FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

DALILA: Design Architectures in a Living Lab

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Abstract

The combined efforts that push integration of renewable energy technologies into power systems are increasing Microgrid (MG) penetration and leading to a scenario where most part of low voltage networks will be composed of controllable aggregations of these units, or Multi-Microgrids (MMG). Both of these concepts are within the Smart Grid paradigm and bring additional security and reliability to energy systems.

Their association with operational and technical challenges requires a network of controllers capable of managing communications and acting autonomously. This is prompting the development of local experimental facilities that can test their concepts and technologies against these control architectures in environments similar to where the product is to be inserted.

This thesis provides an overview on MGs and analyses the differences and similarities between three of the world's leading laboratories in terms of infrastructure and design. The laboratories are MGRL at Aalborg University, EES at the University of Athens and SGEVL at INES TEC. These were specifically selected due to their contributions to the MG research field, distinctiveness and for having features that foreshadow pioneering on MMG testing. The objective is to derive a guideline that can help new players to understand the requirements needed to assemble such a facility and thus accelerate the transformation of power systems. This is done by describing, in an accessible manner, each laboratory's equipment, electrical configuration, control architecture and data acquisition/communication infrastructure. A critical discussion is also provided to highlight the advantages, disadvantages and functionalities enabled by each facility.

This work could not have been develop without first complementing theoretical knowledge with practical experimentation. MMG dynamic behaviour under multiple operation scenarios was tested through numerical simulation in *Matlab Simulink*. This was done to better understand how different control strategies affect the system's response. Experiments with real hardware and Power Hardware in the Loop (PHIL) simulation were also done in the Smart Grid and Eletric Vehicle Laboratory (SGEVL) of INESC TEC with the intent to exemplify validation testing and corroborate simulation results.

Keywords: Laboratory Design, Microgrid, Multi-Microgrid, Control Architectures, Equiment & Infrastructure, Stability Testing, Simulation, RTDS, PHIL

Resumo

Os esforços internacionais de promoção de energias renováveis estão a aumentar a penetração das Microredes (MR) nos sistemas elétricos, conduzindo a um cenário onde a maior parte da rede de baixa tensão será constituída pela aglomeração destas numa outra entidade controlável, a Multi-Microrede (MMR). Ambos estes conceitos estão inseridos no contexto de redes elétricas inteligentes e contribuem para a melhoria da segurança e fiabilidade do sistema.

Estes conceitos estão também associados a exigentes dificuldades técnicas e requerem uma complexa rede de controladores capazes de comunicar e operar autonomamente. Neste sentido, há uma crescente procura para implementar infraestruturas capazes de testar novos conceitos e tecnologias em meios que se assemelhem àquele onde o produto vai ser integrado, garantindo a compatibilidade com as estruturas de controlo.

Esta dissertação proporciona uma visão geral sobre o conceito de MR e analisa as diferenças e semelhanças da abordagem construtiva de três dos mais prestigiados laboratórios a nível internacional. Os laboratórios são o MGRL na Universidade de Aalborg, o ESS na Universidade de Atenas e o SGEVL no INESC TEC. Estes foram especificamente escolhidos pelas suas contribuições na área das MR, distintividade e por terem características que são promissoras para iniciar o teste das MMR. O objetivo é fornecer um guia e orientação a todas as entidades interessadas em construir um laboratório, de maneira a acelerar a transformação do sistema elétrico. Isto é conseguido descrevendo de forma simples e acessível, o equipamento, configuração elétrica, topologia de controlo e sistemas de aquisição de dados/comunicações de cada laboratório. É também feito um levantamento das vantagens, desvantagens e principais funcionalidades proporcionadas por cada abordagem.

Este trabalho não poderia ter sido desenvolvido sem primeiro complementar a vertente teórica com uma abordagem prática. O software de simulação numérica *Matlab Simulink* foi utilizado para estudar o comportamento dinâmico de uma MMR sobre diferentes cenários de operação. Isto foi feito com o intuito de examinar a resposta do sistema face a várias estratégias de controlo. Foram também realizas experiências no Laboratório de Redes Inteligentes e de Veículos Elétricos do INESC TEC, recorrendo a equipamento real e a técnicas de simulação com Power Hardware in the Loop (PHIL), de maneira a exemplificar testes de validação e a corroborar os resultados obtidos nas simulações.

Palavras-chave: Arquitectura de Laboratórios, Microredes, Multi-Microredes, Estratégias de Controlo, Equipamento, Testes de Estabilidade, Simulação em Tempo Real, PHIL

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Miguel

" The struggle itself towards the heights is enough to fill a man's heart. "

- Albert Camus

Contents

List of Figures

List of Tables

Abbreviations

AC	Alternate Current
AMI	Advance Metering Infrastructure
AMR	Automatic Meter Readings
BESS	Battery Energy Storage Systems
BS	Black Start
CAMC	Central Autonomous Management Controller
CERTS	Consortium for Electric Reliability Technology Solutions
CI	Computational Intelligence
CHP	Combined Heat and Power
CPU	Central Processing Unit
CS	Cable Simulator
CSP	Concentrated Solar Power
DAS	Data Acquisition Server
DC	Direct Current
DCP	Digital Control Platform
DER	Distributed Energy Resources
DG	Distributed Generation
DMS	Distribution Management System
DoD	Depth of Discharge
DR	Demand Response
DSO	Distribution System Operator
DUT	Device Under Test
EB	Energy Box
EDLC	Electric Double Layer Capacitor
ENoLL	European Network of Living Labs
EM	Energy Manager
ESS	Energy Storage Systems
EU	European Union
EV	Electric Vehicle
FES	Flywheel Energy Storage System
FLA	Flooded Lead Acid
GPRS	General Packet Radio Service
GTC	Green Tech Center
HV	High Voltage
HMI	Human Machine Interface
ICT	Information and Communication Technology
IED	Intelligent Electronic Devices
I/O	Input/Output

IP	Internet Protocol
JRC	European Comission Joint Research Center
LC	Load Controller
LV	Low Voltage
MAS	Multi-Agent System
MC	MicroSource Controller
MG	MicroGrid
MGCC	MicroGrid Central Controller
MMG	Multi-MicroGrid
MMO	Multi-Master Operation
MS	MicroSource
MV	Medium Voltage
OLTC	On Load Tap Changer
OPC	Open Platform Communications
PCC	Point of Common Coupling
PHIL	Power Hardware in The Loop
PLC	Power Line Carrier
PP	Power Plant
PV	PhotoVoltaic
PWM	Pulse-Width Modulation
P2P	Peer-to-Peer
R&D	Research & Development
RES	Renewable Energy Sources
RET	Renewable Energy Technologies
RTDS	Real-Time Digital Simulation
RTU	Remote Terminal Unit
SG	SmartGrid
SIRFN	Smartgrid International Research Facility
SGEVL	Smart Grid and Electric Vehicle Laboratory
SMES	Superconducting Magnetic Energy Storagee
SM	Synchronous Machine
SMO	Single Master Operation
STATCOM	Static synchronous Compensator
SVC	Static VAR Compensator
SoC	State of Charge
TCP	Transmission Control Protocol
T/F	Transmission and Distribution
THD	Total Harmonic Distortion
TSO	Transmission System Operator
UDP	User Datagram Protocol
USA	United States of America
VAR	Volt-Ampere Reactive
VC	Vehicle Controller
VPP	Virtual Power Plant
VSI	Voltage Source Inverter
V2G	Vehicle to Grid
WT	Wind Turbine
4PQ	Four Quadrant back-to-back inverter

Chapter 1

Introduction

1.1 Context

The current energy/environmental dilemma is leading to the transformation of conventional energy systems. Constant growth of the world's electricity demand requires an increase of total generation capacity, but the depletion of Earth's fossil fuel reserve and concerns on global warming beg for alternative solutions. These factors have prompted international conventions such as the Kyoto Protocol (1992) and Paris Agreement (2016) to set out key targets that bind countries to reduce their greenhouse gas emissions. In this context, industries and institutions have been greatly investing on the research and integration of Renewable Energy Technologies (RET) and Distributed Energy Resources (DER) into power grids, gradually shifting the electricity generation paradigm from centralized to decentralized [14].

In the past, energy systems have been dominated by large-scale, vertically structured designs comprised of three different levels: generation, transmission and distribution. These model were supported by economies of scale with systems being centrally operated and electricity being delivered to customers over long distances in a unidirectional way. Generation was primarily based on fossil fuels (coal, oil and gas), nuclear and hydro power plants; facility size augmenting proportionately to energy demand. Transmission of energy relied on a High Voltage network to link generation centers to industrial and residential locations were substations lowered the voltage levels do adequate consumption levels via substations or electrical transformers.

Due to the circumstances referred above along with technological advancements, the traditional layout of the energy system is being slowly changed and reshaped. Small and medium-scale power sources are penetrating the market and being connected to the MV and LV grid in a modular and distributed fashion. Some examples of Distributed Energy Resources (DER) are Wind Turbines (WT), PhotoVoltaic panels (PV), Battery Energy Storage Systems (BESS), Combined Heat and Power (CHP) and Fuel Cells (FC). These types of technologies are usually placed close to the load they serve and so generated energy can not only be consumed locally (reducing imports), but also excess of energy can be sold to the grid (though at a reduced price). This has greatly empowered customers with more electrical and economic freedom, giving birth to a new term:

'prosumer', a consumer who also produces energy.

Nevertheless, it is important to understand that the transition to power systems that successfully integrate DER comes with many operational challenges, as it involves the evolution from passive electricity networks with unidirectional energy flow (which are simple to control), to active distribution networks with bidirectional energy flow (which involves complex control mechanisms). The next subsection will provide a deeper insight onto this subject.

1.2 Motivation & Problem

Passive electricity networks rely on large-scale high inertia synchronous machines to generate energy and supply its customers through high voltage transmission power-lines. This type of systems are characterized by low observability on the costumer side but since energy flow is unidirectional, a top-down centralized control structure is able to safely monitor the behaviour of the entire system. Utilizing large scale synchronous machines is a crucial element to guarantee the system's stability since these store large amounts of kinetic energy in their rotating masses and can react almost instantaneously to any power imbalances in the grid by injecting or absorbing electrical energy [49].

Active distribution networks, on the other hand, require the implementation of intelligent and extensive control to safely operate the system. Penetration of distributed generation introduces reverse currents (bidirectional power flow) that increases the complexity of protection devices sizing, leads to voltage variability and instability; and most DER are connected to the grid via inverter based technologies meaning that they have low inertia. To tackle these challenges, highly automated control algorithms and communication infrastructures are being implemented in order to control and coordinate the system's components actions and ensure power quality operation. Maximizing DER implies developing advanced forecasting tools to predict renewable energy generation, advanced local distribution grid monitoring, state estimation capabilities from smart metering and coordinated voltage control exploiting controllable generation, flexible loads, storage devices and conventional OLTC transformers.

Given the complexity of these tasks, it becomes crucial that entities involved in the energy business ensure a smooth transition from one paradigm to the next, derisking the transformation of technological development. As electricity becomes the 'fuel of choice' with RET, Electric Vehicles (EV) and other technologies further penetrating the market, the deepening dependency on energy systems will leave little margin for inefficient innovations. This highlights the need for research facilities that are capable of testing procedures and validate components not only against industry standards but also against end-user behaviour. These facilities are the bridge that can guarantee an effective and secure translation from concept to product integration in a secure setting. In this way, a critical guideline that could overview the main features of world leading laboratories and review the advantages and disadvantages of their construction designs could greatly benefit new players. It could provide the necessary orientation and knowledge to instigate laboratory development and increasing competitiveness, accelerating the transformation of power systems.

1.3 Objective

The work developed in this thesis has three main goals.

The first goal is to clearly describe the concepts associated with active distribution networks: Smartgrids, Microgrids and Multi-Microgrids. It is sought out here a good understanding of their context, basic elements, currently available control architectures and recognition of important projects in the field.

The second goal is to analyse existent designs for MG laboratory infrastructures and provide a guideline that can help new players to understand the requirements needed to assemble such a facility. This is done by describing each laboratory's equipment, electrical configuration, control architecture and data acquisition/communications so to derive a basic/common infrastructure. A review of the laboratories features is also provided to highlight the advantages, disadvantages and functionalities enabled by each approach.

Finally, the third goal is to recreate MG/MMG operation and demonstrate how different control strategies shape the system's dynamic response. This was done with the aid of numerical simulation software (*Matlab Simulink*): four extreme operation scenarios were considered and put to test in nine different cases. Two of those tests were under carried in SGEVL at INESC TEC with the aid of PHIL, aiming to exemplify laboratory validation and corroborate the results obtained in the simulations.

1.4 Document Structure

This document is divided into seven chapters.

Chapter 1 contextualizes the problem under investigation, introduces the motivation behind this work and delineates the main objectives to achieve.

Chapter 2 is a state of the art that approaches the topics of SG, MG and MMG. It describes the context of such concepts and their implications on power systems, operational challenges and proposed solutions. It details what characterizes these concepts and the essential components behind them: MG units, ESS and system coordinators. The control algorithms that enable functionalities such as autonomous operation, active demand response and blackstart. There is also mentioning to some international reference projects.

Chapter 3 is related to MG laboratory design. It begins with a general outlook of worldwide laboratories, their topics of research and infrastructure. The concept of Living Lab is introduced to highlight the further necessity of open innovation in power systems. Following, three notorious laboratories that enable advanced MG functionalities are analysed and their design features critically reviewed. A general guideline for basic equipment required to assemble a laboratory capable of performing MG testing is derived.

Chapter 4 is about studying MMG dynamic behaviour through the simulation mechanics of *Matlab Simulink*. The assumptions made to model grid components are described and a base case is considered. Four scenarios and nine different tests were used to study different operation points and control solutions.

Chapter 5 describes the laboratory setup utilized to under carry the experiments in INESC TEC's SGEVL. Since PHIL is a central piece to these experiments, allowing interaction between simulated models and real hardware, the theory associated with it is also explained.

Chapter 6 presents an analysis of the results obtained in the simulations and in the laboratory.

Chapter 7 draws conclusions from the work that was developed and gives prospects for future efforts.

Chapter 2

State of the Art

2.1 Smart Grids

A Smart Grid is an electricity grid where information and communication technologies are extensively exploited [21]. The concept was first introduce in Europe in 2006 by the Smart Grid European Technology Platform as 'an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies.' [8]. A Smart Grid combines real-time telecommunications, data mining and distributed high-processing computing to create an interconnected 'intelligent' cyber-physical electrical system that possesses novel capabilities, such as [21]:

- Increased efficiency and reliability due to the implementation of new optimization strategies;
- Self-restoration through the possibility of automatically detecting, analysing and responding to system faults;
- Anticipation of market prices via broad data collection and refined forecasting;
- Flexibility, with integration of a wide range of technologies (including RES and Electric Vehicles);
- Empowerment of the consumer by gathering and providing data to the end-user on their behaviour and allowing them to actively contribute in energy planning.

Smart Grids provide both energy companies and customers with increased visibility, predictability and control over their assets and services in a system where data flow and management play a crucial role [22]. This requires state observation methodologies and identification techniques trough the widespread of ICT systems and the creation of large digital databases. Controllability involves real-time monitoring, remote control mechanics and smart algorithms embedded in power devices [11]. These two parties aligned propel innovation in power systems were applications emerge in a bottom-up vertical structure as depicted in Figure 2.1. As noted by Farhangi in [22], it is interesting to see that 'although the foundation of the smart grid is built on a lateral integration of basic ingredients, true smart grid capabilities will be built on vertical integration of the upper-layer applications. As an example, a critical capability such as demand response may not be feasible without tight integration of smart meters and home area networks.'.

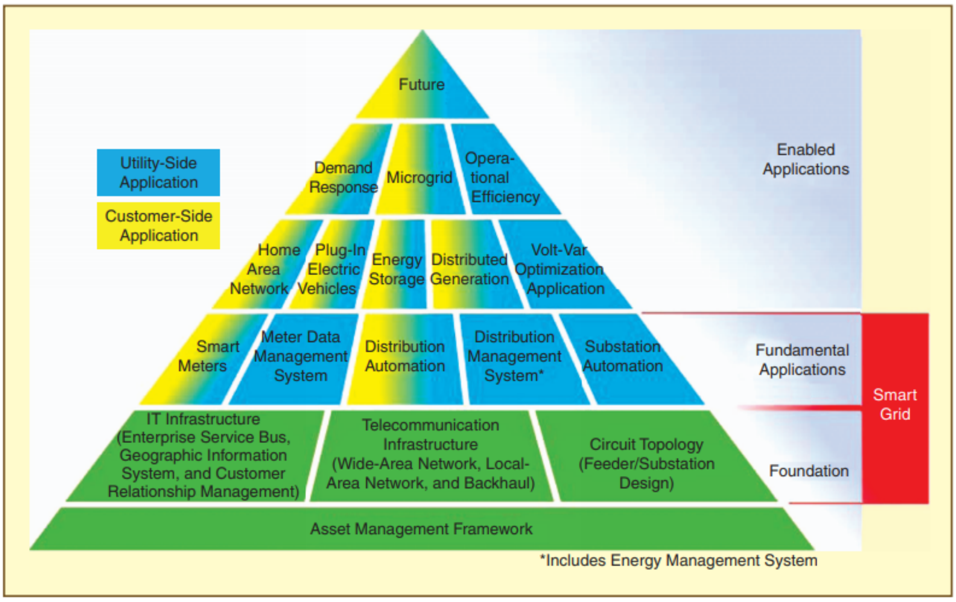

Figure 2.1: Smart Grid Applications [22]

A substantial alteration of conventional electricity grids is to be expected in three main aspects: improvement and automation of the infrastructure, addition of a digital layer and data management, and reshaping of the capitalization process.

The first aspect has been made possible trough advancements in the field of computational intelligence (CI) and power electronics. CI renders innovative and effective tools that tackle complex problems in changing domains with adaptive algorithms [11]. Adaptive algorithms are able to learn from experience by being trained with information stored in databases. Power devices can then be optimized not only from their own 'personal' experience but also with events that occurred to their peers. With this, the grid can be furnished with a multitude of 'intelligent agents' that are able to act independently and take decisions based on the current situation.

The second aspect is related to data collection and its storage. In a SG, components should be equipped with communication systems to guarantee observability and safe and reliable exchange of information. Devices must report their status and accept commands to adjust their performance. With the wide range of communication technologies nowadays (Wireless, fiber optic, satellite, etc.) this is relatively easy to achieve. The real challenge is to ensure interoperability, which can be defined as the 'characteristic of a product or system, whose interfaces are completely understood to work with other products or systems, present or future, in either implementation or access, without any restrictions' [2]. In this regard, a huge effort is being made to create inclusive open standards that will guarantee the system's flexibility. One of the most important steps towards increased observability and control can be achieved trough the widespread of an Automated Metering Infrastructure (AMI). AMI provides utilities with a two-way communication system and the ability to obtain instantaneous information on individual and aggregated demand, as well as the possibility to modify customers' service-level parameters. The monitoring infrastructure should be capable of accurately measuring parameters such as active power, reactive power, voltage, current, demand, and so on. Applications include demand response, asset management, customer informational system, outage detection/restoration to distribution automation [60].

The last aspect is related to the deregulation of the energy market. With the trivialization of DG, new players will abundantly penetrate the market and consumers will be able to choose freely between competing energy suppliers based on energy cost, greenhouse gas emissions and social goals. Trading schemes between prosumers (Peer-to-Peer, P2P) are being projected and tested [80] in many countries with revolutionary business models and monetization schemes being introduced [72], [79].

In conclusion, the Smart Grid concept is associated with the widespread of ICT and the Internet of Things. It is a concept that resonates four 'ility's': observability, predictability, communicability and controllability. These factors are pushing power systems to become more wholesome, allowing the introduction of complex and clean energy resources that promote social benefits like reduced carbon emissions and lower energy prices.

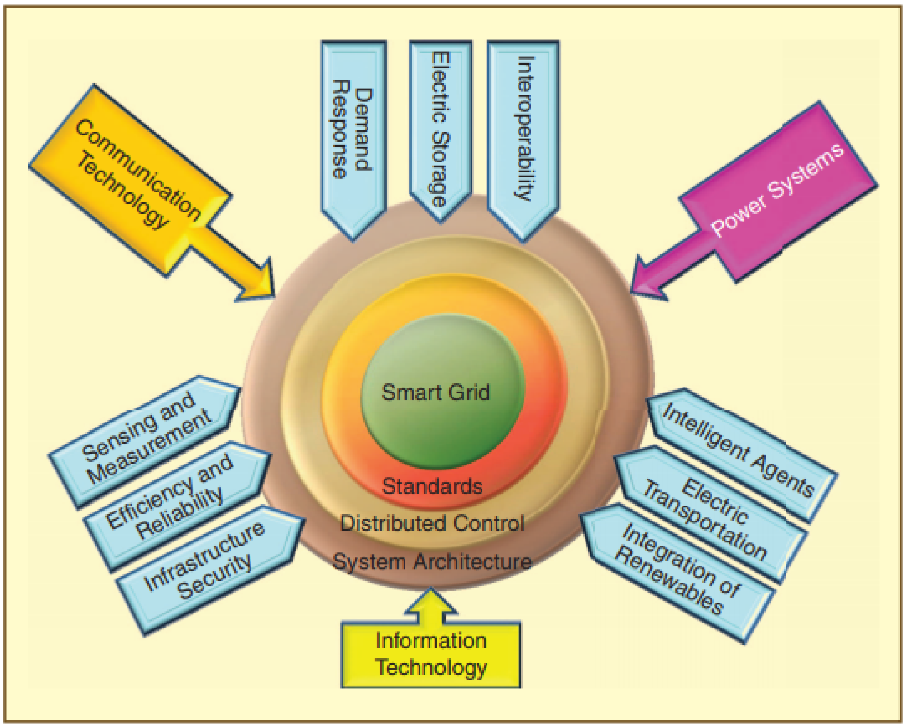

Figure 2.2: Basic Smart Grid components [22]

2.2 Microgrids

2.2.1 Concept

The microgrid concept was initially developed in 2002 in the US by the Consortium for Electric Reliability Technology Solutions (CERTS). The group was formed in 1999 following a series of power outages that occurred in the western grid to research and develop new tools and technologies that would enhance reliability. Their solution consisted on 'the aggregation of controllable loads and microgeneration units operating as a single system providing both power and heat', as depicted in Figure 2.3 [41]. The CERTS Microgrid concept comprises small scale generators named as Micro Sources (MS) connected to the grid via power electronic interfaces that grant controllability and flexibility. The control strategies proposed enable operation while connected to the grid during normal operation or disconnected from it in case of an eventuality (fault, upstream equipment maintenance or power quality deficit).

Connection and disconnection from the upstream grid is made trough a Point of Common Coupling (PCC), which defines the boundary of the microgrid system. When operating in grid-tied mode, voltage and frequency are determined by the macro grid and the microgrid operates by sending or receiving power according to the generation-load conditions. Any deficit of power must be imported from the grid and any excess of power must be exported to the grid. Island mode is only possible if the microgrid available generation capacity is higher than its critical loads, with DER defining voltage and frequency.

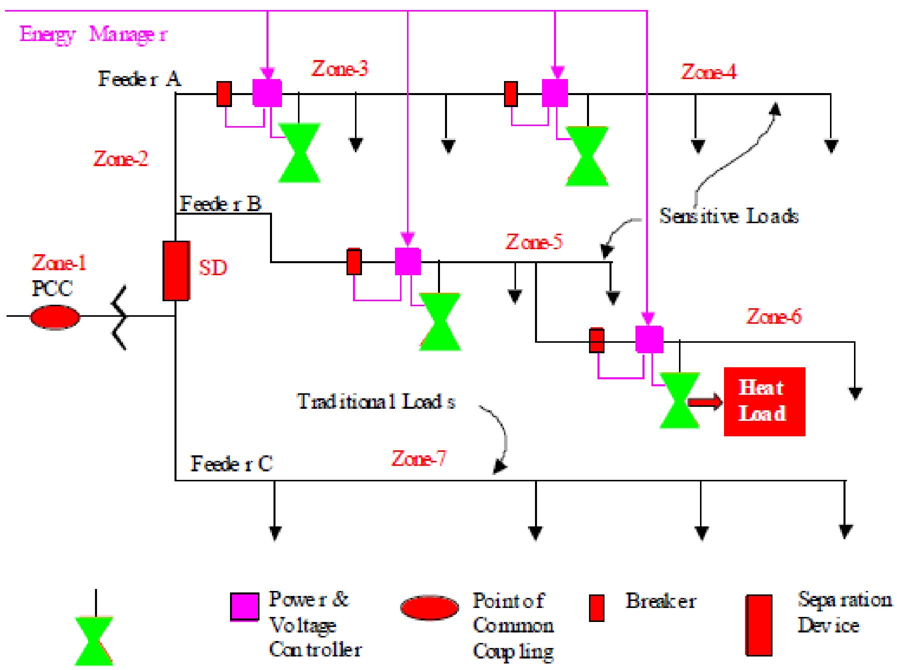

Figure 2.3: CERTS Proposed Architecture [41]

To control such system CERTS relied on 3 components [41]:

- **The MicroSource Controller (MC):** a converter which individually controls the power flow and voltage of MS;
- **The Energy Manager (EM):** a coordinator device that performs economic dispatch calculations and ensures that generation meets demand and power losses are minimized;
- **A novel protection system:** protection devices that ensure selectivity and have alterable set-points for each operation mode

Later on, in 2004, the European Union Fifth's Framework Program (FP5) 'MICROGRIDS' defined microgrids as 'LV distribution systems with distributed energy sources together with storage devices, which can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid' [31]. This time around, the objective was not only to increase the system's reliability but also to further integrate RES into the electrical network. The concept is illustrated in Figure 2.4.

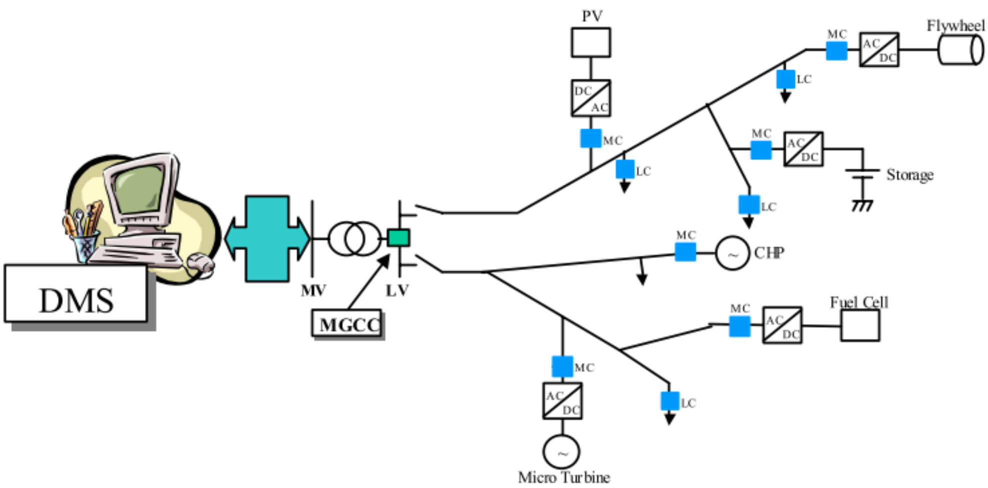

Figure 2.4: MICROGRIDS Proposed Architecture [31]

As it can be seen, the MICROGRIDS architecture also includes small generators connected to feeders via a power electronic interface (MC). MCs are generally power converters that control the voltage and current of the source. These will be later analysed in section 2.2.3. In this case, Load Controllers (LC) have been added to increase observability and provide load shedding functionalities. The EM is substituted by another agent, the Microgrid Central Controller (MGCC), located at the MV/LV substation. The MGCC is the microgrid 'brain' and controls the MCs and LCs by providing set-points, sending commands and ensuring coordination and quality of operation [31].

These two projects are considered the main references for microgrid definition, laying the fundamentals for posterior work. While they both conceptualize a microgrid as an energy system with islanding capabilities, they clearly differ in some aspects and are restrictive in their definition. CERTS perceives that a MG should provide both heat and power and does not address the possibility of grid-connected operation in the definition itself. MICROGRIDS, on the other hand, does not mention heat at all and entails that microgrids are exclusively LV systems that must include storage devices. Naturally, over the years the definitions has been refined. A widely accepted review is the one made from the USA's Department of Energy Microgrid Exchange Group in 2011: 'A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode.' [70]. This definition manages to accurately and liberally describe all of microgrid features, leaving open the possibility of MV/HV system integration, heat production and transfer and storage technologies.

The feasibility of microgrid operation is deeply intertwined with the smartgrid concept. The control system relies heavily on computer based intelligent algorithms with high speed processors and actuators in order to maintain security and stability. The MG should be able to control power flow, load sharing during islanding and protection coordination. These should guarantee not only a safe steady state operation in both modes but also a smooth transition between them. Given MGs distributed topology, an advanced communication infrastructure is necessary to guarantee not only real-time information exchange but also data storage features. [21]. The load controllers (LC) in Figure 2.4 represent the advanced metering infrastructure and the increased observability of smartgrids.

Interoperability and plug and play are important elements to take into account in MG design. Plug and play can be described as the capacity to discover and integrate a hardware component in a system without the need for reconfiguration or user intervention. The objective is to achieve connection flexibility to encourage further integration of DER technologies. In this way, the power system conceptualization is expected to emerge as a 'well-planned plug-and-play integration of smart microgrids that will be interconnected through dedicated highways for command, data, and power exchange' [22] as depicted in Figure 2.5.

Finally, the microgrid concept is associated with the capacity to self-heal. This is not a necessary feature but one that is often included. If following a general blackout or an upstream fault the MG is unable to properly island, then a bottom-up blackstart process can be initiated and service time interruption reduced. This is extremely revolutionary in terms of power system reliability and requires a pre-established coordinated process embedded into the MGs devices. This topic is discussed with more detail in section 2.2.7.

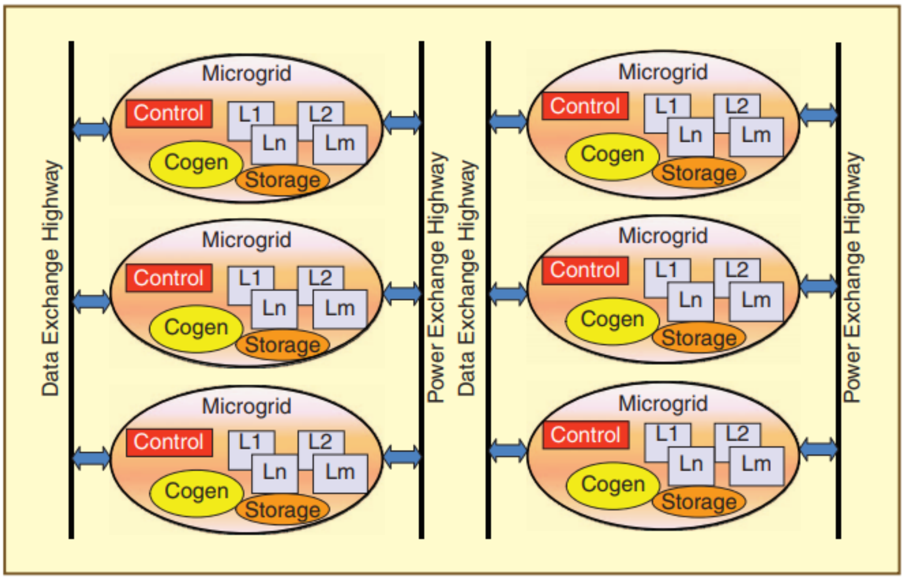

Figure 2.5: The power system of the future [22]

2.2.2 Advantages and Challenges

The development and expansion of the Microgrid concept has been slowly gaining terrain. The ’parcelling’ of the power system as a whole into small and clearly defined agglomerates of loads and micro-sources seems to be the unavoidable future, and reasonably so. The environmental, operational and economical advantages it brings to the table are undeniably positive. Nevertheless, there are always two sides to every coin and this transition does not come without its challenges. This subsection will aim to outline both.

