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Resumo

A integração de recursos renováveis tem contribuído para o aumento dos requisitos de flexibilidade nos sistemas elétricos de energia. Paralelamente a este constante aumento de introdução de produção dispersa, tem-se assistido à criação de novas soluções para colmatar a variabilidade da produção renovável, nomeadamente sistemas de armazenamento de energia. Por conseguinte, surgem dificuldades em coordenar ambas as tecnologias para redes tão vastas, sendo expectável que estas limitações sejam ultrapassadas através da transformação das redes atuais em micro-redes, equipadas com sistemas inteligentes de comunicação, permitindo uma flexibilização de recursos e uma coordenação otimizada. Uma das características distintivas das micro-redes é a capacidade de poderem operar interligadas com a rede de distribuição local, ou de forma isolada, isto é, desligadas da rede. A operação de micro-redes em sistema de energia de países desenvolvidos não se sucede de uma vantagem competitiva, mas sim de uma vontade de integração de energias renováveis. No entanto, em locais de difícil acesso ou com densidade populacional muito baixa, o acesso à eletricidade é deficitário visto que de um ponto de vista económico a extensão da rede a esses locais não é viável, e como tal não é visto como prioritário. As micro-redes possuem assim um nicho de mercado que deve ser explorado. Nesta dissertação é analisada de que forma locais remotos/subdesenvolvidos podem contribuir para a maturação e evolução da tecnologia das micro-redes, dando especial atenção à forma como dimensionamento e estrutura da micro-rede influencia o resultado e a implementação de projetos de eletrificação remotos/rurais. A análise é suportada por uma simulação computacional, em tempo discreto, referente à ligação micro-redes à rede de distribuição de média e baixa tensão, bem como o seu funcionamento em modo isolado. Estes estudos permitem avaliar a contribuição dos diversos elementos de geração e armazenamentono fornecimento de cargas da rede e a adequabilidade da disposição dos sistemas de armazenamento e produção.

Abstract

The integration of renewable resources has contributed to increase flexibility requirements in electric power systems. Parallel to this constant increase in the introduction of dispersed production, new solutions have been created to cope with the variability of renewable production, namely energy storage systems. As a result, there are difficulties in coordinating both technologies for such complex and active networks. It is foreseeable that these limitations may be tackled by the adoption of microgrids, with multiple distributed energy resources and equipped with intelligent communication systems, allowing resource flexibility and optimized coordination. One of the distinguishing characteristics of microgrids is the ability to operate interconnected with the local distribution network, or isolated, meaning, disconnected from the main network. Microgrid operation in developed countries doesn't not reflect a competitive advantage over traditional grid system but rather of the desire to integrate renewable energy resources. Nevertheless, in hard to reach areas or with low density population, grid access is limited since from an economical stand point of view grid extension to those areas is not viable, as so is not seen as a priority. Therefore, it presents as an opportunity for microgrid technology to mature. In this dissertation an analyses on how remote/rural areas can provide an environment where microgrid technology can mature and evolve is presented, focusing on how MG design and sizing affects project outcome in remote/rural areas. A computational simulation to back up the written analysis was developed. The simulation allows for analysing the contribution of energy storage systems and micro-sources in multi-microgrid operation in medium/low voltage grids, testing for islanding feasibility and displacement of loads and generation.

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João Pinho

"O segredo para a saída não é subir altitudes
É quando aponto o importante, é quando
nomeio virtudes
A glória mora onde eu pertenço e o apreço
condecora
E eu estou preso a este peso que me ancora "

Samuel Mira

Contents

List of Figures

List of Tables

List of Acronyms

AC	Alternate current
AMR	Automated meter reading
ANM	Active network management
CAMC	Central autonomous management controller
CHP	Combined heat and power
DC	Direct current
DFIG	Doubly-fed electric generators
DG	Distributed generation
DSM	Demand side management
DOD	Depth of discharge
DSO	Distribution system operator
FACTS	Flexible AC transmissions systems
EC	Electrochemical capacitors
ESS	Energy storage system
ESCO	Energy service company
ICT	Information and telecommunication technology
MC	Micro source controller
MG	Microgrid
MGCC	Microgrid central controller
MPPT	Maximum power point tracking
MV	Medium voltage
MS	Micro sources
NAS	Sodium Sulfur
LC	Load controller
LV	Low voltage
OPF	Optimum power flow
PE	Power interfaces
PV	Photovoltaic
RES	Renewable energy resources
ROI	Return on investment
STATCOM	Static synchronous compensator
SMES	Superconducting Magnetic Energy Storage
SOP	Standard operating procedure
TCO	Total cost of ownership
UPS	Uninterruptible power supply
VPP	Virtual power plant
VSI	Voltage source inverter

Chapter 1

Thesis Motivation

In a sustainable society, natural resources for economic growth are not exploit to the point of environmental degradation. Increasing temperatures, deforestation, desertification, water pollution and species extinction are raising awareness for a need to change the current environmental economic status. Greenhouse gas emissions are one of the greatest environmental and economic challenges facing humanity [7].

People's well-being, industrial competitiveness and the overall functioning of society are dependent on safe, secure and affordable energy. Modern society depends critically on a secure supply of energy, depleting fuel resources are increasing concerns for primary energy availability, moving the electricity sector to the centre of governments' energy policies. The growing political instability around fossil fuels exporting countries and climate change initiatives require a shift in the energy intensive sectors. Moreover, the ageing infrastructure of electricity transmissions and distribution networks, combined with the ever-increasing demand of electricity are pushing electric grids towards a more sustainable, competitive and secure future [8].

Electrical energy production through renewable energy sources (RES) manifests a desired trajectory for a sustainable energy future, a logical approach to achieve energy sustainability. Power generation using RES, is often dispersed depending on the availability of the resource available and the quality of exploration of said resource. e.g. (wind, solar, water). Disperse generation changes the traditional radial structure of the grid. This new structure invalidates the traditional power flow control methods, the radial distribution system and the transient characteristics of the network [9]. The increasing load at low levels of the grid and the future liberalization of generation markets will force the central control approach of the distribution network towards a more decentralized one. Key technical challenges such as circuit protection coordination, power quality, reliability and stability issues must be addressed.

Rather than adopting a revolutionary approach, existing grid systems should be used to provide an excellent foundation from which future challenges and opportunities can be met, to establish interfacing capabilities that will allow new designs of grid equipment and new automation/control arrangements to be successfully interfaced with existing, traditional, grid equipment. A strategy for research, development and demonstration through key laboratory infrastructures, will empower network companies, allowing them to respond to the considerable challenges that they will face in the coming decades. Micro grid testbeds and concepts help generate a solution for increasing load levels at the low voltage part of the distribution network [10].

Governments will be expected to take a heavy share of the responsibility and make substantial investments in diverse areas such as research, development and demonstration in support of innovation in energy technologies and development of new infrastructure to deliver modern energy services. Incentives should encourage a network operator to earn revenue in efficient ways (efficiency gains and lower peak investment needs) instead of volume driven incentives going from volume-based business model to a quality and efficiency-based model, a competitive retail market in the interest of consumers, by facilitating access to new entrants, including energy service companies and ICT (information and telecommunication technologies) providers that can provide services to consumers allowing them to change their behaviour to their benefit. The highly regulated nature of electricity services dictates that the public sector will be a key player in all aspects of activities involving the deployment of new electricity technology.

In countries where the radial/traditional grid is extensively developed, disperse generation through RES reflects underlying factors such as economic development and political priorities of governing bodies, more than a competitive advantage over traditional systems. The annual *Tracking Clean Energy Progress* report, included in *ETP*[1] 2017, examines how various technologies are moving in comparison with global climate targets. The results show that transformation towards a clean energy system is not in line with the stated international policy goals, for most countries. Legal framework and natural monopolies make the scale-up and deployment of RES micro/mini-grids technology dependent on political incentives and close to the market.

However, non-OECD[2] countries encourage off-grid electrification operations through minimal government regulation and present favourable conditions to mini/micro-grid projects to deploy and technology to mature. Sparsely populated and/or low-income regions make grid extension not economically viable, therefore electrification by massive extension of infrastructures fails to be economically viable, has major local constrains such as disperse rural population, low purchasing power and limited potential for load growth were largely overlooked.

As a result microgrids have an opportunity that can be explored where technology can properly mature and become cost competitive.

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[1] Energie technology perspectives

[2] Organisation for Economic Co-operation and Development

1.1 Thesis objectives

Electrifying remote/rural communities has always been a challenge for many years, leaving many without access to electricity. This thesis aims at illustrating how MGs can have a positive impact on remote/rural areas while at the same time benefiting from a niche market, providing and overview on how RES penetration is changing the grid structure and how high technological projects can benefit from the electrification of remote/rural areas. Moreover, a top-down multi-temporal simulating tool for MMG sate estimation is presented. The tool aims at evaluating MG architecture for MG's project feasibility.

1.2 Outline of the thesis

In 2 a review of the state of art of MGs is made. Futhermore, the role of MG in the electrification of remote/rural areas is discussed. In chapter 3, the importance of MG testbeds is reviewed. In addition, MG architecture designs are analysed. Chapter 4 presents the simulation tool for project validation. Where in chapter 5 the results are outlined. Lastly, in chapter 6 some remarks are made about the dissertation.

Chapter 2

Microgrids for the electrification of developing countries

2.1 Introduction

In this chapter, a review of the literature is presented. The role of the microgrid (MG) and how it will impact the grid is discussed. Key technology aspect present in MGs are outlined. Lastly, the role of MGs in the electrification of developing countries is discussed.

2.2 Microgrid concept

The concept of MG was first introduced by the Consortium of electric reliability technological solutions *CERTS*. The concept assumes an aggregation of loads and micro sources (MS) dispatchable units who operated as a single self-controlled entity from the macrogrid perspective [11]. The *CERTS* MG purpose was to provide an easier integration of MS in the power grid [12]. The *CERTS* MG project developed and demonstrated three key features:

1. Seamless transition between grid connected and islanded mode (off-grid) – Displacement flexibility of disperse generation (DG)

2. Different concept and methodologies for protection systems with DG penetration

3. MG voltage and frequency control methodologies not dependent on high-speed communication technologies.

> "A microgrid's key feature is its ability, during an abnormal utility grid disturbance, to separate and isolate itself from the utility grid seamlessly with little or no disruption to the loads within the microgrid. Then, when the utility grid returns to normal, the microgrid automatically resynchronizes and reconnects itself to the grid, in an equally seamless fashion" - Firestone, Ryan and Marnay, Chris[13]

The DG can conceptually be added and removed easily in a ‘Plug and Play’ model. The concept introduced by *CERTS* MG meant that DG technologies could be placed at any point within the MG without requiring re-engineering of MG controls. The peer-to-peer operation insured that no specific component was required for normal operation. This concept was then further developed and adopted to cover the integration of renewable energy resources RES, initially by the European union. The EU project *MICROGRIDS* focused on the development of active management strategies for distribution networks for safe integration of large disperse energy resources at the LV/MV level of the grid,introducing new challenges as well as new opportunities.

CERTS MG introduced three key concepts for successful integration of multiple MS (Micro source), this concepts layout a basic structure for any MG model.

1. Local MS controller
2. Energy Manager
3. Distributed Protection coordinator

Local micro source controller – Was designed for real-time frequency and voltage regulation. In a multilevel control structure considering the time-frame of control action, micro source controllers (MCs) are at the first level of control. Engaged in the inner control loops of grid forming and grid feeding inverters.

The energy manager - Optimizes local system operation providing power and voltage set points for each MS, logic and control for islanding and reconnecting and operational conformity with the transmission system.

The protection coordinator - A protection coordinator is installed in each feeder, in case of an internal fault, disconnection is made such that the out of service section is minimized as well as to isolate the MG from the power grid, when necessary.

The concept was designed to facilitate the intelligent network of autonomous units, allowing for reconfiguration without significant re-engineering. The lack of a master controller adds to the system robustness and allows for simple system expansion.

The concept brought major challenges and outlined the fragility of traditional protection schemes with disperse energy resources (DER) integration. Protection within MG distinguishes itself from traditional over current relays in the sense that the re-configurable nature of the MG creates bi-directional faults as well as different nominal over currents. Furthermore, since the MS nominal power are considerable lower than the generation sites usually present at grid level, over currents are insufficient to trip traditional grid relays. The configuration and layout of the *CERTS* testbed can be viewed in [14]. From the report, a differentiated protection scheme can be easily outlined with shunt trip beakers in every feeder.

2.2.1 Renewable energy sources integration

Integration of renewable energy sources (RES) in the power grid, was first managed in a fit an forget strategy. However, with increased penetration and technology availability RES disperse generation (DG) started to have an impact on the output of the power grid. A different strategy was needed to optimize and manage the stochastic nature of RES DG. Virtual power plants (VPP), appeared with the aim of providing a more robust solution by aggregating multiple RES DG and managing their output has a unit. Has a similar concept the MG operates by aggregating multiple technologies. However, the MG distinguish itself from VPP in the sense that there is a focus on local supply of electricity to nearby loads.

> “Concepts that disregards generation and load location such as cross-regional virtual power plants are not considered microgrids, small island systems can also be termed micro grids , in the sense that a coordinated control of their resources is present, however microgrid’s ability to shift to islanded operation should only be used in emergency cases”. - Nikos Hatziargyriou [15]

Increased RES penetration through the exploitation and extension of RES DG led to the Multi-Microgrid concept, a high level management structure, formed at the medium voltage MV level, consisting of low voltage (LV) DG, MV loads and DG units connected on adjacent MV feeders, all controlled by the demand side management (DSM). The framework was developed by the More Micro Grids project, in which a control unit, central autonomous management controller (CAMC) would be place at the high voltage/medium voltage substation in order to manage the bi-directional flow at the MV feeders[16] [17].

In [18] the microgrid was defined as a “low voltage distribution system to which small modular systems are to be connected”. Such modular systems would allow for adaptable re-configurable solutions for fast response towards future technological or economical changes. Massive integration of MGs, where MGs could be connected to the same LV feeder, MG clusters. In such situation power flow in the LV feeder would be dictated by DER generation. A power grid with stochastic generation as well as stochastic loads, where every user is producer and a consumer, a prosumer. This level of DG integration and interaction between users is conceptualized as the ENERGY Internet, the Smart Grid, since energy could be exchange similar to information. In Smart grids, power grids will heavily rely on advanced metering and communication technologies for system operation as side-by-side demand takes place [19].

2.2.2 Summarizing

The MG as a concept first appeared as solution for seamless integration of dispatchable micro sources with the power grid. Focusing on key concepts as connection and disconnection as well as local control, indistinguishable from normal consumer loads. A desired trajectory for a sustainable energy future pushed forward RES DG penetration. It’s important to highlight RES has the main driver, this because initially the grid evolved from a decentralized structure where generation was near consumption sites to a large centralized radial structure. Power generation was disperse due to technical lock-ins and lack of infrastructures. Now, generation sites are moving to where RES exploitation for power generation is economically viable. Large integration of RES changed the traditional structure of the power network creating new challenges, which gave way to new control/management methods like Multi MG concept. Full immersion of RES DG will eventually lead to MG clustering and side-by-side demand[20].

2.3 Microgrids management and control architectures

The MG structure rapidly evolved to encompass the integration of RES. However, the stochastic nature of RES MS added uncertainty to the generation. Furthermore, RES integration heavily relies on power converters, therefore no generation is directly coupled with the grid, as a consequence the systems vulnerability is increased. Having fewer dispatchable units made the system more susceptible to load changes, specially in island mode. In this context two local controllers the micro source controller (MC) and the load controller (LC) were defined [17]. For system stability and reliability, load shedding mechanisms were added as well as energy storage systems. Furthermore, the MG infrastructure was overlaid with a communication and information system, being the local controllers coordinated by a MG central controller (MGCC), installed at the PCC, responsible for high level decision making for MG continuous operation.

2.3.1 Operation Modes

Within the MG concept two operation modes were devised.

Grid connected – The normal operation of the MG is grid connected, while connected the MG can either be supplying or injecting power to the grid. MG stability is assumed by the grid and the power exchange between the grid and the MG can serve various operation purposes, namely economical, technical and environmental.

Emergency Mode– In case of a fault occurrence (internal or external) the microgrid must have the ability to operate in an isolated mode to operate in an autonomous way similar to the power systems of geographic islands (islanded mode). This function ensures an important advantage of microgrids in terms of improving reliability and continuity of service, by reducing interruption times. Furthermore, if islanding fails and service is lost, a local service restoration can be launched [18]. However, in a heavily inverter based MG, lack of rotational inertia from traditional electromagnetic machines depletes the system of “delayed” frequency adjustments, meaning that when operating isolated from the grid the system is more affected by load variability, which can easily shut down the system, therefore in emergency mode service continuity is insured by energy storage systems.

2.3.2 MG configuration

The modular nature of MGs allows for many possible configurations. MGs configurations will vary depending on the types of feeders used (AC and/or DC). MG configuration should be carefully planned and adapted for each case, taking into consideration existing and planned DG, the logistics of energy storage devices, the difficulty to place new electrical lines, the nature of the load as well as the social and environmental impact.

For AC MGs, the similarity to the power grid provides several advantages in transmission segments regarding its transformer, breaker-based control infrastructure and adaptability to the grid. However, AC MGs have the problem of inrush currents produced by transformers and induction machines. Phase unbalances between the single-phase loads and single-phase generators and the grid must be addressed as well. AC MGs require a high number of power electronics interfaces, which affects the system reliability and complexity.

On the other hand, DC MGs don't have synchronization issues, there is no power factor losses and less losses in general. (No voltage sag, inverter or transformer losses). However, in most cases a DC network needs to be built which adds substantial costs to DC MGs, in addition expensive DC-DC converters are used to interface different voltage DC. Moreover, is hard to design protection systems for DC networks, since traditional protection devices are based on zero crossing set points. Furthermore, incompatibility with AC grids means that DC MG are connected via PE, reducing the system overall reliability.

Hybrid MG try to take advantage of AC and DC feeders. Loads and micro sources, can be coupled according to simplicity and robustness of the overall system.

> "It's easier and more robust to connect several storage devices in parallel to a dc bus, the grid can be connected directly to the AC feeder, providing more reliability to the AC loads." - Iván Patrao et al [21]

A more detailed analysis can be found in [22] and [21] .

2.3.3 MG ownership models

MG are required to function within the energy market with its key players (Market regulator, Consumer, Producer) common challenges relate to the interdependency between competitive generation and regulated activities[15].

In [15], three typical market models were identified. A monopoly energy market where the DSO is part of a vertically integrated utility not only owns and operates the distribution grid but also fulfills the retailer function. A liberalized energy market, in which ESCOs[1] are expected to

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[1] Energy service company

take the lead role to maximize the value of DER aggregation. And in a more futuristic one, when massification of DG in LV grid is present, a prosumer consurtium market, where multiple consumers operate MS to minimize electricity bill and maximize exportation to the grid, in this model the DSO can only passively influence the operation, market participation of private consumers is still very limited. The key market players have different relationships within those markets, as such, MG can serve to maximize multiple objectives. Therefore, standardization of MG models is difficult to achieve. Either way MG can be operated to meet technical and economic objectives. Utility MG's serve the power grid, managing power outages and and RES integration, while commercially owned MG focus on power quality, reliability and efficiency [5].

> "Considering the ever growing integration and availability of RES technologies as well as the liberalization of the electricity market commercially owned MG will constitute the majority of MGs."- Clara Gouveia [5]

2.3.4 MG control architectures

> "MG operation strategies focus on multi-objective optimal operation taking into account economical technical and environmental objectives. The notion of control is central in microgrids. Control is what distinguishes the microgrid from a distribution system with DER, it allows the MG to appear to the upstream network as a controlled, coordinated unit." - Nikos Hatziargyriou [15]

Grid connected operation:

1. Frequency control support
2. Voltage control support
3. Congestion management
4. Reduction of grid losses
5. Improvement of power quality (voltage disp, flicks, compensation of harmonics)

Islanded operation:

1. Black start
2. Grid forming operation
3. Frequency control
4. Voltage control

From [15] [23] [24] [25], two distinct control approaches can be outlined. A central control architecture, where vertically integrated control is present, which allows for optimal output solutions and a decentralized control architecture, more appropriate to multiple stakeholder ownership MG models. Typically, utility services with DER integration are constituted by a distributed management system and the automated meter reading system (DMS and AMR). Control actions are network reconfiguration by switching operations in the main feeder and voltage control. This control structure is insufficient for microgrid management, since it provides limited control capabilities, especially in a market environment.

Control structures must consider:

1. All stakeholders to advanced market participation
2. Being scalable in order to allow the integration of large number of users
3. Ease of installing new components
4. Ease of integrating new functionalities and business cases

MG control functionalities:

1. Upstream Network interface (upstream coordination, market participation and decision for island/interconnected mode)
2. MG control (V/F control P/Q control load control Black start)
3. Local control and Protection (protection, primary V/F control, primary P/Q control battery management
4. Ancillary services - all services required by the transmission or distribution system operator to enable them to maintain the integrity and stability of the transmission or distribution system as well as the power quality.

2.3.4.1 MG centralized control

In a centralized control approach the responsibility for the maximization of the MG total value lies on the MGCC. The MGCC assumes the coordination between the MS and the loads within the MG. A centralized control is usually adopted when the DG is single owned and therefore having a clear goal orientated approach. With this approach installation of new equipment requires specialized personal and high level communication, however optimal operation solutions are easily achieved. The basic feature of centralized control is that decisions about the operation of DER are taken by the MICROGRID operator or ESCO [2] at the MGCC level, being able to interact with the market or not.

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[2] Energy service company

2.3.4.2 MG Decentralized Control

In decentralized control structure, each MC competes or collaborates to maximize MG value, Multi-agent systems (MAS). This approach is valuable when there are different DER ownerships. Applicability of decentralized approaches to large systems might be compromised due to high number of messages exchange between local controllers. A decentralized approach is usually adopted for multiple owned DG with no clear goal definition, achieving sub optimal solutions. Installation of new equipment follows a plug-and-play strategy, being the MG adaptable and modular. Micro Grid Central Controller (MGCC) - provides the main interface between the MG and upstream network such as the (Distribution system operator) DSO and the ESCO, coordinates the local controllers and the MG output. housed at the MV/LV. The main task of MS controllers is to allow power sharing between the different sources and between the grid and the MG. A control approach providing voltage and frequency drop is required since standard static inverters are characterized by a fixed frequency and voltage. The goal of this type of control methods is to be emulate self-synchronizing torque[3].

2.4 Microgrid Distributed Energy Resources

2.4.1 Distributed Storage Solutions

Energy storage solutions will depend on the type of MG to be implemented (utility owned or commercially owned). Generally, applications of energy storage systems can be divided in fast acting short term power supply and power supply over longer periods. Energy storage solutions provide power quality, voltage and frequency support, and power matching between stochastic generation and loads. Usually end user applications require a larger amount of energy as well as longer energy discharge in order to match generation with load demand[23].

Main energy storage applications:[4]

1. **Power quality:** Storage systems are used for UPS (un-interruptible power supplies), providing power supply to critical loads, shortening loss of power, mitigate voltages fluctuations and improve harmonics.

2. **Voltage Support:** In MV/LV grids active and reactive power are not easily decouple so both are needed to regulate voltage levels, storage systems can provide voltage control by controlling both active and reactive power flows while reducing reactive power flow.

3. **Electric energy time shifting:** Storage systems provides efficient use of energy resources by storing when energy demand is low and discharging when energy demand is high. Supports the distribution network by reliving congestion during peak demand periods.

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[3] when two different frequency points tend to the same frequency value by active power sharing

[4] Adopted from[23] [26]

4. **End user Bill Management:** can provide benefits to end users who are on time-of-use (TOU) tariffs by electric energy shifting. Involves storing energy when demand for energy and thus price is low, and then using that energy when prices are high.

