of operation).
- **Emergency Mode:** following a failure in the upstream MV network, or due to some planned actions (for example, in order to perform maintenance actions) the MG can have the ability to smoothly move to islanded operation or to locally exploit a service restoration procedure in the advent of a general blackout. In both cases, the

MG operates autonomously, in a similar way to the electric power systems of the physical islands.

In order to achieve the desired flexibility, the MG system in centrally controlled and managed by the MicroGrid Central Controller (MGCC), installed in the LV side of the MV/LV distribution transformer, which communicates with controllers located in a lower hierarchical level. The second hierarchical control level comprises MS and storage devices being locally controlled by a Microsource Controller (MC) and the electrical loads or group of loads being controlled by a Load Controller (LC) [96]. The proper operation and control of the entire system requires communication and interaction between the referred hierarchical control levels as follows:

- the LC and MC, on one hand, as interfaces to control loads through the application of the interruptability concept, and MS active and reactive power production levels;
- the MGCC, on the other hand, as the central controller responsible for an adequate technical and economical management of the MG according to pre-defined criteria, by providing set-points to MC and LC.

It is also expected the MGCC to be able to communicate with the Distribution Management System (DMS), located upstream in the distribution network, contributing to improve the management and operation of the MV distribution system through contractual agreements that can be established between the MG and the DNO. In order to enable this scenario, the conventional approaches to DMS need to be enhanced with new features related to MG connected on the feeders. The issues of autonomous and non-autonomous operation of the MG and the related exchange of information are examples of new important issues to be tackled in the near future [6].

The MC can be housed within the power electronic interface of the MS. It responds in milliseconds and uses local information and the demands from the MGCC to control the MS during all events. The MC will have autonomy to perform local optimization of the MS active and reactive power production, when connected to the power grid, and fast load-tracking following an islanding situation. LC also need to be installed at the controllable loads to provide load control capabilities following demands from the MGCC, under a Demand Side Management (DSM) policy, or in order to implement load shedding functionalities during emergency situations. By exploiting the proposed architecture, the required MG operation and control functionalities that assure a stable operation in the first moments subsequent to transients are implemented based only on information available locally at the MC and LC terminals. Operational strategies intended for global MG optimization will run periodically (few minutes) in the MGCC and the resulting dispatch (voltage set-points, active and reactive power set-points, loads to be shed or deferred in time, etc.) will be communicated to local controllers (MC and LC) in a second stage corresponding to a larger time frame [6, 96].

The MGCC heads the technical and economical management of the MG. During the Normal Interconnected Mode, the MGCC collects information from the MC and LC in order to perform a number of functionalities. A key functionality to be installed in the MGCC is forecasting of local loads and generation. The MGCC will be responsible for providing system load forecasts (electric and possibly heat). It will also forecast in a simpler manner power production capabilities (exploiting information coming from wind speed, insulation levels, etc.) and it will use electricity and gas costs information and grid needs, together with security concerns and DSM requests to determine the amount of power that the MG should absorb from the distribution system, optimizing the local production capabilities. The defined optimized operating scenario is achieved by controlling the MS and controllable loads in the MG in terms of sending control signals to the field [6].

In the Emergency Mode, an immediate change in the output power control of the MS is required, as they change from a dispatched power mode to one controlling frequency and voltage of the islanded section of the network. Under this operating scenario, the MGCC performs an equivalent action to the secondary control loops existing in the conventional power systems: after the initial reaction of the MC and LC, which should ensure MG survival following islanding, the MGCC performs the technical and economical optimization of the islanded system. It is also important to the MGCC to have accurate knowledge of the type of loads in the MG in order to adopt the most convenient interruption strategies under emergency conditions [6]. Being an autonomous entity, the MG can also perform local Black Start (BS) functions under certain conditions. If a system disturbance provokes a general blackout such that the MG was not able to separate and continue in islanding mode, and if the MV system is unable to restore operation in a specified time, a first step in system recovery will be a local BS. The strategy to be followed will involve the MGCC, the MC and the LC using predefined rules to be embedded in the MGCC software. Such operational functionalities ensure an import advantage of the MG in terms of improved reliability and continuity of service and are discussed in Chapter 4.

3.3.1 THE MICROGRID COMMUNICATION INFRASTRUCTURE

In the proposed MG architecture, some communication capabilities need to established between the MGCC and the local controllers, namely for control and operational optimization purposes. The amount of data to be exchanged between network controllers is small, since it includes mainly messages containing set-points to LC and MC, information requests sent by the MGCC to LC and MC about active and reactive powers and voltage levels and messages to control MG switches. Also, the short geographical span of the MG may aid establishing a communication infrastructure using low cost communications. The adoption of standard protocols and open technologies allows designing and developing modular solutions using off-the-shelf, low cost, widely available and fully supported hardware and software components. These solutions provide flexibility and scalability for future low cost implementations [96].

Having in mind the need to reduce costs in telecommunication infrastructures, an interesting solution could be the exploitation of power lines for communication purposes (using the Power Line Communication (PLC) technology). In this case, the connectivity characteristics of the power grid provide the appropriate physical link between the different elements of the MG control system. Therefore, a careful analysis and evaluation of the power grid as the physical path for the communication system was performed within the MICROGRIDS project, namely in what concerns the characteristics of the physical transmission channels. The attenuation of the communication signal, as it propagates along the cable, can be too high if the communications path is too long. When evaluating the quality of the communications channel, another important factor must also be considered: the level and nature of the interfering signals that are present at the input of the receiver. A number of interfering signals are generated by the connected loads and, hence, have different origins and characteristics, e.g. periodic signals (related to and/or synchronous with the power frequency), impulse-type signals and noise-like signals. If the amount of interfering signals is too large, with respect to signal distortion, then the receiver will have difficulties to reproduce the original information with sufficient accuracy [97].

Concerning the communication protocols to be used, a TCP/IP based transport protocol will provide extra functionality, flexibility and scalability, specially in terms future system evolutions like the exploitation of more complex scenarios (for example, multiple MG) or the use of the physical communication layer of the MG in order to support also other communication services. Additionally, the choice of a TCP/IP as the transport protocol makes possible the choice of any physical infrastructure. Therefore, it was proposed to support the MG control architecture without any specific dependence on the access technology, since a number of alternatives support the basic MG communication requirements [97].

3.4 MICROSOURCES DYNAMIC MODELLING

The development of the MG concept previously presented is based on a hierarchical distributed control architecture, where during some emergency situations an autonomous control should be able to run the system. Conceptually speaking, three operating conditions can be distinguished:

- Grid-connected mode;
- Islanding mode;
- Local Black Start.

In order to demonstrate the feasibility of the referred operating conditions, it is necessary to develop a simulation platform able to simulate the dynamic operation of LV networks with MS. Additionally, the models need to describe the dynamic behaviour of MS and their corresponding power electronic interfaces. Most MS technologies that can be installed in a MG are not suitable for direct connection to the electrical network due to the characteristics of the energy they produce. Therefore, power electronic interfaces (DC/AC or AC/DC/AC) are required and need to be adequately modelled. The usual approach followed by several authors when performing MG dynamic and control studies is to represent MS such as fuel cells or microturbines, that are connected to the network through power electronic interfaces, by a constant DC voltage source placed before the inverter [18, 89, 98, 99]. The authors only addressed the inverter dynamic modelling issues and neglected the dynamics of the primary energy source. This approach has a direct and immediate consequence: the influence of the dynamic response of the MS (for example, the dynamic of chemical reactions in fuel cells) in the overall MG dynamic response or in the interaction among several MS is not tacked into account.

Aiming to consider the full modelling of each MS and the corresponding power electronic interface, Figure 3-3 shows the basic configuration of these types of systems. The blocks represented in the figure are:

- The MS (fuel cell, microturbine or PV);
- A DC-link (DC capacitor C), which connects the MS to the DC-AC inverter (grid-side inverter);
- A low-pass LC filter, which rejects the inverter generated high frequency harmonics;
- A coupling inductance.

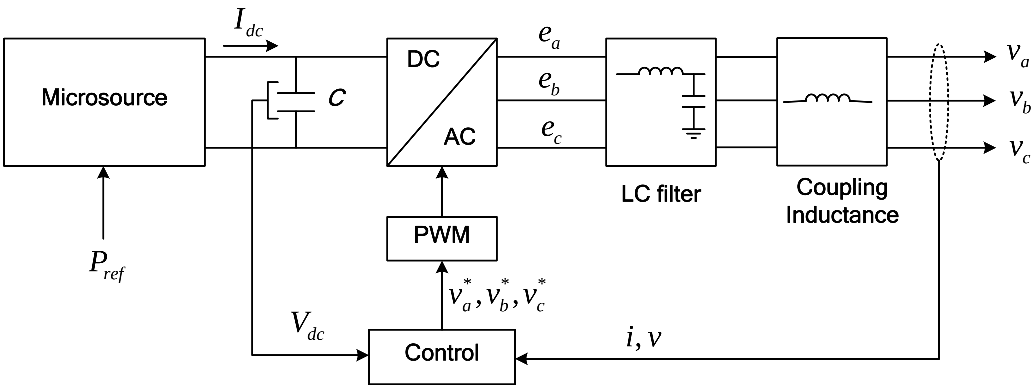


Figure 3-3: Block diagram of an inverter interfaced microsource

In the following sections is presented a brief overview of the dynamic models that were adopted in this dissertation. These models describe the response of different MS and storage devices in order to evaluate the global response of the MG system during islanding operating conditions. Later, the dynamic models for the power electronic interfaces used to connect the MS to the LV grids will be also presented.

3.4.1 SOLID OXIDE FUEL CELL

A Solid Oxide Fuel Cell (SOFC) was chosen to be included in the MG system, since it is particular interesting for stationary power generation applications due to the following advantages [39]:

- The fuel processor requires a simple partial oxidation reforming process, eliminating the need of an external reformer;
- SOFC has relatively low requirements for the fuel reformation process. It can use carbon monoxide directly as a fuel, which do not require a very sophisticated reformer;
- As it operates at extremely high temperatures, it can tolerate relatively impure fuels;
- The waste heat is high grade, allowing for smaller heat exchangers and the possibility of CHP applications to improve the global efficiency;
- Water management is not a concern since SOFC uses a solid electrolyte;
- The SOFC does not need precious metal catalysts.

Nevertheless, being a high temperature fuel cell, the SOFC system present some major drawbacks. Due to the high-temperature operation, it requires a significant time to reach the operating temperature ant to respond to changes in the output power. Also, its start-up time is in the order of 30 to 50 minutes. Packing of the entire system (fuel cell stack, power electronic equipments, etc) is also quite demanding due to the different range of temperatures of the different components.

Complete mathematical models are very difficult to obtain because the fuel cell systems consists of many subsystems, each subsystem interacting with the others in a complex form. Also, fuel cells processes (electrical, chemical and thermodynamic) are strongly non-linear in nature, making difficult the estimation of the parameters of such complex models. Several SOFC models can be found in the literature, with different complexity levels and considering different aspects of the SOFC dynamics, namely dynamics of the chemical species and thermal dynamics [100-102]. However, these models are not adequate to be easily integrated in electrical power system simulation platforms, which require the model to respond network variables, such as node voltages or grid frequency. In order to fulfil these requirements, a SOFC dynamic model is presented in [47, 103] and is used in [104-106] in order to analyze the control and operation of SOFC systems. This SOFC dynamic model is also adopted in this dissertation and is it based on the following assumptions:

- The gases are ideal;
- The stack is fed with hydrogen and air. If natural gas instead of hydrogen is used as fuel, the dynamics of the fuel processor must be included in the model;
- The channels that transport gases along the electrodes have a fixed volume, but their lengths are small. Thus, it is possible to consider one single pressure value in their interior;
- The exhaust of each channel is via a single orifice. The ratio of pressures between the interior and exterior of the channel is large enough to consider that the orifice is choked;
- The temperature is stable at all times;
- The only source of losses is ohmic, as the working conditions of interest are not close to the upper and lower extremes of the cell current;
- The Nernst equation can be applied.

Assuming that the SOFC system is supplied with hydrogen in the anode and oxygen in the cathode, the reactions that take place are described by the following equations:

Anode: $$\mathbf{H_2 + O^{=} \rightarrow H_2O + 2e^{-}}$$

Cathode: $$\frac{1}{2}\,\mathbf{O_2 + 2e^{-} \rightarrow O^{=}}$$

In order to calculate the open circuit voltage E of a stack with N_0 cells connected in series, the Nernst equation is used:

$$E = N_0 \left[E_0 + \frac{RT}{2F} \ln \frac{p_{H_2} \sqrt{p_{O_2}}}{p_{H_2O}} \right] \tag{3-1}$$

where:

E_0 :	**voltage associated with reaction free energy of the cell (V)**
R :	**universal gas constant (8314.51 J.kmol^{-1}.K^{-1})**
T :	**channel temperature (assumed to be constant) (K)**
F :	**Faraday constant (96.487×10^{6} C. kmol^{-1})**
$p_{H_2}, p_{O_2}, p_{H_2O}$:	**partial pressures of hydrogen, oxygen and water vapour, respectively (atm)**

Applying Ohm's law, the stack output voltage can be computed as

$$V = E - rI \tag{3-2}$$

where r is the SOFC resistance used to represent the ohmic losses in the stack (Ω) and I is the current flowing out of the stack (A)

In order to compute the stack voltage, gases pressure inside the stack must be derived. The individual gases (hydrogen, oxygen and water vapour) flowing in the stack will be considered separately, and the perfect gas equation is applied to them:

$$p_i V_{ch} = n_i RT \tag{3-3}$$

where:

p_i :	**pressure of each specie (atm)**
V_{ch} :	**volume of the channel (anode or cathode) (l)**
n_i :	**number of moles of the specie *i* present in the channel**

As the cell temperature is assumed to be constant, by differentiating both sides of Equation (3-3), the following equation stands:

$$\frac{dp_i}{dt} = \frac{RT}{V_{ch}} \frac{dn_i}{dt} = \frac{RT}{V_{ch}} q_i \tag{3-4}$$

where q_i is the time derivative of n_i and denotes the specie molar flow (kmol.s^{-1})

Regarding hydrogen, it flows through the stack anode with volume V_{an} and there are three contributions to its molar flow: the input flow ($q_{H_2}^{in}$), the output flow ($q_{H_2}^{out}$) and the input flow that takes part in the stack reactions ($q_{H_2}^{r}$). Thus,

$$\frac{dp_{H_2}}{dt} = \frac{RT}{V_{an}}(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}) \tag{3-5}$$

The hydrogen molar flow that reacts can be calculated as:

$$q_{H_2}^{r} = \frac{N_o I}{2F} = 2K_r I \tag{3-6}$$

being K_r a constant defined for modelling purposes (kmol.s^{-1}.A^{-1}).

The molar flow of any gas through a valve can be considered proportional to its partial pressure inside the channel. Therefore, the following equation stands:

$$\frac{q}{p} = \frac{K_{ch}}{\sqrt{M}} = K \tag{3-7}$$

where:

K_{ch} **: channel valve constant (** $\sqrt{\text{kmol.kg}}$.(atm.s)$^{-1}$ **)**

M **: gas molecular mass (kg.kmol^{-1})**

K **: valve molar constant (kmol.(atm.s)$^{-1}$)**

Using Equation (3-7) to calculate the hydrogen output flow and substituting in Equation (3-5), the differential equation for the hydrogen dynamics is obtained:

$$\frac{dp_{H_2}}{dt} = \frac{RT}{V_{an}}(q_{H_2}^{in} - K_{H_2} p_{H_2} - 2K_r I) \tag{3-8}$$

Taking the Laplace transform of both sides of the equation and isolating the hydrogen partial pressure, yields the following expression:

$$p_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2} s}(q_{H_2}^{in} - 2K_r I) \tag{3-9}$$

being $\tau_{H_2} = \dfrac{V_{an}}{K_{H_2}RT}$, expressed in seconds, the time constant associated with the hydrogen flow dynamics.

Considering now the oxygen gas flow through the cathode with volume V_{ct}, Equation (3-5) can be rewritten as:

$$\frac{dp_{O_2}}{dt} = \frac{RT}{V_{ct}}(q_{O_2}^{in} - q_{O_2}^{out} - q_{O_2}^{r}) \tag{3-10}$$

According to the electrochemical relationships, the molar flow of oxygen that reacts is $q_{O_2}^{r} = K_r I$. Substituting in Equation (3-10) and taking the Laplace transform, the dynamic behaviour related to the oxygen flow is described by:

$$p_{O_2} = \frac{1/K_{O_2}}{1+\tau_{O_2}s}(q_{O_2}^{in} - K_r I) \tag{3-11}$$

where $\tau_{O_2} = \dfrac{V_{ct}}{K_{O_2}RT}$, expressed in seconds, the time constant associated with the oxygen flow dynamics.

According to the chemical reactions taking place in the SOFC, water is a reaction product in the stack anode. Therefore, for the water vapour, Equation (3-5) can be rewritten as:

$$\frac{dp_{H_2O}}{dt} = \frac{RT}{V_{an}}(q_{H_2O}^{r} - q_{H_2O}^{out}) \tag{3-12}$$

The molar flow of water vapour resulting from the chemical reactions ($q_{H_2O}^{r}$) is $q_{H_2O}^{r} = q_{H_2}^{r} = 2K_r I$. Substituting this equation in Equation (3-12) and taking the Laplace transform, the dynamics related to the water vapour are described by:

$$p_{H_2O} = \frac{1/K_{H_2O}}{1+\tau_{H_2O}s}2K_r I \tag{3-13}$$

being $\tau_{H_2O} = \dfrac{V_{an}}{K_{H_2O}RT}$, expressed in seconds, the time constant associated with the water vapour flow.

The previous equations are related to the dynamics of the chemical species in the SOFC. However, due to safety reasons associated with the physical integrity of the cell under certain conditions, some considerations need to be made in relation to the electric current resulting from the chemical reactions. In order to do this, it is necessary to define the fuel utilization parameter U_f : it is the ratio of the fuel flow that reacts in the stack and the input fuel flow,

$$U_f = \frac{q_{H_2}^{in} - q_{H_2}^{out}}{q_{H_2}^{in}} = \frac{q_{H_2}^{r}}{q_{H_2}^{in}} = \frac{2K_r I}{q_{H_2}^{in}} \tag{3-14}$$

The typical value of the fuel utilization is in the range of 80% to 90%. The underused condition ($U_f < 80\%$) would lead to a fast voltage increase, since the current will be below a minimum value. The overused condition ($U_f > 90\%$) will cause permanent damage to the cell due to fuel starvation. Therefore, for a certain hydrogen molar flow, the current demanded to the fuel cell must be restricted to the following range:

$$\frac{0.8q_{H_2}^{in}}{2K_r} \le I \le \frac{0.9q_{H_2}^{in}}{2K_r} \tag{3-15}$$

The optimal fuel utilization factor (U_{opt}) is assumed to be 85%, allowing the control of the input fuel flow by measuring the output current, so that:

$$q_{H_2}^{in} = \frac{2K_r I}{U_{opt}} \tag{3-16}$$

The stoichiometric ratio of hydrogen to oxygen in the fuel cell stack reaction equation is 2 to 1. However, oxygen is always taken in excess in order to allow a more complete reaction between hydrogen and oxygen. In order to keep fuel cell pressure difference between the hydrogen and oxygen passing through the anode and cathode compartments bellow 4 kPa under normal operating conditions, the ratio of hydrogen to oxygen is controlled by an air compressor to be $r_{H\_O} = 1.145$.

All the reactions occurring in the fuel cell stack has some inherent time delays. The chemical response in the fuel cell processor is usually slow and it is associated with the time to change the chemical reaction parameters after a change in the flow of reactants. This dynamic response function is modelled as a first order transfer function with a time delay T_f. The electrical response time delay in the fuel cells is generally short and mainly associated with the speed at which the chemical reaction is capable of restoring the charge that has been drained by the load. This dynamic response is also modelled as a first order transfer function, with a time delay T_e. Following the previous explanations, Figure 3-4 shows the block diagram of the adopted SOFC dynamic model.

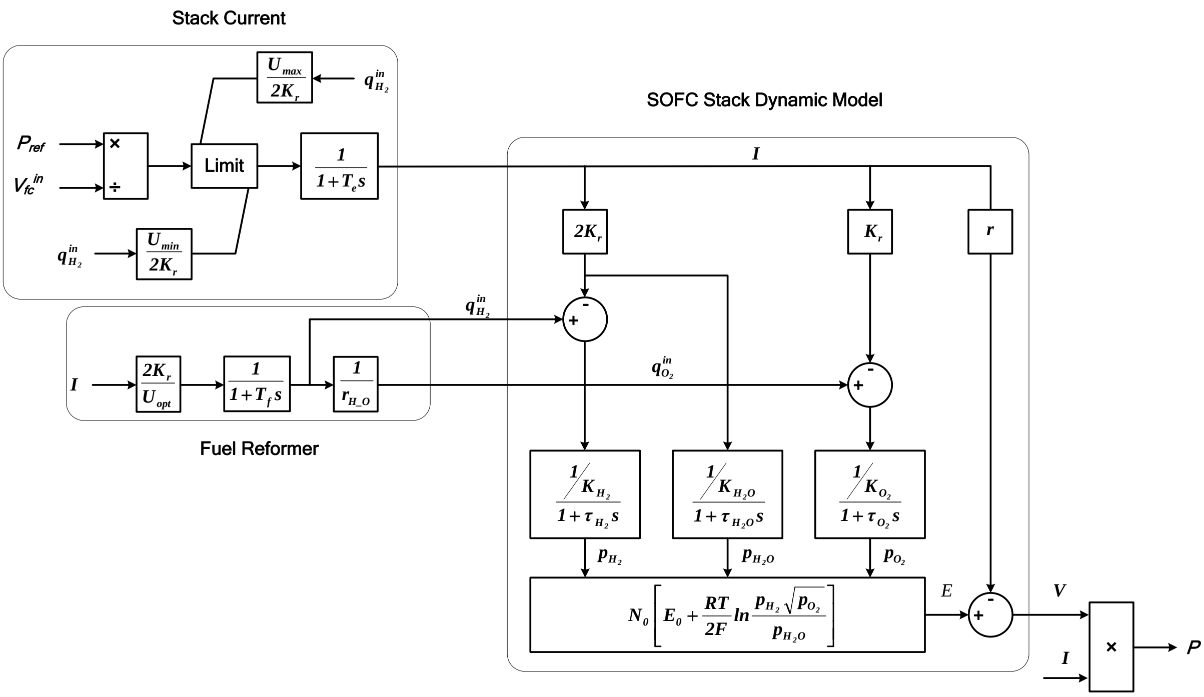


Figure 3-4: SOFC dynamic model

3.4.2 SINGLE SHAFT MICROTURBINE

After providing a short overview of microturbines technological characteristics in Section 2.4.2, modelling aspects must be considered in order to evaluate its impact and possible contribution for MG operation and control issues. Microturbines are recognized to play an increasing importance for small scale power generation applications, but little work on its modelling and simulation is reported in the literature. More specifically, modelling of microturbine dynamic behaviour has a major interest in terms of the slow dynamics, namely its response to load changes and the ability to perform frequency regulation [107].

Modelling of the Single Shaft Microturbine (SSMT) is reported in [108], where it is assumed there is an AC to DC uncontrolled rectifier (full wave three-phase diode bridge rectifier) connected to the Permanent Magnet Synchronous Generator (PMSG), a DC-link with a capacitor and a DC/AC inverter. Regarding the mechanical part of the SSMT, the authors consider the turbine response can be modelled by a first order transfer function with a time constant typically ranging from 5 to 20 seconds. In [109], the authors follow a similar approach to [108], being the main difference the modelling of the mechanical parte of the SSMT. In this case, the fuel demand is the input of a non-linear transfer function representing the dynamics of the fuel system and the corresponding actuator. The actuated fuel demand is used to calculate the turbine output mechanical power through a steady-state relationship. The calculated mechanical power is then passed through a delay representing the dynamic of the compressor, the heat recovery exchanger and the turbine. However, the results obtained with this model present very fast time constants (in the order of 0.1 s) when compared to the results reported in [108]. In [110], the authors follow a modelling approach where the three main components of the turbine section are considered: the compressor, the combustion chamber and the turbine. Due to the small physical dimensions of the turbine when compared to conventional gas turbines, each compartment of the SSMT has very low thermodynamic constants (around 1.5 ms). Therefore, any change in the input fuel or in the air flow affects the mechanical power in a very short time period. The obtained results have time constants for the response of the SSMT to a control signal in the order of 30 milliseconds.

The adopted model for the SSMT has as minimum validation procedure a qualitative comparison with the results obtained in a Capstone SSMT laboratorial test reported in [111]. Therefore, based on the models reported in [47, 107, 112], some assumptions are due in order to derive a model able to conveniently represent microturbine dynamics. As a first consideration, the SSMT engine, while small in size, is assumed to be similar to conventional combustion gas turbines. Additionally, evaluating the integration of microturbines in an electric network from a dynamic point of view requires a model able to represent the electric and mechanic behaviour. The use of hot exhaust gases in the recuperator is not considered in the adopted model since this is only a device used to increase microturbine global efficiency. Also, the large time constants associated to the recuperator has little influence regarding the time scale used for dynamic simulations. It is also frequent to find temperature, speed and acceleration control system in microturbines. These kinds of control system are very important during start-up or loss of power conditions, but have very little influence during normal operating conditions. Thus, they can be neglected when the main interest is focused on the evaluation of microturbine slow dynamics. Based on these assumptions, the model should reflect the dynamics of the blocs represented in Figure 3-5: microturbine control and mechanical system, electrical generator and the power electronic interface to connect the microturbine to the electric power grid. The power produced in the electric generator – a PMSG – is variable frequency AC power due to the variable speed operation characteristic of the microturbine. The power electronic stage can be used to inject power into an external grid or as a controllable source in order to power the electric generator in a motoring mode to allow microturbine start-up.

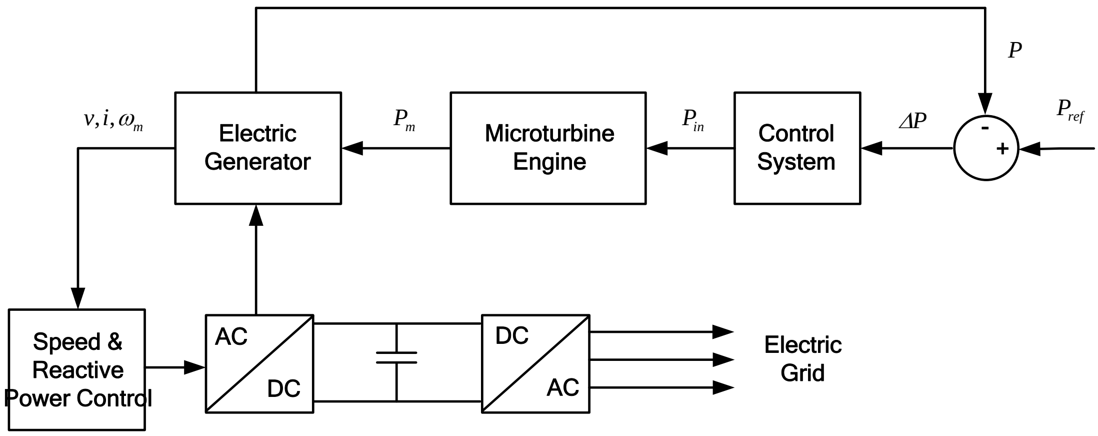


Figure 3-5: Block diagram of the SSMT control system

3.4.2.1 Single Shaft Microturbine Active Power Control

In order to control the power output of the SSMT, a power set-point should be provided to the control system. A simple control of the turbine mechanical power can be performed through a Proportional-Integral (PI) control function [47]. The input of the controller in the error ΔP between the power set-point P_{ref} and the effective power output P. The output of the controller P_{in} is then applied to the microturbine engine.

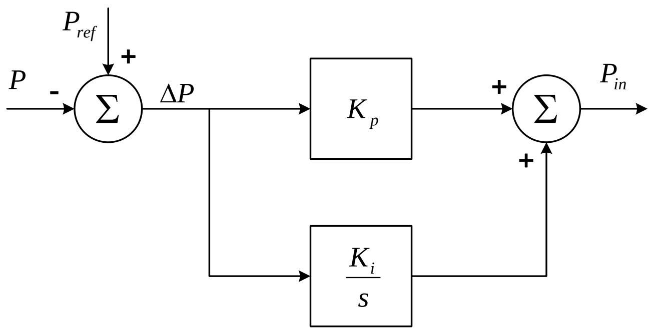


Figure 3-6: SSMT active power control

3.4.2.2 Single Shaft Microturbine Engine

The SSMT engine comprises an air compressor, a combustion chamber, a recuperator and a power turbine driving the electrical generator. This arrangement is quite similar to combustion gas turbines [112]. Therefore, the mechanical part of the SSMT (SSMT engine) is represent through the conventional model commonly use to represent the dynamics of simple cycle single shaft gas turbines, usually know as the GAST (GAS Turbine) model, without the droop control, as in Figure 3-7 [47]. The parameters in the microturbine engine model are:

T_1, T_2	:	**fuel system time constants**
T_3	:	**load limit time constant**
$V_{\max}$, $V_{\min}$	:	**maximum and minimum fuel valve positions**
k_t	:	**temperature control loop gain**
$L_{\max}$	:	**load limit**

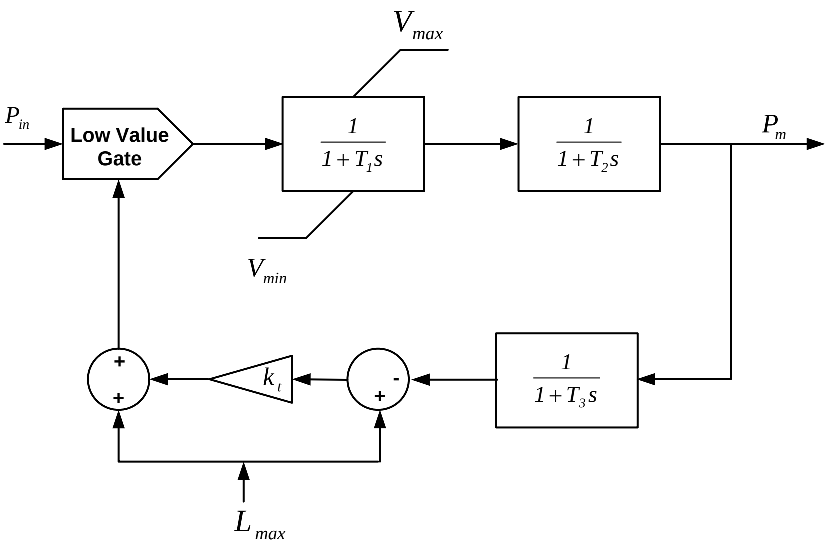


Figure 3-7: Dynamic model of the SSMT engine

3.4.2.3 Permanent Magnet Synchronous Generator

The electrical generator is assumed to be a two pole PMSG with a non-salient rotor. The machine electrical equations can be written in the rotor *d-q* reference frame as follows [107]:

$$v_d = R_s i_d - p\omega L_q i_q + L_d \frac{di_d}{dt}$$
$$v_q = R_s i_q + p\omega L_d i_d + L_q \frac{di_q}{dt} + p\omega\Phi_m \qquad (3\text{-}17)$$
$$T_e = \frac{3}{2} p\left[\Phi_m i_q + (L_d - L_q) i_d i_q\right]$$

where:

L_d , L_q : ***d* and *q* axis inductances (H)**

R_s : **stator windings resistance (Ω)**

i_d , i_q : ***d* and *q* axis currents (A)**

v_d , v_q : ***d* and *q* axis voltages (V)**

ω : **angular velocity of the rotor (rad.s^{-1})**

Φ_m : **flux induced by the permanent magnets in the stator windings**

p : **number of pole pairs**

T_e : **electromagnetic torque (N.m)**

The mechanical equation needs to take into account the combined inertia and load viscous friction of the PMSG, the power turbine and compressor that are mounted in the same shaft:

$$T_e - T_m = J\frac{d\omega}{dt} + F\omega \qquad (3\text{-}18)$$

where:

T_m : **load mechanical torque (N.m)**

J : **combined inertia of the load, PMSG, shaft, turbine and compressor**

F : **combined viscous friction factor of the load, PMSG, shaft, turbine and compressor (N.m.s.rad^{-1})**

3.4.2.3 Machine Side Converter

The variable frequency AC power produced in the PMSG must be rectified and inverted in order to be injected into the AC grid. The machine side converter is responsible for controlling the PMSG operation in terms of rotation speed and power factor [113]. A block diagram of the machine side converter and its control structure is shown in Figure 3-8. The microturbine shaft speed is controlled through a pre-defined characteristic curve (ω versus P) in order to operate the microturbine at optimal efficiency for each value of the output power [107]. The microturbine speed error is used to compute the i_q reference current, which is supplied to a PI controller in order to regulate v_q and thus the microturbine angular velocity. The $i_{d\,ref}$ current can be calculated by another regulator in order to insure a unit power factor for the PMSG.

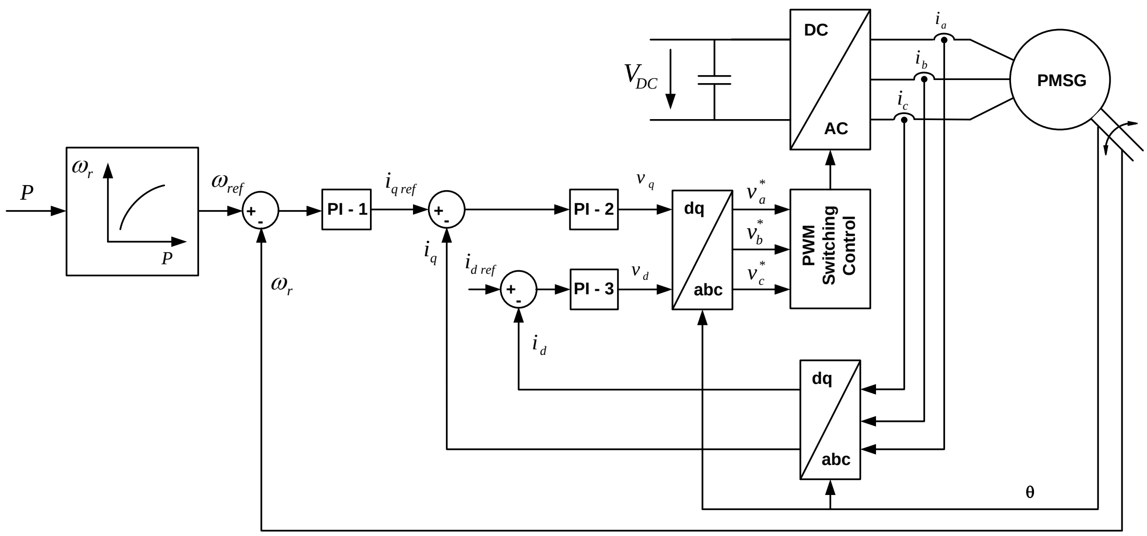


Figure 3-8: Control of the machine side converter

3.4.3 PHOTOVOLTAIC PANEL

There are several models reported in the literature with different complexity levels that can be used to describe the behaviour of a Photovoltaic (PV) cell. The most widely used models are the ones based on lumped circuits, such as single and double diode models [43]. Within this class of mathematical models, the single diode model is one of the most widely used for representing a PV cell. The model reflects the current/voltage characteristic of the cell and can be represented by the equivalent electric circuit shown in Figure 3-9. The relation between the load current and the terminal voltage can be expressed as [114]:

$$I = I_L - I_D - I_{sh} = I_L - I_0 \left\{ exp\left(\frac{Q(V + R_s I)}{AKT} \right) - 1 \right\} - \frac{V + R_s I}{R_{sh}} \tag{3-19}$$

where:

I	:	**load current (A)**
I_L	:	**light generated current (A)**
I_D	:	**diode current (A)**
I_{sh}	:	**shunt current (A)**
I_0	:	**diode reverse saturation current (A)**
R_s, R_{sh}	:	**series and shunt resistances, respectively (Ω)**
Q	:	**electron charge (1.6×10^{-19} C)**
A	:	**curve fitting constant**
T	:	**cell absolute temperature (ºK)**
K	:	**Boltzmann constant (1.38×10^{-23} J.(ºK)$^{-1}$)**
V	:	**load voltage (V)**

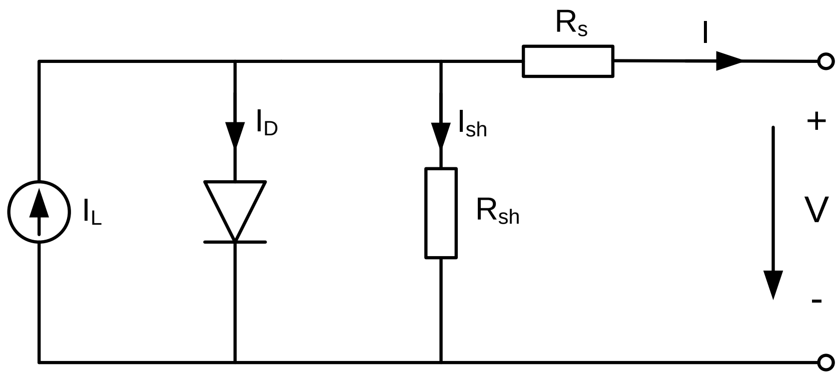


Figure 3-9: Equivalent circuit of a PV cell

The five parameters of the model (I_L, I_0, R_s, R_{sh} and A) depend on the ambient conditions (cell temperature and solar radiation). However, the shunt resistance R_{sh} is usually much higher than the series resistance R_s, making possible the use of a four parameter model described by [114]:

$$I = I_L - I_D = I_L - I_0 \left\{ exp\left(\frac{Q(V + R_s I)}{AKT} \right) - 1 \right\} \tag{3-20}$$

Figure 3-10 represents a typical current-voltage (I-V) and power-voltage (P-V) characteristic of a generic solar cell. It is possible to observe that the maximum power that can be extracted from the PV cell depends on the operating point. The point at which maximum power P_{max}^{C} is extracted from the cell is denominated by Maximum Power Point (MPP) and it is reached with a cell terminal voltage V_{max}^{C} and an output current I_{max}^{C}.

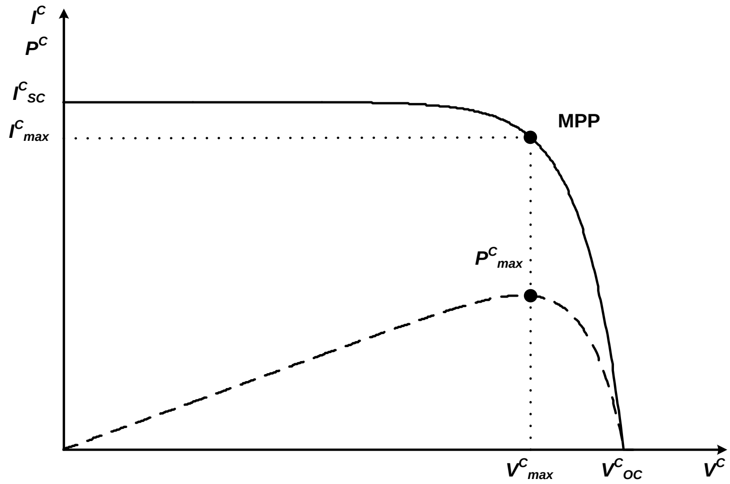


Figure 3-10: A typical I-V and P-V characteristic of a solar cell

PV cell manufactures usually provide a set of data which can be used in order to compute the parameters of the mathematical model defined by Equation (3-20). A method for the calculation of those parameters can be found in [114] and it is based one the following cell data:

- the short-circuit current, I_{SC}^{C};
- the open circuit voltage, V_{OC}^{C};
- the maximum power for a given set of references, P_{max}^{C}.

Additional conditions for the calculation the required parameters are necessary: they can be derived from the knowledge of the temperature coefficients of the short-circuit current μ_{SC}^{I} and open circuit voltage μ_{OC}^{V}, whose influence on the respective parameters is illustrated in Figure 3-11 and Figure 3-12. The influence of the MPP of a PV module depends also on the solar radiation G_T. For a fixed G_T and decreasing temperature, the MPP and the corresponding V_{max}^C increase. Alternatively, for a fixed temperature and decreasing G_T, the MPP decreases, while V_{max}^C remains almost constant.

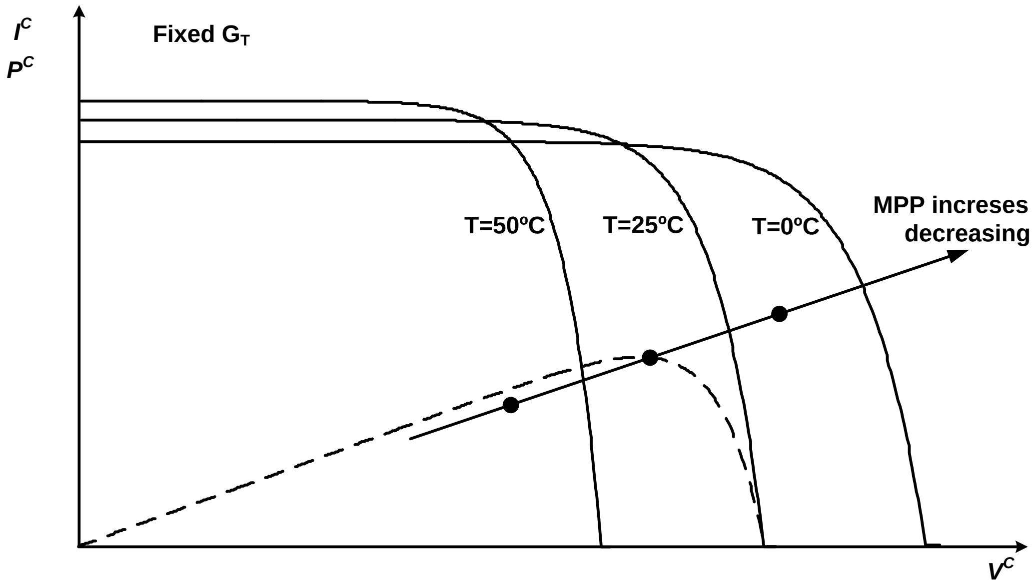


Figure 3-11: Influence of cell temperature in the I-V characteristics

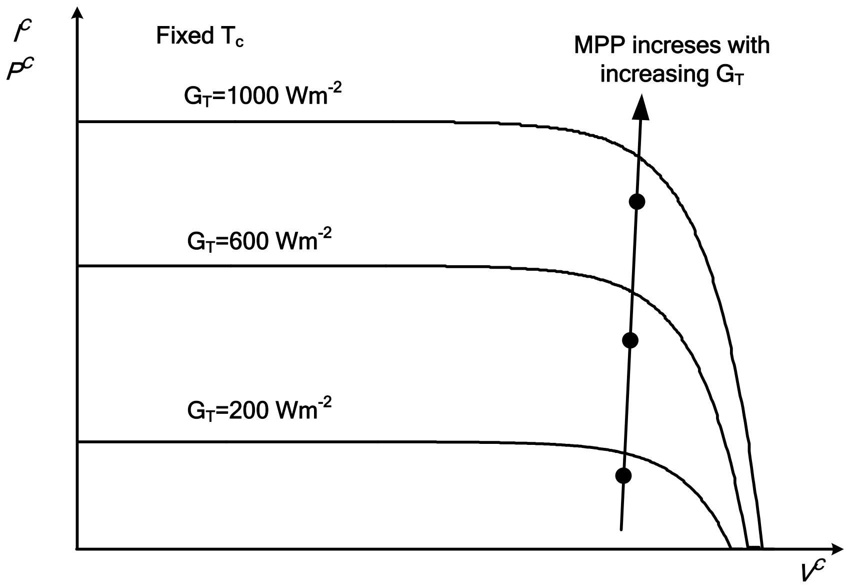


Figure 3-12: Influence of solar radiation in the I-V characteristics

3.4.3.1 Photovoltaic Array with Maximum Power Point Tracking System

Due to the particular I-V characteristic of the PV cells, it is necessary to develop schemes for extracting the maximum energy of the panel, which depends on several parameters as it was previously illustrated. Therefore, a PV system contains a module responsible for achieving an operation point corresponding to the condition of maximum energy extraction. This module is denominated as Maximum Power Point Tracker (MPPT), and is represented in Figure 3-13. Basically, the PV system consists in the PV array, which is connected to the MPPT (a DC/DC converter controlled through proper algorithms to reach the MPP) and the DC/AC converter for connecting the PV system to the grid.

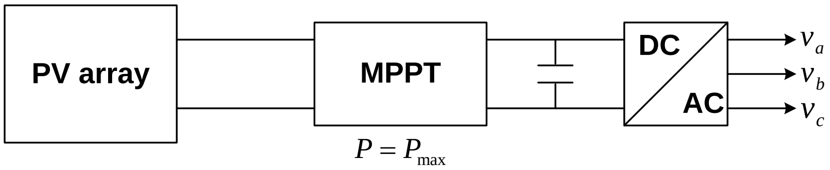


Figure 3-13: Configuration of a PV system

Several MPPT algorithms have been reported in the literature [115], differing among them in many aspects such as the complexity of the algorithm, required sensors, convergence speed and requirement of periodic tuning of the controllers. Within the scope of this dissertation, the performance of the MPPT algorithm is not a key issue since dynamic simulations will be performed over a short period of time during which the solar radiation can be considered constant. Therefore, a simpler algorithm based on the following assumptions can be adopted [43, 116]:

- All the cells of the PV module are identical and they work with the same irradiance level and at the same temperature;
- The PV module and the MPPT system has no losses;
- The PV module is always working on its maximum power point for a given irradiance and ambient temperature conditions;
- If the irradiance and/or ambient temperature conditions change, the model instantaneously changes its maximum power point;

- The temperature of the solar cells depends exclusively on the irradiance and ambient temperature.

Under these assumptions the module maximum output power P_{Max}^{M} can be estimated using the ambient temperature and the solar irradiance as inputs [43, 116]:

$$P_{Max}^{M} = \frac{G_a}{G_{a,0}}\left[P_{Max,0}^{M} + \mu_{P_{Max}}\left(T_M - T_{M,0}\right)\right] \tag{3-21}$$

where:

G_a : **solar irradiance (W.m^{-2})**
$G_{a,0}$: **solar irradiance at Standard Test Conditions (1000 W.m^{-2})**
$P_{Max,0}^{M}$: **PV module maximum power at Standard Test Conditions (W)**
$\mu_{P_{Max}}$: **maximum module power variation with temperature (W/ºC)**
T_M : **module temperature (ºC)**
$T_{M,0}$: **module temperature at Standard Test Conditions (25 ºC)**

In practice, the operating conditions of PV systems differ from the Standard Test Conditions. Then, under arbitrary operating conditions (irradiance G_a and ambient temperature T_a), the working temperature of the PV module is given by

$$T_M = T_a + G_a \frac{NOCT - 20}{800} \tag{3-22}$$

where $NOTC$ is the Normal Operating Temperature of the Cell, which is defined as the cell temperature under a solar irradiance of 800 W.m^{-2}, an ambient temperature of 20 ºC and a wind speed lower than 1 m.s^{-1}. These conditions are usually referred as the Normal Test Conditions. The MPP of a PV array with N modules is therefore given by:

$$P_{Max} = N\frac{G_a}{1000}\left[P_{Max,0}^{M} + \mu_{P_{Max}}\left(T_a + G_a\frac{NOCT-20}{800} - 25\right)\right] \tag{3-23}$$

3.4.4 MICRO WIND GENERATOR

Wind generators comprise several subsystems that need to be modelled independently: the aerodynamic model of the turbine, the electrical generator, the mechanical system and the power electronic converters in case of variable speed wind turbines [51]. Regarding micro wind generators systems, they differ significantly from large wind generators in terms of the technologies used. However, there are not detailed mathematical models reported in the literature for micro wind generators. Without lack of generalization, it was considered that the micro wind generation system can use a squirrel cage induction generator directly connected to the LV grid and a capacitor bank for power factor correction purposes. Therefore the small wind generator model involves both the wind turbine and the induction generator models, as presented in the following subsections.

