

# Islanding Operation and Black Start Strategies for Multi-Microgrids using the Smart Transformer



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**FEUP** **FACULDADE DE ENGENHARIA**  
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# **Islanding Operation and Black Start Strategies for Multi-Microgrids using the Smart Transformer**

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Mário Jorge Teixeira Couto  
*“Islanding Operation and Black Start Strategies for Multi-Microgrids using the Smart Transformer”*

*To my Parents*

*To Eunice*

*To my brother*

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# Acknowledgements

This PhD was a long journey for me. Several things have changed in my life while I was carrying out my PhD. In the beginning, I was working in a control centre in Portugal. Now I am in Ireland, working in a research institute. Meanwhile, a pandemic hit us, changing our social, study and work routines and, more broadly, our purpose in life. While the world was dramatically changing, I was developing my research work.

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# Abstract

This thesis develops control functionalities for the operation in islanded mode and service restoration strategies in multi-microgrids with smart transformers. In a power systems context with an increasing connection of distributed resources such as medium and small-scale generators, distributed storage, electric vehicles and controllable loads, the replacement of the traditional electromagnetic transformer by smart transformers in secondary substations is regarded as a new opportunity to improve the flexibility and resilience of the electric grid.

Smart transformers are based on power electronics devices, which allows the definition of innovative control strategies to tackle future scenarios with large amounts of distributed resources. In the scope of this research, the smart transformer functionalities are exploited under the multi-microgrid concept in order to enhance the distribution grid resilience by operating in islanded mode. Microgrids and multi-microgrids correspond to cells within the distribution grids endowed with capabilities to operate islanded from the main grid. Those concepts are established respectively at low voltage and medium voltage grids. In a three-stage configuration (AC/DC/AC), the Smart transformer enables connecting a storage device to the DC-link. The smart transformer is placed in a secondary substation within a multi-microgrid environment, replacing the traditional electromagnetic transformer. With coupled storage, the ST can support the operation in islanded mode providing fast power response for both grids.

The successful operation of the multi-microgrid in islanded mode requires the proper definition of voltage and frequency control strategies. Additionally, these control strategies need to coordinate the capabilities provided by the Smart Transformer and distributed resources connected to the distribution grid. The smart transformer equipped with a storage device can also be envisioned to launch restoration procedures within the distribution grid. However, the restoration strategies following blackout also require identifying a set of rules to be followed during the restoration stage.





# Resumo

Esta tese desenvolve funcionalidades de controlo para operação em modo ilha e estratégias de restauração de serviço em multi-microrredes com transformadores inteligentes. Num contexto de sistemas de energia com uma crescente ligação de recursos distribuídos como geradores de média e pequena escala, armazenamento distribuído, veículos elétricos e cargas controláveis, a substituição do tradicional transformador eletromagnético por transformadores inteligentes em postos de transformação é vista como uma oportunidade de melhorar a flexibilidade e resiliência da rede elétrica.

Os transformadores inteligentes são baseados em dispositivos de eletrônica de potência, o que permite a definição de estratégias de controlo inovadoras para enfrentar cenários futuros com grandes quantidades de recursos distribuídos. No âmbito desta investigação, as funcionalidades dos transformadores inteligentes são exploradas sob o conceito de multi-microrredes para aumentar a resiliência da rede de distribuição através da operação no modo ilha. Microrredes e multi-microrredes correspondem a células dentro das redes de distribuição dotadas de capacidade para operar isoladas da rede principal. Esses conceitos são estabelecidos respetivamente nas redes de baixa e média tensão. Numa configuração de três estágios (CA/CC/CA), o transformador inteligente permite ligar um dispositivo de armazenamento no barramento CC. O transformador inteligente é colocado num posto de transformação dentro de um ambiente de multi-microrrede, substituindo o transformador eletromagnético tradicional. Com armazenamento acoplado, o transformador inteligente pode suportar a operação em modo ilha, fornecendo energia para os dois lados.

A operação bem-sucedida da multi-microrrede em modo ilha requer a definição adequada de estratégias de controle de tensão e frequência. Além disso, essas estratégias de controle precisam coordenar os recursos fornecidos pelo transformador inteligente e os recursos distribuídos ligados à rede de distribuição. O transformador

inteligente equipado com um dispositivo de armazenamento também pode ser usado para iniciar procedimentos de reposição de serviço dentro da rede de distribuição. No entanto, as estratégias de reposição de serviço após um apagão também requerem a identificação de um conjunto de regras a serem seguidas durante a fase de reposição.