5. **Spinning reserve:** Storage systems can accommodate some of the spinning reserves requirements this would mean higher system efficiency since less part-loaded large generators would be needed. This generators operate at a low efficiency state, since they are online but un-loaded, in order to quickly response to power outages.

6. **Transmissions and upgrade deferral:** With the ever increasing use of electrical energy, and with more demand in the upcoming decades, power grid lines will be overloaded thus demanding circuit upgrades. Storage systems can be used to relieve the congestion of distribution circuits and to postpone upgrades by reducing peak demand.

2.4.2 Energy storage systems

Electrical energy can be stored in many forms. In this section, the most common forms of electrical energy storage systems normally used for MG will be briefly reviewed.[5]

Supercapacitors or electrochemical capacitors: have been extensively developed due to the increasing demand for a new kind of accumulators of electrical energy with a high specific power of more than 10 $kW.Kg^{-1}$ and a long durability [6]. The main advantage of this storage device is the ability of a high dynamic charge propagation [7] that can be used for UPS [8] [28].

Superconducting Magnetic Energy Storage: systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. SMES is characterized by fast charge and discharge rates with electrical power being almost instantaneous. SMES provides very high power output on a short period of time, it's mainly used for power quality and UPS operations.

Flywheels: A flywheel is a mechanical device specifically designed to efficiently store rotational energy. Flywheels resist changes in rotational speed by their moment of inertia. This store rotational energy can be called up instantaneously. At the most basic level, a flywheel contains a spinning mass in its center that is driven by a motor - and when energy is needed, the spinning force drives a device similar to a turbine to produce electricity, slowing the rate of rotation. A flywheel is recharged by using the motor to increase its rotational speed once again.

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[5] Adopted from [27] [23]

[6] Over 10^6 cycles

[7] short-term pulse

[8] Uninterruptible power supply

Solid State Batteries: Batteries store energy in chemical form. The basic concept of a battery consists on two electrodes of opposite charges. The electrodes exchange ions with the electrolyte and electrons with the external circuit. The energy released is the difference between the bond energies of the metals, oxides, or molecules undergoing the electrochemical reaction[29]. Battery systems are used for energy management purposes. The ability to discharge for longer periods of time (few hours) allows for energy allocation. Lead acid and Sodium sulfur batteries are the most used for large utility applications, such as Microgrids, while lithium Ion batteries are mostly used on mobile phones and laptops and more recently in electrical vehicles. NiCd batteries were at one time widely used in portable power tools, photography equipment, flashlights, emergency lighting, and portable electronic devices, but over the decades have been replaced for other storage solutions like Nickle metal hybrids (NiMH), due to environmental concerns.

Flow batteries: A flow battery is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and most commonly separated by a membrane.

Thermal energy storage applications Thermal energy storage applications focus on the preservation of enthalpy either heat/cold to then release the energy stored later. Usually thermal applications allow for low cost storage and provide for grid size energy storage solutions being a efficient alternative to spinning reserves.

2.4.2.1 Energy storage systems and the MG

Energy storage systems (ESS) can be divided into two: **fast acting** and **longer discharge** systems. Thermal energy storage and flow batteries can be more easily dimensioned to fit energy requirements, power and energy can be tailored to the MG itself. However, appropriate infrastructures need to be built in order to correctly operate, flow batteries and thermal storage applications at MG level. Furthermore, flow batteries tend to have lower energy density than integrated cell architectures. Flow batteries are suited for larger, grid level, applications storing power rating form 10's kW to 10's MW, meanwhile thermal energy storage applications can go up to the GW power rating. Economies of scale dictates the use of this type of technology for medium to large enterprises, being a cost efficient solutions specially when compared to traditional standing/spining reserves.

Fast acting storage systems like SMES EC and flywheels are used for power quality service. The fast high energy discharge allows for the correction of sudden power flow unbalances. However, fast acting storage systems are not suited for energy management since they can only sustain discharges for a few seconds to a few minutes. Moreover, fast acting storage systems tend to be expensive, with SMES applications even requiring an external source for cooling purposes. Flywheels and EC are commonly employed in MG with no traditional generation for power compensation and system robustness. The lack of rotational inertia in heavily inverter based RES MG makes the system vulnerable to load changes, this energy applications try to emulate the inertia of traditional generators. Without fast acting storage systems power can easily collapse in RES MG, with load changes easily putting the system out of phase. The use of this applications allows for less frequency reactiveness to load changes, by fast power compensation correcting frequency levels and stabilizing grid power flow.

Battery energy storage systems (BESS) are the most commonly used for MG applications. BESS allows for energy allocation, since discharge rates are in the few hundred minutes range. BESS are mostly used for peak shifting, valley filing, voltage regulation and active power control. When opting for a BESS solution many factors need to be taken into consideration such as power and energy density, life cycle, depth of discharge (DOD), charge and discharge rates as well as self-discharging rates. This parameters will vary according to the materials used for the electrolyte as well as the manufacture. In table B.1 a summary with the main characteristics of the energy storage applications discussed can be found.

2.4.3 Distributed generation

Distributed generation is associated with smaller generations units closer to loads located at the LV/MV level. The use of DG is related to higher quality power service, has in traditional grid systems, DG was always associated with back-up services, employed at sites where continuous electrical service was highly valued [26]. With the deregulation of power industries allowing more power producers to participate in the market and tax incentives for low carbon renewable energy resources the electrical grid is increasingly relying on DG for main power generation.

End users can generally benefit greatly by having a back-up generator or high efficient applications such as combined heat and power. Furthermore, DG users might bill grid operators to use their installed capacity to provide power during grid power shortages or to participate in the energy market.

At the utility level DG can be used for transmission and distribution power relief as well as serve as an hedge to uncertain load growth, postponing grid interventions [30]. The development of DG technology and integration allows for large RES generation and virtual power plants (VPP) [17].

2.4.3.1 Conventional generation and low carbon technologies

Centralized power generation was largely adopted due to economies of scale with generation sites located near fuel and/or water sources. To date, the reciprocating engine generator set is still the most commonly applied DG, since technology is mature and widely available. Gensets are the cheapest option for DG, being diesel generators the most used by end-users. Diesel gensets have the disadvantage of emitting high amounts of greenhouse gases, being limited to a few hours of use per year, thus limited to peak generation and emergency operation. Has an alternative, gas generator sets present a cleaner solution being generally employed at CHP/CCHP [9] applications. Gas CHP solutions raised interest in DG applications has a compact secure low carbon solution. Gas microturbines efficiency ranges from 20-30%, being the efficiency influenced by the air temperature, when employed in a CHP/CCHP solution the wasted heat is recovered and channelled, with efficiency rates considerably raising. Conventional generation systems have the advantage of consistent performances when compared to zero carbon generation technologies such as wind and solar. Furthermore, microturbines can have different type of gas inputs, which contribute to its versatility.

On the other hand, zero carbon generation technologies present no operation costs being cost competitive in favourable areas. However the power variation from renewable sources can cause voltage fluctuations.

In any case, DG systems using microturbines and RES must be supplemented with battery or flywheel storage to achieve the standard reliability of grid systems [26].

2.5 Power electronic devices

The interface between DG and the power system is responsible for most power quality issues. All DG technologies that interface with the grid that produce DC or non-power frequency AC need to be coupled to a power inverter to interface with the grid. Inverter technology adopted pulse-width modulated switching has the preferred switching control. The switching frequency is typically 50 to 100 higher of the power frequency in order to create a sinusoid voltage or current of power frequency, the high frequencies are then attenuated at the output by a filter and the power signal is successfully interfaced. Despite the filtering, the high switching frequency creates harmonics, which in some cases can distort the power signal. Harmonic distortion is caused by non linear devices in the power systems.[10] Compared to electrical machines, the inverters impose additional power quality challenges, requiring the adoption of filters to reduce the emission of high frequency distortion produced by switching actions. Nevertheless, PE devices will be increasingly more present in the future power systems because of the versatility they offer to the power system, which allows for the best use of existing circuits, flexibility and optimum operation of the power system, maximizing energy transmission [26] [23].

Some DG such as wind farms often are required to have reactive power compensation at the point of grid connection. PE such as FACTS[11] can enhance the power flow on existing power lines. Under reactive power norms and requirements for power compensation, line drops and

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[9] Combined heat and power/Combined cooling heating and power

[10] A non linear device is one in which the current is not proportional to the voltage applied, such as a non-linear resistance

[11] Flexible AC Transmission Systems

excessive reactive power can be compensated with the used of FACTS STATCOM[12]. Reactive power compensation is becoming essential to meet requirements set by many utilities using RES DG [23].

2.5.1 Power electronics and the microgrid

PE interfaces are used with DG to control active and reactive power output as well as terminal voltage output. In PV and storage applications PE devices are used to convert DC power into AC suitable for grid connection. In wind and hydro turbine applications, PE devices main function is to decouple turbine speed from the frequency of the grid thus allowing multiple speed operation. For successful integration of multiple DG in the MG a two layer interface is generally adopted, the input-side converter and grid-side converter. The input-side converter(DC/DC or AC/DC) manages the power extracted from the primary source, being controlled to operate at maximum power point tracking (MPPT) [13]. The grid-side inverter core functionalities include the control of the active and reactive power flow with the grid, DC-link voltage and synchronization between the MS and the grid [7]. However, additional functionalities can be added to provide grid support, namely local voltage regulation, frequency regulation and voltage harmonic/unbalance compensation [5][31].

DER unit	Primary Source	Power electronic interface
Non-controllabe MS	PV modules	DC/DC/AC converter
	Variable speed wind turbine	AC/DC/AC converter
Controllable MS	Single-shaft microturbine	AC/DC/AC converter
	Fuel cell stack	DC/DC/AC converter
Storage	Flywheel	AC/DC/AC converter
	Battery	DC/DC/AC converter

Table 2.1: Main power electronic interfaces applied to disperse energy resources generation [5]

Grid feeding inverter controlled through active and reactive power control strategy (PQ control). The inverter is a current-controlled voltage source, designed to deliver a controlled amount of power to the grid. The direction of power flow through a grid feeding inverter is determined by the polarity of the DC voltage while the current flow stays the same. The PQ controlled inverter does not have the ability of imposing voltage and frequency. The grid-side inverters of MS (controllable and noncontrollable) are usually controlled as grid-feeding inverters for both islanded and interconnected operation.

Grid-forming inverters are controlled as voltage sources establishing the phase angle and magnitude of its output voltage. The inverter is usually fed by a DC power source with energy buffering capabilities, as it is the case of batteries. It is usually referred to as Voltage Source Inverter (VSI) and can also incorporate grid supporting functionalities for voltage and frequency regulation. The

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[12] Static compensator

[13] Operation mode that maximizes power output

VSI offers freedom to operate with any combination of active and reactive power, the ability to operate in a weak grid and even black-start.

2.6 Microgrid clustering and multi-microgrids: Advantages and disadvantages

> “A progressive integration of DER in low voltage systems will have a significant impact on planning and operation” - Peças Lopes et al [18]

The increased redundancy from MG deployment will allow for increased reliability and flexibility. Furthermore tailored solutions for load management will have more precision since control management and sensing instruments will be displaced throughout the LV feeders the result is a more efficient and higher quality grid system.

> “A best match between supply and demand. Flexibility in future options for corrective actions based on possible updated information is incorporated into the selection of current-stage optimal decisions” - Nikos Hatziargyriou [17]

Moreover clustering of MGs would balance out energy demands on different energy density zones, energy compensation would postpone the need for larger LV/MV distribution infrastructures. The shorter distance between generation and loads results in a reduction of energy losses as well as improving the voltage support of the whole system [20].

MG will introduce the possibility to create new market/distribution models involving consumers, defining new policies regarding consumers involvement and private enterprises. The research and development, heavily linked to MG projects, helps define work maps and best practices.

On the other hand, the implementation of MG clustering and Multi-microgrids faces difficult challenges crossing multiple stakeholders. The implementation of generation near consumption sites might be unwanted for some locals, high pitch noises and visual pollution being the most common cause of DG reluctancy. Furthermore the high initial investment cost, lack of knowledge and grid compliant quality standards deters many from investing in DG technology. In addition, delegating operations from the utility network towards a broader audience will impose new management challenges. Commercial owned DG reliability will be heavily linked to standardization of technologies and maintenance practices. Moreover, telecommunication infrastructures and communication protocols need to be developed and implemented to help manage, operating and controlling MGs at the LV. Therefore, high initial investment are expected, not to mention that billing the investment costs poses also a challenge since possible development of market driven operation procedures of microgrids will lead to a significant reduction of market power exercised by established generation companies, therefore investment have to heavily rely on public funds which might not be a priority on governments’ agenda [32] [33] [23].

2.7 Microgrid and multi-microgrid emergency operation

Large deployment of MG will allow for self healing techniques. In [18] a black start procedure is explored. Units connected to the MV network could provide service restoration in its area of influence, therefore it's possible to achieve reduction of interruption times, providing a superior energy service. According to [18] restoration procedures could be initiated while HV grid is offline providing a easier starting point for full reenergization. Black start operation should be initialized when the isolation procedure from theMG fails. High number of MG would facilitate zonal restoration of service. In [18] the author suggested the following a set of rules for black start operation where the minimum disturbance path is followed: [14]

1. Sectioning of all feeders
2. Disconnection of all active loads and generation
3. Transformer disconnection
4. Disconnection of reactive loads

From this state of minimum power inertia grid energization is facilitated. The first step in the black start procedure would be transformer reenergization. Dispatchable DG would be used to reenergize transformers' coils. DG should be subsequently connected in order to prevent large inrush currents. After the MV grid is established, reenergization of the LV grid could start. Loads as well should be connected sequentially to prevent large voltage drops. The ability to work isolated from the grid greatly reduces grid outage time. The sequence of load/generation reconnection should be carefully consider has it will depend on local grid characteristics [18] [15].

2.8 Role of microgrids in developing countries

Majority of the population without access to electricity lives in rural areas, mainly due to the challenges of delivering the necessary infrastructure in areas with low population density that are often a long distance from large-scale generation sites. Rural electrification is economically justified only when the emerging uses of electricity are strong enough to ensure sufficient growth in demand, in order to produce a reasonable economic rate of return on the investment. However, due to the high initial costs of building the proper infrastructures this process might not even be realistic. In this context, self-sufficient electricity grids that connect supply and demand but are not part of a regional or national electric grid, can provide an alternative, that could be deployed without the need to increase generation capacity. The number of users served might vary from single users to whole villages [34].

The expected strong demand and market growth for electricity in non-OECD countries provides opportunities for national, international and for private manufactures. Involvement of the private

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[14] Disconnection from the higher voltage side of the grid (either HV or MV)

sector will be vital, in some cases small-scale local entrepreneurs and NGOs are best placed to take the leading role. Stand-alone electricity systems would gain experience and knowledge from many global stakeholders. Extending modern energy services to billions who still lack them, increasing productivity, improving overall health and welfare, contributing to mitigate climate change and improve resource management.

> "With effective policies and adequate financing, the private sector in emerging economies and developing countries will seize the opportunity to deliver more sustainable energy options to growing consumer markets... If a fair cost sharing model is developed, and the right balance is struck between short-term investment cost and long-term profits, grid operators might be willing to invest."- Nathaniel J Williams et al [35]

Reform of subsidy programmes will play an important role in promoting electrification projects, according to [36], subsidising the upfront capital costs rather than consumption is more effective to promote investment and increase project profitability. Community-based businesses might additionally receive assistance and training in technical and financial questions by public entities or other private companies. Another way to increase profitability in off-grid electrification projects is to provide lower power capacity.

Financial viability analysis must take into consideration customer and load density, relative distance to the national or regional grid, landscape, the availability of natural resources such as wind, sun, water and forests, and local economic and financial aspects.[15] Solutions for rural populations may require building of demand and infrastructure. Energy to support important development goals such as access to education, health, communication and water should be targeted, limiting energy services only to income activities may prevent project success and expandability. Reducing labour-intensive and time-consuming tasks and promoting health and education will attract more people create demand for electricity supply, attract and retain professional workers as well as have a greater economic output [37] [38].

Frequent power outages are a common problem in emerging and developing countries and make it impossible to provide a continuous electricity supply. These power outages are often from load-shedding, a frequent practice to compensate generation deficiencies by partly cutting off some load to user. Furthermore, struggle to gain legal and dependable electricity connections, creates a breeding ground for electricity theft and informal electricity markets. High losses are often caused by insufficient maintenance at any point along the supply chain and unqualified technicians. As lost electricity results in lost revenue, financing to operate, maintain and upgrade systems will also be reduced. Development of local experimental facilities is of key importance for testing new technologies and concepts as well as for the training of local teams and companies. Sharing of best practices among sector practitioners will help to operate, manage and maintain the grid

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[15] Including consumer ability and willingness to pay

operability, being a significant contribution towards remote/rural electrification as well as moving towards a low carbon sustainable energy future.

Strategic planning and a long-term vision are required to build the foundation for a flexible, scalable and adaptable electricity system. Deployment of stand-alone systems must avoid technology lock-ins, fit local economical capabilities and allow them to be integrated potentially into a national electrical grid. However, standardization and interoperability are required with higher amounts of supply and demand. Flexibility and robustness are key characteristics to achieve. Minigrids add operating complexity and costs, including load balancing, but they can bring increased functionality and decreased average cost of connections. The use of ICT solutions allows for a large integration of RES within the network while maintaining the overall reliability of the system [39].

2.8.1 Sustainable solutions for the electrification of developing countries

Often in rural/remote areas traditional centralized power distribution is not present or is weakly distributed. Building the infrastructures for remote electrification is often not an economically viable option, rough terrain, long distances and small communities detain any potential investors. A more ecological and focus approach should be applied. Self-sustainable electric generation systems are presented as the best economical alternative to centralized non-renewable DG. For successful, DG RES implementation, the site location is heavily linked with project success. The return on investment (ROI) will be directly influenced by the DG productivity as well as the local economy.

In [40] a study on RES MG implementation was presented. The study focused on the rural areas of Romania. For project success and implementation, a geographical analysis of the terrain was made, in order to estimated RES possible generation. Furthermore, an economic development study by analyzing the Local Human Development Index (LHDI) was made and the most suitable places for MG implementation and RES-based economic growth were pinpointed. The study showed that a carefully geographical assessment of the local resources heavily influenced the project outcome and when correctly deploy DG RES can stimulate emerging local economies. (E.g. creation of biomass supply chain). Therefore, the type of RES exploitation and MG solution will be directly linked to the local resources availability. Solar, wind and hydropower systems are the most common forms of RES exploitation. They constitute also the cleanest forms of electrical generation possible, with zero carbon emissions. However, implementation of clean RES technology is not linear in the sense that this technology is limited by its efficiency, stochastic nature and high investment costs. RES DG is characterized by not being dispatchable, this means that there is no control over energy production time frames, very low/no generation days as well as different generation and load peaks need to be accounted for. Combining dispatchable units with stochastic units presents the best approach to guaranteed power supply while taking advantage of RES zero carbon technology. Biomass generation appeared has the best alternative for traditional dispatchable generation units (coal generation the use of biowaste materials as fuel for electric generation introduces recycling practices, allows for local stakeholder involvement and exploits renewable resources.

Africa and India are where the majority of communities without access to electricity are present, and will be [41]. Given the geographical location of Africa and India, this areas have one of the highest solar irradiance levels on the planet's surface, therefore solar energy seems the best option for rural/remote electrification. In [42] the authors analyzed the main advantages and disadvantages of zero carbon technologies in remote/rural communities. The study identified solar energy has the main solution for remote communities. The low operational cost, low maintenance (no moving parts), long life expectancy and easy integration with small appliances made it the natural option for many enterprises. The study further concluded, that wind and hydro energy systems are niche solutions in the sense that are very geographically limited (near water bodies/ sea coast and mountain tops) and are more suitable for larger enterprises when an higher demand exists. Furthermore, wind and hydropower systems have high maintenance requirements as well as a high impact on the local biosphere. Nevertheless, this solutions are very cost effective at good locations, and are more efficient at converting natural energy resources to electricity than solar powered systems.
In any case, ESS plays an important role in MG reliability by matching the generation output with load demand. For rural communities with weaker economies heterogeneous (heat and electricity) generation MGs are suggested. Heat and electricity carriers should be efficiently tuned to work together providing the most efficient energy output. Priorities should be to provide power for cooking facilities and deep water extraction. The lack of access to electricity represents a road block to modernization and development [34].

In [36] the authors present an in-depth cost analysis breakdown of PV hybrid MG is presented. The study focused on sub Saharan Africa MG's. The study alerts for the multi-dimensional nature of total cost of ownership (TCO) as well as the non-linearity between projects expandability and profitability, the challenge to define a generic solution towards MG implementation. The study concluded that the benefits from emission savings by adopting low/zero carbon emissions do not reflect in the MG's prices. Nevertheless, the study highlights that PV/hybrid mini-grids are already the least cost option for most of the selected locations, when compared with traditional generation with grid extension options, a 20%-70% price reduction could be expected. Local social and economical interactions should be taken into consideration as well. In [43] the author presented a study were the causal relationships and interactions of MG projects in rural areas were analysed. The paper suggests early stakeholder involvement, building trust with stakeholders and project perceived fairness as the major factors for social acceptance. Effect on local's assets must be also taken into to consideration. Both papers concluded local market and policy frameworks and ideologies heavily influence projects outcomes and investment decisions.

2.9 Challenges in the deployment of microgrid systems in remote and rural areas

Remote MG deployment has intrinsic challenges that need to be addressed. The main challenges relate to maintenance, security and continuous autonomous operation. Furthermore, depending on the final purpose of the MG, (e.g. supplying remote rural areas) return on investment is also a challenge. Project success and investor's willingness is directly correlated to ROI. MG deployment for rural communities fail investments due to poorer perspectives on project return. As mentioned before a geographic and weather analysis, prospecting for maximum renewable energy output (either wind solar or biomass) seems to be highly correlated with project success [37]. Geographical accesses and demographic studies aiming at economy growth also need to be accounted for. Furthermore, local grid accessibility, local facilities, consumption and policies seem to have great impact on ROI and the type of MG technology that will be more successful. Furthermore, local interests should be studied as well, conflict avoidance with local communities would mean higher probabilities of project success. Other common challenges, facing remote/rural projects, deal with technology theft and training of local teams for project maintenance. Is not uncommon for locals after acquiring new skills to abandon project site to more prosper jobs or locations, or to MG components or power to be stolen. Management should be done by local public/private companies when possible. In case of a remote MG, pre-planned maintenance as well as more reliable components would mean lower cost in the long term. In rural MG, if maintenance should be delegated to local teams, creation of SOPs appeared as a suggested solution. A standard operating procedure (SOP) is a set of step-by-step instructions compiled by an organization to help workers carry out complex routine operations. SOPs aim to achieve efficiency, quality output and uniformity of performance, while reducing miscommunication and failure to comply with industry regulations.

For remote/rural MG projects having restricted accessibility limits support to infrastructures, adopting technology with high levels of reliability , such as PV provides a viable solution [37]. Near population sites minimization of total area occupancy by MG is a priority, with this in mind BESS and low carbon technologies appear as common solutions. In rural MGs, power theft and technology theft is occurring, opting for MG technologies that can be enclosed decreases the chances of theft. Ideally, RES DG should be deploy at MV grid and be managed by a public/private entity, this would maximize operation efficiency as well as maximum power exportation. While in LV part, adopting ESS and/or dispatchable DG (e.g. uTurbine) would simplify and facilitate operation for locals, as well as increase the system overall robustness. BESS are widely used since they are compact, easily replaced, easily transported, highly commercialized, don't require maintenance (depending on the technology adopted) and are noise free. As for low carbon technology, gas micro turbines/CHP appear has a preferred option; simplicity, mature technology, diversity of fuel sources are the main factors.