3.4.4.1 Wind Turbine

The mechanical power extracted by the wind turbine from the wind kinetic energy, is given by [51]:

$$P_m = \frac{1}{2}\rho \times C_p(\lambda) \times A \times V^3 \tag{3-24}$$

where:

P_m : **mechanical power (W)**

$C_p(\lambda)$: **dimensionless performance coefficient**

λ : **tip speed ratio (rad)**

ρ : **air density (kg.m^{-3})**

A : **rotor area (m^2)**

V : **wind speed (m.s^{-1})**

Independently from the type of wind turbine, its efficiency can be calculated by the quotient between the mechanical power P_m delivered by the turbine and the power effectively available due to the wind flow P_d. This coefficient is usually defined as $C_p(\lambda)$. The parameter λ is defined as:

$$\lambda = \frac{\omega_t R}{V} \tag{3-25}$$

where ω_t is the angular velocity of the turbine (rad.s^{-1}) and R is the turbine radius (m). The mechanical torque, in *N.m*, can be obtained as:

$$T_m = \frac{P_m}{\omega_t} \tag{3-26}$$

3.4.4.2 Squirrel Cage Induction Generator

In dynamic stability studies it is common to represent the induction machine by a third order model that corresponds to a transient electromotive force (emf) behind a transient reactance. The per unit electrical equations of the squirrel cage induction machine in the *d-q* reference frame with the time represented in seconds can be written as follows [51, 117]:

$$\begin{cases} v_{ds} = -R_s i_{ds} + X^{'} i_{qs} + e_d \\ v_{qs} = -R_s i_{qs} - X^{'} i_{ds} + e_q \end{cases} \tag{3-27}$$

$$\begin{cases} \dfrac{de_d}{dt} = -\dfrac{1}{T_0}\left[e_d - \left(X - X^{'} \right) i_{qs} \right] + s \times 2\pi f_s e_q \\ \dfrac{de_q}{dt} = -\dfrac{1}{T_0}\left[e_q + \left(X - X^{'} \right) i_{ds} \right] - s \times 2\pi f_s e_d \end{cases} \tag{3-28}$$

where:

v_{ds}, v_{qs} : **stator terminal voltages**

e_d, e_q : **transient e.m.f.**

i_{ds}, i_{qs} : **stator currents**

X : **open circuit reactance**

X' : **transient or short-circuit reactance**

R_s : **stator phase resistance**

T_0 : **transient open-circuit time constant (s)**

f_s : **system frequency (Hz)**

s : **rotor slip**

The transient open circuit time constant is given by

$$T_0 = \frac{L_r + L_m}{2\pi f_{base} \times R_r} \tag{3-29}$$

where R_r is the rotor resistance, L_r is the rotor leakage inductance, L_m is the magnetizing inductance and f_{base} is the base frequency (usually equal to the system frequency f_s). The transient reactance $X^{'}$, as well as open circuit reactance X, are defined by:

$$X^{'} = X_s + \frac{X_r \times X_m}{X_r + X_m} \tag{3-30}$$

$$X = X_s + X_m \tag{3-31}$$

where X_s and X_r represent the leakage reactance for the stator and rotor windings respectively, and X_m is the magnetising reactance of the machine.

Concerning the rotor slip, it can be derived as follows:

$$s = 1 - \frac{\omega_r}{\omega_s} \tag{3-32}$$

where ω_s the synchronous speed and ω_r is the angular velocity of the rotor.

In order to complete the induction machine model, it is necessary to combine the differential equations describing the electrical part of the machine with the rotor swing equation:

$$\frac{d\omega_r}{dt} = \frac{1}{J}\left(T_m - T_e - D\omega_r\right) \tag{3-33}$$

where J and D are the system (turbine and electric generator) inertia and damping coefficient respectively and T_e is the electromechanical torque, which is given by:

$$T_e = e_d i_{ds} + e_q i_{qs} \tag{3-34}$$

3.4.5 STORAGE DEVICES MODELLING

According to the models previously described, the MS technologies assumed to be used in a MG have very specific characteristics in terms of the response to control signals. The use of storage devices in MG is therefore related to the provision of some form of energy buffering capabilities in order to balance the system following disturbances and/or significant load changes. The need of storage devices for MG operation and control purposes is discussed in detail in the next Chapter.

It is possible to find in the literature models for analysing the behaviour of storage devices such as batteries, flywheels or supercapacitors [118]. However, the nature of the research developed within this dissertation does not require a deep knowledge about the behaviour of the internal variables of storage devices. Storage devices should act as energy buffers in order to ensure MG survival following transients, especially during MG islanding operation. Considering the time period of interest for analysing MG dynamic behaviour, storage devices can be modelled as constant DC voltage sources using power electronic interfaces to be coupled with the electrical network (AC/DC/AC converters for flywheels and DC/AC inverters for batteries and supercapacitors). These devices act as controllable AC voltage sources (with very fast output characteristics) to face sudden system changes such as load-following during islanding conditions. Despite acting as voltage sources, these devices have physical limitations and thus a finite capacity for storing energy [96]. The active power needed to balance generation and consumption inside the MG is injected into the LV grid according to the control strategy implemented in the corresponding power electronic interface as described in the next section. Further explanations on the use of storage devices for MG operation and control are presented in Chapter 4.

3.4.6 POWER ELECTRONIC CONVERTER CONNECTED TO THE GRID

As it was previously described, the characteristics of the energy produced in several MS require the use of power conditioning units in order to interface them with the LV grid. It is also important to note that MG are inverted dominated grids: it will not be common to find fully controllable synchronous generators in a MG, which are normally responsible for voltage and frequency control in conventional power systems. Therefore, understanding inverter control is a key issue to ensure stable MG operation in the presence of arbitrary varying conditions (load or generation variations). Regarding conventional power systems, the synchronous machine is its basic building unit, which influenced the development of the entire system. In a MG, the massive integration of power electronic converters poses distinguishing characteristics in comparison to conventional power systems. Table 3-1 illustrates the key differences between synchronous machines and power electronic interfaces [119].

Table 3-1: Comparison between synchronous machines and inverters general characteristics

Synchronous Machines	Power Electronic Interfaces
Voltage source operation with controlled magnitude through the use of excitation systems.	Voltage source (although current source versions are know) with nearly independent control of the magnitude in each phase.
Ensuring a sine wave voltage output is accounted during the machine design/construction phase.	Sine-wave can be achieved through the use a suitable modulator and reference waveform, but 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.

The inverter control strategies for power export to an AC system can be generally divided in two types [120]:

- **PQ inverter control:** the inverter is used to supply a given active and reactive power set-point. In this case, the inverter operates in a grid-connected mode [119, 121], being the power injected into an energized network. The inverter is not able to form the grid itself by imposing a voltage waveform with suitable amplitude and frequency.

- **Voltage Source Inverter control:** the inverter is controlled to supply the load with pre-defined values for voltage and frequency. Depending on the load, the Voltage Source Inverter (VSI) real and reactive power output is defined. In this case, the inverter is responsible to establish the voltage wave form with suitable amplitude and frequency [119, 121]. The inverters themselves produce an AC voltage;

therefore it is possible to control voltage and frequency in the AC system by means of inverter control.

Due to the fast response of power electronic converters, they can be modelled from the network point of view by a controllable AC voltage source. The magnitude and phase of this voltage source is to be controlled according to the referred control strategies. It is also important to highlight that, when analysing the dynamic behaviour of the MG, inverters are modelled based only on their control functions, so that, fast switching transients, harmonics and inverter losses are neglected. This a general procedure adopted by several authors when dealing with power electronic interfaces in dynamic stability studies [17, 18, 89, 90, 122].

3.4.6.1 PQ Inverter Control

The PQ inverter is operated under a grid-connected mode and should inject a given active and reactive power set-point into the network (the set-points are determined through specific algorithms or control functionalities to be discussed in the next Chapter). In addition to active and reactive power flow control, this inverter is also responsible for the control of the DC-link voltage of the cascading DC/AC/DC system [123]. Therefore, the internal voltage of the inverter is controlled in order to maintain the DC-link voltage at a specified reference and the reactive power output at the desired set-point. Neglecting losses, the power balance in the capacitor of the DC-link (P_C) is the difference between the power received from the MS (P_{MS}) and the inverter output power (P_{inv}), as shown in Figure 3-14:

$$P_C = P_{MS} - P_{inv} \tag{3-35}$$

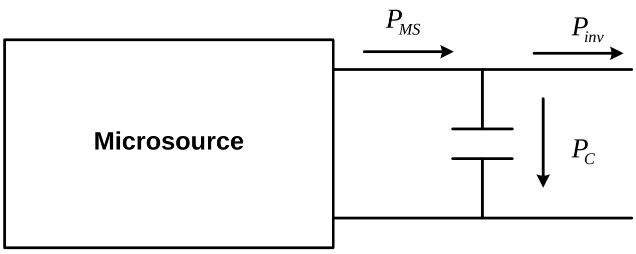


Figure 3-14: DC-link capacitor power balance

The power delivered by the capacitor can also be written as:

$$P_C = V_{DC} \times I_{DC} \tag{3-36}$$

where V_{DC} is the DC-link voltage and I_{DC} is the capacitor current. The DC-link voltage can be computed as:

$$V_{DC} = \frac{1}{C}\int I_{DC} dt \tag{3-37}$$

where C is the value of the capacitance in the DC-link. Combining Equations (3-36) and (3-37) and taking the Laplace transform, the DC-link dynamics can be modelled as in Figure 3-15.

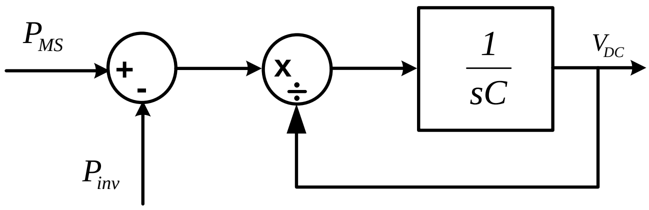


Figure 3-15: DC-link dynamic model

The PQ inverter control is implemented as a current-controlled voltage source, as shown in Figure 3-16. Current components in phase (i_{act}) and quadrature (i_{react}) with the inverter terminal voltage are computed based on a method presented in [124, 125] for power calculation in single-phase inverters. Power variations in the MS induce a DC-link voltage error, which is corrected via the PI-1 regulator by adjusting the magnitude of the active current output delivered to the grid. The reactive power output is controlled via the PI-2 regulator by adjusting the magnitude of the inverter reactive current output. As it can be observed in Figure 3-16, the PQ inverter control system is formed by two cascaded loops. The inner most control loop regulates the inverter internal voltage (v^*) to meet a desired reference current (i_{ref}). The outer most control loop consists on active and reactive power regulators. This inverter can be operated with a unit power factor or receive a set-point (locally or from the MGCC) for the output reactive power.

Although it is possible to find in the literature more advanced inverter control architectures that exploits different reference frames [99, 123], this model was adopted due to its simplicity. In fact, the key issue under consideration is to obtain a controllable AC voltage that allows coupling a DC power source to an AC distribution grid. The fast response dynamics that can be obtained with power electronic interfaces when looking only to its output/input transfer function are not of interest in the present case. Instead, passing to the grid the dynamic behaviour of each MS (fuel cell dynamics, microturbine dynamics, etc) is the key requirement in order to understand the influence each MS has on LV grid dynamics. Therefore, simple models as the one described above or other ones like in [121, 122] have sufficient accuracy in order to perform the required studies.

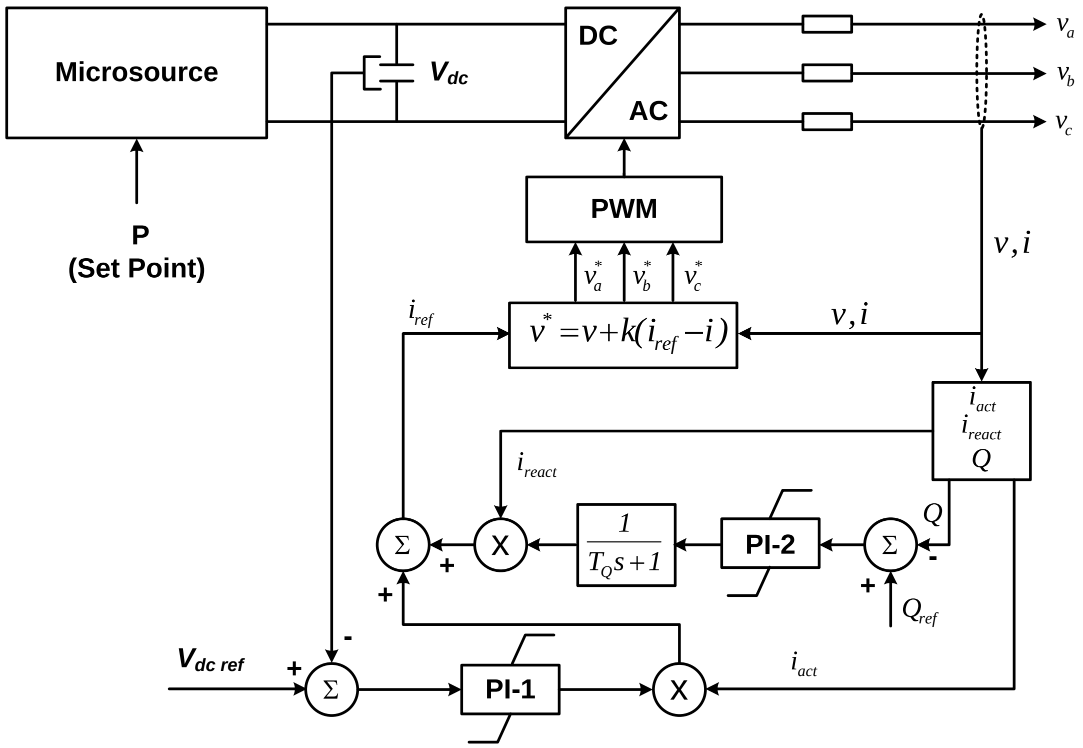


Figure 3-16: PQ inverter control

3.4.6.2 Voltage Source Inverter Control

In conventional power systems, synchronous generators share the load variation in accordance with their droop characteristics. This general principle of conventional power systems can be applied to inverters in order to change its output frequency as a function of the output power. This general principle is also important for parallel operation of variable frequency AC voltage sources, similarly to what happens in conventional power systems. In fact, if fixed frequency and fixed voltage VSI are used, inverters can neither operate in parallel in an islanded grid nor in parallel with a stiff AC system. This is because the measurement errors produced by the sensors used for inverter control, ageing phenomena, temperature effects and small deviations on the crystals frequency introduce errors that are integrated over time and can result in hazardous angle differences among VSI connected in different points of the network [126].

The VSI emulates the behaviour of a synchronous machine, thus controlling voltage and frequency on the AC system [89, 119, 121]. In conventional power systems, synchronous generators share any load increase by decreasing the frequency according to their governor droop characteristic. This principle is also implemented in inverters by decreasing the reference frequency when there in an increase in the load. Also, reactive power is shared by introducing a droop characteristic in the voltage magnitude. Therefore, the VSI acts as a voltage source, with the magnitude and frequency of the output voltage controlled through droops, as described in the following equations:

$$\begin{aligned} \omega &= \omega_0 - k_P \times P \\ V &= V_0 - k_Q \times Q \end{aligned} \tag{3-38}$$

where P and Q are the inverter active and reactive power outputs, k_P and k_Q are the droop slopes (positive quantities) and ω_0 and V_0 are the idle values of the angular frequency and voltage (values of the inverter angular frequency and terminal voltage at no load conditions).

When a VSI is interconnected with a stiff AC system, characterized by an angular frequency ω_{grid} and terminal voltage V_{grid}, the voltage and frequency references are externally imposed [124]. In this case, the desired output powers P_1 and Q_1 can be obtained in the VSI output by adjusting the idle values of the angular frequency ω_{01} and voltage V_{01} as follows (illustration in Figure 3-17):

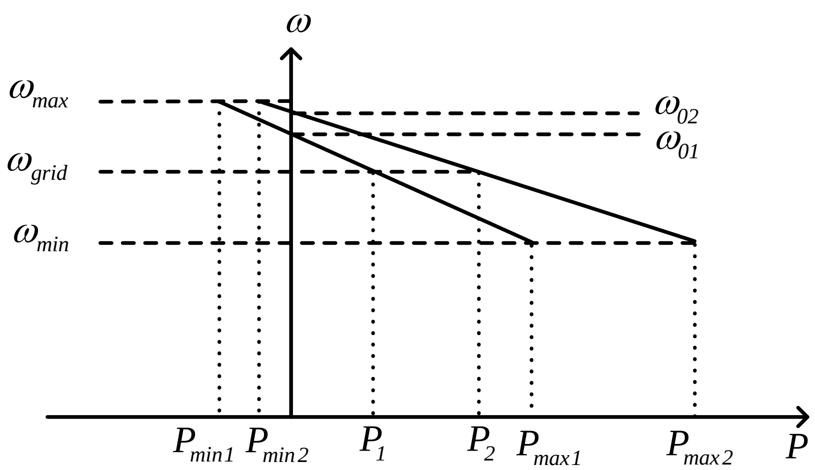


Figure 3-17: Frequency versus active power droop

$$\begin{aligned}\omega_{01} &= \omega_{grid} + k_P \times P_1 \\ V_{01} &= V_{grid} + k_Q \times Q_1\end{aligned} \tag{3-39}$$

If a cluster of VSI operates in a standalone AC system, frequency variation leads automatically to power sharing, such that for a system with *n* VSI the following equality stands:

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \tag{3-40}$$

being ΔP the total power variation and ΔP_i the power variation in the *i-th* VSI. The frequency variation can be computed as:

$$\Delta\omega = \omega_{0i} - k_{Pi} \times P_i - \left[\omega_{0i} - k_{Pi} \times (P_i + \Delta P_i)\right] = k_{Pi} \times \Delta P_i \tag{3-41}$$

Similar considerations can be made for the voltage/reactive power VSI control mode based on droops [89, 121]. However, as voltage has local characteristics, network cable impedances do not allow a precise sharing of reactive power among VSI.

In this dissertation, a three-phase balanced model of a VSI implementing the described droop concepts was derived from a single-phase version presented in [124, 126]. The general block diagram of the control scheme is presented in Figure 3-18, being the complete model shown in Figure 3-19. The VSI terminal voltage and current are measured in order to compute active and reactive powers. This measuring stage introduces a delay for decoupling purposes. The active power determines the frequency of the output voltage by the active power/frequency droop k_P. Similarly, the reactive power determines the magnitude of the output voltage by the reactive power/voltage droop k_Q. A phase feed-forward control was included for stability purposes, corresponding to the k_{ff} gain in Figure 3-19. The output voltages are the reference signals that control the VSI switching sequence using a Pulse Width Modulation (PWM) technique.

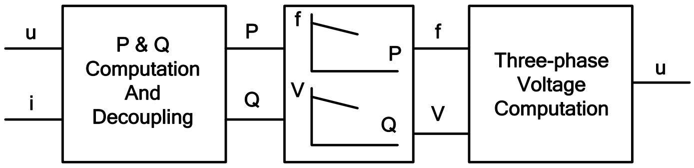


Figure 3-18: General block diagram of the VSI control scheme

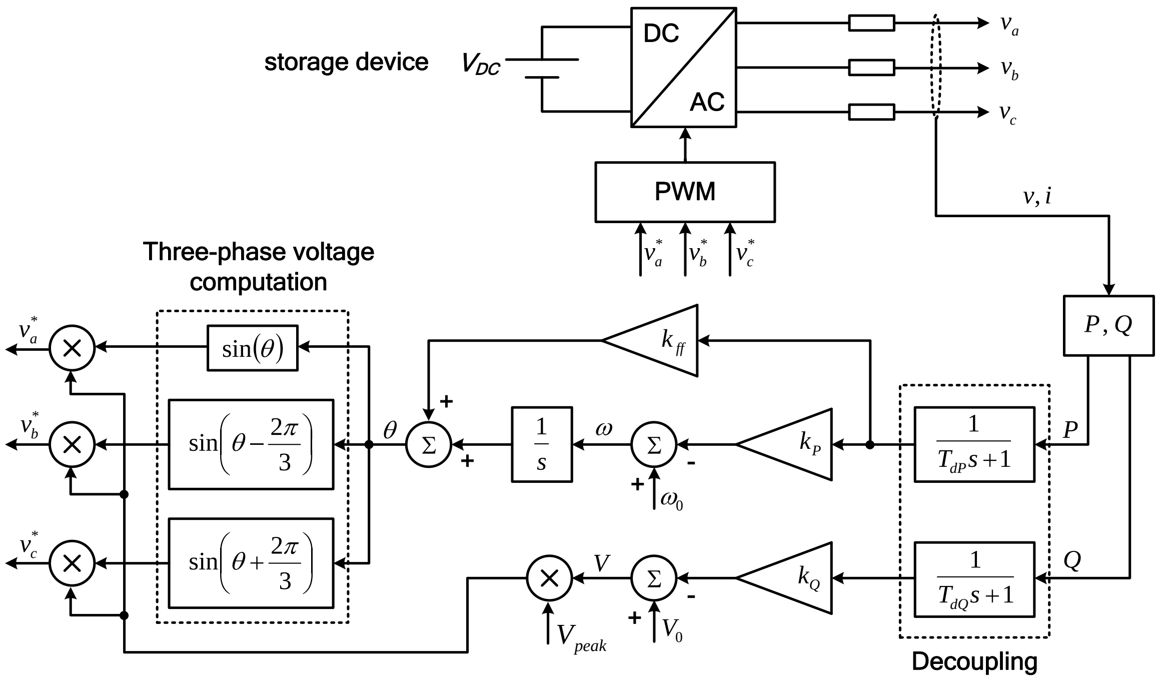


Figure 3-19: VSI control model

3.4.6.3 Inverter Modelling During Transient Overloads or Short-Circuits

Inverter over-currents can be caused by transient overloads (due to the connection of a large amount of load in islanded mode) or by short-circuits. Conventional power plants comprising synchronous generators directly connected to the network provide large short-circuit currents, which are very helpful for fast and efficient fault detection and elimination. However, in a MG, where generation units are mainly connected to the grid through power electronic interfaces, it is difficult to obtain high fault currents. Solid state switching devices used in inverters are selected based on voltage, current carrying capability (under certain cooling conditions and for a defined switching frequency) and safe operating areas. The islanded system can ride through short-circuits if there is sufficient over-sizing of power electronic interfaces in order to provide adequate short-circuit currents. At the same time, a novel protection scheme for the MG must be developed using different types of relays and breakers instead of conventional fuses. Resulting from this explanation, the following considerations were adopted in this dissertation:

- The VSI was selected to be up-rated in order to provide a significant contribution to short-circuit currents (ranging from 3 to 5 p.u.);
- PQ inverters can provide only a small amount of short-circuit current (1.2 to 1.5 p.u.).

After a short-circuit, the time interval during which large current outputs are absorbed from the VSI is dependent on the type of loads and generators connected to the grid (for example, the impact caused by the dynamics of induction machines operating as motors or generators). Induction machines can recover from short-circuits if the stability limit is not over-passed and enough reactive power is provided by external sources. In this case, the VSI will provide reactive power within the specified current limits and this behaviour will be sustained until the induction machines recover. Thus, it is also important that the VSI are able to sustain over-currents for a time interval larger than the one required for fault clearance.

The PQ inverter control scheme allows a simple control over the output inverter current during short-circuit conditions by limiting the total gain of the PI controllers shown in Figure 3-16 (current limiting functions for inverter protection purposes, as previously mentioned). Acting as a voltage source, the output current of a VSI tends to be very high (similarly to what happens in a conventional synchronous machine). In order to limit its output current, a control technique such as the one presented in Figure 3-16 is used. The main difference is that in this case the current reference has a maximum peak value dependent on the characteristics of the solid state switches and its frequency is imposed by inverter frequency/active power droop [96]. In order to avoid transient over-voltages, the injected current reference is progressively reduced after detecting fault elimination.

3.4.7 NETWORK AND LOAD MODELLING

In this research, the evaluation of the feasibility of MG islanded operation was performed through the analysis of the LV network dynamic behaviour considering only three-phase balanced operation, despite the fact that this 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. As will be shown, load characteristics greatly influence the dynamic behaviour of the MG, mainly under short-circuit conditions.

3.5 Summary and Main Conclusions

In this chapter was presented the MG concept, together with the corresponding conceptual hierarchical control architectures that are designed in order to respond to MG specific issues. A common characteristic that can be found in both MG architectures presented in this chapter is the ability of the MG to be operated without relying in fast communication infrastructures among the MS. This characteristic is very important in order to increase MG robustness following disturbances: in order to guarantee an efficient and reliable control of the MG under abnormal operating conditions, the most practical approach should rely on a network of local controllers in order to handle the resulting transient phenomena and guarantee MG survival.

Afterwards, dynamic models of various MS were described, aiming the development of a simulation platform that will support the identification of the control strategies to be adopted in a MG in order to allow a seamless transition to islanding operation. Understanding the dynamic behaviour of MS and storage devices, together with power electronic interfaces are critical issues in order to identify the right decentralized control strategies to be installed in the system.

Chapter 4

MICROGRIDS EMERGENCY CONTROL STRATEGIES

4.1 INTRODUCTION

The successful design and operation of a MicroGrid (MG) requires solving a number of demanding technical issues, in particular related to system functions and controls. The presence of power electronic interfaces in fuel cells, photovoltaic panels, microturbines and storage devices are the distinguishing characteristics of a MG when compared with conventional systems using synchronous generators. The dynamic behaviour of a system like the MG, with very low global inertia, is also quite different from the one observed in conventional power systems. Conventional power systems have the possibility of storing energy in the rotating masses of synchronous generators, thus providing the required energy balance in the moments subsequent to a load connection. In case of MG islanded operation, load-tracking problems arise since microturbines and fuel cells have slow response to control signals and are inertia-less.

A system with clusters of MicroSources (MS) designed to operate in islanded mode requires some form of energy buffering in order to ensure initial energy balance. The active power shortage caused in a MG when moving to islanding operation or resulting from load or power variation during islanding operation mode must be compensated from energy storage devices. Additionally, the slow response of controllable MS to the control signals is a specific issue contributing to the need of providing some form of energy storage with fast response in terms of power injection capabilities in order to enable MG operation under islanded conditions. The necessary energy storage can be provided by batteries or supercapacitors connected on the DC bus of each MS or through the direct connection of independent storage devices to the LV grid (batteries; flywheels, supercapacitors) [89, 90, 96].

MG islanding may result from an intentional disconnection from the Medium Voltage (MV) grid (for example, due to maintenance needs) or from a forced disconnection (due to a fault in the upstream MV network). Concerning an intentional disconnection, some control actions can be performed in order to balance load and generation in the MG and smooth the islanding transient. Following a disturbance in the upstream MV network, MG separation must occur as fast as possible. Depending on the fault and on the load and generation profile in the MG, the switching transient will have different impacts on MG dynamics. Some investigations on the development of specific switches intended for MG and Distributed Generation (DG) applications can be found in [127]. These authors present the development of a system based on a digital signal processor that consolidates in a single device several functions such as power switching, relaying, metering and communications. This device was designed in order to control circuit breakers, as well as faster semiconductor switching technologies such as Silicon Controlled Rectifiers (SCR), Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristors (IGCT). The authors mention that a circuit breaker based switch can respond in a 20 ms to 100 ms range. The faster responses can be achieved with SCR based switch (responding in one-half cycle to one cycle) and with the IGBT based switch (responding in the 100 microsecond time range).

When the MG transfers to islanded operation, an immediate change in the output power control of the MS is required, as they change from a dispatched power mode to one controlling frequency of the islanded section of the network. The control strategy to be adopted has to combine the frequency control strategy with the storage devices response and load shedding possibilities, in a cooperative way to ensure successful overall operation, although acting independently at the Microsource Controllers (MC) and Load Controllers (LC) level [96]. Therefore, in Section 4.2 are presented the MS characteristics in terms of control that can be exploited in order to derive suitable MG control strategies for islanding operation. As it will not be common to find fully controllable synchronous generators in a MG, inverter control is the main concern in MG operation. In [89, 121] a control scheme based on droop concepts to operate inverters feeding a standalone AC system is presented. This concept was further developed in this research (using the two different inverter control schemes described in the previous chapter) in order to derive the control strategies that allow MG running into islanded operation, as it is discussed in Section 4.3 and Section 4.4.

If a system disturbance provokes a general blackout such that the MG is not able to separate and continue in islanding mode, and if the MV system is unable to restore operation in a predefined time, a first step in system recovery will be a local Black Start (BS). The strategy to be followed will involve the MicroGrid Central Controller (MGCC) and the local controllers (LC and MC), using predefined rules to be embedded in the MGCC software, as it is discussed in Section 4.5. Exploiting MG capabilities to provide fast service restoration functionalities at the Low Voltage (LV) level is an innovative aspect that was developed and tested within this dissertation. Such an approach will enable fast restoration times to final consumers, thus improving reliability and reduce customer interruption times. In large conventional systems, tasks related to power restoration are usually carried out manually by system operators, according to predefined guidelines. These tasks must be completed as fast as possible, in real-time basis and under extreme stressed conditions. In an MG, the whole restoration procedure is expected to be much simpler because of the small number of control variables (loads, switches and MS). However, the characteristics of most MS (such as primary energy source response time constants) and the control characteristics of power electronic interfaces require the identification of very specific restoration sequences [128].

Another special feature of the MGCC concerns grid re-connection during BS, helping in this way the upstream Distribution Management System (DMS) that is managing the MV distribution network. During faults on the main grid, the MG may be disconnected from the upstream MV network and will continue to operate with as much connected MS as possible. During grid reconnection, the issue of out-of-phase reclosing needs to be carefully considered. The development of local controllers in close coordination with the MGCC functions needs to be evaluated from the dynamic operation point of view through studies to be performed. The strategies to be followed in order to deal with this two types of problems (MG black start and grid re-connection) will be embedded in the MG local controllers as a set of rules activated by the environmental conditions (characterized by the electrical variables voltage and frequency) and following orders from the MGCC.

4.2 MICROSOURCES CLASSIFICATION REGARDING CONTROL

In conventional power systems load changes are automatically taken by the generators thorough the use of a droop in the frequency of each generator with the real power delivered by the generator. Following a disturbance like a load increase in the system, the frequency is slightly reduced because kinetic energy stored in the synchronous generator rotor is delivered to the system and its angular velocity decreases. The governor systems installed in some generators, usually designated as a primary frequency control, is therefore responsible for increasing the power produced by these units proportionally to the system frequency deviation. This kind of control actions allows the generator to pick-up load changes according to the frequency droop characteristic and using the system frequency as the communication link between the control systems of the electrical generators [117]. Afterwards, the automatic generator control systems, usually denominated as secondary frequency control, and acting in a larger time frame, are responsible for restoring system frequency to the nominal value by re-dispatching (increasing) the power production in the units under automatic generator control.

Depending on the primary energy source used, the MS dimension and the type of power interface, MS to be installed in a MG can be considered as non-controllable, partially controllable (e.g. renewable sources that can reduce output only) and controllable (e.g. small co-generation units and storage units). Independently of this general classification, some additional considerations need to be established about the functions each MS has in the system. In this sense, it is important to characterize three types of MS [129]:

- **Grid forming unit:** the grid forming unit defines the grid voltage and frequency reference by assuring a fast response in order to balance power generation and loads. Standard systems contain just one grid forming unit as a master, which can be a diesel generator or an inverter coupled to a large energy storage device.

- **Grid supporting unit:** the grid supporting unit active and reactive power is determined according to system voltage and frequency characteristics, by allowing some form of dispatch upon their power production levels.

- **Grid parallel unit:** grid parallel units refer to uncontrolled or partially controlled MS like Photovoltaic (PV) systems or micro wind generators. Usually, this kind of MS is operated in order to inject as much power into the grid as possible.

Regarding the types of MS assumed to be used in the MG, the following classification of the units is possible:

- Grid forming units: storage devices;
- Grid supporting units: Single Shaft Microturbine (SSMT) and Solid Oxide Fuel Cell (SOFC);
- Grid parallel units: PV and micro wind generator.

In addition to MS classification, some considerations regarding inverter control are also necessary. The PQ inverter control described in Section 3.4.6.1 is used to connect MS to an already existing grid, whose frequency and voltage is imposed by other units. The MS to be connected to the LV grid through PQ controlled inverters are grid supporting units and grid parallel units. In this sense, the PQ controlled inverter can be regarded as a slave device of an energized grid, since this type of inverter is not capable of energizing the grid (that is, establishing a voltage and frequency reference, in a similar way o what happens with conventional synchronous generators). The Voltage Source Inverter (VSI) control described in Section 3.4.6.2 defines a class of devices that can be used in order to build (energize) an islanded grid, to which other sources can be connected. By definition, the output of a voltage source depends on the load connected to it. Acting as a voltage source, the VSI requires a significant amount of storage capability in the DC-link or a prime power source with a very fast response in order to maintain the DC-link voltage constant. In other words, the power requested to a VSI needs to be available almost instantaneously in the DC-link. Regarding the ability of a VSI to build an islanded grid, it can be regarded as a master device of an electric power system like the MG. As a general conclusion, it is important to note that the main difference between these two classes of inverters is the existence of an energy buffering device able to support load and generation during islanding conditions.

These general considerations are required since the MG is an inverter dominated grid, and all the control issues rely on the inverters. Therefore, a key issue for MG control is to understand how such an islanded grid can be built up through the use of power electronic interfaces.

Although the MG issue is not entirely new, the work reported in literature is based on some basic assumptions. In some cases, the MG comprises synchronous generators to which other MS are connected [17, 18]. In this case, building up the system is not critical since this task is performed by synchronous units. In other cases [89, 90], the authors consider that all the MS installed in the MG have an energy buffering device and are controlled through droops (according to the VSI control principle previously described). The control strategy proposed in this dissertation includes also this possibility. However, it can be regarded as a more general control strategy in order to consider the possibility that the majority of MS do not have a storage device installed in the DC-link (and therefore cannot be controlled through droops). Nevertheless, some MS like SOFC and SSMT have the capability of providing active power on demand (through a convenient control of the input fuel). Exploiting SOFC and SSMT capabilities in terms of responding to a power demand (although they have slow responses to the control signals) requires the development and identification of alternative control strategies in order to demonstrate the feasibility of MG islanded operation.

4.3 MICROGRID CONTROL FOR ISLANDING OPERATION

In a system without synchronous machines to balance demand and supply through its frequency control scheme, the inverters should be responsible for frequency control during islanded operation. If a cluster of MS is operated within a MG and the main power supply (the MV network) is available, all the inverters can be operated in the PQ mode because the voltage and frequency references are defined by the main system. In this case, a sudden disconnection of the main power supply would lead to the loss of the MG, since there would be no possibility for load/generation balancing, and therefore for frequency and voltage control. However, by using a VSI to provide a reference for voltage and frequency, it is thus possible to operate the MG in islanded mode and a smooth moving to islanded operation can be performed without changing the control mode of any inverter. This is possible since the VSI is able to operate in parallel with other voltage sources (for instance, the upstream MV network during MG normal operating conditions, or with other VSI during MG islanded operation) [96]. According to the VSI model described in Section 3.4.6.2, it can react to network disturbances based only on information available at its terminals. This working principle of a VSI provides a primary voltage and frequency regulation mean in the islanded

MG. For example, considering a single VSI operating in an islanded grid, any power variation ΔP and ΔQ causes frequency and voltage variations that can be determined by:

$$\begin{aligned} \Delta\omega &= \omega_0 - k_P \times P - \left[\omega_0 - k_P \times (P + \Delta P)\right] = k_P \times \Delta P \\ \Delta V &= V_0 - k_Q \times Q - \left[V_0 - k_Q \times (Q + \Delta Q)\right] = k_Q \times \Delta Q \end{aligned} \tag{4-1}$$

After identifying the key solution for MG islanded operation, two main MG control strategies are possible: Single Master Operation (SMO) or Multi Master Operation (MMO) [96]. In both cases, a convenient secondary load-frequency control during islanded operation must be considered to be installed in controllable MS, as it will be descried later.

4.3.1 SINGLE MASTER OPERATION

The operation of a MG with several PQ controlled inverters and a single VSI can be defined as a SMO control strategy, as represented in Figure 4-1. In this case, the VSI provides the voltage and frequency reference for the operation of the PQ controlled inverters when the MG is isolated from the main power supply.

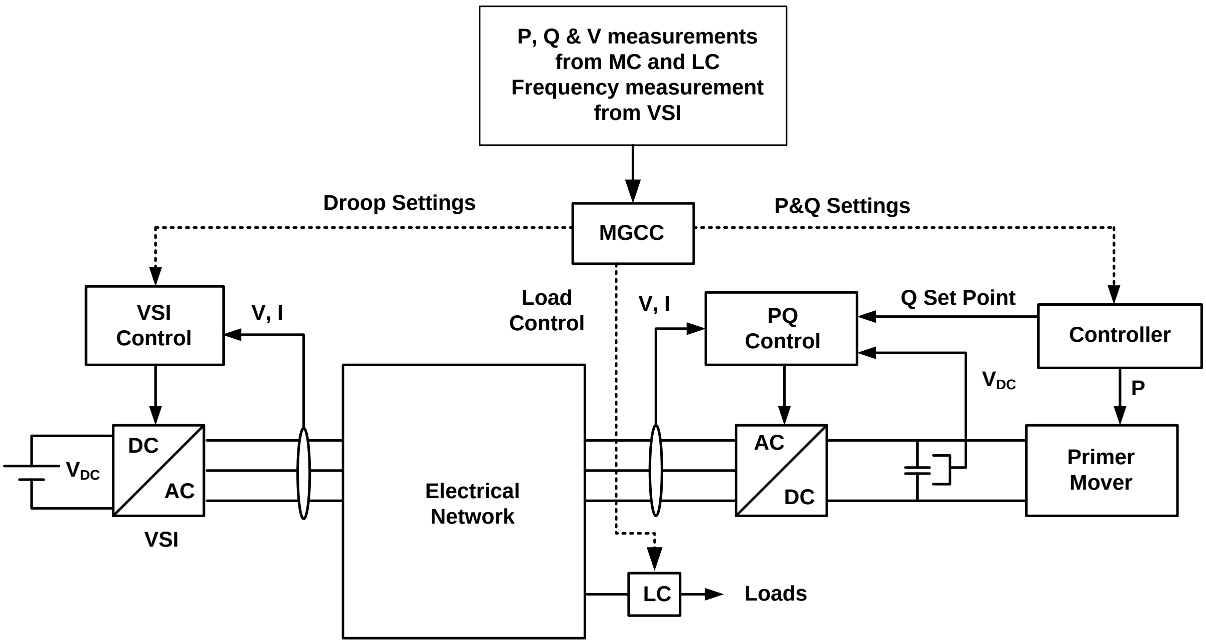


Figure 4-1: Single Master Operation control scheme

The VSI is responsible for fast load-tracking during transients (natural variation of load and consumption, as well as during the islanding transient). Using the communication capabilities of the MG, the MGCC receives information from MG local controllers and it is responsible for updating each PQ inverter set-point in order to achieve an optimal operation scenario regarding voltage levels, reactive power flows and active power dispatch. MGCC is also responsible for load control actions and for the definition of VSI droop settings.

4.3.2 MULTI MASTER OPERATION

The operation of an isolated network with several VSI (Figure 4-2) is similar to a conventional power system with synchronous generators controlling active power/frequency and reactive power/voltage. These functions are usually performed by conventional voltage and speed governors, which are now replaced by the droop characteristics: the frequency/active power and voltage/reactive power droops.

Considering the interconnected operation mode, the frequency of the LV grid is set by the external grid. Each inverter is operating with a pre-defined frequency/active power characteristic droop. The idle frequency f_0 of each VSI (the frequency at which the output active power is zero) can be modified in order to define the desired value of the active power injected by the VSI. As the grid frequency fluctuations of the interconnected system are very small, the idle frequency can be used in order to dispatch generation [124]. This function can be performed by the MGCC, and requires a periodic actualization of several parameters in accordance with the operational criteria used in the MGCC algorithms.

If a fault causes the transition from the interconnected to the islanded mode, it is not necessary to change the control strategies of each MS. When the main power supply is disconnected, the overall system moves to a new operation point (in voltage and frequency), depending on the local load. Then, a secondary control strategy can be made to act on the inverter in order to restore the nominal value of the frequency. This can be done by changing the idle frequency value of each inverter, while keeping the output power constant. This situation corresponds to the calculation of the idle angular frequency $\omega_0 = \omega_{grid} + k_P \times P$, where ω_{grid} is the MG angular frequency nominal value and P is the actual value of the VSI output power. Therefore, it is possible to change MG frequency without changing the power output of the inverters.

As VSI are associated with storage devices, it was assumed that the DC-link voltage variations are not very significant during the time interval used for the dynamic simulations.

In this case, the dynamic model of the MS does not need to be considered in the dynamic simulation studies, since it would not be reflected in the dynamics of the grid. This is the general approach followed in [89, 90].

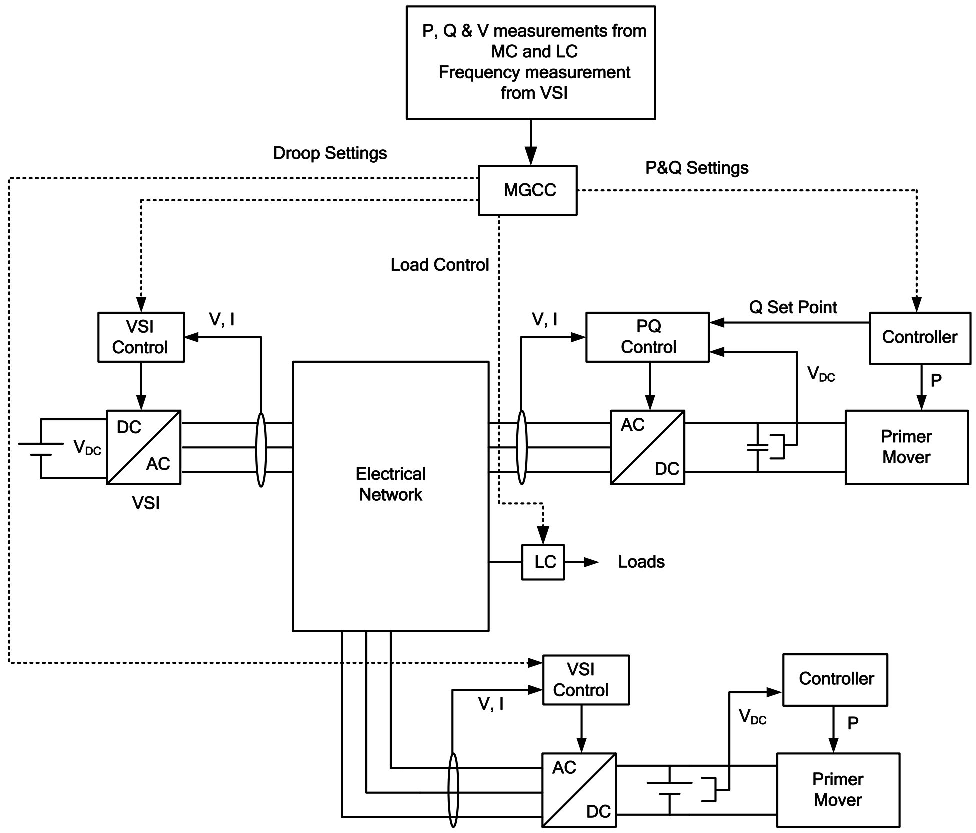


Figure 4-2: Multi Master Operation control scheme

4.4 EMERGENCY STRATEGIES

In case of a fault in the upstream MV network or in other special operating conditions it is necessary to exploit the possibility of moving the MG into an islanding operating mode. This control approach constitutes a solution opposed to the classical belief of not allowing distribution grids with embedded generation to be operated isolated from the main power system. The islanding procedure is therefore regarded as possible operation state and it requires a careful planning of the system conditions in respect to load, MS production levels, existence of faults, etc. In order to ensure system survival following islanding it is necessary to exploit controllable MS, storage devices and load shedding mechanisms in a cooperative way, as described next.

Concerning VSI, it is important to note they can be connected either to independent storage devices or to MS with a storage device in their DC-link. Independent storage devices connected to the grid can be loaded only by absorbing power from the LV grid. In the first case, the finite energy storage capability of the device implies the VSI only injects active power into the grid during transient operation (in other cases, power injection should be zero). MS assumed to be interfaced with the LV grid through a VSI with high storage capacity in its DC-link are responsible for continuously loading the corresponding storage devices by the primary energy source, being its discharge not a key concern.

4.4.1 FREQUENCY CONTROL

In terms of standalone AC system operation, the VSI control principle makes possible reacting to system disturbances (for example load or generation changes) based only on information available at its terminals. In this way, the operation of a MG does not rely on fast communications among MS controllers and the MGCC, which could be impractical. Running in a larger time frame, a secondary control approach can be used to improve system performance, namely restoring nominal frequency values during islanding operation.

4.4.1.1 Primary Frequency Control

Equation (4-1) shows that the VSI active power output is proportional to the MG frequency deviation. In the moments subsequent to MG islanding or due to loads or power variations during MG islanding operation, the first devices reacting to the new system conditions are the VSI coupled to storage devices. Acting as a voltage source, power imbalance following a disturbance demands large currents from the VSI, therefore increasing their measure output power. As a consequence of the increase in the VSI output power, the MG frequency decreases in accordance to the active power/frequency droop, as illustrated in Figure 4-3.

Lets consider in a first place a SMO strategy. When the MG is interconnected with the upstream MV network the storage device is injecting an active power P_0 (that could be zero if it is not a MS with a storage device in the DC-link). In the moments subsequent to MG islanding, the frequency drifts towards a new value ω_1 and the power injected by the VSI increases to P_1. The difference between the power injected after islanding P_1 and the power injected previous to islanding P_0 is $\Delta P = P_1 - P_0$ and corresponds to the amount of power absorbed from the upstream MV network during the interconnected operation mode. In other words, ΔP is the power imbalance between MG local load and generation following islanding.

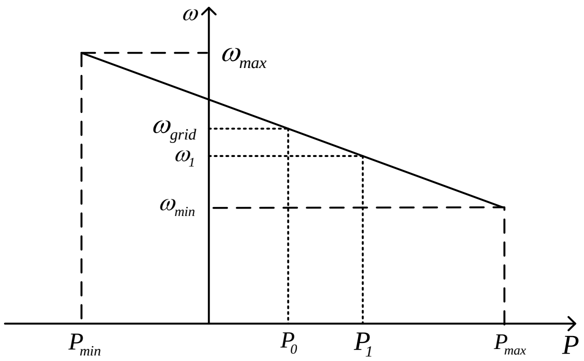


Figure 4-3: VSI frequency decrease due to active power increase $\Delta P = P_1 - P_0$

In case of a MMO strategy (n VSI operating in parallel in a standalone AC system), a power variation ΔP in the system is shared among the VSI, such that in steady state the following equation stands:

$$\Delta P = \sum_{i=1}^{n} \Delta P_i \tag{4-2}$$

being ΔP_i the power variation in the *i-th* VSI. Previous to MG islanding, all the VSI are operating at the same frequency, which is equal to the grid frequency. Combining all the droop characteristics of the VSI inverters, the steady state power variation in each VSI and system frequency in the moments subsequent to the disturbance can be computed using the following matrix equation:

$$\begin{bmatrix} 1 & k_{P1} & 0 & 0 & \cdots & 0 \\ 1 & 0 & k_{P2} & 0 & \cdots & 0 \\ 1 & 0 & 0 & k_{P3} & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \ddots & \vdots \\ 1 & 0 & 0 & 0 & \cdots & k_{Pn} \\ 0 & 1 & 1 & 1 & \cdots & 1 \end{bmatrix} \times \begin{bmatrix} \omega' \\ \Delta P_1 \\ \Delta P_2 \\ \Delta P_3 \\ \vdots \\ \Delta P_n \end{bmatrix} = \begin{bmatrix} \omega_{grid} \\ \omega_{grid} \\ \omega_{grid} \\ \vdots \\ \omega_{grid} \\ \Delta P \end{bmatrix} \tag{4-3}$$

where ω' is the post-disturbance MG angular frequency and $\omega_{grid} = \omega_{oi} - k_i \times P_i$ is the pre-disturbance MG angular frequency. Using Equation (4-3) it is possible to compute MG frequency deviation $\Delta\omega = \omega' - \omega_{grid}$ and the power sharing among the VSI following a generation or load variations ΔP during islanding conditions.

In both cases, it is possible to conclude that the VSI action following disturbances during islanding operation can be regarded as a primary frequency control, similarly to what happens in synchronous generators assigned to primary frequency control in conventional power systems.

4.4.1.2 Secondary Frequency Control

The above explanations clearly show that during MG islanding operation, the frequency drifts from the nominal value following power or load variations. During this transient condition, power balance is assured by energy storage devices. However, if the MG frequency stabilizes in a value different from the nominal one, (due to the use of only proportional droop controls) storage devices would keep on injecting or absorbing active power whenever the frequency deviation differs from zero. This situation is illustrated in Figure 4-4, where it is shown VSI power injection as a function of MG frequency deviation. The figure illustrates that power injection is proportional to MG frequency deviation (within the power ratings of the storage device). This should be only admissible during transient situations, where storage devices are responsible for ensuring the energy balance between load and generation within the MG. However, storage devices (batteries, flywheels or supercapacitors with high capabilities for injecting power during small time intervals) have a finite storage capacity and can be loaded mainly by absorbing power from the LV grid. Therefore, they should inject power into the MG only during transient situations in order to not run out of energy. Consequently, the development of a control procedure to correct permanent frequency deviations during any islanded operating conditions should then be considered as one of the key objectives for any control strategy.

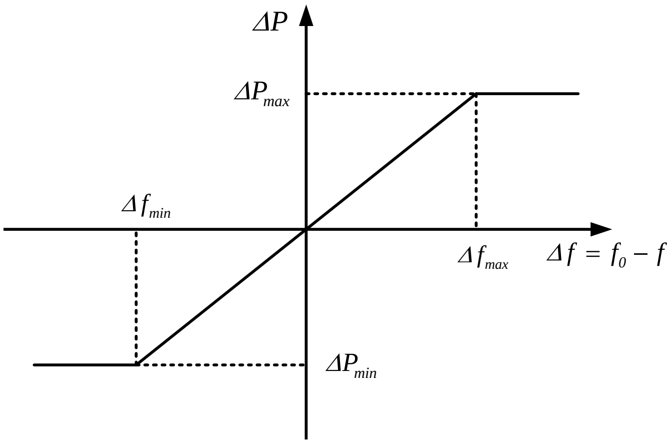


Figure 4-4: Steady state active power characteristic of a VSI coupled to a storage device

In order to promote adequate secondary control aiming to restore frequency to the nominal value after a disturbance, two main strategies can be followed: local secondary control, by using a Proportional-Integral (PI) controller at each controllable MS (Figure 4-5), or centralized secondary control mastered by specific algorithms to be embedded in the MGCC software modules. In this dissertation, a local secondary control strategy is used. In both cases, target values for active power outputs of the primary energy sources are defined based on the frequency deviation error. For SMO, the target value is directly an active power set-point sent to the prime mover of a controllable MS, while for MMO, the target value can be both an active power set-point for a controllable MS connected to a PQ inverter or a new value for the idle frequency of a VSI connected to a MS with storage devices in the DC-link.