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# List of Abbreviations

|             |                                        |
|-------------|----------------------------------------|
| <b>AC</b>   | Alternate Current                      |
| <b>APS</b>  | Auxiliary Power Supply                 |
| <b>BESS</b> | Battery Energy Storage Systems         |
| <b>BS</b>   | Black Start                            |
| <b>CHB</b>  | Cascade Half-Bridge                    |
| <b>CLFT</b> | Conventional Low-Frequency Transformer |
| <b>DAB</b>  | Dual-Active Bridge                     |
| <b>DAM</b>  | Dynamic Average models                 |
| <b>DC</b>   | Direct Current                         |
| <b>DER</b>  | Distributed Energy Resources           |
| <b>DES</b>  | Distributed Energy Storage             |
| <b>DG</b>   | Distribution Generation                |
| <b>DGC</b>  | Distributed Generation Controller      |
| <b>DMS</b>  | Distribution Management System         |
| <b>DSO</b>  | Distribution System Operator           |
| <b>ESS</b>  | Energy Storage System                  |
| <b>EV</b>   | Electric Vehicles                      |
| <b>FB</b>   | Full Bridge                            |
| <b>GFe</b>  | Grid-Feeding                           |
| <b>GFo</b>  | Grid-Forming                           |
| <b>GhG</b>  | Greenhouse Gas                         |
| <b>HFT</b>  | High Frequency Transformer             |
| <b>HV</b>   | High Voltage                           |
| <b>ICT</b>  | Information and Communication          |
| <b>LC</b>   | Load Controllers                       |
| <b>LV</b>   | Low Voltage                            |
| <b>MG</b>   | Microgrid                              |

|             |                              |
|-------------|------------------------------|
| <b>MGC</b>  | Microgeneration Controller   |
| <b>MGCC</b> | Microgrid Central Controller |
| <b>MMG</b>  | Multi-Microgrid              |
| <b>MMo</b>  | Multi-Master Operation       |
| <b>MV</b>   | Medium Voltage               |
| <b>NPC</b>  | Neutral Point Clamped        |
| <b>OLTC</b> | On load-tap Changer          |
| <b>PEC</b>  | Power Electronic Converters  |
| <b>SC</b>   | Substation Controller        |
| <b>SRC</b>  | Series Resonant Converter    |
| <b>SS</b>   | Secondary Substations        |
| <b>ST</b>   | Smart Transformer            |
| <b>SMO</b>  | Single Master Operation      |
| <b>STC</b>  | Smart Transformer Controller |
| <b>THD</b>  | Total Harmonic Distortion    |
| <b>TSO</b>  | Transmission System Operator |



# Chapter 1

## Introduction

### 1.1 Background and Motivation

The decarbonization of the energy sector is an important driver to reduce Greenhouse Gas (GhG) emissions drastically. In order to promote sustainable development, policymakers worldwide are establishing ambitious targets to reduce polluting emissions. As an example, the European Green Deal sets out guidelines for achieving carbon neutrality by 2050 [1]. The definition of such energy policies is pushing a global energy transformation. Within the energy industry, the electric sector is the one that has experienced the most significant changes over the last years. Several factors, such as the decline in renewable energy costs, increasing electrification, and smart technologies, are driving the shift in the electric sector. Power generation is changing to be essentially based on renewable sources to fulfil the decarbonization targets. There are also expected impacts on the power demand due to the increasing electric mobility [2]. Those factors are challenging the power systems since they imply operating an electric system with increased variability and uncertainty while keeping high reliability, quality of supply, and resilience levels. The deployment of Information and Communication Technologies (ICT) is essential to increase the observability and controllability of the power systems. In this regard, the massive integration of Distributed Energy Resources (DER) like Distributed Generation (DG), microgeneration, Electric Vehicles (EV), controllable loads and Energy Storage Systems (ESS) will require communication capabilities and new control architectures to ensure a safe and reliable operation.