In critically undeveloped rural sites, other strategies should be adopted in order to maximize project ROI. Normally this type of projects are subsidized, nevertheless correct allocation of resources will maximize project impact on local communities. Investors should look for investments that incentive local development, creation of a biomass supply chain, presented the best option for local development. Furthermore, allocating energy output for community oriented activities would maximize the welfare of limited DG deployment. Energy could be limited to a few activities or hours of the day directly targeted at achieving specific goals such has deep water extraction, cooking energy, sanitation and lighting for a few public buildings for community usage.

2.10 Summarizing

In this chapter, a holistic overview of MGs was presented. Considering MG implementation and technology the main key points can be outlined as follows:

1. **Project implementation** will strongly depend on the level of local development and resources.
2. **Project scale will drastically influence the type of MG** Usually large low carbon projects consist of solar and wind exploitation and serve the power grid, far away from consumption sites. On the other hand, smaller MG projects focus on the integration of heat and power solutions and generation is on load site and for local communities, where (PV & CHP/Biomass) solutions are often adopted. The deployment of energy storage systems is highly dependent on the local grid and the types of loads the MG will feed. In any case, capacitor banks are usually used for larger enterprises, for voltage regulation. On the other hand, battery banks are mostly used for on-site energy management solutions.

Chapter 3

3. Smart Microgrid Laboratory Infrastructures and pilots

This chapter outlines real world microgrids and testbed identifying key technological components and architectures for microgrids successful design and implementation.

3.1 Introduction

Smooth grid evolution needs to initiate plans/guidelines for the construction of new consumption models, by testing possible upgrades in the current distribution network (DN) system and implementing new distribution concepts/mechanisms with high-technology support, in accordance with the anticipated future requirements. Microgrid testbeds are being implemented, all around the world to study control strategies to tackle unbalance problems and optimal management structures for distributed generation [44].

For simulation purposes offline simulation programs such as MATLAB are not enough especially if power converters with high switching frequency are included. Real time digital simulators (RTDS) using SCADA [1] present a fast, reliable, accurate and cost-effective simulation method for the study of complex power systems used for prototyping and hardware-in the-loop testing [45]. PHill [2] and HILL [3] simulations facilitate the possibility for organizations who do not have large test facilities a realistic and cheap testing ground for MG components being widely use for simulating grid components. This type of simulations, provides real time simulation (RTS) and flexibility by enabling various modelling scenarios. In grid simulations scenarios, the grid is usually simulated in the software part of the simulation and the hardware being tested is integrated in the software via a power interface that simulates the software response according to the hardware characteristics (voltage source/ current source) [30][46] [47] [48] [49] [50] [51] [52].

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[1] Supervisory Control and Data Acquisition

[2] Power hardware in the loop

[3] Hardware in the loop

MG models address the basic organizational characteristics and learning effects (technical, organizational, policy and market learning) of sustainable energy demonstration projects (prototyping, organizing, and market demonstrations).

> “Learn to further develop, apply and commercialize MG concepts, cooperatively organize the improvement and commercialization process of sustainable energy prototype-based products, as an important learning effect. Technical learning is the most important reason for organizations to invest in demonstration projects in sustainable energy, build a body of technical knowledge and aim to learn how to apply new sustainable energy technology, and how to improve its performance. The outcomes could be used to develop public financial incentives as well”-Bart AG Bossink[53]

In [53] the authors review the literature for sustainable demonstration projects. The paper concludes that demonstration projects enable people to learn to further develop, apply and commercialize sustainable renewable and clean technologies detailing specific learning opportunities derived from this type of projects. Furthermore, details different learning practices that demonstration projects offer, outlining learning-by-doing, trial-and-observe, learning-by-interaction and learning-by searching the main practices. Finally, concludes that the demonstration projects reviewed report no empirical evidence in market penetration and in large-scale market growth of sustainable energy technologies, but rather have a positive effect on policy making and organizational learning.

3.2 Integration of smart grids

MGs successful integration with the power network/ DN is an essential step for MGs dissemination and the adoption of a smart distribution network. Successful integration spreads across multidimensional concepts of revolutionizing power systems, from the introduction of intelligent technologies and new key concepts to addressing critical issues from a future perspective [44][54].

Economic and policy aspects of the electric energy system, including well-designed markets, efficient pricing, and appropriate regulatory frameworks, need to be developed. Market, pricing, and government regulation depend on how the grid is operated. Innovation in smart grid operation is the first step towards ensuring that the smart grid of the future will receive and distribute electricity from MG to end-use with maximum efficiency and utilization. Industry stakeholders are becoming encouraged to recognize the need to address these challenging issues and replan the DN structure according to the SG paradigm. Trade-off solutions addressing conflicting objectives for satisfying multiple stakeholders, make multi-objective planning (MOP) a suitable choice for smart distribution networks (SDN) [4].

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[4] smart distribution networks

Implementing modern distribution concepts will require advancements in ICT, forming the backbone of sensing, measurement, monitoring, and metering operations (sensor networks). Therefore, testing modern distribution concepts (MDC) can assist in the implementation of new distribution topologies to improve DN reliability and stability [44].

Grids that apply advanced computing, communication and internet technologies will be able to significantly improve efficiency in all aspects of electricity generation, transmission, and utilization processes. Grid-connected energy storage is also a valuable component that provides flexibility in instantaneous supply demand balance in the presence of intermittent and variable renewables. The proliferation of massive dispersed renewables and end-user energy management systems (nMG), despite reducing centralised generation, brings greater uncertainty in supply and demand on the periphery of the grid. When energy is produced by and shared by MG/nMG, the traditional structure of power network from top to bottom must give way to side-to-side lateral structure.

The MG primarily depends on hardware innovation in power electronics (PE) (IGBTs and thyristors), storage and ICT. Advance in PE is crucial for efficient power control in various modes, storage technologies and high-speed communication infrastructure are needed for enabled support. Existing grids can be easily reconfigured into AC micro grids. However, this represents an expensive implementation with a lot of complex PE interfaces that lowers the overall system reliability. Sophisticated protection systems are a challenge. Adding micro-sources changes the traditional radial structure of the grid. This new structure invalidates the traditional power flow control methods and the transient characteristics of the network [32]. Existing distribution networks (DN) are not designed for significant disperse generation (DG) penetration. PE interfaces do not supply high enough short circuit currents to trigger traditional grid protective devices [55]. For inverter-based microgrids, stability analysis is one of the most important concerns.

Modern distribution concepts (MDC) will vary in terms of centralized (high computation cost) to a decentralized/distributed (high synchronization time) or even hybrid control methodologies. Control methodologies will strive for peak load management, load shifting, rebound peak shifting and valley filling. Strategically addressing load growth and reshaping demands, by managing grid operations on short-term basis, through the shifting of loads/consumption patterns (during peak to low demand periods).

The aim of MDC is to effortlessly transit from the traditional grid to the smart grid, where micro and nano-generation, clusters, are present in the LV grid. A side-to-side structure will take place and real-time operational planning (RT-OP) will be crucial. Grid control must be managed by areas and not big generation centres. A control area must encapsulate its internal workings, shedding load in an emergency when there is insufficient generation to meet the load internally manage its own power generation and consumption in order to maintain its net power balance, coming both from the distributed resources and the MV distribution feeder, taking into account its commitment of external power exchange. A power network that can intelligently integrate the actions of all users connected and make plug-and-play interoperability possible [54][25].

> Future smart homes, equipped with smart meters capable of controlling rooftop PV generation, smart appliances, on-site battery storage, demand-side and vehicle to grid (V2G) management systems, are no different from and EMS-operated power grid. Energy wise, future smart homes will resemble cells in a way, being a sub-unit, a building block of future grids, that provide energy called 'clusters'... Clusters are thus interconnected and hierarchically structured. A core transmission grid cluster will contain many clusters of distribution grids, each of which contains clusters of micro-grids, factories, and homes.- Felix F Wu et al [19]

Nevertheless, for sucessful integration protocols and standards must be further developed in order to achieve plug-and-play interoperability. Standards are not yet available for addressing power quality, operation, and protection issues [17].

3.3 Characterization of Smart Microgrid Laboratory Infrastructures

In 2015, a survey conducted by JRC[5] [56] interviewed several European test lab facilities. The survey results revealed that grid management, storage, demand response, ICT, generation and DER were 80% of lab facilities working topics.

The survey outlined:

1. IEC 61850 has the most used protocol for communication, being narrow-band PLC[6] and wifi the most used technologies.
2. Real-time simulations has the main tests to grid management strategies.
3. Batteries and supercapacitors has the main choice for ESS, which was mainly employed for V/F control as well as peak shift load.
4. V2G has the most represented electro mobility experiments.
5. Most research facilities focused on the distribution concepts rather than remote/islanded grid concepts.

In comparison the 2018 JRC survey [57], which included several non-european microgrids, outlined the following:

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[5] Joint research center

[6] Power line communication

1. Lab research targeted mostly utility sector and the distribution grid.
2. Automation of the distribution network was the main area of interest, being improved DER integration and V-Q control the final purpose of the research.
3. Monitoring and developing diagnosis tools constituted the majority of grid management related topics.
4. Battery technology constituted 80% of energy storage technologies research, focusing on demand shift and peak reduction.
5. V2G represented most electro mobility experiments
6. Market structure represented most market related research topics.

Comparing both reports is safe to say that there were no major shifts in the areas of research however an increase interest in battery technology is noticeable.

A more recent article published by the financial times concluded that non-subsidize renewable energy projects can be cost-competitive. However, RES integration still faces technological lock-ins namely the scalability of battery storage systems, nevertheless a greater interest and investment of major oil companies in microgrid technologies is being taken.

> “ ...We are now seeing a shift towards unsubsidised renewable energy projects...But the cost which needs to fall much more is that for storage, to offset the intermittent nature of solar and wind power...A transition to renewable sources of electricity generation, particularly from solar and wind, seems well entrenched. While these may not fully replace fossil-fuel sources in the near term, they should at least remain a major part of the energy mix for decades to come. Fossil fuel investors, then, may not be doomed. But will have to look over their shoulders to stay ahead of renewable energy.”- Financial times [58]

3.3.1 Microgid sites and pilot cases

In the following sub-section a few remote MG projects and laboratory testbeds were revisited with the intent of drawing some similarities between the projects.

Eigg island, Scotland, Hybrid system
The Isle of Eigg electrification project was an attempt to develop an electricity supply for the island which would be sustainable both environmentally and economically. The main objective was to provide reliable electrical supply. Several RES around the island have been incorporated to allow diversity of energy supply. The main battery inverters provided V/F control and manage the balance between loads and generation by controlling the power into and out of the batteries. Twelve Sunny Island SI-5048 5kW inverters were used, connected in four three phase clusters,

to give a total output rating of 60kW. A MultiCluster Box MC-Box-12 was used to combine the cabling from each of the Sunny Island inverters and provide contactors for the connection to the island grid and the back-up generator. Each cluster was connected to a 48V 2242 Ah battery bank consistin fitted with hydrocaps to reduce maintenance. Total energy storage was estimated around 212kWh to 50% DOD[7]. The project demonstrated a reliable electrical supply for a modern life style usage. However, project cost of operation and tariffs were considerably higher than any central grid elsewhere in Scotland [59]. Micro grid layout:

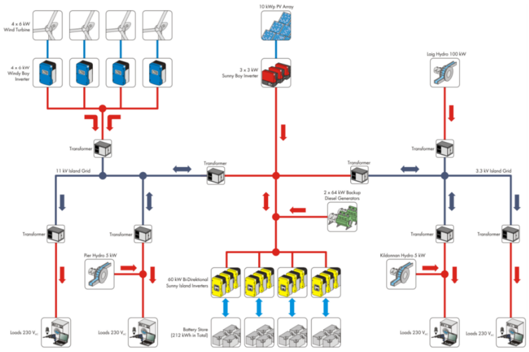

Figure 3.1: Eigg island MG layout

The following table was taken from [6], where the main microgrid components were outlined:

Specification of system components

PV array	Module - Power	60xBP Solar BP31655 PV - 9.9 kWp
	Inverter	2xSMA Sunny Boy SB-3000
	Module - Power	126xBP solar BP4180 180 Wp PV - 21 kWp
	Inverter	3xSMC-7000HV
	Module-Power	90xRECSolar REC250 PE 250Wp PV - 22.5 kWp
	Inverter	3xSMC-7000HV
Wind turbines	Model - Power	KW6 Kinspan - 4x6KW
	Inverter	6xSMA Windy Boy WB-6000A
Hydro turbine	Model - Power	Glikes single jet Turbo - 100kW, 9KW, 10KW
Diesel generator	Model-Power	Thistle generator P80P1
BESS	Model	Rolls Surrete 4KS25 - 4 clusters 24 batteries
	Inverter - Power	12xSunny Island SI-5048 - 5KW

Table 3.1: Eigg island Microgrid system components [6]

Zhejiang laboratory

In [1] a flexible and reliable multi-microgrid structure is presented. The infrastructure presesented, adopted a master–slave control strategy for islanding operation. The integrated microgrid laboratory system aimed at developing control strategies, microgrid related equipment and

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[7] Depth of discharge

study the impact of MG integration with the grid as well as the social-economic outcomes. The multi-microgrid consisted in two microgrids. Microgrid A included 3 busbars, PV generation connected to a three-phase inverter, a DIFG simulation system with an ABB frequency converter coupled with a real generator, a wind turbine and a BESS unit near the PCC. On the other hand, Microgrid B, which had similar control and architecture, had installed a flywheel generation unit as well as diesel and PV generation units. However, the PV generation was connected to three single phase inverters allowing for different connections forms. The microgrid loads were variable RLC branches that could be remotely changed. The system master controller, could switch the inverters control from grid-tied inverters to grid forming inverters. Therefore, optimizing microgrid integration and operation in island mode and grid connected mode.

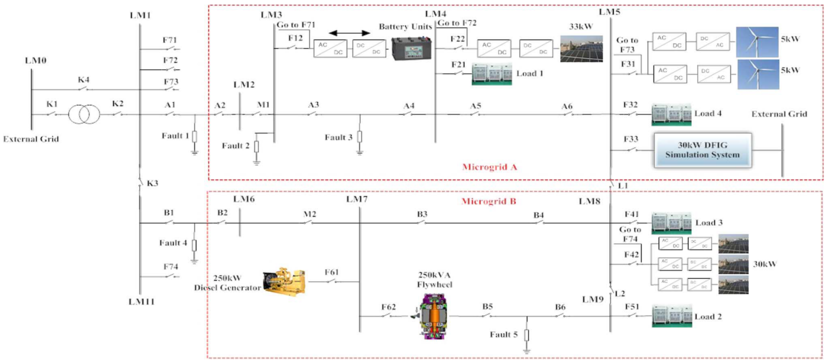

Figure 3.2: Multi-microgrid system [1]

Specification of system components		
PV array	Module - Power	N/A - 63 kW
Wind turbine	Module - Power	N/A - 10 kW
DFIG (Simulator)	Module - Power	N/A - 30 kW
Diesel generator	Module - Power	N/A - 250 kW
BESS	Module - Power	N/A - 168 kWh
Inverters	Module - Power	N/A - 100 kW
Flywheel	Model - Power	N/A - 250 kVA
Loads	1	30 KW + 48 kvar
	2	60 KW + 90 Kvar
	3 & 4	10 KW + 16 Kvar

Table 3.2: Multi microgrid components [1] Bo Zhao, Xuesong Zhang, and Jian Chen

DeMoTec laboratory

In [2] the authors analyzed several microgrid laboratory infrastructures, one of which, the DEMOTEC. The DEMOTEC focused on the utilization of RES and the rational use of energy. The

DEMOTEC was planned and built modularly in order to be expandable, requiring at the same time grid compatibility. All generators and loads could be connected to the same grid bus via a central crossbar switch cabinet. The laboratory facility had a total of 200 kW of generation installed capacity, combining synchronous generators with CHP units and RES based generation. It incorporated 70 kVA commercial SMA inverters, which enabled the validation of MG emergency strategies.The laboratory used SCADA for control and data aquisition, enabling remote monitoring and control systems of the laboratory equipment. The system adopted for the validation of MG concept four grid forming units, two battery banks and two diesel units, loads and microgeneration based on wind and solar.

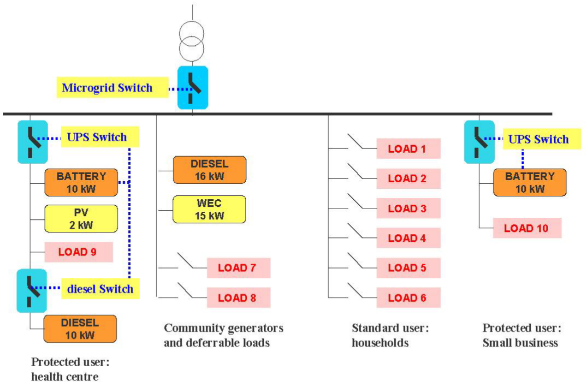

Figure 3.3: Demotec Laboratory testbed layout [2]

3.3.2 Laboratory infrastructures - INESCTEC - Smart Grid and Electric Vehicle laboratory

3.3.2.1 Experimental objectives

The deployment of the SG concept implies major changes in the operation and planning of distribution systems, particularly in the LV networks. INESCTEC focus on testing experimental restoration procedures and MG operation strategies in unbalanced conditions. The laboratory also targets the implementation of different communication technologies and protocols for MG management as well as vehicle to grid functionalities and EV charging.

3.3.2.2 Infrastructure and technologies

To carry out the tests the laboratory allows the integration of both commercially available solutions and in-house developed prototypes. The laboratory focus on the implantation of DER technologies for that purpose it is equipped with:

Specification of system components		
Generation	PV	15.5 kW
	Wind turbine (emulator)	3 kW
Inverters	Module - Power	Static-switch - 20kW
	Module - Power	Sunny island 5048 - 15kW
BESS	Module - Power	Lead acid - 20kWh/50V
EV	Module	Renault Twizy
	Module	Renault Fluenze
Loads	Controllable	2x52kW

Table 3.3: INESCTEC laboratory components

3.3.2.3 Testing capabilities

The laboratory is capable of emulating different communication technologies allowing different communication strategies to be tested. The main communication protocol is Modbus TCP/IP and SCADA is used for data acquisition. The laboratory is capable of modelling, designing and developing algorithms and software modules to add intelligence to the billing management systems and communication solutions that will allow the operation of a distribution network under normal and emergency condition, operation of storage and EV as well as active demand side management monitoring and supervision of LV grid.

3.3.3 TECNALIA– Ingrid (former Labein)

3.3.3.1 Experimental objectives

Tecnalia laboratories integrate traditional electrical engineering capabilities with advanced power electronics and ICTs technologies. It covers areas of expertise such as grid management and operation, power electronics and energy conversion, vehicle-network interfaces, information and communication technologies to electromagnetic compatibility. Tecnalia is described as a technologically advanced experimental infrastructure designed and oriented to meet the needs of electrical equipment manufacturers and utilities in the specification, development, validation and commercialization of innovative products for the smart grids market [60]. Tecnalia focus on dynamic stability studies of DER penetration in power grids, mainly DER penetration in week grid infrastructures (island MG) and evaluation of electrical storage technologies as well as calibration of smart meter technology. Furthermore, the laboratory is engaged in data sets analysis, derived from the usage of smart meters, to exploit more complex and optimized billing and dispatch strategies.

3.3.3.2 Infrastructure and technologies

Tecnalia's multiple testing grounds consisting of: a power laboratory, a high voltage laboratory, a low voltage and environmental laboratory, an electromagnetic compatibility laboratory, a smart metering laboratory and a smart grid communication laboratory.

To carry out smart grid testing the laboratory mainly uses the power electronic laboratory, the smart metering laboratory and the smart grid communication laboratory.The smart metering and communication laboratories are used to assess the interoperability and functionality of smart grid meters and communication between devices. The power electronics laboratory consists of a LV grid fully flexible with 165 AC KW and 300 kW DC of flexible power output capacity with fixed 450 AC KW of DG generation capacity for inverters and converters testing. From the whole Tecnalia's infrastructures the following infrastructures were outlined:

Specification of system components		
Generation	Diesel	2x55 kW
	Microturbine	50 kW
	Pacific power sources simulators	62.5 KVA & 50 kW
	PV	1 ph - 16 kW
	Wind turbine	6 kW
	Fuel cell	1 kVA
	DC power source	165 kW
	Flywheel	250 kVA
ESS	Ultracapacitor	2,8 MJ - 48 V
	Battery banks	48 V - 1925 Ah & 24 V - 1120 Ah

Table 3.4: Tecnalia laboratory components

3.3.4 Testing capabilities

Tecnalia acts in compliance with Measuring instruments Directive (MID) acting as a notified body, performing certification tests of protection and telecommunication equipment as well as quality power supply tests. Each test can be perform to customer specifications or grid standards conditions.

3.4 Conclusions

Several other documents were analyzed [61] [62] [63] [64] [65] [15], a trend for PV/BESS and diesel/biomass generation for electrification of remote rural areas was visible. HOMER software seemed to be the preferred software for sizing hybrid MGs. Inverter control and metering were the main fields of study of MG testbeds, prioritizing steady-state and dynamic analysis, focusing on LV inverter dominated microgrids performance and DER integration. Control strategies were heavily linked to information and communication technologies and a greater interest in energy storage solution was noticeable. The ability to work in islanded mode increased the security of supply and thus contributed to higher reliability standards.

From an economic stand point of view, MGs are still not an appealing solution for heavily meshed grids, found in most cities. On the other hand, MGs seem to be an interesting solution for weakly meshed grids even without subsidies.

Chapter 4

Management and control of a multi-microgrid system

In this chapter a top-down multi-microgrid management (MMG) tool is presented. The simulation aims at evaluating islanding feasibility and MG architecture manipulation, while coordinating voltage/var support for normal operation and island operation.

4.1 Introduction

Traditionally, grids had an unidirectional power flow. Therefore, power dispatch problems were easily optimized. Integration of disperse generation (DG) at the medium voltage (MV) level of the grid was done in fit and forget strategy considering DG to be neglectable when compared to centralized generation. DG integration at the MV level was straightforward due to the reduce number of DG installations and by the fact that MV grids are usually explored in re-configurable radial structure.

On the other hand, integration of DG in low voltage (LV) grids poses a challenge, because LV infrastructures were not adapted to inverter based generation, leading to protection blindness problems [51][66][15][23] [26]. The sheer number of LV nodes makes metering every node or changing protection equipment not economically viable. Moreover, DG ownership models at the LV grid are not well defined therefore managing and billing every DG adds complexity to the problem.A step-by-step integration is best suited for a smooth transition towards active network management (ANM) in LV/MV grids, which is possible if a MMG frame architecture is adopted.

In [16] a MMG control structure, included in the More microgrids project, defined a centralized high-level control structure located at the high voltage/medium voltage (HV/MV) interface, named the central autonomous microgrid controller (CAMC). The CAMC was responsible for managing every LV MG and DG connected to MV feeders. The proposed strategy took into account the MG control structure that was used to estimate nodes P_{inj} Q_{inj} set-points, considering every MG as an active cell. Therefore, multiple control levels were encompassed in the CAMC. This control structure allowed the system to be locally autonomous but centrally managed. Local control had to accommodate some level of autonomy in the sense that computing every grid component in a single central controller would make the task unfeasible for real time operation. Therefore, in [16] each MGCC had to manage its area of influence, being coordinated at the same time by a central controller, which allowed for an optimal dispatch solution. In order to locally control voltage and frequency levels local controllers had to set active and reactive power output. This type of control structure is referred as a multi-master control structure since every local controller can manage voltages and frequency levels. This configuration is achieved by paralleling the voltage source inverters (VSI) that interfaces the MSs by their filters and the network impedances. The multi-master control structure was adopted since it allowed plug-and-play operability, simplified communication and increased system redundancy [23] [15].