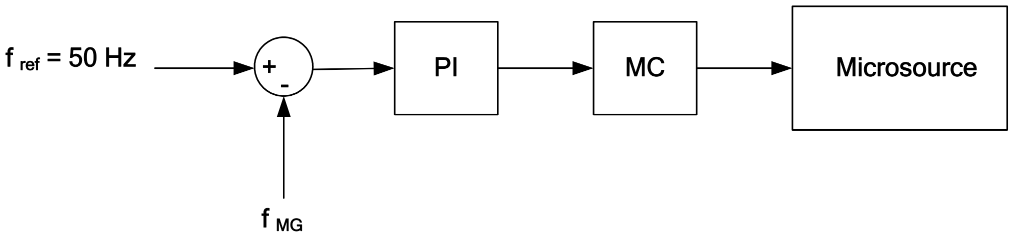


Figure 4-5: Local secondary load-frequency control for controllable MS

4.4.2 LOAD SHEDDING

The controllable loads concept plays an important role under some MG operating conditions, namely those concerning the imbalance between load and generation (load larger than generation). In order to deal with this problem, a load shedding mechanism is proposed to be implemented in a MG as an emergency functionality to aid frequency restoration to its nominal value after MG islanding. The philosophy adopted was based on the monitoring of the amplitude of the frequency deviation, but it would also be possible to include the rate of frequency change in the load shedding mechanism. However, at present, only the frequency deviation was considered as activation variable for the load shedding scheme. Load shedding is used as a remedy against large frequency excursions. Basically, the dynamic behaviour of the system is improved if some percentage of the load is temporarily lost, allowing the generators with frequency regulation functions to react to the frequency deviation. The benefits derived from such a scheme are well known, particularly in what concerns a rapid reaction following a large frequency deviation, leading to a faster stabilization of the system and to the frequency restoration to its nominal value. It is important to note that, in addition to frequency deviation, storage devices have a finite storage capability which also determines the amount of load that must be shed following MG islanding. This topic is developed later in Chapter 6. At this moment, the energy storage capability is not considered.

Following MG recovery after islanding, some loads that were disconnected by load shedding relays can be reconnected again. In order to avoid large frequency deviations during the load reconnection, it was assumed that it is possible to define a certain number of steps for load reconnection. This number of steps can be changed in accordance to the percentage of load shedding. All this functionalities can be easily implemented in LC.

4.4.2 VOLTAGE CONTROL

Although voltage control is not a fundamental issue within the scope of this dissertation, some considerations are needed due to the specific nature of a MG. In LV distribution lines, the resistive parte is predominant over the inductive one. Figure 4-6 represents a VSI, the respective coupling inductance and a LV cable connecting the VSI to a stiff AC power source. The LV cable is represented by its resistance, being the cable reactance neglected. The per unit active and the reactive power injected by the VSI can be calculated as follows:

$$P_{inv} = \frac{V_{inv}^2}{R_C} - \frac{V_{inv} V_{grid}}{R_C} cos(\delta) \tag{4-4}$$

$$Q_{inv} = \frac{V_{inv} V_{grid}}{R_C} sin(\delta) \tag{4-5}$$

where:

P_{inv}: **inverter active power output**

Q_{inv}: **inverter reactive power output**

V_{grid}: **stiff AC source voltage**

V_{inv}: **inverter terminal voltage**

R_C: **LV cable resistance**

δ **phase difference between the inverter and the grid voltage**

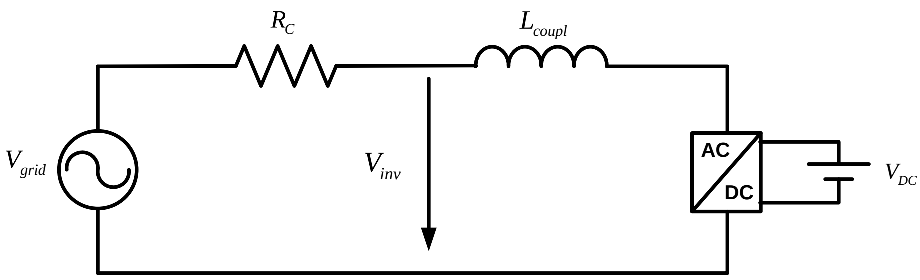


Figure 4-6: VSI coupled to a stiff AC voltage source through a LV cable (resistance)

Previous equations demonstrate the active power flow is linked to the voltage magnitude, while reactive power flow is linked to the phase difference between the voltage sources. This conclusion suggests using active power to control voltage magnitude and reactive power to control grid frequency. If this principle is applied, no power dispatch is possible, since each load will tend to be fully supplied by the nearest connected generator. Therefore, the option is to use the droop characteristics as they were presented earlier [126].

As reactive power injection cannot be used for voltage control purposes, the voltage control strategy in an islanding MG using a SMO strategy is to regulate voltage in the VSI connection point, while the PQ controlled inverters operate under a reactive power support strategy. In this case, reactive power injection by PQ controlled inverters is determined in order to achieve any specific objective (power factor correction of the loads near the MS, losses minimization in a MG, etc.). For example, a loss minimization strategy within the MG will required the MGCC to run an optimization algorithm defining the reactive power set-points of each MS. Within this dissertation, and without lake of simplicity, a partial power factor correction philosophy was adopted. Therefore, MS connected to the grid through PQ controlled inverters receive locally a reactive power set-point in order to compensate the power factor of the load connected to the same node. The reactive power balance within the islanded MG is assured by the VSI.

When a MMO strategy is used, the voltage reference is defined simultaneously by the several VSI connected in different nodes. In this case, the application of reactive power/voltage droops may cause reactive current circulation between VSI, which depends on the active power dispatch assigned to the inverters and on the VSI idle voltage. The following example is used in order to illustrate these issues. Figure 4-7 shows two VSI connected by a LV (high resistance) cable, whose characteristics are also indicated in the figure. Relevant VSI data is presented in Table 4-1. At t = 10 s, S_1 is disconnected from the system. Figure 4-8 shows the power output and terminal voltage following the disconnection of S_1.

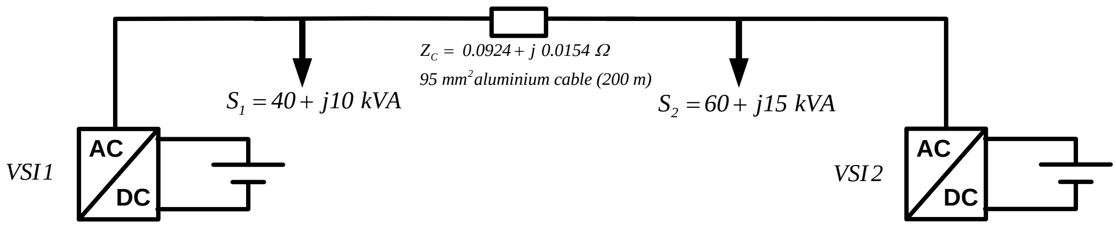


Figure 4-7: Two VSI feeding a load through a LV (high resistance) cable

As it can be observed in Figure 4-8, VSI 2 is injecting almost the totality of reactive power required by load S_2. Due to the use of active power/frequency droops, both inverters share system active power perfectly (in Figure 4-8, active power curves of both inverters are perfectly coincident). Due to the high resistance of the LV cable, terminal voltage in VSI 1 is higher then in VSI 2 in order to allow active power flow from VSI 1 to supply S_2. Following the disconnection of S_1, both inverters share the active power absorbed by S_2. Due to the disconnection of S_1, VSI terminal voltages increase. The new system state requires VSI 1 to absorb reactive power in order to increase its terminal voltage (this effect is possible due to the coupling reactance) and make possible the active power flow from VSI 1 to S_2.

In order to avoid the reactive power flow between the inverters, it is necessary to change the reactive power/voltage droop characteristic of the inverters. A simple procedure can consists on increasing the idle voltage of VSI 1 in order to reduce its reactive power absorption. In this case, Figure 4-9 shows the effect of a progressive increase of VSI 1 idle voltage at t = 20 s. As can be observed, the reactive power in VSI 1 is reduced to zero, while both inverters perfectly share active power.

Table 4-1: VSI parameters for Figure 4-7

Parameter	VSI 1	VSI 2
Idle frequency (Hz)	50	50
Idle voltage (p.u.)	1.0	1.1
Active power decoupling delay (s)	0.6	0.6
Reactive power decoupling delay (s)	0.6	0.6
Active power droop (rad.s^{-1}.W^{-1})	-1.2566×10^{-4}	-1.2566×10^{-4}
Reactive power droop (V(p.u.). var^{-1})	-3.0×10^{-6}	-3.0×10^{-6}
Phase feed-forward gain (rad.W^{-1})	-5.0×10^{-6}	-5.0×10^{-6}
Coupling inductance (mH)	0.5	0.5

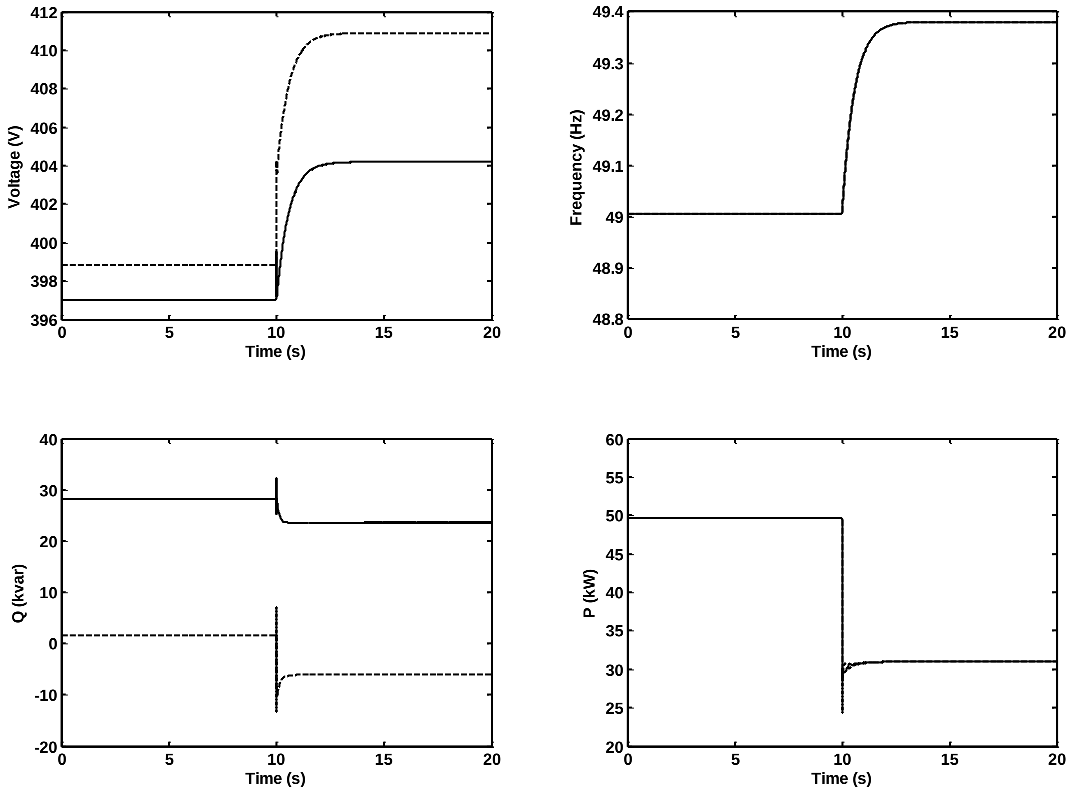


Figure 4-8: Reactive power circulation between VSI 1 (dash line) and VSI 2 (solid line)

The MG emergency control strategies previously discussed (primary frequency control, secondary frequency control, load shedding mechanism and voltage control) were implemented in a simulation platform, together with the MS dynamic models presented in Chapter 3. Some details on the MG dynamic simulation platform can be found in Appendix B. In Chapter 5 are presented and discussed the numerical simulation results that illustrate the feasibility of the proposed MG emergency control strategies.

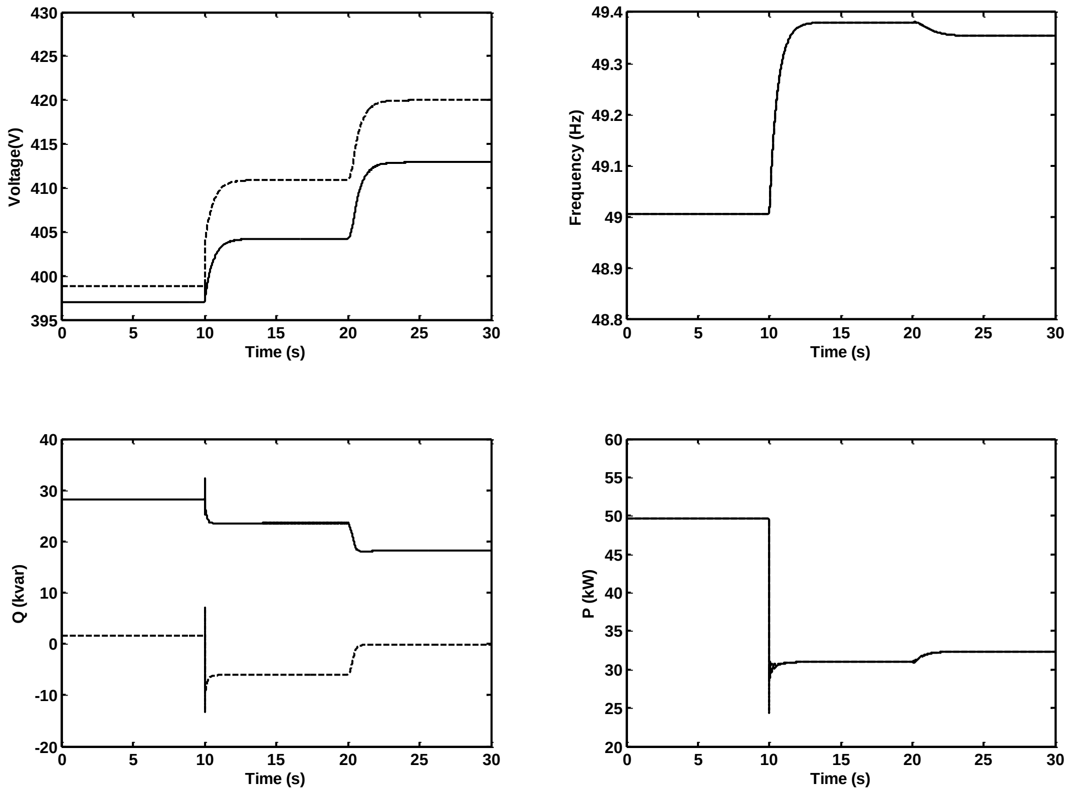


Figure 4-9: Reducing reactive power flow between VSI 1 (dash line) and VSI 2 (solid line) following a load disconnection

4.5 EXPLOITING LOW VOLTAGE MICROGRIDS FOR SERVICE RESTORATION

Although DG has been increasing significantly in the recent years, there is little work on the identification of its contribution for power systems restoration. Conventional restoration procedures focus on the restoration of bulk power transmission systems and its loads. The general policy for the integration of DG in electrical power systems is based on the principle that DG should not jeopardize the power system to which it is connected and it should be quickly disconnected following any disturbance. Additionally, it is only reconnected when distribution circuits are energized and present stable values of voltage and frequency.

Power system conventional restoration procedures are usually developed before any emergency situation occurs, adopting heuristic approaches, which reflect human operators experience to deal with the problem. Furthermore, the size and specific characteristics of actual power systems precludes the definition of an universal methodology [130]. The restoration plan is defined step by step, based on pre-defined guidelines and operating procedures, sometimes exploiting decision support tools, which are an extremely valuable resource to assist system operators [131]. The restoration procedure is focused on the plant preparation for restart, network energization and system rebuilding. Depending on system characteristics, a choice must be made between a strategy of energizing the bulk network before synchronizing most of the generators or a strategy of restoring islands that will be synchronized later [132]. In order to exploit the new possibilities offered by the increasing amounts of DG units connected to electrical power systems, new approaches are required in order to make possible DG participation in several system services, such as power system restoration. In this scenario, it would be possible to develop a new restoration process that will run simultaneously in the transmission and distribution system. Such a strategy will exploit the conventional power system restoration strategy in the upstream transmission level, while the energization of some islands by means of DG units will allow expanding service restoration at the downstream distribution level based on the availability of DG units with BS capability. Contrary to what are the current restoration strategies followed by the utilities, (wait several hours for the restoration at the transmission level before restoring service in the distribution level and allow DG connection), DG could allow the formation of several distribution network cells through the exploitation of DG black start capabilities. The coordination between the upstream and downstream restoration will allow a better service continuity, increasing the amount of restored load and shortening the electric power system restoration times [128, 133].

Concerning the MG concept previously presented, the reduction of LV consumers interruption time can be performed by allowing MG islanded operation, until MV network is available, and by exploiting MG generation and control capabilities to provide fast BS at the LV level. If a system disturbance provokes a general or local blackout, such that the MG is not able to successfully separate and continue to operate in islanded mode, and if the MV network is unable to restore operation within a pre-defined time, a first step in system recovery will be a local BS in the LV grid, which is a quite innovative approach. This first step will be afterwards followed by the MG synchronization with MV grid. Based on the MG control strategies proposed before and making use of the MG communication infrastructures, special issues for MG service restoration are identified in order to totally automate MG restoration procedure. Within a MG, local self healing techniques can be derived, since MG can be used for service restoration in their area of influence. The entire power system restoration procedure can then exploit a simultaneous bidirectional approach: a conventional top down strategy, starting from large plant restart and transmission energization, and simultaneously a bottom-up strategy, starting from the distribution side and exploiting DG units and microgeneration capabilities. Synchronization among these areas follows afterwards. This approach helps to reduce restoration times and to reduce the unserved electric energy during major failures [128].

During conventional power system restoration, a set of critical issues should be addressed carefully: reactive power balance, switching transient voltages, load and generation balance and coordination, sequencing of generating units start-up and definition of the relays settings [134]. In case of a MG, the restoration procedure is much simpler due to the reduced number of controllable variables (switches, MS and loads). On the other hand, it is important to stress it will not be expectable to find conventional synchronous machines in a MG, which are liable for voltage and frequency control in conventional power systems. As previously referred, most of the MS currently available are not suitable for direct connection to the LV grid, requiring power electronic interfaces (DC/AC or AC/DC/AC). Another special issue related to MS operation concerns its slow response to the control signals in order to change the output power. The absence of synchronous machines connected to the LV grid requires that power balance during transients should be provided by energy storage devices. Furthermore the controllability characteristics of the power electronic interfaces used in MS contributes to the definition of very specific restoration strategies.

4.5.1 An Overview on Conventional Power Systems Black Start

In the last decades there have been a significant number of power system blackouts worldwide that, due to its extense, causes significant impacts to the power system itself, to the economy and to the society in general. After the major blackouts in the north-western United States in the mid 1960s and in the early 1970s, power system restoration problems start deserving a special attention, namely in what concerns power systems restoration plans development and periodic actualization [135].

Despite all the efforts that electric power systems industry has been developing in order to increase global system security and to mitigate the risk of failures, the operation of bulk power systems close to their technical limits and the uncertainty arising from liberalization is contributing to increase the risk of major blackouts. Following a blackout, effective means need to be taken in order to restore the system to normal operation as soon as possible, being the main objective the maximization of the restored loads within the minimum elapsed time. This procedure is usually referred as the BS or service restoration and can be defined as the process that a system suffered from a complete blackout is restarted through reconstructing its networks and restoring its service depending on its self-starting units and without help from other systems [136].

As it was already briefly mentioned before, system restoration after a general blackout is a complex and time consuming task, which is very dependent on specific power system characteristics. Therefore, it is a common practice followed by electric utilities to develop specific restoration schemes that meet their particular needs. The restoration process requires coordination among generating plants, load characteristics and the bulk transition system constraints (time, frequency, voltage and security constraints). However, the restoration stage presents unique characteristics that make conducting the overall restoration plan a very difficult task. First, operators in the control centres are not faced with this situation very often because power systems are designed to prevent system collapse through the extensive use of protection devices that are coordinated in order to isolate disturbances and reduce the propagation of its side effects. Second, the pressure and stress in order to complete the restoration process in a minimum amount of time, together with the unavailability of many resources difficult the accomplishment of the tasks. Additionally, the restoration process is usually conducted with limited information due to several reasons (unavailability of communication channels, unavailability of data due to its usefulness during normal operating conditions). Also, Supervisory Control And Data Acquisition (SCADA) and Energy management Systems (EMS) applications are usually not designed to hold restoration process efficiently [132]. Since the power system is a dynamic system, and the restoration procedure is carried out in real time, it can be subjected to unforeseen disturbances which may put in cause the prepared guidelines. All these factors lead to the conclusion that a decision support tool integrated in existing EMS environments would be a valuable resource to help power system operators during the restoration stages [137].

From a mathematical point of view, the restoration problem can be seen as combinatorial multi-objective, multi-stage, non-linear, constrained optimization problem. The inherent complexity of this problem has been precluding the development of a general methodology to determine the set of restoration actions in a systematic way. Instead, a more heuristic approach has been followed by power system operators, which is strongly based on its knowledge about power system specific characteristics. This approach relies on the utilization of knowledge based systems that can help system operators when conducting the restoration process [138]. The motivation for embedding knowledge based systems in EMS is related to its ability to act fast on the information about the disturbances which occurred in the network by means of the following characteristics: quick information gathering and high capacity for examining and applying many more rules than the operator could do during the same time [137]. A practical overview on the use of knowledge based in power systems restoration is provided in [135].

4.5.1.1 Conventional Power Systems Restoration Strategies

As previously stated, the main objective during power systems restoration is the maximization of the load supplied and the minimization of the time required to achieve a complete system restoration, satisfying also the required security and operating constraints. Although the strategies electric power utilities follow in order to achieve these general goals are very dependent on specific system characteristics (electrical and geographical), there are two main restoration strategies that can be distinguished [132, 139]:

- **Build-down approach**, based on a top-down sequential restoration of the entire system skeleton;

- **Build-up approach**, based on the parallel restoration of several electric islands created inside the bulk power system, which are synchronized later.

Both strategies share a common characteristic, which is the choice of the source of initial power, that is, the BS unit (a unit which has the ability to start-up without any power supply from the electric power system). BS units are usually those with gas or hydraulic turbines, having the ability to restart quickly and to be paralleled with the grid in a short time. In the initial phase of the restoration process, special attention should be given to thermal units, which were shut down following system collapse. In particular, a quick supply of auxiliary consumption of thermal units is required in due time, since this units have very severe operating constraints namely in what concerns hot restart following a shut down [131, 139]. Following the start-up of the BS unit, a special effort should be oriented to synchronize as many units as possible in order to increase the voltage and frequency regulation capacity of the system being restored and make possible the incremental load pick-up.

4.5.1.1.1 The Build-Down Strategy

The build-down approach is usually applied to power systems having generating units and consumption centres in two geographically remote parts of the system, aiming the creation of a global system skeleton. This is usually the case of hydro-thermal systems, being the hydro component the predominant one [139]. The procedure consists on the energization of the entire bulk power transmission system in a first step and providing station service to the auxiliary systems of all thermal generation units. Afterwards, a step by step restoration of loads and generation is followed [132].

Nevertheless, this procedure has some inherent limitations due to the reactive power production of unloaded high voltage transmission lines, that may exceed the reactive absorption capacity of the generator used to energize the network. As a result, unacceptable over-voltages in remote locations may arise.

4.5.1.1.2 The Build-Up Strategy

The build-up strategy is the one more commonly used for power system restoration due to operating system stability requirements. In this case, the restoration strategy is based on the sectionalisation of the system into two or more subsystems (electrical islands), flowed by the parallel restoration of transmission lines and generation assets within each island. Afterwards, the islands are to be synchronized in order to build the bulk transmission system [139, 140]. The definition of the boundaries of each island to be restored is based on some considerations regarding the geographical location of the production units and the consumption centres. It is also necessary to assure each electric island has at least one BS unit.

During the restoration of each island, load connection should be made in small increments in order to avoid excessive under-frequency deviation that may lead to generation tripping or load curtailment. Also, reactive power balance and voltage levels should be maintained by proper control of excitation systems. When two islands are to be synchronized by switching a tie-line, the magnitude and/or frequency mismatch between the island nodes to be interconnected need to be carefully evaluated and reduced by voltage and generation control in order to avoid instability in the moments subsequent to the islands synchronization [134].

During the restoration of an island, only a portion of the load is usually supplied, which should be sufficient to satisfy the minimum technical limits of thermal units that are in service and to stabilize voltage levels within the island. When at least two electric islands are restored following these general principles, they are synchronized in order to form a new island, and so forth. Afterwards, the load is picked up for the whole system [141].

Although this is the most commonly used procedure for power system restoration, it presents some limiting factors, namely the number of available units with BS capability, the ability to match generation and load within prescribed frequency and voltage limits and the existence of tie points capable of measuring synchronization with neighbouring systems [139].

4.5.1.2 Power Systems Restoration Planning

The power system restoration plans to be used by system operators when the system suffers a major disturbance are usually prepared in advance. In order to prepare these plans, different numerical simulation tools are required in order to evaluate the plans feasibility: load flow analysis, transient stability analysis, voltage stability analysis, electro-magnetic transient program, long term dynamic simulation program, short-circuit analysis program, etc [142]. These tools consist of a set of on-line and off-line programs that are able to describe the transient, dynamic and static behaviour of power systems during the restoration phase. The restoration plan is then prepared based on the critical analysis of output results of these programs, together with operators experience and knowledge about the control problems of each specific power system. As the power system is in permanent change over the years in terms of load patterns and electric equipment, a periodic actualization of the restoration plans is also an essential task.

Generally, power system restoration is based on specific guidelines developed to meet each utility needs. In order to give a formal structure to the power system restoration problem, it is presented in [143] a method aiming to systematize power system restoration planning. The proposed algorithm formulates a non-linear optimization problem and provides the way to find the most suitable set of control variables that satisfy the steady state operating constraints. The proposed approach aims to eliminate the trial-and-error based approaches, thus contributing to reduce the time for system restoration. The optimization criterion that measures the performance of the restoration procedure during the several stages is the minimization of the bus voltage deviations from their prescribed values. However, this approach considers only the successive steady state conditions in each restoration stage, neglecting possible dynamic constraints that may hinder plan development.

As previously referred, power system restoration plans are developed based on extensive simulation studies in order to demonstrate the theoretical feasibility of the overall restoration procedure. However, the restoration plans are usually presented to power system operators as a detailed sequential list of instructions. This form of presenting the restoration plan to system operators denotes some critical drawbacks that may affect the performance of the overall restoration strategy [144]:

- Plan understanding by operators is difficult;
- Precedence relationships among restoration actions are not explicitly shown;
- Difficulty on the perception of changes that may occur during the restoration stages;
- Operators training sessions are difficult;
- Delays plan consultation;
- Ignore time duration issues.

In order to overcome these difficulties, a methodology based on the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) graph theory was first introduced in [145] and further explored in [144]. These tools are valuable resources, since they are able to provide a visualization of the existing restoration plans and can also contribute for its actualization. The main benefits arising from the use of the proposed methodology are:

- Provision of user friendly graphic tools to guide power system operators during restoration and allow inference on the precedence relations among the restoration actions;

- Possibility of helping operators on the determination of the most suitable procedure to be envisaged following unexpected events not foreseen in the prepared in advance restoration plans;

- Possibility of making an "*a priori*" evaluation of some restoration plans characteristics, namely the estimation of the restoration duration;

- Identification of the investments that should be made in order to reduce power systems restoration times.

4.5.1.3 Specific Issues during Power System Restoration

Any restoration procedure is to be carried out with the aim of supplying the consumers as soon as possible. In order to achieve this goal, production units must be restarted and the network must be strengthened in order to maintain secure and stable power system operation and to assure acceptable quality parameters to the consumers. Based on general considerations that are common to several power systems independently of its specific characteristics, it will be possible to derive a general procedure and a list of guidelines that would enhance restoration plans. Nevertheless, specific and detailed restoration plans must be developed in order to satisfy the particular requirements of each power system [139]. The next section provides a brief discussion on a set of issues that are common to every restoration strategies, although the restoration plans may be different.

4.5.1.3.1 Black Start Capabilities and Units Restart Coordination

Production units restart is one of the initial control actions that must be accomplished in any restoration procedure. At this restoration stage, BS units are of utmost importance since these units will produce power for the auxiliary systems of the generating units without BS capabilities. BS units are usually those with combustion turbines (presenting a fast cold restart that takes about 15 minutes) and hydroelectric units [139]. Following the restart of these units, the priority of supply is given to auxiliary systems of thermal units. Usually, some load must be picked up in these early restoration stages in order to maintain the real power balance, which is constrained by the minimum technical limits of the thermal units running in the system.

It is also necessary to take into account some critical intervals for the thermal units restart. For example, some thermal units may be restarted only after a minimum critical time (cold start), while others must be synchronized on the network before a minimum critical time is elapsed (hot restart). Therefore, the priority is given to hot restart units since, if its synchronization is not accomplished within the minimum critical time, they will not be available during a long time interval. Regarding these general considerations, it is necessary to know several critical intervals of the prime movers, such as: interval between the shut down and restart, interval between the restart and the synchronization, interval between the synchronization and the technical minimum and the interval between the technical minimum and the full load [130, 132].

Regarding the procedure to determine the units start-up sequence, some utilities create diagrams that show the available real and reactive power as a function of time, which depend on the prime movers response to sudden load pick-up (load-generation balance projections). This diagram allows system operators to perceive simple guidelines based on the approximate off-line system analysis [137].

4.5.1.3.2 Switching Operations

Following plant preparation, the network must also be prepared for the energization procedure. The switching operations are carried out with the aim of reconnecting the network. In the initial stages, priority is given to lines linking the BS units with the thermal plants whose auxiliary systems need to be supplied in due time. Therefore, switching sequence plans during the early restoration stages are usually prepared in advance. The switching strategies that may be used in the restoration of the transmission system can be divided in two groups [130]:

- **All open:** all the circuit breakers of each substation are opened by EMS programs, according to the commands of the system operator;

- **Controlled operation:** control the configuration of the restoration by operating only the equipment that is necessary to restore the power system.

4.5.1.3.3 Voltage and Reactive Power Control

During the initial stages of power system restoration, the energization of high voltage transmission lines may create some over-voltages that can be divided in three categories [146]:

- **Sustained power frequency over-voltages**, which are caused by charging currents of lightly loaded transmission lines. The duration of sustained over-voltages is a critical issue for circuit barkers, surge arresters and power transformers. Usually, a 1.2 p.u. over-voltage can be withstood by power transformers during 1 minute; however, a 1.4 p.u. over-voltage can be withstood by power transformers and surge arresters during only 10 seconds. In order to evaluate and identify sustained over-voltages, a simple power flow study can be used. The disconnection of shunt capacitors, the under-excitation of synchronous generators, the connection of shunt reactors, a careful planning in order to energize only those lines which will be more loaded, the operation of parallel power transformers with different taps in order to cause reactive losses are possible solutions in order to control sustained over-voltages during restoration.

- **Transient voltages** are usually caused by the energization of large sections of transmission lines or due to the switching of shunt capacitors. These transient over-voltages are usually well damped and have very short durations. However, in conjunction with sustained over-voltages, they can seriously affect surge arresters. Therefore, if sustained over-voltages are properly controlled and maintained below 1.2 p.u., transient over-voltages are usually not limiting factors in system energization. Switching transients are usually evaluated by an RLC model of the network (lines and transformers), being the generators considered as ideal sources and loads converters to its equivalent impedances [147].

- **Harmonic resonance voltages**: sustained over-voltages can be sufficient to over-excite (saturate) power transformers and increase the amount of harmonic content they produced during no load (or light load) conditions. If the combination of the system impedance with line capacitance is adverse, harmonic resonance phenomena will result. Usually, software tools able to analyze fast transient phenomena are used to develop detailed models of system components and identify the possible conditions of harmonic resonance.

Another issue that needs to be considered during the early stages of power system restoration is the reactive power capability curves of synchronous generators. These curves are provided by manufactures and are defined as a function of machine design parameters at the rated voltage. The information they provide shows that different generation loading produce different thermal effects in several parts of the machine (such as the rotor or the armature) and limit its operating range in the (P, Q) plan. Additionally, when supplying power to the auxiliary systems of synchronous generators, specific constraints of this system further limit the generator reactive power capabilities. In [148] is provided an overview on the constraints imposed by the auxiliary systems and a method for calculating its influence of the original reactive power capability limit curve is presented. In [149], this issue is further exploited. In this case, the authors present a method for selecting the most suitable tap positions for the generator set-up and auxiliary system transformer in order to achieve the desirable reactive power capabilities.

4.5.1.3.4 Frequency and Active Power Control

During power system restoration, power and generation need to be matched in order to assure stable frequency and avoid large frequency deviations. During the early stages, the reduced number of synchronous generators on the network makes the system week in terms of global inertia. Therefore, load pick-up is usually performed in small increments that can be accommodated by the inertia and response of the on-line generators. Load restoration in small increments tends to increase the restoration duration. However, persecuting the restoration task with large load steps increases the risk of a frequency decline beyond recovery and the occurrence of some outages [139].

The size of the load to be picked up is limited by the response of the prime movers. As a rule of thumb, small and radial loads are usually picked up prior to larger and network loads, while maintaining a reasonably constant real to reactive power ratio. Feeders equipped with under frequency relays are picked up later, when the system frequency is more stable [134]. In order to evaluate the effect of the response of several types of prime movers during system restoration, it is presented in [150] a study on the size of the load that can be safely restored, together with the evaluation of the system reserve and its distribution among the several types of generators in order to maintain system stability following the outage of the biggest generator.

During the early stages of power system restoration, it is important to know the approximate amount of real and reactive power loads to be picked up at any time. As the blackout duration increases, the coincident load factor also increases. The variation of the load with the elapsed time after the blackout depends on the normal peak and light loads, load power factor, power factor corrections, load types and the total connected loads. In [151] it is presented a methodology to predict the magnitude and duration of the peak demand following a general blackout. The authors conclude that after an hour of service interruption, the magnitude and duration of the peak demand is high enough to deserve a special attention during the planning of a power system restoration strategy.

Following an initial phase, where the skeleton of the power transition system is re-integrated and some loads are connected in order to stabilize the system and run thermal units with power outputs higher than their minimum technical limits, most of the load is picked up in a second phase. In this second phase, the voltage and active power set-points of the generators need to be updated according to the load pick-up plan. Also, transmission capacity is reinforced by energizing additional circuits. The problem of determining a suitable sequence of operations to peak up load is a highly combinatorial optimization problem with multiple constraints. In order to solve this problem, a genetic algorithm based approach in proposed in [152]. The authors aim to find the most suitable restoration actions for different initial states of the power system after the skeleton has been successfully created. In order to evaluate the power system variables used in the fitness function of the genetic algorithm and to avoid the violation of power system technical constraints (voltage levels, overloads, frequency deviations, generators technical limits, etc), a long term dynamic simulation program was used. From the results of this optimization procedure, the authors found that several restoration sequences are suitable for the same initial power system state. Therefore, the optimization procedure was further exploited in order to generate different pairs (initial system state, optimized load restoration sequence), being the relations among them to be extracted through the use of a decision tree. Although the optimization procedure is a time consuming task, the obtained knowledge is then integrated in a decision tree, which is fast enough to be integrated in any computational module to support system operators in real time.

4.5.1.3 Conventional Power System Restoration versus MicroGrid Restoration

After providing a brief overview on conventional power system restoration techniques, some considerations are needed in what concerns the exploitation of general issues that are common in conventional power systems and in MG for service restoration (despite the complete different nature of both systems).

In conventional power systems, restoration plans requires a strong interaction with system operators due to the reduced intelligent systems installed in the control centres. Although conventional power systems have been continuously automated, the human factor is still a key concern for its operations. In the case of a MG, an advanced communication and control system is assumed to be available. In this case, the advanced control system installed in a MG should have the ability to run the system autonomously (without human intervention). This is also possible do the reduced number of devices that need to be controlled, when compared to conventional power systems. Regarding MG communication systems, it is important to assure they will be conveniently supplied in any situation, as it is expected to happen in conventional power systems.

In conventional power systems there are operation rules and contracts describing precisely the responsibility of the producers and control centres during system restoration. In the case of a MG, it is expected that some MS like SSMT will play a crucial role in service restoration (due to its ability to restart without the presence of an external power supply). Therefore, this type of MS will have also some form of contractual agreement in order to be restarted promptly in the initial stages of system restoration. This type of assignments should be performed in advance in order to avoid any form of negotiation actions in the initial of service restoration, which could be a time consuming task.

In conventional power systems, finding paths in order to provide crank power to thermal units without BS capability could be a difficult task due to serious damages the system may suffer after a blackout and due to the meshed nature of the transmission system. On the contrary, a low voltage MG is a radial system, which makes easy to find the path to provide crank power to a MS without BS capabilities. It is also expected that MG are not seriously affected (in terms of equipment injuries) due to bulk transmission system blackouts. In this way, MS can be rapidly prompt for restart, even after a major blackout.

As it was previously described, a usual approach during power system restoration is to open all the switches in order to guarantying a no load network in the first moments of the restoration procedure. In a MG, this same concept should be transposed and adapted. First, if there are controllable loads, switching them off during the initial restoration steps will help the development of the restoration plan. If it is not possible to disconnect all the loads, it should be studied how to deal with the frequency and voltage variations at non-disconnected loads during the initial restoration stages in order to avoid damaging them. Otherwise, switching devices to be controlled by the MGCC should be added in order to disconnected those loads in the initial stages of the restoration procedure.

A commonly used approach for power system restoration is the build-up strategy, previously described. In the case of a MG a similar strategy can be used. In this case, several MS with BS capability can start-up simultaneously, pick-up some local load in order to be stabilized, and start to be synchronized in order to build-up the entire MG system. Regarding voltage and frequency control problems in the MG, the use of droop control concepts allow the derivation of simple procedures in order to evaluate the expected effect of a load connection. Also, the existence of LC throughout the MG allows defining precise control action for each type of load.

4.5.2 MICROGRID BLACK START

Based on the MG control strategies previously discussed and making use of the MG communication infrastructures, this section tackles the identification of special issues for MG service restoration in order to totally automate the entire procedure. The MG black start will be centrally guided by the MGCC software. Under this philosophy, the BS software module is responsible for controlling a set of rules and conditions to be checked during the restoration stage, which should be identified in advance. These rules and conditions define a sequence of control actions to be carried out during the restoration procedure. The main steps to be considered include [128]:

1. Building the LV network;
2. Connecting MS;
3. Controlling voltage and frequency;

4. Connecting controllable loads;

5. MG synchronization with the upstream MV network, when it becomes available.

The MG restoration procedure will be triggered if a general or local blackout occurs or if major injuries affecting the MV network do not allow feeding the MG from the MV side after a pre-defined time interval. The MGCC should also receive information from the Distribution Management System (DMS) about the service restoration status at the MV level in order to help deciding to launch the local BS procedure. The flow chart shown in Figure 4-10 delineates the procedure followed by the MGCC to detect the occurrence of a blackout and decide when to trigger the MG black start procedure.

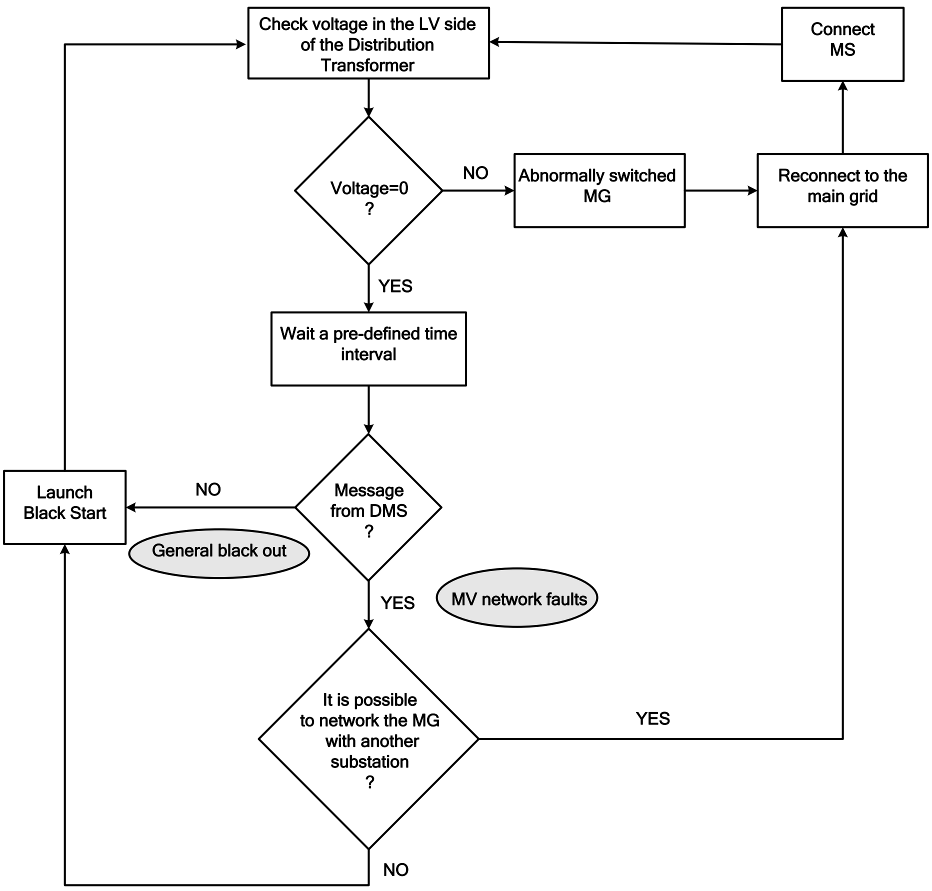


Figure 4-10: Flow chart defining the conditions to trigger MG black start procedure

The MG protection scheme is also a concern during service restoration. Conventional power systems comprising synchronous generators provide large fault currents which are helpful for fast and efficient fault protection. In MG, generation is mainly connected to the grid using inverters which can provide sufficient fault currents only by a convenient over-sizing. Due to economic reasons inverters over-sizing is limited and during islanded operating conditions the load current/fault current ratio is quite small when compared to conventional systems. Therefore, novel protection scheme for low voltage MG must be developed. A simple solution may consist on the use current sensing relays and section breakers (instead of conventional fuses) conveniently placed in the LV feeders in order to trip them when faults occur and isolate the smallest possible faulted section of the MG [153]. As the BS procedure involves a step by step connection of MS to the LV grid, the short-circuit power at the point where protection devices are installed changes. Thus, under such protection strategy, the MGCC should be responsible for changing protection devices settings, while the restoration procedure takes place, in order to efficiently detect and isolate MG faults.

4.5.2.1 General Assumptions

MG local controllers and the MG communication infrastructure are of utmost importance for the success of the restoration scheme. Thus, small auxiliary power units are required to power the communication network elements and local controllers (LC and MC). Another basic requirement is the availability of MS with BS capability, which involves an autonomous power supply to launch this kind of generation. MS restart procedure is carried out previously to building the LV network so it is not reflected in the LV network. Beyond this essential condition, it is also required availability for:

- Updated information, obtained before disturbance, about the status of load/generation in the MG and about availability of MS to restart. During normal operation, the MGCC periodically receives information from the LC and MC about consumption levels and power generation, storing this information in a database. It also stores information about technical characteristics of the different MS in operation, such as active and reactive power limits. This information will be used to restore the critical loads of the consumption scenario before blackout occurrence.

- Preparing network for re-energization. MG loads and generators must be disconnected from the LV grid after system collapse. Also, the MV/LV distribution transformer should be disconnected from the LV and MV networks.

During the BS procedure development it was assumed that MS with BS capability are the SSMT and the MG main storage unit. It was also assumed that, at least during the first stages of this sequence, a multi master control approach is adopted, since several VSI can operate in parallel, which can be turned into a SMO in the final stages of the BS procedure.

4.5.2.2 Sequence of Actions for MicroGrid Black Start

After a general blackout, the MGCC will perform service restoration in the LV area based on the information stored in a database about the last MG load scenario, as described before, by performing the following sequence of actions [128]:

1. Sectionalizing the MG around each MS with BS capability in order to allow it to feed its own (protected) loads. These actions lead to an initial creation of small islands inside the MG, which will be all synchronized later. In this case, each MS with BS capability is running and feeding a load, which helps to stabilize its operation.

2. Building the LV network. The MG main storage device is used for energising an initial part of the LV network, followed by switching on all the remaining LV switches not connected to loads or MS. An additional issue during LV energization is related to MG neutral earthing, since the TN-C-S system is suggested to be adopted [154]. MG neutral earthing should be created at the MG storage unit.

3. Small islands synchronization. MS already in standalone operation mode should then be synchronized with the LV network. The synchronization conditions (phase sequence, frequency and voltage differences) should be verified by local MC, after the procedure is enabled by the MGCC, in order to avoid large transient currents which may compromise inverters operation.

4. Connection of controllable loads to the LV network is performed if the MS running in the LV network has the capability to supply these loads. The amount of power to be connected should take into account the available storage capacity in order to avoid large frequency and voltage deviations during load connection. Motor load starting is a critical issue due to the large current absorbed in the first moments.

5. Connection of non-controllable MS or MS without BS capability, such as PV and micro wind generators. At this stage, the system MS are sufficiently loaded in order to smooth voltage and frequency variations due to power fluctuations in non-

controllable MS, so they can now be connected. LV network paths can also be created so that MS without BS capability can absorb power from the grid in order to restart.

6. Load increase. In order to feed as much load as possible, depending on generation capability, other loads can then be connected. Motor load start-up is a critical issue due to the large current absorbed in the first moments. Large motor loads must be connected when the main MS are feeding the LV grid in order to increase the short-circuit power.

7. Changing the control mode of MS inverters. The MG main storage inverter is controlled as a VSI, providing system voltage and frequency references. Then the MS with BS capability inverters operated as VSI may be changed to PQ control.

8. MG synchronization with the MV network when it becomes available. The synchronization conditions should be verified again, after the order is given by the MGCC. This means the distribution transformer should be previously energized from the MV side, being the synchronization then performed through LV switches.

During MG restoration stages, special attention should be given to frequency and voltage control (or reactive power flow among VSI). The voltage and frequency control principles described in Section 4.4 are to be used in order to guarantee stable operating conditions.

4.6 Summary and Main Conclusions

In this chapter were presented and discussed the control strategies that are able to run the MG under islanded conditions. These strategies are required in order to demonstrate that MS can be exploited further in order to develop local self healing strategies and to reduce customer interruption times. The next chapter demonstrates, through extensive numerical simulation, the feasibility of the control strategies discussed in this chapter.

In a MG the inverters need to be operated in order to provide stable voltage and frequency in the presence of arbitrary varying loads or power production. The specific nature of the MG, namely in terms of very reduced global inertia and high resistance compared to the reactance of LV lines requires the development of specific strategies for voltage and frequency control. Additionally, in a system with a larger number of MS, communication of information is impractical. This implies the inverter control system should be based on terminal quantities. Therefore, it was presented and discussed control strategies that are able to run the system in the moments subsequent to disturbances without relying on sophisticated communications. Nevertheless, communication systems are used with the sole purpose of improving global system operation, but are not be critical for system operation.

A variety of technical and economical barriers hinder MG dissemination and more work and adaptation on conventional power systems control centres is required in order to get fully profit from MG potentialities, namely its contribution for system restoration. Equipment failures after a general blackout in a conventional power system may create difficulties to system restoration. MG black start is thus proposed as an emergency resource to be used in case of faults outside the MG not affecting seriously its equipments. The control strategies to be adopted for MG black start and subsequent islanded operation as well as the identification of the set of rules and conditions were derived and discussed. It is expected that a restoration strategy that exploit a simultaneous restoration at the transmission and distribution level will undoubtedly contribute to reduce power system restoration times.

Chapter 5

EVALUATION OF MICROGRID EMERGENCY CONTROL STRATEGIES DURING ISLANDING AND BLACK START

5.1 INTRODUCTION

In the previous chapter were presented and discussed the control strategies to be adopted in a MicroGrid (MG) when the system becomes isolated or it has to deal with a Black Start (BS) situation. The main objective of this Chapter is to evaluate the performance of the proposed control strategies through extensive numerical simulations. Therefore, a simulation platform was developed under the *MatLab®/Simulink®* environment, where it is possible to analyse the dynamic behaviour of several MicroSources (MS) and storage devices (whose dynamic models were described is Chapter 3) connected to a Low Voltage (LV) network, together with the proposed control strategies for MG islanding operation. Additional details on the *MatLab®/Simulink®* simulation platform can be found in Appendix B.