Advantages

Environmental

- Integration of Renewable Energy Sources: this is by far the most important aspect. Encouraging the utilization of RES helps reduce green house gas emissions and redirects our global trajectory to a more sustainable and healthy future. Microgrids are able to exploit the full potential of distributed intermittent resources by means of their control architectures.

Operational

- Reliability Improvement: DG helps reduce dependency upon certain systems components (e.g. transmission line or transformers). Island and blackstart capabilities reduce power outage frequency and duration.

- Efficiency Improvement: DG is located closer to loads than conventional technologies, thus reducing energy losses in the transmission and distribution network.

- Voltage Profile Improvement: being distributed throughout the energy network, DG can enhance the voltage quality of the grid and provide reactive power support.

Economics and Market

- Investment savings for the TSO and DSO: local generation availability diminishes the need for further investments in the transmission network
- Indemnity fee reduction for energy companies: customers affected by system outages must be compensated by responsible entities. Lesser outage occurrences mean more savings.
- Increase in revenue for industrial companies: in the same way, lesser and shorter outages in factories translates into higher productiveness and profit.
- Reduced energy prices: RES proliferation may result in electricity prices dropping due to the increase in energy supply coming from free and abundant natural resources.
- Ancillary Services: microgrids can provide ancillary services when generation is higher than load, translating into financial compensation (applications include operating reserve, reactive power and voltage control).
- Energy Market de-Monopolization: allowing for open market investments will limit the power exerted by established energy companies and increase costumers freedom of choice.

Challenges

Operational

- Frequency and Voltage Control: in conventional power systems stability is assured by the high inertia of large-scale synchronous machines. The further penetration of intermittent energy sources leads to frequency and voltage fluctuations. These are difficult to control, involving a lot of know-how and advanced engineering.
- Protection Sizing: bidirectional power flow demands adjustments in the protective devices of electric systems. Devices must be able to alter their set-points to operate in grid-connected and island mode, dealing appropriately with reverse currents.
- Information and Communication Technologies: there is a lack of technical experience in controlling and coordinating in real-time physically distributed systems with plug-and-play capabilities.

Economics and Market

- Renewable Energy Technology Prices: although prices of RET are gradually decreasing, they are still considerably high. Most countries have to rely on governmental or international subsidies to encourage investments for a transitional period (and governmental subsidies are commonly generated by raising consumer energy taxes)
- Remuneration schemes: generation remuneration schemes must be created for grid-tied and islanded operation mode, clearly defining commissioning rules and protecting consumers against abusive fees when supply is exclusively provided by the microgrid.

Administrative

- Lack of Legislation: unfortunately many countries simply lack the legislation to regulate and operate microgrids with monopolization of energy systems often exerting too much power to indulge change.

- Absence of Technical Standards: transitioning to new energy architectures means that new standards and protocols must be developed, while conventional ones are reassessed and reformed. Extensive research and testing procedures should be carried to validate power quality, operation and safety specifications that apply to products that want to commercially enter the market.

- Electric Vehicles: regulation for the charging and discharging of electric vehicles must also be elaborated before they start significantly penetrating the market. EV's will drastically transform the traditional layout of load diagrams, upbringing operational and market challenges.

2.2.3 Micro Source Modelling

Generally most of the MG's components namely MS, storage units or EV's involve DC and therefore coupling to AC microgrids is only made possible trough power converter interfaces (DC/AC inverters). MS that produce AC current also usually require AC/DC/AC converters to adapt voltage levels, regulate frequency and implement other functionalities. The control strategy adopted for each converter can be of two kinds:

Voltage Source Inverter Control

In the Voltage Source Inverter (VSI) control, also known as grid-forming control, the inverter is modeled as a voltage source with pre-defined values of voltage and frequency, as shown in images (a) and (c) in Figure 2.6. The inverter is then capable of regulating its output voltage according to its delivered power via P-Q measurements on its load [46]. The series impedance is not negligible and derives from the closed-loop control, which will be detailed in the next section.

PQ Inverter Control

In the PQ Inverter control, also known as grid-feeding, the inverter is modeled as a current source with pre-defined values of active and reactive power, as shown in images (b) (d) inf Figure 2.6. In this case, the inverter seeks to maintain its PQ reference via a current control loop, which is much simpler than the VSI control loop. Good functioning of PQ inverters depends greatly on stable voltage and frequency values at its terminals. [9].

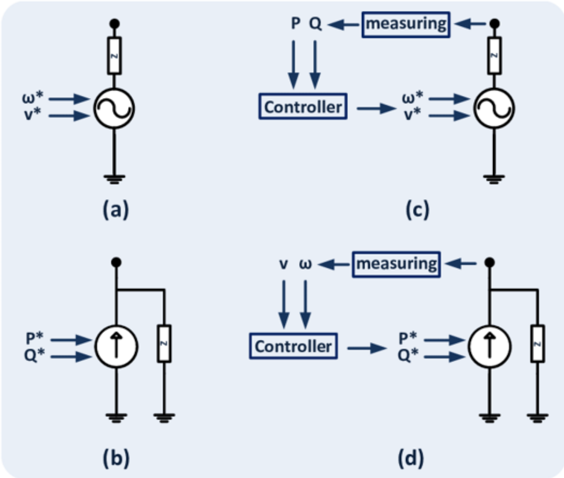

Figure 2.6: Inverter Modelling in AC Microgrids

It is normal for each inverter to be attributed a single control strategy which mainly depends upon the MS type it is coupled to (see Table 2.1). However, the same inverter can be equipped with both control modes and switch between them when commanded. In grid-tied mode, since frequency regulation is reassured by the main grid, inverters operate in grid feeding mode with the objective of extracting the maximum power possible out of their respective sources. During island mode and blackstart operation, the type of inverter control applied to each MS will have to be carefully selected because due to its impact on MG safety and stability. Many MS produce electrical energy through intermittent RES (e.g. sunlight, wind) which makes them unreliable for grid-forming tasks as they are incapable of maintaining steady operation values. Grid-forming inverter controls should then only applied to highly controllable technologies such as CHP, diesel engines or ESS (batteries, flywheels) where one can ensure power quality trough constant output. Another important aspect in a MG is that grid-forming sources should be able to ensure minimum power to supply critical loads. PQ inverters are still necessary in island mode to maximize energy availability but should only be connected after stabilization is achieved.

Operation and Sources	**Intermittent Energy Source**	**Controllable Energy Source**
Grid-connected microgrid	Grid-feeding converters	Grid Feeding converters
Islanded microgrid	Grid-feeding converters	Grid-forming converters

Table 2.1: Inverter control application scenarios [9]

When the MG is in island mode, two possible operational strategies can be followed according to the number of grid-forming inverters [46]:

- **Single Master Operation:** the MG operates with a single grid-forming inverter. All other controllable or non-controllable MS are controlled by grid-feeding inverters.
- **Multi Master Operation:** the MG operates with more than one grid-forming inverter.

2.2.4 Control Architectures

Microgrid control and operation is cemented on clearly defined coordination and management strategies. The system should be capable of receiving input measurements and autonomously decide on which actions to take [9]. Independently of the type of approach used to achieve this, it is possible to categorize each arquitecture according to a hierarchical three layer representation based on functionality and time response (Figure 2.7).

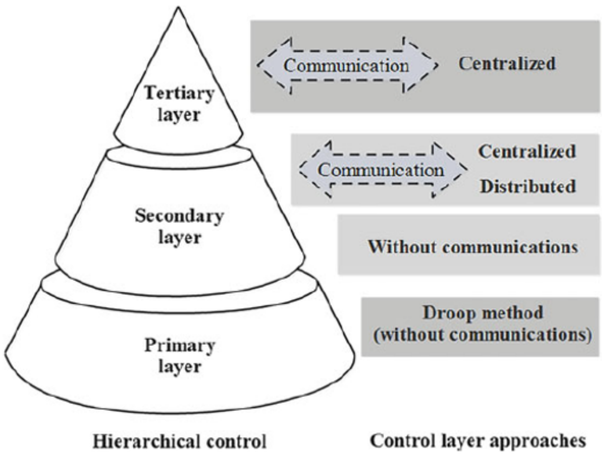

Figure 2.7: Microgrid Hierarchical Control Architecture [61]

2.2.4.1 Primary Control

Primary control is the first control level, featuring the fastest response. The objective of this layer is to guarantee frequency stabilization trough proper power sharing. To do so, one of two power sharing approaches can be adopted: communication-based or droop-based [51].

Communication techniques allow for proper power sharing as well as voltage regulation, with smaller frequency and voltage deviations (power quality indexes are closer to their reference values without secondary control). However, since a communication infrastructure is required, this approach is costlier and can be affected by external interference (noise), making it less reliable and expandable [51].

Droop on the other hand, does not require communications, enabling proper power sharing via local measurements only. This improves reliability while avoiding complexity and high costs. The most important feature of this method is, however, its plug-and-play capabilities: one device can be connected/disconnected from the system without the need for interruption nor reconfiguration. All the characteristics above-mentioned make droop control the most commonly adopted power scheme. A general P-Q droop control function can be expressed as follows:

$$F_1: \quad f = f_0 - m(P_0 - P) \tag{2.1}$$

$$F_2: \quad V = V_0 - n(Q_0 - Q) \tag{2.2}$$

where in F1, f and f_0 are the frequency and its reference, respectively, m the primary droop coefficient for active power and P and P_0 the active power output and its reference. In F2, V and V_0 are the voltage and its reference, n the primary droop coefficient for reactive power and Q and Q_0 the reactive power output and its reference.

Representation of the above equations can be visualised in Figure 2.8. It is important to understand that the relationships expressed between active power/frequency and reactive power/voltage depend greatly on the resistive or inductive nature of the electrical network. As a reminder, lets take a look at the following circuit model of a microgrid power converter coupled to an AC network in Figure 2.9.

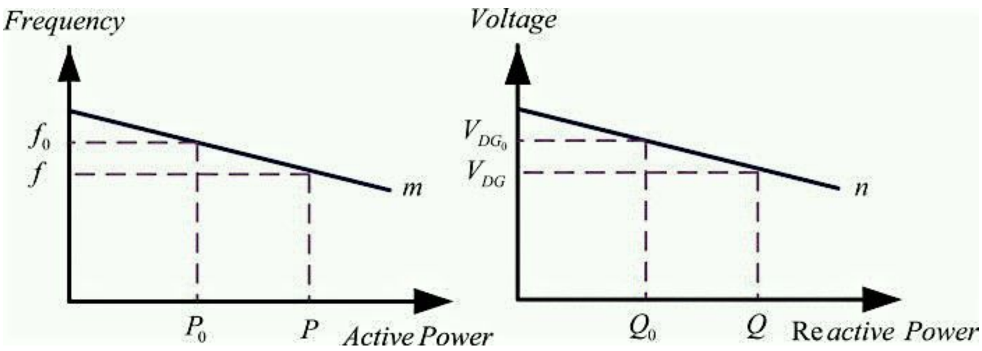

Figure 2.8: Droop Control Functions [51]

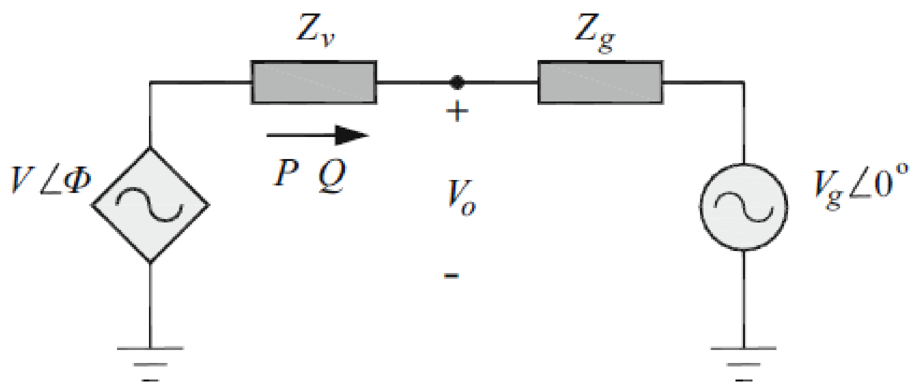

Figure 2.9: Microgrid Power Converter Coupled to AC network [9]

Being Z and θ the magnitude and angle of the equivalent impedance between Zv and Zg, active and reactive power delivered by the converter to the grid can be expressed as:

$$P = \frac{V_g cos\theta}{Z}(V cos\phi) - \frac{V_g^2 cos\theta}{Z} + \frac{V_g sin\theta}{Z}(V sin\phi) \tag{2.3}$$

$$Q = \frac{V_g sin\theta}{Z}(V cos\phi) - \frac{V_g^2 sin\theta}{Z} - \frac{V_g cos\theta}{Z}(V sin\phi) \tag{2.4}$$

Generally ϕ is small and it is safe to assume that $cos(\phi) \approx 1$ and $sin(\phi) \approx \phi$. Therefore, if the equivalent impedance is predominantly inductive $\theta \rightarrow 90^o$, injected active power depends directly on the phase angle ϕ while reactive power depends on the voltage V.

$$P \approx \frac{V_g V}{Z}\phi \tag{2.5}$$

$$Q \approx \frac{V_g}{Z}(V - V_g) \tag{2.6}$$

In the same way, if the equivalent impedance is predominantly resistive $\theta \rightarrow 0^o$ then injected active power is depends directly on the voltage of the converter (V) while reactive power depends on phase angle ϕ.

$$P \approx \frac{V_g}{Z}(V - V_g) \tag{2.7}$$

$$Q \approx -\frac{V_g V}{Z}\phi \tag{2.8}$$

This example serves to point out that primary droop control functions must take into account the nature of the network they are inserted into to effectively impact the system. For simplicity purposes, a predominantly inductive network is assumed throughout the rest of this chapter, unless mentioned otherwise.

In a droop control scheme, accommodation of load and proper power sharing can then be achieved according to each converter's droop characteristic. Frequency stabilization will depend on the microgrid operation mode (grid-tied or islanded), as represented in Figures 2.10 and 2.11.

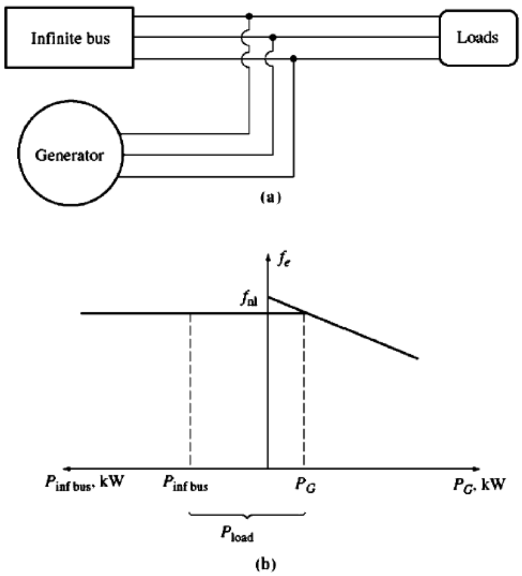

Figure 2.10: Power Converter Operating in Grid Tied Mode. **a)** Diagram Representation **b)** Droop Function Representation [13]

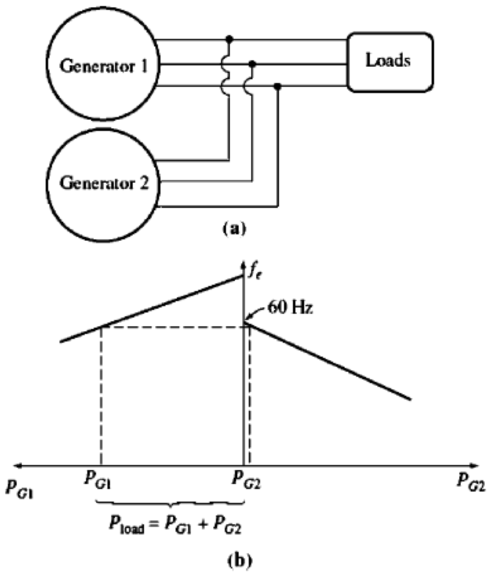

Figure 2.11: Power Converter Operating in Islanded Mode. **a)** Diagram Representation **b)** Droop Function Representation [13]

Figure 2.10 illustrates power sharing when a MS (Generator) is in grid-tied mode, connected to a power system much larger than its own. Notice how the macro grid droop curve has no slope, meaning that no power deviations from the power converter can alter the system's frequency point. This is related to the idealized concept of an infinite bus: a power system so large that its voltage and frequency do not vary regardless of how much power is drawn from or supplied to it [13]. In this operation mode, and assuming that the power converter is supplying its maximum active power (Pg), an increase in load does not decrease the system frequency since the difference will be accommodated by the infinite bus. The same phenomena applies to voltage and reactive power. It can then be said that in grid-tied mode the frequency and terminal voltage of the power converter are constrained by the infinite bus and operation is highly stable.

Figure 2.22 illustrates power sharing when a MS (Generator) is in island mode, connected to a power system of relatively the same size. Notice how each generator possesses a negative slope droop curve and that an increase in load implies a decrease in the system's frequency. A decrease in load would signify an increase of the systems operating frequency and probably the curtailment of generator 2.

What if the power converter is operating in grid-connected mode at grid frequency (Pg point in Figure 2.10) and the load increases, but this time around Pg is not the maximum power of the converter? And suppose this power converter is connected to a wind turbine and that there is a policy of maximizing renewable energy generation. What happens then? How can the power supplied by the wind turbine be increased and constant frequency/voltage maintained at the same time? And since electrical loads are designed to operate at standard voltage and frequency, how can a microgrid in island mode guarantee equipment safety if power quality indexes deviate from their reference values? The answer to both of these questions is frequency/voltage restoration, also known as secondary control.

2.2.4.2 Secondary Control

Secondary control is the second control level, featuring a slower response than primary control. Operation in a slower time frame allows decoupling from primary control functions and more time to perform complex calculations. This control unit seeks to guarantee power quality by eliminating voltage and frequency deviations, restoring the system to its reference (and more stable) operating points [51]. Figure 2.12 illustrates primary and secondary control layers levels, where the difference between stabilization and restoration is distinguished.

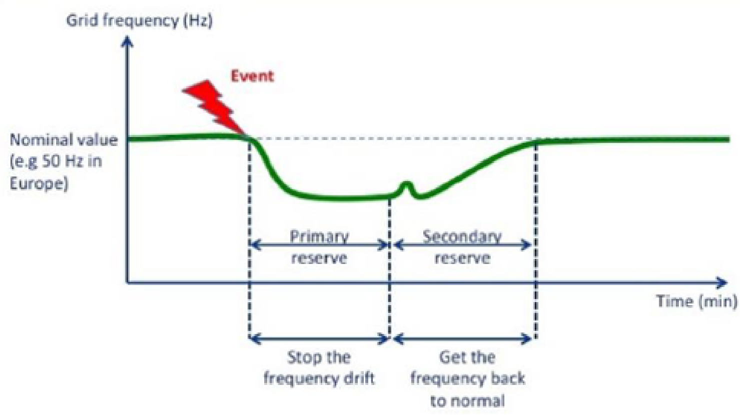

Figure 2.12: Frequency response under primary and secondary control [51]

Secondary control helps achieve stability by determining the optimal droop curve set-points for each scenario. In this way, an alteration of balance in generation and load comes associated with a secondary correction term that guarantees that the system always operates at the specified reference point. The equations below demonstrate this in mathematical terms and Figure 2.13 in graphical terms.

$$F_1: \quad f_i = f_0 - m_i P_i + \delta_i^f \tag{2.9}$$

$$F_2: \quad V_i = V_0 - n_i Q_i + \delta_i^V \tag{2.10}$$

where in F_1, f_i and f_0 are the frequency and its reference, respectively, m_i the primary droop coefficient for active power, P_i the active power output and δ_i^f the secondary control term for frequency. In F_2, V_i and V_0 are the voltage and its reference, respectively, n_i the primary droop coefficient for reactive power, Q_i the reactive power output and δ_i^V the secondary control term for voltage.

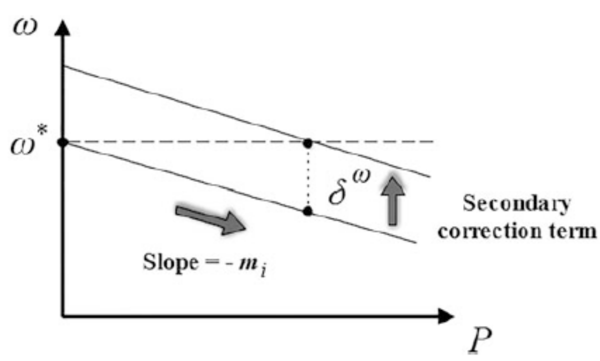

Figure 2.13: Primary and Secondary Control Actions [15]

The secondary term can assume positive and negative values and therefore any power deviations causes a shift of the no-load frequency/voltage. An increase in load (or a decrease in generation from other machine) will cause an upward shift, meaning that the power converter will be able to supply more power while still maintaining operation at the desired reference frequency/voltage (Figure 2.14). Likewise, a decrease in load (or an increase in generation from another machine) will provoke a downward shift to maintain stability (Figure 2.15). Do not forget, however, that frequency and voltage are never really kept constant at all times since secondary control takes time to act.

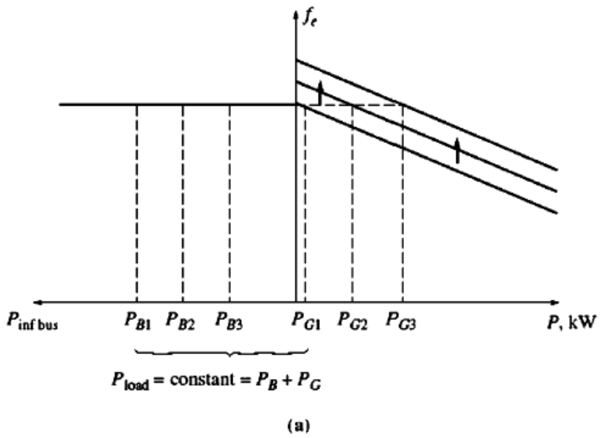

Figure 2.14: Secondary Control Actions in grid-tied mode [13]

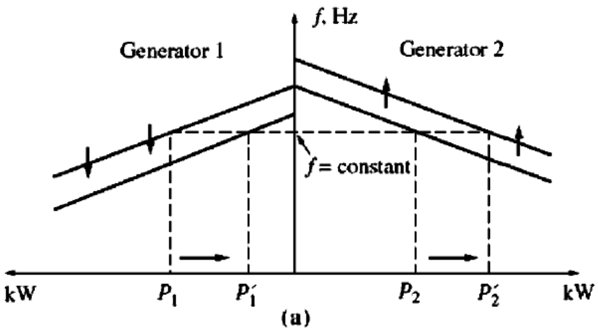

Figure 2.15: Secondary Control Actions in island mode [13]

Three main strategies can be followed in order to implement secondary control functionalities: centralized, distributed or without communications. The difference between them resides in the communication infrastructure utilized to coordinate the power converters and exchange information. Nevertheless, the mathematics behind each strategy's action commands are very similar, being adaptations of equations 2.9 and 2.10.

2.2.4.2.1 Centralized

According to [61], a centralized architecture follows a one-to-all communication scheme (star scheme) where there are no communications between power converters. All communications are channeled through the Microgrid Central Controller (MGCC), which receives the local measurement data and performs calculations, sending the respective set-points and command actions back to each Microsource Controller (MC) [71]. The MGCC is generally located at the bus that connects to the PCC (control bus) [64]. Measurements at the control bus allow to compute the secondary term by error deviations according to the following equations [61]:

$$F_1: \quad \delta_i^f = k_{pc}(f_0 - f_{bus}) + k_{ic}\int (f_0 - f_{bus})dt \tag{2.11}$$

$$F_2: \quad \delta_i^V = h_{pc}(V_0 - V_{bus}) + h_{ic}\int (V_0 - V_{bus})dt \tag{2.12}$$

where in F_1, f_{bus} is the frequency of the control bus and k_{pc} and k_{ic} are the control parameters of the frequency PI compensator. In F_2, V_{bus} is the voltage of the control bus and h_{pc} and h_{ic} are the control parameters of the voltage PI compensator. Parameters should be designed according to the desired response behaviour.

It is also possible to assign a reference to each MS or load sensitive bus and create a certain voltage profile if the microgrid topology is known [63]:

$$F: \quad \delta_i^V = h_{pc}(V^* - V_i) + h_{ic}\int (V^* - V_i)dt \tag{2.13}$$

where V^* is the reference voltage for MSi and V_i is the bus voltage at which MS_i is connected.

Advantages

- Pratical in terms of design, since the migrogrid is controlled as a single unit
- Allows voltage control of specific and critical nodes, which can be very useful.

Disadvantages

- Operation depends on the non-fallibility of a single device, requiring backups.
- No plug-and-play capabilities since introducing a new player requires updating the MGCC.
- Requires an extensive communication system, implying high costs and complexity.

2.2.4.2.2 Distributed

According to [61], a distributed architecture follows an all-to-all communication scheme where power controllers interact locally with their neighbours. The MGCC is often still utilized here to perform functionalities such as black start coordination and tertiary control [43]. Distributed approaches are classified according to the control calculation technique, with two methods being commonly utilized: average and consensus.

Average

In the average technique, the average frequency and voltage of the system is calculated by each converter via receiving the measured local values of its neighbours. By comparing the average to a reference value, convergence is forced and each DG is able to generate its own secondary term [61]:

$$F_1: \quad \delta_i^f = k_{pc}(f_0 - f_{ave}) + k_{ic}\int (f_0 - f_{ave})dt \tag{2.14}$$

$$F_2: \quad f_{ave} = \frac{1}{n}\sum_{i=1}^{n} f_i \tag{2.15}$$

where in F_1, f_{ave} is the average frequency of the system and in F_2, n is the number of power converters included in the control.

Since voltage is a local variable, proper reactive power sharing is harder to achieve. A proposed solution consists of adding a reactive power term to the voltage restoration term [65].

$$F_1: \quad \delta_i^V = \delta_i^{V_{ave}} + \delta_i^{Q_{ave}} \tag{2.16}$$

$$F_2: \quad \delta_i^{V_{ave}} = \alpha_{pc}(V^* - V_{ave}) + \alpha_{ic}\int (V^* - V_{ave})dt \tag{2.17}$$

$$F_3: \quad \delta_i^{Q_{ave}} = \beta_{pc}(Q_{ave} - Q_i) + \beta_{ic}\int (Q_{ave} - Q_i)dt \tag{2.18}$$

where V_{ave} and Q_{ave} are the average voltage amplitude and reactive power, calculated in the same way as 2.15.

Consensus

In the consensus technique, the secondary term is computed for each controller by utilizing two different error vectors (e_i and ε_i). One (e_i) compares the frequency of the controller with both its reference value and with its neighbours values. Another (ε_i) compares the secondary term generated with the secondary term of its neighbours [29] [61]:

$$F_1: \quad \delta_i = k_{co}\left(\int(\beta_{coi}e_i+\gamma_{coi}\varepsilon_i)dt - f_i\right) \tag{2.19}$$

$$F_2: \quad e_i = \sum_{j=1}^{m}(f_j - f_i) + \alpha_{coi}(f_0 - f_i) \tag{2.20}$$

$$F_3: \quad \varepsilon_i = \sum_{j=1}^{m}(\delta_j - \delta_i) \tag{2.21}$$

For the generation of the secondary voltage term, a combination of consensus frequency control and averaging technique voltage control has been proposed in [66]. It considers in its equation both a voltage error and a normalized reactive power error:

$$F: \quad \delta_i^V = \alpha_{pc}\int(V^* - V_i)dt + \beta_{pc}\int\sum_{j=1}^{n}a_{ij}\left(\frac{Q_j}{Q_j^*} - \frac{Q_i}{Q_i^*}\right)dt \tag{2.22}$$

where a_{ij} is the matrix that describes the communication links between agents (see [66] for more detail).

Advantages

- Reduced communication infrastructure complexity and costs when compared to centralized architecture. Notice that there is no need that all converters communicate with one another since interaction with a minimum number of neighbours will be sufficient to achieve robustness.
- Operation based on Multi-Agent System (MAS) solves the 'single-point-of-failure' problem of the centralized approach.
- It has high adaptability to different microgrid topologies.

Disadvantages

- High traffic data exchange and dependability on the communication system

2.2.4.2.3 No-Communications

According to [61], in a no-communications control scheme, the secondary term is calculated exclusively through local measurements and predefined references [76] [34]. A possible and simple solution is to implement a PI controller:

$$F: \quad \delta_i^f \quad = \quad k_p(f_0 - f_i) + k_i \int (f_0 - f_i)dt \tag{2.23}$$

where k_p and k_i are the parameters of the proportional and integral compensators.

A scheme like this requires a low pass filter to set the timescale for the secondary control, decoupling it from the transient response of the primary control.

$$F: \quad \delta_i^f \quad = \quad k_n \int (\alpha_n(f_0 - f_i) - \delta_i^f)dt \tag{2.24}$$

where k_n and α_n are the cut-off frequency and the gain of the filter. This implementation has a trade-off between accuracy and speed of response: a low secondary frequency represents an accurate frequency restoration but a slow response while a high one represents a fast response but a big restoration error.

When it comes to voltage response this approach requires the pre-study of the microgrid topology and load profile. Since no external commands can modify the predefined references, this strategy becomes only an option when loads are invariable.

Advantages

- Simple and cheap to implement.
- Provides plug-and-play capabilities.
- Not affected by communication issues (packet losses, noise) nor by inherent time-delays, enabling a very fast transient response.

Disadvantages

- Distributed parallel operation of integral controllers has power sharing problems due to the clock drifts of inverters and the hunting phenom.
- Reduced flexibility, requiring a pre-study of the MG topology.

It is important to understand that this control architecture is still an open research field that is being highly investigated in order to overcome its challenges.

2.2.4.3 Tertiary Control

Tertiary control is the last control level, operating in the largest time frame and seeking to optimize microgrid performance while assuring long-term objectives. Optimization objectives include minimization of operational costs, energy prices, power flow losses and CO_2 emissions as well as maximization of system reliability and renewable energy integration [73].

To do so, an Energy Management System (EMS) is employed to provide data management, grid supervision and control over all micro sources, storage devices and loads. The EMS receives as input data the load and weather forecasts, generators availability, market prices, SoC of the ESSs, operation and security constraints, power quality requirements, operational costs and state of the Energy Distribution System. As outputs it determines unit commitment (which generator will be activated and when), optimal power flows (generator set-points to minimize losses), load shedding intervals and microgrids imports/exports [48]. Figure 2.16 details the different modules that usually compose an EMS an their informational exchange.