With VSI control a phase shift between two voltage sources causes active power flow, while a voltage differential causes reactive power flow. Assuming standard values of inductances the result is a very sensitive system to voltage and frequency variation. On the other hand, in LV grids there is a high resistance to reactance ratio, meaning that active and reactive power are not so easily decoupled. Thus active power flow would be more appropriate to directly control voltage levels and reactive power flow frequency levels.[1]. However, adopting this methodology would mean loss of compatibility between LV generators and the upward network, since it wouldn't be possible to dispatch power, every load would be supplied by the nearest generator [15].

In LV networks, in order to use conventional drop methods voltage regulation has to be done through indirect operation of droops. The reactive power of each generator is tuned in a way that the resulting voltage profile satisfies the active power distribution. Indirect methods are mostly related to line impedance compensation and power- angle droop control. In this management tool impedance compensation was used to better control V/F set points through conventional drop methods.

4.2 Development of high-level management tool for multi-microgrid system

In [16] the author outlined substation data measurements, critical grid nodes state measurement and user load data estimation has the most important inputs for development of a high-level management tool for a multi-microgrid system. Furthermore, the paper took into consideration the uncertainty in the topology of a multi microgrid state estimation (MMSE) and the numbers of islands possibly created, leading to a splitting problem and a fuzzy state estimation. Several other papers were reviewed [44] [67] [68][69]. AS with every simulation model, this one introduces

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[1] Opposite drop methods

approximations and has a domain of validity. The proposed approach was developed using MATPOWER. The data accuracy obtained from the simulation can be discussed since the simulation fails to consider load unbalance conditions typically present at the LV level of the grid and the grid components are elementary modulated. Nevertheless, the value proposition of the simulation still holds. As mentioned before, MMG control structure consist on short-term fast acting local control functionalities [70] [71] and long-term centralized control functionalities [72] . Depending on the time-frame control functionalities will have different objectives, long term objectives focus on optimal power flow (OPF), considering steady state conditions. The OPF mathematical formulation is a multi-objective optimization problem with an objective function, in this case cost minimization, and multiple constraints, power flow equations (equality constraints) and V/F levels and branch limits (inequality constraints). MATPOWER[4] was chosen because it has already a very developed application for OPF calculations, every data structure is already built as well as the solver, with a flexible and simple data structure it allows for fast and quick calculations. Moreover, customized constraints as well as fuzzy state estimations are also possible.

The management tool works by replicating matpower base case data, taking has input a configuration matrix which is a [N_B [2] by N_{iter} [3]] matrix. Each column represents a iteration and each line represent a grid bus. The matrix consists in ones and zeros values, being value one symbolic of bus connected and zero value symbolic of bus generation/bus to be disconnected. This approach allows for testing disconnection scenarios and different topology scenarios without reformulation of the base case data. Furthermore, in case of no conversion for the specified number of iterations the program tries to compile successively to previous iterations. In order to model ESS in the OPF problem, a customized constrain was built adopting the strategy of [73]. This approach takes into consideration previous iterations by constraining the power generation according to the total power output in all previous iterations similar to a state of charge, therefore modeling an ESS. OPF dispatches are heavily used during planning and grid operation phases, since it allows for system state estimation, voltage and phase estimation of every grid node as well as the injected power in every branch. The power flow consists in solving a set of equations that define the electric grid where the grid branches are modeled by their π elements and load and power generation by a current [74].

4.2.1 AC power flow

The MATPOWER allows for AC or DC power flow. The tool developed was based in AC power flow. In this section the fundamentals of AC power flow were briefly reviewed.

$$I_{12} = \frac{|V_1|\angle\delta_1 - |V_2|\angle\delta_2}{|Z|\angle\gamma} \tag{4.1}$$

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[2] N_B-number of buses

[3] N_{iter}-number of iterations

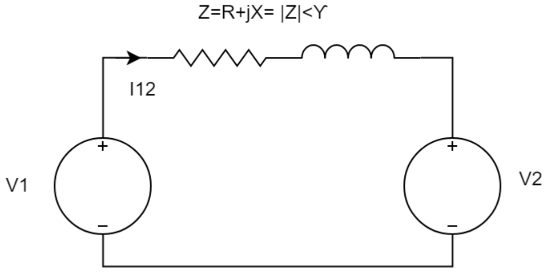

Figure 4.1: Complex power flow adapted from [3]

$$= \frac{|V_1^2}{|z|}\angle\gamma - \frac{|V_1||V_2|}{|Z|}\angle\gamma + \delta_1 + \delta_2 \tag{4.2}$$

The real and reactive power at the sending end are the real and imaginary part of the apparent power therefore:

$$P_{12} = \frac{|V_1|^2}{|Z|}\cos(\gamma) - \frac{|V_1||V_2|}{Z}\cos(\gamma + \delta_1 - \delta_2) \tag{4.3}$$

$$Q_{12} = \frac{|V_1|^2}{|Z|}\sin(\gamma) - \frac{|V_1||V_2|}{Z}\sin(\gamma + \delta_1 - \delta_2) \tag{4.4}$$

For small resistance to reactance ratio lines, such as transmission lines, resistance can be assumed has zero, therefore the above equations becomes:

$$P_{12} = \frac{|V_1||V_2|}{Z}\sin(\delta_1 - \delta_2) \tag{4.5}$$

$$Q_{12} = \frac{|V_1|}{|X|}[|V_1| - |V_2|\cos(\delta_1 - \delta_2)] \tag{4.6}$$

In R«X lines, small changes in δ_1 or δ_2 will have a significant effect on the real power flow, while small changes in voltage magnitudes won't be significant.

4.2.1.1 Line model

Short line model

Line capacitance can be ignored without much error if the lines are less than about 80km long or if voltage is not over 69 kV. The short line model is obtained by multiplying the series impedance per unit length by the line length.

$$Z = (r + j\omega L)l \tag{4.7}$$

Where r and L are the per-phase resistance and inductance per unit length, respectively, and l is the line length. More details such as how to obtain per unit length values can be found in [3].

Medium line model

For lines above 80 km and below 250km in length (considered medium length lines), the line charging current becomes appreciable and the shunt capacitance must be considered. For medium length lines half of the shunt capacitance is lumped at each end of the line, this is referred as the nominal π model.

Total shunt admittance of the line is given by:

$$Y = (g + j\omega C)l \tag{4.8}$$

Under normal conditions, the shunt conductance per unit length, which represents the leakage current over the insulators due to the corona, is negligible and **g** is assumed to be zero. **C** is the line to neutral capacitance per km, and l is the line length.

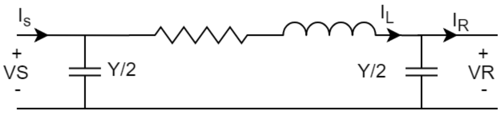

Figure 4.2: Medium line model

From Kirchhoff's circuit laws:

$$I_L = I_R + \frac{Y}{2}V_R \tag{4.9}$$

$$V_S = V_R + ZI_L \tag{4.10}$$

$$V_S = (1 + \frac{ZY}{2})V_R + ZI_R \tag{4.11}$$

$$I_S = Y(1 + \frac{ZY}{4})V_R + (1 + \frac{ZY}{2})I_R \tag{4.12}$$

The ABCD constants for the nominal π model are given by:

$$A = (1 + \frac{ZY}{2}), B = Z, C = Y(1 + \frac{ZY}{4}), D = (1 + \frac{ZY}{2}) \tag{4.13}$$

Solving the receiving end quantities can be expressed in terms of the sending end quantities by:

$$\begin{bmatrix} V_R \\ I_R \end{bmatrix} = \begin{bmatrix} D & -B \\ -C & A \end{bmatrix} \begin{bmatrix} V_S \\ I_S \end{bmatrix} \tag{4.14}$$

When performing AC power flow calculations the grid system is converted to the per-unit (PU) system, where various physical quantities such as power,voltage, current and impedance are expressed as decimal fraction or multiples of base quantities. The transformation to the PU system

is to eliminate voltage levels in the power grid.
Per-unit value:

$$\text{Quantity in per-unit} = \frac{\text{actual quantity}}{\text{base value of quantity}} \tag{4.15}$$

For the power flow four base quantities are required to completely define a per-unit system: Apparent power, voltage, current, impedance.

$$S_{pu} = \frac{S}{SB}, V_{pu} = \frac{V}{VB}, I_{pu} = \frac{I}{IB}, Z_{pu} = \frac{Z}{ZB} \tag{4.16}$$

Where

$$I_B = \frac{S_B}{\sqrt{3}V_B}, Z_B = \frac{V_B/\sqrt{3}}{I_B} \tag{4.17}$$

And S_B and V_B are selected values.

4.2.1.2 Transformer model

A simplified transformer model was adopted. The shunt impedance was neglected and only the winding resistance and leakage reactance were used. The per phase equivalent circuit is represented as:

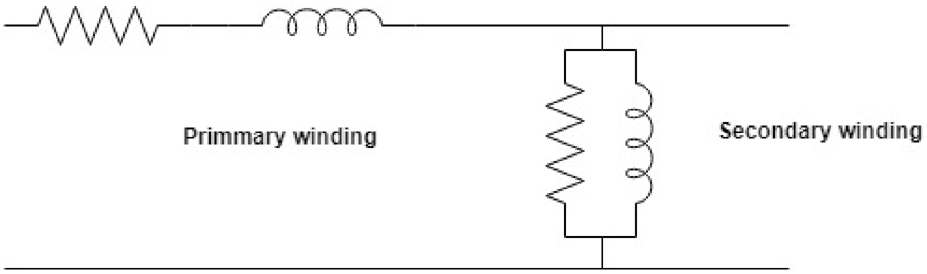

Figure 4.3: Transformer model in power flow studies

In order to convert to the per-unit system the transformer is model has an ideal transformer in series with an impedance as:

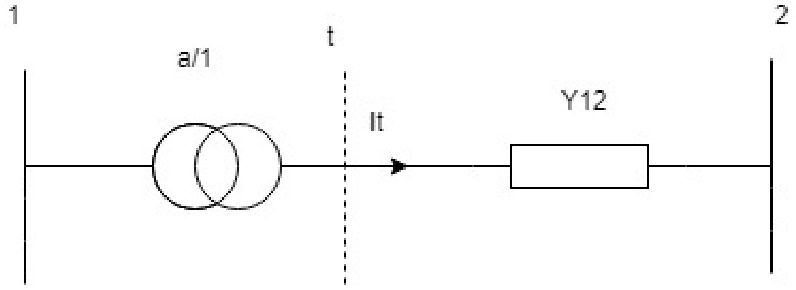

Figure 4.4: Ideal transformer model

From Kirchhoff's circuit laws:

$$I_1 = \frac{I_t}{a} \tag{4.18}$$

$$I_1 = \frac{V_1 - V_2}{Y_{12}} \tag{4.19}$$

$$V_t = \frac{V_1}{a} \tag{4.20}$$

$$I_1 = (\frac{V_1}{a} - V_2)\frac{Y_{12}}{a} = (V_1 - V_2 a)\frac{Y_{12}}{a^2} \tag{4.21}$$

$$= (V_1 - V_2 a)\frac{Y_{12}}{a^2} \tag{4.22}$$

$$I_2 = (\frac{V_1 - V_2}{Y_{12}} = \frac{V_2 - V_1}{a} \tag{4.23}$$

$$Y_{12} = (aV_2 - V_1)\frac{Y_{12}}{a} \tag{4.24}$$

Rearranging in matrix form:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} Y_{12}/a^2 & -Y_{12}/a \\ -Y_{12}/a & Y_{12} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \tag{4.25}$$

As a result the transformer is modeled as:

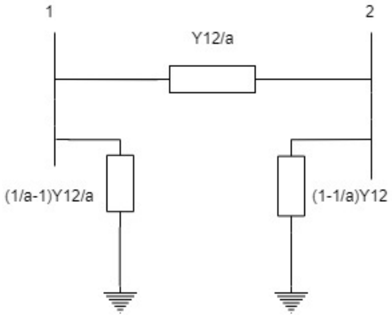

Figure 4.5: Transformer π line model[4]

In MATPOWER, the line/transformer parameters are added in the branch data structure B.2 . Every branch is modeled has an ideal transformer in series with a π line model:

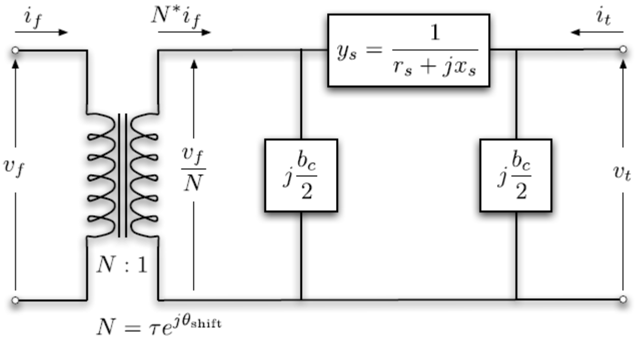

Figure 4.6: Matpower branch model [4]

Extending for multiple nodes:

$$\frac{S_i^*}{V_i^*} = \sum_{k \in i} Y_{ik} V_k \tag{4.26}$$

$$Y_{ii} = \sum_{k \in i} Y_{ik} \tag{4.27}$$

$$Y_{ik} = -Y_{ik} \tag{4.28}$$

where:

S_i^*-The conjugate apparent power injected at node i

V_i^*- The conjugate voltage magnitude at node i

V_k- Voltage magnitude at node k

Y_{ik}- Mutual admittance between node i and k

Y_{ii}- Self-admittance of node i

4.2.2 OPF problem definition

The OPF problem is then formulated as follows:

$$min_{\theta_i, v_i, P_{gi}} \sum_{n=i}^{ng} f_P^i(P_g^i) \tag{4.29}$$

subject to:

$$\sum_{n=1}^{ng} s_g^h = \sum_{n=1}^{nLoad} {s_{Load}}^h - \sum_{n=1}^{nBESS} {s_{Bess}}^h \tag{4.30}$$

$$\frac{S_i^*}{V_i^*} = \sum_{k \in i} Y_{ik} V_k \tag{4.31}$$

$$SOC_i^h = SOC_i^{h-1} + \eta_{C_i} P_{C_i}^h - (\frac{P_{Di}^h}{\eta_{D\,i}}) \tag{4.32}$$

$$S_{ik}^h \leq S_{ikmax} \tag{4.33}$$

$$V_{imin} \leq V_i^h \leq V_{imax} \tag{4.34}$$

$$SOC_{min} \leq SOC_i^h \leq SOC_{max} \tag{4.35}$$

where:

f_P^i- Active power price coefficient at generator i

P_g^i- Active power generated at generator i

S_g^h- Apparent power generated at hour h

S_{Load}^h- Apparent power demand at hour h

S_{BESS}^h- Apparent power discharged through BESS at hour h

V_i^h- Voltage magnitude at bus i at hour h

V_{imin}- Lower Voltage restriction at bus i

V_{imax}- Upper Voltage restriction at bus i

soc_i^h- State of charge of VSI ate hour h

soc_{min}- Lower state of charge restriction

soc_{max}- Upper state of charge restriction

The management tool heavily relates to the generation cost function. By manipulating the cost function it's possible to modulate different generators and different generators behaviors. To input generator cost MATPOWER defined a polynomial equation[4], typically used in generator cost functions. The function is divided by three coefficients. The first coefficient is time independent. The constant coefficient modulates the initial investment/installation cost of the generator. The first order coefficient correlates to operation and maintenance costs which have linear tendencies with time. Lastly, the second order coefficient correlates to the generator efficiency which modulates running time costs. Efficient optimization of generation dispatch will overall increase MG performance while managing voltage levels and enforcing quality constrains.

4.2.2.1 Cost functions

For simplicity reasons, a qualitative approach was taken when assigning cost functions to the system generators and only active power generation costs were considered.

PV generators where modulated has a generator with no running costs. As for BESS units and the grid, two different generators[5] where used. One generator for power consumption and another for power discharging. 4.7. BESS charging was taken a priority, as so the operating cost to absorb power in BESS units was assigned to be less than the operating cost for the grid generators to absorb power. As for power injection into the system, a priority was given to the grid generators, as so, the operating cost of the grid generators was less than the BESS generators. Lastly, a second order coefficient was assigned to the grid generators cost function, with the objective of rising operation costs during high grid demand. The total output of each unit (BESS/Grid) will be the sum output of both generators. Both models are identical, the only difference is the cost functions and power constraints, being the BESS generators limited in time as well

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[4] Classical generation cost function

[5] An infinite power capacity generator is used to modeled the grid, a standard consideration in power flow analysis

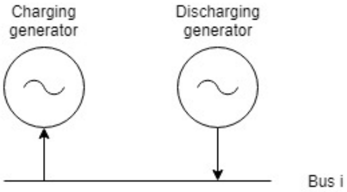

Figure 4.7: Cost model

4.2.2.2 BESS constraints

In BESS units the state of charge is modulated by summing the output of generators 4.7 in each iteration and adding to the previous energy value of each BESS unit. In order to simulate inverter losses, a charging and discharging offset is added to increase BESS energy losses represented in 4.32.

4.2.3 Summary

Power flow analysis is often used during grid planning and exploration as it helps plan grid architecture and operation, define procedures that impact/ affect load demand, take into consideration geographic location of loads and generation, load profile evolution, energy tariffs and quality of service to be provided. Planning the grid structure and operation for load demand needs a time frame, typically the uncertainty on both generation and load decreases as the time nears the real-time and therefore the adoption of a multi-stage stochastic framework decision process will maximize system flexibility, efficiency and optimal decision making.

Chapter 5

5. Definition of testing scenarios and results

5.1 Case study

In order to illustrate the exploitation of the tool that can be used for active and reactive power scheduling and voltage/var control in autonomous multi-microgrid system, a base case consisting of two identical microgrids (MGs) was created. The MGs were adapted from [5]. This configuration consists on two identical low voltage (400 V) MGs with 3 voltage source inverters (VSI), 17 buses, 13 loads and 8 photovoltaic (PV) generators. Furthermore, a 15kV medium voltage grid was designed consisting of a grid interface and fixed medium voltage (MV) load, the case study can be found in the appendix A.1. The lines of the LV microgrids module predominantly resistive R/X ratios, as it is a typical characteristic of LV distribution grids. In the overall procedure that is proposed, a three-phase balanced operation of the system was assumed. Finally, the base power quantity for the grid was choosed as 0,16 MVA and the base voltage quantity as 0,4/15 kV (LV/MV).

Considering A.1, the bus voltages constraints and bus types where the following:

Bus	Bus type	Vmin (p.u.)	Vmax(p.u.)
37 (Grid Bus)	REF	1	1
1, 2, 3 (BESS) 20, 21, 22 (BESS)	PV	0.9	1.1
4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36	PQ	0.9	1.1

The slack bus was assigned to BUS 37, BESS buses were assigned as PV, since the amount of power supplied by each BESS unit is not pre-specified, and thus these DG units are dispatchable. The other buses were assigned as PQ buses (loads and /or pv generation). PV generation was considered a non-dispatchable unit since it's operating at the maximum power point generation mode.

5.1.1 Battery energy storage System

The battery energy storage systems were modulated as in voltage source inverter (VSI) power flow model from [73]. With this model the VSI can be regarded as an AC voltage source connected to the grid through a coupling inductance. For the storage system a 80% charging and discharging efficiency was considered. Every BESS had the same energy storage capacity, with a maximum SOC of 300kWh and a minimum of 30kWh [1], every BESS started at 180 kWh (60%) of maximum energy storage capacity. Each BESS had the following power characteristics:

	Pmax (kW)	Qmax (kvar)	Pmin (kW)	Qmin (kvar)
BESS 1	200,0	130,0	-200,0	-130,0
BESS 2	100,0	65,0	-100,0	-65,0
BESS 3	50,0	32,5	-50,0	-32,5
BESS 20	200,0	130,0	-200,0	-130,0
BESS 21	100,0	65,0	-100,0	-65,0
BESS 22	50,0	32,5	-50,0	-32,5

5.2 Test scenario 1 - Grid connected

This test scenario projects a day ahead market scenario with typical load profiles and generation. The load profile is presented in A.7 and A.8 PV generation was considered to be present from 7 am to 7 pm. In grid connected mode is expected that grid generation sustains all load demand. During PV generation hours, the system must prioritize PV power consumption, as for excess energy periods or low load demand periods, BESS charging should occur. Finally, during peak load demand, as grid cost are high, BESS units should inject power to the system.

5.2.1 Results

In this section the graphical results are analyzed [2]. The results of the first test scenario are presented in 5.1 and at A.6. From the bar plot is noticeable that PV generation provided energy for the whole system during hours 11, 14 and 16 (represented in black). Bess charging, occured during low load demand and excess PV generation periods, which is represented by negative power generation. On the other hand, during high power grid demand periods, (from hour 19 to hour 24), BESS discharge occured.

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[1] 10% of the maximum SOC

[2] Every plot is available in a larger scale at the appendix

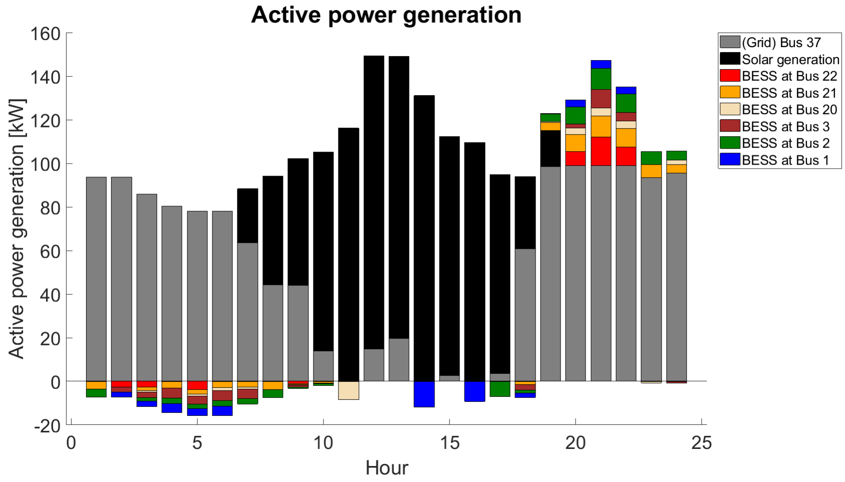


Figure 5.1: Test scenario grid connected active power generation

5.2.1.1 BESS state of charge

In 5.2 and at A.6 the state of charge of every BESS unit can be analyzed. From 5.2 it can be clearly observed two charging periods, one from low load hours and the other from excess PV generation and a discharging period corresponding to high grid demand hours. 5.1.

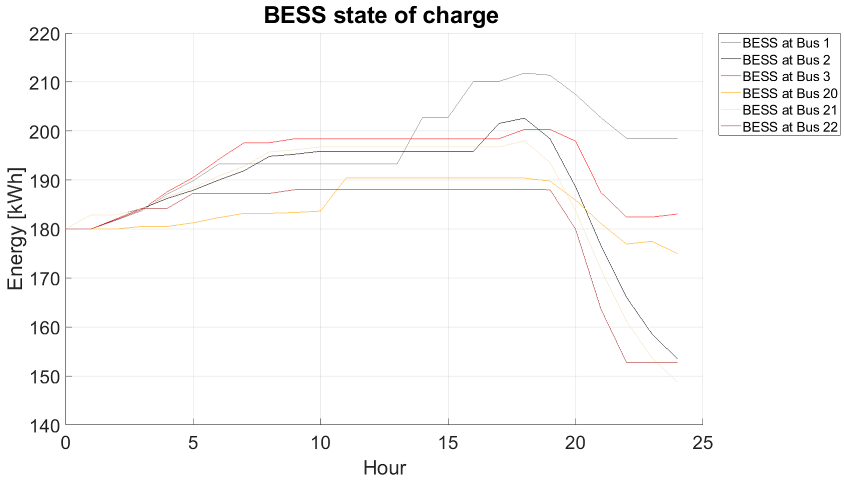


Figure 5.2: Test scenario grid connected BESS state of charge

5.2.1.2 Power flow and voltage levels

In transmission lines the direction of power flow will be along the part of the grid whose voltage leads, to the part whose voltage lags. From analyzing figure presented in 5.3, which can be found at A.5 it's clear to see that during PV generation periods, PV buses , mainly (13, 17, 15, 32, 34, 36), have leading phase angles, and during no generations periods lagging phase angles, which was expected. The same happens with BESS buses, during high power grid demand periods (19-24h).