As previously referred, MG islanding can be considered intentional (for example, when maintenance procedures are required to take place in the upstream Medium Voltage (MV) network) or forced (due to faults occurring in the upstream MV network). Simulation results obtained with the referred simulation platform will illustrate the resulting impact in the MG dynamic behaviour for both cases and considering different operating conditions. Therefore, several scenarios characterized by different load and generation levels were defined in order to have a thorough analysis of the performance of the proposed control strategies in different situations.

In order to study and evaluate the feasibility of the restoration sequences, two simulation platforms were exploited to deal with a LV study case network. An *EMTP-RV®* tool that was developed within the framework of the MICROGRIDS project was used in order to analyse the fast transients associated with the initial stages of the restoration procedure, as described in [155]. Afterwards, the *MatLab®/Simulink®* simulation platform was used in order to evaluate the longer term dynamic behaviour of the islanded MG during the restoration phase and following the implementation of the proposed sequence of control actions.

5.2 THE MICROGRID TEST SYSTEM

The single line diagram of the LV test system used in this research was adapted from a study cased defined under the framework of the MICROGRIDS project, and it is shown in Figure 5-1 [156]. This LV test system is composed by a MV/LV distribution transformer and two LV distribution feeders. A LV distribution feeder is used to supply an industrial consumer, which has connected two 30 kW Single Shaft Microturbines (SSMT 1 and SSMT 2). The industrial consumer load is composed by a mix of induction motor loads and constant impedance loads. The other LV feeder is used to supply a residential area with two apartment buildings and a group of residences. Within the residential area there are several microgeneration technologies connected to the grid. It was also assumed that some residential loads are to be modelled as induction motor loads. The MG main storage device (a flywheel, battery or supercapacitor) is connected trough a LV cable to bus 1 and it is indented to allow MG running into islanding operation. The MG separation device is assumed to be the LV breaker located in the LV side of distribution transformer. The MG peak load is around 170 kVA, while the total MS installed capacity is 155 kW (storage device is not considered since it only injects energy in the grid during transient situations). As the total MS capacity is not able to cover the MG peak load, MG islanding can only take place if it assumed the possibility of disconnecting some loads in the moments subsequent to MG islanding. The test system relevant data for simulation purposes is presented in Appendix A.

The dynamic models of the MG components adopted in this dissertation, together with the proposed control strategies were implemented in the *MatLab®/Simulink®* environment, by exploiting general control blocks and the *SimPowerSystems* library. All the MS models were developed and implemented in a modular way, thus allowing a quick implementation of a simulation case. As it will be described later, the implementation of a load shedding mechanism was also considered in some controllable loads.

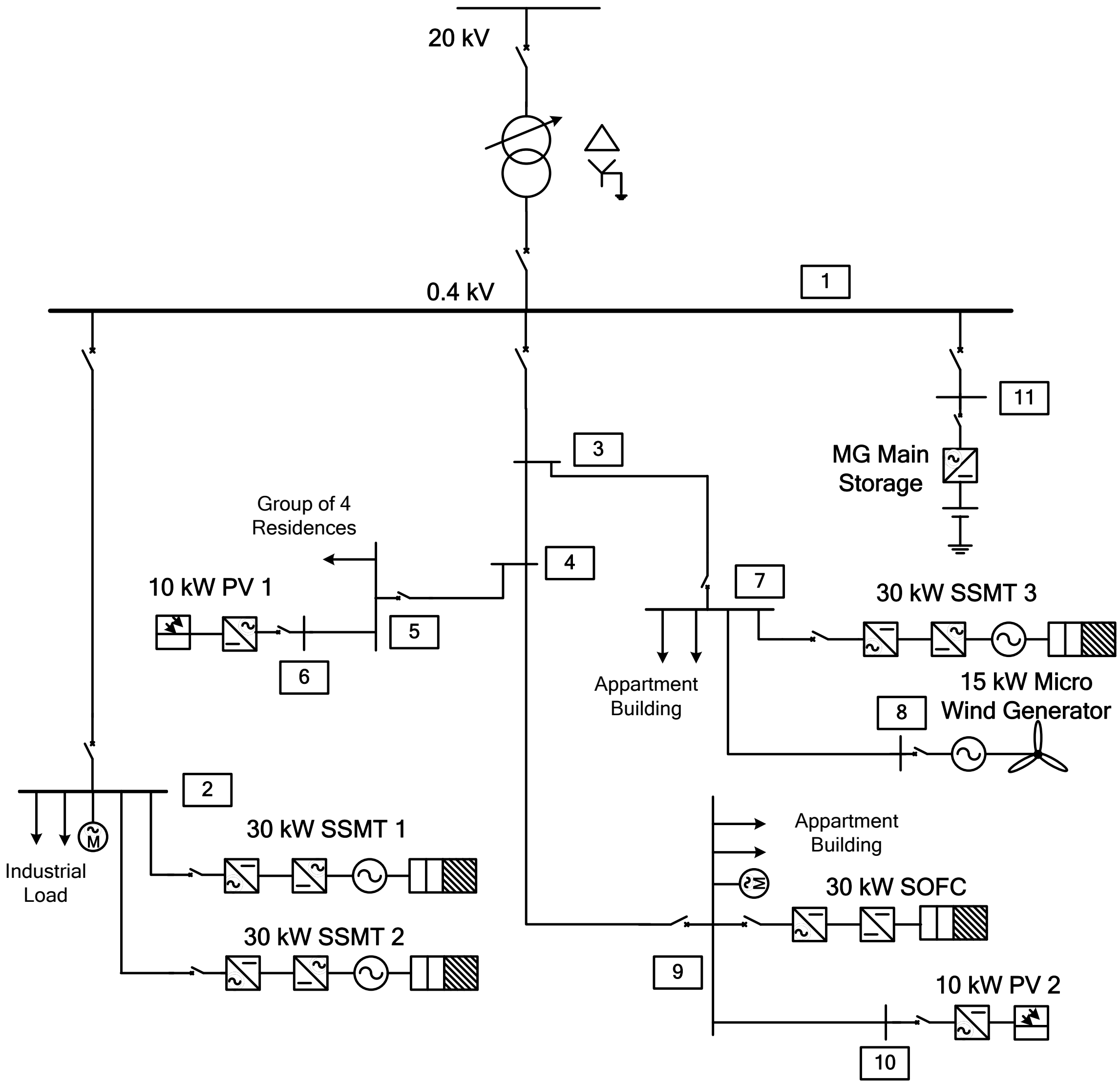


Figure 5-1: LV MicroGrid test system

5.3 MicroGrid Formation Due to Pre-Planed Islanding

As previously referred, the MG islanding can result either from pre-planed or unplanned switching events. When considering a pre-planed MG island formation (for example, resulting from the need of performing some maintenance actions), it is possible to define an appropriate sharing of the MG load among several controllable MS or to consider the disconnection of less important loads in order to reduce the power flow between the MG and the upstream MV network. In other words, MG pre-planned islanding should be preceded by the balance between local load and generation, thus reducing the power imported from the upstream MV network. In order to illustrate this situation, the simulation platform was used for the evaluation of the transient phenomena resulting from MG pre-planed islanding.

The MG was assumed to be operating under a single master control strategy (a single grid forming unit is used to define the MG voltage and frequency during islanding operation), being the pre-islanding load and generation scenario described in Table 5-1 (generation in bus 1 refers to the power exchange with the upstream MV network). In this scenario, the MG total load is *110.5+j45.5* kVA and the MG total generation is *75.0+j37.1* kVA (the MG is importing *35.5+j8.4* kVA from the upstream MV network). Before MG islanding takes place, the MicroGrid Central Controller (MGCC) defines a new power set-point for each controllable MS in order to reduce the power imported from the upstream MV network. Figure 5-2 and Figure 5-3 show the active and reactive power output of each controllable MS following the definition of a new active power set-point at t = 10 s and a new reactive power set-point at t = 120 s. MG islanding takes place at t = 150 s and has a negligible impact on the MG. Following the definition of the new active and reactive power set-points for each MS, their output power is adjusted according to the respective dynamic response time. As it can be observed in Figure 5-2 and Figure 5-3, the active and reactive power imported from the upstream MV network (P – MV and Q – MV, respectively) were reduced and have a value near zero prior to MG islanding.

Table 5-1: Pre-islanding load and generation scenario

Bus	Load		Generation	
	P (kW)	Q (kvar)	P (kW)	Q (kvar)
1			35.5	8.4
2	47.6	22.8	29.5	15.3
5	12.1	4.0		
6			5.0	0.0
7	30.0	10.9	14.8	8.2
8			10.4	0.0
9	20.8	7.7	10.3	5.1
10			5.0	0.0
11			0.0	8.5
Total	110.5	45.5	75.0	37.1

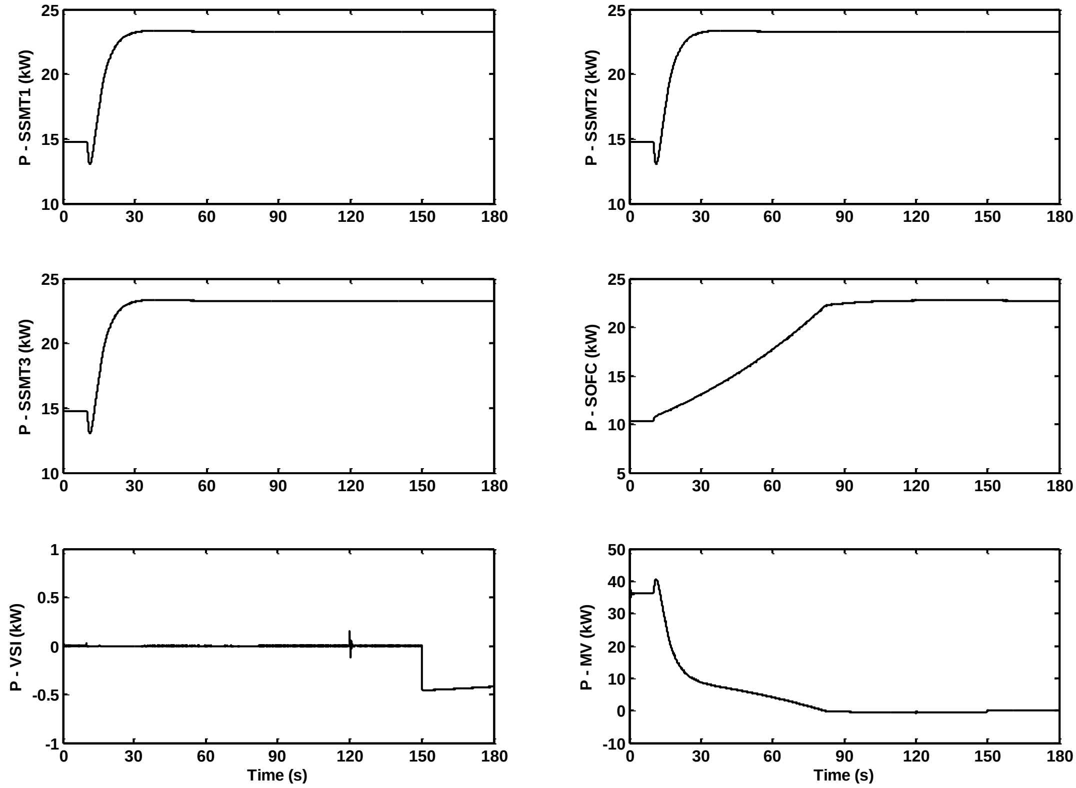


Figure 5-2: MG pre-planed islanding – MS active power and active power flow from the upstream MV network

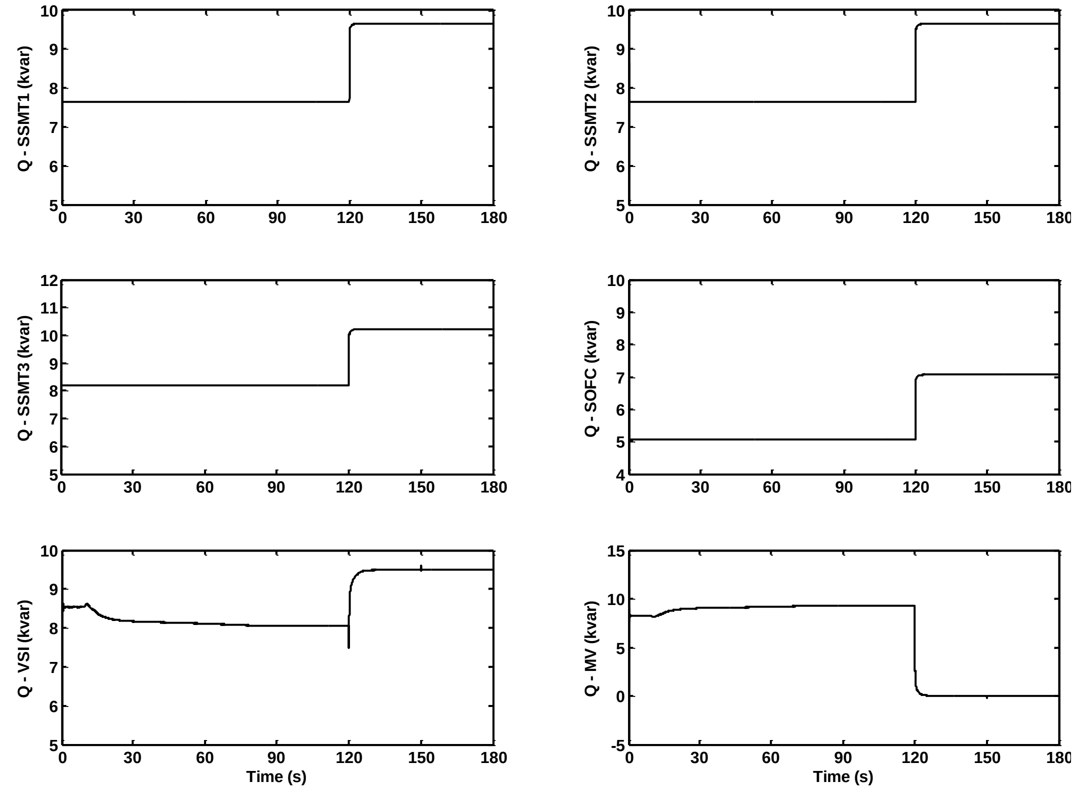


Figure 5-3: MG pre-planed islanding – MS reactive power and reactive power flow from the upstream MV network

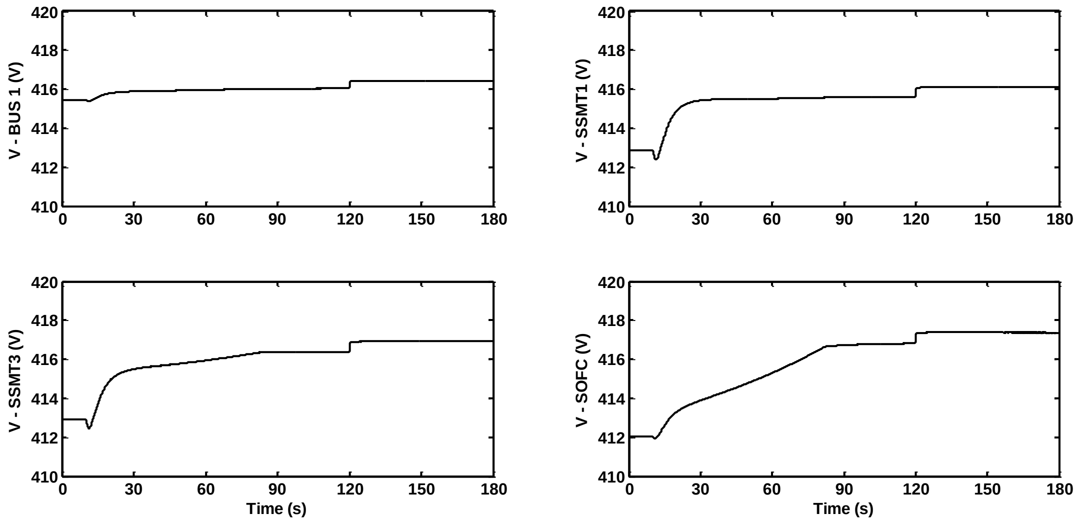


Figure 5-4: MG pre-planed islanding – node voltages

Figure 5-4 shows the MG node voltages during MS power re-dispatch and in the moments subsequent to MG islanding. In terms of node voltages, the MG islanding transient is negligible. As it can also be observed, the shape of each node voltage profile closely follows the MS power generation profile. For example, the shape of SSMT 1 terminal voltage closely follows the shape of SSMT 1 active power generation. This behaviour is due to the coupling between active power flow and node voltages, which is a common characteristic in predominantly resistive grids like LV distribution grids.

5.4 MicroGrid Formation Due to Unplanned Islanding

Faults occurring in the upstream MV network will require a fast disconnection of the MG from the faulted part of the system. This fault ride through capability will provide lower interruption times especially for critical loads inside the MG area. Following a fault in the upstream MV network, it was assumed the protective devices installed at the MG Point of Common Coupling (PCC) are able to separate it fast from the faulted part of the system. On the contrary to a pre-planned islanding, the MG pre-fault scenario can not be modified in order to reduce the transient phenomena resulting from islanding. Prior to MG islanding, the operating conditions (load and generation profile) can be widely varied, thus resulting in different conditions in terms of the power being imported from or exported to the upstream MV grid. Therefore, the MG control strategies should be able to handle the resulting phenomena in order to assure a smooth moving to islanding operation under several power flow conditions in the interface between the MG and the upstream MV network. The dynamic phenomena resulting from unplanned MG islanding are highly dependent on the pre-islanding operating conditions and on the dynamic response of the MS. The next sections provide a detailed evaluation of the MG islanding under several operating conditions, being the main objective the demonstration of the feasibility of the proposed control strategies.

5.4.1 MicroGrid Operating Scenarios

In other to evaluate the performance of the proposed MG emergency control strategies, three operating scenarios were defined: two scenarios (scenario 1 and scenario 2) correspond to a situation where the MG is importing power from the upstream MV grid and a third scenario (scenario 3) corresponds to a situation where the MG is exporting power to the upstream MV grid. The following tables show the details of each scenario regarding MG generation profile and the decomposition of MG load in terms of constant impedance load and induction motor loads. In all the scenarios, motor loads are assumed to be operating at rated power. Relevant electric data for motor loads is provided in Appendix A.

In the next tables, power generation in bus 1 refers to the power flow between the MG and the upstream MV grid (positive values correspond to power imported from the upstream MV grid, while negative values correspond to power export to the upstream MV grid). The performance of the MG control strategies was evaluated through the numerical simulation of these study-cases. Both single master and multi master control strategies for MG islanding operation were tested.

Table 5-2: Characterization of scenario 1

Bus	Constant Impedance Loads		Induction Motor Loads		Generation	
	P (kW)	Q (kvar)	P (kW)	Q (kvar)	P (kW)	Q (kvar)
1					66.1	16.8
2	39.0	14.7	17.5	11.5	19.7	15.3
5	16.0	5.2				
6					5.0	0.0
7	39.5	14.4			19.6	8.2
8					10.4	0.0
9	17.7	4.0	7.4	4.6	12.4	5.1
10					5.0	0.0
11					0.0	9.3
Total	112.2	38.3	24.9	16.1	138.2	54.7

Table 5-3: Characterization of scenario 2

Bus	Constant Impedance Loads		Induction Motor Loads		Generation	
	P (kW)	Q (kvar)	P (kW)	Q (kvar)	P (kW)	Q (kvar)
1					30.6	12.0
2	28.1	10.4	17.5	11.7	29.5	12.7
5	11.3	3.7				
6					5.0	0.0
7	28.1	10.2			14.8	5.7
8					10.4	0.0
9	12.6	2.9	7.4	4.6	10.3	4.4
10					5.0	0.0
11					0.0	8.6
Total	80.1	27.2	24.9	16.3	105.6	43.4

Table 5-4: Characterization of scenario 3

Bus	Constant Impedance Loads		Induction Motor Loads		Generation	
	P (kW)	Q (kvar)	P (kW)	Q (kvar)	P (kW)	Q (kvar)
1					-26.7	12.6
2	25.7	9.5	17.5	11.8	52.7	12.1
5	10.3	3.4				
6					6.0	0.0
7	25.8	9.4			23.5	5.1
8					14.0	0.0
9	11.6	2.6	7.4	4.7	23.4	4.2
10					6.0	0.0
11					0	7.8
Total	73.8	24.9	24.9	16.5	98.9	41.8

5.4.2 THE SINGLE MASTER CONTROL STRATEGY

This section aims to demonstrate the feasibility of the MG emergency control functionalities under a single control strategy. In this case, a single Voltage Source Inverter (VSI), which is the grid forming unit, is connected to the MG, as it was previously shown in Figure 5-1. The simulation results show the MG dynamic behaviour in the scenarios defined above, after a three-phase fault occurring in the MV network at t = 10 s, which is followed by MG islanding in 100 ms (MG islanding takes place at t = 10.1 s).

5.4.2.1 MicroGrid Importing Power from the Upstream Medium Voltage Network

In order to demonstrate the need of the proposed MG emergency control strategies (primary frequency control, secondary frequency control and load shedding mechanisms) some results are presented next in order to illustrate the effectiveness of each emergency control strategy. In a first place, it is considered that MG islanding takes place and only the primary frequency control mechanism is activated (active power/frequency droop control). Figure 5-5 shows MG dynamic behaviour in the moments subsequent to islanding. The power mismatch between MG load and generation is picked up by the storage devices (VSI), while MG frequency decreases according the VSI active power/frequency droop settings. As the only active control mechanism is droop control, the other controllable MS maintain their pre-fault output power levels.

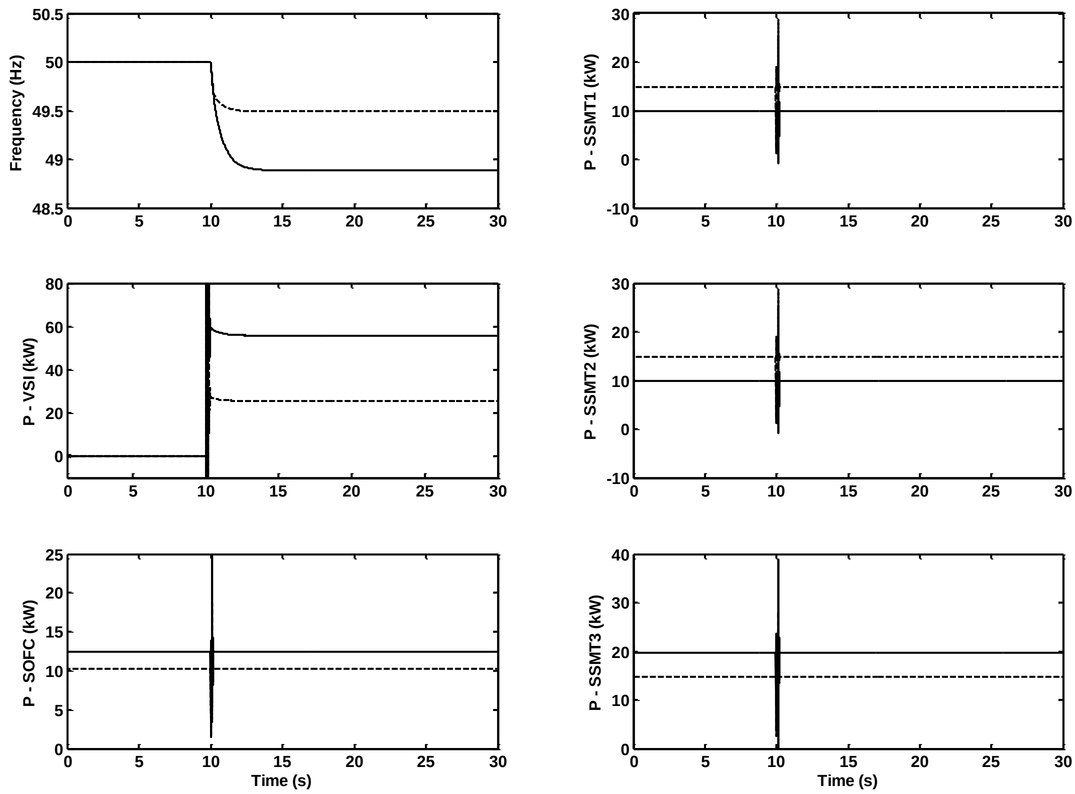


Figure 5-5: MG frequency and controllable MS active following MG islanding and considering only droop control in scenario 1 (solid line) and scenario 2 (dash line)

Concerning the simulation results for the scenarios previously described, no stability problems were identified. In the moments subsequent to MG islanding, system stability is guaranteed by MG main storage device coupled to the VSI. However, storage devices keep on injecting active power into the islanding MG if no other mean of balancing local load and generation is envisaged. In order to balance local load and generation and restore MG frequency to the nominal value, the MG secondary frequency control is used in controllable MS (Solid Oxide Fuel Cell (SOFC), SSMT 1, SSMT 2 and SSMT 3) being the results plotted in Figure 5-6. The results show that the MG main storage device is responsible for the balance of local load and generation in the moments subsequent to the islanding; at the same time, controllable MS participate in frequency restoration using the Proportional-Integral (PI) control strategy described in Section 4.4.1.2 and its power output increases according to their dynamic time constants. The large time constants of the MS lead to a relatively slow process for restoring frequency to its nominal value. Following the power increase in the controllable MS, storage devices progressively reduce its power output while MG frequency is increasing towards the nominal value. The storage device is responsible for matching local load and generation during this process. Its contribution in terms of active power injected in the MG and its evolution according to the MG frequency is also shown in Figure 5-6.

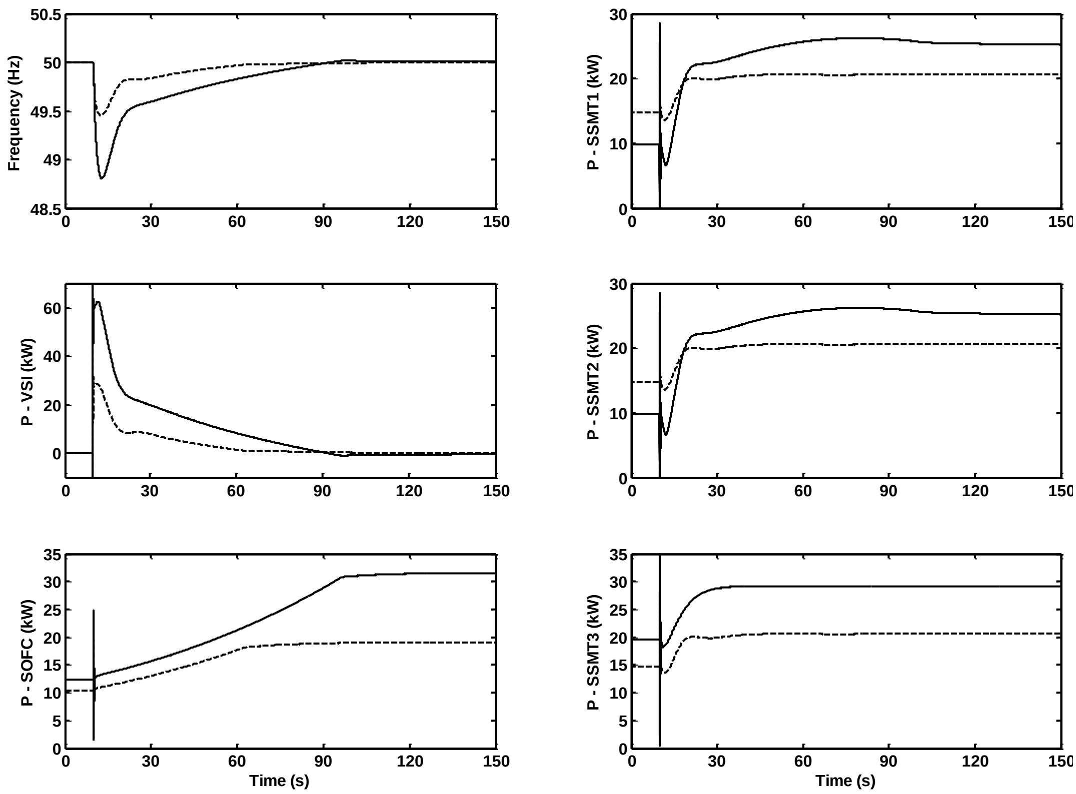


Figure 5-6: MG frequency and controllable MS active following MG islanding, considering droop control and secondary active power/frequency control in scenario 1 (solid line) and scenario 2 (dash line)

Figure 5-7 and Figure 5-8 show the time evolution of the terminal voltages in the VSI and SOFC and the generated reactive power in the SOFC and SSMT (details on MG behaviour during the fault will be shown later). Voltage control in the islanded MG is performed by the reactive power/voltage droop installed in the VSI. Thus, the VSI is responsible for compensating reactive load transients (for example, in the moments subsequent to MG islanding due to the mismatch between local reactive power generation and load) as can be observed in Figure 5-7. The other MS are operating with fixed reactive power output (although they could receive settings locally or from the MGCC) in order to optimize the reactive power dispatch in the islanded MG. As it can be observed in Figure 5-7 and Figure 5-8, the voltage control strategy used ensures MG stability and no reactive power oscillations are found among the MS.

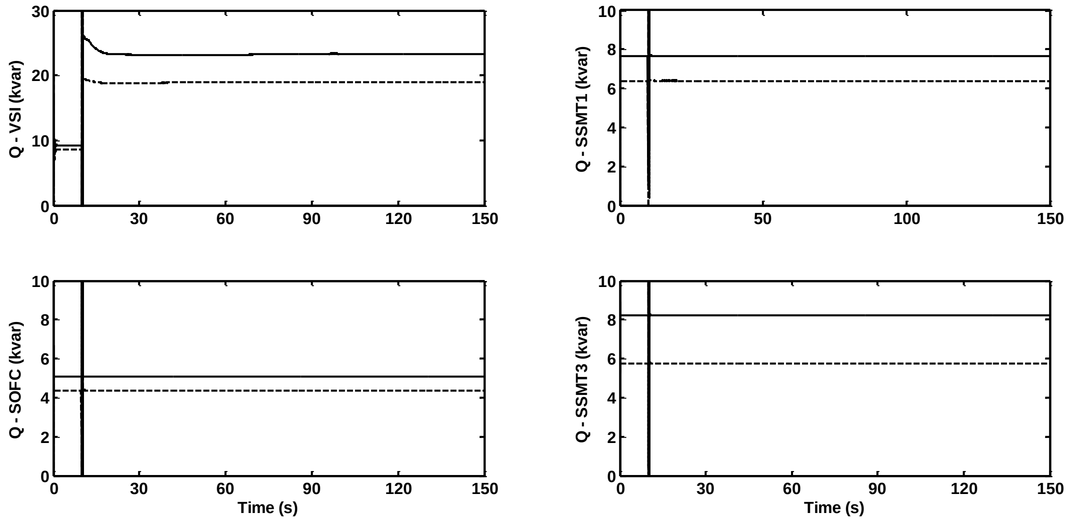


Figure 5-7: Reactive power in several MS for scenario 1 (solid line) and scenario 2 (dash line)

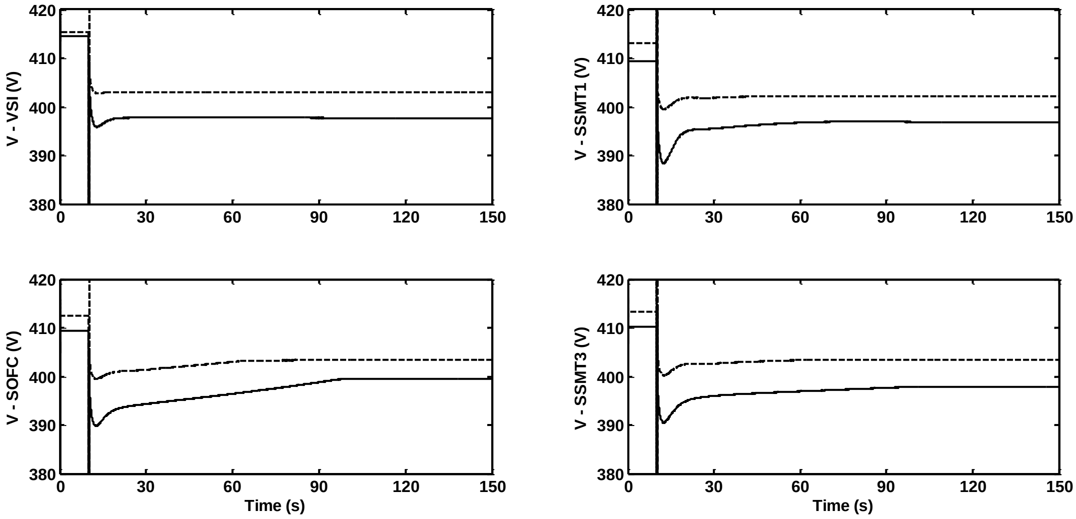


Figure 5-8: MS terminal voltages in scenario 1 (solid line) and scenario 2 (dash line)

MG frequency in the moments subsequent to islanding has a long period with a quite pronounced deviation from the nominal value. Load shedding mechanisms were also proposed as an emergency action against large frequency excursions. Basically, the dynamic behaviour of the system is improved if some percentage of the load is temporarily disconnected. The implementation of automatic and local load shedding mechanisms is based on four load disconnection steps that can be independently parameterized (each load disconnection step corresponds to a certain deviation in the system frequency). Table 5-5 shows the settings adopted for the load shedding mechanisms installed in controllable loads (load shedding is applied in constant impedance loads connected to buses 2 and 7).

Table 5-5: Settings for load shedding mechanisms in controllable loads

Frequency Deviation	Load Shedding (%)
0.25	30
0.50	30
0.75	20
1.00	20

The combined effect of primary frequency control, secondary load-frequency control and load shedding mechanisms is shown in the next figures. Due to the large initial frequency deviation following MG islanding, an amount of load is automatically shed through the activation of under frequency load shedding relays installed in Load Controllers (LC). As it can be observed in Figure 5-9, the introduction of load shedding mechanisms significantly reduces frequency deviations following MG islanding in comparison with the case where the load shedding mechanisms are not considered. The amount of load that was automatically shed in buses 2 and 7 is around *46+j17* kVA in scenario 1 and *17+j7* kVA in scenario 2.

The MS selected for load-frequency control participate in frequency restoration using the PI control strategy previously referred. The large time constants of the MS lead to a relatively slow process for restoring frequency to its nominal value. Primary frequency control is performed by the storage device and its power electronic interface (the VSI). The storage device is responsible for matching local load and generation during frequency restoration. Its contribution in terms of active power injected in the MG and its evolution according to the MG frequency can also be observed in Figure 5-9.

Regarding MS reactive power and voltage control, some results are plotted in Figure 5-10 and Figure 5-11. Similar results are obtained in comparison to Figure 5-7 and Figure 5-8.

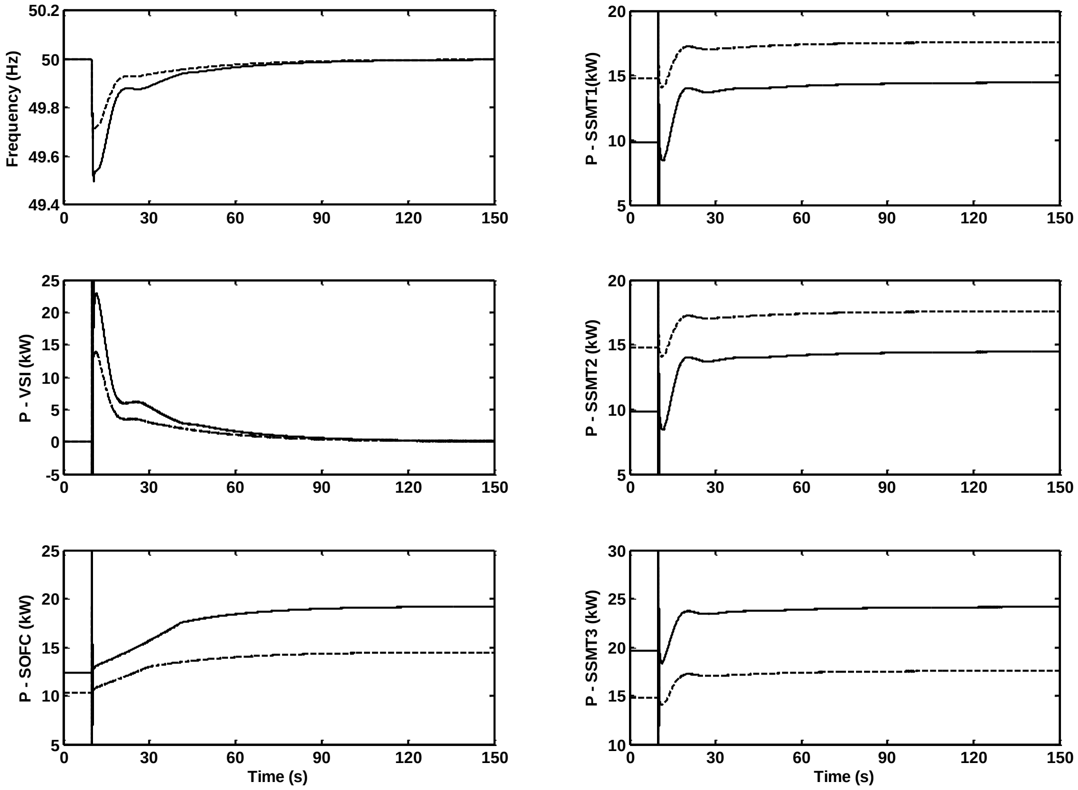


Figure 5-9: MG frequency and controllable MS active power following MG islanding in scenario 1 (solid line) and scenario 2 (dash line)

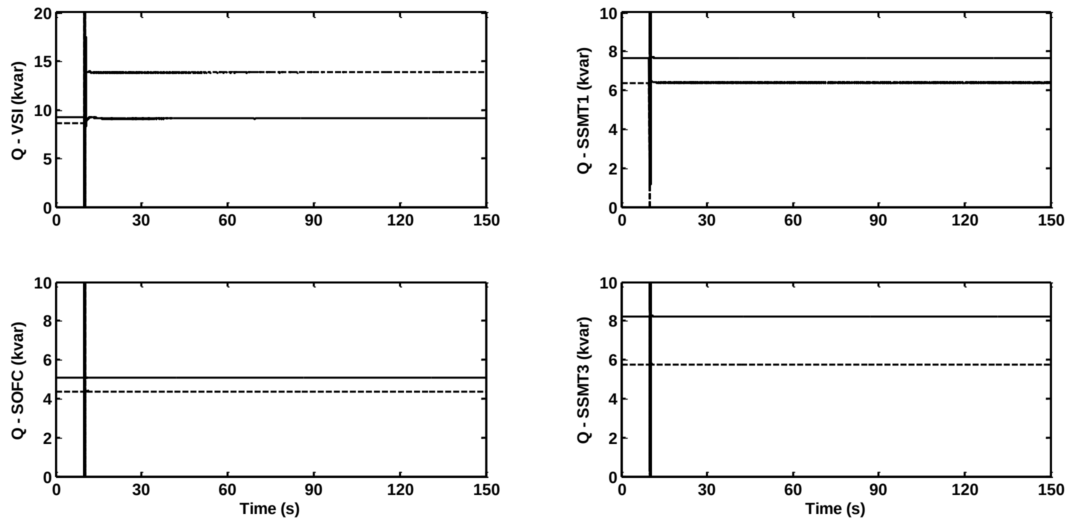


Figure 5-10: MS reactive power following MG islanding in scenario 1 (solid line) and scenario 2 (dash line)

The principles described for current limitation in inverters during fault conditions can be observed in Figure 5-12 for the VSI and for a PQ controlled inverter (SSMT 1 inverter) in scenario 1. A detail on the corresponding active and reactive power outputs of the inverters is also shown in Figure 5-13. The presence of motor loads and induction generators leads to a relatively slow ramping up of the voltage after fault clearing. Motor loads and asynchronous generators absorb high currents after disturbance elimination, which lead to the activation of the short-circuit current limitation function in the VSI, as depicted in Figure 5-12. After fault elimination, there is a transient period for restoring normal operation of asynchronous generators, which also contributes to the impact on inverter current and voltage, as it can be observed in Figure 5-12 after t = 10.1 s. Thus, a slower restoration of the MG voltage is observed. In this case no motor loads were disconnected because all of them were able to successfully reaccelerate after fault elimination. The asynchronous generator (micro wind generator) was not disconnected in order not to lose generation in the islanded system).

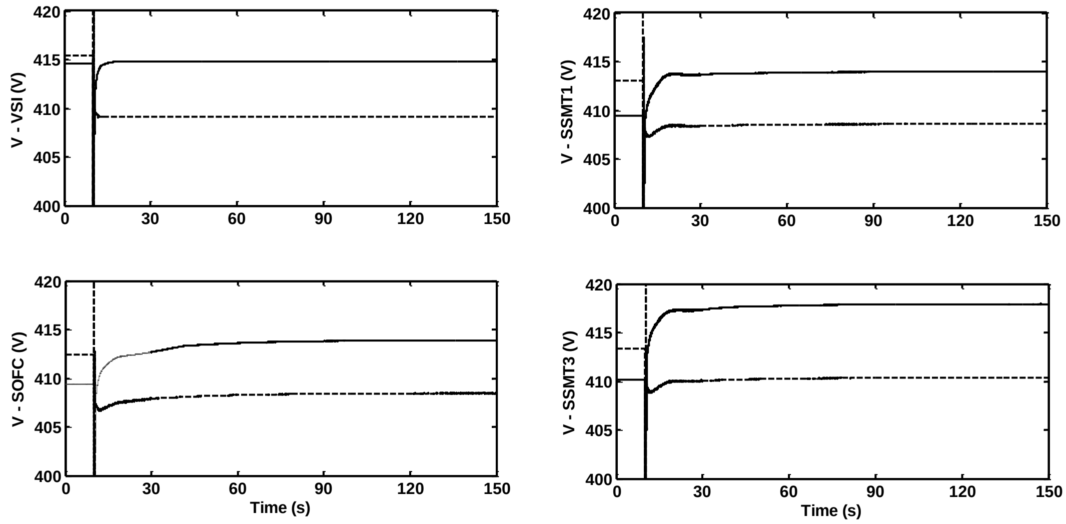


Figure 5-11: MS terminal voltages in scenario 1 (solid line) and scenario 2 (dash line)

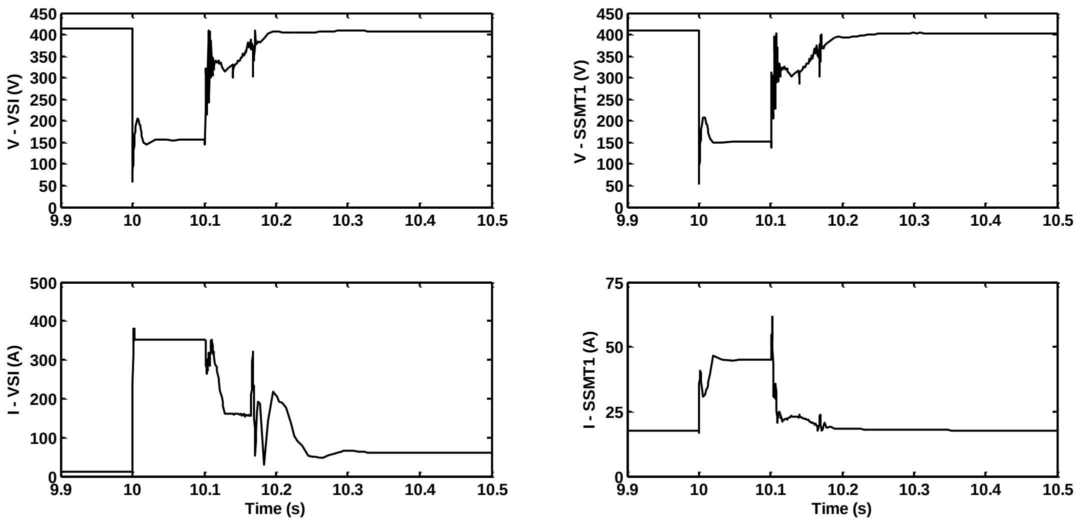


Figure 5-12: Short-circuit voltage and current details

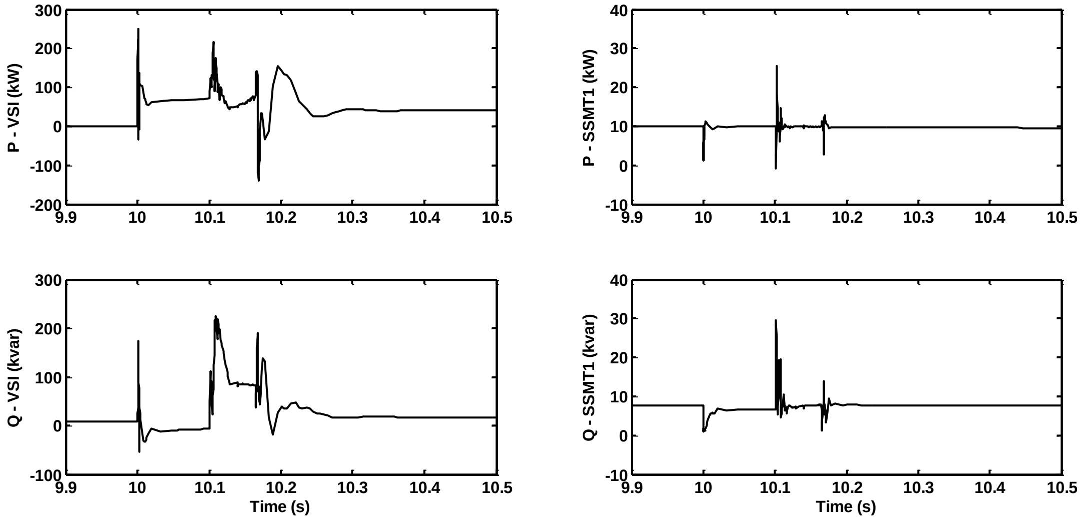


Figure 5-13: Detail of MS active and reactive power injection

5.4.2.2 MicroGrid Exporting Power to the Upstream Medium Voltage Network

Scenario 3 previously described corresponds to a situation where power is exported to the upstream MV network. In order to demonstrate that the proposed MG control strategies are valid for these operating conditions, simulation results are presented next. In a first stage, it is assumed that only MG frequency droop control is used when moving to islanding operation. As can be observed in Figure 5-14, in the moments subsequent to MG islanding, the power surplus is absorbed by the VSI, while the power produced by the other MS remain constant. In this case, the special issue to ensure a successful MG islanding is the management of the state of charge of the storage device so that it can absorb the power generation surplus after an unpredicted system islanding.

In a similar way to what was explained in the previous section, the balance of local load and generation and the restoration of MG frequency to the nominal value can be achieved if the MG secondary frequency control is used in controllable MS (SOFC, SSMT 1, SSMT 2 and SSMT 3). The results show in Figure 5-15 demonstrate that the MG main storage device is responsible for the balance of local load and generation in the moments subsequent to the islanding; at the same time, controllable MS participate in frequency restoration using the PI control strategy described in Section 4.4.1.2. Controllable MS progressively reduce their output power while MG frequency is returning to the nominal value. Storage device contribution in terms of active power injected in the MG and its evolution according to the MG frequency is also shown in Figure 5-15.