On the other hand, electric utilities have been increasing their concerns on the power system resilience beyond the challenges derived from integrating distributed resources. Climate changes are increasing the intensity and frequency of extreme

weather-related events such as hurricanes, large fires, floods and snowstorms, which strongly threaten the normal operation of power systems [3],[4],[5]. The occurrence of such events may cause wide power outages and significant damages to the grid infrastructures. Alongside, the deployment of ICT in power systems also exposes them to human-made power outages, namely cyberattacks [6]. Malicious attackers can enter the operating systems to shut down partially or wholly the grid or cause maloperations. Recovery from those disruptive events is time-consuming since the restoration can last from hours to days, which is critical given society's dependency on the power system.

The resilience analysis goes further than the traditional practices in power systems reliability which ensure the N-1 secure. Resilience is a broad concept ranging from the short-term to the long-term. It is generally addressed in three main domains [7]: planning, response and restoration. Resilience-based planning studies identify long-term actions for improving grid resilience. These measures may involve undergrounding power lines, hardening power system infrastructure, installing backup generators, increasing the number of automatic switches and optimal placement of ESS. The resilience response concerns preventive measures and emergency response. Preventive actions are usually triggered when warnings are detected via weather forecasting. Through weather forecasting, electric utilities can anticipate the impacts of forthcoming critical events and adopt operational strategies to mitigate them (e.g., allocating additional human resources, changing the grid reconfiguration, optimal allocation of mobile generators). The recovery phase aims to implement restoration plans. This phase aims to maximize the restored load and minimize the power outage duration following disruptive events.

Within the solutions envisioned to improve resilience, the formation of islands in the distribution grid arises as an alternative given the proliferation of distributed generators (DG). Some distribution feeders can be healthy following a fault or catastrophic event, while neighbor areas or the upstream system are damaged. The healthy areas can be energized to supply loads using local DG units. Microgrids (MG) and Multi-Microgrids (MMG) concepts have been developed for dealing with the islanded operation within the distribution grids [8]. MG corresponds to a small scale power system at the Low Voltage (LV) with the ability to operate autonomously [9]. The MMG corresponds to an extension of the MG concept to the Medium Voltage (MV) grids [10]. Following a fault or a disruptive event in the upstream grid, MG and MMG

can operate in islanded mode, which requires proper control architecture to manage the local resources in order to ensure a stable operation.

Although the integration of DER requires more flexibility to the power systems operation, a key element in the grid still has a low level of controllability: Conventional Low-Frequency Transformer (CLFT). It is a highly reliable and mature technology used in power systems for more than a century. However, they do not provide the desired flexibility to deal with scenarios of a large amount of DER connected to the distribution grids. Technological advancements in the power electronics field bring new opportunities to empower grid flexibility by deploying distribution transformers based on solid-state devices - Smart Transformer (ST) [11], [12]. Beyond similar features to the CLFT, it has control and communication capabilities that allow the development of advanced functionalities such as reactive power support, power flow control and harmonics filtering [11], [12].

Under the current power system framework characterized by massive integration of DER and resilience challenges, this thesis intends to develop new solutions for islanded operation and restoration procedures within distribution grids by exploiting the ST capabilities. New operation strategies in islanded mode can be designed considering that the ST is envisioned to replace some of CLFT in MV/LV substations. The MMG concept can be revisited, considering the integration of ST in distribution grids. Therefore, this research is conducted to identify and develop control functionalities for the islanded operation of MMG comprised of ST and plenty of DER inverter-interfaced.

## 1.2 Objectives of the Thesis

The work conducted in this thesis intends to answer the following research questions:

- **Q1:** *How can the Smart Transformer be included in a Multi-Microgrid framework with a fleet of distributed energy resources?*
- **Q2:** *How to exploit the flexibility of Smart Transformer to improve the robustness of the Multi-Microgrid operation in islanding mode and restoration procedures?*

The first phase of the research intends to understand the features of the ST and its possible configurations. The analysis allows identifying the working principle and

the new functionalities ST brings to enhance the electric grids' power management and power quality. This identification aims to address the research question Q<sub>1</sub> and is performed by analyzing the state of the art publications describing the ST's concept, features, and envisioned functionalities. Based on identifying the ST functionalities highlighted in the background literature, the next step consists of defining the new MMG framework with ST. The framework is envisioned for future scenarios with plenty of DER connected to the MMG via power electronic interfaces.