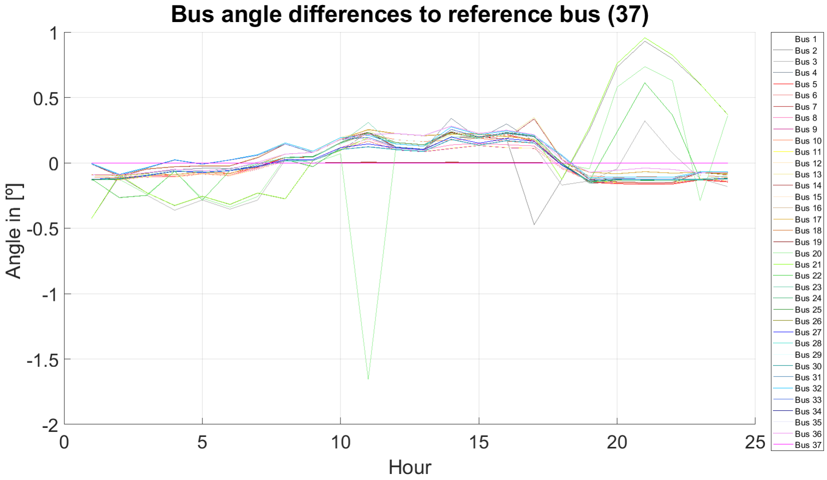


Figure 5.3: Test scenario grid connected voltage phase angles

In figure 5.4 and at A.4 the bus voltage levels of test scenario 1 are presented. From the figure it's clear to see a voltage rise at PV generation buses mainly (13,17,15, 32,34,36), which was expected.

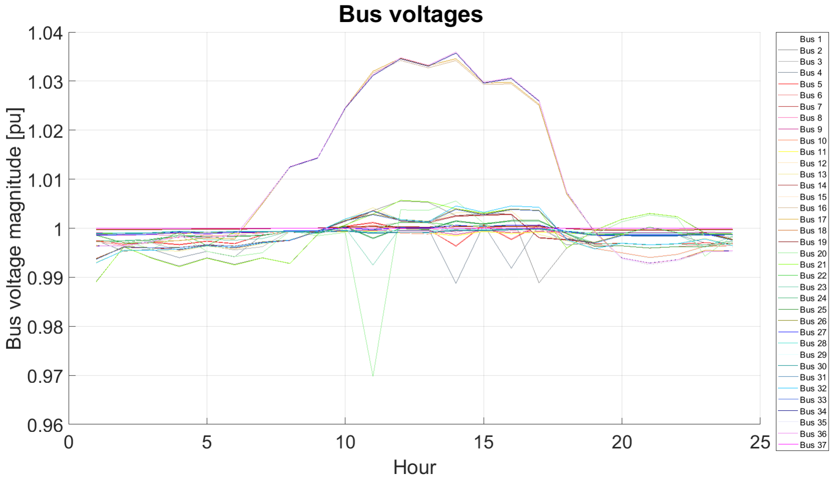


Figure 5.4: Test scenario grid connected voltage amplitude

5.3 Test scenario 2 - Islanding from the grid

In this test scenario the grid is disconnected at hour 19 and 20. During island mode, the slack bus was assigned to BESS 1. Assigning the slack bus to a DG unit with limited capacity might not be practical, however in this case study, BESS 1 had enough power capacity. In test scenario 2 the load profile is the same as test scenario 1, and can be found in A.20 and A.21.

The MMG system was subjected to islanding operation during hours 19 and 20 as mentioned before. The operation proved to be successful. In figure 5.5 and A.17 the voltage profile of test scenario 2 is presented, it's clear to see that during hour 19 and hour 20 the voltage profile was similar to the grid connected scenario 5.4, which was expected.

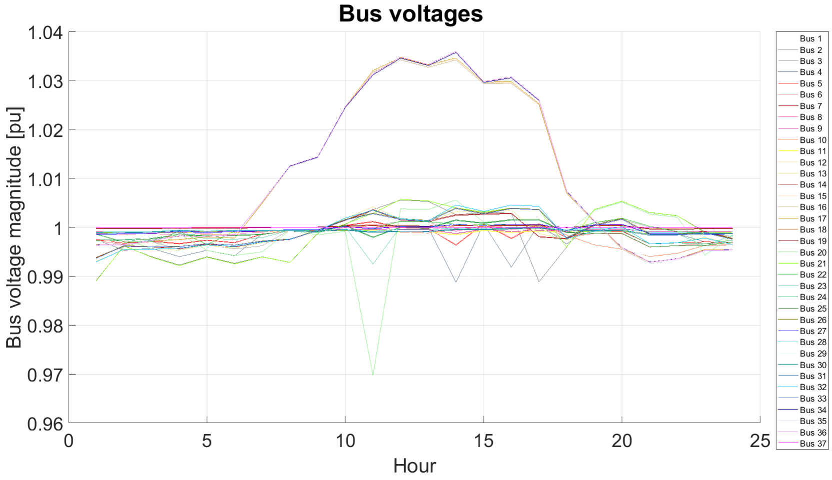


Figure 5.5: Test scenario grid disconnected voltage amplitude

5.3.0.1 Generation profile

In 5.6 the active power generation during the island test scenario is presented. From the figure, it can be observed that during hour 19 the system was powered by BESS and solar generation, while at hour 20 solely by BESS generation. Furthermore, it highlighted the system fragility to islanding operation since during island operation the system heavily relies on BESS 3 and BESS 22 to provide power, since they are the nearest BESS units to the MV load and most of the LV load demand, being this BESS units limited to 50 kW maximum discharge.

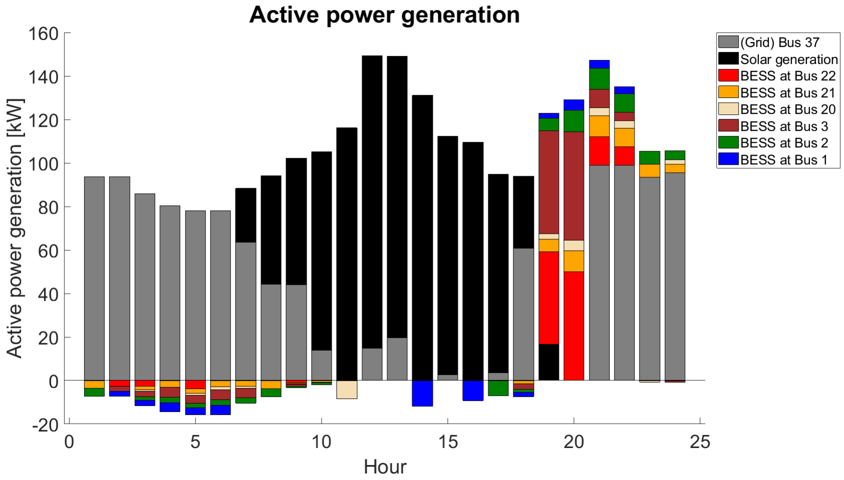


Figure 5.6: Test scenario grid disconnected active power generation

Comparing figure 5.7 with 5.6 it's noticeable that during island operation bus 37 stops being the reference bus and compensation is provided by the BESS units.

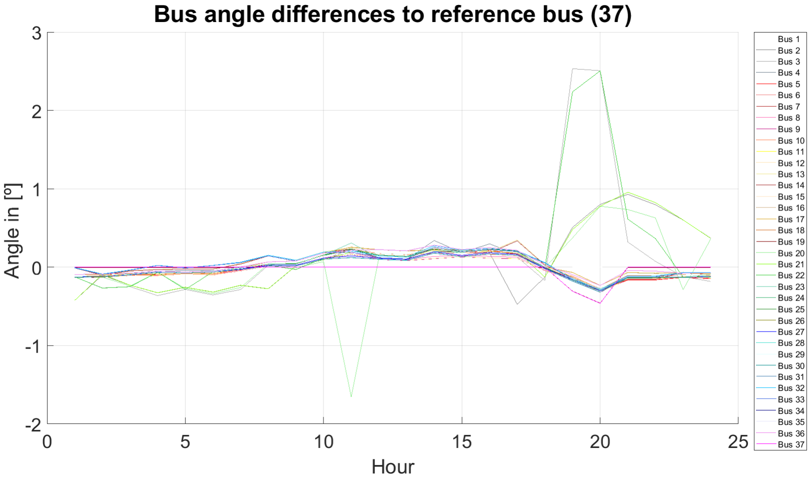


Figure 5.7: Test scenario grid disconnected bus voltage angles

5.3.1 BESS state of charge

In 5.8 it's clear to see that the sate of charge of BESS 3 and BESS 22 peak drops during island operation, discharging near nominal capacity.

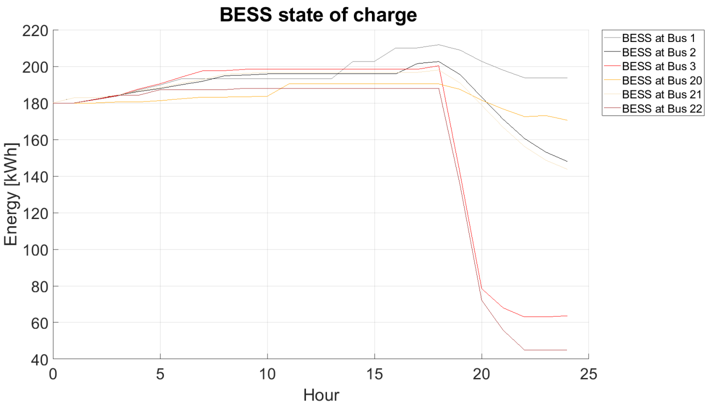


Figure 5.8: Test scenario grid disconnected BESS state of charge

5.3.1.1 VSI coupling inductance voltage drops

As mentioned in 4 in order to use the conventional drop methods and decentralized load sharing mechanisms in LV grids, the line impedance must be inductive enough to model the DG unit as an ideal voltage source whose voltage and frequency are determined by conventional droop methods($\phi \approx 90$) as in 4.5 and 4.6 [75]. Therefore, an inductance was added to the BESS units simulating, a

VSI virtual impedance. This was accomplished by creating an extra bus (internal bus) as in figure 5.9 in each BESS unit and coupling the buses by a inductance [73].

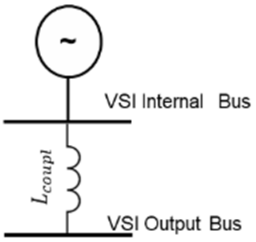


Figure 5.9: VSI power flow study model

From the two-bus model, the idle voltage in the output bus can be determined as:

$$V_0 = V_{int} + k_Q * Q_{OUT} \tag{5.1}$$

where,

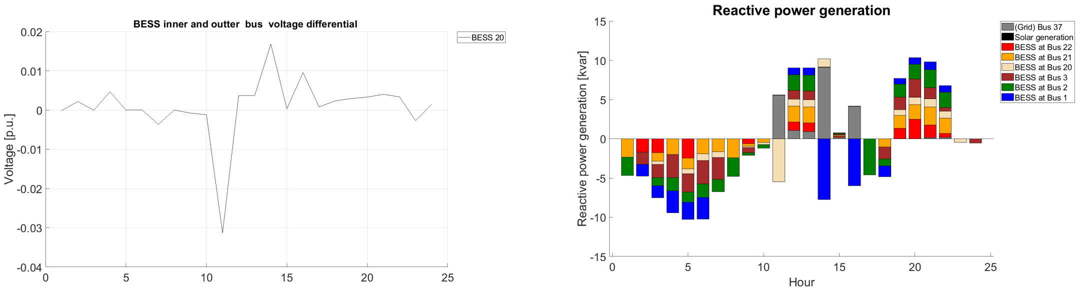
V_{Int}-Internal VSI bus voltage.

Q_{out}-VSI reactive power output.

k_Q- A fixed characteristic of each VSI.

Taking into consideration figure 5.9 a comparison can be made to the inner and outer voltage magnitude of BESS buses testing the coupling inductance method for voltage drops. If a decouple between active power and reactive power is present, then the difference between the inner (fictitious bus) and the outter bus voltages will generate reactive power flow and the difference between the inner and outter voltage phases will generate active power flow.

In A.14 the difference between the inner and outer voltages magnitudes of BESS 20, for test scenario 2, during the 24 hour period is presented. When comparing figure 5.10b with figure 5.10a a dip in the voltage magnitude differential can be associated with negative reactive power injection to the grid (reactive power consumption), and positive spikes with reactive power injection. The same was done for every other BESS unit and the results are similar.

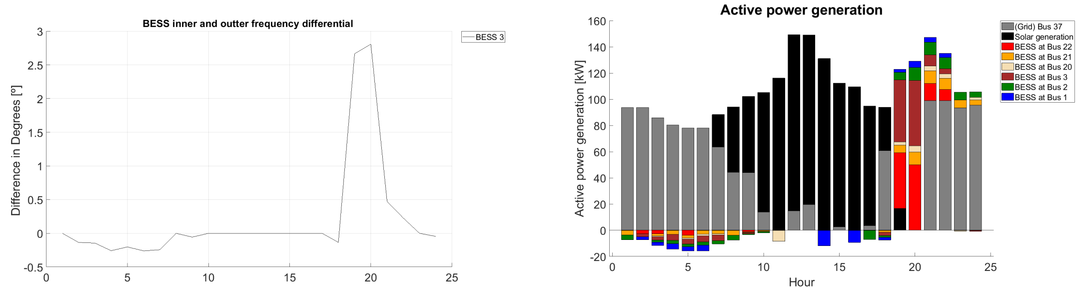


(a) BESS 20 $V_{InnerBus} - V_{OuterBus}$

(b) Test scenario grid disconnected reactive power generation

Figure 5.10: Voltage magnitude differential of BESS 20 and reactive power generation in the grid islanding scenario

Applying the same method to the voltage phase difference similar results are obtained, but this time for active power generation.



(a) $Bess3\angle InnerBus - \angle OuterBus$

(b) Test scenario grid disconnected active power generation

Figure 5.11: Voltage phase differential of BESS 20 and active power generation in grid islanding scenario

Chapter 6

Conclusions and future work

6.1 Conclusion

This dissertation analyzes MG architectures and design, focusing on remote/rural electrification. A MATPOWER simulation was also performed, analyzing the behaviour of the MMG and its elements in steady-sate time domain. The purpose of this analysis was to provide a tool for project design, due to the need of studying the impact of different types DG (MSs) at different points of Low Voltage (LV) MGs.

MGs are presented as a pathway towards the smart grid, as they can provide a flexible and modular solution. Typical network infrastructures do not provide reliable service with increased LV DG integration and high density load demand. Upgrading current grid infrastructures should aim at DG integration near consumption sites, focusing on implementation of low carbon technologies. Moving from economic driven towards environmental driven grids.

RES DG integration at the LV would require a complete redesign, including huge investment costs, of all existing protection systems, metering equipment and ICT at the lower voltage levels of the grid. To be presented as a viable solution MG technology needs to mature and develop standards of operation for MG dissemination. With more flexible legislation and limited access of traditional grids remote/rural areas present an opportunity for MG technology to mature.

Due to the relevance and pertinence of this subject, an analysis on MG design was carried out, to study the impact of MG architectures in the project outcome, focusing on remote/rural projects. According to the literature review, DG generation that stimulates local economy yields higher ROI in rural/remote projects, geographical analysis on local natural resources and economy is also heavily related to project success. Furthermore, early stakeholder involvement should be taken into consideration to avoid conflict of interest. Lower/easy maintenance generation such as PV/micro turbines are ideal for remote/rural MG. For less developed areas combined heat and power generation yields higher success rates.

MG deployment is limited by energy storage systems scalability, being considered the technological lock in. The study revealed that transition towards decentralized LV power generation is not of the best interest for well established energy companies as it could present new energy market dynamics such as consumer to consumer trades, which creates conflicts of interest.

The MATPOWER simulation allows for different MG configurations to be tested as well as island mode scenarios by allowing grid components to be disconnected.The aim of this model was to test power and energy capacity of MG, taking into consideration grid infrastructures. To be used as an auxiliary tool to test load and generation scenarios.
The simulation revealed some limitations, data accuracy obtained from the simulation can be discussed since the simulation fails to consider load unbalances conditions typically present at LV grids and grid components are elementary modulated. Nevertheless, for steady state conditions the value proposition still holds.

In conclusion, MG implementation appears has a logical step for the transition towards the smart grid future, MG successful implementation will depend on how well the system meets local needs and limitations, being MG design and sizing two major factors. Finally, with the accomplishment of this work, the importance of such study became evident, since contributing towards successful MG implementation is crucial for bridging the gap between current grids and smart grids.

6.2 Future work

In order to continue developing MG-based simulations, it is necessary to minimize errors found in its modelling and also study the transition from on-grid mode to isolated mode and the reconnection to the grid, besides the ability of the system to withstand these transitions, respecting the limits associated with power quality parameters. Developing more realistic testing scenarios such as PHILL and HILL simulations would help develop standards of operation and guidelines for MG implementation. Other points of interest would be the study new billing mechanism and market models to enhance the value proposition of MG such as consumer to consumer markets and integration of consumer preferences in the power dispatch problem. The MATPOWER simulation presented could be enhance in terms of speed by implementing the code in C.