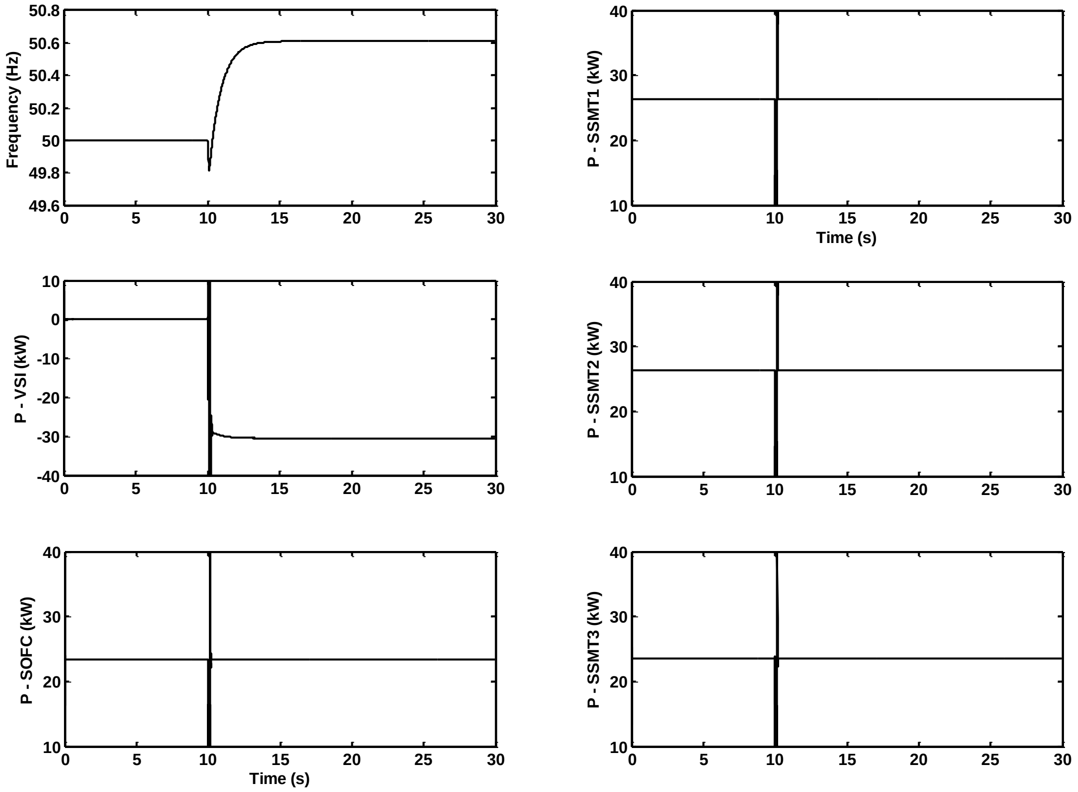


Figure 5-14: MG frequency and controllable MS active following MG islanding and considering only a droop control in scenario 3

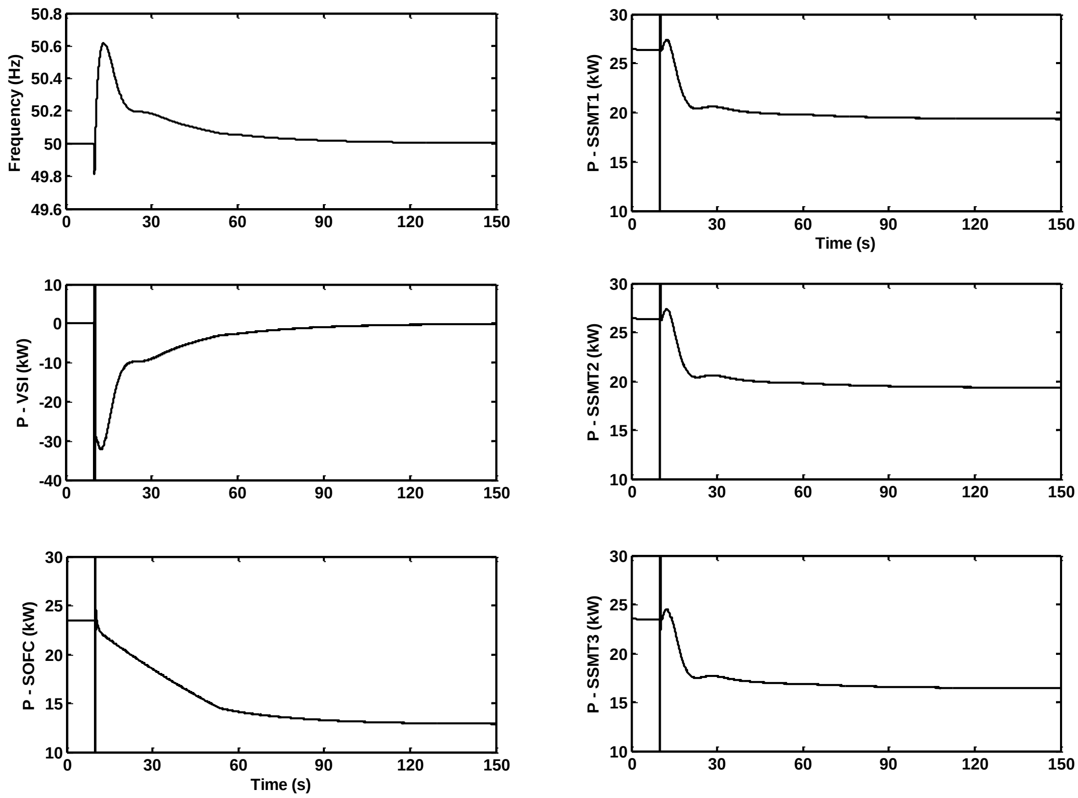


Figure 5-15: MG frequency and controllable MS active following MG islanding, considering droop control and secondary active power/frequency control in scenario 3

In terms of MG voltage control (Figure 5-16 and Figure 5-17), the general comments stated in the previous section remain valid for this situation. MG voltage control is ensured by the reactive power/voltage droop installed in the VSI. Before MG islanding, some reactive power is absorbed from the upstream MV network. Therefore, in the moments subsequent to MG islanding, the VSI increases its reactive output power in order to ensure reactive power balance in the islanded MG, while the other MS maintain their reactive power output levels.

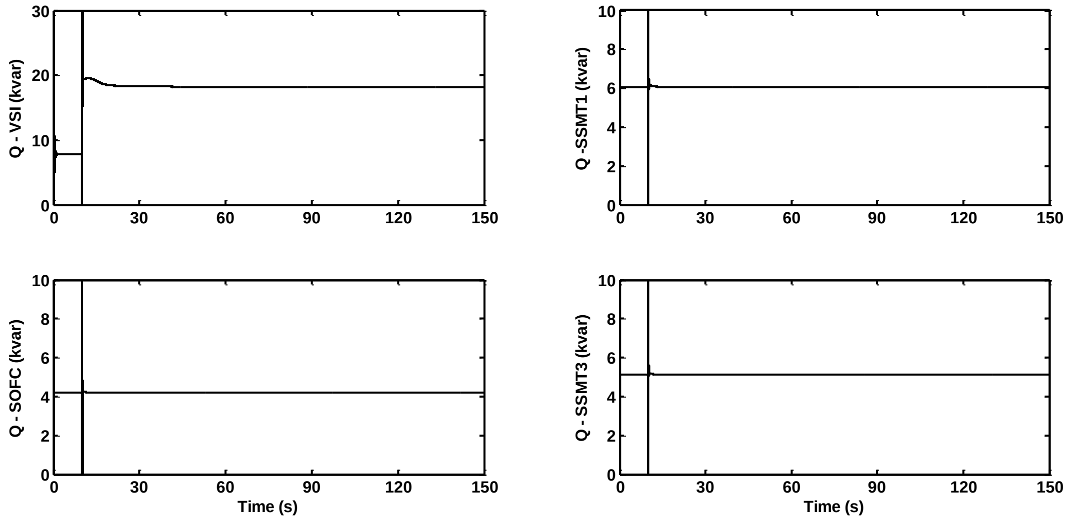


Figure 5-16: Reactive power in several MS for scenario 3

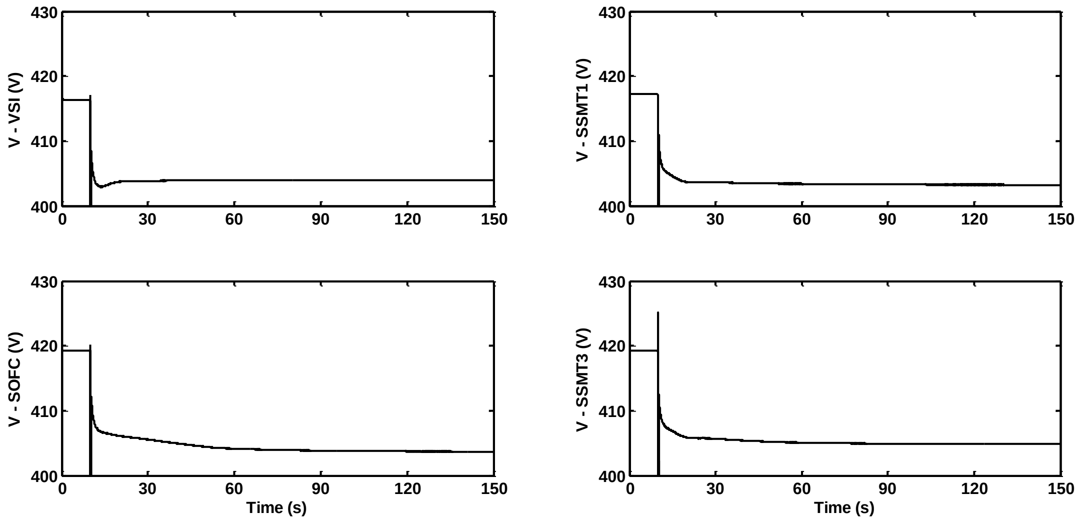


Figure 5-17: MS terminal voltages in scenario 3

5.4.2.3 Load Following during Islanding Operation

Following MG islanding, the natural load and generation variations need to be accommodated in order to ensure stable operation. Concerning scenario 2 previously described, the effects of load step connection were evaluated during MG islanding operation. Firstly, the loads that were disconnected due to the action of under frequency load shedding relays assumed to be installed in LC can be reconnected. Depending on the amount of load that was disconnected, a procedure based on a smooth step load connection should be used in order to avoid large frequency deviation that might compromise load reconnection.

Concerning scenario 2, the shed load was reconnected in two steps at t = 160 s and t = 190 s, as can be observed in Figure 5-18 and Figure 5-19. Later, at t = 250 s, a *25+j6* kVA load was connected and disconnected at t = 400 s. As can be observed from the obtained results, the proposed MG primary and secondary frequency control strategies ensure a stable operation in load following conditions.

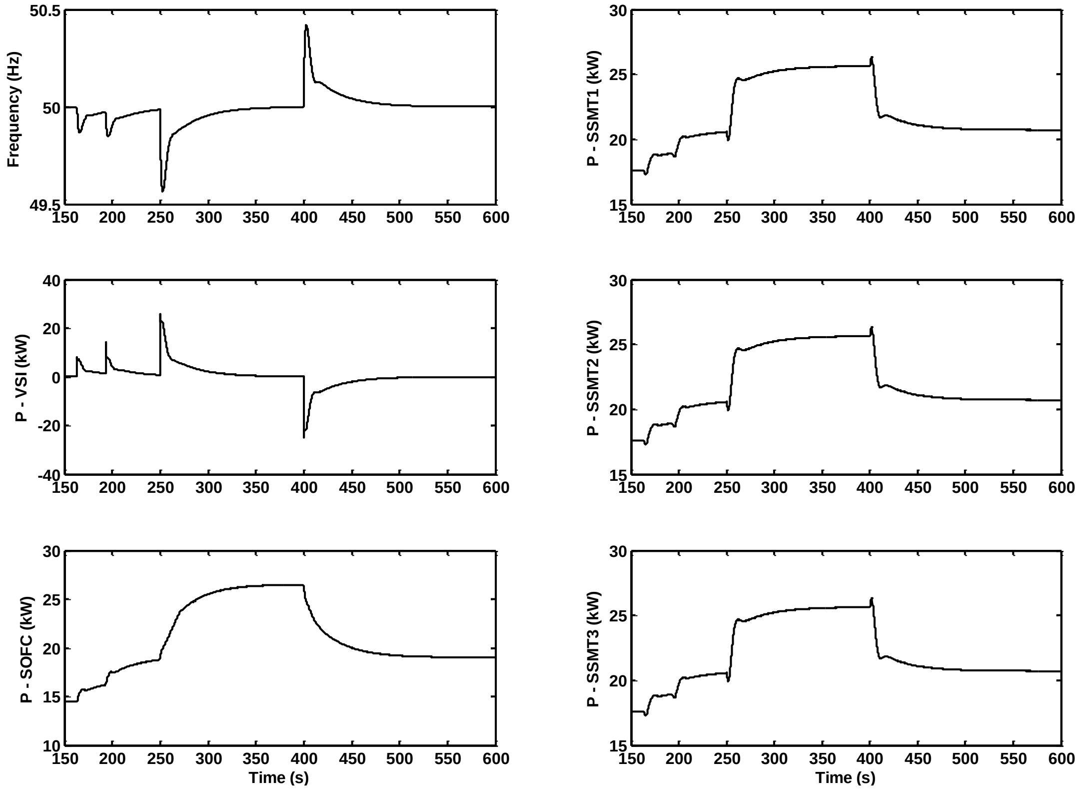


Figure 5-18: MG frequency and controllable MS active power during islanding operation (load following)

In the presented results, MG voltage is controlled by the VSI through the use of the reactive power/voltage droop characteristics. The other MS are operating with a fixed reactive power set-point. Therefore, reactive power balance is also ensured by the VSI.

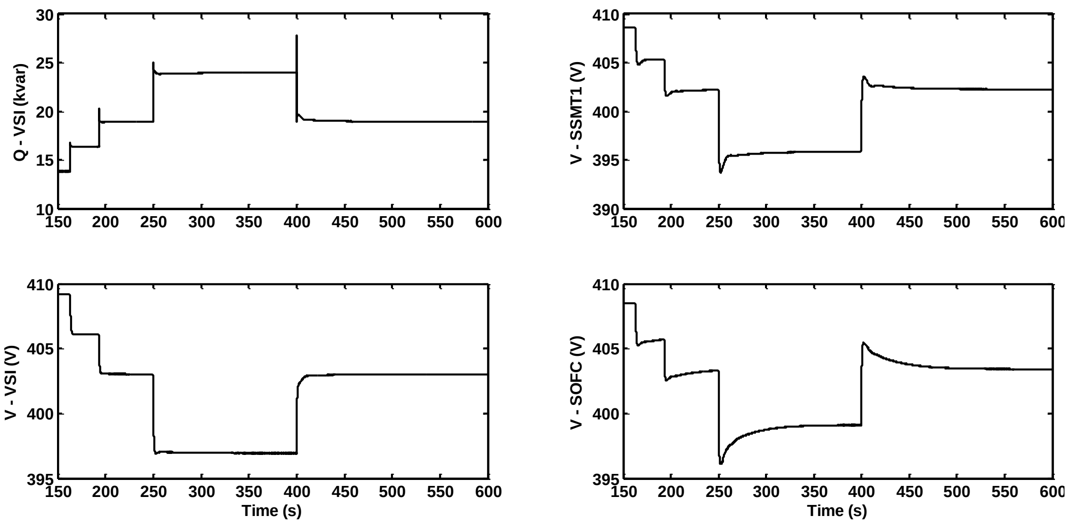


Figure 5-19: VSI reactive power and MS terminal voltages during islanding operation (load following)

5.4.3 THE MULTI MASTER CONTROL STRATEGY

This section aims to demonstrate the feasibility of the MG emergency control functionalities when the MG is being operated under a multi master control strategy. In this case, the SSMT 2 shown in Figure 5-1 is considered to have a storage device connected to its DC-link. Therefore, the inverter interfacing the SSMT 2 to the LV grid is also considered as a VSI (its control parameters were conveniently adapted in order to maintain the pre-islanding generation profile previously assigned to SSMT 2 in the defined operating scenarios). The simulation results show the dynamic behaviour of the MG in the scenarios previously defined, after a three-phase fault occurring in the MV network, which is followed by MG islanding in 100 ms (MG islanding takes place at t = 10.1 s).

5.4.3.1 MicroGrid Importing Power from the Upstream Medium Voltage Network

The performance of MG emergency control strategies under a multi master control approach are demonstrated next through numerical simulation results. In a first stage, it is considered MG islanding takes place and the MG load shedding mechanisms and secondary load frequency control schemes are not activated. Figure 5-20 shows MG frequency and MS output power following MG islanding. In the case where the MG is operating under a multi master strategy, two grid forming units are used to build the grid. Following MG islanding, the same two units contribute to the power balance of the islanded system. Therefore, it is possible to observe that the MG frequency deviation is lower than the one observed when a single master control strategy is used.

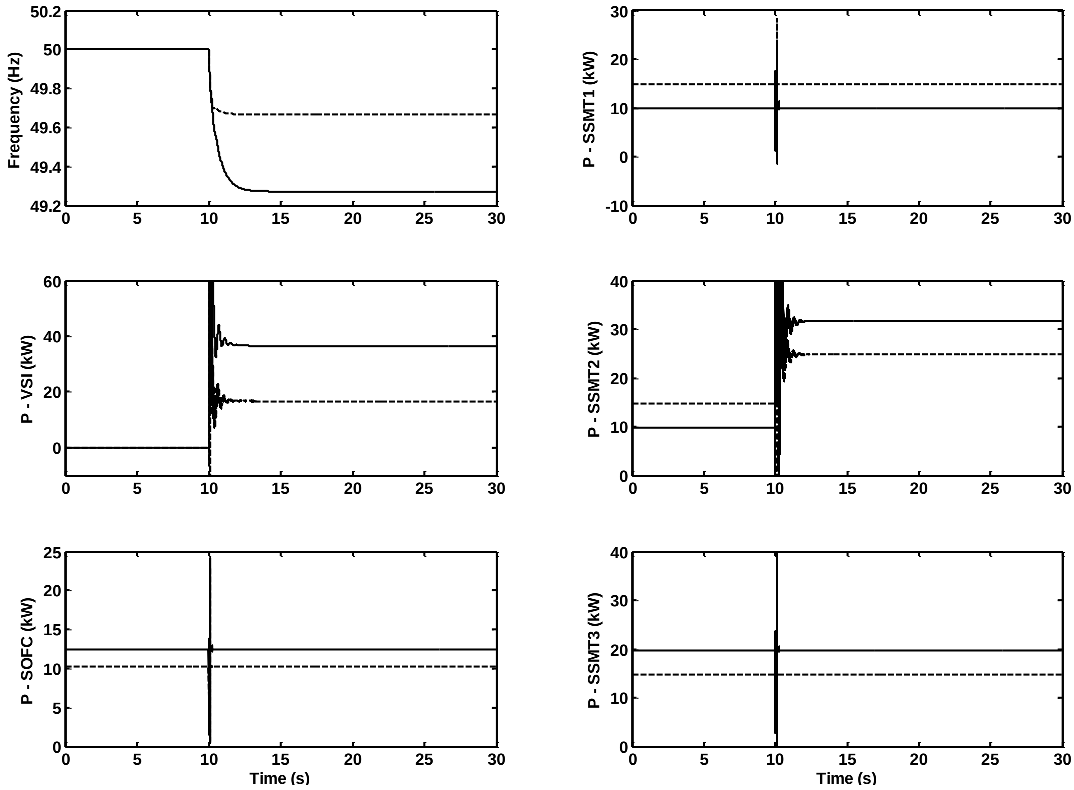


Figure 5-20: MG frequency and controllable MS active following MG islanding and considering only droop control in scenario 1 (solid line) and scenario 2 (dash line)

In order to restore MG frequency to the nominal value, the secondary frequency control strategy is used. Concerning SSMT 1, SSMT 3 and the SOFC, the secondary load frequency control strategy is equal to the one use in the previous section. As SSMT 2 is operating as a grid forming unit coupled to the grid through a VSI, its contribution for the restoration of the MG frequency to the nominal value consists on the definition of a new value for the idle angular frequency ω_0, witch can be computed as $\omega_0 = \omega_{grid} + k_P \times P_{schedule}$ (ω_{grid} is the nominal value of the MG angular frequency and $P_{schedule}$ is the active power to be assigned to SSMT 2 following MG islanding). In Figure 5-21 it is possible to observe that at t = 20 s the value of the idle angular frequency in the SSMT 2 VSI is updated according to this rule, which causes an immediate increase in its power output. The MG mains storage device also contributes for the balance between local load and generation in the islanding MG during the frequency restoration period. As in the single master operation strategy previously illustrated, its output power progressively decreases to zero while frequency returns to the nominal value.

In a multi master operation strategy, the use of more than one grid forming unit provides an higher support to the islanded system. Therefore, it is possible to observe that in both scenarios, whose main results have been presented in the previous figures, MG frequency deviation is smaller than the one occurring in a MG operating with a single grid forming unit (single master operation).

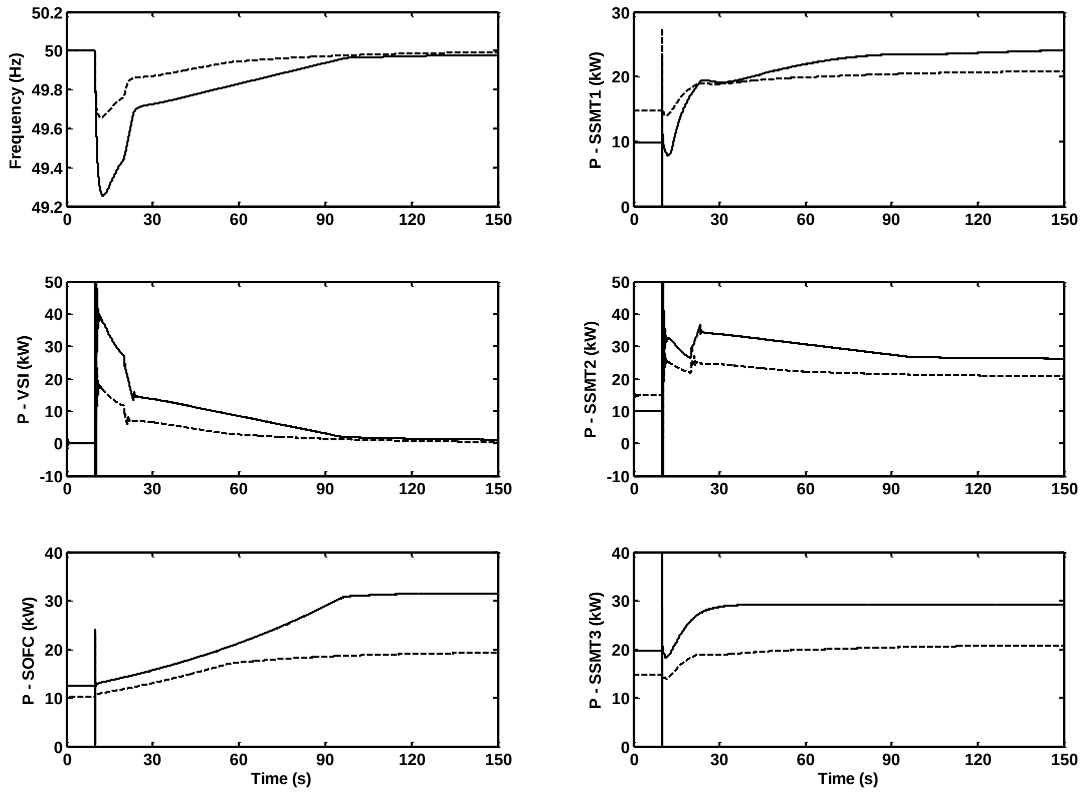


Figure 5-21: MG frequency and controllable MS active following MG islanding, considering droop control and secondary active power/frequency control in scenario 1 (solid line) and scenario 2 (dash line)

Figure 5-22 and Figure 5-23 show the time evolution of the reactive power in each MS as well as its terminal voltage values. In this case, two grid forming units (the MG main storage device VSI and the SSMT 2 VSI) are responsible for voltage control in the islanded MG through the implemented reactive power/voltage droop characteristics. Therefore, both VSI are responsible for compensating reactive power in the islanded MG, while the other MS operate with fixed reactive power output. It is also possible to observe that the voltage control strategy ensures MG stability and no reactive power oscillations are observed among the MS.

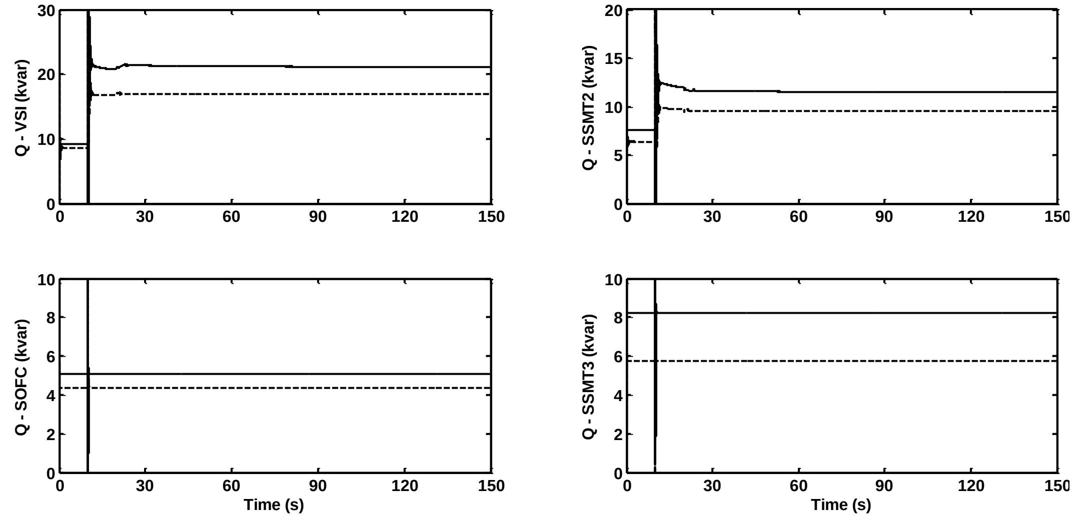


Figure 5-22: Reactive power in several MS for scenario 1 (solid line) and scenario 2 (dash line)

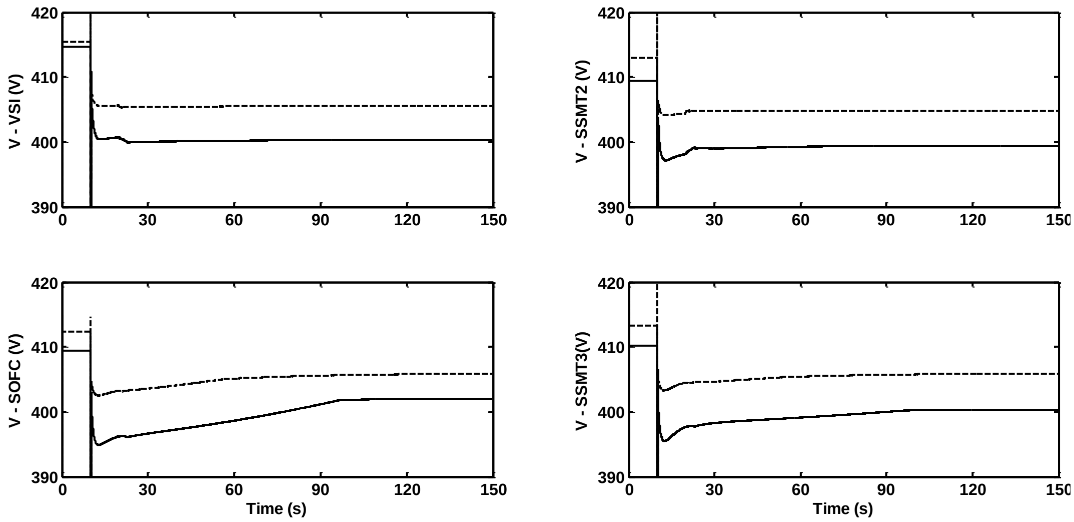


Figure 5-23: MS terminal voltages in scenario 1 (solid line) and scenario 2 (dash line)

Figure 5-24 shows the obtained simulation results when the load shedding mechanisms are also considered. When the use of load shedding mechanisms is also considered (the load shedding settings are those defined in Table 5-5), it is possible to observe that although high frequency support is provided in the islanded MG, the amount of load that was disconnected in both scenarios is the same for the case where the MG is operating under a single master control strategy. In fact, load shedding is required due to the large imbalance between MG local load and generation, which causes a significant frequency deviation in the moments subsequent to islanding. For example, in scenario 1, the first step of load shedding (30% load shedding at a frequency deviation of 0.25 Hz) is around 24 kW. According to the droop settings of the inverters presented in Appendix A, the estimated frequency increase due to a disconnection of a 24 kW load is around 0.3 Hz. Without load shedding, the minimum frequency deviation of scenario 1 is 0.75 Hz. Therefore, the frequency deviation after the disconnection of the first load step will be around 0.45 Hz, which is near the limits of the load shedding settings defined in Table 5-5. Additionally, the initial response of the SSMT, which tend to reduce their output power during a few seconds, contributes also to a larger frequency deviation. Therefore, MG frequency deviation is slightly higher than 0.5 Hz after the first load disconnection, leading to the activation of the second set of the load shedding mechanism. For instance, in the single master control approach, the frequency increase due to the disconnection of the first set of loads is 0.48 Hz. As in this case the minimum frequency deviation was around 1.2 Hz, the need of a second step in the load shedding mechanisms is clearly justified. In Figure 5-24 it is possible to observe that at t = 20 s the value of the idle angular frequency in the SSMT 2 VSI is updated according to the procedure previously described, which causes an immediate increase in its power output.

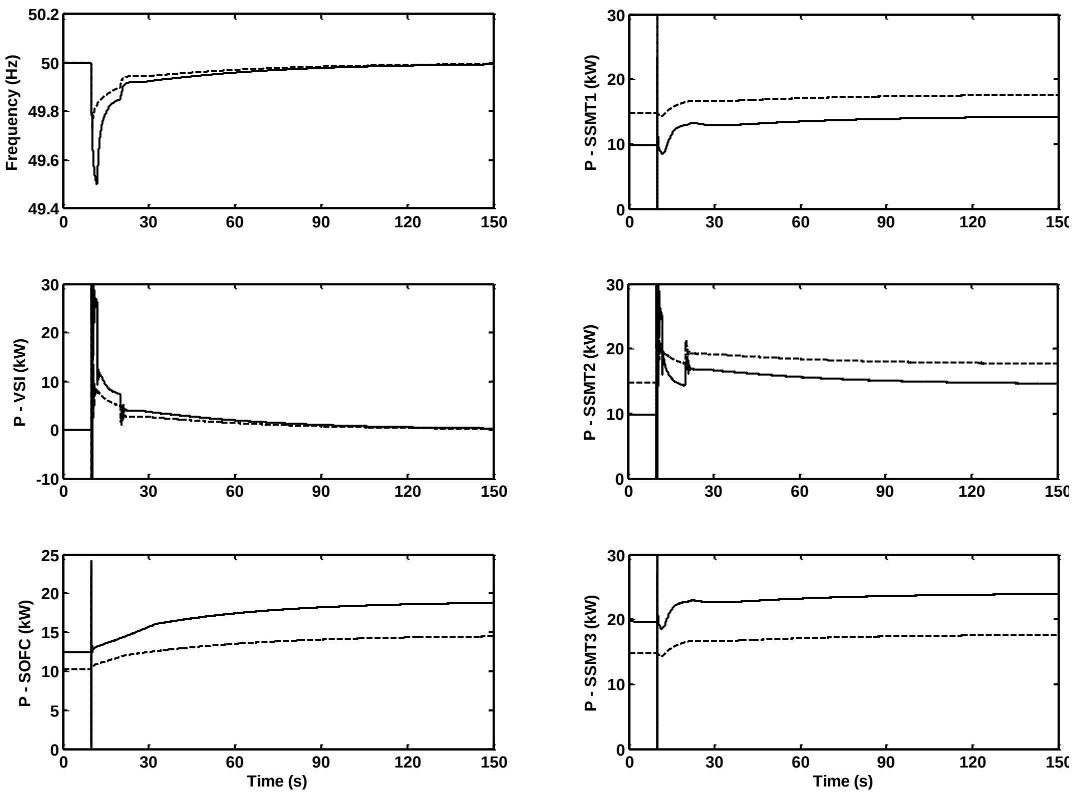


Figure 5-24: MG frequency and controllable MS active following MG islanding for scenario 1 (solid line) and scenario 2 (dash line)

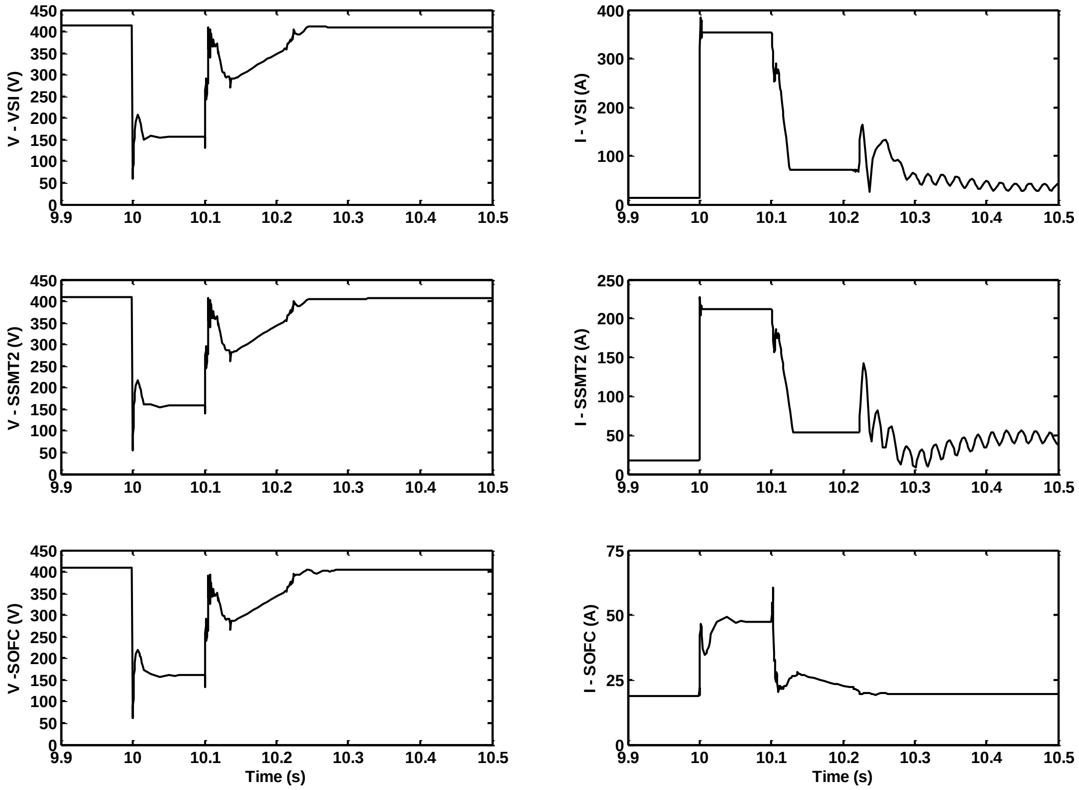


Figure 5-25: Short-circuit voltage and current details

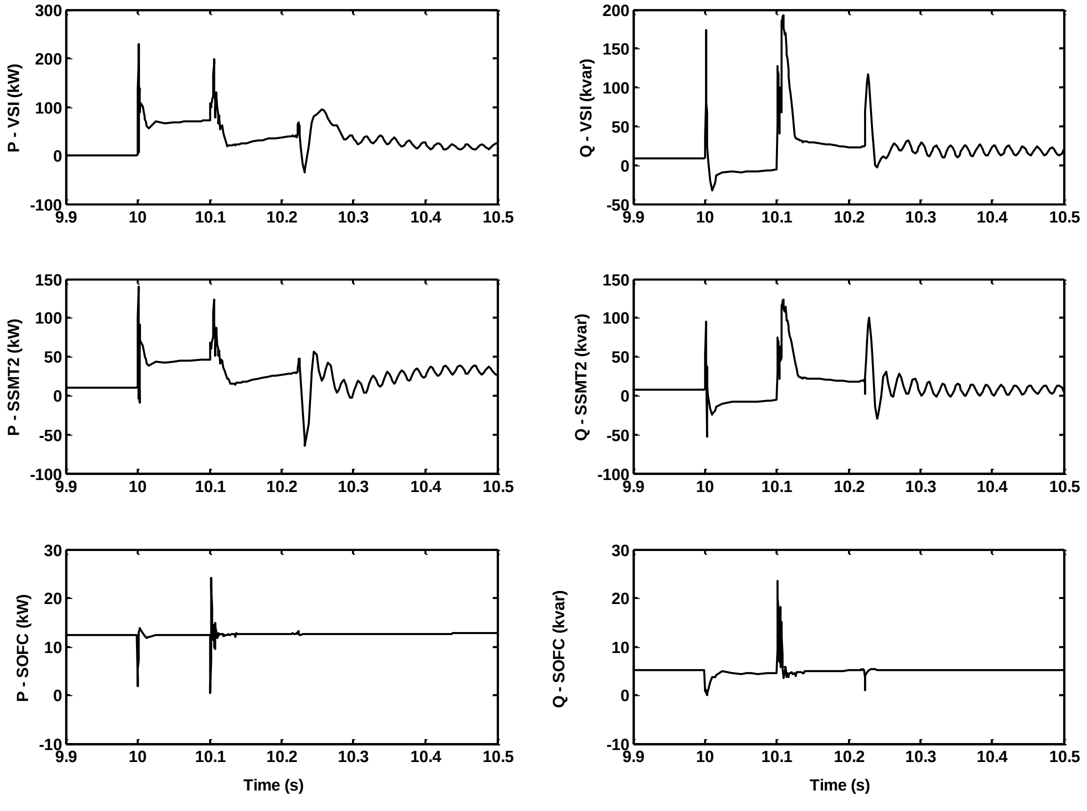


Figure 5-26: Detail of MS active and reactive power injection

Concerning the multi master operation, some details on the MG dynamic behaviour during and in the moments subsequent to fault clearance and MG islanding are presented in Figure 5-25 and Figure 5-26 (scenario 1 is considered).

5.4.3.2 MicroGrid Exporting Power to the Upstream Medium Voltage Network

Considering again scenario 3 previously characterized, results are shown in the next figures in order to demonstrate the performance of the MG emergency control strategy under a multi master operation scheme. Initially, it was assumed that only MG droop control in grid forming units is used for active power/frequency and reactive power/voltage control in the moments subsequent to MG islanding.

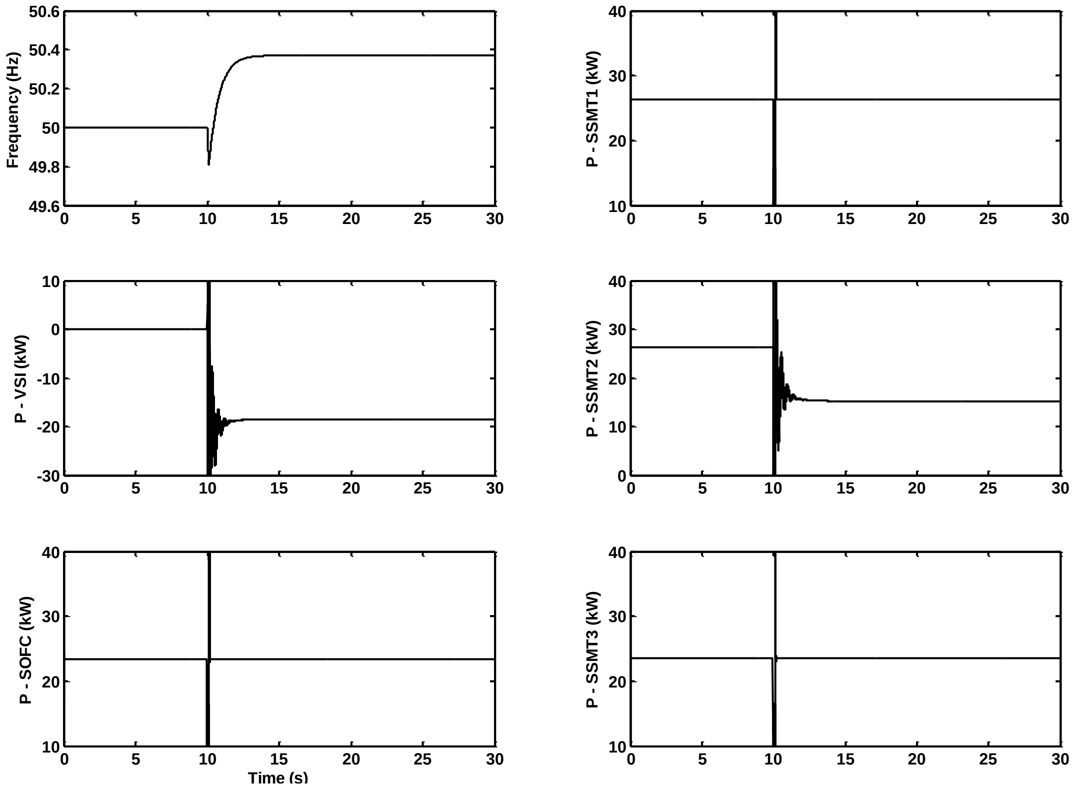


Figure 5-27: MG frequency and controllable MS active power following MG islanding and considering only a droop control

As can it be observed in Figure 5-27, both grid forming units (MG main storage and MMST 2 VSI) are responsible for absorbing the power surplus following MG islanding. In order to progressively restore MG frequency to the nominal value, the proposed secondary frequency control is applied. SSMT 1, SSMT 3 and the SOFC reduce their output power level by means of the PI control action described in Section 4.4.1.2. As SSMT 2 is operating as a grid forming unit coupled to the grid through a VSI, its contribution for the restoration of the MG frequency to the nominal value consists on the definition of a new value for the idle angular frequency in accordance to the schedule power for this unit. As it can be observed in Figure 5-28, when the new idle angular frequency value is defined at t = 20 s, an immediate reduction in the SSMT 2 output power can be observed.

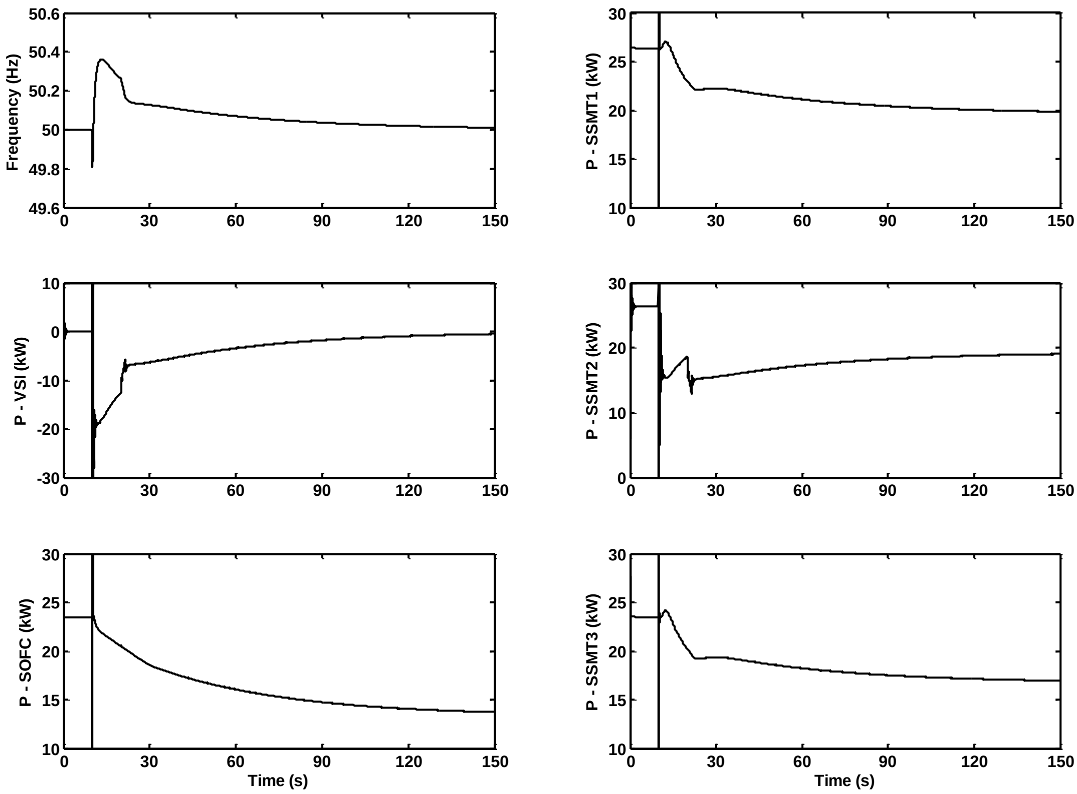


Figure 5-28: MG frequency and controllable MS active power following G islanding, considering droop control and secondary active power/frequency control

Regarding MG reactive power (Figure 5-29), the general consideration that have been stated before are also applicable in this situation. MG voltage control is performed through the reactive power/voltage droops installed in the grid forming units, which are responsible for the balance of reactive load and generation after MG islanding.

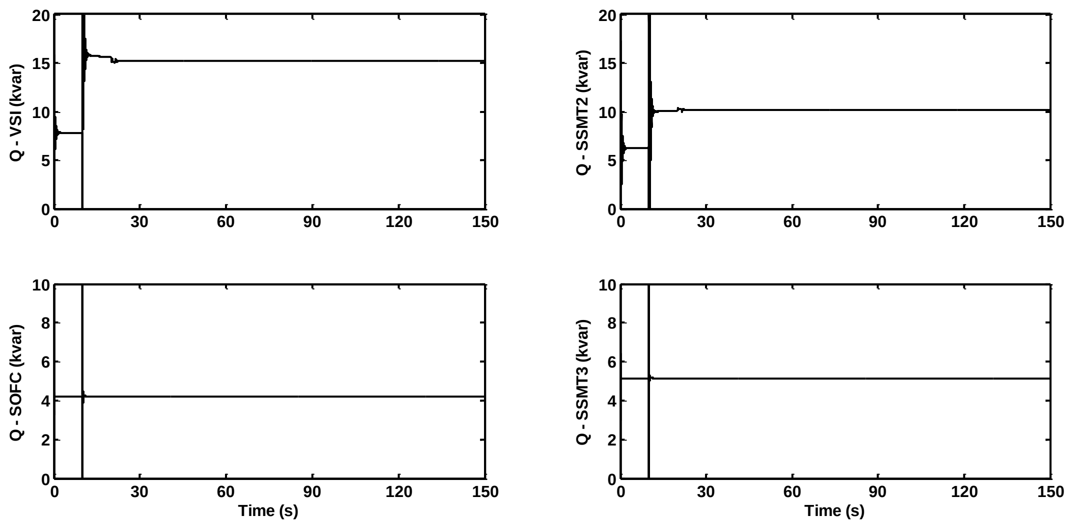


Figure 5-29: Reactive power in several MS for scenario 3

5.4.3.3 Load Following during Islanding Operation

Similarly to what was described in Section 5.4.2.3, scenario 2 was used in order to evaluate the effects of load connection and disconnection during MG islanded operation. As it was previously described, the loads that were disconnected due to the action of under frequency load shedding relays assumed to be installed at the LC level can now be reconnected again. The shed load was reconnected in two steps at t = 160 s and t = 190 s, as it can be observed in Figure 5-30. The definition of the SSMT 2 active power set-point was performed at t = 210 s through the corresponding modification of the active power/frequency droop idle angular frequency. Later, at t = 250 s a *25+j6* kVA was connected and disconnected at t = 400 s. For the connection and disconnection of this load, the SSMT 2 VSI idle angular frequency was modified at t = 280 s and at t = 430 s respectively. As previously stated, the use of two grid forming units ensures an higher MG support. Therefore, the observed frequency deviations are quit smaller than in the case where the MG is operating under a single master scheme.

MG voltage is controlled by the reactive power/voltage droop characteristics installed in grid forming units. The other MS are operating with a fixed reactive power set-point. Therefore, reactive power balance is also ensured by the two VSI connected to the MG during islanding operation. Both units are also responsible for the reactive power balance in the islanded MG, as can be observed in Figure 5-31.

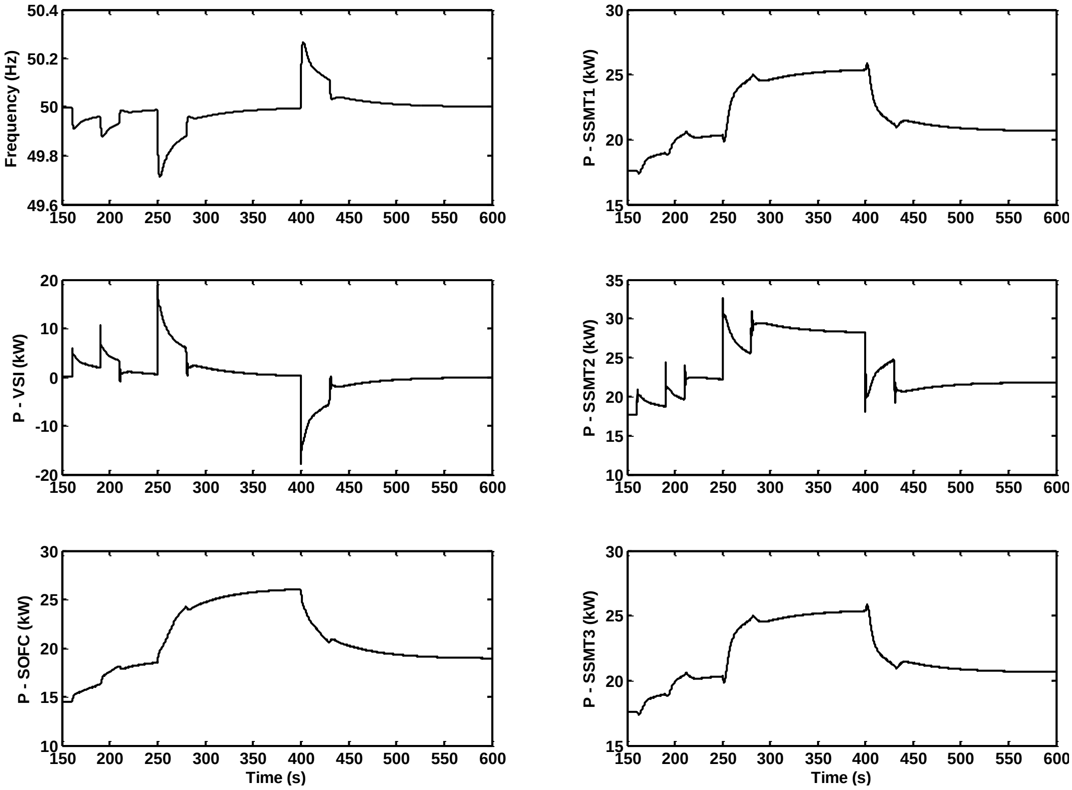


Figure 5-30: MG frequency and controllable MS active power during islanding operation (load following)

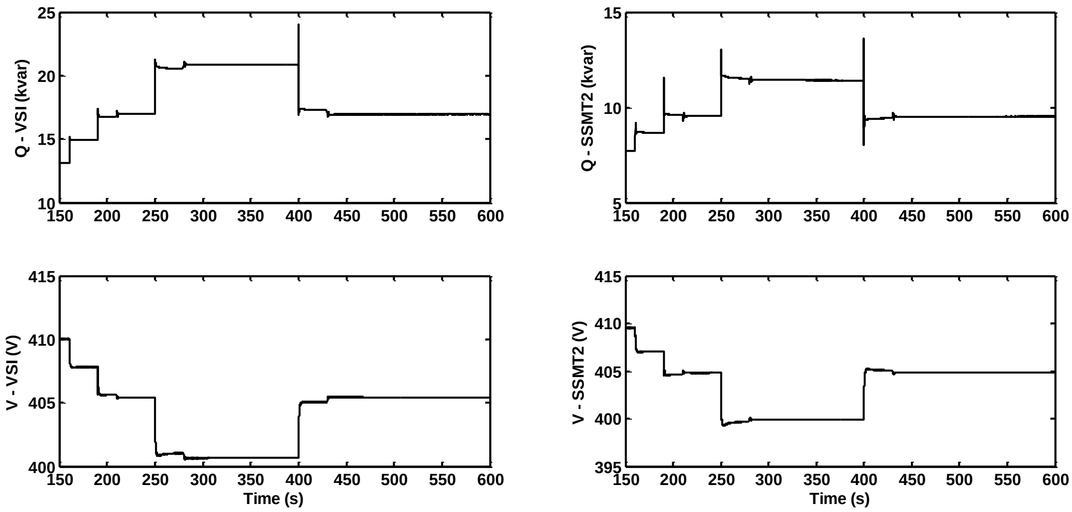


Figure 5-31: VSI and SSMT 2 reactive power output and terminal voltages during MG islanding operation (load following)

5.5 MICROGRID BLACK START

The LV voltage test system used in order to evaluate the performance of the proposed MG restoration plan is shown in Figure 5-32. The modifications introduced comparatively to the test system shown in Figure 5-1 results from the types of MS used for this case, since

SOFC are not suitable for a fast start-up following shut down. Therefore, the SOFC was substituted by a SSMT. Without loose of generalization, SSMT 1 and SSMT 2 in Figure 5-1 were combined in an equivalent microturbine, with rated capacity of 60 kW. It is also important to notice that the scope of the results to be presented next is focused on the feasibility of the proposed restoration plan in terms of sustained power frequency over-voltages and on the ability of MS to balance load and generation. Harmonic resonance voltages and transient over-voltages that may occur specially in the presence of capacitive elements are out of the scope of this dissertation.