The second phase intends to define control strategies to operate the MMG in islanded mode by coordinating the ST with the inverter-interfaced distributed resources. The ST model is defined for its inverters control functionalities and is derived from the literature review findings performed in the first phase. As a device based on power electronics components, the ST brings additional conversion stages, requiring proper coordination strategies to ensure frequency and voltage control in islanded mode. Then, the thesis intends to leverage the control strategies for the islanded mode to set out service restoration strategies within the MMG following blackout events or unsuccessful transition to the island mode. In this scope, the thesis seeks to identify a set of rules for launching service restoration strategies in the MMG comprised by ST.

The third phase involves developing a dynamic simulation platform to demonstrate the effectiveness of the defined control strategies for the islanded mode and service restoration strategies. The second and third phases provide answers to the research question Q<sub>2</sub>.

### 1.3 Outline

This thesis is organized into seven chapters.

Chapter 1 provides the motivation and the context for this thesis. The research questions defined in the early stage of the research are also presented. This chapter encompasses the structure of the thesis and the list of publications resulting from the research work.

Chapter 2 provides a literature review on the development and main features of the ST. The purpose is to characterize the envisioned role for the ST in electric grids since it can provide new control functionalities and grid services. Furthermore, this chapter also intends to identify how the ST can be modelled for long term dynamic

studies. Finally, this chapter reports the current challenges and opportunities to deploy the ST in power systems.

Based on the literature review, chapter 3 intends to describe what type of applications are being developed to exploit the ST capabilities in the power systems. In this regard, this chapter seeks to ultimately identify the works addressing the islanded operation and service restoration strategies by exploiting the ST capabilities.

Chapter 4 presents the new MMG operational framework for supporting the islanded operation and its control architecture derived from the research developed in this thesis. The ST replaces the traditional electromagnetic transformers in secondary substations within this framework. The chapter describes the main role played by ST in supporting the islanded mode. Accordingly, the modelling adopted to include the ST in dynamic simulations studies is presented in chapter 4. These models are based mainly on the control functionalities envisioned for the ST inverters. The control strategies for the islanded operation are developed for a MMG with plenty of DER connected to the electric grid via inverters. Therefore, the control strategies are designed to coordinate the capabilities of the ST and DER in the primary and secondary frequency control.

In chapter 5, the strategies developed in this thesis for service restoration within the MG following a blackout or unsuccessful transition to the islanded mode are presented. The control strategies and hierarchical control structure described in the chapter 4 are used to manage the restoration procedure. The restoration strategies are developed by exploiting the local resources connected to the MMG system. A set of rules are defined to develop service restoration procedures following two variants. In the first one, the ST is the key enabler for launching the restoration procedure since it is the single unit with black start (BS) capability. In the second one, it is considered that some MG are capable of launching a BS procedure autonomously. For this last case the chapter also describes the coordination strategy adopted to synchronize both BS procedures running simultaneously..

Chapter 6 intends to demonstrate the feasibility and robustness of the proposed control strategies to operate the MMG in islanded mode and coordinate restoration procedures. The assessment of the control strategies are performed through numerical simulations. The chapter is divided into two parts; the first describes the simulation results for an unintentional transition to the islanded mode, while the second one

depicts the outcomes from the BS procedures.

Chapter 7 summarizes the main contributions of the thesis and identifies some topics for further research.

Next section lists the already published material that resulted from this Thesis. Another paper has also been submitted to another journal.

## 1.4 Publications

- **International Journals**

- Couto, M.; Lopes, J.P.; Moreira, C. *"Control strategies for Multi-Microgrids islanding operation through Smart Transformers"* Electr. Power Syst. Res, 2019.
- R. Zhu, M. Andresen, M.Langwasser, M.Liserre, J. P. Lopes, C. Moreira, J. Rodrigues, M. Couto *"Smart transformer/large flexible transformer,"* in CES Transactions on Electrical Machines and Systems, vol. 4, no. 4, pp. 264-274, Dec. 2020.