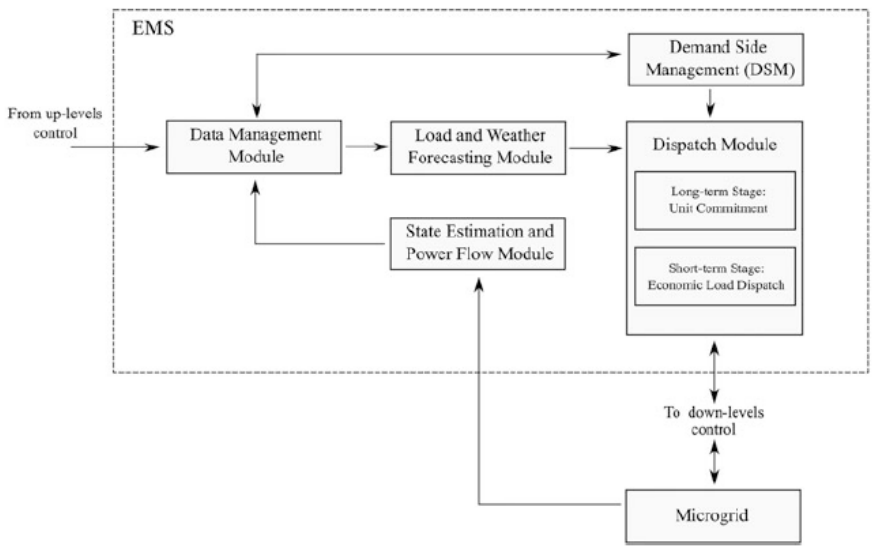

Figure 2.16: Generalized Structure of an EMS [73]

Calculations are usually made within two steps with distinct time frames. The first one is in respect to economic optimization and works with a 24h horizon. The second one relies on the results of the first to achieve technical optimization, working with a few hours horizon. Nonetheless, in both cases the calculus is done considering time intervals of 15 minutes.

In order for tertiary control to be applied efficiently, its scope should expand besides a single microgrid and instead be applied to an aggregate of several microgrids, eventually including the host grid. This way, economic optimization can be achieved globally and not locally, benefiting end costumers trough cheaper energy prices. Generally, the DSO/TSO is responsible for coordinating the EMSs [51].

2.2.5 Storage

Storage technologies are a key component of microgrids as they contribute with a wide range of functionalities and applications that boost its safe operation. A general description of those applications has been adapted from [57] and is highlighted below.

Frequency regulation: By injecting and absorbing electrical power ESS can help keep the balance between generation and load, thus helping to balance the system's frequency.

Voltage support: An ESS can act as a support voltage source to maintain the system voltage within its limits. In order to achieve this the ability to exchange reactive power is required. Since LV system are mostly resistive, this type of application is more effective when used locally.

Black start: Since ESS can act as highly controllable energy sources, they are ideal for the re-energization of microgrids and to keep its critical loads and communication channels operating.

Energy arbitrage: Storing energy when generation prices are low and selling energy when electricity prices are high grants economic savings or even gains.

Peak shaving: Similar to energy arbitrage but with a technical objective instead: to store energy when demand is low so that peak load can be guaranteed at a fair price. ESS for peak shaving are usually installed at the consumer side whereas energy arbitrage systems are located on the supply side.

Load following: Load can vary frequently and ESS can provide a rapid response to its changes by either discharging (if load increases) or storing (if load decreases), guaranteeing a more stable operation of the energy system.

Transmissions and upgrade deferral: Electrical energy demand is rising constantly an this causes an overload of power lines. Storage systems can be used to relieve the congestion of distribution circuits and postpone upgrades by reducing peak demand.

Spinning reserve: The spinning reserve is the section of the generation pool that does not take part in normal operation. If there is a general power shortage the ESS must be able to inject power for a long period until the system is restored.

Power quality: Due to the increased integration of RES and their intermittent nature, the power system is more vulnerable to voltage fluctuations and harmonics introduction. ESS are the go-to solution to respond rapidly to short-duration events and guarantee power quality.

Power reliability: Power reliability is the continuity of power quality for long periods of time as seen from the customer perspective. It follows that if ESS can steadily guarantee power quality, power reliability will derive as a consequence.

Technologies are characterized by their power and energy capacity, response and discharge time. Microgrid operation requires mainly storage systems with high power density and fast response times (some ms) to balance transient disturbances. A review of all types of storage technologies is addressed in [69] and [57]. Below a brief description of the most common MG ESS and their characteristics is presented. Table 2.2 is the culmination of a cross-reference between [5], [69] and [27].

Solid State Batteries: This type of batteries stores energy in chemical form. The basic concept consists of two electrodes of opposite charges that exchange ions with the electrolyte and electrons with an external electric circuit. The energy released is the difference between the bond energies of the metals, oxides, or molecules undergoing the electrochemical reaction. Currently, lithium ion batteries are the mostly used.

Superconducting Magnetic Energy Storage: In a SMES unit, energy is stored in a magnetic field created by the DC flow in a superconducting coil. Power output is available almost instantaneously and large capacity can be achieved. Due to self-requirement of power for refrigeration and high cost of superconducting wires, SMES systems are currently used just for short duration energy storage.

Flywheel: A FES is a mechanical unit that stores electrical energy in the form of rotational kinetic energy at a very high speed. Flywheels resist changes in their rotational speed by their moment of inertia. Charge and discharge of a FES can be done instantaneously trough a device similar to a turbine: when electrical energy is needed the spinning rate is slowed; when the device is to store energy its rotational speed is increased.

Supercapacitor: Supercapacitor is also named ultracapacitor or electric double layer capacitor (EDLC). It stores energy in the two series capacitors of the electric double layer, which is formed between each of the electrodes and the electrolyte ions. Without chemical process, electrical energy can be stored directly and thus the response time is very small.

Type	**Efficiency**	**Specific Energy (Wh/kg)**	**Specific Power (W/kg)**	**Response Time (ms)**	**Cycle Life**	**Cost ($/kWh)**
Lithium ion battery	92-100	150	250-340	-	1900	200
Superconducting magnetic storage (SMES)	95-98	30-100	1e4-1e5	5	1e6	High
Flywheel	95	5-50	1e3-5e3	5	>20,000	180-2500
Supercapacitor	95	<50	4000	5	>50,000	250-350

Table 2.2: MG Storage technologies comparison (retrieved from [27])

Different applications require different technologies and only by considering both requirements and characteristics, and undergoing testing and experimentation can suitability be defined. In [57] suitability is addressed for a wide range of technologies; Appendix A.1 contains an adaptation exclusively for Microgrids.

2.2.6 Multi-Microgrids

The further penetration of microgrids in energy systems causes networks to increasingly become an agglomerate of clearly defined and independent units with islanding capabilities. In this case, the aggregation of multiple microgrids expands its original concept and leads to a new one: the Multi-Microgrid [4].

This concept was introduced by the EU project MORE MICROGRIDS, which involved adapting and creating novel architectures for managing the increasingly complexity and dimension of distribution systems. Their proposed solution consisted of a high-level structure that enabled DG Medium Voltage exploitation under a highly controllable and flexible strategy. Since the multi-microgrid included a higher level of the distribution network, its coordination layers should had also reflect that, and a new layer was added to the already known microgrid hierarchical control scheme (Figure 2.17) [47].

This new architecture has the MGCC (which communicated directly with the DMS in a MG) interact instead with a new intermediate agent, the CAMC (Central Autonomous Management Controller), which is located at the HV/MV substation and is responsible for the MMG (Figure 2.18). This architecture has the advantage of alleviating the DMS burden and single-point fallibility by sharing complex tasks with new smaller control agents. The CAMC performs both steady state and emergy functionalities: tertiary control, demand side management, dispacth module and blackstart coordination [48] . The main disadvantage of this implementation is promoting the need and dependability on communication infrastructures with the introduction of more agents.

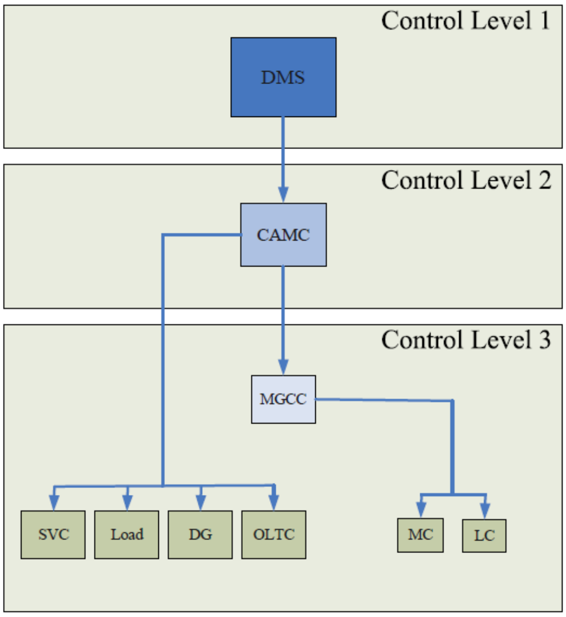

Figure 2.17: Hierarchical Control Scheme of a Multi-Microgrid System [47]

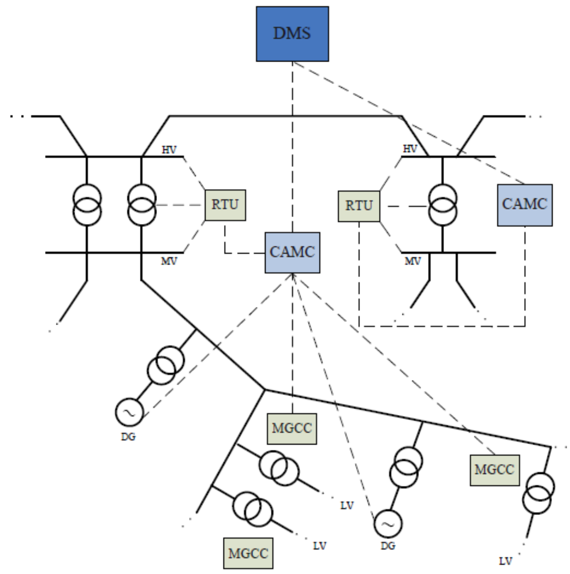

Figure 2.18: Control and Management Architecture of a Multi-Microgrid System [47]

Multi-microgrids fill the gap between the microgrid concept and the smart grid paradigm. Since they are simply a magnification of the former, they behave quite similarly. They also have two modes of operation (grid connected and islanded), blackstart capabilities and control functions organized in the same three-layer hierarchical architecture (primary, secondary and tertiary control). The DMS is likewise the highest authority when it comes to task delegation and action commands. The main difference resides in the nature of the distribution system. Microgrids are located in the Low Voltage network, which is tipically more resistive meaning that the decoupling between P-f and Q-V is harder to achieve and controllability through droop functions is less effective. The inductive nature of Medium Voltage systems allows for more accurate control loops in this regard, with Voltage-VAR control playing a key role in maintaining the power quality of operation. Nevertheless, the MV network is far more complex, including components that are usually not present in LV systems, such as OLTCs, capacitors, SVCs, STATCOMS, etc. The CAMC will be responsible for managing these devices, requiring that they are equipped with RTU that enable communications. Figure 2.19 illustrates the range of functionalities performed by the CAMC.

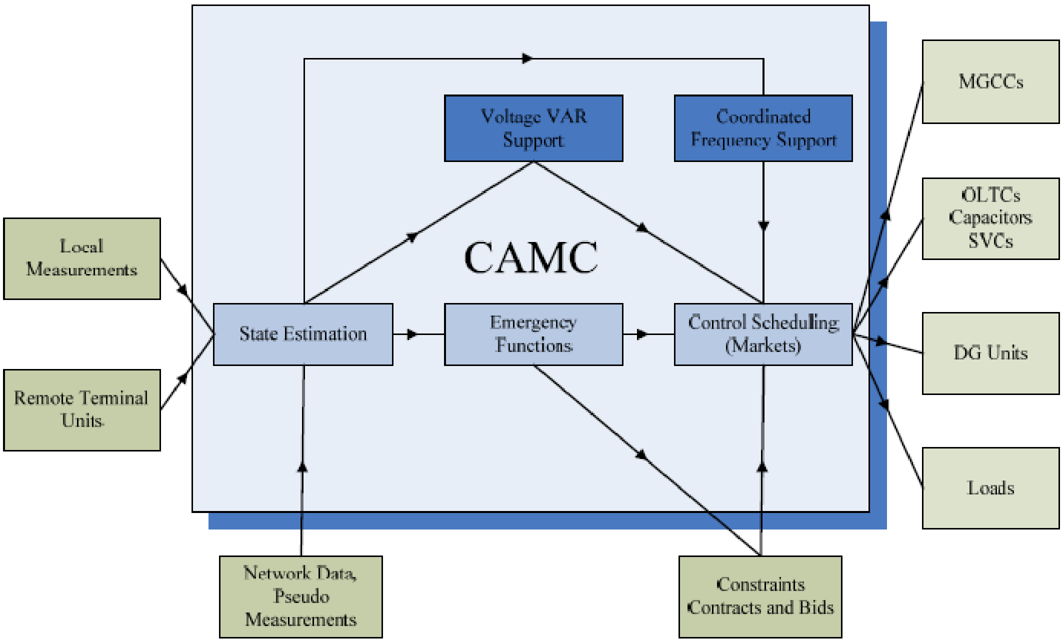

Figure 2.19: CAMC Functions [47]

It is important to note that MMGs are not only exclusively LV/MV AC systems and can also include LV MGs, MV MGs, DC MGs or AC/DC hybrid implementations (see 2.2.8). However, since this is a relatively new concept and not many entities have tried to clearly define it, the MORE MICROGRIDS project definition was used.

2.2.7 Blackstart

One feature that boosts MG and MMG reliability is their ability to perform a bottom-up blackstart. If following an upstream fault or a general blackout the MG is unable to continue operation in islanded mode, then the blackstart process can be initiated to reduce service interruption time. Conventional approaches used to rely on top-bottom strategies procedures for bulk power restoration that would take up to many hours and only allowed DGs to reconnect to the grid after stabilization was completely achieved. Due to the MG concept characteristics, energy restoration is now much simpler due to the reduced number of controllable variables, which has enabled full automation. The process is initiated by allowing microgrid islanded operation until the MV grid is available, and then promoting connection between multiple MG and the MV network in a MMG islanded operation until the HV grid becomes available. Nevertheless, launching a bottom-up blackstart is still very challenging, since the volatility of power electronic interfaces restrict the process to a very specific set of steps and requirements [47].

Requirements include the existence of auxiliary power reserves to power the communication infrastructure and controllable MS with BS algorithms. The general build-up strategy is to have several MS with BS capability start-up simultaneously, picking-up some local load in order to be stabilized in a multi-master control approach. The MGCC plays a crucial role in this process by assuring synchronization between the VSI [55]. Prior to the BS launch, a no-load network must be established so it is also necessary that all generators, loads, transformers, SVCs, etc., are equipped with RTUs that command open their switching devices. Since the build-up process involves step by step connection of MS, the short circuit current is not always constant and therefore protection devices must feature multiple short-circuit set-points that the CAMC/MGCC is responsible for changing according to the microgrid's setting. Energy storage systems are of great help in launching a BS, being able to provide the power reserve for communications or critical loads and helping to smooth oscillatory transients with their fast response. Beyond this essential requirements, the CAMC/MGCC should be equipped with a database to store the MG status prior to disturbance (load/generation, active/reactive set-points, DG with restart availability, etc.) so that the BS build-up addresses critical loads first and that after service reposition the system is lead to a state similar to prior disturbance.

In a MG, the BS procedure itself will be started by the MGCC after a pre-defined time interval of zero voltage in the Low Voltage distribution network as shown in Figure 2.20. Similarly, in a MMG the procedure will be started by the CAMC. The conditions embedded into the CAMC control algorithms define the sequence of actions to be performed during restoration, which were defined in advance trough mathematical simulation. The availability of a database in the CAMC/MGCC allows for minor adjustments and refinement of the control actions. A step by step energization generic sequence can be found for MGs in [55] and for MMGs in [47]. The latter is here described.

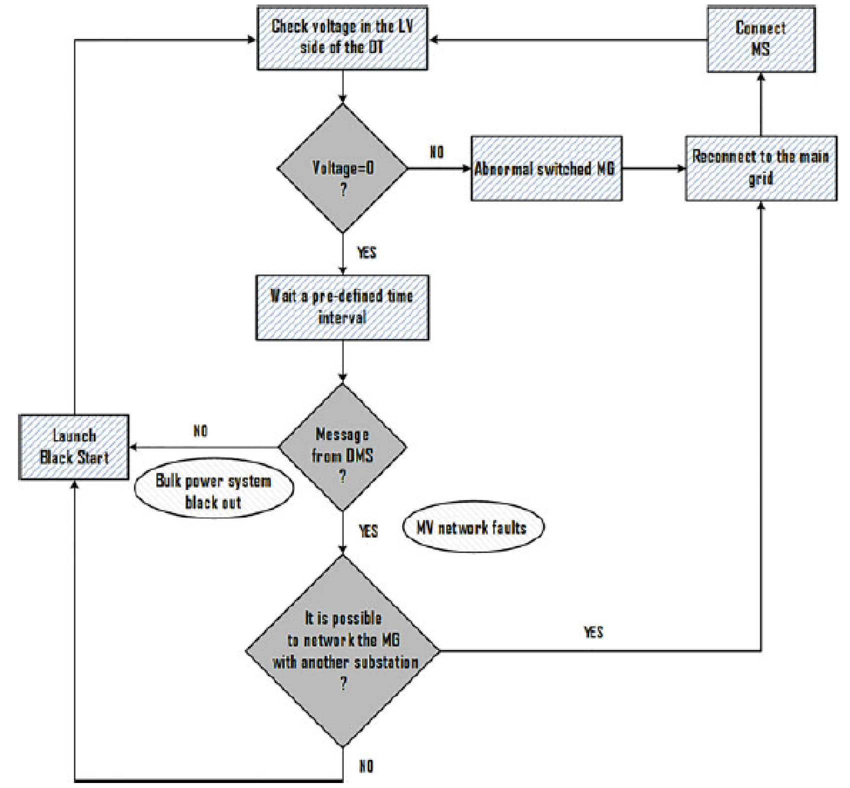

Figure 2.20: Flow chart defining the conditions to trigger MG black start procedure [55]

1. **Disconnect the MMG from the HV network, sectionalize HV/MV and MV/LV transformers, disconnect all feeders, loads and DG units, switch off reactive power sources.** This will avoid large frequency and voltage deviations during network energization.

2. **Sectionalize around each DG unit with BS capability.** Allowing each DG to gradually pick-up their own load will start MG build-up and stabilize operation. This will lead to the creation of dispersed small islands. In LV systems build-up is often started by ESS.

3. **Build the MV network.** A diesel group or another controllable source is initially utilized to energize the MV network and its most important loads.

4. **Synchronize MG islands with the MV network.** Small islands can now be synchronized with the MV network. The synchronization condition errors (phase, frequency and voltage difference) should be small enough to avoid large transient currents. Since MGs are able to perform their own BS procedure, connection at this point is not compulsory and might jeopardize the correct functioning of both the MV and LV network.

5. **Connect more load.** This step can be switched with the one above. The grid is now more robust and additional load can be connected to the system, always taking into account available generation capacity.

6. **Energize the remaining MV branches and MV/LV transformers.** Since there is generally a large number of unloaded transformers, this should be carried out in several steps.

7. **Connect uncontrollable DG units.** The MMG is now sufficiently robust and intermittent sources are allowed to participate in generation.

8. **Fully restore load.** At this stage the MMG network is fully energized and the remaining loads can be connected.

9. **Re-connect the MMG to upstream network.** Connection to the macro grid is possible when the HV side becomes available and the synchronization conditions are verified again.

2.2.8 Electrical implementations

MG and MMG can be implemented in many forms. Three aspects define their electrical design: current type, voltage rating and phase sequence. This section is a summary adaptation of [77]. For simplicity sake lets refer to MG and MMG simply as MG in this subsection.

2.2.8.1 Current type

Microgrids can be divided into three current types: AC, DC and AC/DC hybrids. These refer to actual bus types and not to MS or loads.

AC Microgrids

AC Microgrids is the classical implementation since it complies with the original structure of the power grid. In this case, all buses are AC and so DC MS or ESS must be connected trough DC/AC inverters. Examples of this implementation were already presented in section 1.1 in Figures 2.3 and 2.4.

DC Microgrids

DC microgrids seek to avoid the excessive need for power electronic interfaces and complex control algorithms [18]. They are composed entirely of DC buses and rely on DC/AC converters to make the connection to the PCC and the macro-grid (Figure 2.21). These are generally implemented for specific applications or customer owned facilities.

Advantages	Disadvantages
Lower power losses	Reduced real-life applicability
No reactive power flow	No zero current points makes it much more
No harmonics	difficult for breakers to open a circuit
No power factor correction	Complexity of protection system
Faster energy exchange with BESS	

Table 2.3: Advantages an Disadvantages of DC Microgrids, adapted from [50]

DC/AC Hybrid Microgrids

Hybrid microgrids have AC and DC buses, in an architecture that tries to draw the advantages from both previous topologies. Literature examples include [42], [75] and [45].

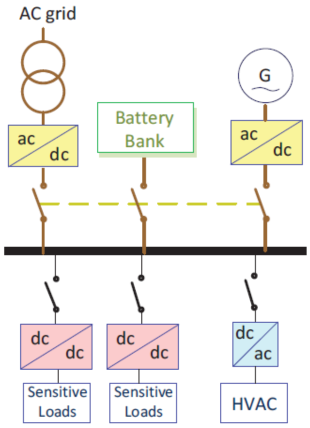

Figure 2.21: DC Microgrid [18]

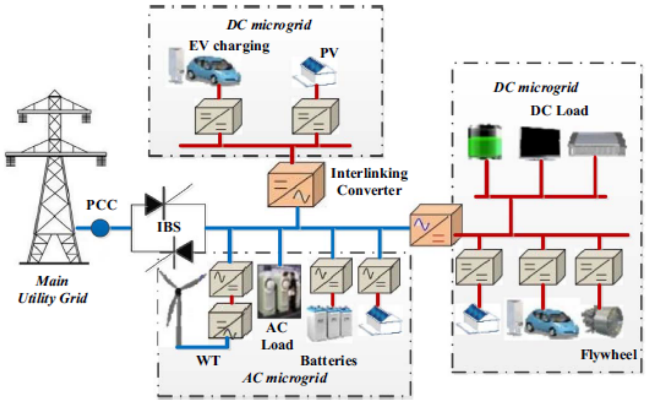

Figure 2.22: Hybrid MG [42]

2.2.8.2 Voltage rating

This is respectful to the voltage level of the microgrid. MGs are typically explored in LV networks, but exploration in MV or in both LV and MV combined is also possible. As described in section (section 2.2.6), the inductive nature of MV networks allows for more accurate droop control but coordination and operation is far more complex due to components that are not present in LV systems (OLTCs, capacitors, SVCs, STATCOMS, etc.).

Voltage Level	AC System	DC System
Extra Low Voltage	U <50V	U <120V
Low Voltage	U <1000V	U <1500V
Medium Voltage	U <45kV	
High Voltage	U <110 kV	U >1500 V
Extra High Voltage	U >110 kV	

Table 2.4: Voltage levels in Portugal [20]

2.2.8.3 Phase sequence

Microgrid wire systems can be categorized into three types: single-phase, three-phase or single-phase/three-phase hybrids.

Single-phase

In a single-phase MG, the network downstream of the distribution transformer is always composed of a single-phase 2 or 3 wire system: Phase and Neutral (always required) + Ground.

Three-phase

In a three-phase MG, the network downstream of the distribution transformer is always composed of a three-phase 4 wire system: 3 Phases + Neutral. Upstream of the transformer (MV network) there is always a three-phase 3 wire system composed of 3 Phases.

Single-phase/ Three-phase Hybrid

In a hybrid-phase MG, both previous modes are present and the system has increased flexibility of operation, benefiting economy of supply and reliability.

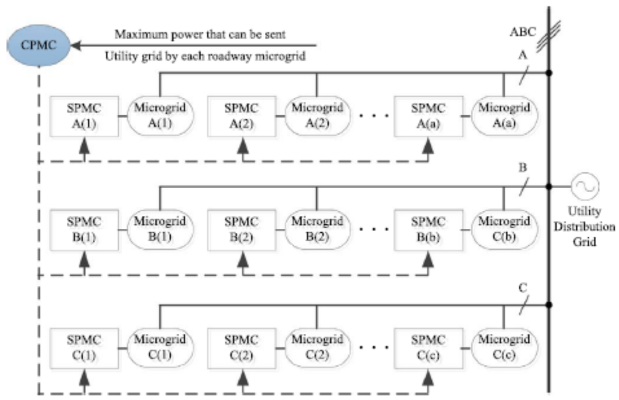

Figure 2.23: Single-phase MG [77]

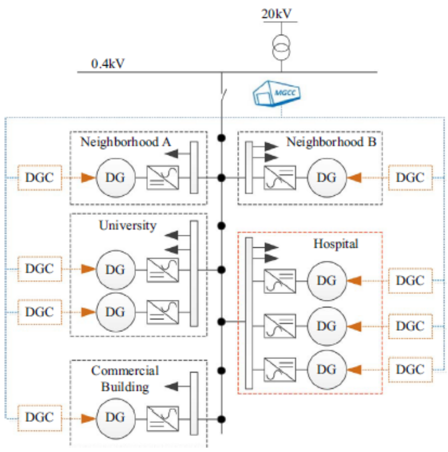

Figure 2.24: Three-phase MMG [53]

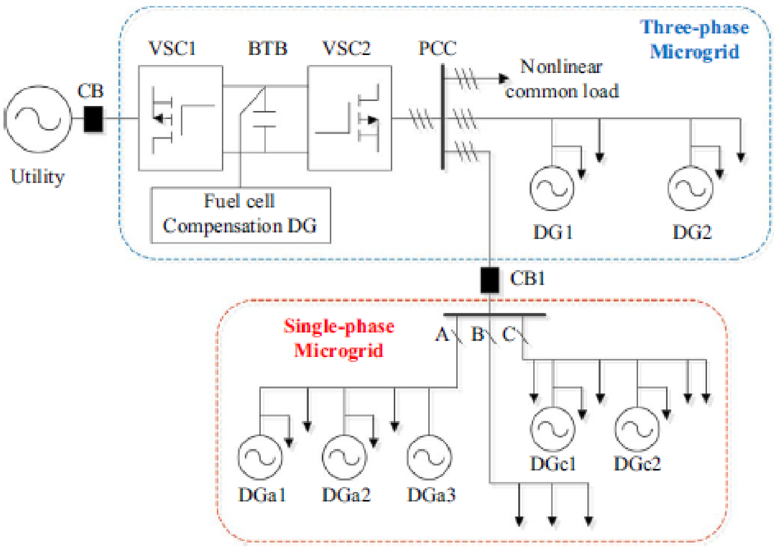

Figure 2.25: Single-phase/ Three-phase MG Hybrid [68]

2.2.9 Project Examples

At the moment, most developed regions (Europe, USA, China, Japan) have completed basic research regarding MGs and have successfully established demonstration projects and experimental platforms [26] [23].

The European's FP7 and H2020, for example, financed multiple projects in the area of 'Smart Energy Networks'. The objective of this projects was to increase efficiency and reliability of power systems trough their transformation into interactive customers/operators service networks while deploying large-scale DER. Some projects include:

- FENIX (FP7) - 'Flexible Electricity Networks to Integrate the Expected Energy Evolution'
  `http://www.fenix-project.org/`
- SUSTAINABLE (FP7) - 'Smart Distribution System Operation for Maximizing the Integration of Renewable Generation'
  `http://www.sustainableproject.eu/`
- ADRESS (FP7) - 'Active Distribution Networks with Full Integration of Demand and Distributed Energy Resources'
  `http://www.addressfp7.org/`
- UPGRID (H2020) – 'Real proven solutions to enable active demand and DG flexible integration, through a fully controllable LOW Voltage and medium voltage distribution grid'
  `http://upgrid.eu/`
- SENSIBLE (H2020) – 'Storage-Enabled Sustainable Energy for Buildings and Communities'
  `https://www.projectsensible.eu/`

There are also multiple other projects regarding different applications such as remote area energization, residential area optimization, office buildings economization, and experimental validation. Literature [77], [33] and [44] highlights reference projects in many of those areas. A comparison of demonstration and real-world microgrid cases around the world, ordered by known year of completion is presented here [67]. This dissertation focuses on laboratory experimental validation only.

Chapter 3

Laboratory Design

3.1 Introduction

Power system evolution requires the construction of facilities that enable testing possible upgrades and the implementation of new distribution concepts/mechanics with high-end technology. Experimental studies at these laboratories are at the forefront of industrialization development, pushing standard creation and anticipating future requirements [36]. This chapter outlines worldwide infrastructures in the scope of SG, MG laboratory testing.

3.2 An outlook on worldwide laboratories

3.2.1 Research topics

Before addressing laboratory infrastructures and design it is important to have a worldwide picture of the most currently researched topics in respect to the power system revolution. This is crucial to understand the multidimensional scope of these areas.

In this regard, the European Commission Joint Research Centre (JRC) has under-carried for the third straight year (2015, 2016, 2018) a survey to collect information regarding worldwide laboratories activities and enterprises: the Smart Grid Living Lab Inventory. In 2018 they were able to reach out to 89 different laboratories, 69 of which located in Europe [7]. The survey divided topics of research into 12 different categories and asked each laboratory to identify which ones they focused on, resulting in Table 3.1.

Note that most laboratories work on multiple categories and that activities may overlap in many categories, leading to the high percentages obtained. Subsequently, the laboratories were asked to specify the topics of investigation within each of the activities they previously selected. Results of the survey were highly compacted and inserted into Tables 3.2 and 3.3. Specific topics of research results are ordered according to the percentage of laboratories that mentioned them (see appendix A.1).

Category	Percentage
Generation and DER	85.2
Grid Management	75
Demand Response	75
Storage	70.5
Smart Home/Building	62.5
Information and Communication Technologies	62.5
Electromobility	61.4
Distribution Automation	59
Smart City	50
Advanced Metering Infrastructure	45.5
Market	44.3
Cyber Security	61.4

Table 3.1: Percentage of Labs per activity [7]

Activity	**Specific Topics of Research**
Generation and DER	PV, Wind energy, CHP, Hydro, Fuel cell, Biomass, Concentrated solar, Gas power plants, Nuclear PP, Coal PP, Tidal
Grid Management	Monitoring and diagnosis tools, Automated critical management, Big data analysis
Demand Response	DER integration. Storage, Smart home/building, DR management systems, Automated DR, EVs, Demand modelling, Generation, Grid load, AMI, Pricing, Customer energy management systems
Storage	Demand shifting and peak reduction, Voltage support, Frequency regulation, Variable supply resource integration, Load following, Off-grid, T/D congestion relief, Arbitrage, Blackstart, T/D infrastructure investment deferral, CHP, Spinning reserve, Seasonal reserve, Non-spinning reserve, Waste heat utilization
Smart Home/Building	Energy management strategies/Cost-control, Demand response, Integration of RES, Smart appliances, Temperature control, Power quality, Interoperability, Lightning, safety, Movement sensors, Security, User account and billing
ICT	Substation LAN, WAN, FAN, HAN, NAN, PAN
Electromobility	V2G, Energy storage, Charging technologies, Grid load impact, Demand response, Energy efficiency, Power quality, Interoperability, Energy management and vehicle autonomy, Car battery technologies, Environmental impact (pollution, noise), Citizen behaviour, Safety, Heating and ventilation and air-conditioning, Security, Pricing and billing
Distribution Automation	Automation of distribution networks, substation automation, Self-healing networks, Power converters, Integration of DG, Voltage control and reactive power, Reliability, Efficiency

Table 3.2: Specific topics of research per activity (Part 1)

Activity	**Specific Topics of Research**
Smart City	Energy generation, ICT, Energy storage, Mobility (traffic, transport, parking), Lightning, Environment (pollution, noise, temperature), Government (administration, buildings)
AMI	Monitoring, Demand response, Communications, Interoperability, Management, Customer information, Security, Installation and configuration, Electromagnetic compatibility, Pricing, Billing, Safety
Market	Market structure, Impact of RES integration on electricity prices, New regulation schemes for deregulated actors, Analysis of market barriers in smart grids, Novel trading schemes, Transmission and distribution intelligence, Structure of Generation, Trading Systems, Marketplace, Modelling of new financial frameworks, Structure of the electrical supply industry
Cyber Security	Integrity, Confidentiality and privacy, Authentication, Incident response, Risk assessment, Identity, Authorization, Contingency planning, Risk response, Forensics

Table 3.3: Specific topics of research per activity (Part 2)

The table above illustrates the amount of effort that is being done worldwide to push forward the transformation of power systems. Given this panoply of research topics it is uneconomical for a single laboratory to cover all areas and therefore specialization is necessary. This has lead to multiple joint ventures and partnerships between players that seek to gain leverage in shared knowledge. A reference example on this type of partnerships is DERlab.