The test system relevant data for simulation purposes is presented in Appendix A.

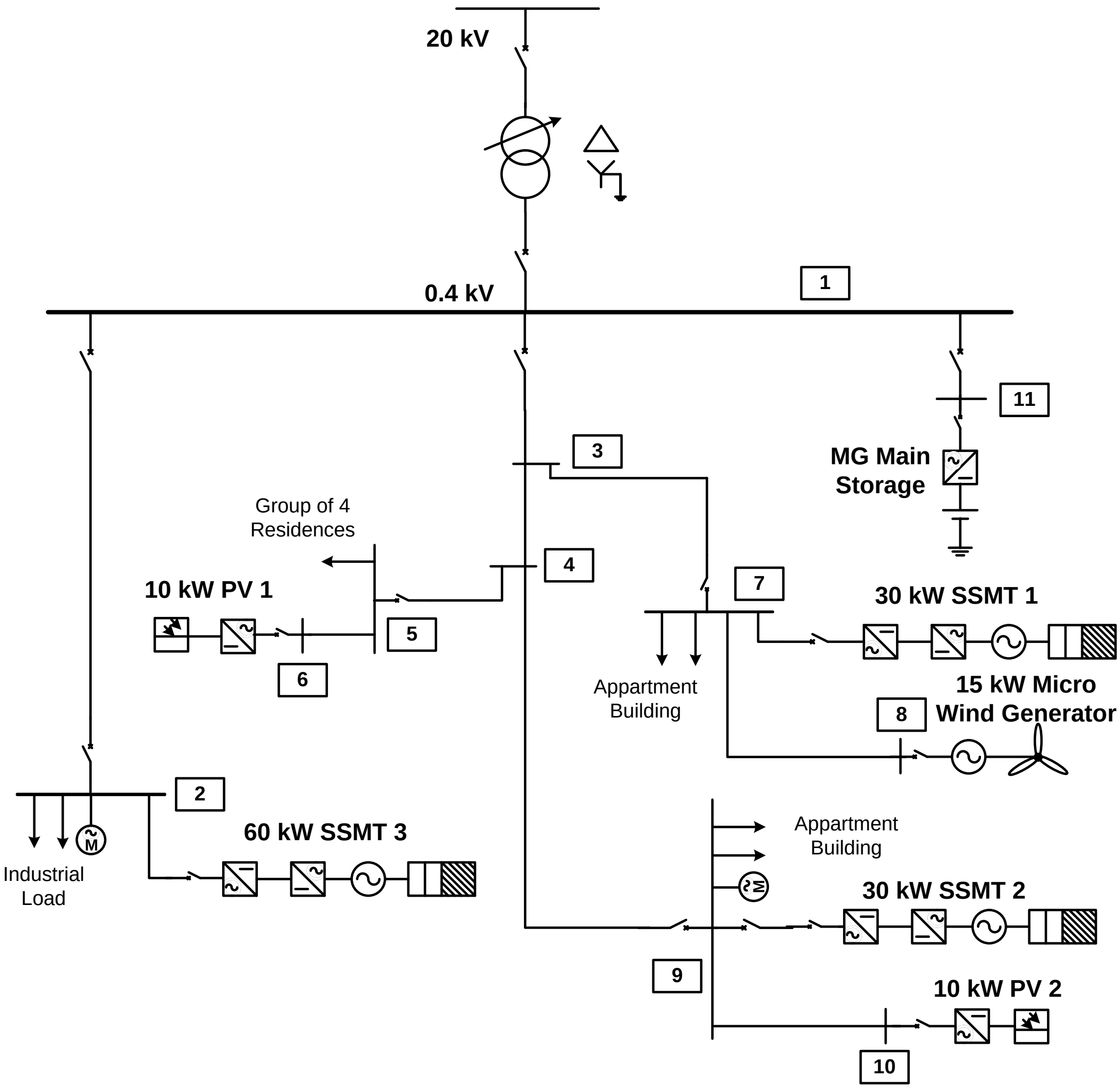


Figure 5-32: MG test system for black start

In order to evaluate the performance of the proposed restoration plan for a LV MicroGrid, it was assumed that a general blackout took place and it was followed by:

- Disconnection of the LV grid from the distribution transformer;
- Disconnection of loads and renewable energy sources;
- MG sectionalisation and automatic creation of small islands operating or to be operated in standalone mode to supply protected loads associated with each SSMT.

Assuming that all SSMT restarted successfully after system collapse, the main storage device is selected to energize the LV network. The small islands formed by SSMT and their protected loads can be synchronized later. The fast transients associated to the initial stages of the MG restoration process (including power electronic controls and commutation details) were analysed using an *EMTP-RV®* tool, being the long term dynamic behaviour of the restoration procedure evaluated using a tailor made *MatLab®/Simulink®* based simulation platform.

The *EMTP-RV®* tool was used to test the feasibility of the restoration procedure during the initial steps. The part that concerns the development of the *EMTP-RV®* simulation platform is however out of the scope of this dissertation. The simulation platform that exploits *EMTP-RV®* was developed within the framework of the MICROGRIDS project and it allows the detailed modelling of power electronic interfaces (which includes the VSI and the associated switching functions of power electronic devices according to a PWM technique) [155].

The evaluation of the feasibility of MG service restoration after a general blackout was performed through the analysis of the LV network dynamic behaviour considering only three-phase balanced operation, despite the fact that this is not the most common situation in LV distribution networks.

It is also important to notice that the key issue for a successful MG black start is the availability of MS with BS capability. As previously referred, SSMT are able to autonomously restart following a complete shut down, by making use of energy storage devices (batteries) in their DC-link. Due to the use of this energy buffering devices, the inverter coupling the SSMT to the grid can be operated as a VSI (that is, a droop controlled inverter, as described in Section 3.5.6.2. Therefore, during the initial stages a multi master control approach is used. In terms of the modelling approach used for testing the MG restoration sequence, it is possible to neglect the dynamics of the primer mover in SSMT, since they are assumed to have an energy buffer device in their DC-link. Therefore, SSMT are modelled as VSI for BS simulation purposes. The models adopted for uncontrollable MS such as micro wind energy converters or Photovoltaic (PV) panels are those presented in Chapter 3.

5.5.1 INITIAL RESTORATION STEPS

Results from the analysis of the initial restoration steps obtained within the MICROGRIDS project are briefly described next for sake of completeness. Additional details can be found in [128, 157]. Assuming that all SSMT restarted successfully after system collapse through the use of their DC-link energy storage device, the main storage device is selected to energize the LV network. After energizing the LV network using the MG main storage, the next step of the restoration procedure is to synchronize a SSMT (in this case SSMT 1) with the LV grid. In this case, it is assumed SSMT 1 successfully restarts following the shut down. For simulation purposes, it was considered that SSMT 1 was operating close to its nominal power at its operating frequency was also close to the nominal value, as can be observed in Figure 5-33.

The MGCC is responsible for sending the synchronization order to the Microsource Controller (MC) associated to the SSMT 1. Following the reception of the synchronization command, the SSMT 1 local controller sends instructions to the SSMT 1 inverter to produce a small frequency change in order to achieve the desired synchronization conditions in terms of phase difference between SSMT 1 and LV grid voltages (in this case, the voltages magnitudes were within acceptable limits, otherwise, a voltage correction should also be made by the SSMT 1 in order to be close enough to the grid voltage). The frequency deviation introduced by the SSMT 1 inverter can be observed in Figure 5-33 at t = 4 s. The synchronization conditions are met at t = 4.8 s. After synchronizing the SSMT 1 with the LV grid, it was simulated the connection of controllable load at t = 7 s. Following load connection, frequency decreases and the power is shared between the two MS.

Results shown in Figure 5-33 prove the feasibility of the initial restoration steps proposed for the LV service restoration procedure (considering a detailed representation of

MG components, namely the full modelling of the VSI). However, this approach requires high computational effort and does not allow simulation of the entire BS procedure.

In order to get an extended overview of the long term dynamic behaviour induced by the overall BS procedure, the *MatLab®/Simulink®* based simulation platform was used. In this case, inverters are only modelled through their control functions so that fast switching transients and harmonics are neglected (as previously described in Chapter 3) without compromising results accuracy.

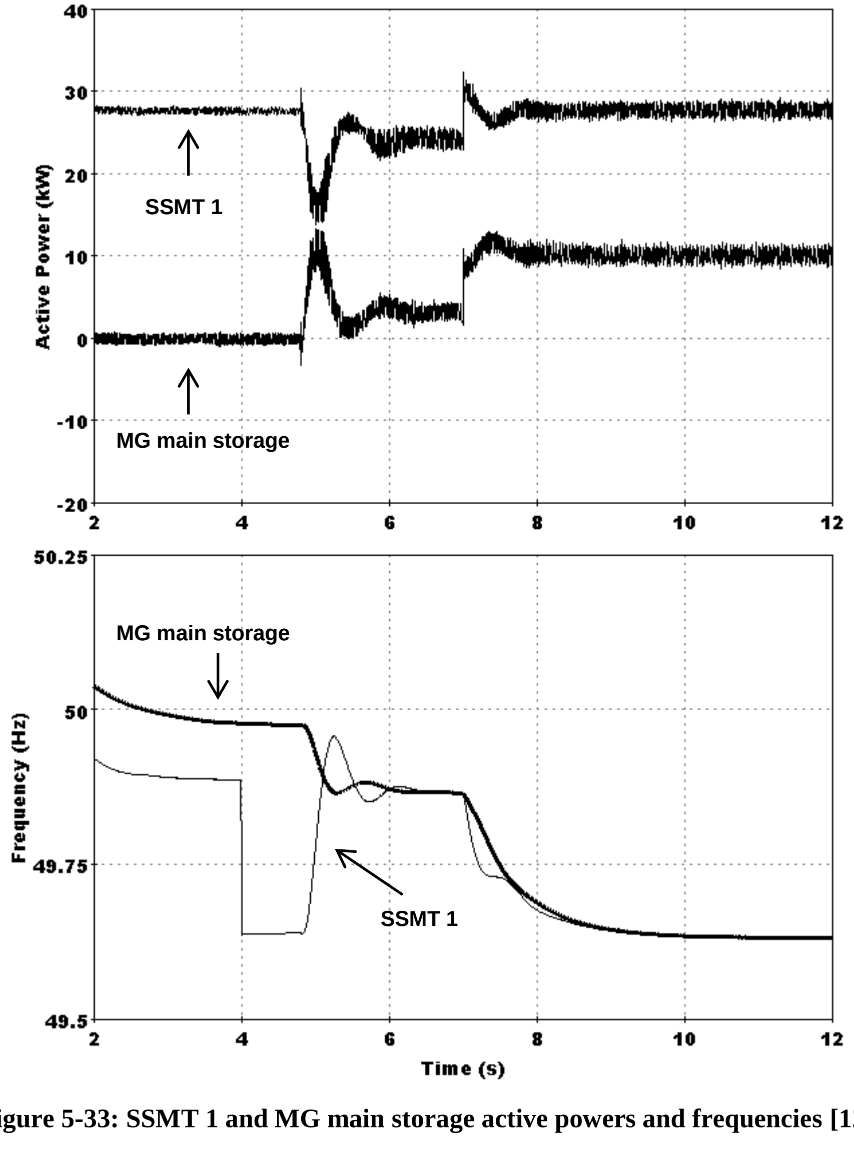


Figure 5-33: SSMT 1 and MG main storage active powers and frequencies [128]

5.5.2 LONG TERM SIMULATION OF MICROGRID BLACK START PROCEDURE

Although the initial steps of the restoration procedure were tested in the *EMTP-RV®* simulation tool, they were also implemented in the *MatLab®/Simulink®* simulation platform intended for the long term evaluation of the MG restoration procedure. As previously stated, it is assumed that all microturbines restarted successfully following the general blackout. The initial steps consist on the connection of the SSMT protected loads, as shown in Figure 5-34 at t = 5 s, t = 10 s and t = 15 s. Following the load connection to each SSMT operating autonomously, the frequency drifts according to the droop characteristic used in each VSI. Frequency deviation after load reconnection is a critical issue in this procedure, thus requiring a special attention. In order to maintain MG frequency within thigh limits (±0.2 Hz), a local secondary control is used to restore MG frequency to nominal value. This secondary control is used to define the values of the VSI idle angular frequency as a function of frequency deviation.

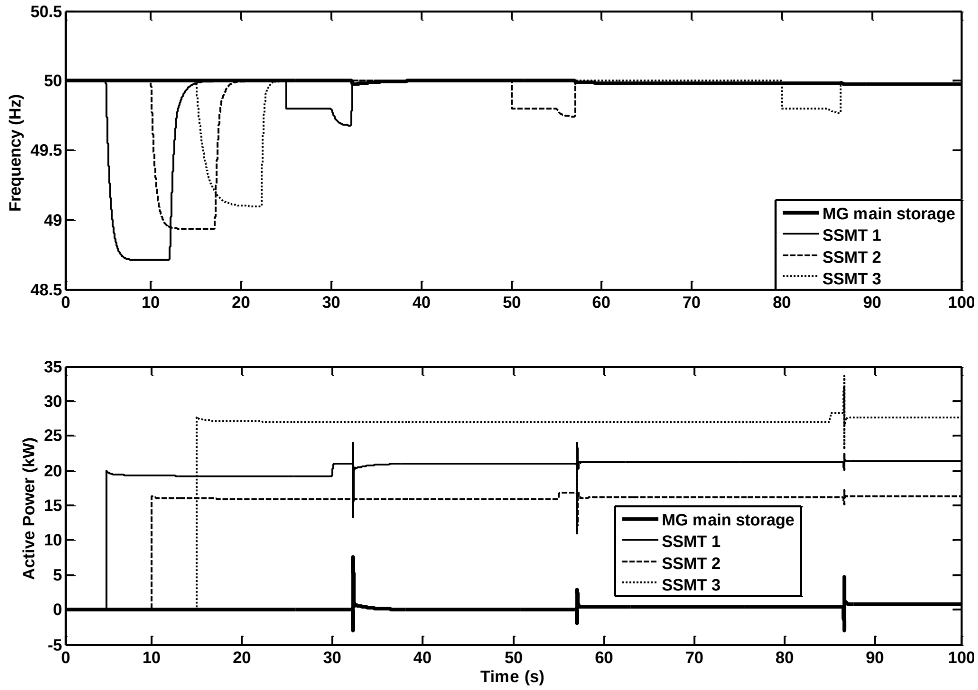


Figure 5-34: MS frequencies and active power during the first steps of the black start procedure

Following the energization the LV network and the connection of SSMT protected loads, the restoration procedure consists on the following sequence of actions:

1. Synchronizing the SSMT 1 with the LV network (t = 32.3 s);

2. Synchronizing the SSMT 2 with the LV network (t = 57.0 s);

3. Synchronizing the SSMT 3 with the LV network (t = 86.5 s);

4. Connecting controllable loads (t = 100 s);

5. Connecting wind generator (t = 119.7 s);

6. Connecting PV 1 (t = 130 s);

7. Connecting PV 2 (t = 140 s);

8. Motor loads start-up (t = 170 s and t = 175 s);

9. Changing the control mode of the SSMT (t = 190 s, t = 195 s and t = 200 s);

10. Synchronizing the MG with the MV network (t = 250.2 s).

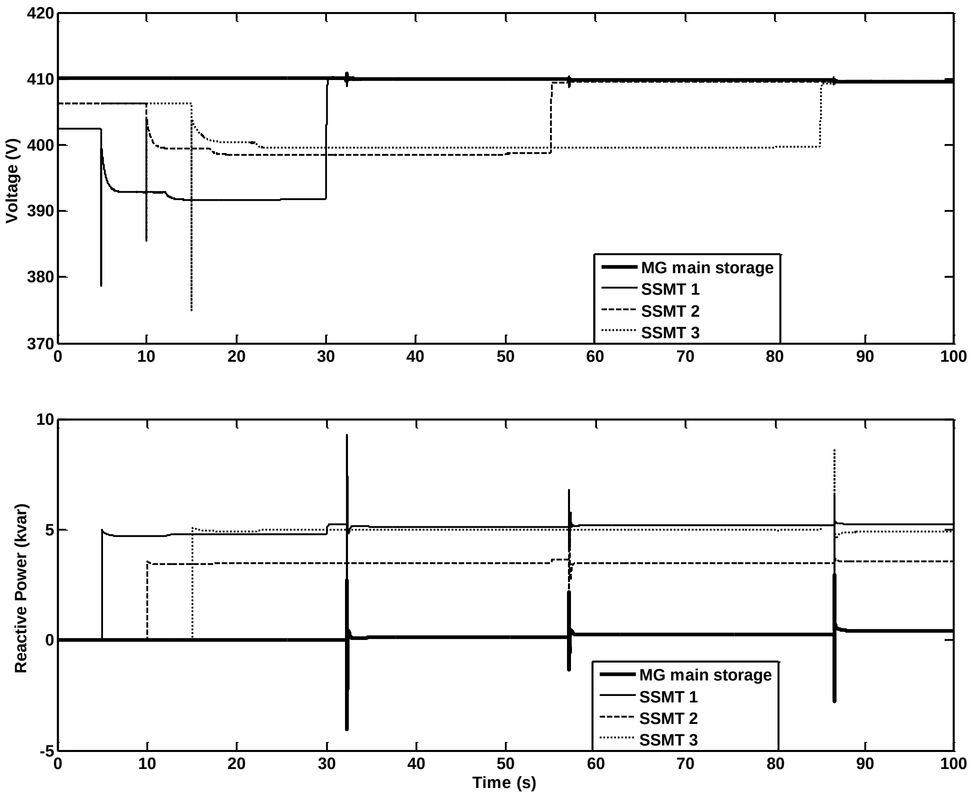


Figure 5-35: MS voltages and reactive power during the first steps of the black start procedure

During the reintegration phase (synchronization of several controllable MS to the LV grid), a careful verification of the necessary synchronization conditions is required, involving correction in the voltage magnitude and phase angle (frequency) of each VSI to be synchronized with the LV network. The procedure is enabled centrally by the MGCC, but the synchronization conditions are checked locally by each MC. For example, when synchronizing the SSMT 1 with the LV network, the procedure is enabled at t=25s; at the same time, a slight frequency variation is made upon the SSMT 1 inverter so that a small phase error can be achieve between the SSMT 1 and MG voltages in order to synchronize them with negligible impact in the network (Figure 5-34). The voltage magnitude is also corrected so that it matches the grid voltage, as it can be observed from Figure 5-35 at about t = 30 s. As MG loads are modelled as constant impedances, voltage correction causes a small power increase that can be observed in Figure 5-34 and Figure 5-35 around t = 30 s. For synchronizing SSMT 2 and SSMT 3 with the LV grid a similar procedure is followed.

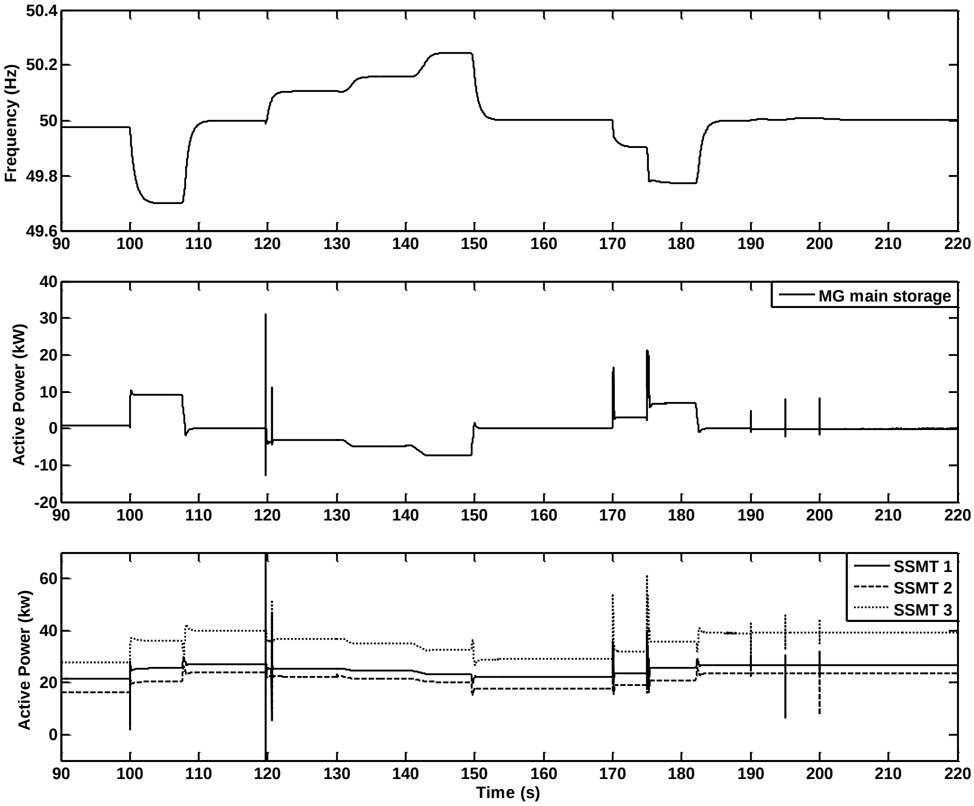


Figure 5-36: MG frequency and MS active power output

The MG long term dynamic behaviour was studied using a voltage droop control scheme in all MS with BS capability. Only small adjustments on the idle voltage of inverters are performed in order to minimize the errors in the voltage magnitude before the synchronization. The results obtained demonstrate that the used voltage regulation principle ensures MG stability and no reactive power oscillations among MS are observed (Figure

5-37). To the contrary of what happens in the active power sharing situation (where active power generation sharing is defined by a droop control approach), LV network impedances do not allow a reactive power sharing proportionally to the inverter ratings: the node where load is connected influences the reactive power sharing due to its specific node voltage drop.

The effect of small motor loads start-up can be observed in Figure 5-36 and Figure 5-37 around t = 170 s and t = 175 s. Although starting up from the stall position, the effect on the system is not a critical issue because motors are starting up under a multi master operation scheme, as it can be observed in Figure 5-37 when analysing node voltage drop.

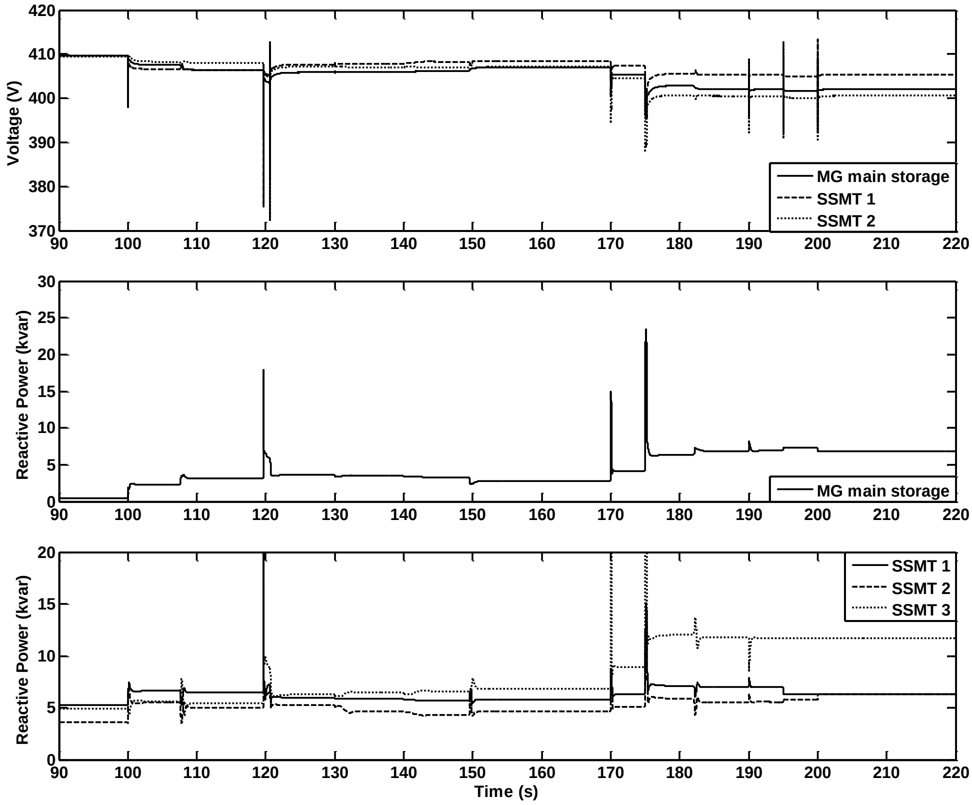


Figure 5-37: MS terminal voltages and reactive power output

After restoring the full operation of the MG, the control scheme of the SSMT inverters is changed from VSI to PQ control, which is the normal operation mode whenever an external source is used to define MG frequency and voltage. It is possible to observe in Figure 5-35 and Figure 5-36 that changing the control mode has no significant impact in the MG since the power levels in the MS are maintained (changing the control mode of the several SSMT occurs at t = 190 s, t = 195 s and t = 200 s).

When the MV network becomes available, the MGCC requires the VSI of the MG main storage device to change slightly its frequency and voltage in order to check the synchronization conditions. Figure 5-38 shows a detail of the impact of the synchronization procedure in terms of current, active and reactive power flowing in the LV side of the distribution transformer. As the majority of the MG loads is represented as constant impedances, voltage correction (increase) prior to synchronization provokes an increase in the active power consumption within the islanded MG. After synchronization this power surplus is supplied by the MV network (Figure 5-38), since the MG main storage droop imposes a zero power output after synchronization.

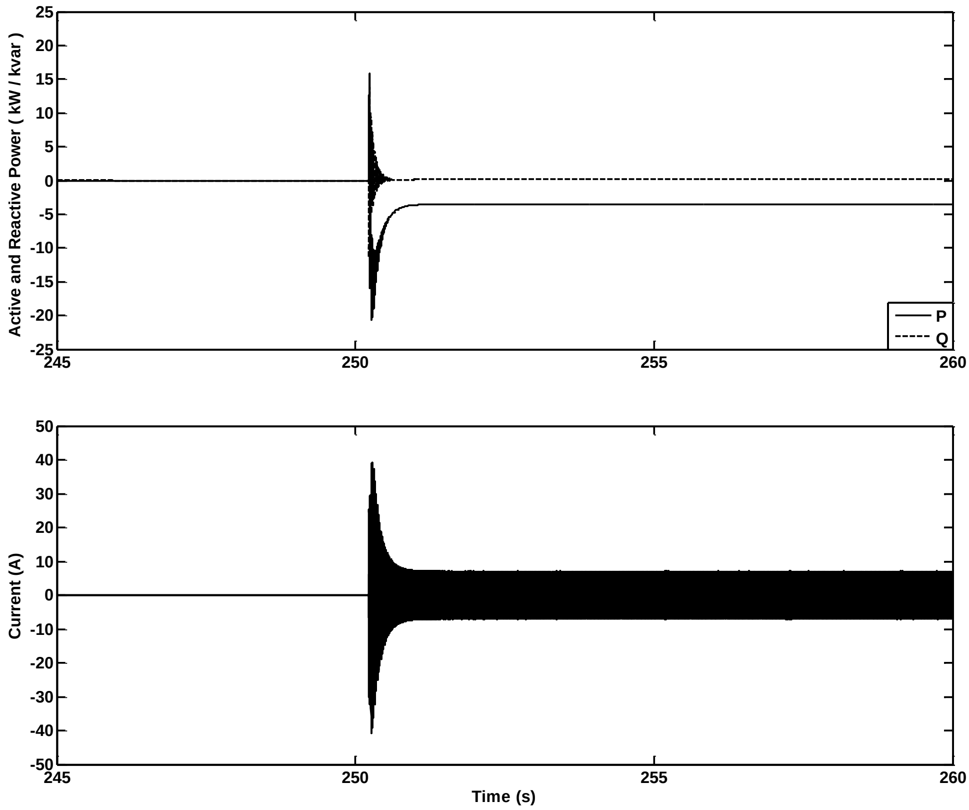


Figure 5-38: Synchronization current, active and reactive power in the low voltage side of the distribution transformer

5.6 SUMMARY AND MAIN CONCLUSIONS

The numerical simulation results described in this chapter focused on the validation of the control strategies for MG islanded operation, mainly when the MG becomes isolated after a fault in the MV network. The proposed control strategies were tested in several scenarios, which proves the feasibility of MG intentional or forced islanding under different power importing and exporting conditions. The test systems and the different scenarios analysed do not reveal instability problems. The obtained results highlight three fundamental conditions for successful MG islanded operation:

- **The need of storage devices** coupled with static converters emulating the behaviour of a synchronous machine in order to provide primary load-frequency and voltage control in the islanded MG.

- **The need of an implementation of load shedding mechanisms** in order to avoid large frequency excursions and overloads on the storage devices, which have no significant thermal overload capabilities; these mechanisms are of great importance, especially in situations where there are few units providing regulation, in order not to use all storage capacity available.

- **The use of a convenient secondary load-frequency control** to be installed in controllable MS, combined with load shedding and a convenient storage device capacity is required in order to maintain the MG frequency within tight limits around 50 Hz during islanded operation.

In this chapter it was also demonstrated the feasibility of using the MG concept for service restoration. Such achievement was accomplished in a situation where no synchronous generators were available and only electronic interfaced MS and asynchronous generators were assumed to be in operation. The control strategies to be adopted for MG black start and subsequent islanded operation as well as the identification of the set of rules and conditions were derived and evaluated by numerical simulations. The results obtained prove the feasibility of such procedures and show that storage devices are absolutely essential to implement successful control strategies during all restoration stages. The feasibility of MG black start procedure put in evidence that MS resources can be exploited further to develop local self healing strategies and to reduce local restoration times.

Concerning the use of VSI controlled through droops in order to ensure a successful MG moving to islanding operation it is important to make some consideration regarding its operation in parallel with a stiff AC system (the upstream MV network, which operates at the frequency of the interconnected power system). Prior to MG islanding, frequency variations in the interconnected power system is very small, and its mean value will be zero. Therefore, the net energy exchange by the VSI with the grid due to these natural frequency variations will be also zero. Consequently, this situation has no significant impact in terms of stored energy in the storage devices coupled to VSI. In case of a sudden frequency variation in the interconnected power system, the VSI will promptly respond to it, as previously explained. This situation corresponds to the provision of a primary frequency regulation capability by VSI, which is a service that can be exploited and valuated in a scenario characterized by a massive integration of MG in distribution networks. Under such scenario, Transmission System Operators could develop an aggregation program in order to exploit the contribution of VSI for primary frequency regulation in the interconnected system. At the same time, it will be necessary to develop the adequate mechanisms for the proper valuation of the corresponding ancillary service.

Chapter 6

MICROGRID ROBUSTNESS EVALUATION FOLLOWING ISLANDING

6.1 INTRODUCTION

Moving to islanding operation mode in a MicroGrid (MG) is a critical step, since if there is not enough balancing capacity, such operation mode is infeasible. Therefore, a critical issue that is being analysed in this dissertation concerns MG islanding due to faults occurring in the upstream Medium Voltage (MV) network. Depending on the load and generation profile, sudden MG islanding requires an effective balance between local load and generation, which means a fast response by local MicroSources (MS) and a very efficient use of storage devices and load shedding mechanisms. Additionally, frequency control problems may arise in the moments subsequent to MG islanding due to the slow response of MS to control signals and due the inexistence of rotating masses directly connected to the grid (inertia-less system). Regarding this critical contingency that can affect MG normal operation, there are two important issues that need to be considered:

- The adequacy of the local resources to meet at least the critical loads (this issue intrinsically considers the need of performing load shedding in the moments subsequent to MG islanding);
- The ability of the local generation resources (grid forming units and grid supporting units) to provide the dynamic response in order to keep the islanded MG in synchronism in the moments subsequent to islanding.

Concerning the first issue, if the MG generation capacity is not enough to feed all the loads during islanding conditions, load shedding mechanisms need to be used. Depending on the MG load and generation profile, a load curtailment corresponding to the difference between the MG load and the MG generation capacity may be required. Additionally MG reserve capacity during islanding operation can be achieved through load curtailment. However, management and definition of MG reserve requirements during islanding operation is out of the scope of this dissertation. Regarding the second issue previously pointed out, the MG dynamic behaviour was already characterized and the possible control approaches that take in consideration the dynamic response of different MS technologies were presented and validated through numerical simulation. Nevertheless, the management of MG storage capabilities and load curtailment need to be exploited further through the use of on-line control functionalities, since these are the available means that can be used in order to ensure MG survival in the moments subsequent to islanding.

6.2 MICROGRIDS ENERGY BALANCE ISSUES

Contrary to what happens in isolated systems comprising diesel units and renewables (for example, wind generation), frequency deviation is not a key issue for stable MG operation, since it can be easily determined as it was demonstrated in Equation (4-3). In isolated power systems there are some technical constraints limiting renewable power sources integration due to dynamic security problems that may arise in certain conditions. In fact, isolated power systems are week grids due to the low inertia time constants and to the inexistence of interconnection with neighbouring systems that help reducing reserve requirements. Isolated power systems with significant wind power integration are exposed to sudden wind speed variations and to the loss of wind power generation due to faults occurring in the system which leads to wind generation tripping by under voltage relays operation. Nowadays, ride through fault capabilities is being implemented in new wind energy conversion systems in order to avoid under voltage tripping in case of faults. Wind generation tripping or wind power variations in isolated systems need to be quickly compensated by thermal units (diesel power stations) in order to avoid large frequency and voltage excursions that may lead to system collapse. In fact, it may happen that a fault occurring in an isolated system may cause cascading events leading to system collapse: frequency deviation may lead to the activation of under frequency load tripping of generation groups while the wind generators may be disconnected by under voltage relays. In order to face severe contingencies, system operators usually follow very restrictive policies in terms of spinning reserve requirements, which may lead to the under exploitation of wind power generation capabilities (namely the definition of certain constrains that limit the construction of new wind parks).

The most critical issue when evaluating system security in isolated power systems is the system frequency deviation (sometimes combined with the rate of change of frequency) following a pre-defining disturbance (short-circuit, wind gust, short-circuit followed by disconnection of wind generation, tripping of a thermal power station). Therefore, minimum frequency deviation is the security index used for dynamic security assessment in isolated power systems. In order to develop the security assessment structures, Automatic Learning (AL) techniques such as Artificial Neural Networks (ANN) and decision trees has been extensively used [158-160]. Both techniques are based on the exploitation of a large data set containing information about power system dynamic behaviour for a large number of credible operating scenarios. This data set is generated off-line through the use of dynamic simulation programs. The security evaluation tool can be used on-line for the continuous monitoring of system security based on inputs provided by the SCADA. These advanced control systems continuously monitor system security regarding some pre-defined disturbances and are also responsible for presenting to system operators adequate preventive control actions (namely re-dispatching functionalities of thermal stations) and the determination of secure unit commitment alternatives for the upcoming hours in case of insecure scenarios are identified based on load and renewable generation forecasts [158-160].

Regarding the MG, it was already described that its primary frequency regulation method is based on a droop control strategy used in Voltage Source Inverters (VSI) coupled to storage devices. The use of droop control allows also the determination of frequency deviation as a function of the expected power imbalance in the system, as it was demonstrated in Equation (4-3). Using Equation (4-3) it is possible to compute MG frequency deviation following a generation or load variations ΔP during islanding conditions. Equation (4-3) also shows that frequency variation in the islanded MG is perfectly controlled by the droop settings and therefore can be easily predicted. Consequently, more than the frequency deviation, the ability of local generation devices to assure the balance between load and generation following islanding is the key issue that needs to be evaluated. In fact, the limited storage capacity available in storage devices to be installed in a MG is a major drawback and might compromise successful MG islanded operation. Depending on the MG operating conditions, such as local load, local generation profile and MS availability for active power/frequency regulation, high amounts of energy may be required to be injected in the MG in the first moments subsequent to islanding. Due to the slow response of controllable MS to control signals, the most significant part of this energy must be provided by energy storage devices, which has a finite storage capacity. This problem is related to frequency stability, since it depends on the MG ability to restore balance between load and generation during islanded conditions and with the minimum loss of load [161].

In order to illustrate the referred issues, a simple example is described next. Concerning the MG test system presented in Figure 5-1 (MG operation under a single master control strategy), three different scenarios were defined and are characterized in Table 6-1. Figure 6-1 illustrates typical MG dynamic behaviour and the energy required to be injected by storage devices in the moments subsequent to system islanding. In Cases 1 and 3, the MG is importing power from the MV network and the storage device must inject energy after MG islanding; in Case 2, the MG is injecting power into the MV network and therefore storage devices must absorb the energy surplus after MG islanding. In Case 3 it is also possible to observe that the MG does not have enough generation capabilities for load/frequency regulation. In this case, MG frequency is not restored to the nominal value and the storage device will kept injecting energy, which is not an admissible situation due to its limited storage capacity.

Table 6-1: Scenarios characterization

	Case		
	1	**2**	**3**
SSMT 1 + SSMT 2 Active Power (kW)	6.5	41.1	24.4
SSMT 3 Active Power (kW)	4.7	13.4	24.3
SOFC Active Power (kW)	14.9	29.9	29.5
PV 1 + PV 2 Active Power (kW)	4.8	16.2	2.5
Micro Wind Generator Active Power (kW)	6.3	13.9	3.7
Power Imported form the MV Network (kW)	55.7	-29.1	65.5

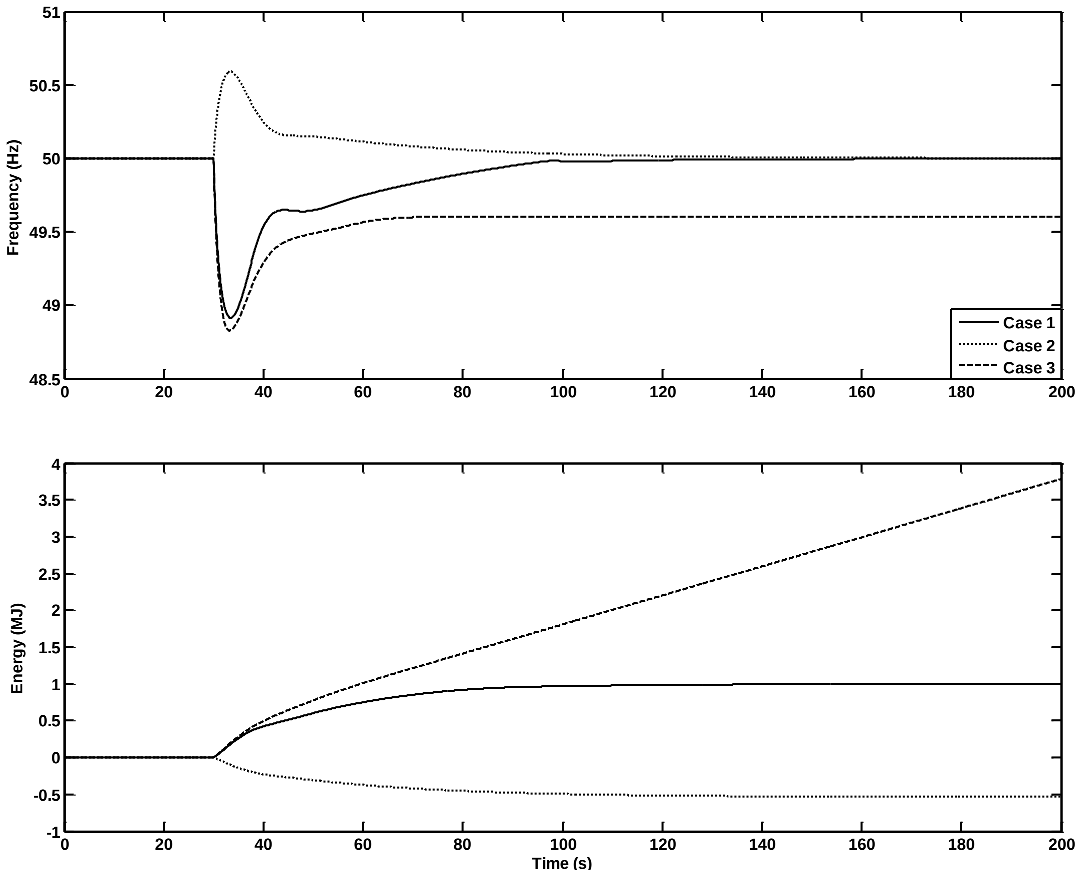


Figure 6-1: Frequency and energy injected by storage devices in different operating conditions during and subsequent to MG islanding

This example clearly shows that MG robustness in the moments subsequent to islanding is intrinsically linked to the energy storage capacity available in storage devices [161]. If it is possible to quickly determine the amount of energy that is required to balance the system in the moments subsequent to MG islanding (it does not mean that MG islanding effectively occurs), it will be possible to efficiently manage the state of charge of storage devices in order to assure MG survival after islanding. Management of the state of charge of storage devices can be achieved by:

- **Load shedding actions** to be adequately parameterized in Load Controllers (LC) in order to automatically disconnect MG loads through under frequency load shedding relays (parameterization of load shedding steps and the frequency deviation values at which load curtailment occurs);

- **Inclusion of robustness constraints** in the economic scheduling problem of the MG in order to minimize the amount of load to be disconnected in case of islanding;

- **Definition of generation curtailment** (or additional load connection) following islanding if the MG is injecting power into the upstream MV network and the storage devices are not able to absorb the power surplus in the moments subsequent to MG islanding.

However, the on-line management of storage devices and load shedding mechanisms must be performed in real time environment, thus requiring knowledge about the MG dynamic behaviour for each specific scenario. The traditional and most accurate analysis of this kind of problems involves the numerical solution of a system of non-linear equations (requiring the use of simulation platforms like in the previous chapter), which is a very demanding and time consuming computational task and it is not suitable for on-line purposes. Therefore, AL based tools are alternative approaches since they provide effective means of extracting high level knowledge from large data sets in order to help on-line system management regarding these dynamic issues. The referred data sets should contain detailed information about MG dynamic behaviour. This information should be generated off-line by making use of appropriated simulation platforms.

In order to perform the on-line management of storage devices, it is necessary to develop a tool able to emulate the energy required to be injected in the MG in the moments subsequent to islanding based on real time operational information. After the development of such a tool, it will be possible to parameterize the control actions that were previously referred in order to ensure the state of charge of storage devices will be maintained within pre-defined limits following MG islanding. The MG communication infrastructure and its hierarchical control system are of paramount importance for the effective application of such a procedure. The MG management and control system will be responsible for taking system measurements to perform MG robustness evaluation and communicate the preventive control actions to MG local controllers (by pre-defining the amount of load or generation to be curtailed immediately following islanding). Through the inclusion of these additional control functionalities in a MG it will be possible to increase costumer benefits arising from the exploitation of DG units integrated in LV distribution networks.

6.3 MICROGRID ROBUSTNESS EVALUATION TOOL

As it was previously stated, the on-line management of storage devices, load shedding mechanisms and MG power production capabilities requires knowledge about the MG dynamic behaviour. In order to emulate the energy E required to be injected in the MG to stabilize the system in the moments subsequent to islanding, it is necessary to develop an intelligent system able to predict the energy E as a function of pre-disturbance variables that are able to characterize MG operating scenario. It is well known that ANN are a class of AL tools that can be easily exploited in order to perform regressions over a set of input-output pairs. The development of a tool in order to deal with the referred MG dynamic issues involves the following steps:

- Off-line generation of a large data set containing information on MG dynamic behaviour for the selected disturbance (moving to islanding operation);
- Training and performance evaluation of the ANN structure in order to predict the energy E as a function of pre-disturbance variables;
- Exploiting the ANN tool for the on-line identification of preventive control actions in order to ensure MG survival in the moments subsequent to islanding.

6.3.1 ARTIFICIAL NEURAL NETWORKS

ANN can be defined as a massively parallel distributed processor built up of simple processing units, whose development is inspired in the way biological nervous systems, such as the brain, process information [162]. The field of knowledge in ANN is quite vast and it covers several domains of application. Concerning the specific case that is being analysed, some references are made to a type of ANN widely used to solve regression problems, that is, a mapping function between a set of input and an output variables. Additional information on the foundation of ANN and its applications can be found in [162].

The basic processing unit of an ANN – a neuron – is presented in Figure 6-2. As it can be observed in Figure 6-2, each processing unit *i* has a set of input variables x_1, x_2, … , x_n which are subjected to some basic operations:

- The weighted sum of the input variables $\sum_{k=1}^{n} \omega_{ik} \times x_k$, where ω_{ik} is the weight of input variable x_k in the processing unit *i*;

- To the weighted sum of the input variables is added a bias parameter b_i: $s_i = \sum_{k=1}^{n} \omega_{ik} \times x_k + b_i$;

- The output of the basic processing unit *i* is computed through the activation function f_i as $f_i(s_i)$.

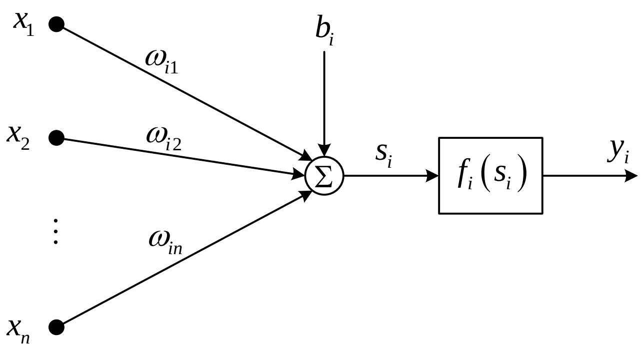


Figure 6-2: Schematic of an ANN basic processing unit

The activation function f_i can take any form, but common choices are functions of the saturation type such as hyperbolic tangent functions, negative exponential functions and linear functions, which are illustrated in Figure 6-3:

$$f(x) = \tanh(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}} \tag{6-1}$$

$$f(x) = \frac{1}{1 + e^{-x}} \tag{6-2}$$

$$f(x) = x \tag{6-3}$$

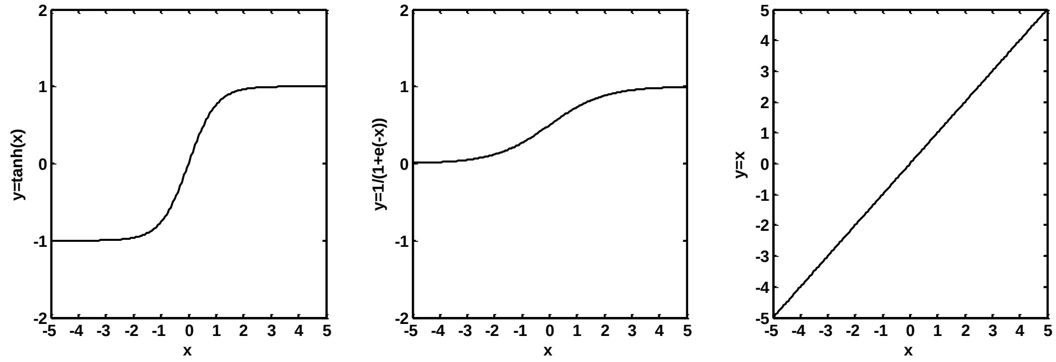


Figure 6-3: Activation functions commonly used in ANN

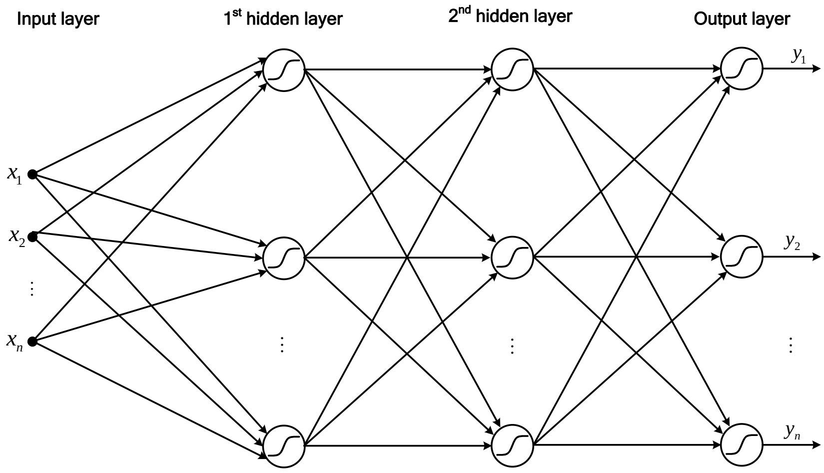


Figure 6-4: Feed forward ANN

One of the possible forms of linking the basic processing units in an ANN is shows in Figure 6-4, which is commonly referred as a Multi Layer Perceptron. As can be observed in the figure, the neurons are arranged in several layers, where the output of each neuron in a layer is one of the inputs of each neuron of the following layer. Since the linkage between the layers in always from the input to the output direction, such that the input signal propagates through the network in a forward direction, this type of ANN are usually denominated by feed forward ANN. The number of hidden layers and the number of neurons to be included in each hidden layers are attributes of the ANN that need to be defined before starting the training phase. Concerning the ANN architecture (number of hidden layers and number of neurons in each hidden layer), there are some authors who have identified heuristic based approaches in order to defined the ANN structure [163]. Alternatively, it is possible to follow a trial and error approach in order to select the ANN with best performance. This is the approach that was followed within this dissertation. Concerning the number of hidden layers, it is usual to state that an ANN with a single hidden layer is able to approximate any continuous function with the desired accuracy, if an adequate number of neurons is used [164]. However, it is not common to use more than two hidden layers. In terms of the number of basic processing units in each hidden layer, it is well know that if the ANN uses a small number of neurons, it will not be able to approximate desired functions. Contrarily, if a large number of neurons are used, the ANN will loose generalization capabilities.