- **Conferences**

- M. Couto, J. A. P. Lopes and C. L. Moreira, *"Smart transformer control strategies for multi-microgrid islanding operation,"* Mediterranean Conference on Power Generation, Transmission, Distribution and Energy Conversion (MEDPOWER 2018), 2018, pp. 1-6.
- M. Couto, J. P. Lopes and C. Moreira, *"Developing Black Start Strategies in Multi-Microgrids Exploiting Smart Transformers,"* 2020 International Conference on Smart Energy Systems and Technologies (SEST), 2020, pp. 1-6.

# Chapter 2

## The Smart Transformer

### 2.1 Introduction

This chapter aims to identify the main characteristics of the ST and the advanced services that it can provide to improve power management and power quality in distribution grids. In order to accurately model the ST in dynamic simulations for islanding operation and BS strategies, it is necessary to understand its features and working principles.

The chapter starts by identifying the main drivers highlighting the ST as a key device for distribution grids. It describes the evolution of the solid-state technologies for the distribution transformers that contribute to the development of the Smart Transformer concept. This chapter also provides the main findings from the literature regarding the advantages and disadvantages of the different ST topologies. Although the scope of the thesis is not the constructive aspects of the ST, it is analyzed the three-stage configuration since it is reported in the literature as the most promising one for distribution grid applications. In this regard, the chapter intends to figure out ways to model the inverters that interface MV and LV grids to create the ST model for the dynamic simulations.

Lastly, the chapter presents some considerations about the main challenges and opportunities for deploying the ST in distribution grids

## 2.2 The Emergence of the Smart Transformer

Over the last century, CLFT has been playing an important role in power systems. The first commercial demonstration of electric transformers was done in 1885 by Zipenowsky et al.[13]; and later, Nicola Tesla proposed the application of transformers into the distribution grids [14]. Indeed, the bulk electric AC power system was designed to deliver energy produced centrally in power plants until the end-users under a traditional approach generation-transmission-distribution. In this arrangement, the power flow is unidirectional from generation to consumption. The voltage conversion throughout the electric system, either for step-up or step-down functions, is done by the CLFT operating at 50 Hz or 60 Hz. This ability of the CFLT to step up and step down AC voltages was indeed the important reason that driven the development of the AC power systems. Furthermore, CLFT have been proved highly reliable, robust and efficient devices. Nonetheless, they are passive devices without control capabilities and DC connectivity.

The increased integration of DER into the power systems, particularly in the distribution networks, pushes the grid to its limits and imposes new challenges to operating it. The high penetration of small and medium scale DER units connected directly to the MV and LV grids which were designed to unidirectional power flows, poses a challenge for voltage control. The distribution grids are facing several issues for controlling the voltage as stated in [15] such as the need to select different control architectures (local, decentralized, distributed, and centralized), definition of proper settings for local controllers and the cost-effective coordination of a large number of DER. Besides, in some cases, the generation from DER does not meet the peak consumption hours (e.g. solar generation), and consequently, the generation can be higher than the consumption leading to the reverse power flow. This change in the power flows patterns also requires enhanced control capabilities on the power flows and new protection strategies [16].

In order to accommodate the variability of renewable generation and improve the reliability and resilience of the distribution grid, Battery Energy Storage Systems (BESS) are required to be installed in the electric grids. In the first case, the BESS can be connected to the grid with different goals like arbitrage [17], provision of ancillary services [18] and reduction of renewable energy curtailment [19]. For reliability and resilience purposes, BESS will be important for ensuring the electric supply, injecting



into the grid the energy stored, when the main grid can no longer provide power due to a failure [20]. As the output power of the BESS is in the form of DC, Power Electronic Converters (PEC) are required to convert the DC power to AC.

The deployment of an inverter-dominated grid in which DER units are interfacing electric grids through PEC [21] also brings power quality issues. The PEC interfacing the DER and the electric grid can be accountable to create harmonic distortion once they operate at a high-frequency switching. Additionally, the output of most of the DER generation relies on the wind speed changes and solar radiation conditions which can suddenly vary creating variations in the output power leading to voltage fluctuations in the waveform. On the demand side, the proliferation of apparatuses based on power electronics increases the sensitivity of the consumers' appliances to the power quality. Apart from that, nonlinear loads, power electronic loads, rectifiers and motor drives are very often sources of harmonic pollution. Hence, the electric grid of the future also has increased needs to incorporate devices to act as active filters to reduce harmonic pollution and with the ability to act as dynamic voltage restorer for mitigating voltage sags.