Appendix A

Graphic Results

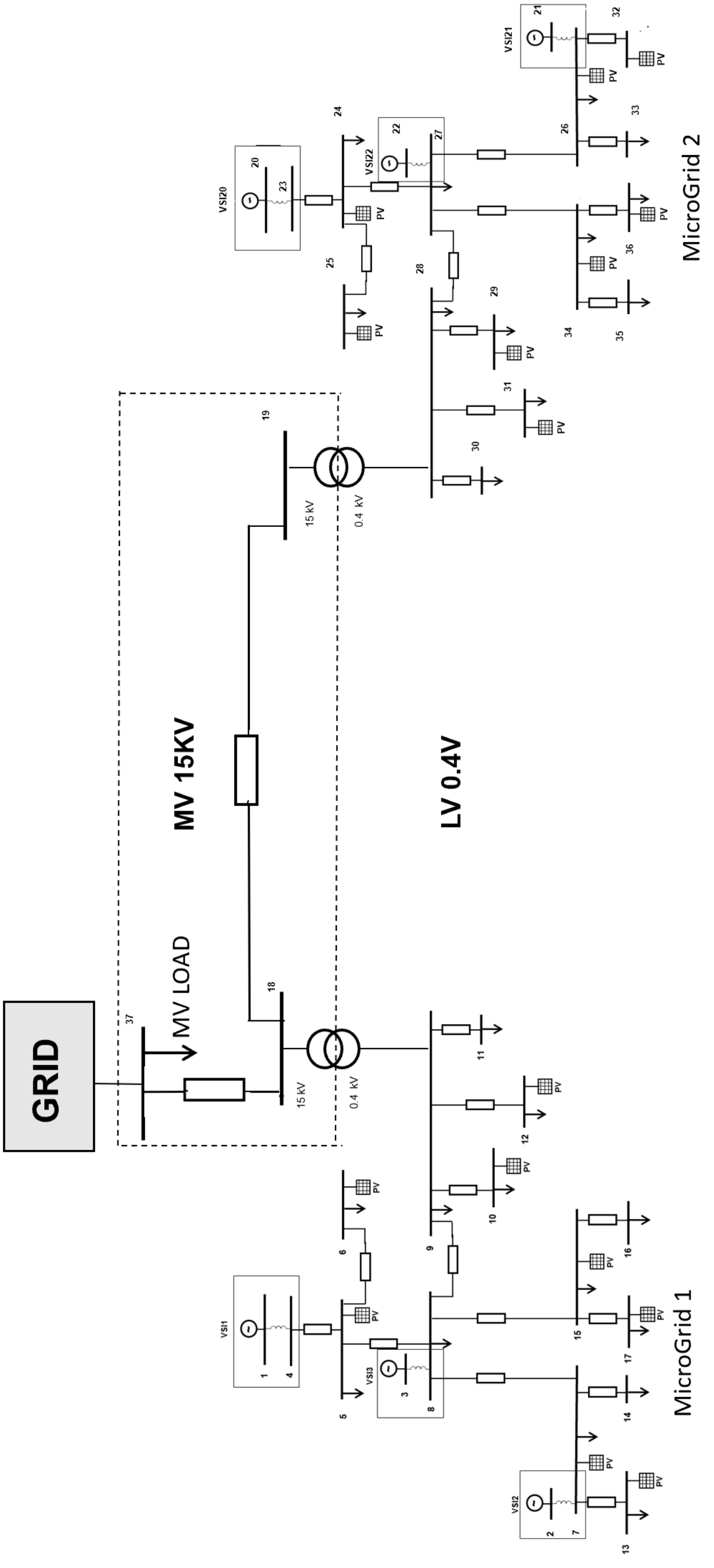


Figure A.1: Base case

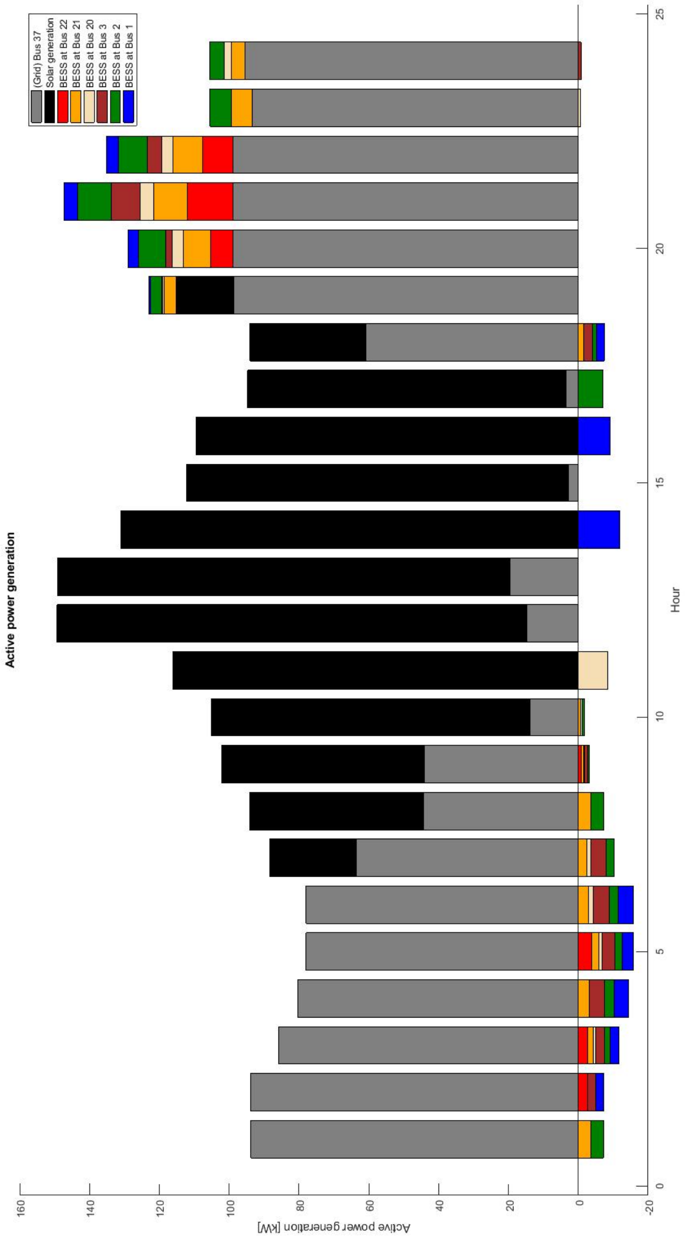


Figure A.2: Test scenario grid connected active power generation

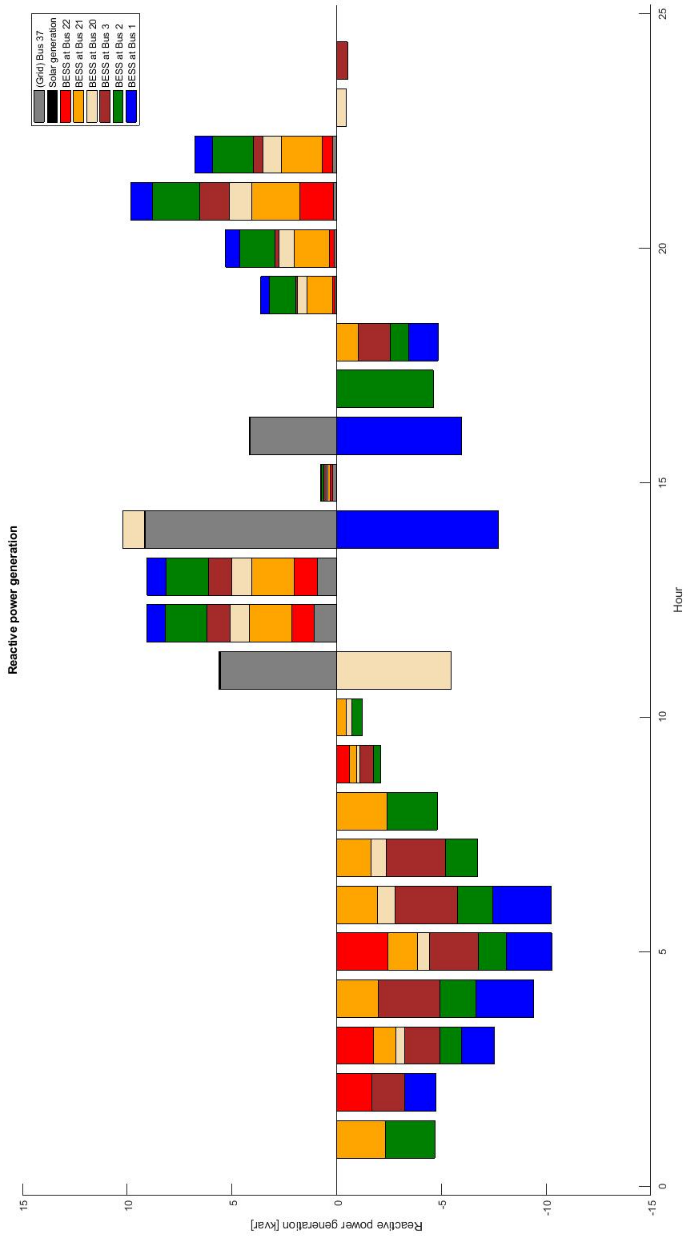


Figure A.3: Test scenario grid connected reactive power generation

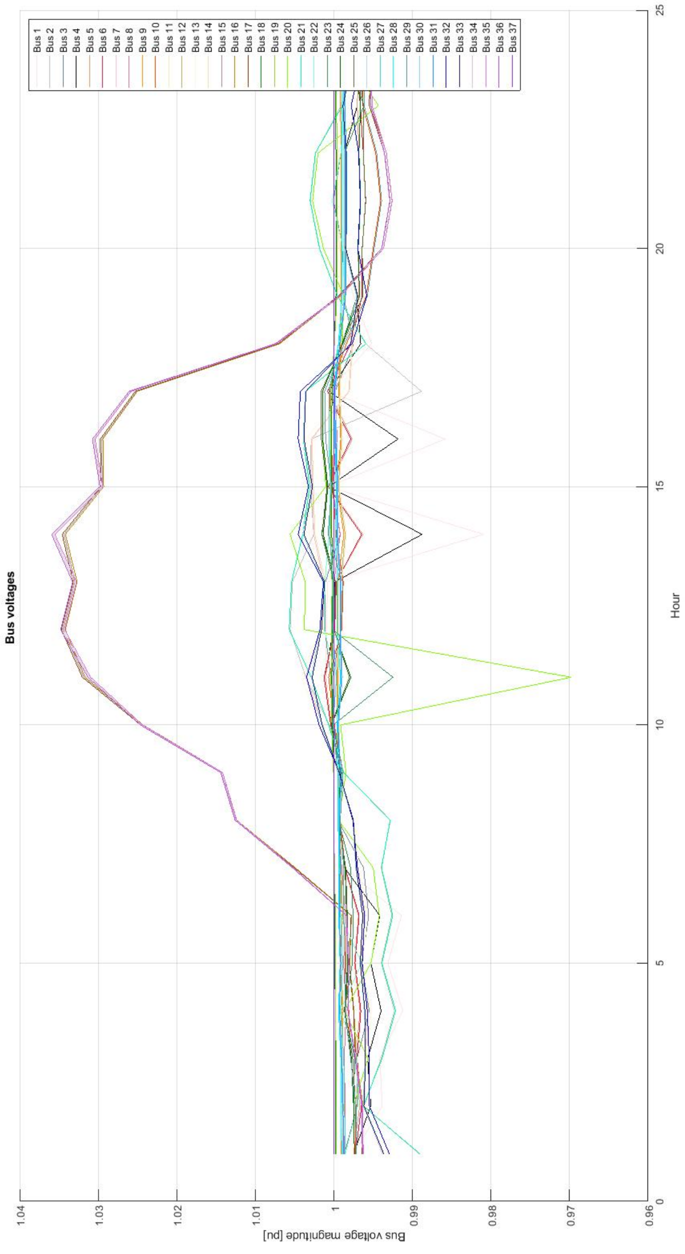


Figure A.4: Test scenario grid connected bus voltages

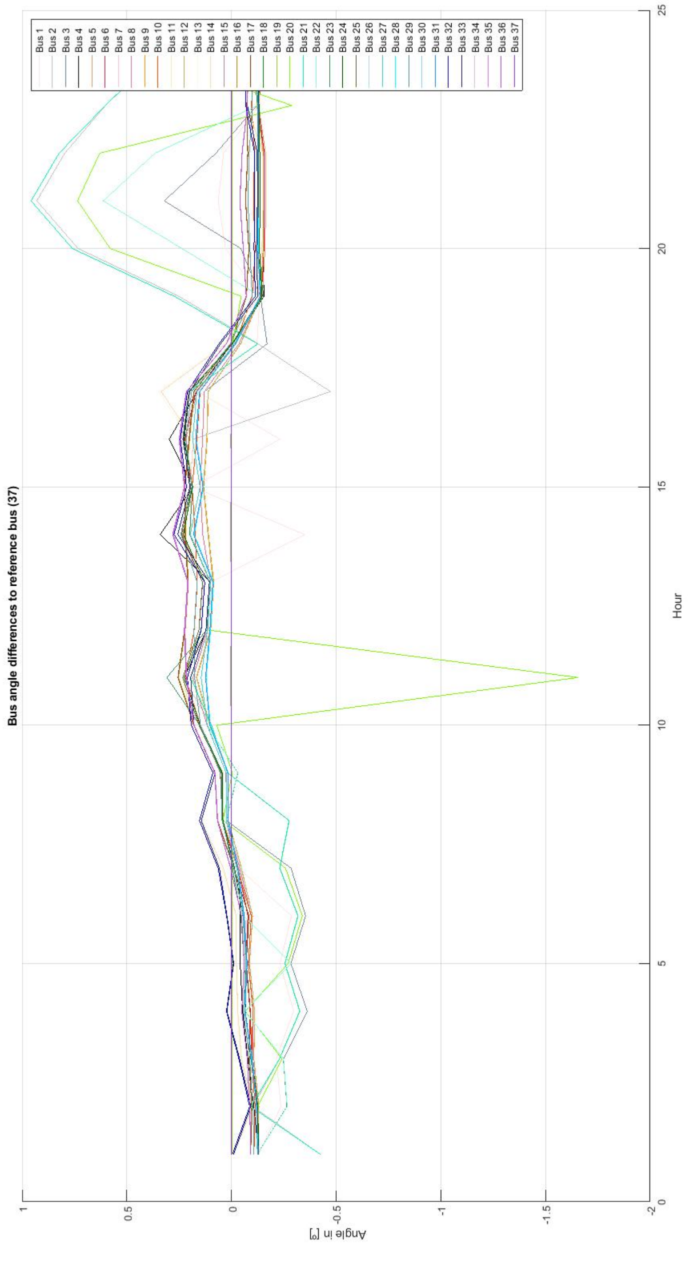


Figure A.5: Test scenario grid connected bus voltages angles

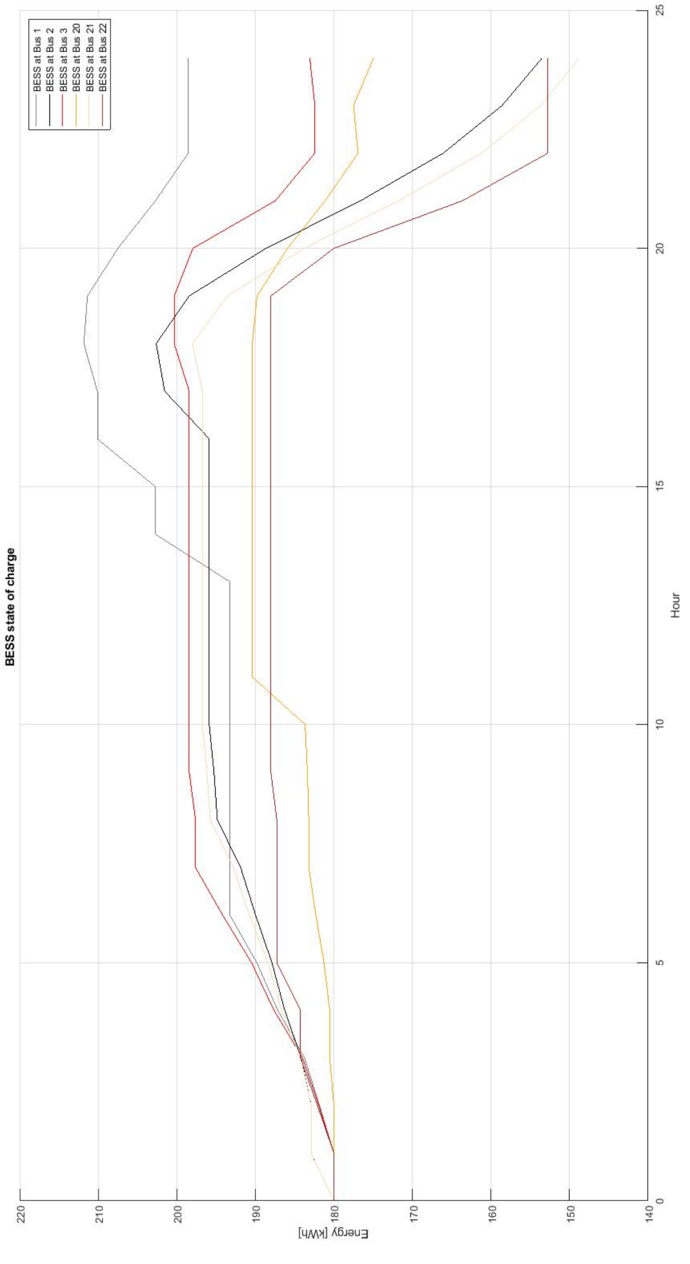


Figure A.6: Test scenario grid connected BESS state of charge

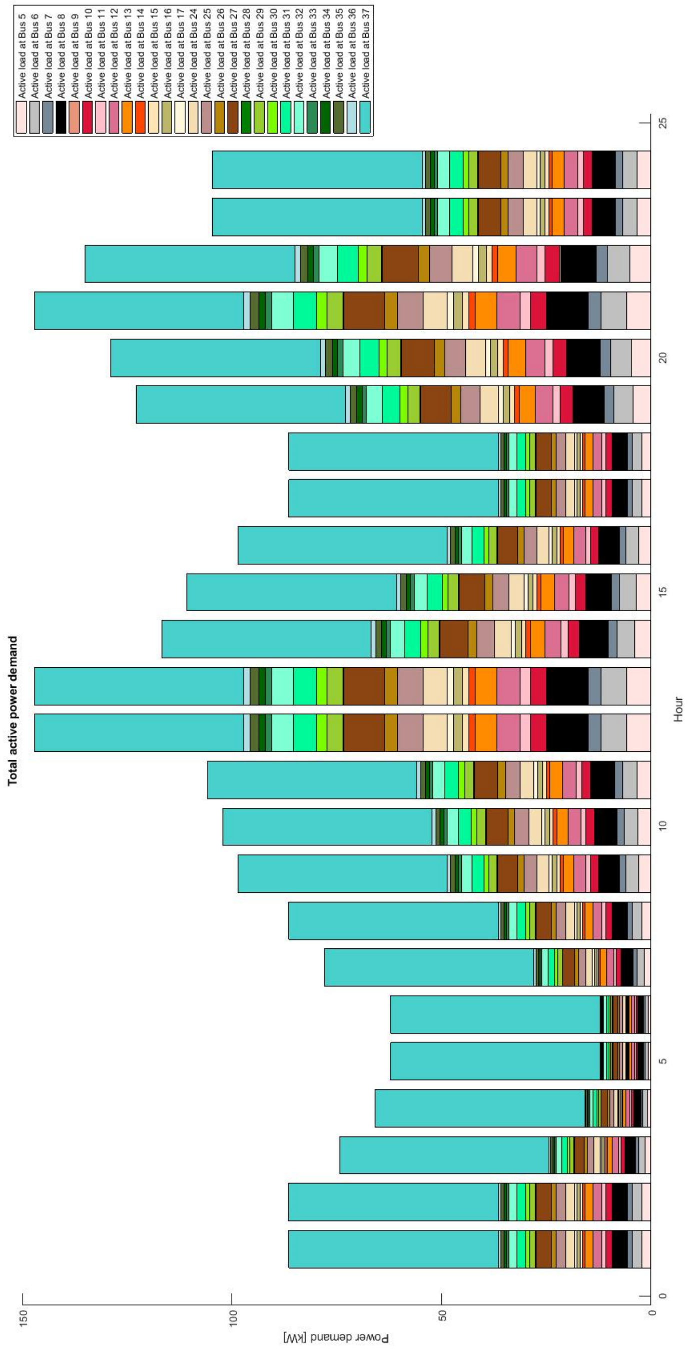


Figure A.7: Test scenario grid connected active power demand

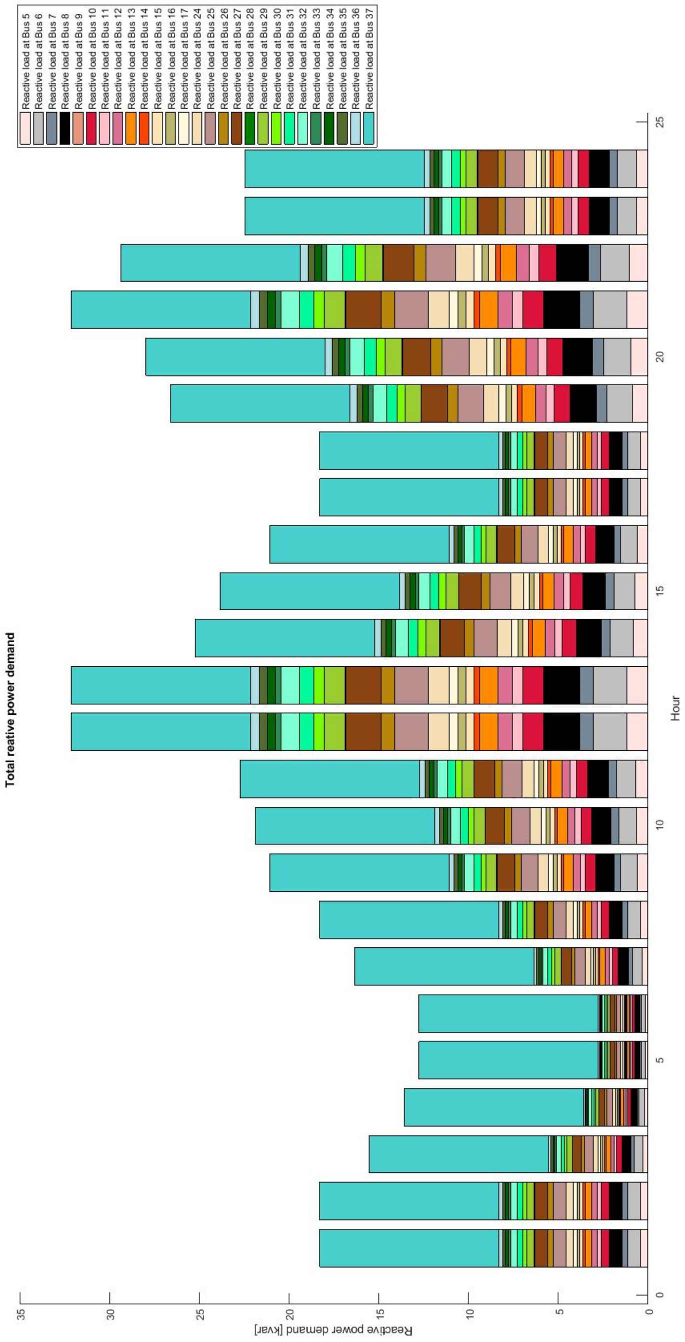
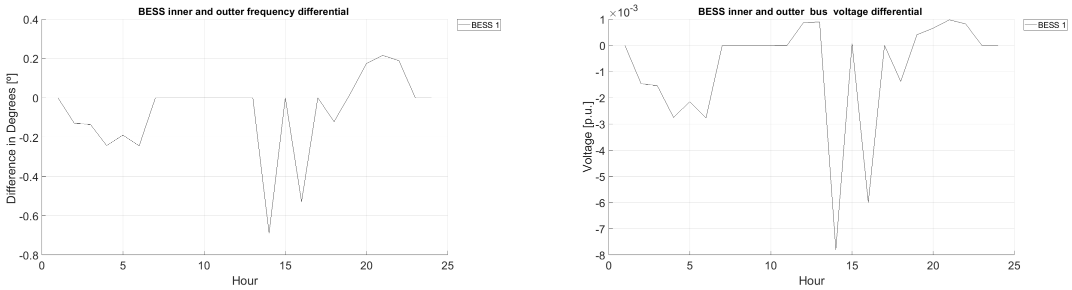
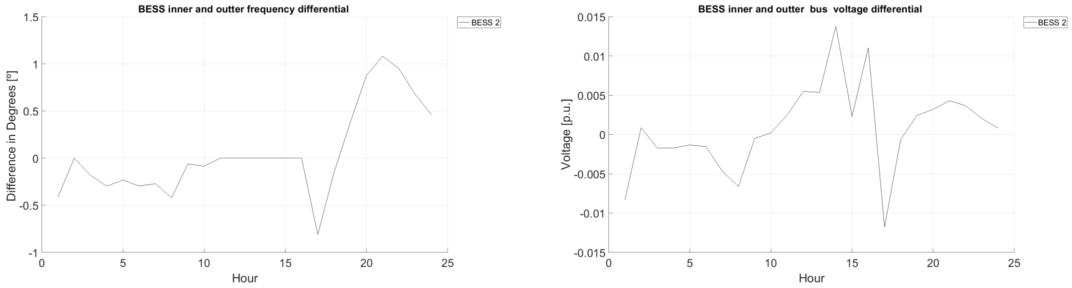


Figure A.8: Test scenario grid connected reactive power demand



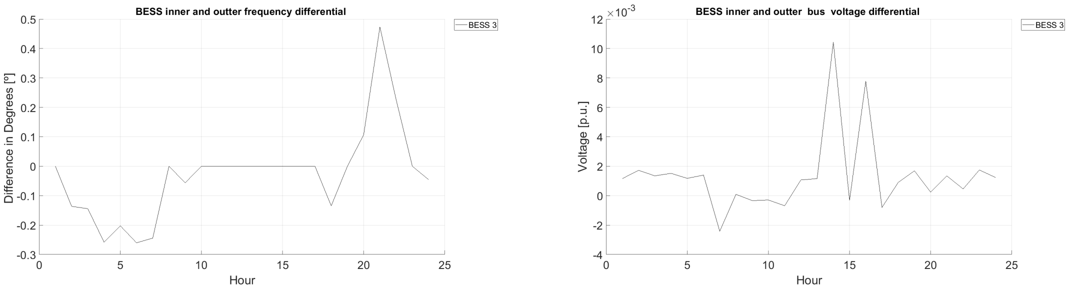
(a) BESS 1 $\angle InnerBus - \angle OuterBus$ (b) BESS 1 $V_{InnerBus} - V_{OuterBus}$

Figure A.9: Voltage magnitude and angle differential of BESS 1 in grid connected scenario



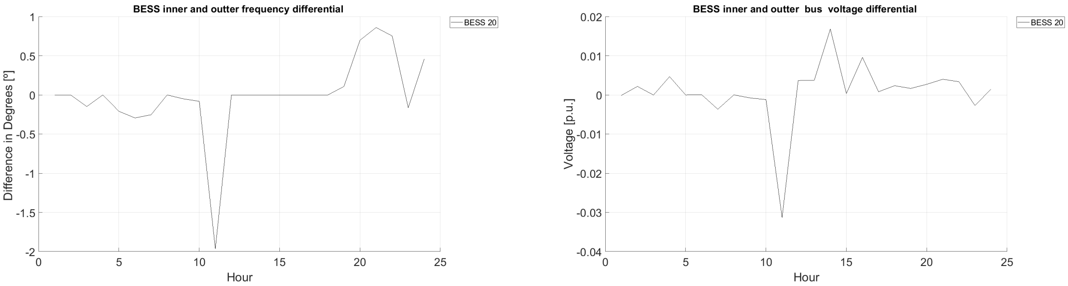
(a) BESS 2 $\angle InnerBus - \angle OuterBus$ (b) BESS 2 $V_{InnerBus} - V_{OuterBus}$

Figure A.10: Voltage magnitude and angle differential of BESS 2 in grid connected scenario



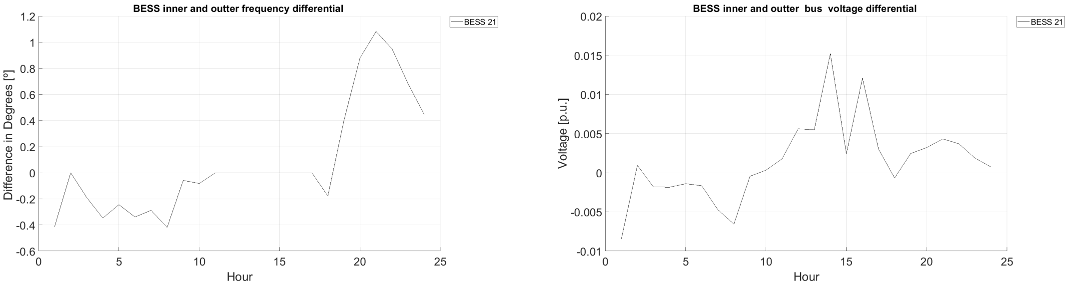
(a) Bess 3$\angle InnerBus - \angle OuterBus$ (b) Bess 3$V_{InnerBus} - V_{OuterBus}$

Figure A.11: Voltage magnitude and angle differential of Bess 3 in grid connected scenario