DERlab (Distributed Energy Resources Laboratories) is an umbrella organization with a total of 33 laboratories as members. It seeks to accelerate the development and deployment of smarter, cleaner electricity grids through DER technologies and quality criteria for its connection and operation to power systems. DERlab grants its members the opportunity to evaluate pre-competitive technologies in a wide range of Smart Grid use cases. Individual members drive research and create value according to their own unique settings but through common test procedures; results are later made available to other members.

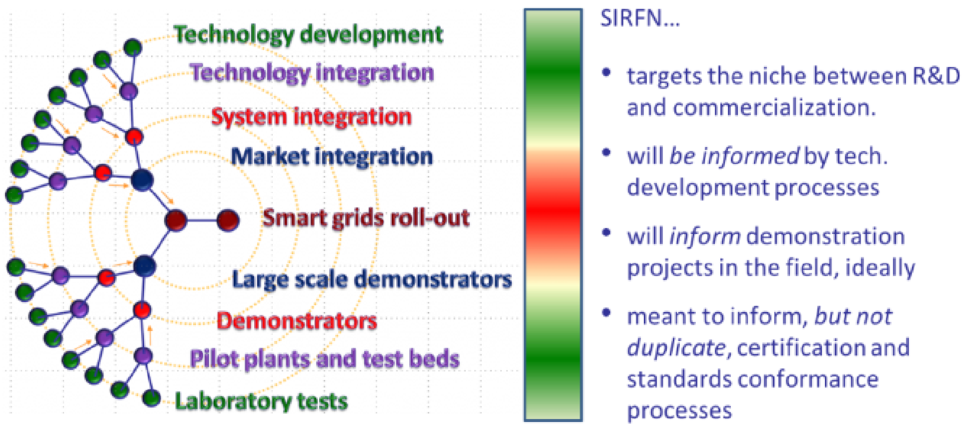

Figure 3.1: SIRFN platform (programme under DERlab administration)

3.2.2 Infrastructure

This section provides a general outlook on the main infrastructure of Europe's leading laboratories. The image below was retrieved from DERlab's Activity Report of 2016/2017 [19], which compiled information related to the facilities and capabilities of all its members.

Figure 3.2: DERlab Research Infrastructure [19]

Notice that this corroborates the results obtained in the Smart Grid Living Lab Inventory (2018) despite the differences between polled parties. Generation and DER related infrastructure are the most explored areas (PVs, Power Eletronics and Inverters) followed by grid management, DR and storage (Hybrid Systems Microgrids, Smart Metering and Storage); areas such as Biomass and System Security being the least explored.

For more information on specific equipment, power range, standard compliance, simulation tools and offered testing services, DERlab maintains a website that can be freely consulted [16].

3.2.3 The Living Lab approach

Living Lab is a concept used to describe a user-centered open innovation ecosystem. Many laboratories are promoting public-private-people partnerships that involve both stakeholders and end-users on performance tests. This constitutes an experimental environment where citizens and companies have the opportunity to engage and help design their own future. This significantly boosts prototyping and validation, leading to refined new policies and regulations before product impact is felt by the public [6].

Within the current context of smart grids and electric vehicle technologies, the behaviour of end-users will increasingly affect the utilization mechanics and effectiveness of certain energy innovations. Testing techniques are developing a dynamic component where an equipment is experimented against real life conditions that recreate the environment where the product is intended to be inserted to de-risk its market integration both technically and economically. This can be done, for example, with the auxiliary of Information and Communication Technologies (ICT) and Human Machine Interfaces (HMI) by aquisition of heterogeneous sets of data [24].

Living Lab applications are broad and implementations can vary drastically depending on the area of work. Some typically researched topics are Smart Cities, Energy, Mobility, Education, Social Innovation, Health & Well being, etc. However, four common elements can be identified within all areas, which define a Living Lab:

- **Co-creation:** bringing together technology push and application pull into a single environment where multiple partners share their knowledge and expertise.
- **Exploration:** new engagement approaches between stakeholders and user community.
- **Experimentation:** discovery of new applications and behaviours through live or simulated scenarios alongside data collection.
- **Evaluation:** Analysis of the experimentation phase and assessment of product performance and suitability against target environments.

This subsection might seem somewhat out of scope with the rest of the thesis. However, since this document is directed at new players seeking to assemble a new laboratory, it is most relevant that they are introduced to the concept of a Living Lab and are given an example of open-innovation.

Example: Green Tech Center in Denmark

Green Tech Center is a Living Lab in Vejle, Denmark that is operational since 2014 and aims to provide the means for Smart Grid concepts to quickly integrate the market [3]. GTC works mainly in the areas of Smart Buildings, AMI, DER, storage and electromobility. Despite not being the most advanced in terms of SG technology, it is a perfect example of open innovation. The facilities are available for products to be tested and demonstrated by developers, public authorities, educational institutions, installers, customers or investors. GTC is a triple helix collaboration (Business, Public Entities and Scientific Institutions) between 9 parties.

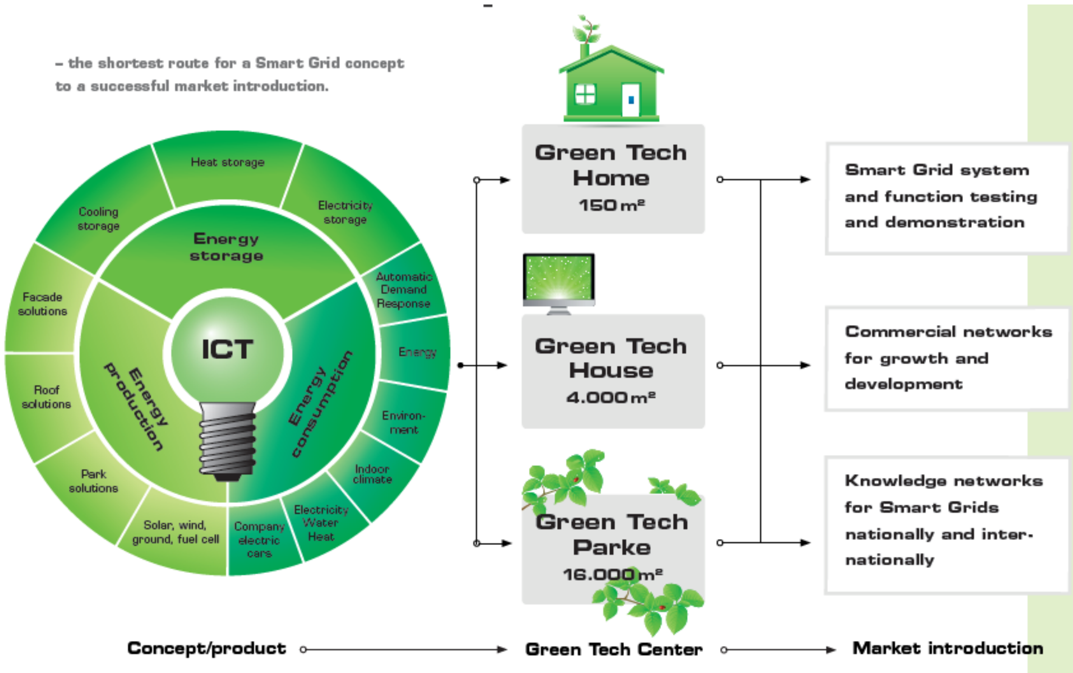

Figure 3.3: Green Tech Park structure and applications [3]

As illustrated in Figure 3.3 the facility is divided into 3 main buildings that offer testing of different solutions:

- **Green Tech House:** This building hosts 200 employees and has been prepared for future Smart Grid solutions in energy production, storage and management of office buildings. It contains data loggers for energy monitoring down to the individual workplace and a Building Management System with intelligent control that can be open tested and demonstrated from the 'tech room'. It is also equipped with information systems for behaviour tests as well as inside and out controls for electricity, heat and cold storage and EVs. The roof is prepared for the installation and testing of various RES technologies. 40% of the building is available for individual desk renting, while the remaining is reserved for energy companies and institutions that work there full-time.

- **Green Tech Park:** 16,000 m2 energy park (Figure 3.4) which possesses multiple micro generation technologies (solar panels, CSP, wind turbines, geothermal and fuel cells), district heating and gas transport (hydrogen). Electric vehicle charging stations with monitoring systems are also available for employers and employees. Here, a product (e.g. a wind turbine, EV) can be quickly installed and the effect of it in the rest of the system can be visualized in the control room which gathers and processes all this data.

- **Green Tech Lab:** This building is designed to support entrepreneurs and companies to test and demonstrate their prototypes. It has laboratories, prototype workshops and training rooms. In the control room it is possible to monitor all the data from GT Park and GT Home.

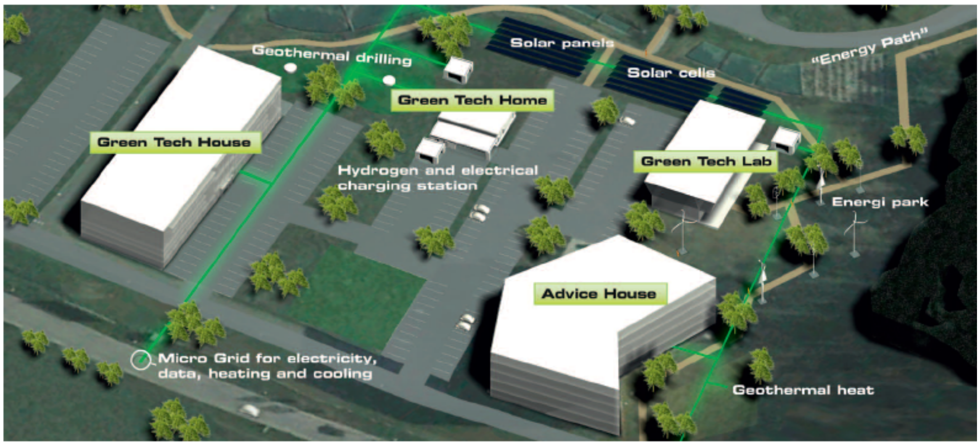

Figure 3.4: Green Tech Park [3]

3.3 Laboratories description

This section describes the main features of three laboratories that are highly renowned for their contributions in the Microgrid research field.

The facilities described are:

- The Microgrid Research Laboratory at Aalborg University;
- The Electrical Energy Systems Laboratory at the National Technical University of Athens;
- The Smart Grid and Electric Vehicle Laboratory at INESC TEC.

These three were specifically selected due to having features that foreshadow pioneering on MMG testing, the distinctiveness in their approach and also availability of information.

Regarding this last aspect, not too many laboratories provide a general overview of their infrastructure and control design. Most published articles are specifically related and unveil only equipment and capabilities related to certain applications. This section comprises mainly information that is described in detail in the following three documents (with respect to each laboratory): [53], [54] and [35].

3.3.1 MGRL at Aalborg University

The Microgrid Research Laboratory (MGRL) in Aalborg, Denmark seeks to implement real-time control and optimal energy management solutions for Microgrids. Their workbench, as depicted in Figure 3.5, allows to set multiple configurations in grid-connected and island modes of operation as shown in Figure 3.6.

Their main equipment comprises a 80kVA bi-directional power supply, a 45kVA grid simulator, multiple *Danfoss* converters, transformers, an advanced metering infrastructure (AMI) and intelligent electronic devices (IEDs). Photovoltaic panels, a small wind turbine and a Flywell ESS are also located outside of the building but most often DC sources are emulated by the bi-directional power supply.

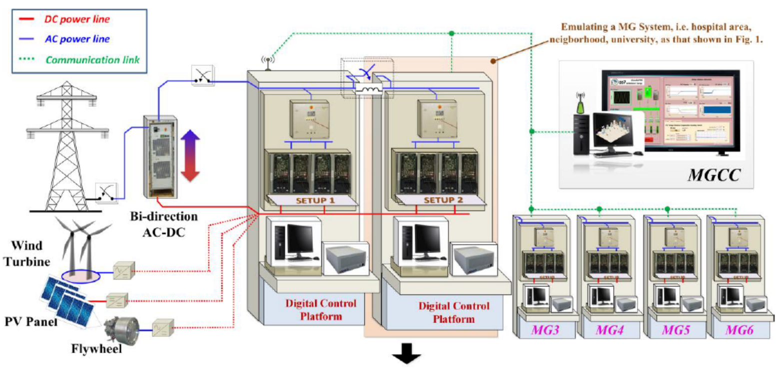

Figure 3.5: Laboratory workbench [53]

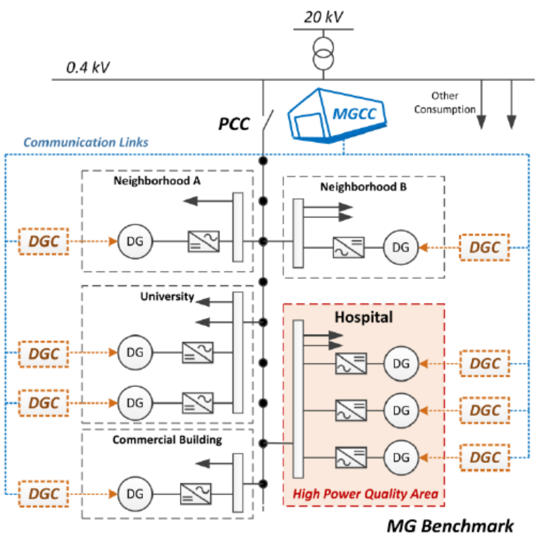

Figure 3.6: MG Cluster [53]

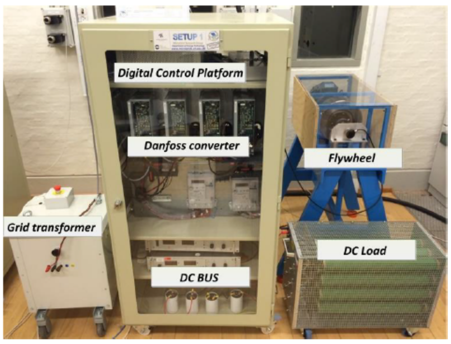

Figure 3.7: Individual setup [53]

The AC side of each inverter connects to a common load bus trough a series of contactors and filters, as illustrated in Figure 3.8 and this is how multiple configurations can be set. According to [53], the laboratory is adapted to replicate independent MG behaviour by having each inverter emulate a MG setup. Each setup can pursue it own objectives, by means of being controlled individually through a digital platform (PC), Figure 3.7. However, no more details are given on this topic on the document and no results of independent operation and nor published articles were found, so one must be cynical about these capabilities. Nevertheless, if they were to be true, it would constitute an important step towards MMG testing.

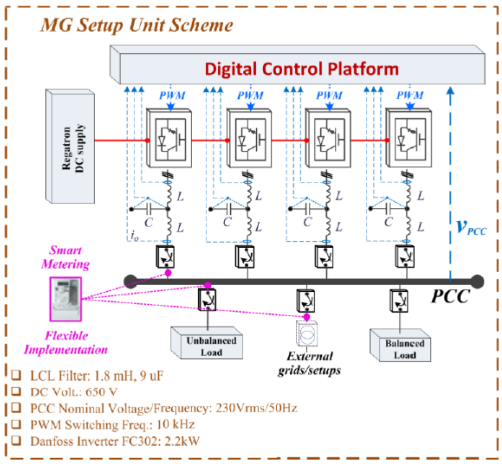

Figure 3.8: Individual setup detail [53]

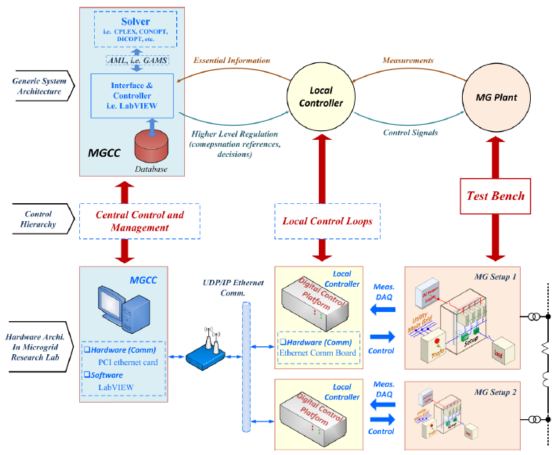

Figure 3.9: Control scheme [53]

Control Architecture

The control architecture follows a centralized three-level hierarchy (Figure 3.9). The primary layer is implemented locally on DG controllers (droop loops for power sharing and voltage control) and the secondary and tertiary layers in an MGCC. The secondary control layer provides adjustments and compensation references to act over the primary layer whereas the tertiary layer defines the optimal set-points to achieve efficiency of operation. Within subsequent layers the bandwidth decreases in order to decouple the dynamics of each control (see section 2.2.4 for reminder).

Local controllers directly measure and act on components, such as DGs and loads (*MG Setup* block). They receive commands and transmit information to the MGCC. The latter is equipped with a database for data analysis, prediction and scheduling purposes [53]. Also, at its core is an EMS capable of solving complex mathematical problems and a HMI interface that provides information on the MG setup, DG/load status and allows alteration of the secondary control parameters (Figure 3.10). An interesting aspect of the architecture implemented is that it also offers the possibility of implementing a distributed control strategy (consensus type): the MGCC algorithm can ’transfer’ secondary control functions to the local side, creating a Multi-Agent System.

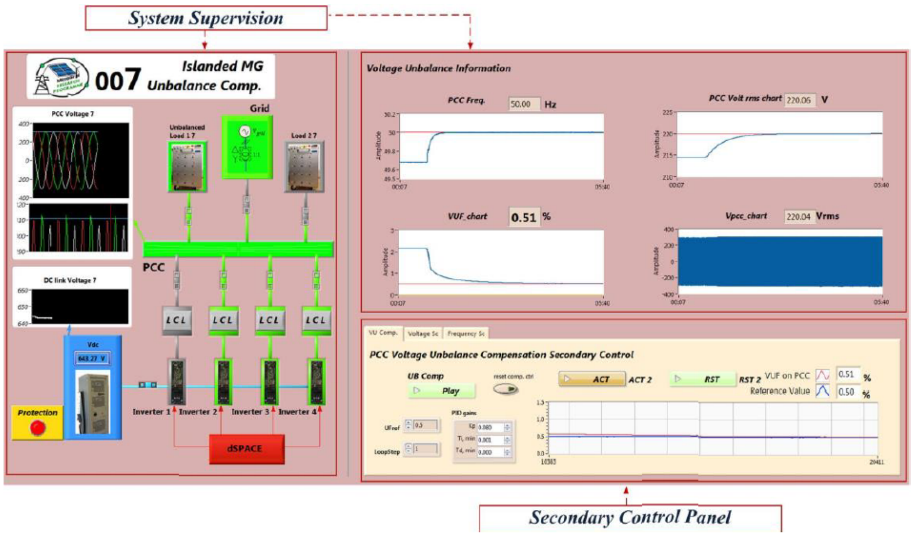

Figure 3.10: Supervision system interface [53]

Data Collection & Communication System

The laboratory is equipped with an Advanced Metering Infrastructure (AMI) formed by smart meters, data concentrators, a database system and a software for user interface (LabVIEW). The smart meters are setup as illustrated in Figure 3.8 and supply information regarding voltage, current and power per phase; power quality indexes and time stamps on power failures, over-voltages and under-voltages; detection of sags, swells, total harmonics distortion (THD) and voltage unbalances. The meters can provide on demand readings for short term events or programmable automatic readings (AMR) for long term events (maximum resolution of 5 minutes interval) which are saved in two distinct databases and can be used to recreate scenarios or load profiles.

Communication within SM and with the data concentrator is made via radio mesh (based on standard EN 13757-5). The data concentrator receives all the information from the meters and transfers it to the data storage system using Ethernet, GPRS or 3G (based on DLMS/COSEM standard). Communications between the MGCC and DG controllers is done trough wired and wireless ethernet links based on UDP/IP.

3.3.2 EES at University of Athens

The Electrical Energy Systems laboratory and the Electrical Machines laboratory, located both at the National Technical University of Athens (NTUA), combine to form a facility equipped with two single-phase microgrids and one three-phase microgrid.

Their main equipment consists of a Real Time Digital Simulator (RTDS), a 15kVA three-phase PHIL converter, lead-acid batteries, real photovoltaic panels, a small wind turbine, controllable loads, multiple power electronic converters and a SCADA system. Its schematic is presented in Figure 3.11.

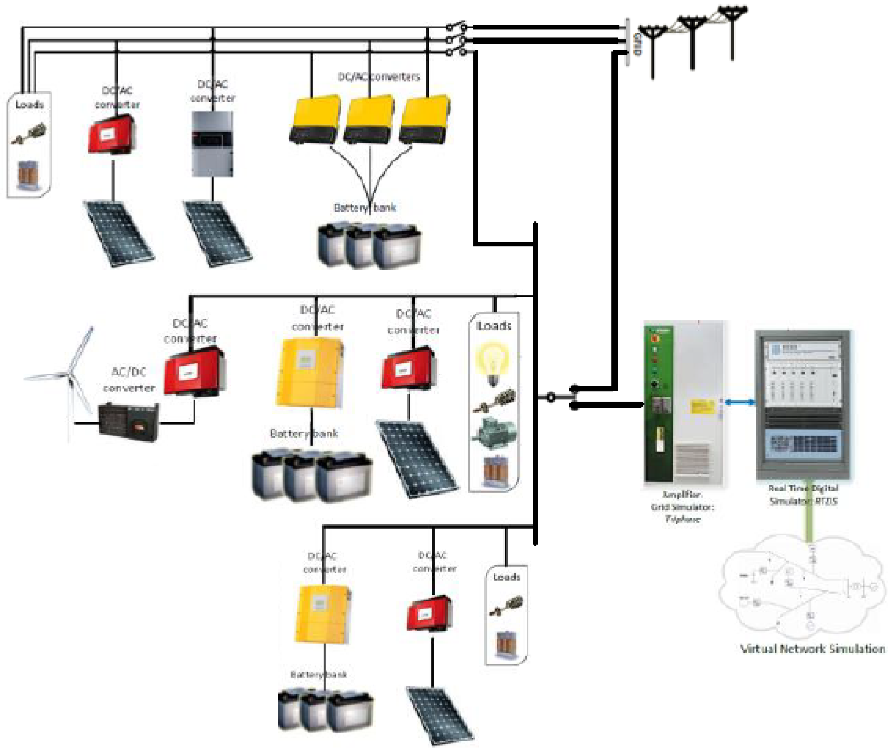

Figure 3.11: Multi-Microgrid scheme [54]

The PVs, battery units and wind turbine connect to the AC grid respectively via Sunny Boy, Sunny Island and Whisper DC-AC inverters. The converters are controlled to enable both grid-tied and stand alone operation with a seamless transition from one mode to another.

PHIL is a very interesting approach for testing since it provides a bridge between simulation environments and hardware devices, opening up innumerable possibilities. (The theory behind PHIL is described in section 5.1 and will not be addressed here). The RTDS rack at NTUA works with the dedicated software *RSCAD* and has several analogue and digital input/output ports that allow multiple components to be connected (generators, loads, transformers or protection devices).

Control Architecture

It is important to mention that in 2014 the control strategy only applied to single microgrid (single-phase), as illustrated in Figure 3.12. The authors of [54] envisioned a future setup capable of integrating the three MGs together but as of 2019 no further information was found on the topic.

The control architecture follows a distributed MAS layout where components (inverters and loads) are governed by intelligent Power Meters (PM) with communication capabilities. Their algorithm was implemented with JADE (JAVA platform) and ultimately depends on the requirements of the corresponding application. Many implementations follow a peer-to-peer (P2P) design where the agents to be controlled exchange information exclusively with their adjacent nodes. This topology is effective to test the quality of different telecommunication links.

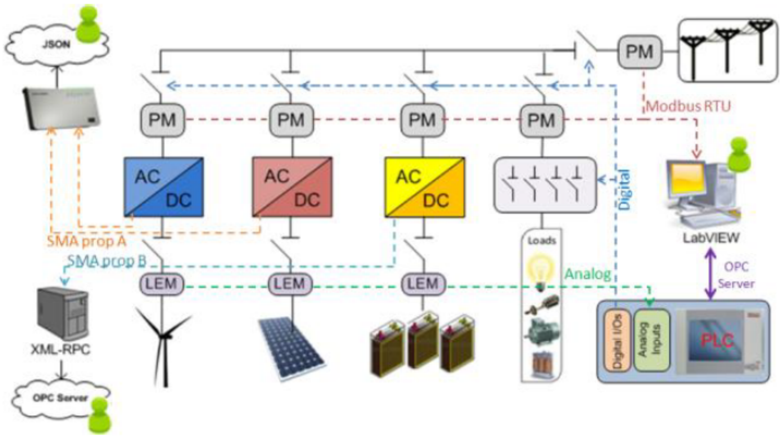

Figure 3.12: Control scheme [54]

Data Collection & Communication System

The PM are used to monitor the AC side of the system and are equipped with multiple analog digital I/O. They communicate with other PM via TCP/IP and with the central PC through Modbus via RS-485. At the central PC a SCADA system is used for data acquisition, monitoring and high level control. This system is implemented trough a PLC (Programme Logical Controller) and communicates with it through an OPC server. At the DC side, measurements are collected via LEMs that connect analogically to the PLC. The latter communicates them to the SCADA and receives back commands detailing the state of system relays. In this way, the PCL is able to remotely connect/disconnect power sources and loads. LabVIEW is used to store the measurements from the PM and to provide a graphical interface where the user can specify active/reactive power setpoints and manually control the loads (Figure 3.13). This software can also be used to implement programmable load curves for MG long term testing (e.g. a week).

Figure 3.13: HMI for PM using LabVIEW [54]

3.3.3 SGEVL at INESC TEC

The Smart Grid and Electric Vehicle Laboratory (SGEVL) is located in Porto, Portugal at the Institute for Systems and Computer Engineering, Technology and Science (INESC TEC). It conducts research on commercial control and management solutions for DER, SG and EV.

The laboratory possesses a reconfigurable LV panel comprising two microgrids, each with 3 separate buses and 15 accessible connection nodes, as illustrated in Figure 3.14. This system uses a cable simulator and a contactor based system to alter and define its MG network topology. Connection with the main LV grid is made through the bus A. Among the available equipment, SGEVL disposes of a 15kVA PHIL setup that interacts with an OPAL-RT^{TM} (RTDS), a 15kW 4-quadrant DC power source, real PVs, a micro wind turbine emulator, FLA batteries, transformers, multiple power electronic converters, two electric vehicles, controllable loads, a SCADA system and a smart meter infrastructure.

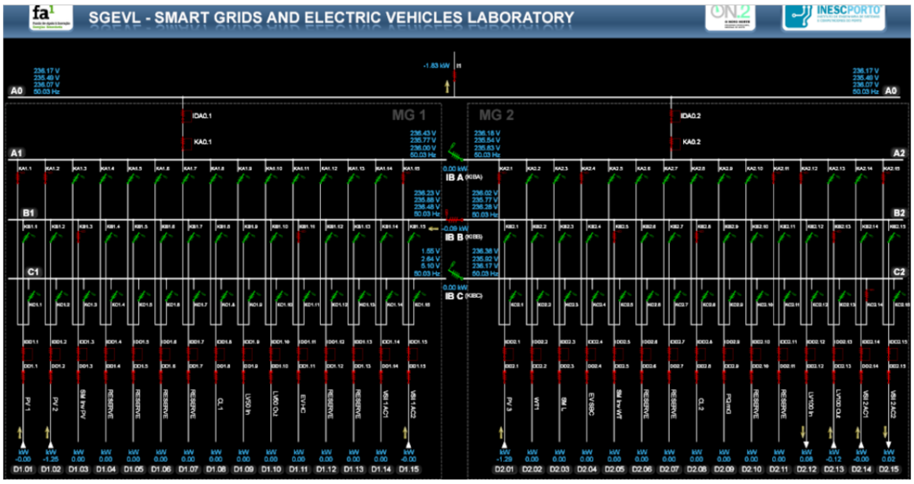

Figure 3.14: Reconfigurable network

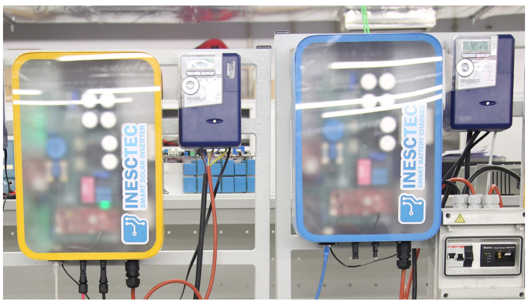

Figure 3.15: PV inverter (left) and BESS inverter (right)

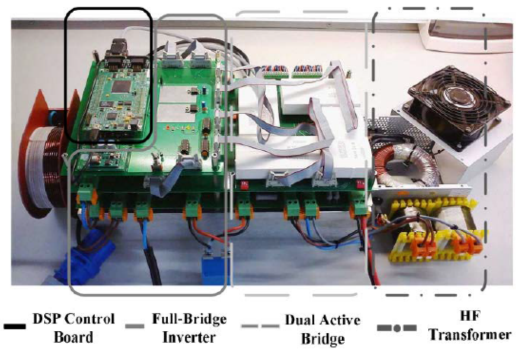

Figure 3.16: Bidirectional EV charger prototype

The PVs and the battery units can be connected to the AC grid respectively via commercial Sunny Boy and Sunny Island inverters or through the inverters developed at INESC TEC, which are depicted in Figure 3.15. Four quadrant inverter prototypes are also available, enabling remote control of injected and absorbed active power and allowing emulation of a controlled MS, load or ESS. The EV available (Renaullt Twizzy and Renault Fluenze) are connected trough a bidirectional charger also developed in-house (Figure 3.16).

Control Architecture

The control architecture follows the centralized scheme depicted in Figure 3.17. Management and operation is done by the MGCC whose objective is is to control frequency and voltage levels and coordinate emergency procedures. This is done by receiving measurements and sending droop configuration parameters to lower control levels through the SM infrastructure (Figures 3.18 and 3.19) [27]. Functionalities associated with tertiary control (e.g. energy balance, billing) are also embedded in the control algorithm of the MGCC. Implementation and development of this component was done at INESC TEC via Phyton programming language.

The MGCC communicates with a SCADA system whose goal is to supervise all operations and define the MG topology. This is done by communicating with the SM through a Data Acquisition System (DAS) that also has a database for storing data.