As described previously, the distribution grids are under a rapid and dynamic change that requires new control strategies for improving power management and power quality. The advancements in power electronics technologies have proved how they can be useful to improve the controllability of the electric grids. For that reason, the transformers based on solid-state devices are being designed to cope with the challenges of the future smart grid once they upgrade and expand the capabilities of the conventional transformers [22], [23], [24], [25]:

- voltage regulation
- reactive power compensation
- power factor correction
- control of power flow
- voltage sag compensation
- harmonic compensation
- isolating disturbances from source and load or vice versa

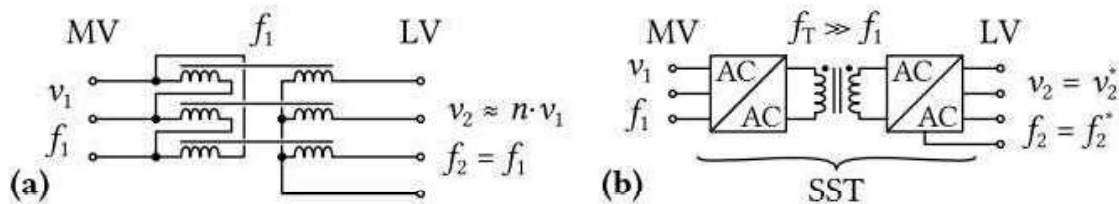
- variable frequency output
- interfacing DC and AC port(s)
- interconnecting asynchronous networks
- eliminating the use of mechanical actuators or tap changers

The rationale to develop the ST is to combine the features of the traditional distribution transformers with the provision of functionalities described above in a single piece of equipment. Therefore, the ST is envisioned to operate as a universal energy buffer for DER, loads, grids (AC, DC, MV, LV), communication interface and controller device [12], [25].

## 2.3 Smart Transformer: Concept and Developments

In the literature, several terms have been adopted to naming a transformer based on solid-state devices: Solid-State Transformer [26], Power Electronic Transformer [27], [28], Electronic Transformer [29], Intelligent Transformer [30], Intelligent Universal Transformer [31], [32], [33], Intelligent Semiconductor Transformer [34], Energy Router [25], and Smart Transformer [11]. Regardless of the term adopted, the basic concept lies in a power electronic interface between the MV and LV grids providing galvanic isolation via a high-frequency transformer (HFT) [35], as depicted in Figure 2.1.

Generically, the input and output behaviors of the ST and CLFT are similar. The ST modifies the 50 Hz AC voltage to an high frequency voltage (in range of the kHz), step-down or step-up the high-frequency voltage through the HFT; lastly, it changes the HF waveform back to the 50 Hz voltage.



**Figure 2.1:** Schematics for a traditional distribution transformer in a delta-wye-connection (a) and a solid-state transformer (b) [35]

Although the concept of the ST has gained the attention of the power system sector over the last decade, the concept is not fully new. Actually, in 1971, William McMurray

proposed the first concept of SST [36] which was based on a high-frequency link for AC/AC power converter. The designation of SST arose as an alternative to the auto-transformer and was proposed by J.L. Brooks in 1980 [26]. The authors presented the concept of a step-up/down transformer with the ability to regulate AC output voltage through switching elements. In 1999, Sudhoff presented a patent concerned with the application of an SST as a distribution transformer [37]. Heinemann and Mauth also proposed in 2001 a power electronic transformer based on a high-frequency switching to be applied in MV/LV substations [38]. Also, an example of a design of a 10 kVA electronic transformer for distribution systems and the respective experiment results were also presented in [29].

Several prototypes of ST has been reported in the literature over the last years (Table 2.1). Some of them have been mainly developed for traction applications where the size and weight are more relevant than the ST's capabilities. In UK, the electric utility SP Energy Networks developed an innovation project called "LV-Engine" with the purpose of designing the first set of functional specifications and control strategies for the ST [39]. In the table 2.2, it is possible to find the interest from the research activities through the number of literature reviews on the ST topic in recent years.