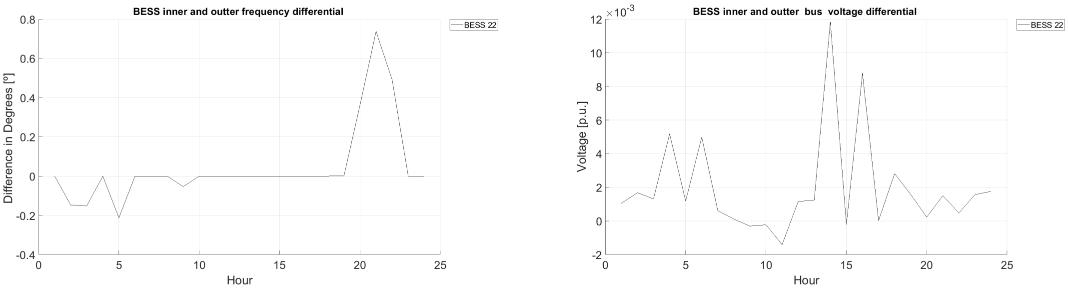
(a) BESS 20 $\angle InnerBus - \angle OuterBus$ (b) BESS 20 $V_{InnerBus} - V_{OuterBus}$

Figure A.12: Voltage magnitude and angle differential of BESS 20 in grid connected scenario



(a) BESS 21 $\angle InnerBus - \angle OuterBus$ (b) BESS 21 $V_{InnerBus} - V_{OuterBus}$

Figure A.13: Voltage magnitude and angle differential of BESS 21 in grid connected scenario



(a) Bess 22$\angle InnerBus - \angle OuterBus$ (b) Bess 22$V_{InnerBus} - V_{OuterBus}$

Figure A.14: Voltage magnitude and angle differential of Bess 22 in grid connected scenario

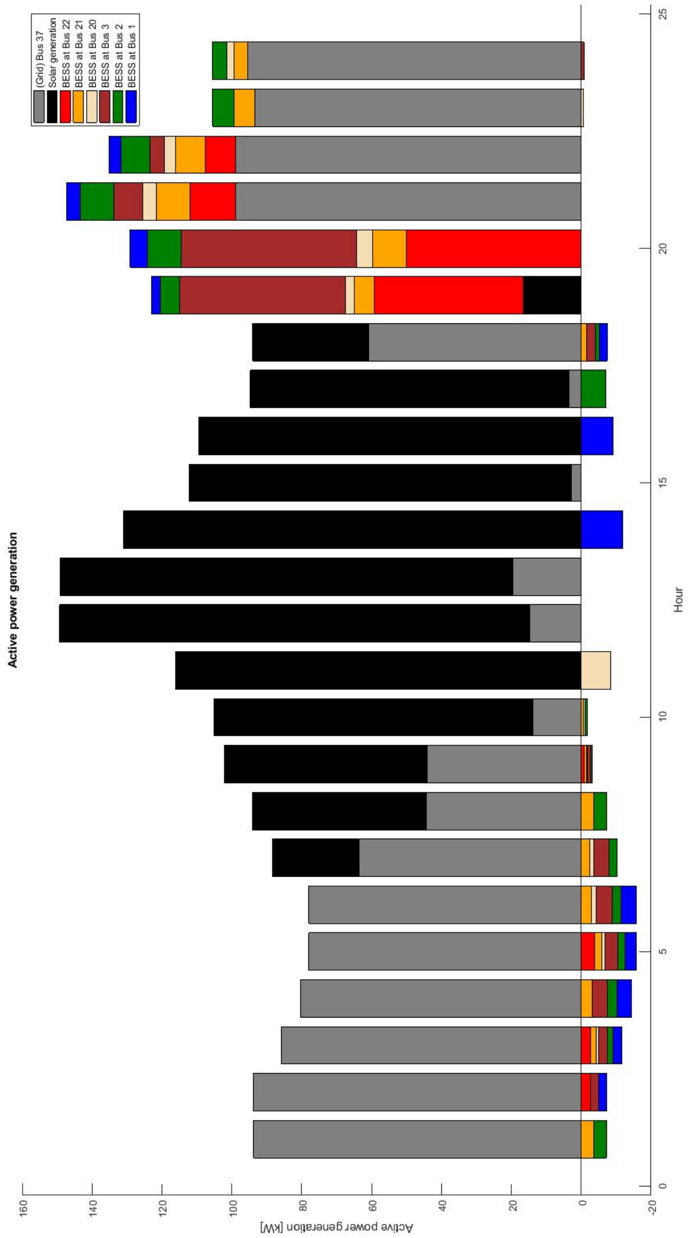


Figure A.15: Test scenario grid disconnection active power generation

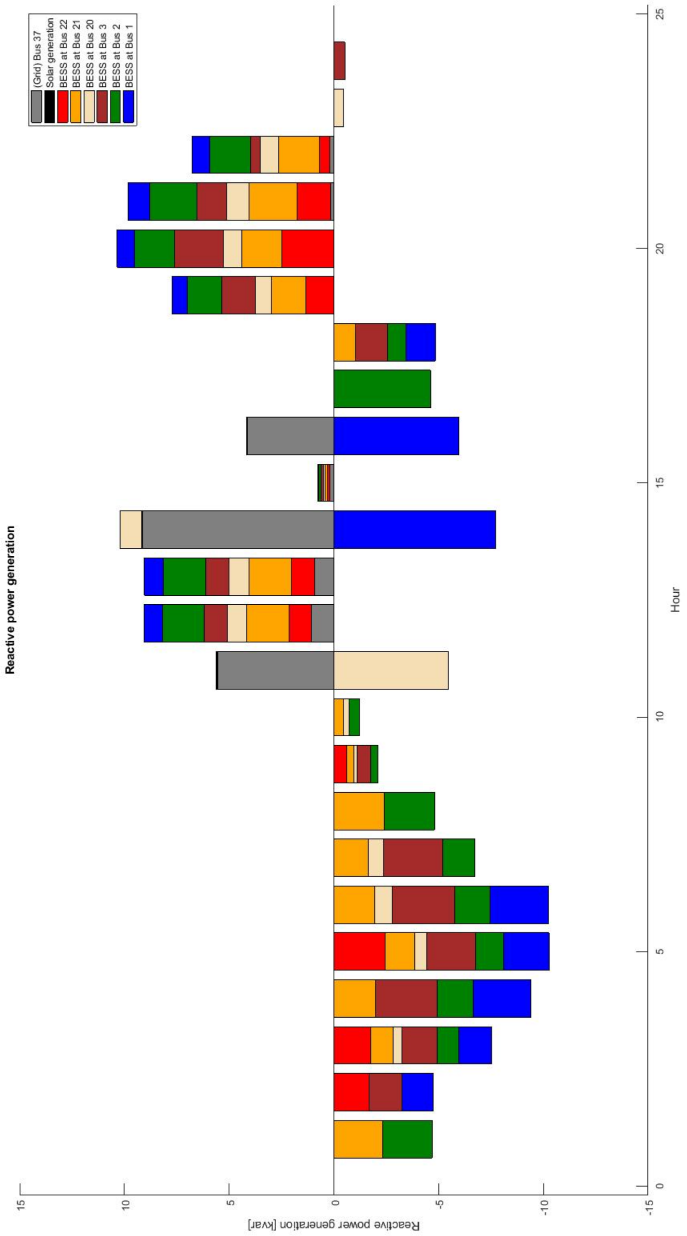


Figure A.16: Test scenario grid disconnection reactive power generation

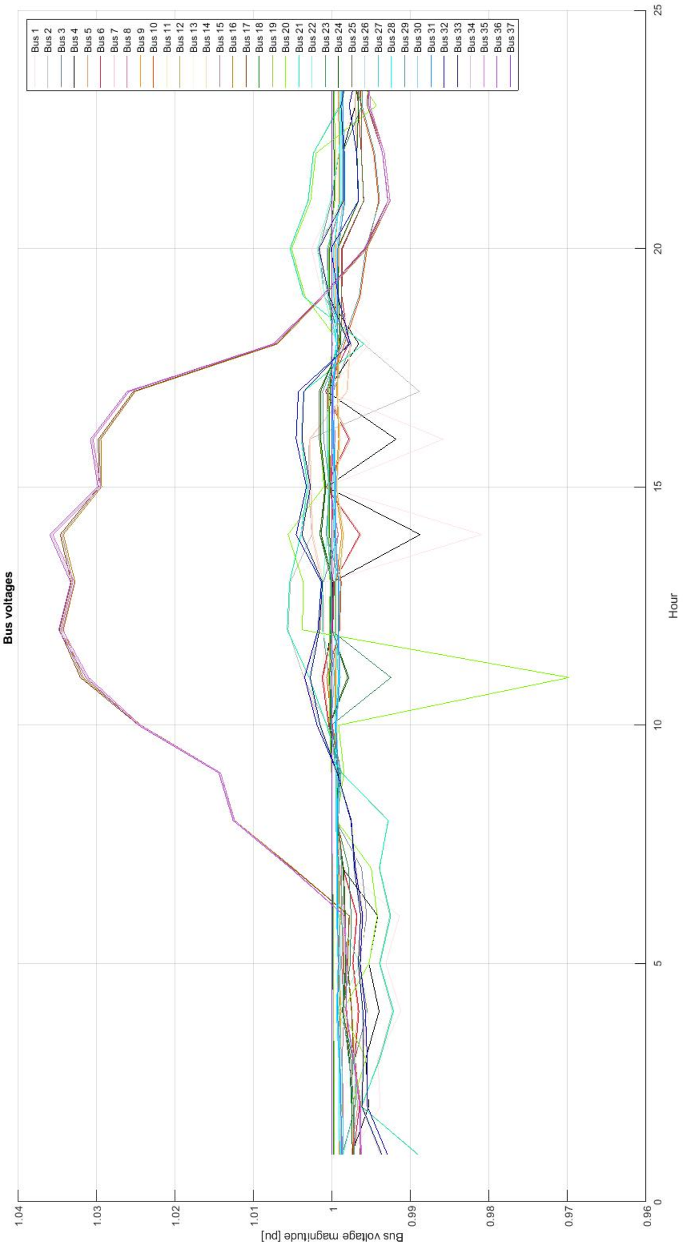


Figure A.17: Test scenario grid disconnection bus voltages

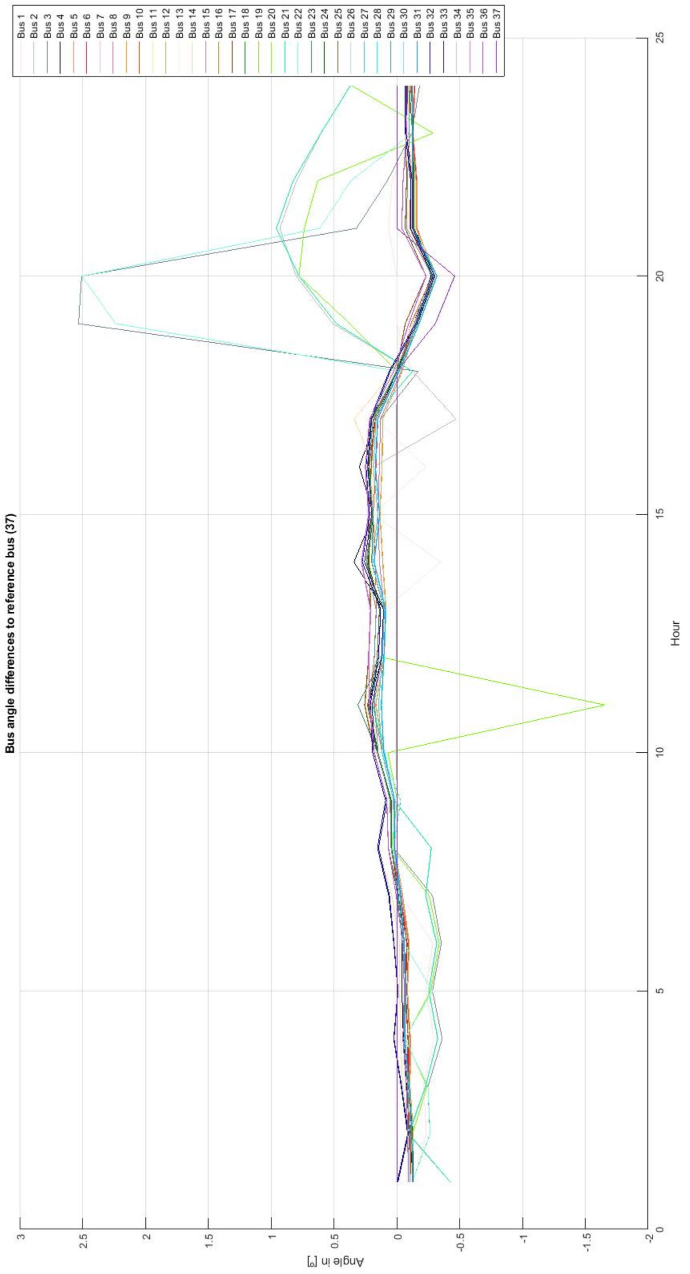


Figure A.18: Test scenario grid disconnection bus voltages angles

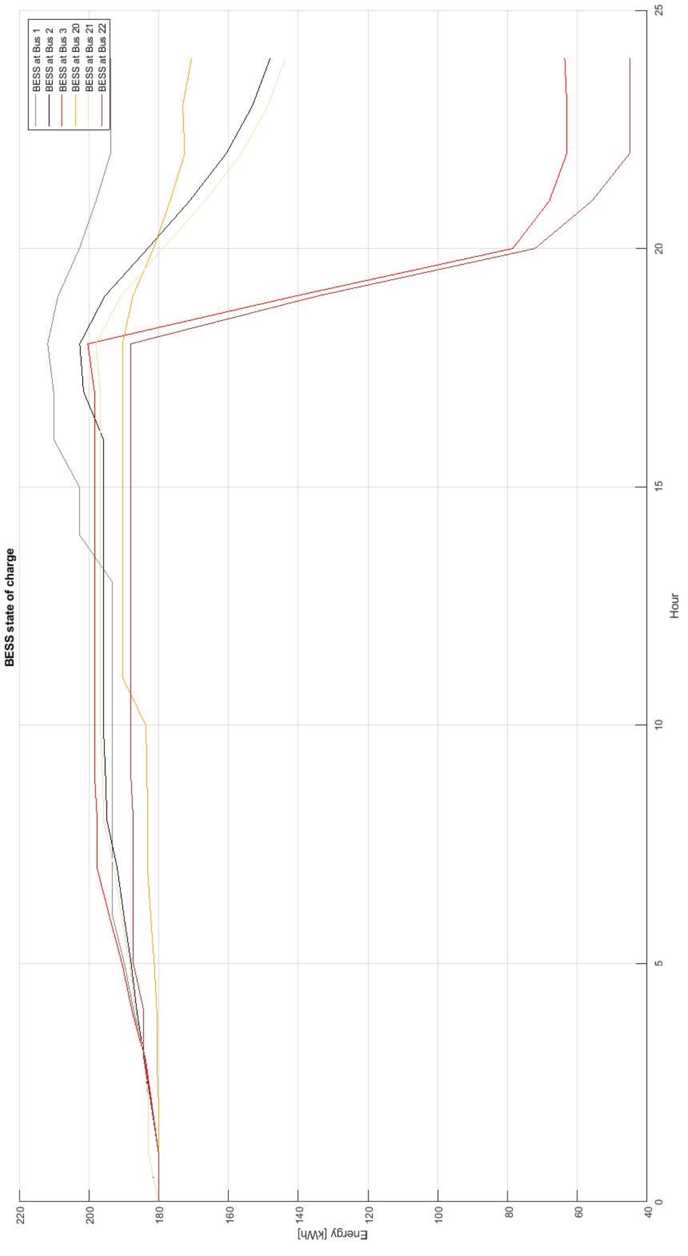


Figure A.19: Test scenario grid disconnection BESS state of charge

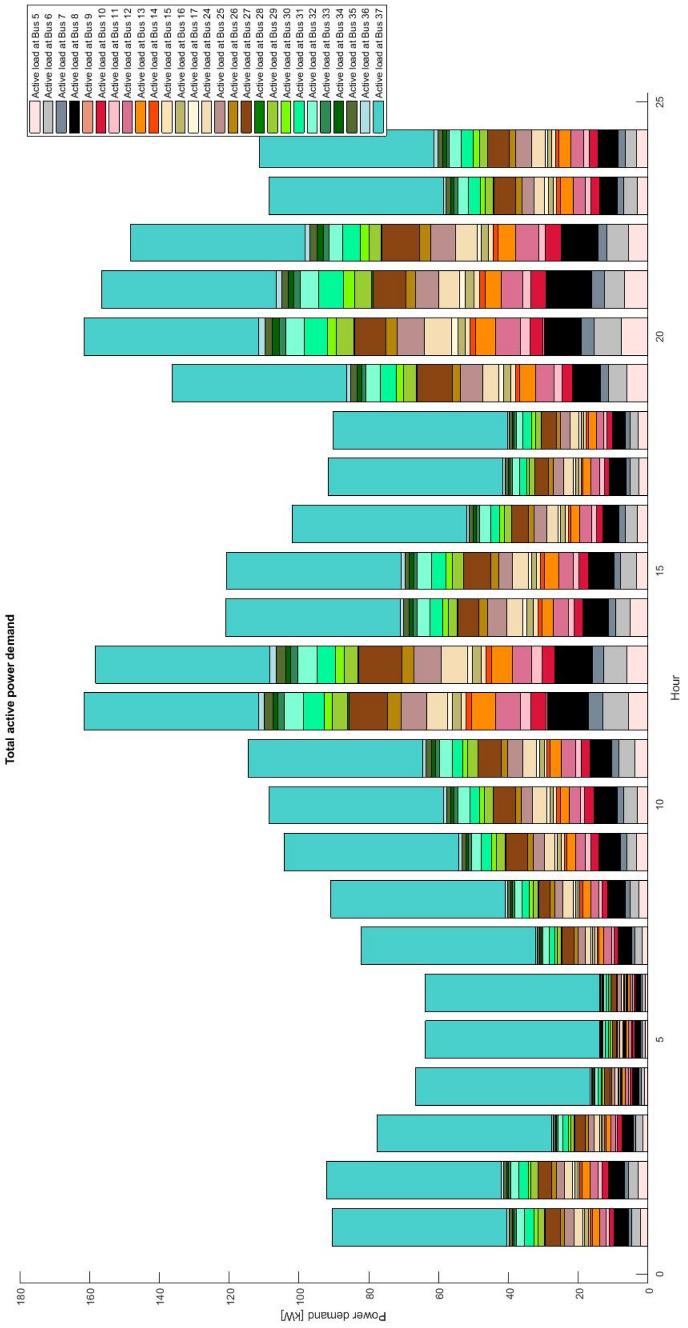


Figure A.20: Test scenario grid disconnection active power demand

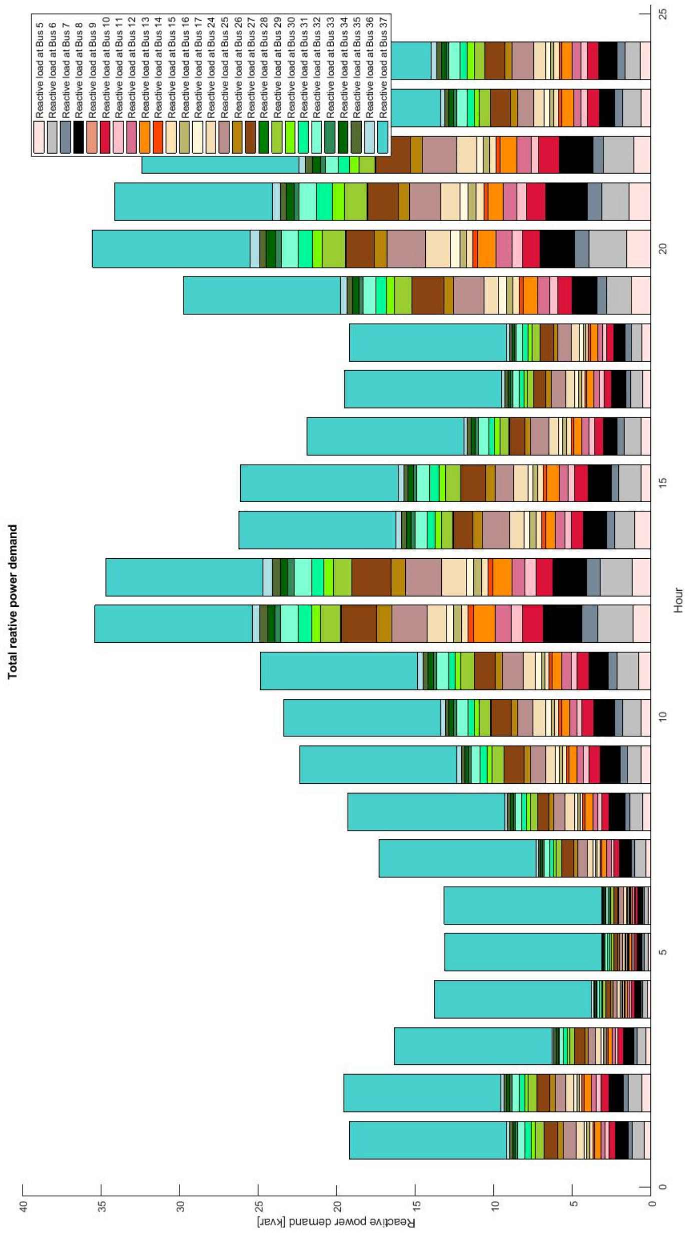
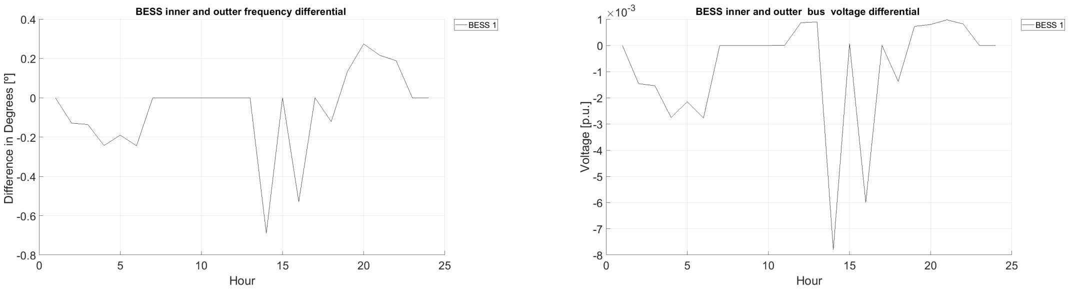
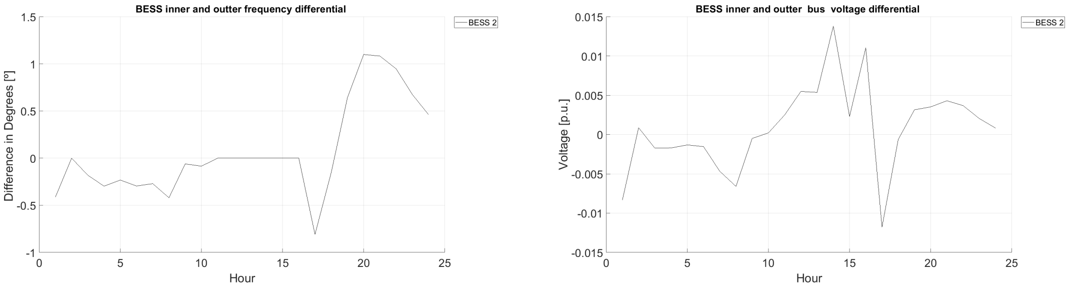