6.3.1.1 Training Artificial Neural Networks

The parameters of an ANN (weights and bias) have to be tuned such that the application of a set of inputs produces the desired outputs. A possible approach to tune the ANN parameters consists on its iterative adjustment by feeding the ANN with input/output patterns and changing the parameters according to some learning rule. This general ANN training scheme is schematically represented in Figure 6-5. The ANN training process consists on solving an optimization problem: in each iteration, the actual value of the ANN output $\hat{y}$ is compared with the target value y, being the error signal $\varepsilon = y - \hat{y}$ used to adjust the ANN parameters and minimize the deviations between the target values and the ANN outputs.

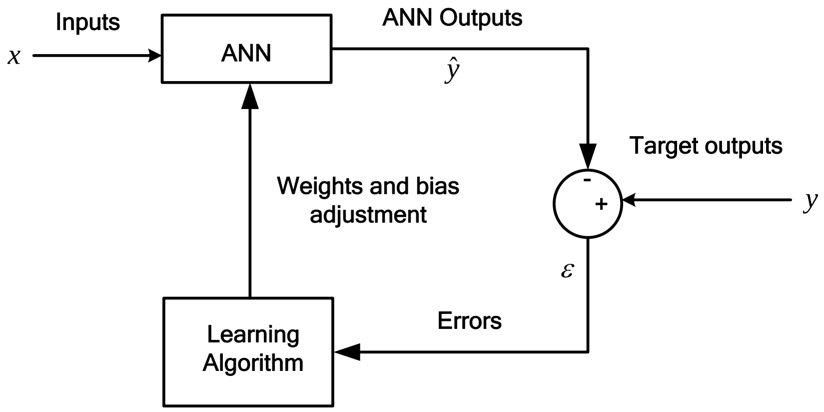


Figure 6-5: General scheme for training ANN

One of the first methods that were used for training ANN is based on a gradient descendent technique, in which the parameters p are adjusted in the direction in which the performance function decreases most rapidly [162]:

$$p_{k+1} = p_k - \eta_p \frac{\partial E}{\partial p} \tag{6-4}$$

where p_k is the current vector of the ANN parameters, p_{k+1} is the updated vector of the ANN parameters, $\frac{\partial E}{\partial p}$ is the gradient of performance function and η_p is the vector of the learning rates. The numerical index commonly used to characterize the ANN performance is the Mean Square Error (MSE) given by:

$$E = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2 \tag{6-5}$$

where N is the number of training patterns.

There are two different ways in which this gradient descent algorithm can be implemented [165]: incremental mode and batch mode. In the incremental mode, the gradient is computed and the ANN parameters are updated after each input pattern is applied to the network. In the batch mode, all the inputs are applied to the network before updating the parameters. In both methods, whenever the set of input paters in presented to the network, it is said that it was performed a training epoch of the iterative process.

Regarding the computation of the partial derivatives of the performance function $\frac{\partial E}{\partial p}$, the backpropagation algorithm is commonly used. This technique allows the computation of the partial derivatives of the error function in relation the ANN parameters through the successive application of the chain rule of calculus from the ANN output layer to the ANN input layer. A detailed mathematical explanation on the explanation algorithm can be found in [162].

Nowadays there are other algorithms that can be used as alternatives to the gradient descendent techniques. For example, in *MatLab*® ANN toolbox there are several training methods in addition to the classical training algorithm: conjugate gradient algorithm, quasi-Newton algorithm and Levenberg-Marquardt algorithm [165]. All the training methods are implemented in the batch training mode and are oriented in order to accelerate the convergence of the training process. In order to train a feed forward ANN it is generally recommended to apply the Levenberg-Marquardt algorithm. It provides a fast convergence, it is robust and it is not necessary for the user to initialize any strange design parameters such as the learning rate that has a strong influence on the algorithm performance in its classical implementation [165].

6.3.2 DATA SET GENERATION

The MG dynamic behaviour in the moments subsequent to islanding is highly dependent on the MG load and generation profile. Therefore, the data set to be generated should cover a larger number of operating scenarios of load and generation. The scenarios to be considered should be based on information regarding the MG operational criteria, namely having in mind that some MS are operating in Combined Heat and Power (CHP) applications during the normal interconnected mode. However, instead of defining rules for the MG environment, it was adopted general criteria for selecting the operating scenarios:

- If the MG load is bellow 30%, it was considered that the power production in the Solid Oxide Fuel Cell (SOFC) and in the Single Shaft Microturbines (SSMT) must be lower than 60% of their nominal capacity. Conversely, if the MG load is higher than 60%, SOFC and SSMT production should be higher than 20%;

- For MG loads lower than 30%, it was considered that Photovoltaic (PV) units production is zero (a significant part of night hours corresponds to the valley of the load diagram; therefore, this is a simple rule in order to not perform PV generation sampling at least during a part of the night period. Although this is a very simplistic rule, it never leads to the disregard of realistic operating conditions. Instead, it may lead to the creation of some infeasible scenarios from the physical point of view);

- If MG load is higher than the maximum MG generation capacity (120 kW in controllable MS, plus the actual renewable energy sources production), the scenario is not considered. In this case, MG islanding operation requires load curtailment as least equal to the difference between the MG load and the MG generation capacity.

Following the definition of the basic conditions for data set generation, a structured Monte Carlo sampling method [160] was used in order to generate knowledge about MG dynamic behaviour, since it demonstrates to provide a well distributed and highly representative data set throughout the defined operating range. The Monte Carlo parameters shown in Table 6-2 correspond to the MG operating conditions in which the sampling method is applied. The definition of the data set resolution was performed by defining the resolution of each Monte Carlo parameter, i. e., the number of intervals of each parameter operating range. By defining the resolution of each of these parameters, the data set operating range (a 6-dimension hyperspace) is divided into hypercells. The data set generation procedure consists on the random sample over the Monte Carlo parameters according to the pre-defined operating range and resolution. It is a set by step procedure in which for each hypercell, a pre-defined number of values of the 6-dimension hyperspace are sampled using an uniform distribution for each variable.

Table 6-2: Monte Carlo parameters

Monte Carlo Parameter	Range (p.u.)	Resolution
SSMT 1 and SSMT 2 Active Power	[0.1; 1]	5
SSMT 3 Active Power	[0.1; 1]	5
SOFC Active Power	[0.3; 1]	5
PV 1 and PV 2 Active power	[0; 1]	3
Wind Generator Active Power	[0.1; 1]	3
MicroGrid Total Load	[0.2; 1]	5

In order to include some representative knowledge in the data set about MS unavailability due to maintenance or other unplanned reasons, the following procedure was used. The unavailability of controllable MS (SSMT and SOFC) was considered by applying the previously sampling procedure for the data set generation in the following scenarios: unavailability of one SSMT in MG bus number 2, unavailability of SSMT 3 and the unavailability of the SOFC. The unavailability of wind generator was also considered in case of very low or very high wind speeds. Concerning the PV panels, its unavailability is implicitly considered by using the operating range assigned to it, as in Table 6-2. The simultaneous unavailability of more than one controllable MS was not considered, since it would lead to a MG operating scenario with reduced secondary load-frequency regulation capabilities. In this case, it is assumed that MG islanding is not successful following a disturbance occurring in the MV network. However, the simultaneous unavailability of a single controllable MS and a renewable energy source (PV or micro-wind generator) was considered to be possible.

Using the rules and conditions previously stated, 12043 MG operating conditions were created. For each one of these scenarios, a dynamic simulation was performed in order to evaluate the MG behaviour in the moments subsequent to islanding. It was considered that a fault occurs in the MV network in a point not next to the MG location, so that it is possible that the MG successfully moves to islanding operation and none of its MS is disconnected. A key variable that is monitored is the energy injected in the MG three minutes after islanding. This time interval was chosen by extensive simulation and it was found adequate in order to guarantee the MG dynamic model reached a steady state condition following islanding.

6.3.3 THE NUMERICAL SET-UP FOR DATA SET GENERATION

The *MatLab®/Simulink®* simulation platform previously referred is not suitable to perform the large number of dynamic simulations required to generate the data set due to time required to perform each simulation. This simulation platform uses a time domains solution for both sources and for network components (network cables, transformers), which increases the complexity of the system and the simulation time. Therefore, an alternative simulation platform was developed. It follows the general principles used for dynamic stability studies in conventional power systems, which consists on keeping the sources model in the time domain (solution of a set of differential equations) and to use a steady state frequency domain model to represent the electrical network. In this case, network components are represented as constant impedance elements, being the network currents computed through the network algebraic equation. Due to the fact that the terminal voltages and currents at the sources terminals are instantaneous values obtained from the time domain solution at discrete time points while a phasor representation is required for the network solution, the "sources stator transients" are usually neglected, but it does not compromise the results accuracy. Notice that the term "stator" has a larger ambit within this dissertation, since it can correspond to the coupling inductance of power electronic converters. In general terms, the following approach was used [122, 166]:

- Each MS generates an electromotive force (emf), which can be regarded as a "emf behind a reactance", as it is the usual approach followed in conventional power systems dynamic studies (in this case, the reactance may corresponds to the inverter coupling inductance);

- The electric network is represented by its admittance matrix in the *d-q* reference frame, in which the fast transients associated to the network are neglected;

- The *d-q* components of the power electronic interfaced MS emf must be provided to the network as an output solution of the MS differential equations;

- In case of rotating machines directly connected to the LV grid, the conventional approach based on an emf behind a transient or subtransient reactance is followed, as described in [167];

- The network model output will be the *d-q* components of the currents injected by each MS and the MG node voltages.

A general block diagram illustrating the approach used on the developed of the new simulation platform is shown in Figure 6-6.

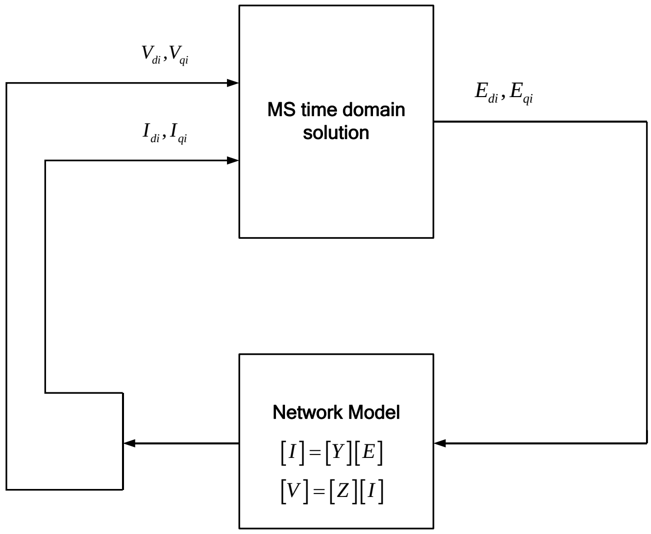


Figure 6-6: Illustration of the MG dynamic simulation algorithm

6.3.4 TRAINING THE ARTIFICIAL NEURAL NETWORKS STRUCTURE

The use of ANN is intended for the on-line evaluation of the energy E required to be injected in the system in the moments subsequent to islanding. Each point of the generated data set is characterized by a set of system measurements (physical MG parameters). Regarding the problem under analysis, which is related to power balance, the MG variables which will implicitly contain the information required to be used as the inputs of the ANN are:

- MG total active power (P_{MG});
- Active power produced in controllable MS:
    - Power produced by the SOFC (P_{SOFC});
    - Total power produced by SSMT 1 and SSMT 2 ($P_{SSMT12} = P_{SSMT1} + P_{SSMT2}$);
    - Power produced by SSMT 3 (P_{SSMT3});
- Active power from uncontrollable MS ($P_U = P_{wind} + P_{PV}$);
- Reserve margin in controllable MS, which is the difference between the nominal power of each MS and its actual active power production level:
    - Reserve margin in SOFC ($R_{SOFC} = P_{SOFC}^{nom} - P_{SOFC}$);
    - Reserve margin in SSMT 1 and SSMT 2 ($R_{SSMT12} = P_{SSMT12}^{nom} - P_{SSMT12}$);
    - Reserve margin in SSMT 3 ($R_{SSMT3} = P_{SSMT3}^{nom} - P_{SSMT3}$);

The variables selected as inputs for the ANN are easily obtained from the MicroGrid Central Controller (MGCC) data base, which is periodically updated with data provided by MG local controllers by using the MG communication infrastructure. In order to consider the unavailability of a MS, its produced power is set to zero and in case of controllable MS its reserve margin is also set to zero.

6.3.4 DEFINITION OF PREVENTIVE CONTROL ACTIONS

The ANN previously presented is intended to be embedded in a **robustness evaluation module** in the MGCC. The MGCC robustness evaluation module will periodically evaluate the MG robustness by making used of the appropriate variables as previously described (for example in a 15 minutes time basis). In case of detecting that the energy to be injected in the system is not enough to stabilize the MG in the moments subsequent to islanding, preventive control actions must be derived in order to ensure that the MG securely moves to islanding operation in the event of a disturbance in the MV network. As the ANN emulates the behaviour of the energy injected/absorbed, the preventive control actions can be determined by finding the values of the control variables that satisfy the following constraint:

$$\begin{aligned} & E < E_{\max} \\ & or \\ & E > E_{\min} \end{aligned} \tag{6-6}$$

Where $E_{\max}$ is the maximum amount of energy that can be injected by the storage devices and $E_{\min}$ is the maximum value of the energy that can be absorbed by the storage devices.

It will be frequent that MG will not have enough generation capabilities in order to supply the entire load during islanding operation, leading to the adoption of load shedding strategies (as it was previously referred, in this case it is necessary to curtail an amount of load corresponding to the difference between the actual MG load and the MG generation capacity). Furthermore, adding a security constraint to an economic dispatch problem for the MG will increase the electricity price, and it will not be a very likely situation due to the existence of thermal and electric loads, which should be met during the interconnected mode. In case of system islanding such restriction must not be considered in order to achieve load-frequency control capabilities. As it was previously referred in Chapter 4, when the MG moves to islanding operation, controllable MS change from a dispatched mode (responsible for meeting the thermal loads requirements) to one controlling voltage and frequency in the islanded system. Therefore, it is suggested that in such a case the preventive control strategy will be a load shedding strategy. Determining the minimum amount of load to be shed L_{shed} in order to satisfy the first condition of Equation (6-6) can be easily performed through a gradient technique and by computing the derivative $\dfrac{\partial E}{\partial P_{MG}}$, as described in [160].

In other operating conditions the MG can export power to the MV network. In this case, storage devices must be managed in order to be able to absorb the power surplus while controllable MS respond to the control signals and reduce the output power. If storage devices are not able to absorb the energy surplus, a preventive control strategy must also be envisaged. Such a preventive control must include the reduction of the output power of some MS. Controllable MS respond to this situation by reducing its power output according to the MG control strategy previously proposed. Nevertheless, according to the models adopted for controllable MS, their response to the control signals has an inherent time constant, being desirable to find alternatives to achieve a faster reduction of the power produced within the islanded MG (for example, reducing renewable generation or connecting dump loads). Concerning controllable MS, a possible solution is its disconnection from the grid. However, disconnection of SSMT and SOFC has major implication in MG security, because they have long down time periods after shut down. Therefore, the preventive strategy in this case includes the temporary reduction of the output power in micro-wind or/and PV generators or the connection of less important loads. Determining the minimum amount of power to be reduced in non-controllable generators in order to satisfy the second condition of Equation (6-6) can also be performed through a gradient technique and by computing the derivative $\frac{\partial E}{\partial P_U}$. Determining the generation curtailment share in uncontrollable MS can be performed proportionally to their output power.

The proposed preventive control actions are to be sent as set-points to MG local controllers – Load Controllers (LC) and Microsource Controllers (MC) – and will be activated only if MG islanding effectively occurs. Detection of MG islanding by local controllers will be performed by measuring system frequency. Therefore, LC and MC need to be sensitive to MG frequency and must be adequately parameterized. LC need to be parameterized in terms of underfrequency load shedding (frequency deviation and amount of load to be disconnected). MC need to be parameterized in terms of over frequency generation curtailment (frequency deviation and amount of load to be curtailed). System frequency in the moments subsequent to MG islanding can be easily predicted as a function of MG power unbalance, as it was previously explained. In the moments subsequent to MG islanding, the MG power imbalance ΔP is equal to the power being interchanged with the upstream MV network prior to MG islanding. Making use of Equation (4-1), the MG frequency deviation following islanding can be computed as:

$$\Delta f = \frac{k_p \Delta P}{2\pi} \tag{6-7}$$

6.4 RESULTS AND DISCUSSION

In order to train the ANN structure the previously referred data set was divided in a training set and in a test set containing respectively 2/3 and 1/3 of the total operating points. Concerning the training set, 1/3 of its points were separated in order to be used as a validation set during the ANN training phase. The test set is used for ANN performance evaluation and for comparison between different ANN. For the ANN training procedure, the *MatLab®* Neural Network Toolbox was used. Prior to the ANN training phase, the data set was normalized in the interval [-1, 1]. ANN parameters were found through the Levenberg-Marquardt backpropagation algorithm. In order to obtain the best ANN performance, different ANN topologies (number of layers and number of neurons in each hidden layer) were tested.

In order to improve the generalization capabilities of the ANN, the early stopping technique was used [165]. In this technique, the training set is used to compute the gradient function and update the ANN weights as bias. The ANN error in the validation set is monitored during the training phase. The validation error normally decreases during the initial phase of training, following the behaviour of the training set error. However, when the network begins to over-fit the data, the error on the validation set typically begins to rise. When the validation error continually increases for a specified number of iterations (in this case the maximum number of iteration for a continuous increase in the validation set error is 5), the training is stopped, and the weights and biases at the minimum of the validation error are reloaded and assumed to be the final parameters of the ANN.

The ANN presenting the best performance has 8 inputs and a single hidden layer with 80 neurons. Figure 6-7 depicts the linear regression between the predicted and observed values (test set) of the energy injected by the storage devices three minutes after islanding. The obtained performance in terms of the Root Mean Squared Error (RMSE) and Relative Mean Squared Error (RE) are:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2} = 0.0086MJ \tag{6-8}$$

$$RE = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(y_i - \hat{y}_i\right)^2}{\frac{1}{N}\sum_{i=1}^{N}\left(y_i - \overline{y}_i\right)^2} = 2.3144\times 10^{-4} \tag{6-9}$$

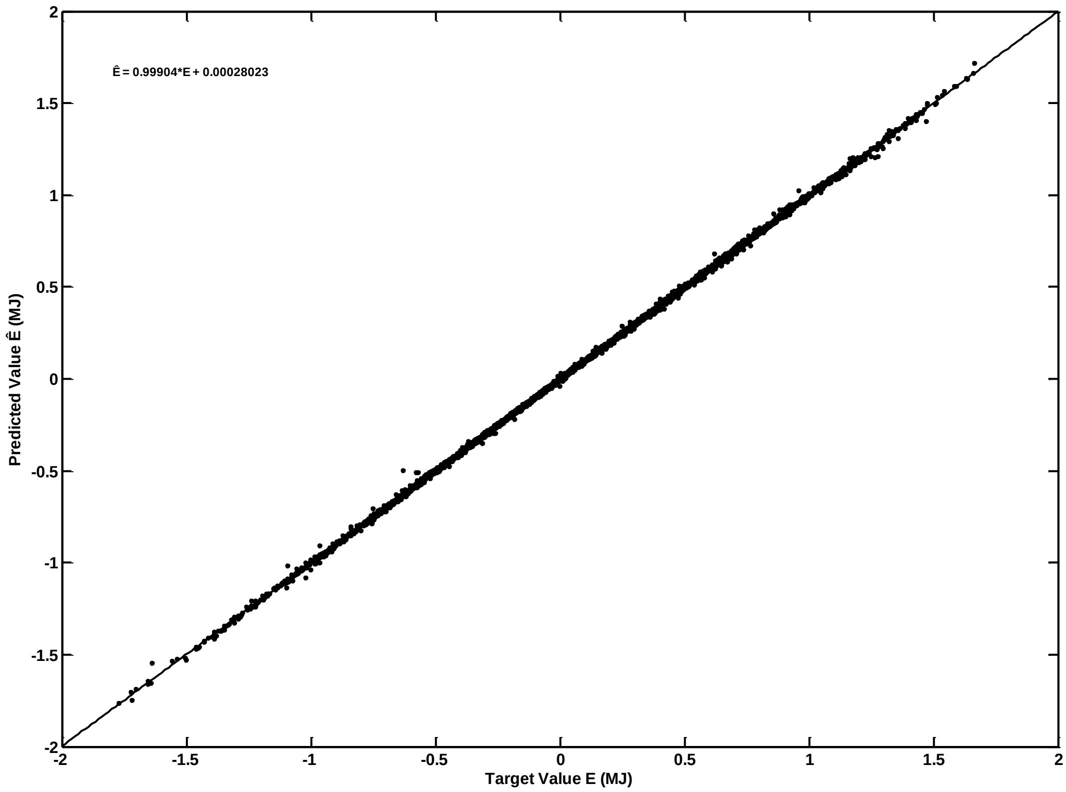


Figure 6-7: Observed and predicted values and the linear regression model results

The RE is the quotient between the MSE and the standard deviation of the ANN output value. In other words, the RE is a comparison between the MSE and a regression model represented by the ANN mean value. Therefore, the less the value of RE, the best performance is achieved in the ANN prediction model in comparison to a simple regression model based on the mean output value.

After building the ANN model able to predict the energy required to be injected in the MG in the moments subsequent to islanding, it is necessary to specify the value of the energy that is available to be injected into the islanded system by the storage devices. By defining the MG robustness conditions as $E < 0.5$ MJ, one can use the ANN based tool in order to calculate the amount of load to be shed for an operating scenario that will require higher amounts of energy to be injected in the moments subsequent to islanding. Determining the amount o load to be shed is performed through the proposed methodology to derive the preventive control actions. For illustration purposes, the procedure is described graphically next. The curves shown in Figure 6-8 correspond to two different operating conditions, which are described in Table 6-3. For these scenarios, all the operating conditions are maintained constant and the MG load is changed in order to plot the graphs. The interception of the horizontal line (corresponding to the energy level of 0.5 MJ) with the energy function of each scenario defines the maximum value the MG load should be in order to not exceed the pre-defined amount of energy that can be injected into the MG during three minutes after islanding. The difference between the actual MG load and the load calculated as stated before corresponds to the amount of load to be disconnected in the moments subsequent to MG islanding (Table 6-3).

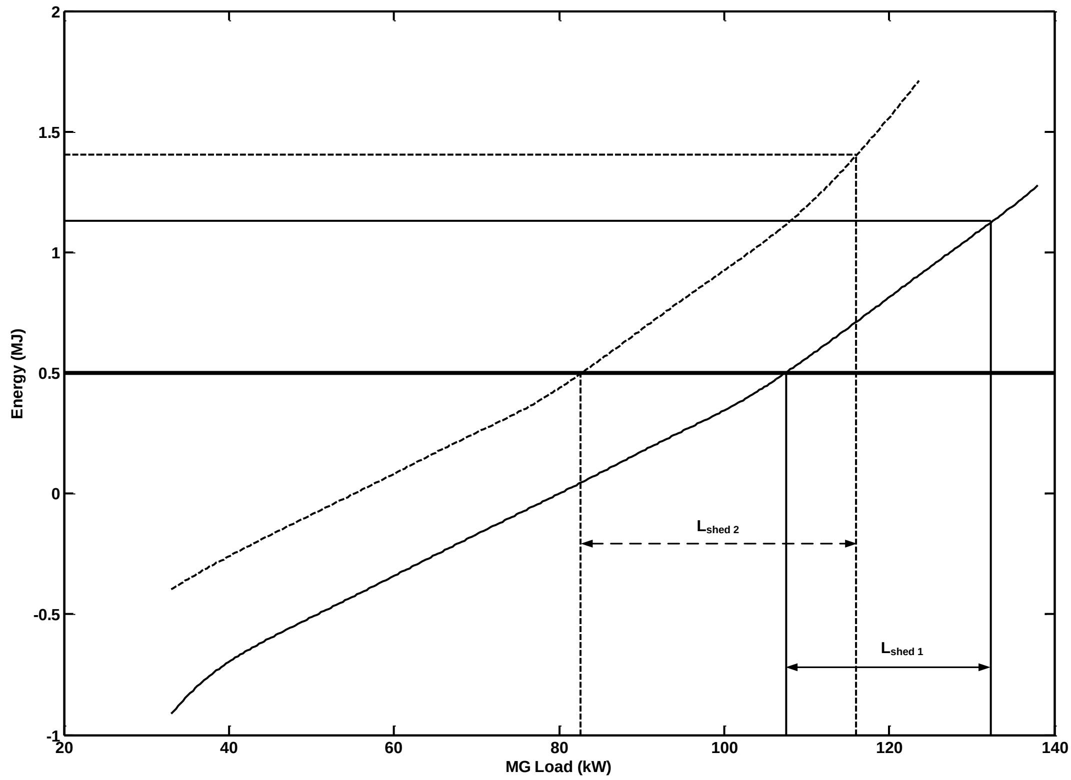


Figure 6-8: Amount of load to be shed in scenario 1 (solid line) and scenario 2 (dash line)

The approach developed in this research regards therefore the definition of strategies to assure MG survival at least in a short time interval after an unplanned islanding. However it may happen that the total controllable MS generation capacity is not enough to supply the entire MG load. As it was previously referred, the first set of actions to be envisaged in this case is the determination of minimum load to be curtailed, which corresponds to the difference between the actual MG load and the MG maximum generation capability. After considering this amount of load curtailment, the new MG operating conditions (power generation and new MG load) can be used as inputs in the ANN tool to evaluate if the MG can successfully move to islanding operation (note that all this steps are run on-line, but prior to MG islanding). However, this new situation may continue to have energy balance problems. In this case, a new step of load curtailment can be suggested by the robustness evaluation tool.

Table 6-3: Load shedding set-points in several scenarios

	Case		
	1	2	3
SSMT 1 + SSMT 2 Active Power (kW)	20.7	11.0	10.4
SSMT 3 Active Power (kW)	13.6	15.2	-----
SOFC Active Power (kW)	23.5	23.2	13.9
PV 1 + PV 2 Active Power (kW)	13.2	-----	1.5
Micro Wind Generator Active Power (kW)	6.9	5.0	11.9
MG Total Load (kW)	132.3	116.0	87.0
Energy Injected by the Storage Devices (MJ)	1.14	1.40	1.15
Load Curtailment Following Islanding (kW)	24.9	33.3	25.7

As an illustrative example, Figure 6-9 and Figure 6-10 show the dynamic behaviour of the MG in Case 1 and Case 2 before and after the application of the load shedding strategy (MG islanding taking place at t = 20 s). The obtained results demonstrate the effectiveness of the load shedding strategy in order to limit the energy required to be injected by MG storage devices.

Regarding the scenarios where the MG exports power to the MV network, it was considered that the capacity of MG storage devices to absorb the energy surplus is 0.8 MJ. The results of the application of the proposed preventive control strategy to several cases are shown in Table 6-4. After calculating the total amount of renewable power to be reduced, the effective power reduction in each generator could be calculated proportionally to the actual power production. However, other rules can be adopted. As an illustrative example, Figure 6-11 shows the dynamic behaviour of the MG in Case 1 (Table 6-4) before and after the application of the generation curtailment strategy (MG islanding taking place at t = 20 s).

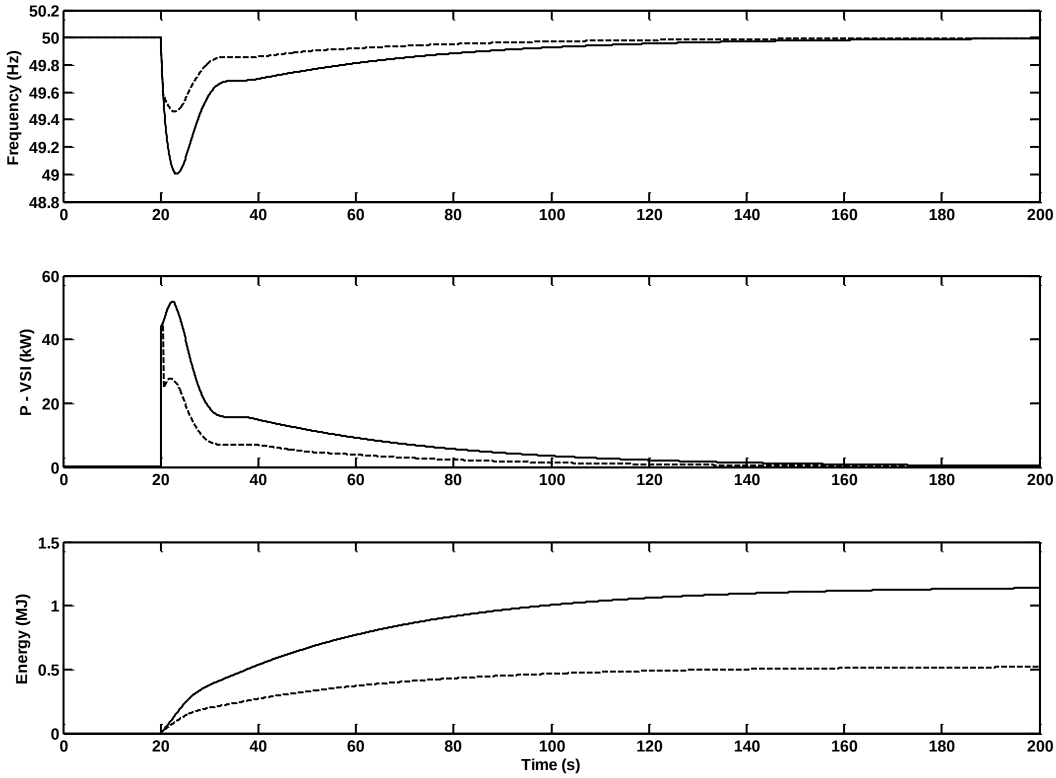


Figure 6-9: MG dynamic behaviour in Case 1 before applying the load shedding mechanisms (solid line) and when the intelligent load shedding scheme is used (dash line)

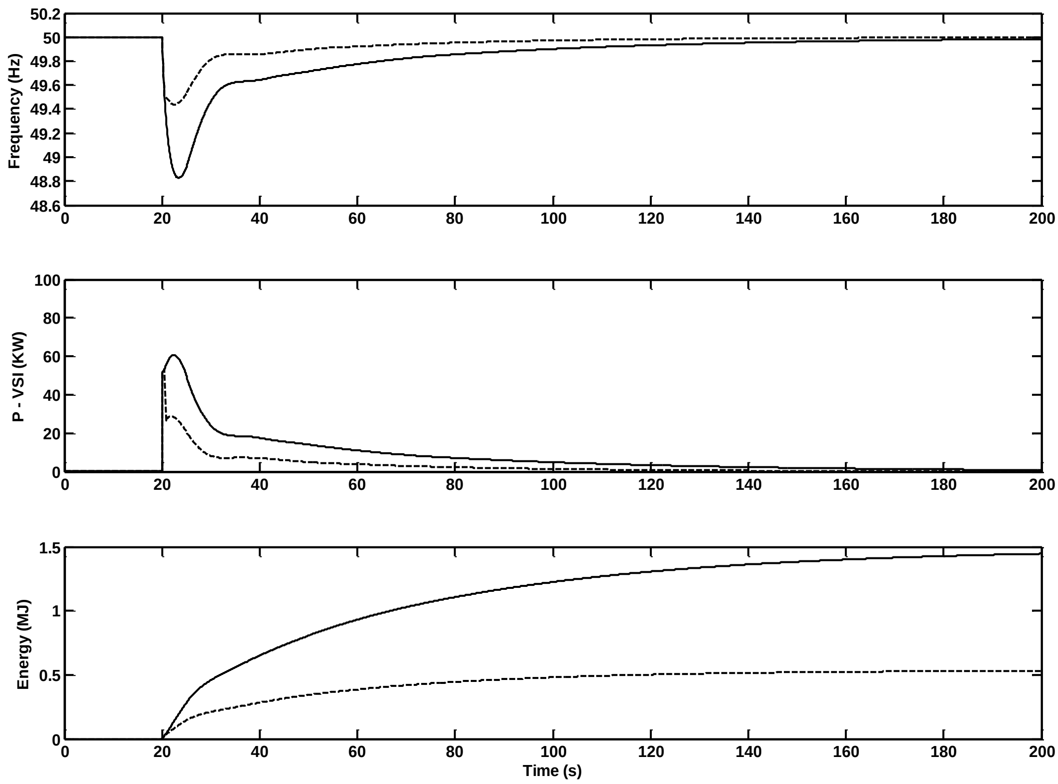


Figure 6-10: MG dynamic behaviour in Case 2 before applying the load shedding mechanisms (solid line) and when the intelligent load shedding scheme is used (dash line)

Table 6-4: Generation curtailment in several scenarios

	Case		
	1	2	3
SSMT 1 + SSMT 2 Active Power (kW)	46.6	39.6	27.3
SSMT 3 Active Power (kW)	24.6	17.9	19.1
SOFC Active Power (kW)	16.9	18.4	13.4
PV 1 + PV 2 Active Power (kW)	11.0	19.3	18.4
Micro Wind Generator Active Power (kW)	13.2	10.8	3.0
MG Total Load (kW)	63.6	53.0	50.4
Energy Injected by the Storage Devices (MJ)	-1.09	-1.14	-0.99
Generation Curtailment Following Islanding (kW)	11.4	13.4	5.2

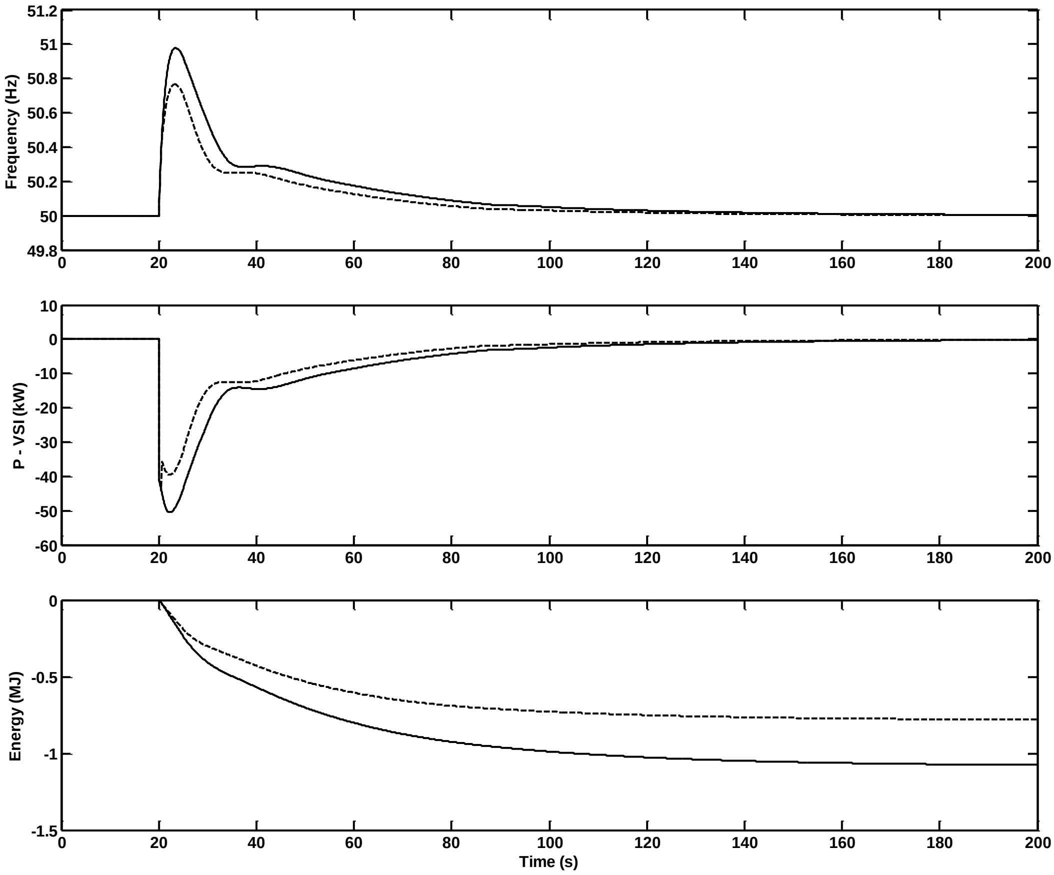


Figure 6-11: MG dynamic behaviour in Case 1 before applying generation curtailment (solid line) and when the intelligent generation curtailment scheme is used (dash line)

If the MG robustness evaluation tool running in the MG detects an operating condition that, following islanding, will led the system to collapse, the preventive control strategy determines the amount of load to be disconnected and defines the suitable load shedding set-points for each LC. It can also determine the generation curtailment in PV and micro-wind generators. Each LC or MC will be sensitive to the frequency deviation in order to detect MG islanding and to activate the pre-defined action assigned to them. Therefore, the definition of the frequency deviation at with the preventive control actions should take place can be based on the droop equation and on the MG power imbalance in the moments subsequent to islanding, as defined by Equation (6-7).

6.5 SUMMARY AND MAIN CONCLUSIONS

This chapter concerns the development of an on-line MG robustness evaluation tool and the derivation of preventive control measures in order to allow successful MG islanding. The use of such tools is of paramount importance for the on-line MG operation and management, aiming the seamless transition to islanding operation after the occurrence of contingencies in the main power system. From the results obtained in a LV test MG it is possible to conclude that the derived approach provided effective results. In fact, the reduced test errors obtained with the ANN and the illustrative cases evaluated through dynamic simulations demonstrate the quality and the feasibility of the proposed robustness assessment tool when dealing with this problem. This approach allows coping with a wide range of operating scenarios.

The tool used to predict the energy required to be injected by the MG storage devices following MG islanding can be further exploited in an optimization process in order to define the sizing of MG storage devices, by taking into account the cost of unsupplied loads and credible operating scenarios.

Chapter 7

CONCLUSIONS

7.1 MAIN CONTRIBUTIONS OF THE THESIS

Following the increasing penetration of Distributed Generation (DG) in Medium Voltage (MV) networks, the dissemination of different microgeneration technologies such as microturbines, fuel cells, Photovoltaic (PV) panels and micro wind generators, is expected to become one possible approach to face the continuous electricity demand growth. The current practice for the connection of any type of DG units to the distribution networks is based on the "fit and forget" policy. However, the massive integration of DG units under this approach may cause more problems than those it may solve. Therefore, it is imperative to define new DG integration strategies, through which a system perspective is used in order to exploit the potential benefits DG may provide. The MicroGrid (MG) concept presented in this dissertation consists on the aggregation of loads and MicroSources (MS) operating in a single system with appropriate management and control functionalities and providing both power and heat to local consumers, aims to be a solution for the referred MS integration strategy. In fact, the MG concept leads to the development of an active cell of the distribution network, which has the ability of autonomous operation. Exploiting such an active cell of the distribution network – the MicroGrid – as an entity that is able to be operated autonomously or interconnected with the upstream MV network provides high flexibility and can contribute with important benefits to the distribution network operator and to the end-user.

The traditional approach for DG integration concerns the impact resulting from the connection of a small number of DG to the grid as stated in the IEEE P1547 standard [79]. The focus of this standard is to assure DG is quickly disconnected following the event of grid disturbances. On the contrary, the MG is regarded as an aggregation of loads and MS within an active cell that can be operated connected to or separate from the main electricity grid.

Such operation mode that can be exploited in a MG is a radical change in the current practice followed by distribution network operators, which do not allow islanded operation of parts or sections of the distribution network.

Successful design and operation of a MG capable of islanding operation requires solving a number of demanding issues, in particular related to on-line management functionalities and system control. The presence of power electronic interfaces in fuel cells, PV, microturbines or storage devices is one of the main characteristics of a MG that requires the development of specific control approaches. During MG islanded operation, load-tracking problems arise since microturbines and fuel cells have slow response to control signals and are inertia-less. Therefore, a system with clusters of MS designed to operate in islanded mode requires some form of energy buffering to ensure initial energy balance. Concerning these general MG operation and control issues, the main contributions of this dissertation dealt with the development of specific emergency control functionalities, namely:

- **Primary frequency control mechanisms**, which are associated to grid forming units, that is, storage devices coupled to the Low Voltage (LV) grid through Voltage Source Inverters (VSI). This primary frequency control mechanism mimics the primary frequency control on conventional power systems and is responsible to ensure system synchronism during any islanding operating conditions. This control scheme was developed and successfully tested in this research.

- **Secondary frequency control schemes**, which are to be implemented in grid supporting units (controllable MS like fuel cells and microturbines). The secondary frequency control mechanisms are similar to those implemented in conventional power systems and are intended to restore frequency to the nominal value following a disturbance during islanding operation. Such an approach was developed and tested in this work.

- **Load and generation curtailment mechanisms:** in addition to MG frequency deviation following islanding, a key issue that needs to be considered is the ability of MS and storage devices to provide the dynamic response to keep the system in synchronism, especially in terms of available storage capacity. Therefore, it is necessary to quickly evaluate MG behaviour following islanding in order to efficiently manage load or generation curtailment and storage devices. For each disturbance to be considered, the traditional and most accurate analysis involves the numerical solution of a system of non-linear equations, which is a very demanding and time consuming computational task ant it is not suitable for on-line purposes. Artificial intelligence based tools, such as Artificial Neural Networks (ANN), are alternative approaches since they provide effective means, with fast time responses, of extracting high level knowledge from large data sets in order to help on-line system management regarding these dynamic issues. An ANN was developed and successfully tested in this research.

Concerning voltage control, although it was not the main topic of this dissertation, some important remarks can be refereed. In LV distribution systems, active power flow is linked to the voltage magnitude, while reactive power flow is linked to the phase difference between the voltage sources. Consequently, reactive power injection cannot be used for voltage control purposes. The proposed voltage control approach, which demonstrated to ensure MG stability during islanding operation, is to regulate voltage in the VSI connection point, while the PQ controlled inverters operate under a reactive power support strategy. Regarding voltage control through VSI, the application of reactive power/voltage droops may cause reactive current exchanges among VSI, which depend on the active power dispatch assigned to the inverters and on the VSI idle voltage. From these facts, one concludes that it is important to derive supervisory voltage control functionalities in a MG with multiple VSI (multi master operation scheme).

If a system disturbance provokes a general blackout at the upstream network, such that the MG is not able to automatically separate and continue in islanding operation mode, and if the MV system is unable to restore operation in a specified time, **it was demonstrated that local MS can provide Black Start functionalities at the LV level**. Moreover, the MicroGrid Central Controller (MGCC) can support re-connection during Black Start (BS), helping in this way the upstream Distribution Management System (DMS) system that is managing the MV distribution network. Based on the MG control strategies identified in this research and making use of the MG communication infrastructures that are assumed to be in the field, rules and conditions for MG service restoration were identified in order to totally automate the restoration procedure. The MG black start functionalities can be centrally guided by a specific software module to be housed in the MGCC. Under this philosophy, the BS software module is responsible for controlling a set of rules and conditions to be checked during the restoration stage, which were identified and carefully evaluated within this dissertation. These rules and conditions define a sequence of control actions to be carried out during the restoration procedure. The main steps to be considered include building the LV network, connecting MS, controlling voltage and frequency, connecting controllable loads and MG synchronization with the upstream MV network, when it becomes available.

The identification and development of local BS strategies that were tackled within this dissertation requires a deep reorganization in the overall electric power system restoration plans. The entire power system restoration procedure can then exploit a simultaneous bidirectional approach: a conventional top-down strategy, starting from large plant restart and transmission energization, and simultaneously a bottom-up strategy, starting from the distribution side and exploiting DG units and microgeneration capabilities. Synchronization among these areas follows afterwards. This approach helps to reduce restoration times and to reduce the unnerved electric energy during major failures.

The work developed within this dissertation brought relevant contributions on the evaluation of the feasibility of the control strategies needed for MG islanded operation, where no directly grid-connected synchronous generators are used. A set of new control procedures and strategies for the on-line MG operation and management were developed, aiming the seamless transition to islanding operation after the occurrence of contingencies in the main power system. The control strategies to be adopted for MG black start and subsequent islanded operation, as well as the identification of the set of rules and operational conditions related with these strategies, were derived after the understanding MG specific control issues, being its effectiveness evaluated through numerical simulations.

7.2 SUGGESTIONS FOR FUTURE WORK

As already mentioned, the work presented in this dissertation provides an insight on MG operational and control issues. This topic is quit vast and additional research is required in order to approximate theoretical research and systems deployment in the field. Therefore, further developments could consist on:

- MG analysis under unbalanced operation conditions: LV distribution systems are three-phase four-wire unbalanced systems. Additionally, small scale MS like PV or micro wind generators with power ratings of a few kW will be single-phase units, which can contribute to worst unbalance conditions. Therefore, it is necessary to evaluate the effectiveness of the proposed control strategies for unbalanced MG systems during islanding and BS and to evaluate the need of additional voltage balancing control functions during islanding operation.

- Following the development of MG service restoration strategies, it is necessary to evaluate how a massive deployment of MG and other DG units can contribute to improve the conventional restoration strategies at the MV level and what type of modifications are required to be introduced in the global conventional restoration plans.

- At the MV distribution networks level, the coordination of several MG and Distributed Energy Resources (DER) need to be investigated, together with modifications required to be included in the DMS in order to implement the Virtual Power Plants concept in a *SmartGrid* environment. The main objective is to allow DER to take the responsibility for delivery some services to the network operators, in deep co-operation with central generation.

- Extensive laboratorial tests are required to be performed in order to validate the models of several microgeneration technologies and the corresponding power electronic interfaces. Additionally, it is necessary to perform a thorough analysis in terms of the practical implementation of the MG controllers, together with the functionalities that are assigned to them, in order to demonstrate in depth the feasibility of MG islanding operation.

- Development of field tests in order to evaluate the technical functionalities of the MG control strategies and corresponding components for different generation and load profiles, to monitor electric parameters (load, generation, power quality indexes), to monitor the performance of Combined Heat and Power (CHP) applications, to test the performance of the communication systems and to evaluated real investment costs in a MG system.

- The MG operational and management architecture can be exploited further for the development of the Vehicle to Grid (V2G) concept, due to the distributed nature of the plug-in vehicles. V2G provide dispersed storage that can be exploited for the operation of the MG during islanding operation, to provide reserve capacity to be exploited through a wide area control communicating with the MGCC or other control functionalities such as congestion management or peak shaving.

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Appendix A

TEST SYSTEM SIMULATION PARAMETERS

In this appendix are presented the electrical parameters of the MicroGrid (MG) test system used in this dissertation (Figure A–1). Additionally, the parameters of the dynamic models of the different types of microgeneration units and the corresponding power electronic interfaces that were described in Chapter 3 are also presented.