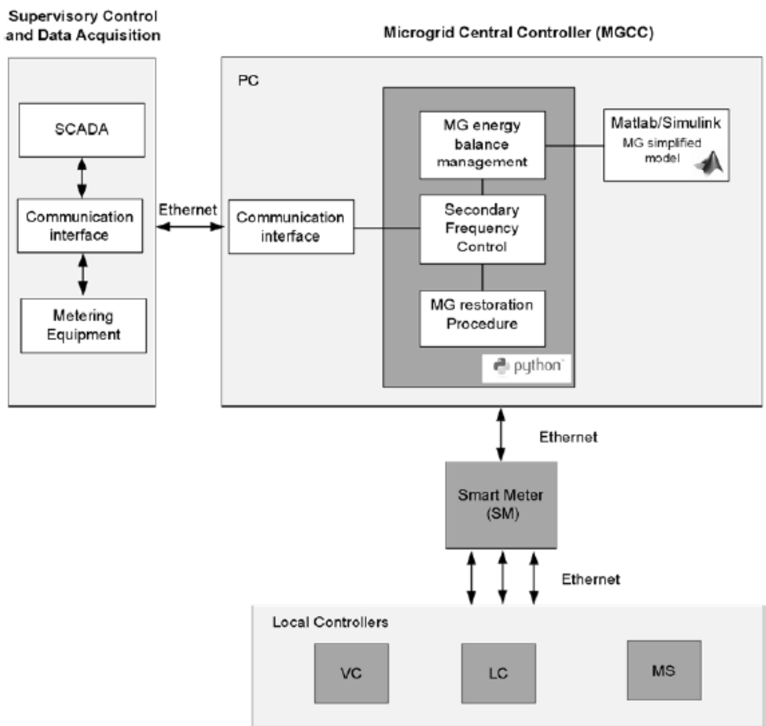

Figure 3.17: SGEVL Control Architecture [27]

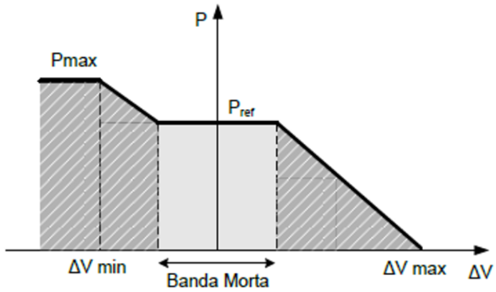

Figure 3.18: P-V Droop for the MG units

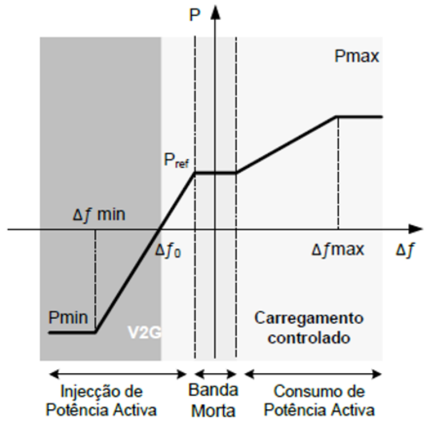

Figure 3.19: P-f Droop for the EV units

At lower levels there are the MC, the LC, the VC (Vehicle Controller) and the Energy Box. The EB is prototype developed at INESC representing the interface with the household. This element is responsible for managing local electrical appliances. It collects measurements, receives commands from the MGCC and re-sends them to the other elements of the level. Measurements include, for instance, maximum and minimum voltages, factor generating imbalances between inverse and zero-sequence voltage and total amounts of energy produced and used. This last aspect can be used alongside with the DAS database to estimate energy balances and costs, enabling tertiary control functionalities. The EB also decides the best EV charging strategy. Even though the action of the commercial charger is only on/off, it is possible to decide on when is the best time to charge EV's.

Data Collection & Communication System

The data flow between components as described above is represented in Figure 3.20. Electrical measurements are collected by the system's SM, which are present in each feeder and bus and the data is sent to the DAS via Modbus RS-485. The DAS then communicates with the rest of the system (SCADA, MGCC, EB, MC, LC and VC) through TCP/IP by wireless or ethernet: it is possible to select the communication network so that different communication scenarios can be tested. Load banks can be controlled remotely via ethernet through their I/O ports.

Two graphical interfaces have also been developed in order to interact with the MGCC. One is responsible for displaying system information to the operator: generation, load, EV state, RES integration and real-time measurements of voltage, current, frequency and quality indicators (Figure 3.21). The second interface enables the operator to manually define the droop control parameters of lower levels (Figure 3.22).

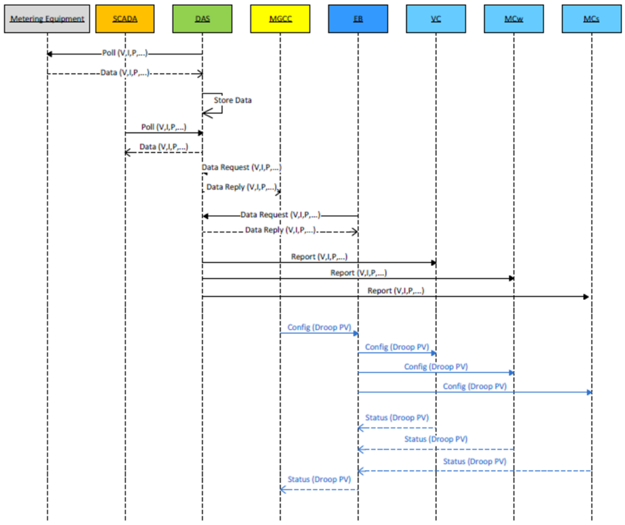

Figure 3.20: Interaction between MG elements

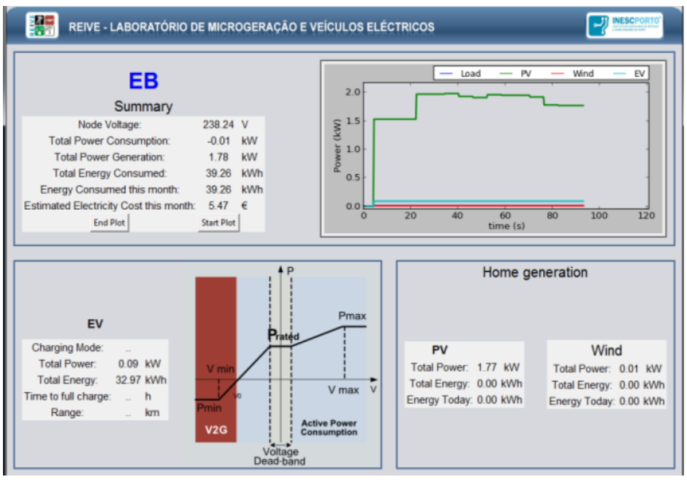

Figure 3.21: HMI with general system information

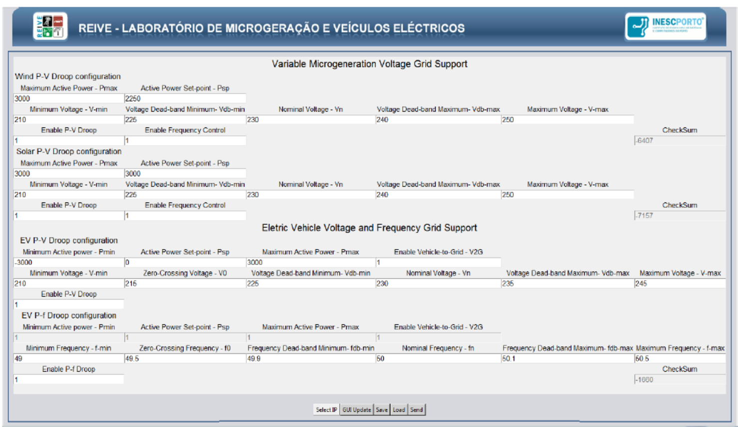

Figure 3.22: HMI for droop definition

3.4 Analysis & Guideline

This section provides a critical discussion on the laboratory infrastructures presented in the previous section. It reviews their advantages, disadvantages and enumerates main functionalities enabled while trying to derive a basic design guideline from the common elements between all three laboratories. It is also debated here how each laboratory could try to take advantage of its features to enable MMG testing in the near future.

3.4.1 Analysis of MG setups

Since MGs are electrical systems, it is necessary to guarantee an appropriate electrical setup. Each laboratory managed to accomplish this through a different method.

MGRL built its electrical network trough a 45kVA grid simulator and a bidirectional AC-DC power supply. This enables emulation of both upstream network and DC sources at the same time, giving this laboratory a compact design. Real three-phase 4-wire cables were used to connect the inverters AC side to a common bus (PCC). This bus can be connected to both balanced and unbalanced loads, therefore allowing balanced and unbalanced studies [64] [52]. Islanding occurs by disconnecting the PCC and different MG topologies can be achieved by opening/closing the contactors upstream of the inverters. MGRL sacrificed topology complexity to assemble a highly advanced infrastructure. Its main advantage is having a lot of processing power (each one of its MG setups has their own DCP), thus enabling complex functionalities such as MG independent operation. Its main disadvantage is the simplicity of its topology, which does not develop into the typical radial layout of a LV network.

EES built its network by using RTDS and PHIL to model the grid upstream of the MG [37]). Real single-phase 2-3 wire cables were used to guarantee connection between components. This system is inherently unbalanced since it is a single-phase MG and topology wise it is also rather simplistic. The document analysed did not mention any controllable DC power source, which conditions the laboratory to perform RET experiments only when the weather allows so. Another disadvantage is that only one MG is controllable, not allowing diverse configurations and also postponing 'real' MMG testing considerably. Its main advantage is being equipped with PHIL which allows great flexibility and can be used to overshadow its disadvantages.

SGEVL can build its electrical grid by either directly connecting the upper bus of its Cable Simulator (CS) to the Portuguese LV grid or by emulating the upstream network through PHIL. MG building is done through the CS in a 3-phase 4-wire fashion that allows the definition of multiple configurations and selection of two resistance values. It is also possible to under carry balanced and unbalanced studies not only by changing the load configurations as in MGRL but also because the lab is equipped with three-phase and single-phase sources [58] [27]. These characteristics give SGEVL an advantage in terms of physical flexibility and complexity. Drawbacks include not having 'real conditions' such as resistances between cable connections. SGEVL already possesses two controllable MG and a way of physically connecting them. Taking advantage of this feature for MMG testing should not take long. On top of this, the lab is also equipped with PHIL, expanding its testing possibilities.

PHIL is a very good acquisition for a laboratory setup since it manages to infinitely expand testing possibilities. It is an expensive equipment but one that might be worth in the long run. It allows the testing of more complex solutions in a safely manner (e.g. faults, higher voltage ratings, etc.)

3.4.2 Analysis of control architectures

The laboratories utilized either centralized or distributed approaches to control their systems. A brief reminder of the advantages and disadvantages of each one is given below (see section 2.2.4.2). It should be noted that describing each functionality mentioned is out of the scope of this thesis.

Centralized approaches have the advantage of controlling the MG as a single unit and being able to control specific nodes; disadvantages include depending on the non-fallibility of a single device and not allowing plug-n-play without updating the MGCC. Distributed approaches cover up this disadvantages, by being highly flexible (allowing plug-n-play) and redundant (there is no single vital communication link); cons include high traffic data exchange and dependability of communication system.

MGRL is highly advanced in terms of capabilities, possessing simultaneously a centralized and a distributed strategy. This is tremendously advantageous in terms of testing possibilities and also in terms of long-term reliability for the MG/MMG. Future energy systems will probably incorporate this function, where the system operator toggles between strategies according to the most favourable situation, ultimately enabling the benefits of both strategies. Examples of functionalities implemented at this laboratory include islanding, energy optimization [32], V/f restoration [28] [53], voltage unbalance compensation [64] and fault response [53].

EES possesses various distributed control algorithms based on MAS theory. The main advantage of experiments conducted with this type of control strategy is that they are all scalable. Primarily developed functionalities consisted of islanding and frequency restoration through emergency load shedding [17] and market participation of loads/DG in formulation of a VPP [30]. More recently, functionalities such as voltage control [40], congestion management [38] and energy optimization [39] have been implemented.

SGEVL possesses a centralized strategy with an additional hierarchical level which is the Energy Box. Instead of the commands going directly from the MGCC to the MC, LC or LV, they go through this agent first. This increases the system's fallibility since it is now strictly dependent of both elements (MGCC & EB). Nevertheless, this topology is able to alleviate communications congestion from the MGCC and also emulate small household applications. Examples of functionalities implemented include islanding, V/f restoration [25], demand side management with EV [27], voltage/VAR control [10] [56] and DER low-voltage-ride-through [62]. Converter grid-code compliance testing with PHIL can also be found here [59].

3.4.3 Guideline on basic infrastructure

This section takes into account the common elements between all the laboratories analysed and the knowledge detailed in the state-of-the-art to deliver a list of the basic infrastructure required to perform MG testing.

1. **DG Units and Loads**
   Laboratories should have both controllable and non-controllabe DG sources. The former are required to allow island operation; ESS are typically used due to their vast control applications (see section 4.4.3). The latter are required to emulate the behaviour of RES. Commercialized products of PVs and small wind turbines are typically used; emulation through a controllable DC source is also possible and has the advantage of allowing testing independently of weather conditions.

   Active and reactive loads are obviously necessary. Controllable loads are useful for testing applications such as BS and emergency shedding. Since most electrical systems are naturally unbalanced, laboratories tend to conduct unbalanced studies by using unbalanced loads.

2. **Power Electronic Interfaces**
   Power electronic interfaces are required for three reasons: first, to control DG units, ESS or other type of sources; second to allow the interaction of elements of different current types (AC and DC); and third to adjust voltage levels, e.g. AC/AC or DC/DC (most inverters and rectifiers adjust voltage levels internally). Two types of controllers will always have to be considered: grid-forming and grid-feeding. The former are coupled to controllable sources to define voltage and frequency in island operation. The latter are coupled to non-controllable sources to control extracted power.

3. **Advanced Metering Infrastrucute (AMI)**
   Laboratories need an infrastructure that grants them control over they assets through the capability of measuring, collecting and analysing data. Usually, such is achieved by utilizing an AMI that is composed of three elements: electricity meters, a bi-directional communication channel and a data repository. The meters are responsible for gathering information such as voltage and current per phase, THD and time stamps on power failures. These readings are sent to the management system to be used in the control algorithms and to be displayed to the operation manager. The communication channel enables not only the reception of information from the meters but also for output commands actions to be sent from the management side to the utility side, allowing performance actions such as demand-response or remote service disconnection. An AMI is often associated with smart meters and the capability of automatically obtaining information based on a schedule (Automatic Meter Readings, AMR), aggregating it in the data repository. For MG testing, the meters should possess AMR schedules for short-term events (analysis of transitory phenomena) and long term events (daily/weekly operation scenarios).

4. **Coordination Agent**
   The laboratory must have some sort of coordination agent that supervises operation and outputs orders and commands. In the last section it was seen that MGRL used a MGCC, EES used a SCADA system and SGEVL used both together. Regardless of the agent used, what must be guaranteed is that the device has considerable processing power to quickly translate data inputs (measurements) into action commands. This requires programming the device and involves a lot of engineering know-how.

5. **Intelligent Protection System**
   Since in MG's power flow is bi directional, protection sizing cannot be performed as in conventional power systems in which power flow is unidirectional. Consequently, a fast communication layer is needed to coordinate all circuit breakers. This is generally performed by digital protective relays, which are primarily IED's that communicate with the coordination agent. For the laboratories analysed, these IED's were embedded in the AMI infrastructure, corresponding to the SM and the PM. Protection sizing is usually done according to IEC 61850.

6. **Human Machine Interface**
   A HMI interface is necessary to allow control of the system from the human end while simultaneously granting feed back information that aids the decision-making process of operators. A well designed interface minimizes undesired display of information and allows the operator to provide minimum input to achieve the desired output.

3.5 Summary and main conclusions

This chapter aimed to give the reader a broader understanding of the state-of-the-art of current laboratory infrastructures. Regarding the results of worldwide polls, it served to illustrate that MG research is booming across many specific topics.

The main conclusion to be taken from the three specific laboratories analysed, is that all manage to perform MG basic functionalities such as islanding, V/f regulation and economic optimization. Each laboratory has its pros and cons and so there is no clear better choice since it ultimately depends on the applications to be performed. MGRL is superior in terms of controllability since it can emulate independent MG setups and also possesses the possibility to operate with centralized an distributed strategies. However, this laboratory is inflexible in terms of physical topology. EES is the least physically flexible of the three and lacks some important functionalities such as fault response. However, it has developed interesting economic applications such as market participation of DG units and is scalable in all its experiments. SGEVL is the most physically flexible of all and has also developed advanced functionalities such as DSM with EV. This laboratory does not have any significant restrictions (apart from not including a decentralized strategy as well).

Chapter 4

Case Study & Simulation Modelling

4.1 Introduction

This chapter describes the base case used to study and understand MMG dynamic behaviour in face of severe power unbalances trough a simulation environment. The system considered is analysed in different load scenarios that are used to test both its resilience and control operation. The system's model was built in *Matlab Simulink* and the theoretical assumptions behind it are explained.

A large period of the dissertation was dedicated to this chapter, the intent being to implement MMG control strategies and better learn how they interact with the system's components; to build the model to be interfaced with the PHIL converter, deriving results that could later be compared to ones produced by real components in the laboratory; and also to become more acquainted with *Matlab Simulink* which is a useful tool in an electrical engineer's career.

4.2 Case study

The modelled system is a MMG comprised of two LV rural microgrids connected trough a 5km MV power line. It has a radial configuration and comprises 14 nodes with approximately 100 kW of peak load in a 3-phase system with a nominal voltage of 380V. Each microgrid has DG units widespread across its several buses and 150 kW battery units at the LV side of the MV/LV substation. No synchronous machines are available. The network's single line diagram is presented below in Figure 4.1. A screenshot of the model built in Simulink is available in appendix A.3.

The system was adapted from a real LV rural network located in Spain (MERGE project) [27], a decision which was made given the large amount of information available at INESC TEC. The adaptations made included the following:

- **Restructuring the model**. The two modelled microgrids were derived from the single microgrid of the project (Appendix A.2). Instead of modelling each microgrid with the same 13 buses, the buses were 'split' and distributed differently. This was done not only to reduce computation times but also to ensure that the microgrids have different power flows.

- **Considering a balanced 3-phase load system**. This greatly simplifies simulation while still maintaining the desired scope for dynamic studies. The adaptation is presented in appendix A.2.
- **Considering a balanced 3-phase generation system**. Same reason as above. Adaptation is presented in appendix A.3.
- **Studying dynamic events only.** This involves exclusively transitory phenomena and has implications on the modelling of the systems components, which will be described below.
- **Considering all DG to come from PV**. PV's are easy to model in *Matlab Simulink*. Also, at the time of modelling the objective was to emulate an hypothetical MMG at Ouarzazate, Morocco, and generation deriving from PV's would be the most likely scenario.
- **Reducing nominal rated power of load and DG to 50%.** The original project included distributed ESS that helped maintain specified voltage values in all of the systems buses. Since this is not the case, voltage drop on power lines was too high, compromising the MMG proper operation. Halving the nominal rated power solved this problem while still presenting a plausible real life scenario.
- **Considering reactive power generation to be 20% of active power generation.** Reactive power generation was unspecified in the MERGE project. Therefore typical values for a coupled PV were utilized.

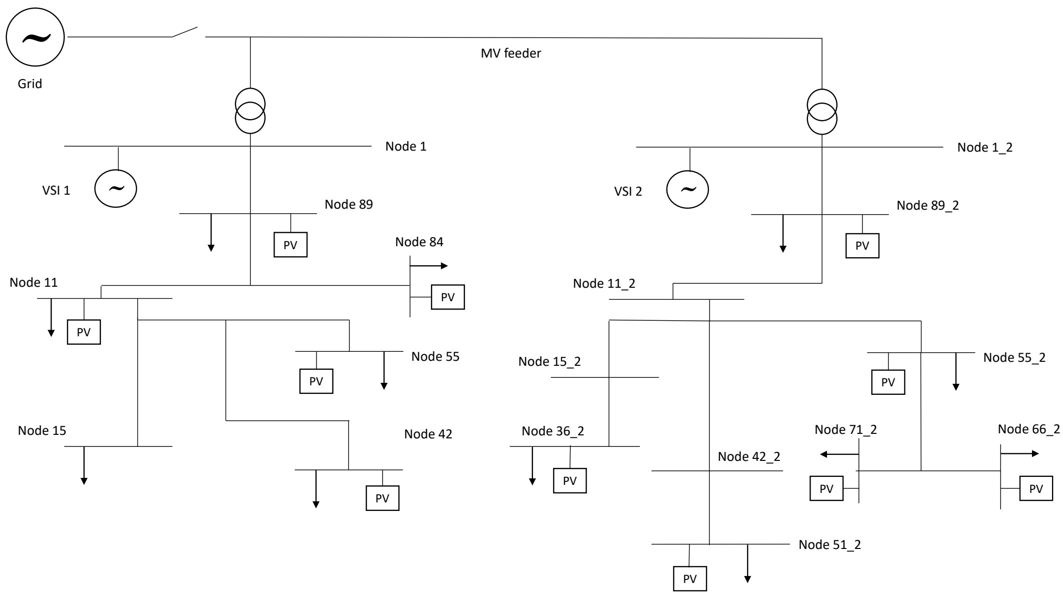

Figure 4.1: Single Line Diagram of the MMG under study

As typically expected from a rural network, the LV feeders have a high resistance compared to its reactance. Cable line impedances can be found in appendix A.4 (LV) and A.5 (MV). Line

15_2-36_2 resistance was changed from 0.199 Ω to 0.370 Ω. This had nothing to do with the simulation itself and it was only done to guarantee a better comparison between simulated and real experiments. (INESC TEC's cable simulators only allows 0.370 Ω as the minimum value for an LV cable. Line 15_2-36_2 was chosen specifically since its resistance was the closest to that value).

The battery storage units at Nodes 1 and 1_2 are connected and controlled by a VSI that enables autonomous island operation for each microgrid. The inverters are controlled locally trough P-f and Q-V droop functions that enable proper power sharing (primary control) and frequency restoration (secondary control). The nature of the control system is decentralized, with no-communications. Frequency restoration is inactive when the MMG is operating grid tied and active when islanded, in one or in both of the inverters, depending on the chosen configuration.

4.3 Definition of case study scenarios

The most straightforward method to assess MMG resilience in face of severe power unbalances is to submit it to the two most pessimistic perturbations. Those correspond to the following scenarios:

- **Scenario 1:** MMG forced to island when operating with maximum load and no distributed generation (Table 4.1).
- **Scenario 2:** MMG forced to island when operating with minimum load and maximum distributed generation (Table 4.2).

In the first scenario there is a deficit of generation in the MG and all energy must be imported from the grid. When the MG is forced to disconnect due to a random event, its battery banks must be able to react fast enough and supply the entire system. In order to do this, their inverter control systems must be tuned and adapted to perform grid-forming operations and maintain voltage and frequency within admissible values. In the second scenario there is a surplus of generation in the MG and excess energy must be exported to the grid. When the MG is forced to disconnect, the battery banks should act as a load and absorb energy and solar panels should reduce their power output.

It is from here on defined that the system's control variables should be within the following range:

- **Frequency:** 50Hz $\pm$ 1;
- **Voltage:** 1 p.u. $\pm$ 0.1 .

Scenario 1: Peak Load, No DG									
Microgrid 1					**Microgrid 2**				
	Load		Gen			Load		Gen	
Nodes	**P (kW)**	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**	**Nodes**	**P (kW)**	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**
89	12,1	2,5	0	0	**89**	12,1	2,5	0	0
84	12,8	3,9	0	0	**55**	6,4	1,6	0	0
11	20,2	4,1	0	0	**51**	4,3	0,9	0	0
55	6,4	1,6	0	0	**36**	8,1	2,4	0	0
42	3,2	0,9	0	0	**71**	3,2	0,6	0	0
15	1,1	0,2	0	0	**66**	10,5	2,1	0	0
Total	55,7	13,1	0	0	**Total**	44,6	10,1	0	0
			Total Load (P, Q)		100,3	23,2			

Table 4.1: MMG operation point in scenario 1

Scenario 2: Low Load, Full DG									
Microgrid 1					**Microgrid 2**				
	Load		Gen			Load		Gen	
Nodes	**P (kW)**	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**	**Nodes**	**P (kW)**	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**
89	3,0	0,6	12,3	2,5	**89**	3,0	0,6	12,3	2,5
84	3,2	1,0	7,8	1,6	**55**	1,6	0,4	11,2	2,2
11	5,0	1,0	9,1	1,8	**51**	1,1	0,2	6,4	1,3
55	1,6	0,4	11,2	2,2	**36**	2,0	0,6	3,8	0,8
42	0,8	0,2	3,1	0,6	**71**	0,8	0,2	13,5	2,7
15	0,3	0,0	0,0	0,0	**66**	2,6	0,5	7,3	1,5
Total*	13,9	3,3	43,4	8,7	**Total**	11,1	2,5	54,4	10,9
			Total Load (P, Q)		25,1	5,8			
			Total Gen * (P, Q)		88,0	19,6			
			Diff (Gen - Load)		62,9	13,7			

Table 4.2: MMG operation point in scenario 2.
$*$ Total Gen (P) is multiplied by 0,9. All PVs inject 90% of Pn at steady state and up to a maximum of 100% in low freq regimen (<50Hz)

Two more scenarios were implemented:

- **Scenario 3:** MMG forced to island when operating with maximum load and no DG but this time with four BESS distributed throughout the network.
- **Scenario 4:** MMG operating at 50% of peak load and with some DG when a blackout occurs and a blackstart procedure begins (Table 4.3).

In the third scenario 10kW battery banks were placed on buses 11, 42, 89_2 and 66_2. These buses were selected specifically for having rather a high load or being distant from the MV/LV substation. In the fourth scenario an MGCC is responsible for coordinating the BS procedure. Its implementation in *Simulink* is presented in Appendix A.5. Figure 4.2 presents the logic behind it in a flowchart diagram.

Case 4: Blackstart									
Microgrid 1					**Microgrid 2**				
	Load		Gen			Load		Gen	
Nodes	**P (kW)**	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**	Nodes	**P (kW)**	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**
89	6,0	1,2	6,1	1,2	**89**	6,0	1,2	6,1	1,2
84	6,4	2,0	3,9	0,8	**55**	3,2	0,8	0,0	0,0
11	10,1	2,0	4,6	0,9	**51**	2,2	0,4	3,2	0,6
55	3,2	0,8	0,0	0,0	**36**	4,1	1,2	1,9	0,4
42	1,6	0,5	1,6	0,3	**71**	1,6	0,3	0,0	0,0
15	0,6	0,1	0,0	0,0	**66**	5,3	1,1	3,6	0,7
Total	27,8	6,6	16,1	3,2	**Total**	22,3	5,0	14,8	3,0
			Total Load (P, Q)		50,1	11,6			
			Total Gen (P, Q)		27,8	6,2			
			Diff (Gen - Load)		-22,3	-5,4			

Table 4.3: Operation point in Scenario 4

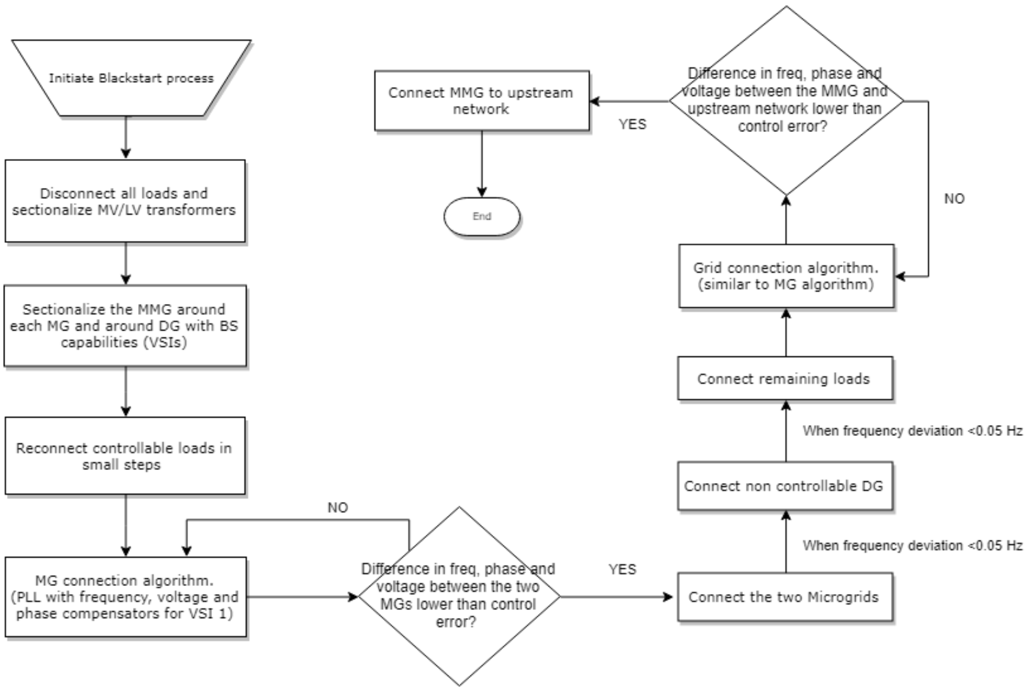

Figure 4.2: BS procedure utilized

Table 4.4 briefly synthesises the tests that were performed and their respective conditions. Notice that all tests are exclusively simulations apart from Test 5 and Test 7.

Scenario 1
Test 1: SM Mode
Test 2: MM Mode, secondary control on a single VSI
Test 3: Conditions of Test 2 but with load shedding capabilities incorporated
Test 4: MM Mode, secondary control on both VSIs
Test 5: Laboratory implementation of Test 3 (with PHIL and a real load)
Scenario 2
Test 6: MM Mode, no secondary control on both VSIs
Test 7: Laboratory implementation of Test 6 (with PHIL, real inverter, DC source as PV panel and real load shedding)
Scenario 3
Test 8: Conditions of Test 3 but with distributed BESS throughout the network
Scenario 4
Test 9: MM Mode, secondary control on both VSIs while each MG is functioning separately; VSI-2 secondary control is deactivated once the MMG re connection is made.

Table 4.4: MMG mode of operation for each test

4.4 System Modelling

Simulation softwares allow the study of complex microgrid layouts by emulating the behaviour of components trough their mathematical models. This section provides a brief explanation on the dynamic models adopted for the MS and power electronic interfaces. Mostly *Sim Power Systems* library blocks were utilized.

4.4.1 Voltage Source Inverter

Inverter dynamic models are described by their control functions. Fast transients related with commutation of the solid state switches are not considered and power is assumed to be injected at the AC side without harmonics, distortions, losses or delays [46].

Short time frames implies that some of the parameters of the battery banks connected to the VSI (Internal voltage, State of Charge, etc.) do not have to be modelled explicitly since simulation time is too small to allow notorious variations and they can be considered a constant DC voltage source. The VSI can then be represented, by formal equivalence, as a Synchronous Machine (SM) reduced to its first order model.

This model is represented by a constant voltage behind a R-L impedance plus the swing equations with no damping effects (meaning no friction losses). To allow proper P-f and Q-V decoupling, the internal reactance should be considerable greater than internal resistance. In order to contain frequency deviations, SM are equipped with a governor that controls its mechanical power input.

In the Laplace domain, for small frequency variations, the following equation holds [49]:

$$\frac{\triangle\omega}{\triangle P} = \frac{1}{2Hs} \tag{4.1}$$

Additionally, if we consider the direct feed-back action through a seep-droop function (R) of the SM, we have:

$$\triangle\omega = \frac{1}{2Hs}(\triangle P - \frac{1}{R}\triangle\omega) \Rightarrow \frac{\triangle\omega}{\triangle P} = \frac{1}{2Hs + \frac{1}{R}} \tag{4.2}$$

In a VSI, the relation between active power variations and angular variations is dependent of the active power droop *kp* and its actuation delay *TdP*. As a result, it can be represented through the following linear transfer function [12]:

$$\frac{\triangle\omega}{\triangle P} = \frac{kp}{TdPs + 1} \Rightarrow \frac{1}{\frac{TdP}{kP}s + \frac{1}{kp}} \tag{4.3}$$

Notice now that equations 4.2 and 4.3 have an equivalent arrangement, allowing to define the following equivalences:

$$H = \frac{TdP}{2kP} \tag{4.4}$$
$$R = kP \tag{4.5}$$

This means that in the *Simplified Synchronous Machine* block model available in *Matlab Simulink*, there is a link between the emulated machine inertia (H) and the control parameters of the active power droop of a VSI, Figures 4.3 and 4.4.