Figure A.21: Test scenario grid disconnection reactive power demand



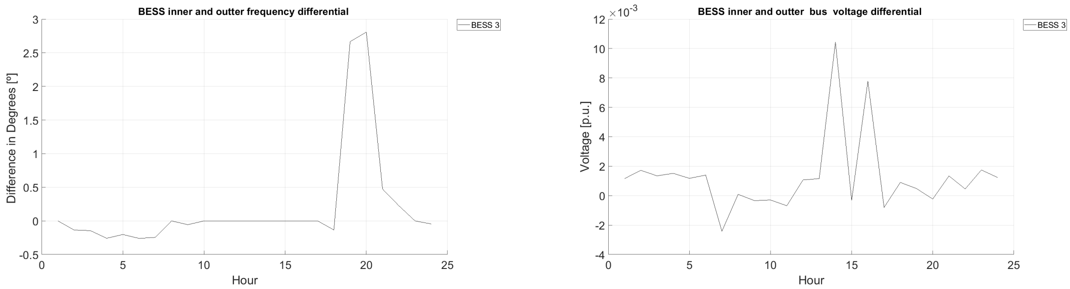
(a) BESS 1 $\angle InnerBus - \angle OuterBus$ (b) BESS 1 $V_{InnerBus} - V_{OuterBus}$

Figure A.22: Voltage magnitude and angle differential of BESS 1 in grid disconnection scenario



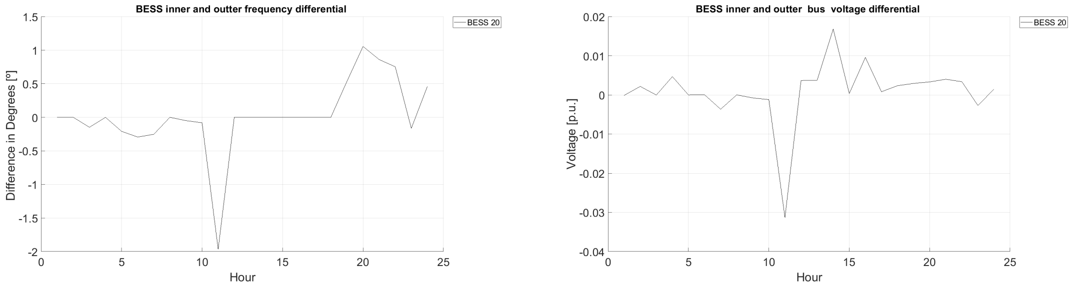
(a) BESS 2 $\angle InnerBus - \angle OuterBus$ (b) BESS 2 $V_{InnerBus} - V_{OuterBus}$

Figure A.23: Voltage magnitude and angle differential of BESS 2 in grid disconnection scenario



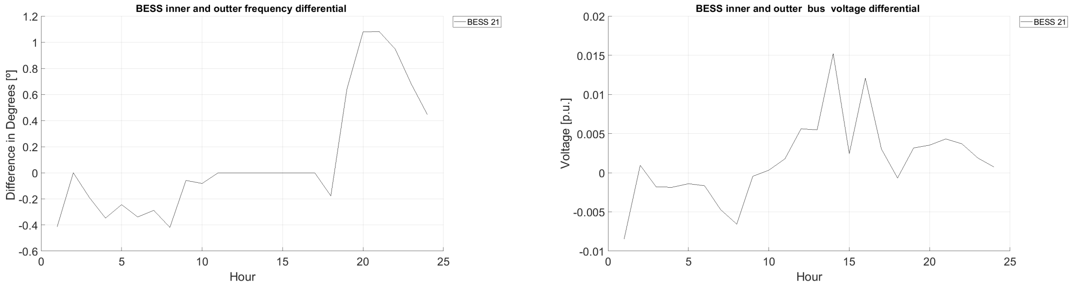
(a) Bess 3$\angle InnerBus - \angle OuterBus$ (b) Bess 3$V_{InnerBus} - V_{OuterBus}$

Figure A.24: Voltage magnitude and angle differential of Bess 3 in grid disconnection scenario



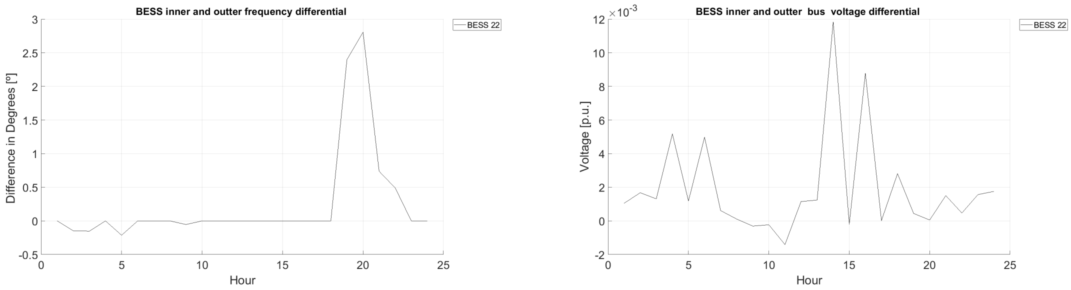
(a) BESS 20 $\angle InnerBus - \angle OuterBus$ (b) BESS 20 $V_{InnerBus} - V_{OuterBus}$

Figure A.25: Voltage magnitude and angle differential of BESS 20 in grid disconnection scenario



(a) BESS 21 $\angle InnerBus - \angle OuterBus$ (b) BESS 21 $V_{InnerBus} - V_{OuterBus}$

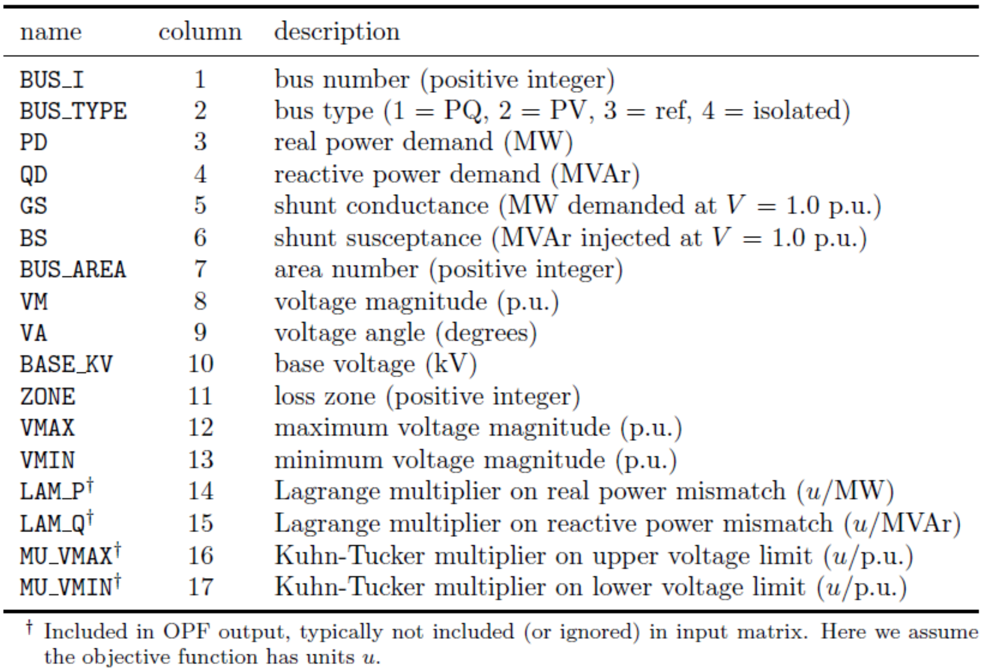
Figure A.26: Voltage magnitude and angle differential of BESS 21 in grid disconnection scenario



(a) Bess 22$\angle InnerBus - \angle OuterBus$ (b) Bess 22$V_{InnerBus} - V_{OuterBus}$

Figure A.27: Voltage magnitude and angle differential of Bess 22 in grid disconnection scenario

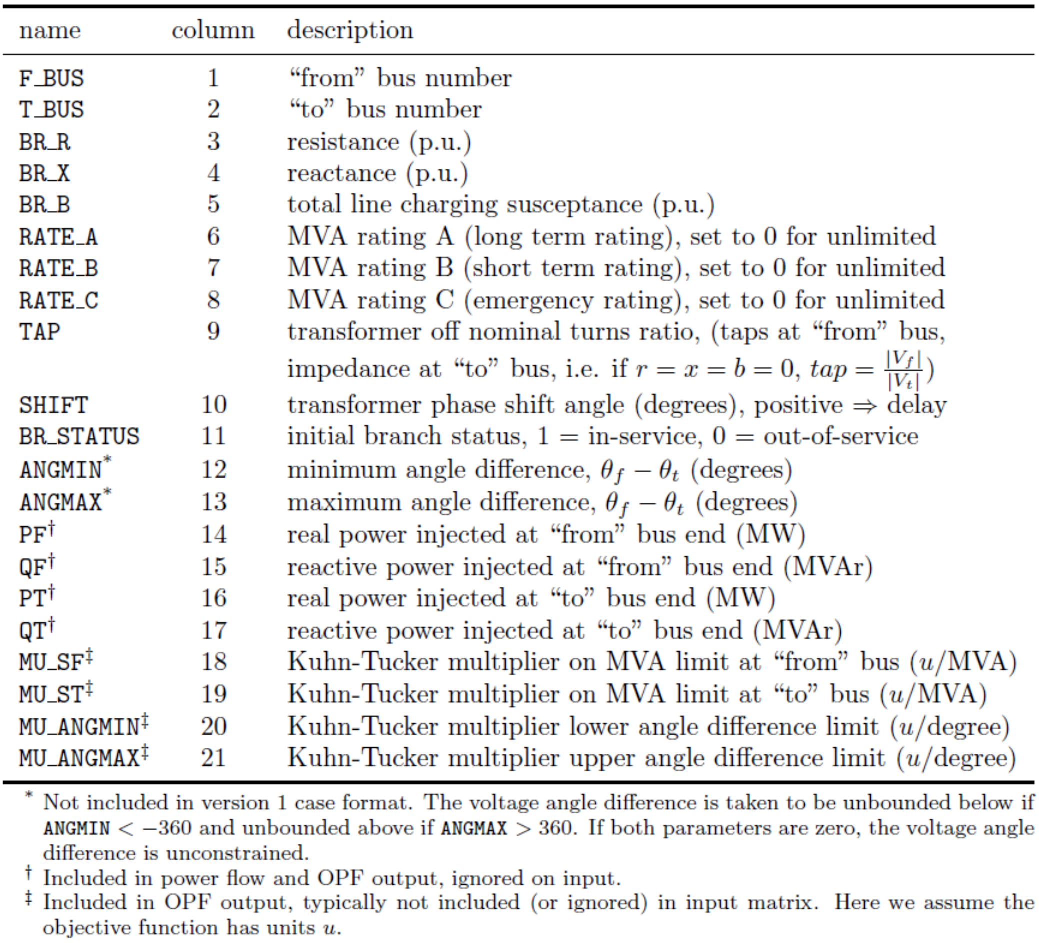
Appendix B



name	column	description
BUS_I	1	bus number (positive integer)
BUS_TYPE	2	bus type (1 = PQ, 2 = PV, 3 = ref, 4 = isolated)
PD	3	real power demand (MW)
QD	4	reactive power demand (MVAr)
GS	5	shunt conductance (MW demanded at V = 1.0 p.u.)
BS	6	shunt susceptance (MVAr injected at V = 1.0 p.u.)
BUS_AREA	7	area number (positive integer)
VM	8	voltage magnitude (p.u.)
VA	9	voltage angle (degrees)
BASE_KV	10	base voltage (kV)
ZONE	11	loss zone (positive integer)
VMAX	12	maximum voltage magnitude (p.u.)
VMIN	13	minimum voltage magnitude (p.u.)
LAM_P[†]	14	Lagrange multiplier on real power mismatch (u/MW)
LAM_Q[†]	15	Lagrange multiplier on reactive power mismatch (u/MVAr)
MU_VMAX[†]	16	Kuhn-Tucker multiplier on upper voltage limit (u/p.u.)
MU_VMIN[†]	17	Kuhn-Tucker multiplier on lower voltage limit (u/p.u.)

[†] Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.

Figure B.1: Matpower Bus data format [4]



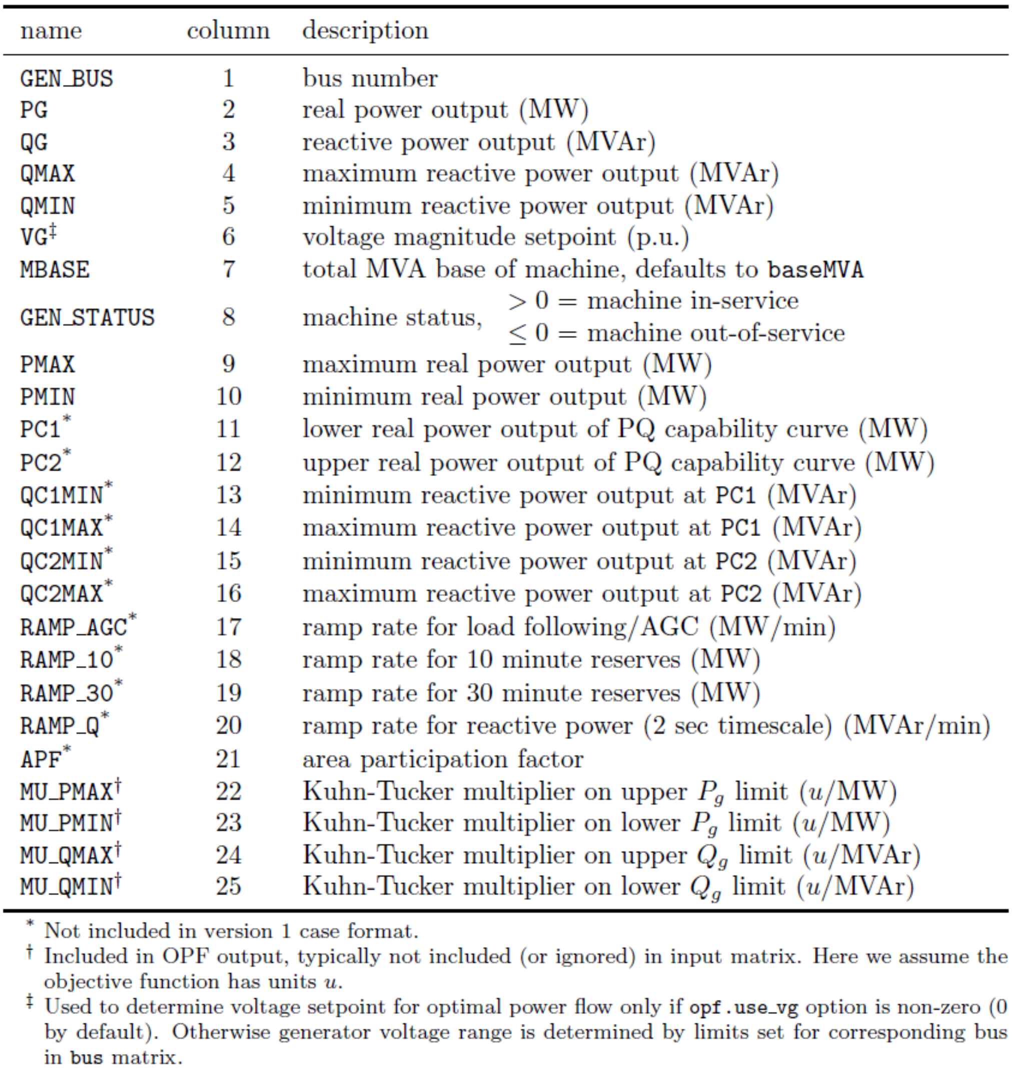
name	column	description
F_BUS	1	“from” bus number
T_BUS	2	“to” bus number
BR_R	3	resistance (p.u.)
BR_X	4	reactance (p.u.)
BR_B	5	total line charging susceptance (p.u.)
RATE_A	6	MVA rating A (long term rating), set to 0 for unlimited
RATE_B	7	MVA rating B (short term rating), set to 0 for unlimited
RATE_C	8	MVA rating C (emergency rating), set to 0 for unlimited
TAP	9	transformer off nominal turns ratio, (taps at “from” bus, impedance at “to” bus, i.e. if $r = x = b = 0$, $tap = \frac{\lvert V_f \rvert}{\lvert V_t \rvert}$)
SHIFT	10	transformer phase shift angle (degrees), positive $\Rightarrow$ delay
BR_STATUS	11	initial branch status, 1 = in-service, 0 = out-of-service
ANGMIN*	12	minimum angle difference, $\theta_f - \theta_t$ (degrees)
ANGMAX*	13	maximum angle difference, $\theta_f - \theta_t$ (degrees)
PF†	14	real power injected at “from” bus end (MW)
QF†	15	reactive power injected at “from” bus end (MVAr)
PT†	16	real power injected at “to” bus end (MW)
QT†	17	reactive power injected at “to” bus end (MVAr)
MU_SF‡	18	Kuhn-Tucker multiplier on MVA limit at “from” bus (u/MVA)
MU_ST‡	19	Kuhn-Tucker multiplier on MVA limit at “to” bus (u/MVA)
MU_ANGMIN‡	20	Kuhn-Tucker multiplier lower angle difference limit (u/degree)
MU_ANGMAX‡	21	Kuhn-Tucker multiplier upper angle difference limit (u/degree)

[*] Not included in version 1 case format. The voltage angle difference is taken to be unbounded below if `ANGMIN` < -360 and unbounded above if `ANGMAX` > 360. If both parameters are zero, the voltage angle difference is unconstrained.

[†] Included in power flow and OPF output, ignored on input.

[‡] Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.

Figure B.2: Matpower Branch data format [4]



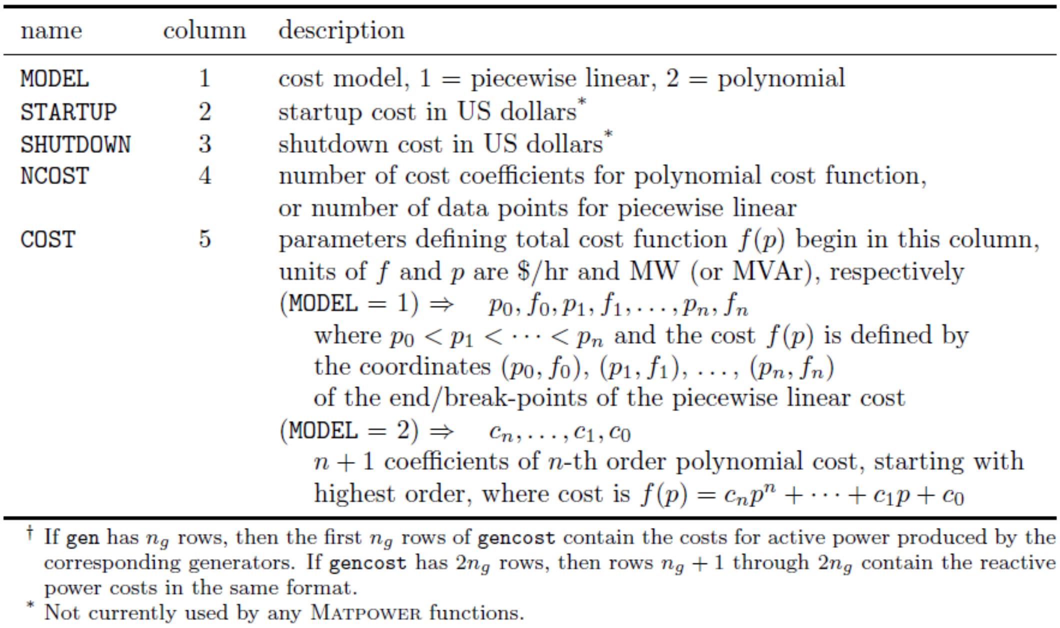
name	column	description
GEN_BUS	1	bus number
PG	2	real power output (MW)
QG	3	reactive power output (MVAr)
QMAX	4	maximum reactive power output (MVAr)
QMIN	5	minimum reactive power output (MVAr)
VG[‡]	6	voltage magnitude setpoint (p.u.)
MBASE	7	total MVA base of machine, defaults to `baseMVA`
GEN_STATUS	8	machine status, > 0 = machine in-service ≤ 0 = machine out-of-service
PMAX	9	maximum real power output (MW)
PMIN	10	minimum real power output (MW)
PC1[*]	11	lower real power output of PQ capability curve (MW)
PC2[*]	12	upper real power output of PQ capability curve (MW)
QC1MIN[*]	13	minimum reactive power output at PC1 (MVAr)
QC1MAX[*]	14	maximum reactive power output at PC1 (MVAr)
QC2MIN[*]	15	minimum reactive power output at PC2 (MVAr)
QC2MAX[*]	16	maximum reactive power output at PC2 (MVAr)
RAMP_AGC[*]	17	ramp rate for load following/AGC (MW/min)
RAMP_10[*]	18	ramp rate for 10 minute reserves (MW)
RAMP_30[*]	19	ramp rate for 30 minute reserves (MW)
RAMP_Q[*]	20	ramp rate for reactive power (2 sec timescale) (MVAr/min)
APF[*]	21	area participation factor
MU_PMAX[†]	22	Kuhn-Tucker multiplier on upper P_g limit (u/MW)
MU_PMIN[†]	23	Kuhn-Tucker multiplier on lower P_g limit (u/MW)
MU_QMAX[†]	24	Kuhn-Tucker multiplier on upper Q_g limit (u/MVAr)
MU_QMIN[†]	25	Kuhn-Tucker multiplier on lower Q_g limit (u/MVAr)

[*] Not included in version 1 case format.

[†] Included in OPF output, typically not included (or ignored) in input matrix. Here we assume the objective function has units u.

[‡] Used to determine voltage setpoint for optimal power flow only if `opf.use_vg` option is non-zero (0 by default). Otherwise generator voltage range is determined by limits set for corresponding bus in `bus` matrix.

Figure B.3: Matpower Gen data format [4]



name	column	description
`MODEL`	1	cost model, 1 = piecewise linear, 2 = polynomial
`STARTUP`	2	startup cost in US dollars*
`SHUTDOWN`	3	shutdown cost in US dollars*
`NCOST`	4	number of cost coefficients for polynomial cost function, or number of data points for piecewise linear
`COST`	5	parameters defining total cost function $f(p)$ begin in this column, units of f and p are \$/hr and MW (or MVAr), respectively (`MODEL` = 1) $\Rightarrow$ $p_0, f_0, p_1, f_1, \ldots, p_n, f_n$ where $p_0 < p_1 < \cdots < p_n$ and the cost $f(p)$ is defined by the coordinates (p_0, f_0), (p_1, f_1), $\ldots$, (p_n, f_n) of the end/break-points of the piecewise linear cost (`MODEL` = 2) $\Rightarrow$ $c_n, \ldots, c_1, c_0$ $n+1$ coefficients of n-th order polynomial cost, starting with highest order, where cost is $f(p) = c_n p^n + \cdots + c_1 p + c_0$

† If **gen** has n_g rows, then the first n_g rows of **gencost** contain the costs for active power produced by the corresponding generators. If **gencost** has $2n_g$ rows, then rows $n_g + 1$ through $2n_g$ contain the reactive power costs in the same format.

* Not currently used by any MATPOWER functions.

Figure B.4: Matpower Gen cost format [4]

Table B.1: Energy storage applications analysis

		Power quality	DG management	Voltage regulation	Frequency regulation	Discharge time	Life cycle	Price kWh	Price kW	Initial Investment
SMES		x			x	Seconds	Very high	Very high	Low	High
EC		x			x	Seconds	Very high	Very high	Low	High
SSB	Li-on		x	x		Minutes	Medium	Medium	Low	Medium/high
	Ni-cd		x	x		Minutes	Medium	Low	Low	Low
	Nas		x	x		Minutes	Medium	Low	Low	Medium/high
	Lead-acid		x	x		Minutes	Low	Low	Medium	Low
Flow batteries	Redox	x	x	x		Hours	NA	Low	Medium	High
Flywheels	Low-speed	x	x	x	x	Minutes	Very high	Very high	Low	High
	High-speed	x	x	x	x	Minutes	Very high	Very high	Low	High
Thermal	Compressed air energy	x	x	x	x	Hours	NA	Low	Low	Very high
	Pumped Heat Electrical Storage	x	x	x	x	Hours	NA	Low	Low	Very high

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