Table A–1: Electrical parameters of the LV MicroGrid test system

Line	Bus i	Bus j	R (Ω)	X (Ω)
1	1	2	0.0528	0.0142
2	1	3	0.0341	0.0103
3	1	11	0.0123	0.0021
4	3	4	0.0199	0.0058
5	3	7	0.0660	0.0128
6	4	5	0.0261	0.0025
7	4	9	0.0687	0.0149
8	5	6	0.0414	0.0026
9	7	8	0.0870	0.0084
10	9	10	0.0414	0.0026

Table A–2: Maximum simultaneous loads in the MG test system

Bus Number	Load (kVA)
2	67.2+j19.6
5	19.6+j4.0
7	48.8+j11.1
9	29.3+j6.7

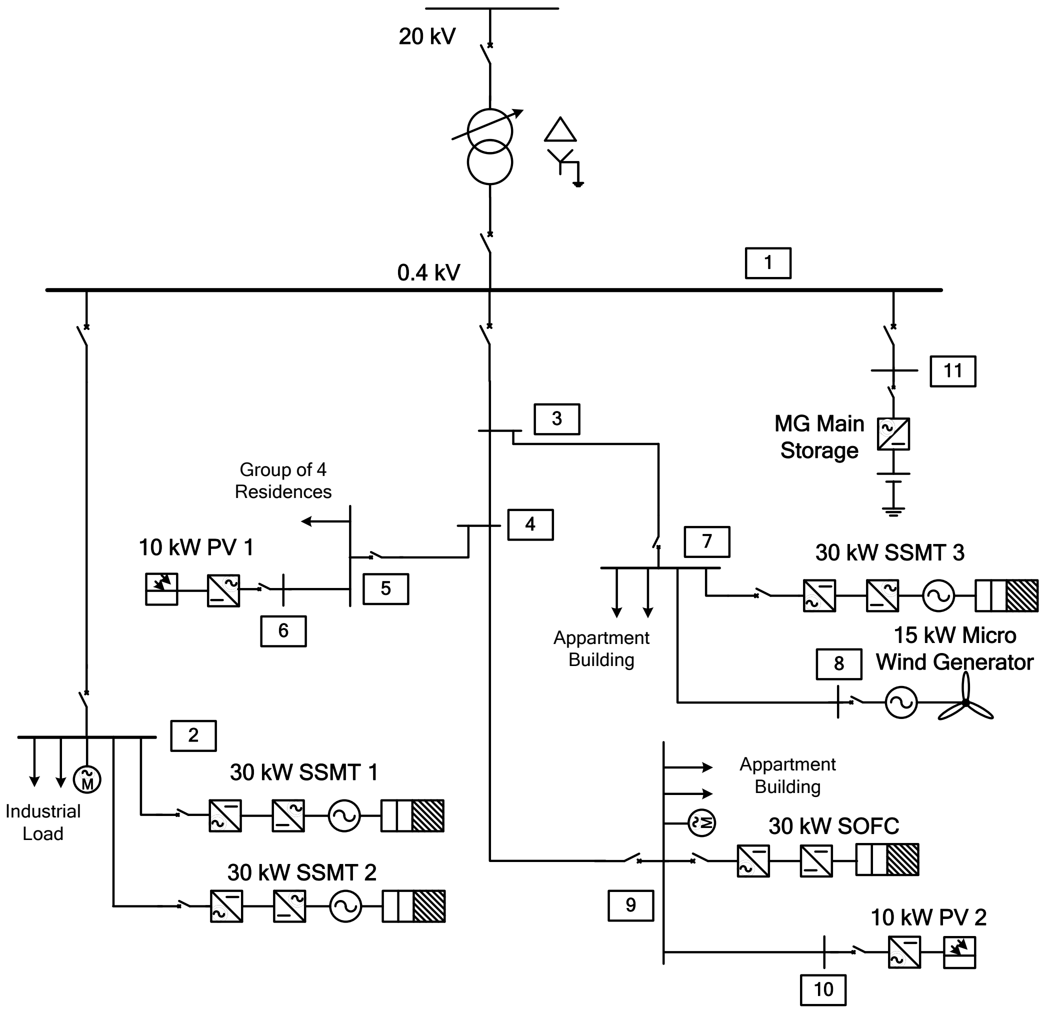

Figure A–1: MicroGrid test system

Table A–3: Motor load parameters

Parameter	Motor 1 (Bus 2)	Motor 2 (Bus 2)	Motor 3 (Bus 9)	Unit
Nominal Power	10	7.5	7.5	*kW*
Nominal Voltage	400	400	400	*V*
Nominal Frequency	50	50	50	*Hz*
Stator Resistance	0.55	0.7384	0.7384	Ω
Stator Inductance	2.324	3.045	3.045	*mH*
Rotor Resistance	0.38	0.74	0.74	Ω
Rotor Inductance	3.0558	3.045	3.045	*mH*
Magnetizing Inductance	83.0789	124.1	124.1	*mH*
Inertia	0.15	0.08	0.08	$Kg.m^2$
Friction Factor	0.0085	0.000503	0.000503	*N.m.s*
Number of Pole Pairs	2	2	2	-

Table A–4: Voltage Source Inverter (VSI) parameters

Parameter	Designation	Value	Unit
P_n	Nominal power	50	*kW*
V_n	Nominal voltage	400	*V*
f_0	Idle frequency	50	*Hz*
V_0	Idle voltage	1.06	*p.u.*
T_{dP}	Active power decoupling delay	0.6	*s*
T_{dQ}	Reactive power decoupling delay	0.6	*s*
k_P	Active power droop	-1.2566×10^{-4}	$rad.s^{-1}.W^{-1}$
k_Q	Reactive power droop	-3.0×10^{-6}	$V(p.u.).\ var^{-1}$
k_{ff}	Phase feed-forward gain	-5.0×10^{-6}	$rad.W^{-1}$
$\underline{Z}_f$	Coupling filter impedance	0.005+j0.16	Ω
$I_{\max}^{cc}$	Maximum short-circuit-current (rms)	355	*A*

Table A–5: Parameters of the Solid Oxide Fuel Cell (SOFC)

Parameter		Value	Unit
	Electrical Ratings		
P_n	Nominal power	30	*kW*
V_{int}	Fuel cell system desired voltage	333.8	*V*
	Fuel Cell system		
r_{H_O}	Ratio of hydrogen to oxygen	1.145	-
τ_{H_2}	Hydrogen flow time constant	26.1	*s*
τ_{O_2}	Oxygen flow time constant	2.91	*s*
τ_{H_2O}	Water vapour flow time constant	78.3	*s*
$U_{\max}$	Maximum fuel utilization	0.9	-
$U_{\min}$	Minimum fuel utilization	0.8	-
U_{opt}	Optimal fuel utilization	0.85	-
T_e	Electrical response time constant	0.8	*s*
T_f	Fuel reformer time constant	5.0	*s*
r	Internal resistance	0.126	*Ω*
N_0	Number of cells in the stack	384	-
T	Absolute cell temperature	1273	*ºK*
	Secondary load frequency control		
k_P	Proportional gain	12.5	-
k_I	Integral gain	1.5	-

Table A–6: Parameters of Single Shaft Microturbines (SSMT 1, SSMT 2 and SSMT 3)

Parameter		Value	Unit
	Electrical Ratings		
P_n	Nominal power	30	*kW*
P_n	Nominal voltage	400	*V*
	Active power control		
K_p	Proportional gain	3	-
K_i	Integral gain	0.23	-
	Microturbine engine		
T_1	Fuel system time constant 1	15	*s*
T_2	Fuel system time constant 2	0.2	*s*
T_3	Load limit time constant	3	*s*
$L_{\max}$	Load limit	1.5	*s*
$V_{\max}$	Maximum fuel value position	1.2	-
$V_{\min}$	Minimum fuel value position	-0.1	-
k_t	Temperature control loop gain	1	-
	Permanent magnet synchronous machine		
L_d	d-axis inductance	0.6875	*mH*
L_q	q-axis inductance	0.6875	*mH*
R_s	Resistance of the stator windings	0.25	*Ω*
Φ_m	Flux induced by the permanent magnets in the stator windings	0.0534	*Wb*
p	Number of poles pairs	1	-
J	Combined rotor and load inertia	0.003	*Kg.m*^{2}
	Machine side converter control		
k_{P1}	Proportional gain of PI-1	30	-
k_{I1}	Integral gain of PI-1	10	-
k_{P2}	Proportional gain of PI-2	100	-
k_{I2}	Integral gain of PI-2	150	-
k_{P3}	Proportional gain of PI-3	50	-
k_{I3}	Integral gain of PI-3	20	-
	Secondary load frequency control		
k_P	Proportional gain	20	-
k_I	Integral gain	1.1	-

Table A–7: SSMT "ω versus P" curve

SSMT output power (kW)	SSMT rotation speed (krpm)
7	66.9
14	78.0
21	87.0
28	90.4

Table A–8: Parameters of PQ controlled inverters used in SSMT and SOFC

Parameter	Designation	Value	Unit
S_n	Nominal power	40	*kVA*
V_n	Nominal voltage	400	*V*
$\underline{Z}_f$	Coupling filter impedance	0,005+j0,15	*Ω*
C	DC-link capacitor	0,001	*F*
$V_{dc,ref}$	Voltage reference of DC link	800	*V*
k_{P1}	Proportional gain of PI-1	-5	-
k_{I1}	Integral gain of PI-1	-3	-
k_{P2}	Proportional gain of PI-2	0	-
k_{I2}	Integral gain of PI-2	100	-
$I_{\max}^{cc}$	Maximum short-circuit current (rms)	70	*A*

Table A–9: Parameters of PV systems

Parameter	Designation	Value	Unit
G_a	Ambient irradiance	870	$W.m^{-2}$
T_a	Ambient temperature	20	*ºC*
$P_{Max,0}$	Module maximum power at Standard Test Conditions	25	*W*
$\mu_{P_{Max}}$	Maximum power variation with module temperature	-0.005	*W/ºC-*
$NOCT$	Normal cell operation temperature	47	*ºC*
N	Number of modules in the PV system	400	-

Table A–10: Parameters of PQ controlled inverters used in the PV systems

Parameter	Designation	Value	Unit
S_n	Nominal power	10	*kVA*
V_n	Nominal voltage	400	*V*
$\underline{Z}_f$	Coupling filter impedance	0,01+j0,22	*Ω*
C	DC-link capacitor	0,0005	*F*
$V_{dc,ref}$	Voltage reference of DC link	800	*V*
k_{P1}	Proportional gain of PI-1	-5	-
k_{I1}	Integral gain of PI-1	-3	-
k_{P2}	Proportional gain of PI-2	0	-
k_{I2}	Integral gain of PI-2	100	-
$I_{\max}^{cc}$	Maximum short-circuit current (rms)	20	*A*

Table A–11: Micro wind generator

Parameter	Value	Unit
Nominal Power	15	*kW*
Nominal Voltage	400	*V*
Nominal Frequency	50	*Hz*
Stator Resistance	0.2147	Ω
Stator Inductance	0.991	*mH*
Rotor Resistance	0.2205	Ω
Rotor Inductance	0.991	*mH*
Magnetizing Inductance	64.19	*mH*
Inertia	0.75	$Kg.m^2$
Friction Factor	0.0095	*N.m.s*
Number of Pole Pairs	2	-
Capacitor bank	8.5	*kvar*

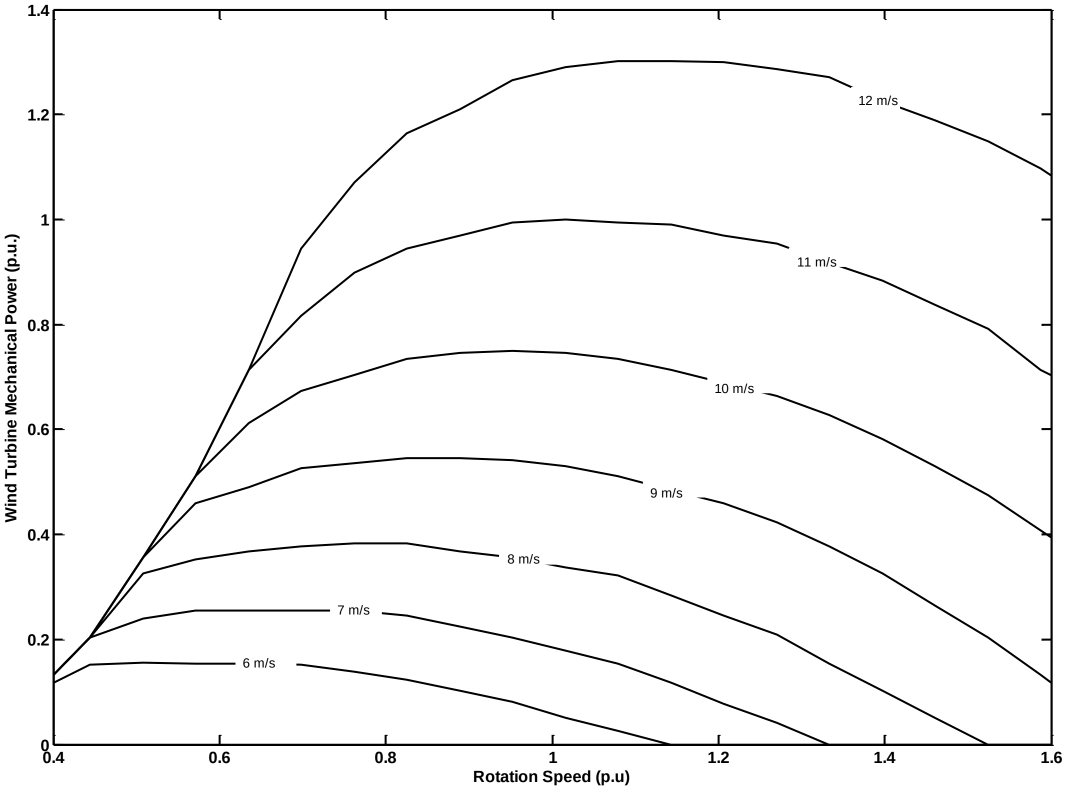

Figure A–2: Micro wind turbine power curves

Table A–12: SSMT 2 Voltage Source Inverter parameters for the multi master operating conditions

Parameter	Designation	Value	Unit
P_n	Nominal power	30	*kW*
V_n	Nominal voltage	400	*V*
f_0	Idle frequency	Depends on the SSMT active power dispatch	*Hz*
V_0	Idle voltage	Depends on the SSMT active power dispatch	*p.u.*
T_{dP}	Active power decoupling delay	0.5	*s*
T_{dQ}	Reactive power decoupling delay	0.5	*s*
k_P	Active power droop	-2.0944×10^{-4}	$rad.s^{-1}.W^{-1}$
k_Q	Reactive power droop	-5.0×10^{-6}	$V(p.u.).\ var^{-1}$
k_{ff}	Phase feed-forward gain	-3.33×10^{-6}	$rad.W^{-1}$
$\underline{Z}_f$	Coupling filter impedance	0.008+j0.25	Ω
$I_{\max}^{cc}$	Maximum short-circuit current (rms)	215	*A*

Concerning the test system for the analysis of the MG service restoration procedure (test system of Figure A–3), the next tables present the VSI parameters used in the simulation platform. The VSI idle voltage and angular frequency are adjusted during the simulation for voltage and control purposes (the exception is the MG mains storage device, whose VSI idle frequency is 50 Hz). Therefore, these values are not presented in the following tables. The parameters for PQ controlled inverters and for induction motor loads are those previously presented.

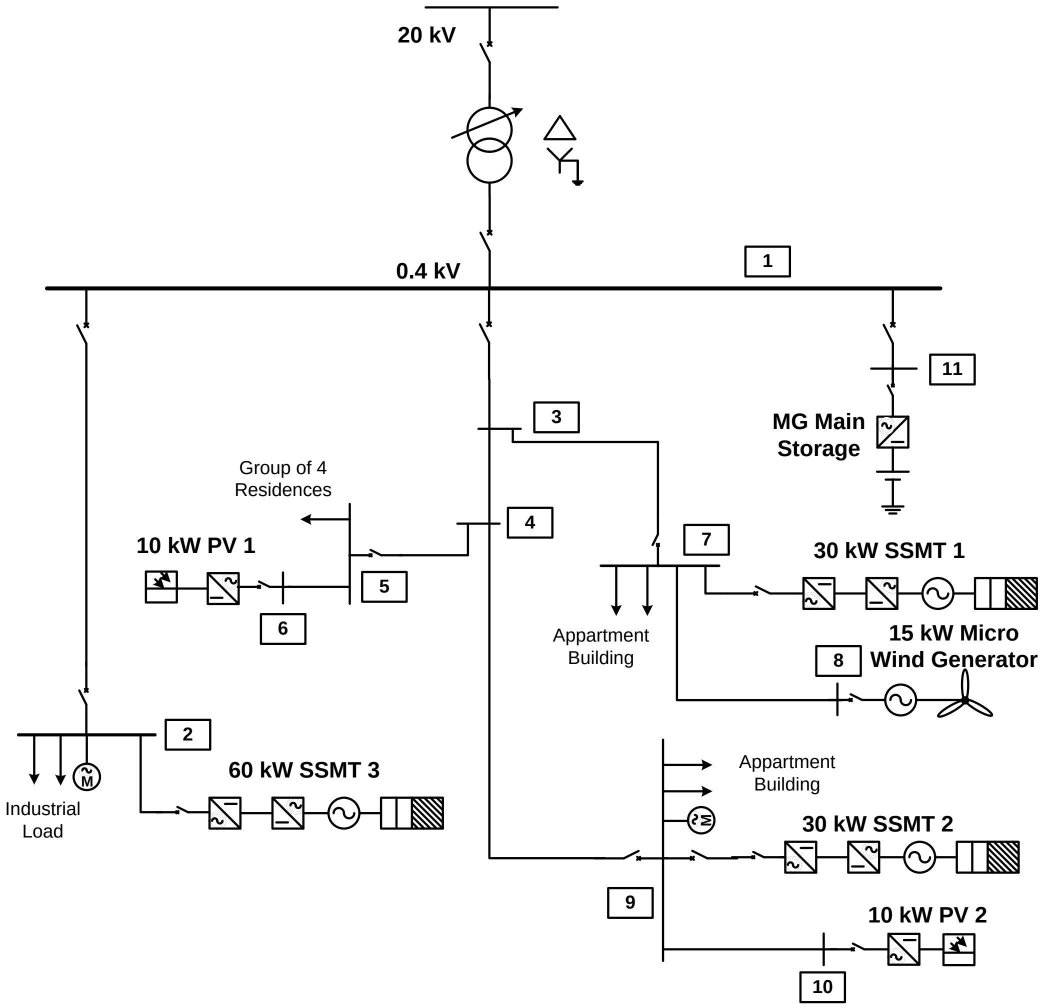

Figure A–3: LV test system for MG service restoration

Table A–13: VSI parameters of the different MS – part I

Parameter	Designation	MG main storage	SSMT 1	Unit
P_n	Nominal power	30	30	*kW*
V_n	Nominal voltage	400	400	*V*
T_{dP}	Active power decoupling delay	0.8	0.5	*s*
T_{dQ}	Reactive power decoupling delay	0.8	0.5	*s*
k_P	Active power droop	-2.0944×10^{-4}	-4.1888×10^{-4}	$rad.s^{-1}.W^{-1}$
k_Q	Reactive power droop	-2.0×10^{-6}	-4.0×10^{-6}	$V(p.u.).\ var^{-1}$
k_{ff}	Phase feed-forward gain	-3.5×10^{-5}	-1.5×10^{-5}	$rad.W^{-1}$
$\underline{Z}_f$	Coupling filter impedance	0.005+j0.16	0.005+j0.19	Ω

Table A–14: VSI parameters of the different MS – part II

Parameter	Designation	SSMT 2	SSMT 3	Unit
P_n	Nominal power	30	60	*kW*
V_n	Nominal voltage	400	400	*V*
T_{dP}	Active power decoupling delay	0.5	1.0	*s*
T_{dQ}	Reactive power decoupling delay	0.5	1.0	*s*
k_P	Active power droop	-4.1888×10^{-4}	-2.0944×10^{-4}	$rad.s^{-1}.W^{-1}$
k_Q	Reactive power droop	-4.0×10^{-6}	-2.0×10^{-6}	$V(p.u.).\ var^{-1}$
k_{ff}	Phase feed-forward gain	-1.5×10^{-5}	-5.5×10^{-5}	$rad.W^{-1}$
$\underline{Z}_f$	Coupling filter impedance	0.005+j0.19	0.003+j0.1	Ω

Appendix B

DYNAMIC SIMULATION PLATFORM

This appendix aims to illustrate the MicroGrids dynamic simulation platform that was developed under the *MatLab®/Simulink®* environment, by exploiting *the SymPowerSystems* toolbox. In this simulation platform it is possible to analyse the dynamic behaviour of several MicroSources (MS) and storage devices (whose dynamic models were described is Chapter 3) connected to a LV network, together with the proposed control strategies for MG islanding operation (derived in Chapter 4).

The implementation of the LV test system of Figure 5-1 under the *MatLab®/Simulink®* environment is shown in Figure B–1. The simulation platform was developed in a modular way, where the control parameters and models can be easily included and modified using the "mask" functionalities provided by *MatLab®/Simulink®*. In order to illustrate this feature, Figure B–2 shows the connection of a Single Shaft Microturbine (SSMT), generally represented by a block whose details are shown next, to an external three-phase source. As can be observed, in addition to the electrical connections corresponding to the terminals A, B and C in the SSMT box, it is possible to have access to a set of internal variables of the SSMT, namely its active and reactive output power (P/Q), the voltage in the DC-link (Vdc), the rotation speed (wr), etc. This simple system was built in the *MatLab®/Simulink®* environment, using what is called the "mask" concept. The mask allows the aggregation of the model representing a specific system in a single block, therefore allowing building user-friendly models from the graphical point of view.

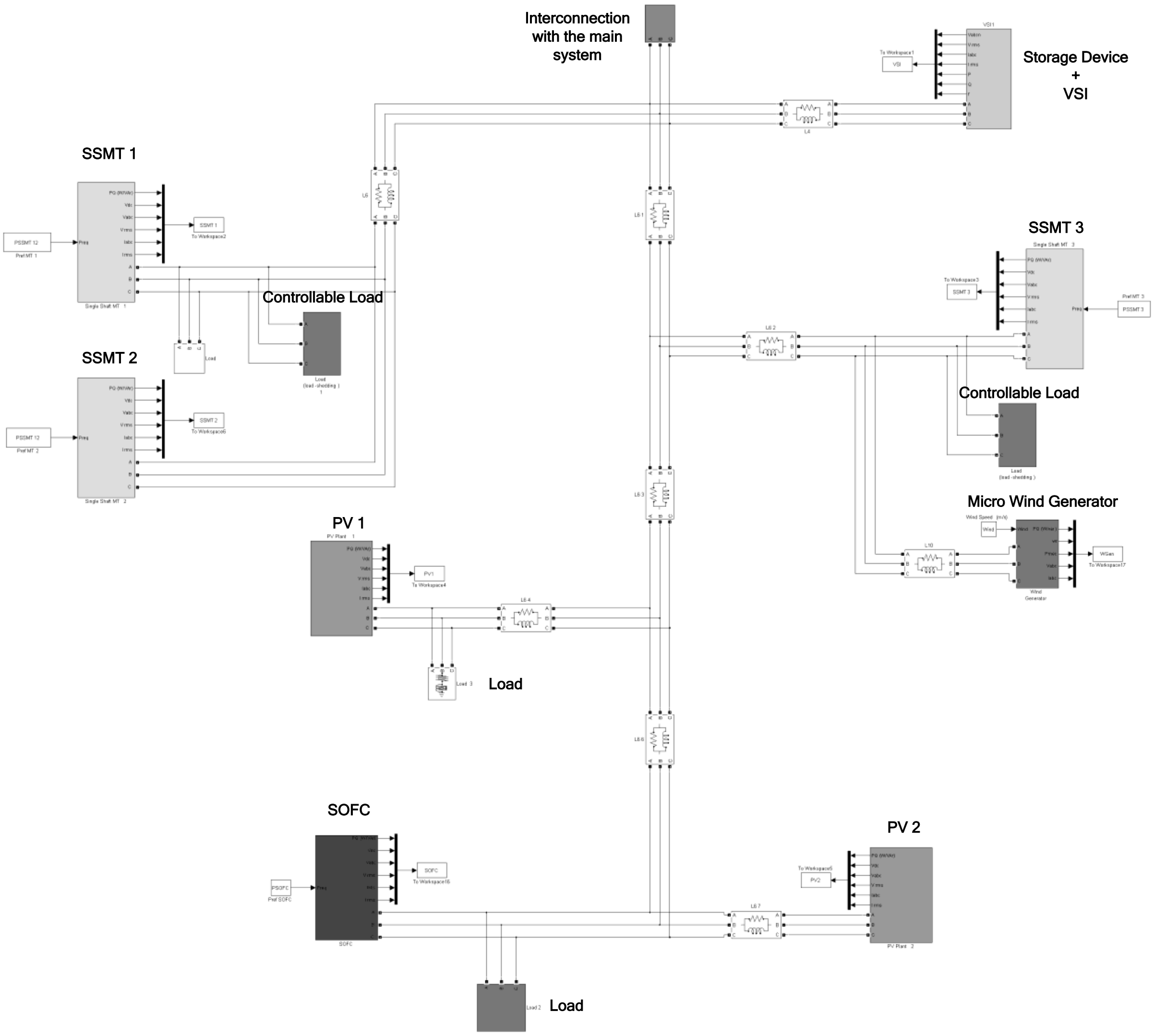

Figure B–1: ***MatLab®/Simulink®*** **simulation platform**

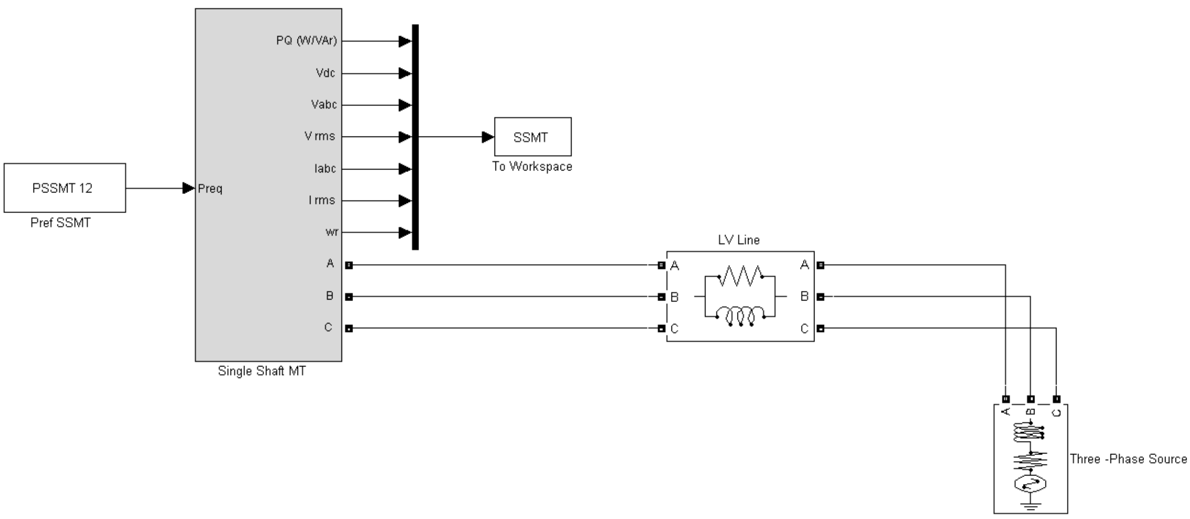

Figure B–2: SSMT connected to a three-phase source

In order to illustrate the *MatLab®/Simulink®* "mask" functionality, Figure B–3 shows the dialog box that is opened when the SSMT box of Figure B–2 is double clicked. As can be observed in Figure B–3, this dialog box allows the input of all the SSMT parameters, according to the model described in Chapter 3.

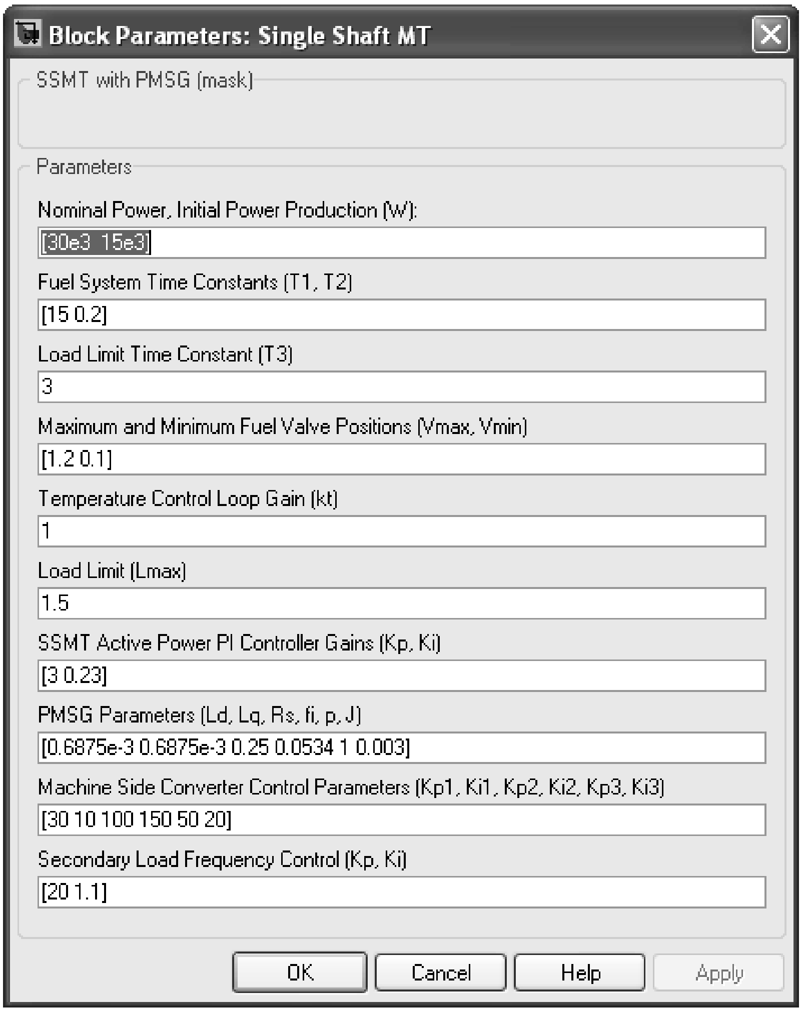

Figure B–3: Dialog box for the SSMT model

By looking under the mask of the SSMT block shown in Figure B–2, it is possible to see additional blocks which contain the detailed dynamic model of the SSMT, the model of the PQ controlled inverter and the secondary load frequency control described in Chapter 4 (Figure B–4). Continuing to explore the main blocks (masks), it is possible, for example, to observe the implementation of the SSMT model (SSMT mechanical part, the Permanent Magnet Synchronous Generator (PMSG) and the machine side converter), as it was described in Chapter 3 (Figure B–5).

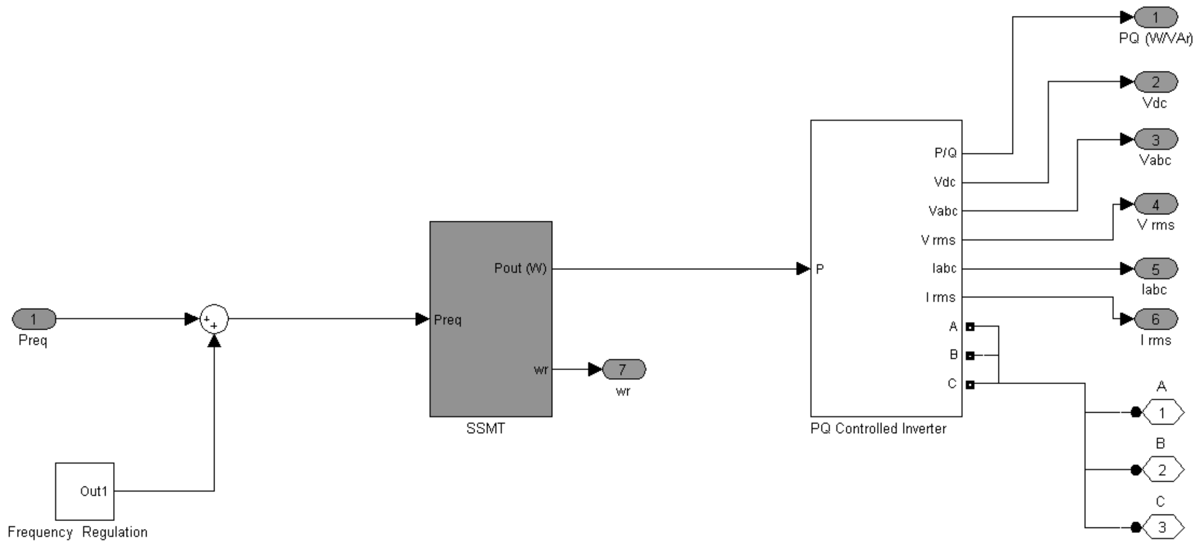

Figure B–4: A detail of the SSMT mask

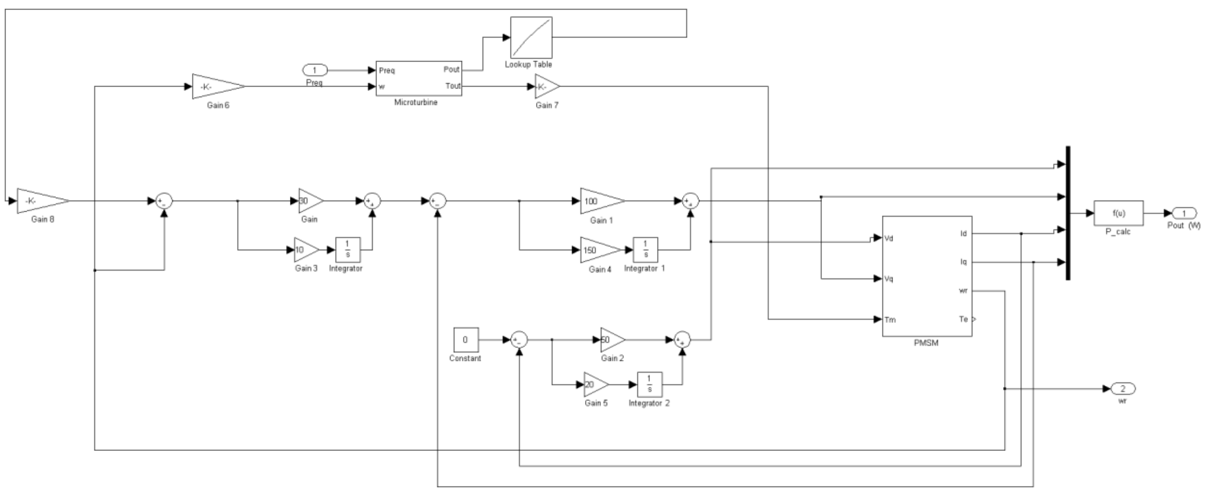

Figure B–5: SSMT model, including the SSMT mechanical part, the PMSG and the machine side converter

The main idea that is important to retain is the modularity of the simulation platform that was developed under the *MatLab®/Simulink®* environment. As can be observed from the figures presented above, the *MatLab®/Simulink®* environment allows the development of very user friendly models.

Concerning the Solid Oxide Fuel Cell (SOFC) model, it was also developed according to the same concepts previously described for the implementation of the SSMT model. In order to illustrate the *MatLab®/Simulink®* "mask" functionality for the SOFC model, Figure B–6 shows the dialog box that is opened when the SOFC block is double clicked. As can be observed in Figure B–6, this dialog box allows the input of all the SOFC parameters, according to the model described in Chapter 3. By looking under the mask of the SOFC block, it is possible to see additional blocks which contain the detailed model of the SOFC, the model of the PQ controlled inverter and the secondary load frequency control described in Chapter 4 (Figure B–7). Continuing to explore the main blocks (masks), it is possible, for example, to observe the implementation of the SOFC electrochemical model, as described in Chapter 3 (Figure B–8).

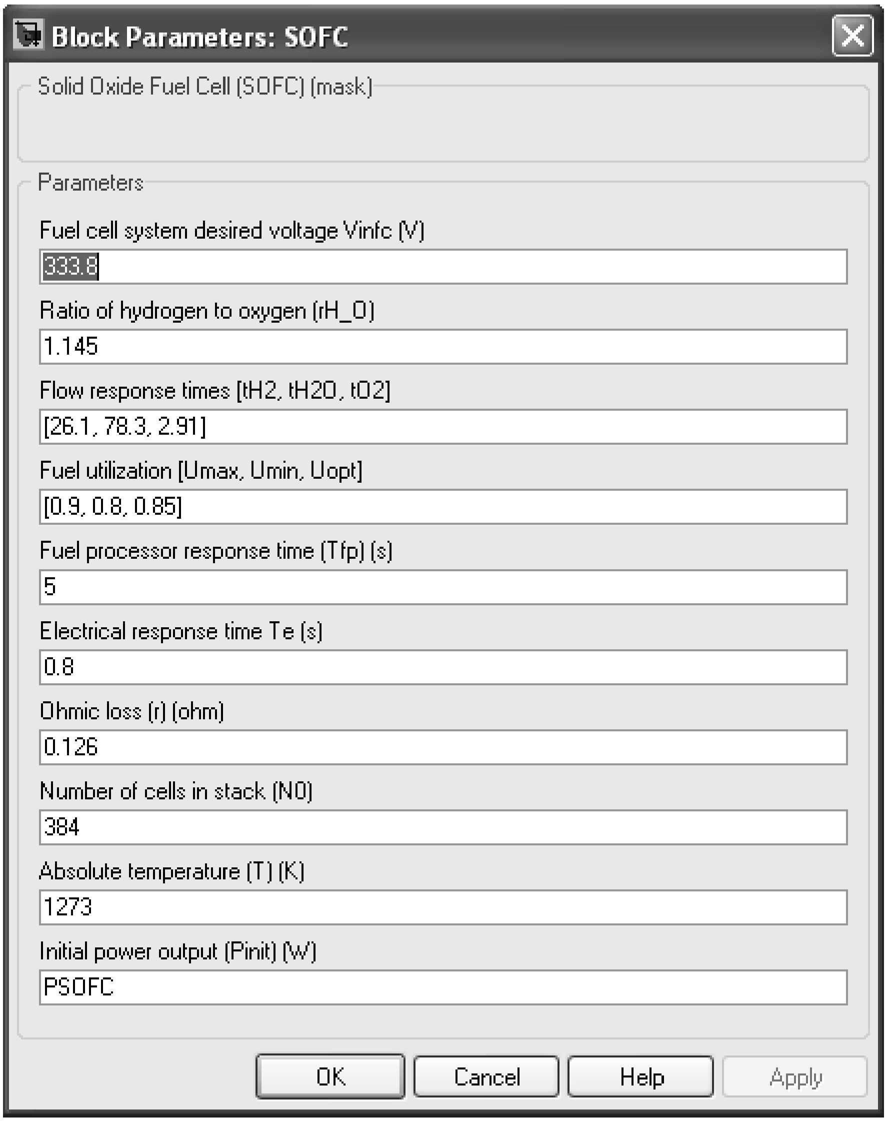

Figure B–6: Dialog box of the SOFC model

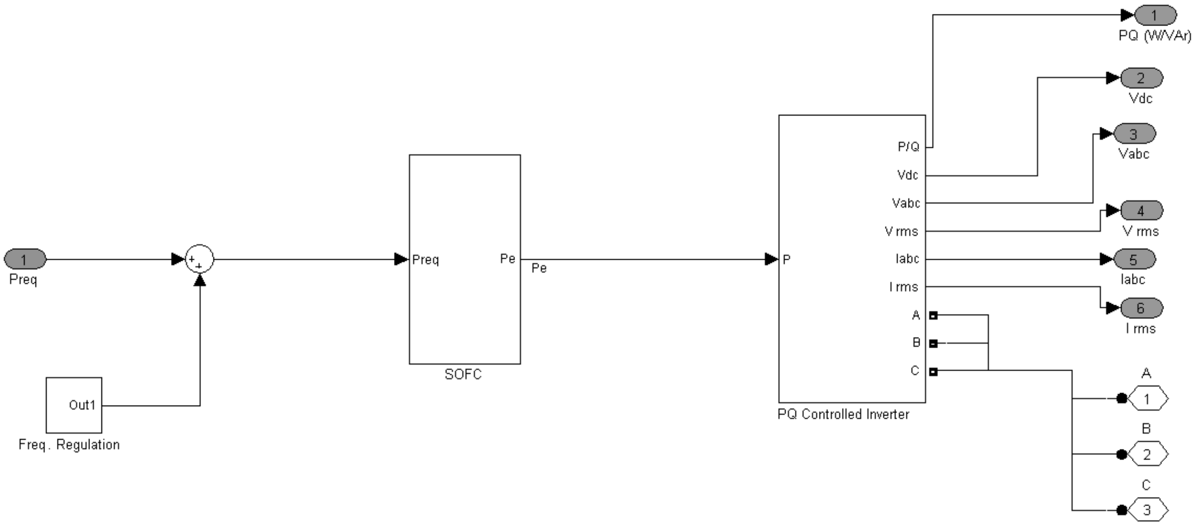

Figure B–7: A detail of the SOFC mask

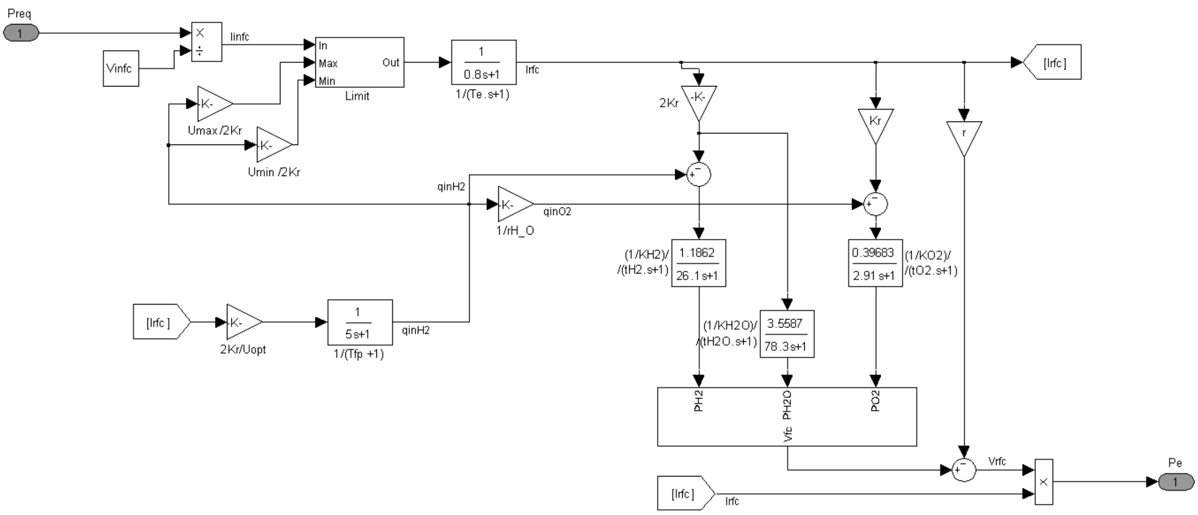

Figure B–8: SOFC model in the *MatLab®/Simulink®* environment

Another special issue that require a special attention during the development of the simulation platform concerns the implementation of load shedding mechanisms in controllable loads. Usually, the load shedding mechanism consists on the disconnection of a load controlled by an under frequency load shedding relay when the grid frequency (or its time derivative) is lower than a pre-defined value. In order to avoid the inadvertent tripping of under frequency load shedding relays, they are usually parameterized with a time delay (relay activation time), such that load curtailment occurs only if frequency deviation is sustained for a time interval higher then the relay activation time. Following the restoration of the grid frequency, the disconnected loads can be reconnected; however, it is important to notice that they should not be reconnected simultaneously in order to avoid large frequency deviations, which will lead to new load curtailments.

Having in mind these general considerations, the load shedding mechanism that was implemented can be parameterized according to the dialog box show in Figure B–9.

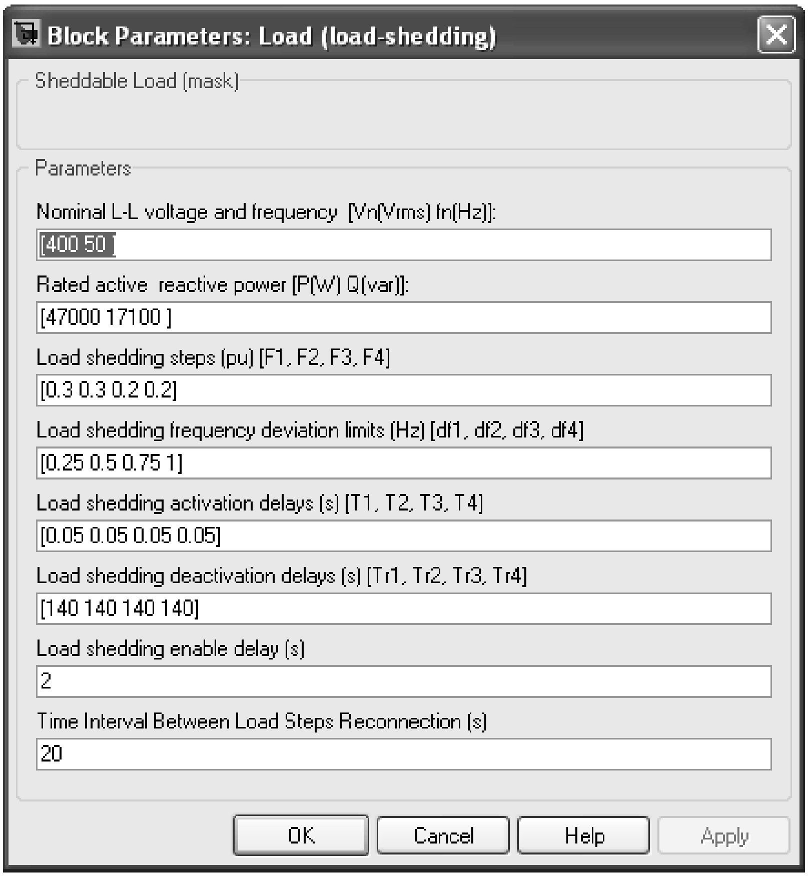

Figure B–9: Load shedding parameters

Concerning the parameters defined in Figure B–9, they have the following meaning:

- The first two sets of parameters define the load nominal operating conditions (voltage, frequency, active and reactive power).

- The filed *load shedding steps* is used in order to define the steps for load shedding. In this case, the implemented model allows the definition of 4 load shedding steps. To each step can be assigned a certain percentage of the load to be disconnected.

- The load *shedding frequency deviation limits* allows the definition of the frequency deviation at which the load shedding will occurs. According to the parameters shown in the Figure B–9, 25% of the load is disconnected if the frequency deviation reaches 0.25 Hz; if the frequency deviation reaches 0.5 Hz, an additional step of 30% is disconnected (at a frequency deviation of 0.5 Hz, 60% of the load is disconnected).

- The *load shedding activation delays* corresponds to the relay activation delays previously referred; a different value can be specified for each load shedding step.

- The *load shedding deactivation delays* defines a time delay after which load reconnection can be performed.

- The *load shedding enable delay* is a control parameter in order to disable load shedding mechanism in the beginning of the simulation.

- The last parameter defines the time interval between load steps reconnection. The model intrinsically considers that if it were activated *n* load disconnection steps, the load is to be reconnected in *2n* steps.

Following the explanation of the general concepts associated to the implementation of the load shedding mechanisms, Figure B–10 shows the content of the mask that implements the referred behaviour.

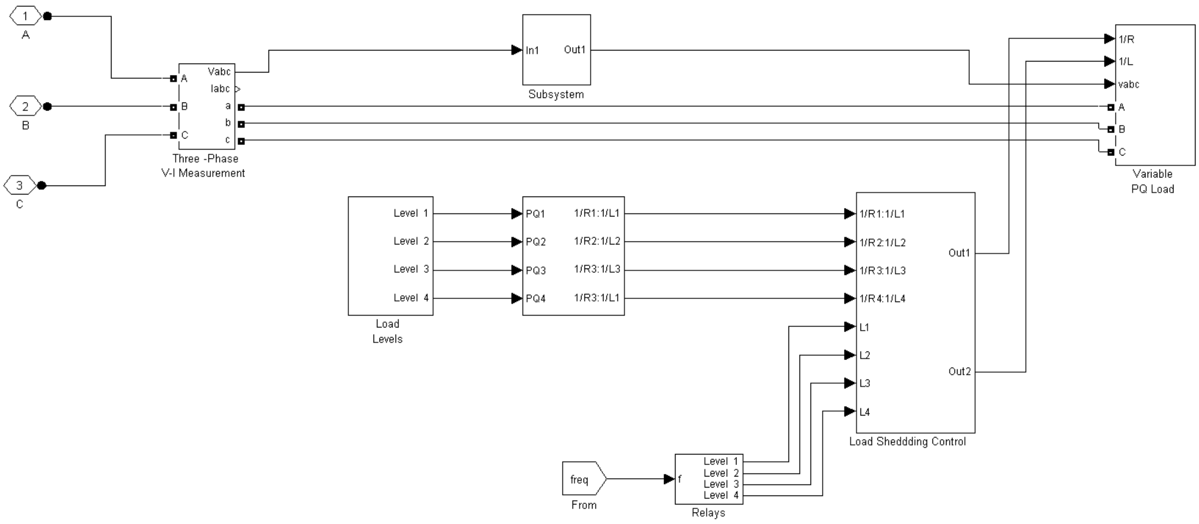

Figure B–10: Implementation of the load shedding scheme