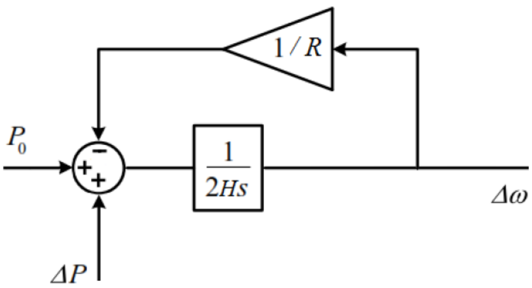

Figure 4.3: SM transfer function

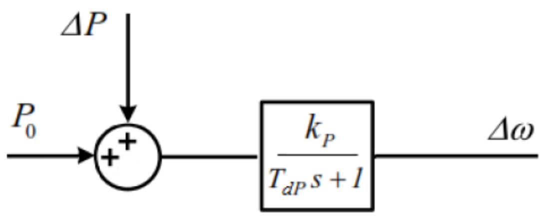

Figure 4.4: VSI transfer function

The VSI is then able to emulate the governors with which SMs are equipped to control their mechanical power input and contain frequency deviations. In real life, such governors have observer, actuation and integral time delays [59]. The total response time delay corresponds to the sum of observer and actuation delays but since the former is much smaller than the latter, only the actuation delay was considered (*TdP*). The integral response is responsible for providing frequency restoration and in this case it was implemented by using a low pass filter.

Similarly, the VSI Q-V droop characteristic can be defined with respect to a simplified SM by the transfer function depicted in Figure 4.5. Where V is the internal voltage of the machine, Q is the reactive power output, *TdQ* the reactive power decoupling delay and *kQ* the reactive power droop. The observer response was also neglected and the integral control is non existent. The decoupling of the control parameters into P-f and Q-V can seem odd given the resistive nature of the network analysed. However, this can be justified by both VSI being located near near the MV/LV transformers and the existance of a MV line between them, which guarantees the necessary inductive nature. The general scheme of the VSI control implemented is presented in Figure 4.6.

The *Simulink* implementation is presented in Figure 4.7.

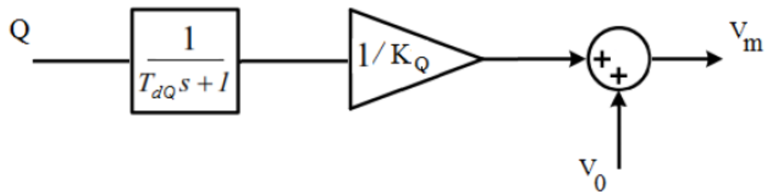

Figure 4.5: VSI reactive droop control

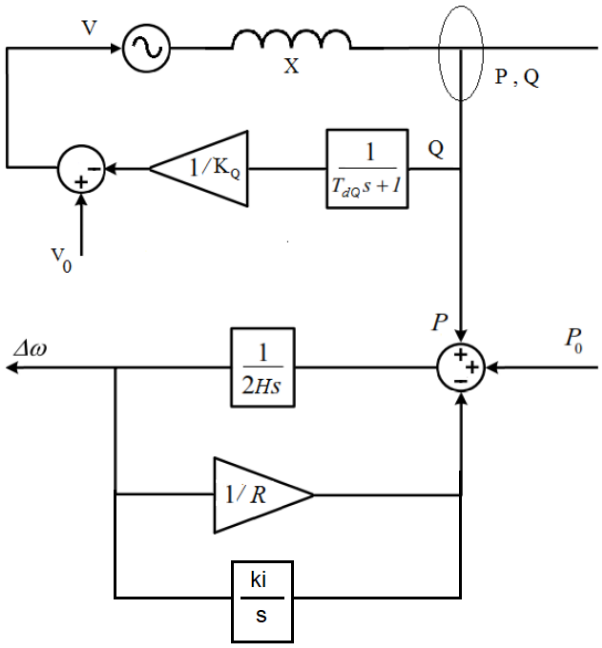

Figure 4.6: Equivalent model of VSI with droop control based on a simplified SM

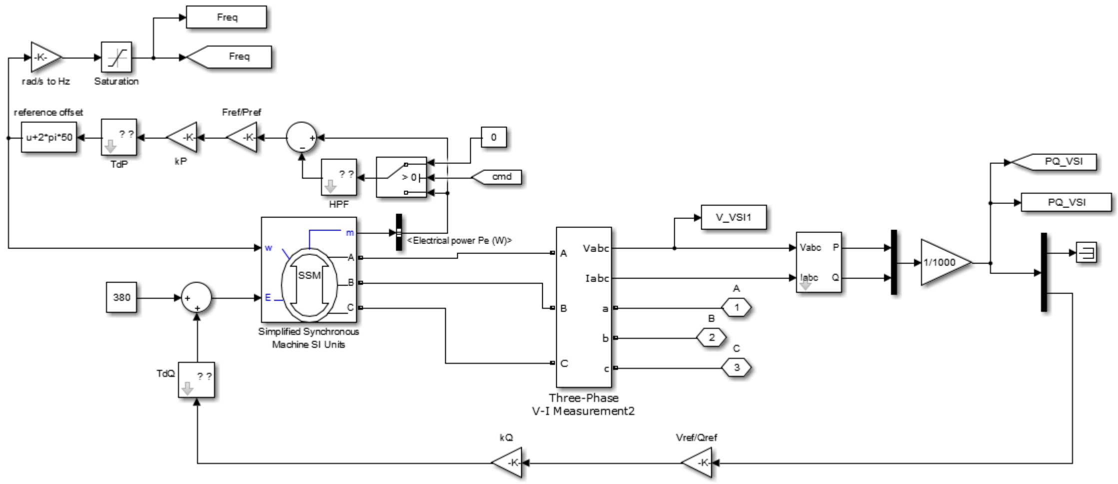

Figure 4.7: Equivalent model of VSI, *Simulink* implementation

4.4.1.1 Control Parameters

It is necessary to define and tune the VSI's control in a logical way. Since the systems resilience is to be tested with power unbalances, and given that active power consumption/generation is much greater than reactive power consumption/generation, the system's stability will be mostly affected by the P-f control loop, which in this case is controlled by three key variables:

- The active power-frequency droop, *kP*
- The active power decoupling delay, *TdP*
- The secondary control delay, *TdI*

Although these variables can assume an 'arbitrary' value, it has to be within a range that not only properly controls the system but also makes sense in the field of power systems. The main restriction is the inertia emulated by a VSI. Synchronous machines have kinetic energy stored in their rotating masses. Inertia is defined by the relation between that stored kinetic energy (Wc) and their nominal power rating (S) [49]. Inertia values are approximately constant for each type of machine, independently of their speed and nominal power. Generators of thermal power plants typically have inertia constants in the order of 4-9s. Machines designed for hydroelectric generation have constants of 2-5s. VSI's on the other hand, cannot store kinetic energy, and therefore it is said that their P-f response is an emulation of inertia, or 'virtual inertia'. Typical values revolve around 0,5-2s [49]. In this way, it is necessary to guarantee that the relation expressed in equation 4.4 is within appropriate limits. Scenario 1, Test 1 was used to test the 'tuning' of all three parameters.

Active power droop, *kP*

Droop can be defined as the relationship between the variation in power and frequency [1]:

$$kP = \frac{\triangle f}{\triangle P} \times \frac{Pref}{fref} \Rightarrow \triangle f = kP \times fref \times \frac{\triangle P}{Pref} \tag{4.6}$$

As it can be seen from equation 4.6 and verified in Figure 4.8, *kP* only affects the magnitude of the frequency sag. For the same power unbalance (△P), a smaller droop leads to a smaller frequency deviation.

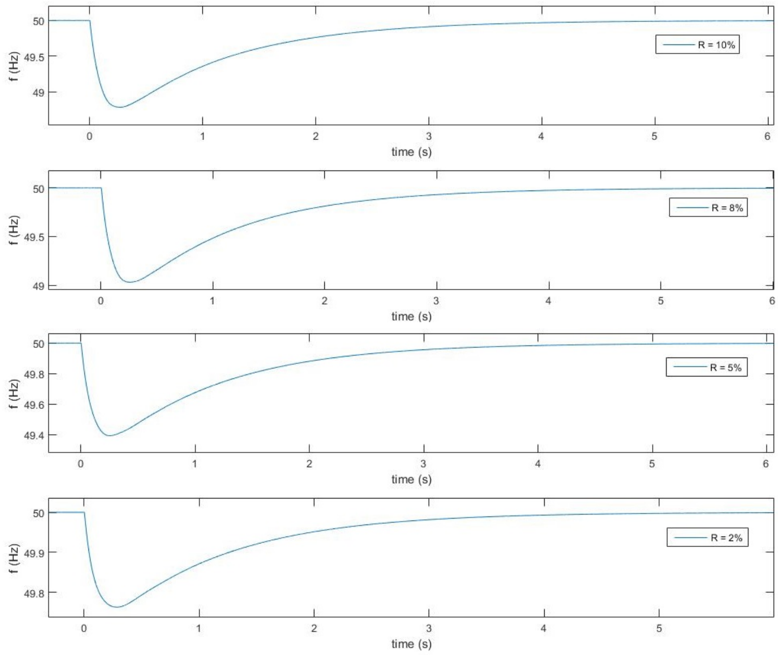

Figure 4.8: Influence of *kP* on controlling the frequency during a transient

In this case, a *kP* of 0,1 (10%) was used. The minimum frequency allowed in the system is 49Hz, and in this series of tests it is desirable to go below that value to be able to clearly distinguish the contributions of other control solutions to the system's response.

The active power decoupling delay, *TdP*

The active power delay controls the speed of the response. This delay is what emulates the virtual inertia of the system. Notice that in MMO VSIs will have different control characteristics from one another. When a power unbalance occurs, the inverter with the natural fastest response time will try to accommodate the power difference all by itself. If the unbalance is superior to the power of the inverter, the latter might collapse and lead to system failure. When a 'forced' delay is introduced in the active power loop, to give time for all inverters to participate in the power sharing, the response is much smoother, increasing system stability.

An inverter with a greater value of *TdP* possesses a higher virtual inertia. Notice from Figure 4.9 that *TdP* does not influence the magnitude of the frequency sag but only the time it takes to achieve its lowest point. If the actuation delay is too big, it might lead to cause loss of synchronism and system failure. In this case, it was considered that a *TdP* of 0.5s and 1s take too long to stabilize, and a *TdP* of 200ms was used.

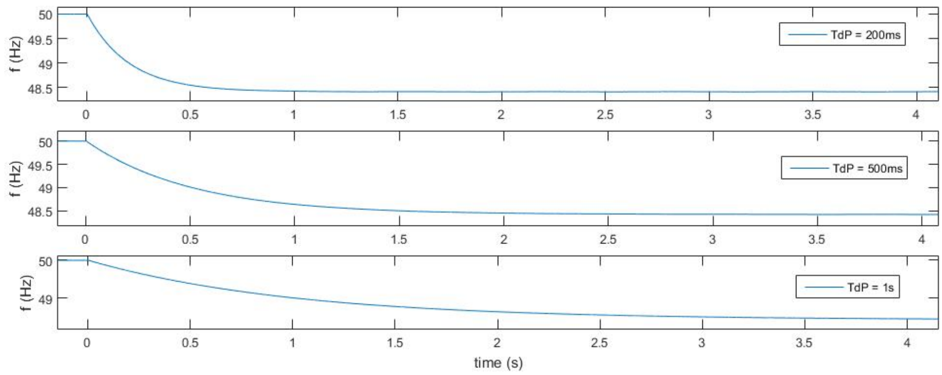

Figure 4.9: Influence of *TdP* on controlling the frequency during a transient

Having both *TdP* and *kP* defined, it is now possible to calculate the virtual inertia emulated by the VSI. These values will remain constant throughout the 9 tests.

$$H = \frac{TdP}{2kP} = \frac{0.1}{2 \times 0.2} = 1s \qquad Equation\ 4.4\ revisited$$

The secondary control delay, *TdI*

The secondary control delay sets the timer for frequency restoration activation. This delay time is usually much greater than the active power decoupling delay so to allow the proper actuation of the primary control. Secondary control should also not take too long to act so to restore the system to its normal conditions. 4 to 5 seconds are typical values for restoration times (Notice that $TdI \neq$ restoration time). In Figure 4.10, *TdI* = 0.25 interferes with the primary control and *TdI* = 4s takes too long to act. *TdI* = 1s was the option chosen.

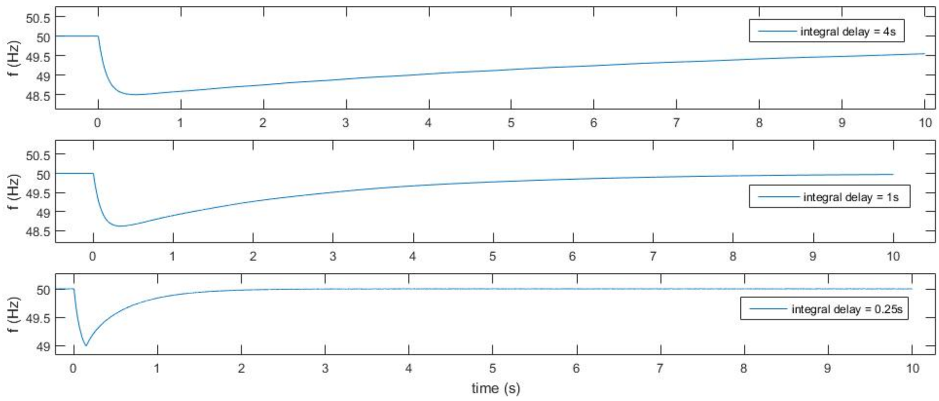

Figure 4.10: Influence of *TdI* on controlling the frequency during a transient

The reactive power droop, *kQ* and the reactive power delay *TdQ*

In this case, it was verified that given the small amounts of reactive power involved (20 kVAR), the V-Q control droop had a negligible effect on the dynamic response of the system voltage profiles/ reactive power flow. Nevertheless, the parameters were defined at *kQ* = 5% and *TdQ* = 0.1s.

4.4.2 Photovoltaic Sources

Photovoltaic panels are governed by PQ inverters, which are simpler. The power extracted by these inverters is dependent on the availability of the primary energy source: the inverter current is controlled in amplitude and phase to meet the desired set-points of active and reactive power. Short time frames means that they can be modelled as a constant current source since irradiance varies slowly. The good function of the inverter depends upon the stability of voltage and frequency at its terminals. Implementing this in *Matlab Simulink* was much simpler and was achieved by utilizing the block *Three-Phase Dynamic Load* with a negative reference of PQ.

Some additional control functionalities were implemented to illustrate real life regulation compliances. For example, the EU regulation [1] forces generators to have a Limited Frequency Sensitive Mode for both under and over frequencies. This means that power generators operating in this mode should be able to change their active power output according to certain frequency values. The objective is to reduce power output when frequency is too high and increase power output when frequency is to low.

In order to do this, the *Three-Phase Dynamic Load* model of each PV receives as P reference 90% of its nominal rated power so that in under frequency (<50Hz) active power generation can be gradually augmented up to 10%. As for over frequency, the PVs are able to gradually decrease their power output by 100%. The same P-f droop control with no dead-band is responsible for governing both responses, as depicted in Figure 4.11. Droops were defined at 5% in the same way as *kP* in equation 4.6 (droop on Bus 36_2 was defined at 10%). To emulate a realistic response an actuation delay of 250ms was added.

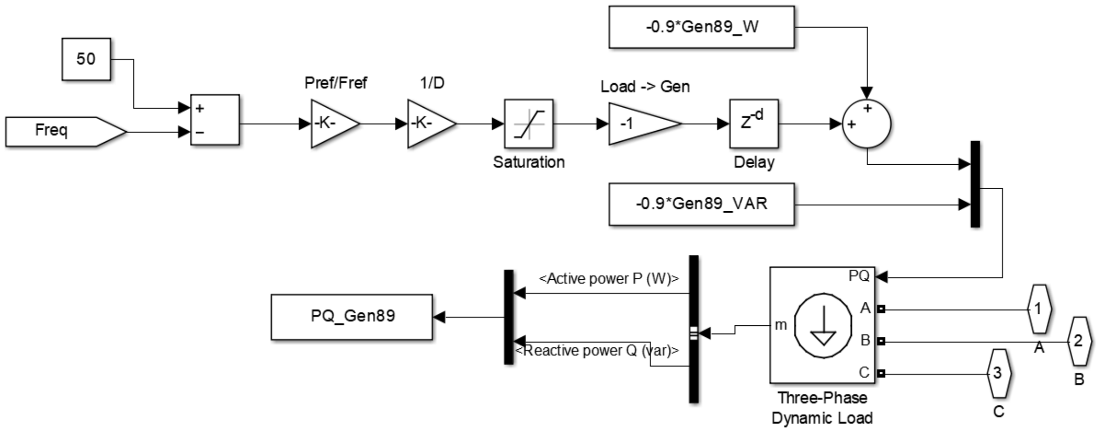

Figure 4.11: PV control, *Simulink* implementation

4.4.3 Battery Storage Systems

The short time frames involved means that some of the parameters (Internal voltage, State of Charge, etc.) do not vary considerably and that the BESS can be assumed a constant DC voltage source. In fact, not just batteries but most ESS (flywheels, SMES, Supercapacitors, see) can also be modelled like this. Unlike the VSIs however, these baterries are to be controlled by PQ inverters and so the *Three-Phase Dynamic Load* block was can be used just like the PVs.

The batteries *Simulink* implementation is presented below. They were modeled to represent fast-acting devices that help maintain the system's stability in emergency situations. They were equipped a 0.2 Hz dead-band, a strong P-f droop control of 2% and an actuation delay of 5 ms.

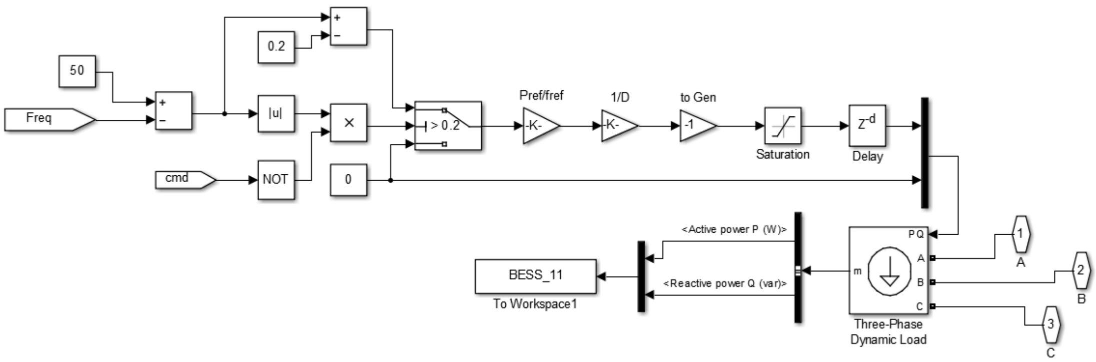

Figure 4.12: Distributed BESS *Simulink* implementation

Chapter 5

Laboratory Setup

In this chapter the laboratory setup for Tests 5 and 7 are described. Since both tests required the use of PHIL technology, the theory associated with it is briefly explained first.

5.1 PHIL

Hardware In the Loop (HIL) simulation is one of many real-time simulation techniques available nowadays to analyse Microgrid behaviour. HIL sets itself apart by being capable of merging physical equipment (Device Under Test) with virtual simulations. A fully RT digital simulation models the entire system within the software, meaning that there is no interaction with the external world. On the other hand, in HIL, part of the system is physically present and interacts with the simulation software through a converter interface that has input and output (I/O) ports [74] (Figure 5.1). This is highly advantageous as it can reproduce closer to real-world results.

The principle behind HIL is that voltage measured at the simulated model's interactive bus is replicated at the real system's bus in the form of its Thevenin equivalent. The interface converter measures the hardware behaviour against that certain scenario and sends a current back to the simulated model to close the loop. Since the simulated model and the DUT p.u. systems may differ, the interface converter needs to include voltage and current scaling. In order to properly and safely do this, it is necessary that the DUTs rated power does not exceed the interface rated power.

There are multiple categories of HIL: Controller HIL, Power HIL and Mechanical HIL (less used). The difference lies in the levels of voltages and currents exchanged through the interface converter. For the scope of this dissertation only PHIL is of interest. PHIL is a newer and more complex technique which deals with power systems and larger currents, enabling experiments that were usually considered too risky, difficult or uneconomical.

As with other digital simulation techniques conducting performance tests, running the software involves describing the system through mathematical models and solving differential equations by means of numerical integration techniques. Correctly defining the model, integration techniques and its time-step greatly influences the stability of the testing.

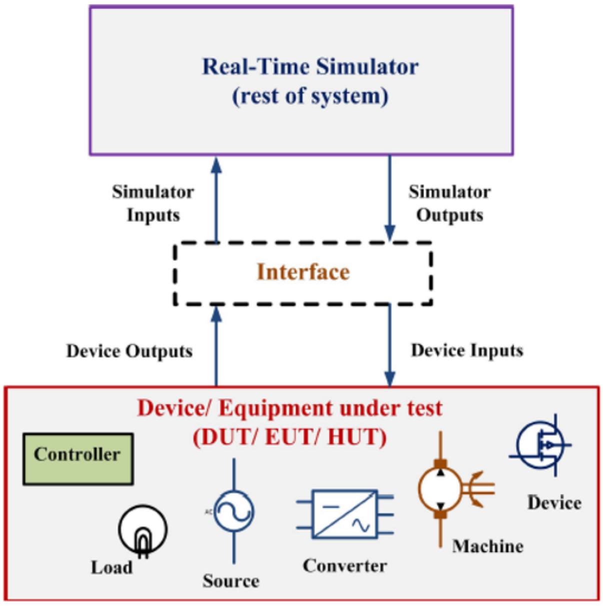

Figure 5.1: Concept of HIL (retrieved from [74])

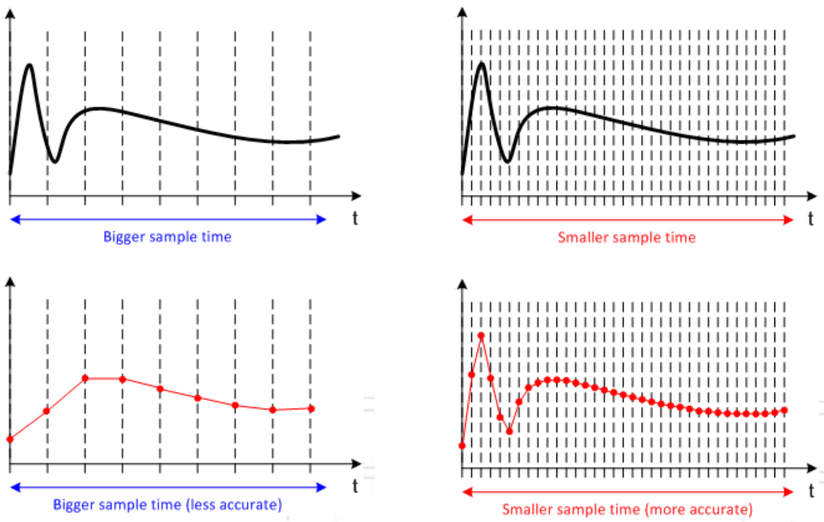

Figure 5.2: Time-step implications

When it comes to time step selection, in RT simulation only fixed step intervals are allowed, since the duration of each iteration is not know *a priori*. The step size should be small enough to give accurate results (Figure 5.2), but not too small so to ensure that the processor can solve all equations necessary and avoid an overrun (execution time < integration time, Figure 5.3) [74] [78].

The way real-time simulation is made possible is by grouping, within the software, functionally related blocks together in a subsystem and then assigning subsystems to different CPU cores. The computation of each subsystem will be executed in real-time (or accelerated simulation mode)

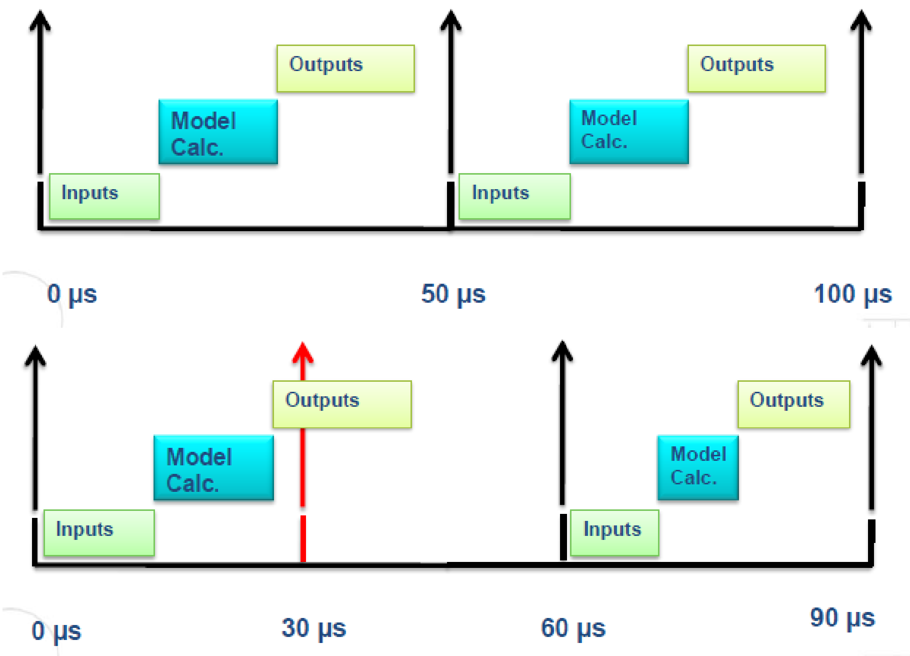

Figure 5.3: Adequate time-step vs inadequate time-step (too short)

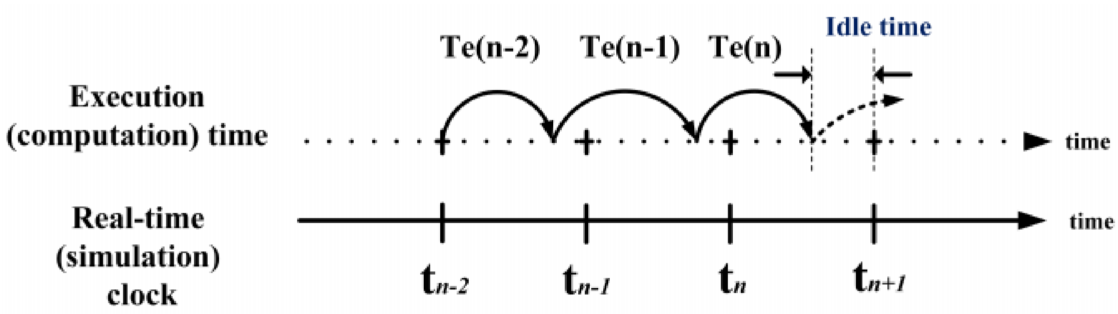

Figure 5.4: Concept of accelerated simulation (retrieved from [74])

by each CPU and information exchange between CPUs is made synchronously through shared memory. Accelerated mode is when the idle time of a computational state is used to compute the next time step. In comparison, a RT simulator waits until the clock ticks to compute the next time-step (see Figure 5.4 for a better understanding). Graphical User Interface (GUI) functionalities should be carefully excluded from these subsystems as they will operate asynchronously from them. Generally the GUI and the computation subsystem communicate through TCP/IP. Both of these requirements should be done in a specific software that interacts with the RTDS. In this case, the producer of the RTDS designed a *Matlab Simulink* library (RT-Lab) that allows the original simulink model to be adapted according to the conditions referred above.

5.2 Setup

The setup was assembled by using INESC TEC SGEVL's equipment. The power converter utilized is a model by Triphase™(PM15F70) which has a power rating of 15kVA and maximum current rating of 22A. The RT simulation device used was OP5607 from OPAL-RT™. The workbench setup for both scenarios is presented below.

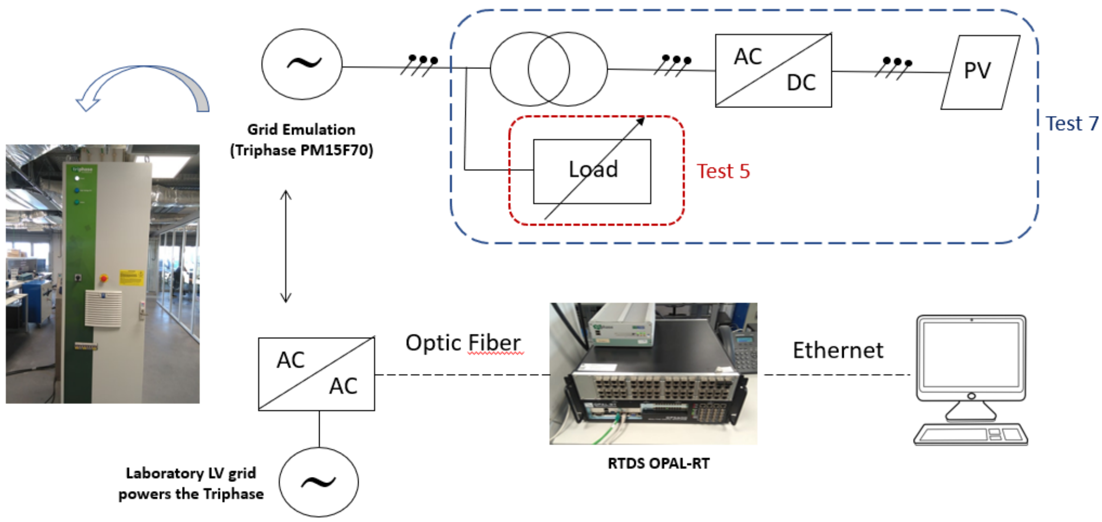

Figure 5.5: Laboratory setup for Test 5 and 7

In Test 5 a frequency measurement block in the GUI automatically commands the load to be shed at 49Hz via TCP. In Test 7, the DC/AC inverter used includes frequency response functionalities that can control the PV behaviour. In this case the PV was modelled by a DC source, allowing the test to be performed with the absence of sunlight and in a more controlled manner. The load used was setup for 3 kW and the PV nominal rating was set at 3,75kW. The P-f droop settings were defined directly in the inverter to match the ones used in the simulation.

Figure 5.6: DC Source (left), inverter (middle) and transformer (right)

Chapter 6

Results

This chapter provides and analysis the results obtained in the various tests under carried in *Matlab Simulink* and INESC TEC's Smart Grid and Electic Vehicle Laboratory. Please consult section 4.3 for the description of each scenario and test.

6.1 Scenario 1

6.1.1 Test 1 - Single Master Mode

This test illustrates a situation were the batteries connected to VSI 1 are solely responsible for supplying both Microgrids when islanding occurs at 0s. Figure 6.1 demonstrates that even with a single generation source the system can withstand the power unbalance due to the fast discharge of its batteries, Figure 6.2. However, this architecture makes MG2 unable to act independently from MG1. Frequency response is smooth but there is an under frequency that violates the minimum limit (49Hz) for almost an entire second, which is considered severe. Transient drop in voltage also infringes the lowest admissible limit but can be considered negligible due to magnitude and duration. Bus 36_2 was selected for voltage control since it is the one who experiences the highest voltage drop along its lines.

The absence of DG inevitably causes steady state voltages to be under 1 p.u.. There was a reduction of 0,03 p.u.(6,6V) from grid-tied to island mode as result of the VSI's inferior power quality (not an ideal voltage source). Voltage drop throughout the network decreases the total active power consumed by loads in 5kW (5,4%) because of the relation expressed in equation 6.1; the last graphic of Figure 6.2 also illustrates this: the total active power to MG2 is reduced.

$$P = \frac{V^2}{Z} \tag{6.1}$$

In conclusion, this first test proved that system is capable of operating smoothly in SMM, but that when the MMG is forced to island with maximum load and no DG, grid codes are infringed.

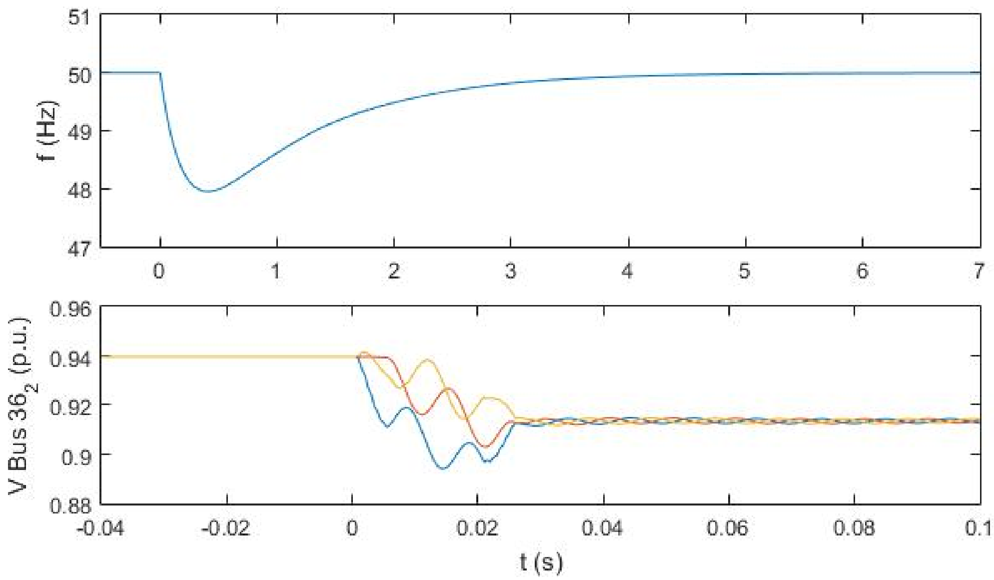

Figure 6.1: Frequency and Voltage response in Test 1

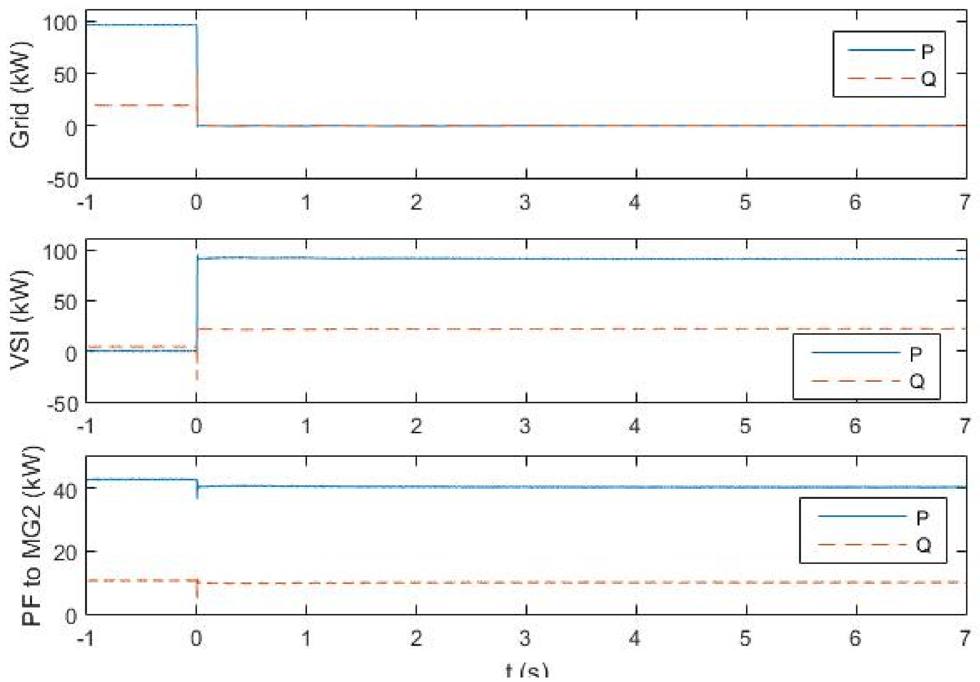

Figure 6.2: MMG Power Flow in Test 1

6.1.2 Test 2 - Multi Master Mode (1)

This test illustrates a situation were both MGs have a VSI but the system relies on only one of them to perform secondary control. The introduction of a second generation source (VSI 2) helps accommodate the power imbalance and greatly improves the system's frequency response, Figure 6.3. Although frequency limits are still violated, duration and sag are reduced. Voltage response also improves, given the distributed nature of generation. Notice from Figure 6.4 that since both VSIs have the same active power droop, the power is shared evenly between them on a first instance but as frequency is restored by VSI 1, the active power contribution of VSI 2 is gradually diminished and the former is forced to increase its power output. This reduction of active power output by VSI 2 causes the voltages in MG2 to drop. Also, both VSIs provide reactive power support, even in grid-tied mode; despite the Q-V droop parameters being the same, reactive power sharing is not performed evenly due to cable line impedance's (voltage is a local variable, unlike frequency).

Table 6.1 presents the steady state results for this test. Although steady state analysis is out of the scope of this work, it proves useful to confirm the consistency of the results and assure a logical foundation. It is interesting to see that almost 20% of the MMG reactive power is supplied by the MV lines capacitances (see Equation 6.2). From grid tied to island mode, power losses are slightly reduced, especially reactive ones, since the VSIs are located downstream of the MV/LV transformers and closer to loads.

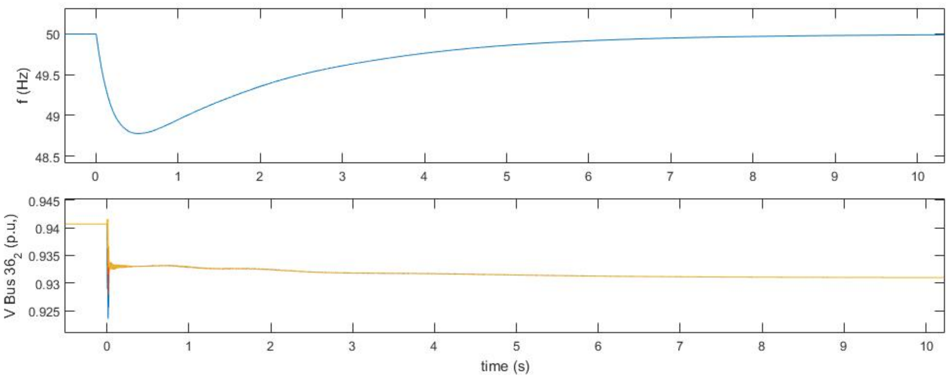

Figure 6.3: Frequency response and Voltage on Bus 36_2, Test 2

$$Qcapacitor(VA) = \frac{V^2}{Z} = \frac{V^2}{jwC} \tag{6.2}$$

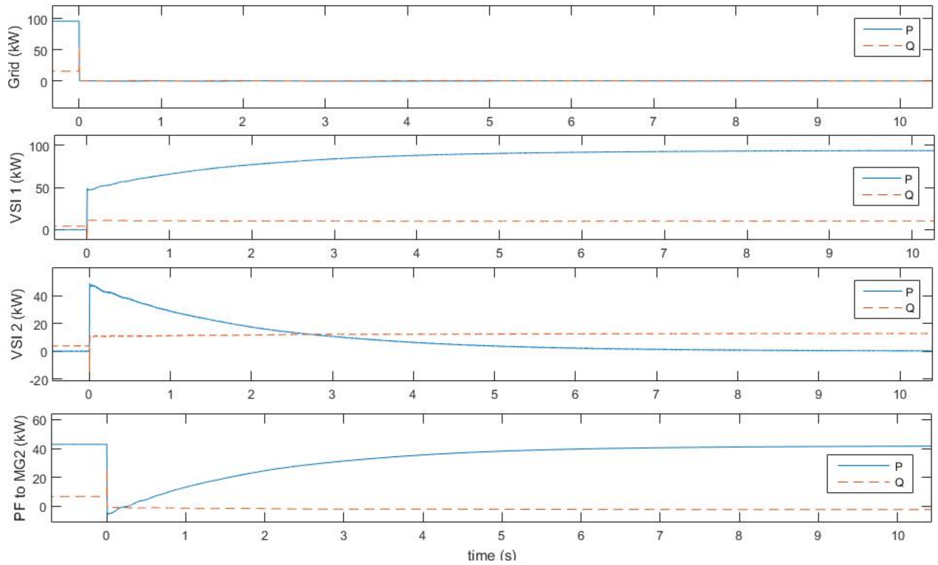

Figure 6.4: MMG power flow in Test 2

	Prior to Isolation		After Isolation	
	P (kW)	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**
Grid	96,2	15,6	0	0
VSI_MG1	0	4,1	94,1	10,2
VSI_MG2	0	4	0	12,7
Capacitances (MV Line)		3,9		3,8
Total Gen	96,2	27,6	94,1	26,7
Total Load	91,9	21,3	90	20,8
Losses	4,3	6,3	4,1	5,9
Power Flow to MG2	42,9	6,8	41,8	-2,3

Table 6.1: Steady state results, Test 2

6.1.3 Test 3 - Load shedding

Considering the conditions of Test 2, let it now be defined that the system's frequency is not allowed to go below 49Hz at any given moment. One way of guaranteeing this is to equip some loads with sensitive relays that provide load shedding capabilities. In this case, such relays were equipped in the loads on Bus 11 (20,2kW) and Bus 89_2 (12,1 kW), acting at 49Hz with no delay. Results are shown in Figure 6.5. The sudden disconnection is enough to guarantee that frequency remains within desired limits. Also, it is important to guarantee load re-connection once the system has stabilized. This should be done in small steps, to avoid reactivating the relays (Figure 6.6).

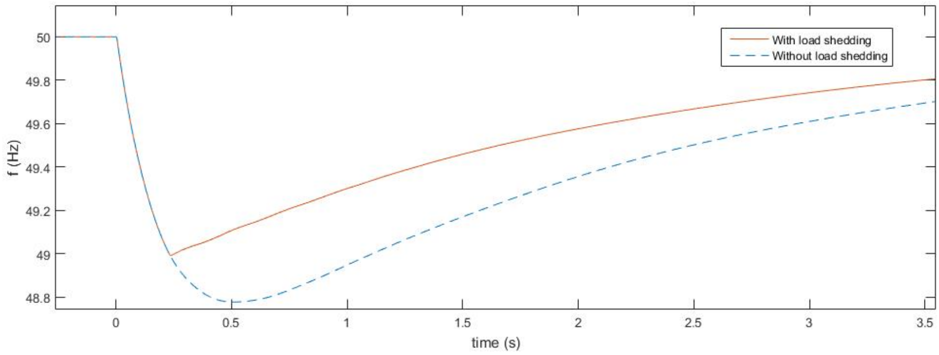

Figure 6.5: Frequency improvement with load shedding, Test 3

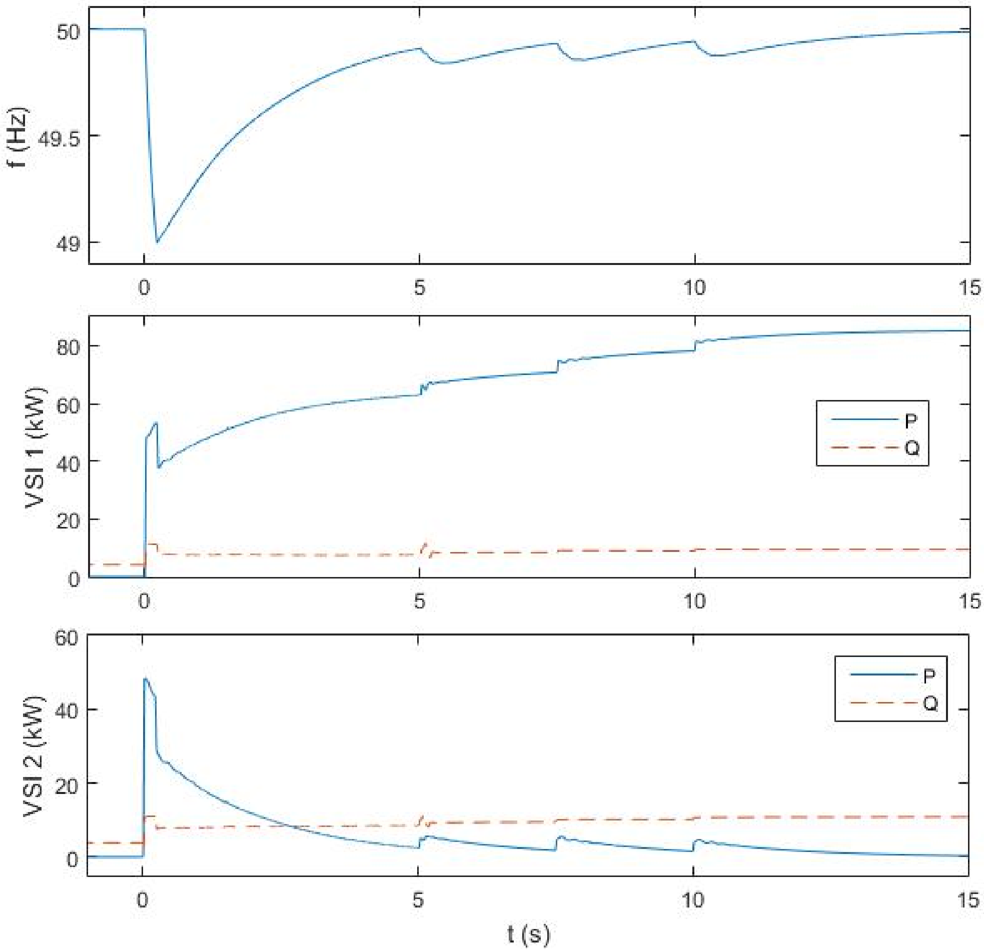

Figure 6.6: Load11 re-connection, Test 3

6.1.4 Test 4 - Multi Master Mode (2)

In this test VSI 2 also possesses integral control. As it can be seen from Figure 6.7, this helps the system restore its frequency twice as fast and reduces the maximum frequency sag by 0.2 Hz. The main advantage of this architecture is that it enables MG2 to act independently from MG1. Compared to Test 2, after the perturbation the batteries of VSI 2 are now constantly being discharged (Figure 6.8), improving voltage profiles in MG2 and reducing the power flow between MG1 and MG2.

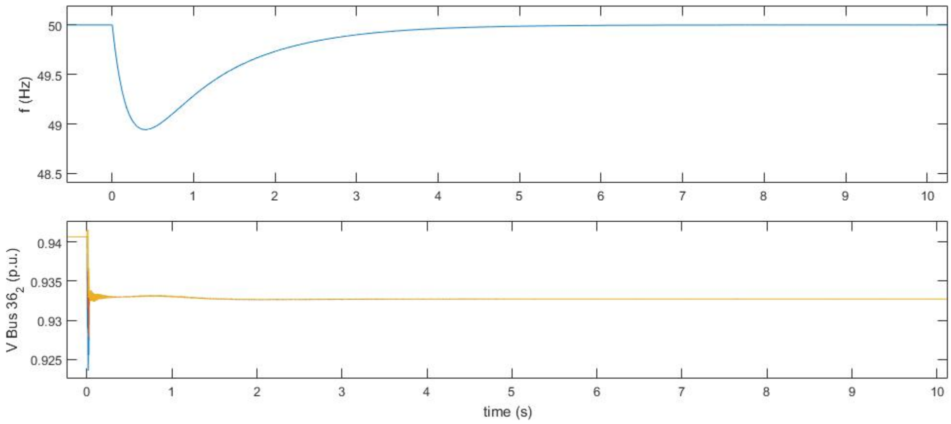

Figure 6.7: Frequency response and Voltage on Bus 36_2, Test 4)

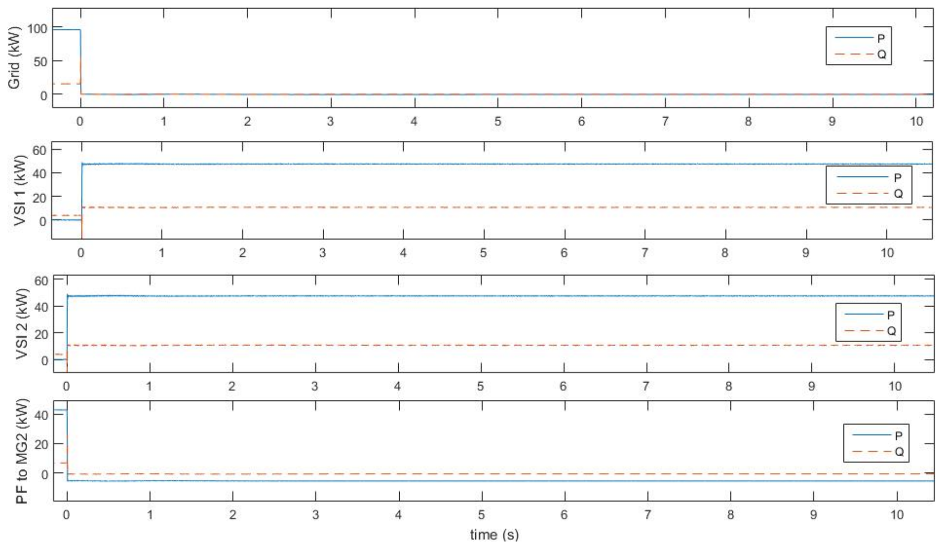

Figure 6.8: MMG power flow, Test 4

6.1.5 Test 5 - Load shedding (Laboratory)

The laboratory setup for this test is described in section 5.2. Load shedding was performed by the simulated Bus 11 (20,2kW) and by a real resistive load of 6,7kW in Bus 36_2, both set to curtail at 49Hz. It can be seen from 6.9 that the shedding process occurs in two different steps: one immediately when the system's frequency reaches 49Hz at 84.5s (load Bus 11) and another approximately 200ms later at 84.7s (load Bus 36_2). This is enough for the frequency to go slightly below 49Hz and highlights that sheddable devices should take into account this actuation time and be designed to act at a previous frequency point.

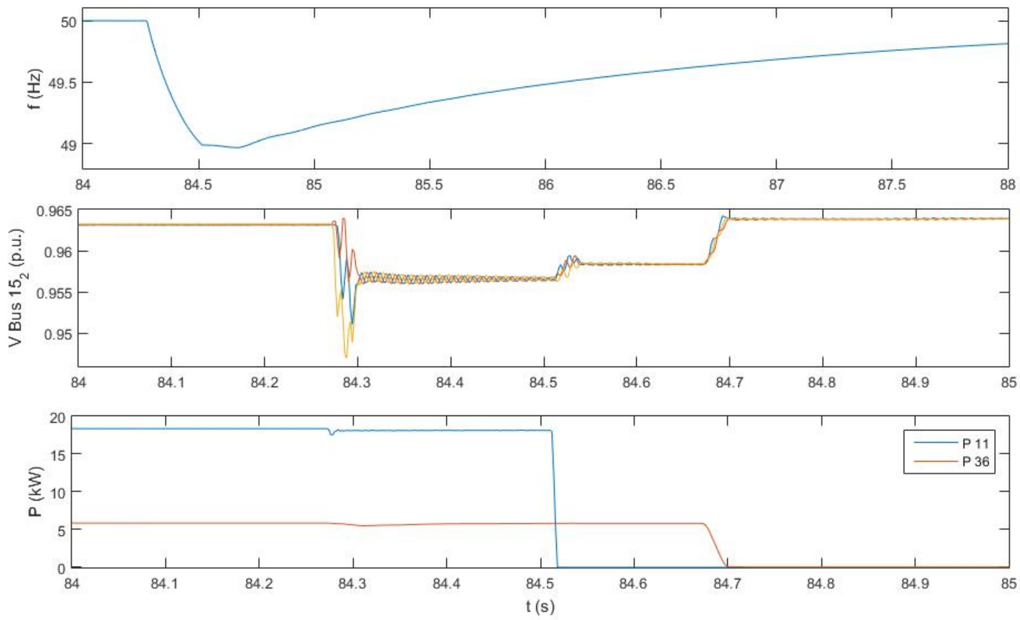

Figure 6.9: Frequency response and Voltage on Bus 15_2, Test 5

Since bus 36_2 voltage measurements were not available in the simulator, voltage on bus 15_2 is presented here since it is the one immediately before 36_2 and their behaviour is similar (Bus 15_2 has no load nor generation). Note that despite load 36 is much smaller than load 11, its curtailment affects the voltage on bus 15_2 much more due to its proximity. The voltage on bus 36_2 was measured directly at the loads terminals using the laboratory acquisition software and is presented in Figure 6.10 where the two disconnection steps can also clearly be distinguished.

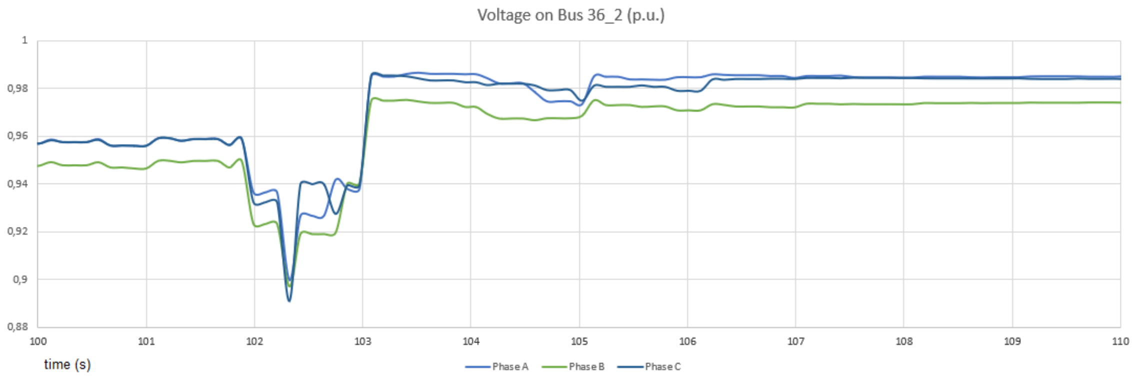

Figure 6.10: Voltage on Bus 36_2, Test 5

6.2 Scenario 2

6.2.1 Test 6 - Simulated PV Response

In this test the system operates in Multi Master Mode, with secondary control being purposely deactivated so that the solar panels response is not camouflaged. When the MMG islands, the 60kW that were being exported to the grid create a power unbalance, causing the frequency to rise. Frequency rising is put to a halt firstly due to the rapid energy absorption of the battery banks; levels are later reduced due to the actuation of the P-f droop of the PVs (Figure 6.13). Maximum voltage is reached at bus 71_2 given its high difference between generation and load. Values successfully remain within the desired band.

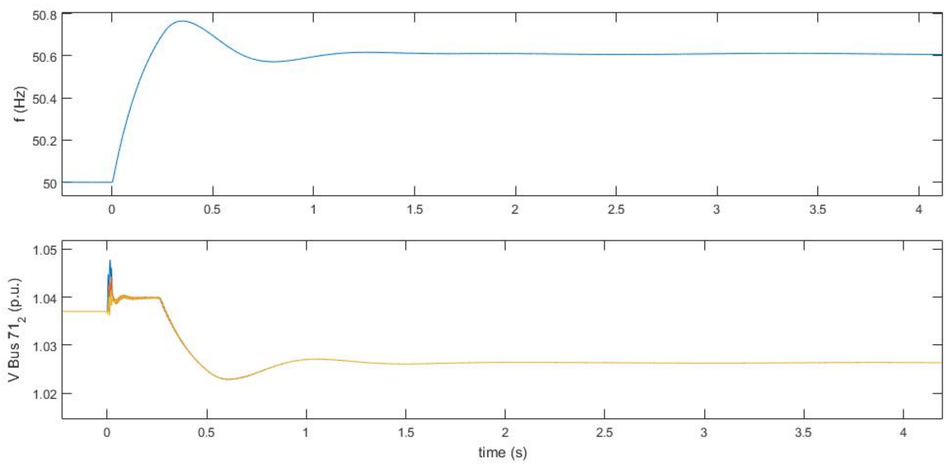

Figure 6.11: Frequency response and Voltage on Bus 71_2, Test 6

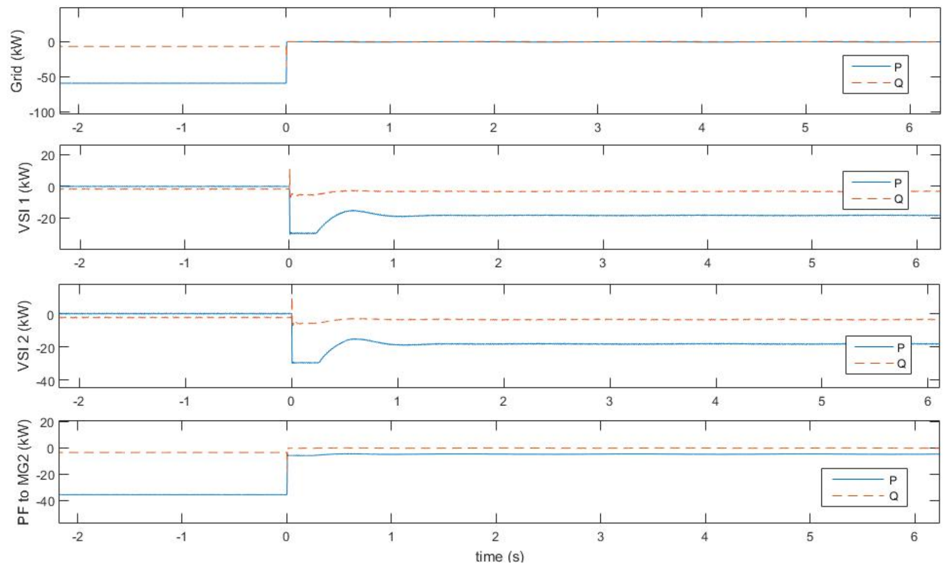

Figure 6.12: MMG power flow, Test 6

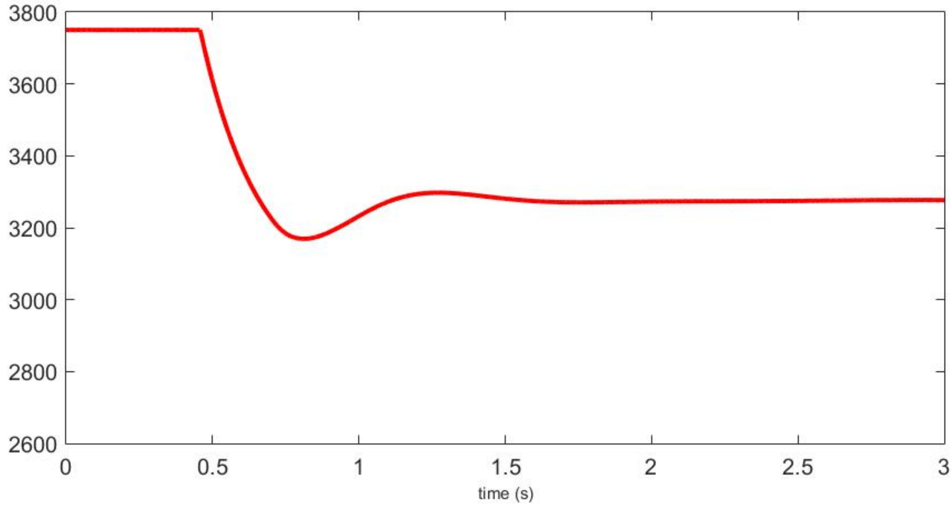

Figure 6.13: Active Power Generation on Bus 36_2, Test 6

	Prior to Isolation		After Isolation	
	P (kW)	**Q (kVAR)**	**P (kW)**	**Q (kVAR)**
Grid	-59,3	-6,6	0	0
VSI_MG1	0	-1,7	-18,3	-3,3
VSI_MG2	0	-2,3	-18,3	-3,5
Capacitances (MV Line)		3,9		3,9
DG	88,0	17,6	64,1	12,8
Total Gen	88,0	21,5	64,1	16,7
Load	26,3	6,1	25,9	6,1
Total Load (+ VSI, +Grid)	85,6	16,7	62,5	12,9
Losses	2,4	4,8	1,6	3,8
Power Flow to MG2	-35,5	-3,5	-4,7	-0,2

Table 6.2: Steady state results, Test 6

6.2.2 Test 7 - PV Response (Laboratory)

The previous test illustrated the behaviour of a PV in response to an over frequency. Its behaviour is actually controlled by the PQ inverter coupled to it. The inverter in the laboratory was programmed to have the same P-f settings, resulting in a very similar response, as illustrated below. The measuring equipment in the laboratory samples every 200ms, which leads to a lesser detailed curve. Notice that the difference in power measured (3600W instead of 3800W, 3100W instead of 3300W) can be explained by power losses in the wiring, inverter and transformer. Also, notice that the power nadir is lower (2800W instead of 3200W) since the internal actuation delay is smaller.

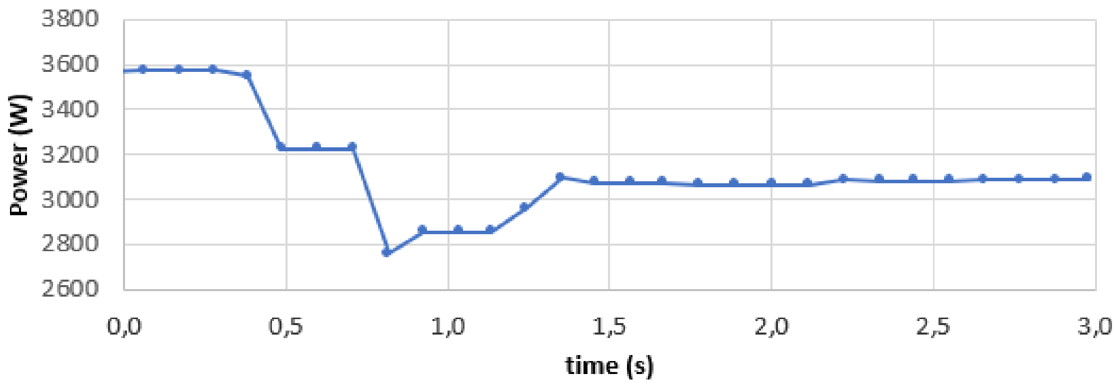

Figure 6.14: Active Power Generation on Bus 36_2, Test 7

The voltage curves clearly explain what happens in the system and validate simulation results. In the first ms after isolation, voltage rising is contained by the VSI energy absorption and approximately 250ms later, the PVs start reducing their power output, reducing voltages levels.

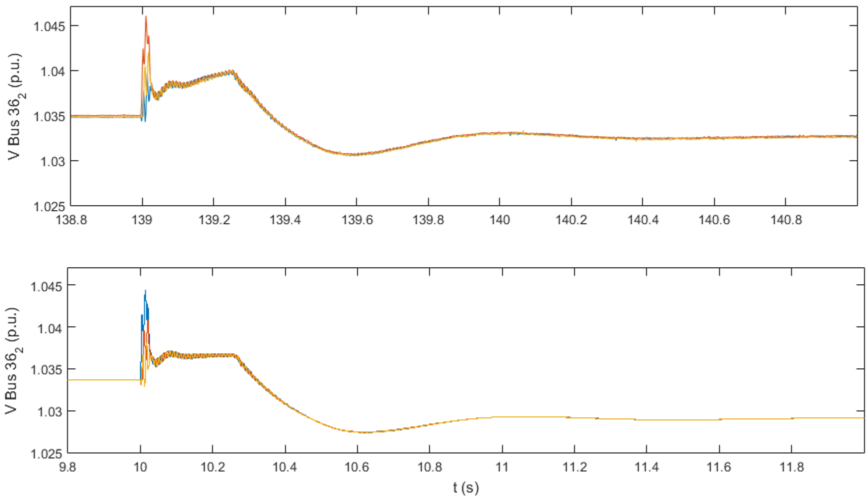

Figure 6.15: Bus 36_2 voltage response in laboratory (top, Test 7) and simulation (bottom, Test 6)

6.3 Scenario 3

6.3.1 Test 8 - Distributed Storage

The conditions of this test are the same as in 'Test 3 - Load shedding'. However, four small BESS with the same power rating where distributed across the MMG LV network. Their agressive P-f droop (2%) allows them to quickly discharge when the frequency falls outside the deadband (50 $\pm$ 0.2Hz), maintaining the system's frequency above 49Hz and preventing loads 11 and 89_2 from disconnecting. Their contributing is evident in the voltage profile of bus 36_2.

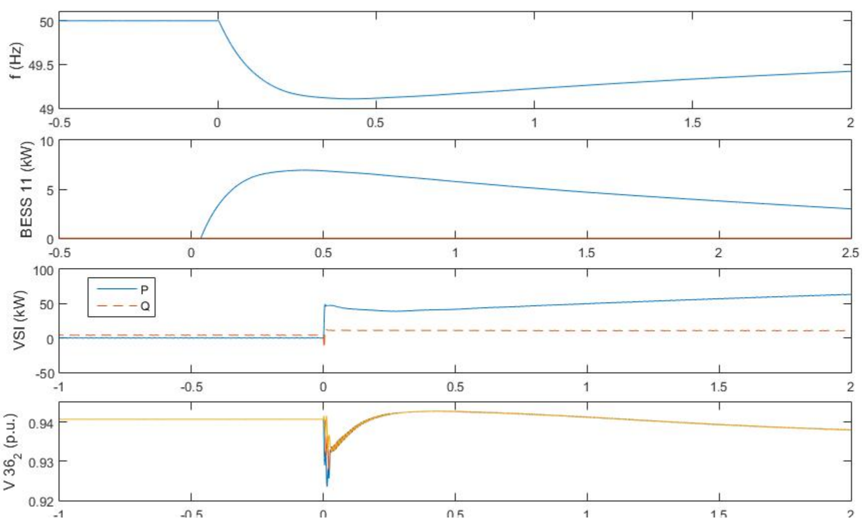

Figure 6.16: PV on Bus 36_2 response to over frequency, Test 8

6.4 Scenario 4

6.4.1 Test 9 - Black Start

This test sought to recreate a five-step blackstart process based on simulation only.

Step 1 - Re-connection of priority loads and MG build-up;

Step 2 - MG synchronization and connection (MMG);

Step 3 - Connection of DG;

Step 4 - Connection of remaining loads;

Step 5 - Connection to upstream grid.

The blackstart process is initiated at 8s when all loads, generators and transformers are sectionalized. After a 1s interval the VSI of each microgrid starts to slowly pick-up some load step by step (Figure 6.17, seconds 9 to 16). Build-up should be done with controllable sources only to guarantee stability. At this stage each MG operates independently and load and frequency differs between them. After all priority loads have been reconnected, a PLL is activated and voltage, phase and frequency compensators act on VSI 1 to hunt for the values of VSI 2. This can clearly be seen on Figure 6.18.

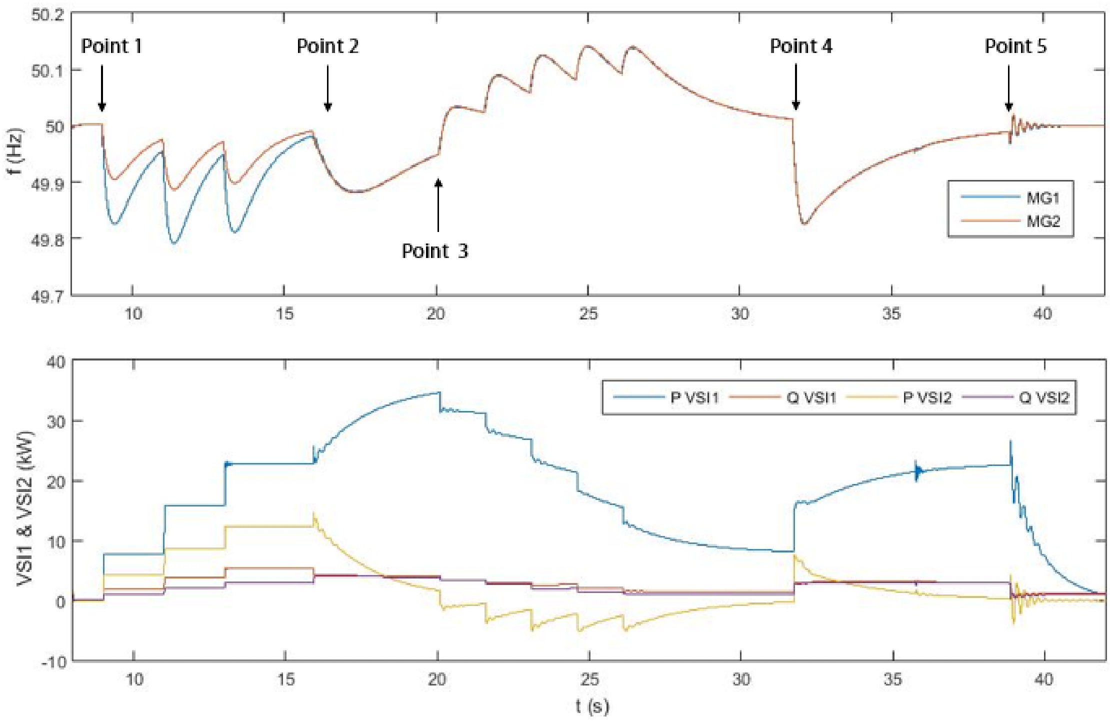

Figure 6.17: MMG frequency and VSIs power output throughout the BS, Test 9

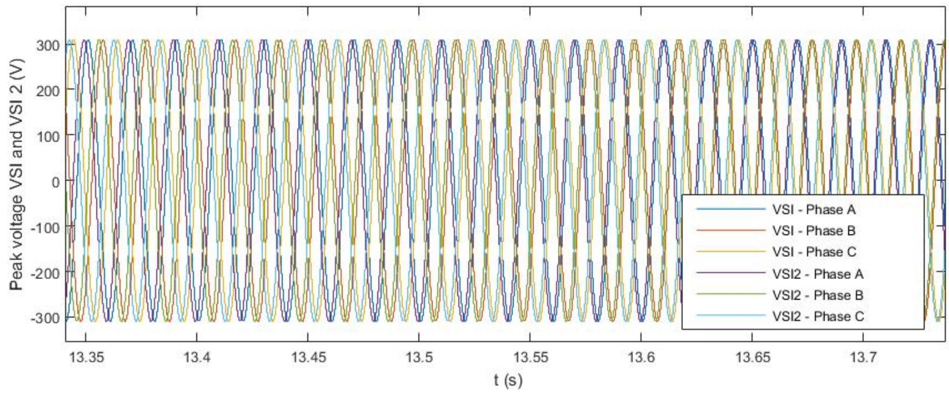

Figure 6.18: VSI 1 hunting for VSI 2, Test 9

Synchronization takes a few seconds and at approximately 16s the breakers near the LV/MV substation close and the two MGs are connected. Both MGs were operating with relatively similar loads (10kW differential) and so frequency remains stable, with just a small dip due to MV line losses. When re-connection occurs the secondary control in VSI 2 is deactivated; because of this, the two VSIs share the power evenly in the first moments but progressively VSI 1 accommodates all of it (second graph of Figure 6.17, seconds 16 to 20). In this operation the closing breakers are not ideally located since they are separated by a 5km MV line. This line is initially open circuited and its sudden energization causes its capacitances to resonate for approximately 100ms, leading to an over voltage of almost 1.1 p.u. in both VSIs and their nearest loads in buses 89 and 89_2 (Figure 6.19). This resonance can also clearly be seen in the MV line power flow, first graphic of Figure 6.20.

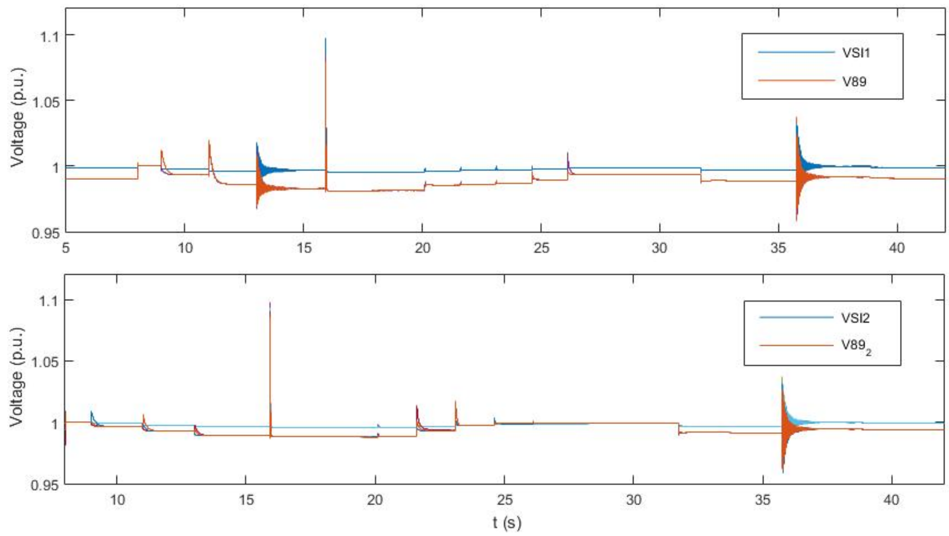

Figure 6.19: Voltage response of the VSIs and nearest buses, Test 9

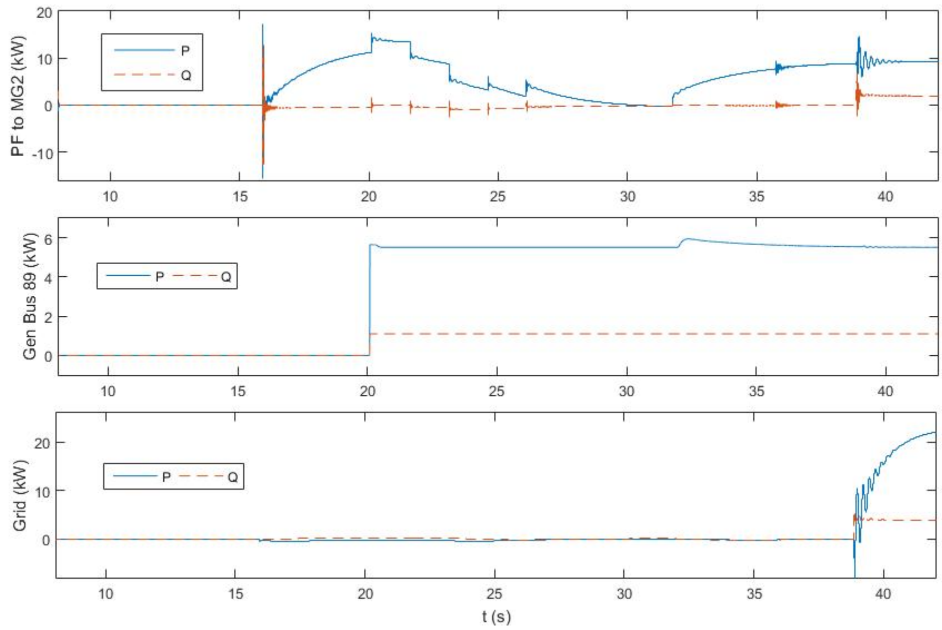

Figure 6.20: MMG power flow, Test 9

Following, each DG unit is connected individually and consecutively, in the same way as the loads in the MG build up, to prevent severe over frequency and over voltages. During this phase the batteries of VSI 2 are charged to reduce the power imbalance while VSI 1 continues to supply the majority of the loads (but also reducing power output), Figure 6.17, seconds 20 to $\tilde{3}$0. In this test the over frequency response of the PV panels was deactivated so that it is VSI 1 who decreases its discharge and not RE generation that is curtailed. Under frequency response remained activated, helping stabilize the re-connection of the remaining non-priority loads at approximately 32 seconds. Finally, in the last step and in order to synchronize the MMG with the macro grid, voltage, phase and frequency compensators act on both VSIs equally. Control voltage measurements were taken immediately downstream and upstream of the grid interconnection point, resulting in a smooth coupling transition with no significant deviations of standard frequency and voltages.

6.5 Summary and main conclusion

The strategies implemented to control the MMG successfully demonstrated how P-f droop functions on BESS and PVs and load shedding techniques can be used to control the system. Strategies helped attenuate frequency deviations and maintain voltage profiles within desired limits during transitory events. Also, the experiments in the laboratory managed to present logical results and illustrate a behaviour similar to its twin simulation tests. Finally, the Blackstart process proved the capacity of MGs and MMGs to self-heal.

Chapter 7

Conclusions & Future Remarks

The widespread of RET in distribution systems is environmentally necessary, but brings along operational challenges such as instability due to lack of inertia, unpredictability, voltage fluctuations, reverse currents, among other. The objective is to be able to overcome these challenges, or at least contain their aversive behaviour, by managing the system adequately through a network of intelligent and communicative devices capable of solving real-time operation constraints. This is an inter-dimensional problem that is directing high-end worldwide laboratories into a panoply of novel research fields. A general overview of those research fields and their specific areas of research is provided in a compact manner in chapter 3.

7.1 Main contributions of this thesis

The increasing electrification of developing countries and the transformation of power systems in developed ones has led to an increased interest in the development of facilities capable of testing technologies that improve the system's flexibility and reliability. In this way, providing a guideline that overviews the main features of existent solutions and reviewing the pros/cons of their designs could greatly benefit players seeking to assemble new facilities. It might give the necessary orientation required and instigate valuable laboratory development and ultimately accelerate power system transformation.

The major achievements of this thesis were the following:

- **Providing a critical analysis on current existent laboratory designs:** the main conclusion to be taken from the three laboratories analysed is that all of them manage to perform MG basic functionalities such as islanding, V/f regulation and economic optimization. Each one of them has a distinctive approach in its design that has advantages and disadvantages. MGRL is highly controllable and offers advanced testing possibilities with centralized and distributed toggling capacities, but is also rather simplistic topology wise. EES is physically very limited but has greatly developed MAS and has a lot of scalability in their applications. SGEVL is more complex topology wise in terms of configuration and uses a control strategy that can emulate household applications but does not allow any plug-n-play application. In conclusion, there is no approach that is overall superior to the others. Excelling in all three areas (controllability, scalability and topology complexity) is very difficult and costly and so each laboratory ends up specializing in a certain application.

- **Providing a guideline on basic infrastructure necessary to assemble a MG setup:** Taking into account the common elements between all laboratories and the knowledge detailed in the state-of-the-art, a guide was derived to orient new players. All summed up, it was verified that 6 elements constitute the backbone of a MG laboratory setup: DG Units and Loads, Power Electronic Interfaces, Advanced Metering Infrastrucute, Coordination Agents, Intelligent Protection System and Human Machine Interfaces.

- **Analysing laboratory capabilities in respect to MMG testing:** dedicated research found no other documents rather than MGRL that claimed to possess MMG testing capabilities. Even so, no proven results confirmed this claim and the way of achieving this was not thoroughly explained, raising skepticism. SGEVL and EES both possess multi-microgrid setups, but they are not capable of operating them independently. In conclusion, MMG laboratory testing is not really 'fully' available yet.

- **Successfully studying MMG dynamic behaviour through a simulation environment:** a real LV network was adapted into a LV/MV MMG in *Matlab Simulink* and the dynamic modelling of each of the system's components was thoroughly described. An emphasis was given to the tuning process behind each one of the VSI's control parameters, so to justify their settings throughout the experiments. Four operation scenarios were considered in which the MMG was able to withstand severe power unbalances in both SMO and MMO by resorting to strategies such as emergency load shedding, distributed storage and PV P-f droop control. Also, a BS process was successfully demonstrated, where both MG's self-heal independently and manage to re-establish connection with the MMG and upstream network.

- **Successfully performing validation testing with PHIL**: experiments were carried in the SGEVL at INESC TEC and utilized RTDS and PHIL to replicate the MMG previously implemented in *Matlab Simulink* and emulate its interaction with real equipment at the laboratory. The two tests consisted of an emergency load shedding and a PV response to respectively, an under frequency and an over frequency. It was verified that the DUT's behaved properly and as expected: the load was curtailed at 49Hz to prevent an under frequency and the PVs reduced their power output. These experiments also served to demonstrate the capabilities and benefits of PHIL simulation in regard to laboratory validation testing.

7.2 Future Remarks

The work presented in this thesis provides a guideline on the basic design architectures behind a laboratory capable of performing MG testing. Further developments on this issue consist of:

- **Including a cost analysis:** budget will probably be a great concern for new players trying to assemble a new facility. Including a cost analysis in regard to each infrastructure would provide better orientation.
- **Asking the three considered laboratories for updated information.** The documents reviewed date back to 2014 and 2015, it could be the case that as of 2019 they have modified or improved their setup. SGEVL, for instance, has partially modified its control architecture, but the lack of documentation made it difficult to describe and illustrate.
- **Extending research and enhancing the document:** research was restricted to three laboratories due to availability of information and also time.

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Appendix A

Appendix

Type	Suitable Applications	Possible Applications
Lead Acid baterry	Load following, Voltage support, Black start, Frequency regulation, Power quality, Power reliability	Spinning Reserve, RES integration
Lithium ion battery	Voltage support, Black start, Frequency regulation, Power reliability	Load Following, Power Quality, RES integration
SMES	Power quality	Power reliability
Flywheel	Load following, Voltage Support, Power quality, Power reliability	Spinning reserve, Primary frequency regulation, RES integration
Supercapacitor	Power quality	-

Table A.1: MG Storage technologies applications

Peak Load (kW/kVAR)										
	3 phase		**Phase A**		**Phase B**		**Phase C**		**Balanced Adaptation**	
Node	P	Q	P	Q	P	Q	P	Q	Total P	Total Q
89	0	0	5,17	1,051	8,62	1,751	10,35	2,1	24,14	4,902
84	0	0	6,61	2,11	14,69	4,24	4,28	1,47	25,58	7,82
11	37	7,51	0	0	0	0	3,3	0,67	40,3	8,18
55	0	0	2,55	0,64	7,64	1,914	2,55	0,64	12,74	3,194
71	6,32	1,28	0	0	0	0	0	0	6,32	1,28
66	9,46	1,92	11,54	2,34	0	0	0	0	21	4,26
15	0	0	0	0	0	0	1,1	0,16	1,1	0,16
42	6,43	1,88	0	0	0	0	0	0	6,43	1,88
51	8,69	1,76	0	0	0	0	0	0	8,69	1,76
36	7,1	2,07	9,17	2,68	0	0	0	0	16,27	4,75
25	0	0	11,75	1,67	7,05	1,01	4,7	0,67	23,5	3,35
22	6,67	1,67	0	0	3,3	0,83	0	0	9,97	2,5
45	6,23	2,05	0	0	0	0	0	0	6,23	2,05
							Total		196,04	46,086

Table A.2: Peak Load of Rural Grid (original nominal rated power)

Peak Generation (kW/kVAR)												
	EV			**PV**			**WT**			**SSMT**		
Node	A	B	C	A	B	C	A	B	C		Total P	Total Q (0,2*P)
89	6	6	0	0	0	12,5	0	0	0	0	24,5	4,9
84	3	0	0	0	12,5	0	0	0	0	0	15,5	3,1
11	6	6	0	0	0	0	0	6,2	0	0	18,2	3,64
55	0	0	0	0	14,4	0	0	0	8	0	22,4	4,48
71	0	0	12	0	0	0	0	0	0	15	27	5,4
66	0	0	0	10,5	0	0	0	0	0	4	14,5	2,9
15	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	3	3,2	0	0	0	0	0	0	6,2	1,24
51	0	0	6	0	0	0	0	6,8	0	0	12,8	2,56
36	0	0	0	0	0	7,5	0	0	0	0	7,5	1,5
25	0	0	0	5,2	0	0	0	0	0	4	9,2	1,84
22	0	0	12	0	0	0	0	6,2	0	0	18,2	3,64
45	0	3	0	0	2,7	0	0	0	0	0	5,7	1,14
							Total				181,7	36,34

Table A.3: Peak Generation of Rural Grid (original nominal rated power)

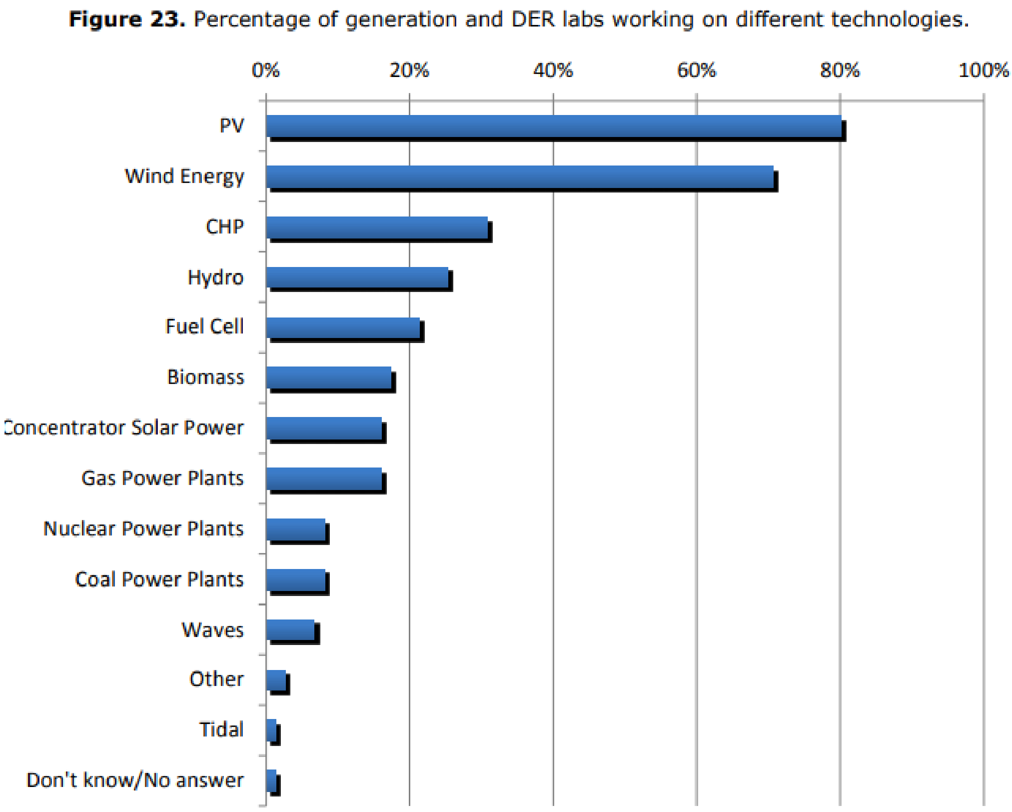

Figure A.1: Percentage of generation and DER labs working on different technologies [7]

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

Table A.4: Rural Network - LV Feeder Impedance

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

Table A.5: Rural Network - MV Feeder Impedance (values per km)

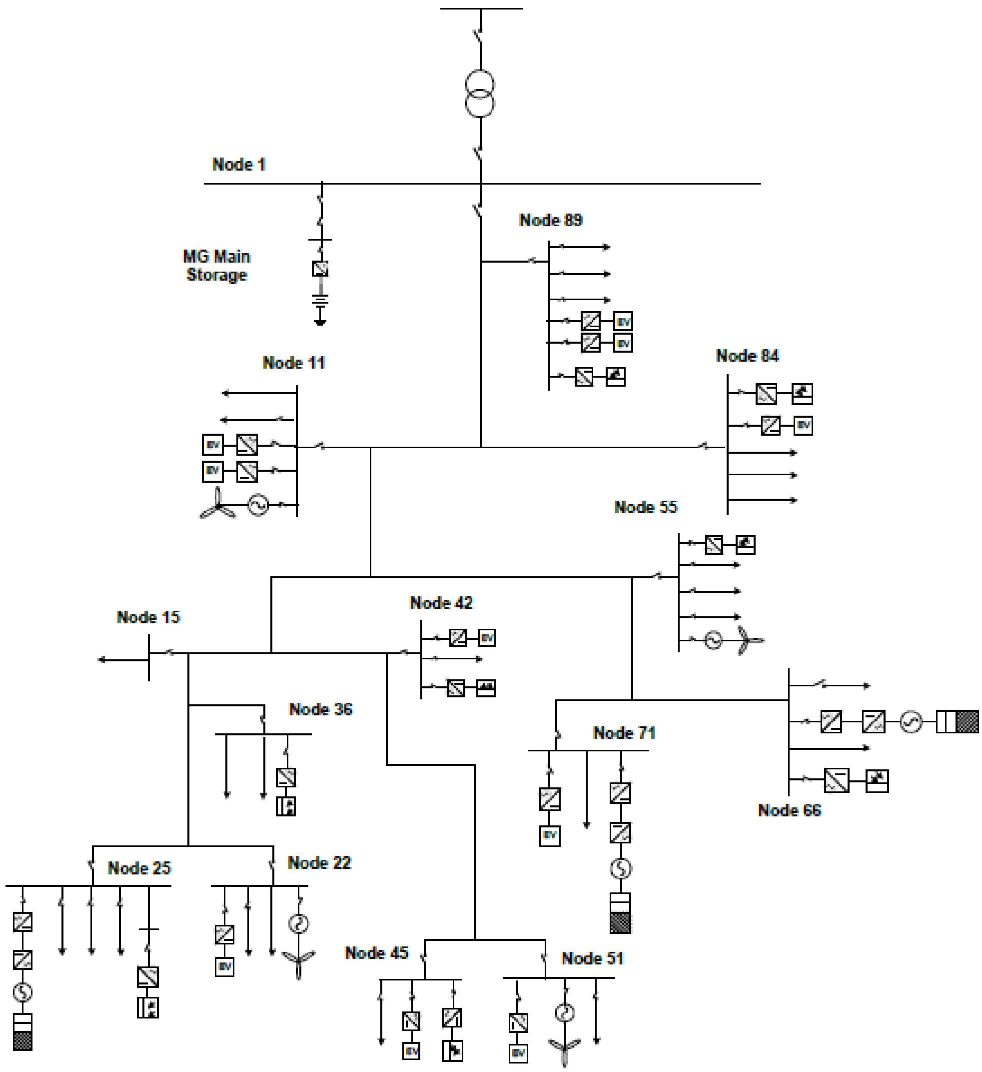

Figure A.2: OriginalMG, MERGE project

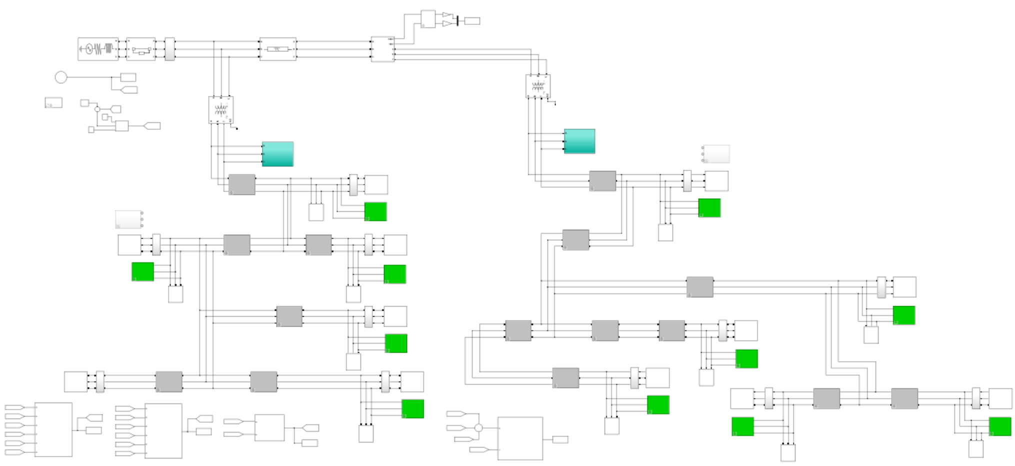

Figure A.3: Multi-Microgrid model in Matlab Simulink

Nodes		Cables	Length (m)				
From	To		1	2	3	4	Total
1	89	RZ 0.6/1 KV 3X150/95 AL	391	-	-	-	391
89	84	RZ 0.6/1 KV 3X150/95 AL	121	-	-	-	121
89	11	RZ 0.6/1 KV 3X50/54.6 ALM	85	-	-	-	85
11	15	RZ 0.6/1 KV 3X95/54.6 ALM	13	-	-	-	13
15	36	RZ 0.6/1 KV 3X95/54.6 ALM RZ 0.6/1 KV 3X50/54.6ALM RZ 0.6/1 KV 2X25AL DN 0.6/1 KV 25 CU	26	6	58	161	251
11	42	RZ 0.6/1 KV 3X95/54.6 ALM RZ 0.6/1 KV 3X50/54.6 ALM	23	2	-	-	25
42	45	RZ 0.6/1 KV 3X95/54.6 ALM	5	-	-	-	5
42	51	RZ 0.6/1 KV 3X95/54.6 ALM	66	-	-	-	66
11	55	RZ 0.6/1 KV 3X50/54.6 ALM	32	-	-	-	32
55	71	RZ 0.6/1 KV 3X50/54.6 ALM	32	-	-	-	32
55	66	RZ 0.6/1 KV 3X50/54.6 ALM RZ 0.6/1 KV 3X25/54.6 ALM	2	56	-	-	58

Figure A.4: LV feeder characteristics, adapted from [27]

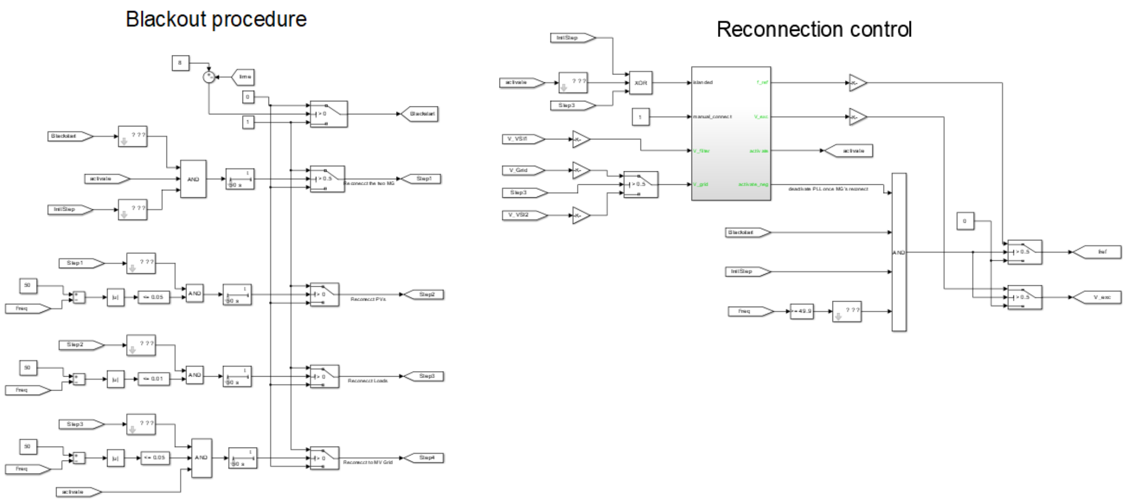

Figure A.5: MGCC implementation in *Simulink*, BS controls