**Table 2.1:** Some ST prototypes presented in the literature

| Company                | Topology | Power Rating | MV Voltage | MV Switch           | Switching Frequency |
|------------------------|----------|--------------|------------|---------------------|---------------------|
| <b>Bombardier</b> [40] | Type D   | 400 kW       | 15 kV      | IGBT (4.5 kV)       | 8 kHz               |
| <b>Alstom</b> [41]     | Type D   | 1.5 MW       | 15 kV      | IGBT (6.5 kV)       | 5 kHz               |
| <b>ABB</b> [42]        | Type D   | 1.2 MW       | 15.7 kV    | IGBT (6.5 kV)       | 1.75 kHz            |
| <b>GE</b> [43]         | Type D   | 1 MW         | 7.2 kV     | SiC MOSFET (10 kV)  | 20 kHz              |
| <b>UNIFLEX</b> [44]    | Type D   | 300 kW       | 3.3 kV     | IGBT (6.5 kV)       | 3 kHz               |
| <b>EPRI</b> [33]       | Type D   | 25 kW        | 6.6 kV     | SiC MOSFET (1.2 kV) | 9.3 kHz             |

The slow switching and lower power rating of semiconductors were two substantial drawbacks for developing the ST aiming its application into power systems [52]. However, developments in the power electronics field become possible to tackle HV and high current power conversion at lower losses level. The latest generations of semiconductors based on wide-bandgap materials like silicon carbide (SiC) or gallium nitride (GaN) enables the operation at higher blocking voltages [23], [51], [53]. In addition to the developments in semiconductors technologies, magnetic materials with

**Table 2.2:** Literature review papers about the Smart Transformer

| Title                                                                                                                                   | Year | Reference |
|-----------------------------------------------------------------------------------------------------------------------------------------|------|-----------|
| Medium-Voltage Solid-State Transformer: Technology for a Smarter and Resilient Grid                                                     | 2016 | [23]      |
| Solid-State Transformers: On the Origins and Evolution of Key Concepts                                                                  | 2016 | [24]      |
| The Smart Transformer: Impact on the Electric Grid and Technology Challenges                                                            | 2016 | [11]      |
| The Smart Transformer: A solid-state transformer tailored to provide ancillary services to the distribution grid                        | 2017 | [12]      |
| Solid state transformer technologies and applications: A bibliographical survey                                                         | 2018 | [45]      |
| Solid-State Transformers for Distribution Systems–Part II: Deployment Challenges                                                        | 2019 | [46]      |
| Solid-State Transformers for Distribution Systems–Part I: Technology and Construction                                                   | 2019 | [47]      |
| Applicability of solid-state transformers in today's and future distribution grids                                                      | 2019 | [35]      |
| Surveying Solid-State Transformer Structures and Controls: Providing Highly Efficient and Controllable Power Flow in Distribution Grids | 2020 | [48]      |
| Solid Solid-State Transformers: Concepts, Classification, and Control                                                                   | 2020 | [49]      |
| State of the Art of Solid-State Transformers: Advanced Topologies, Implementation Issues, Recent Progress and Improvements              | 2020 | [50]      |
| A review on solid-state transformer: A breakthrough technology for future smart distribution grids                                      | 2021 | [51]      |

higher saturation flux density and lower core losses have also been essential to making the ST feasible technically and economically [52]. The high-frequency operation of the magnetic field requires a smaller size of the winding contributing to reducing the size and weight of the ST [24], [52]. However, at the high-frequency operation of the magnetic field, there is an increase in hysteresis and eddy current losses [52], [54]. For that reason, the design of the ST corresponds to a trade-off process between size (frequency) and efficiency, which requires a proper choice of the core materials.

ST is designed to have higher controllability than the CLFT since it is a device based on power conversion stages. In this way, ST presents a wide range of controllability on the terminal currents and voltages, and consequently, on the active and reactive power flows [11], [35], [48]. Furthermore, the ST is highlighted as an energy router towards

digitalisation and decentralisation of the electric grid [25].

The "Smart Transformer" concept was widely developed in the scope of the research project funded by the European Union - HEART ("The Highly Efficient And Reliable smart Transformer, a new Heart for the Electric Distribution System") [55]. The term "Smart Transformer" is derived from the advanced functionalities that the device can play, combined with a wide range of controllability offered by the power electronic devices and the communication capabilities [12],[12]. Under this concept, ST manages the distribution grid on both the energy flow and the real-time communication among controller elements, as depicted in Figure 2.2 .

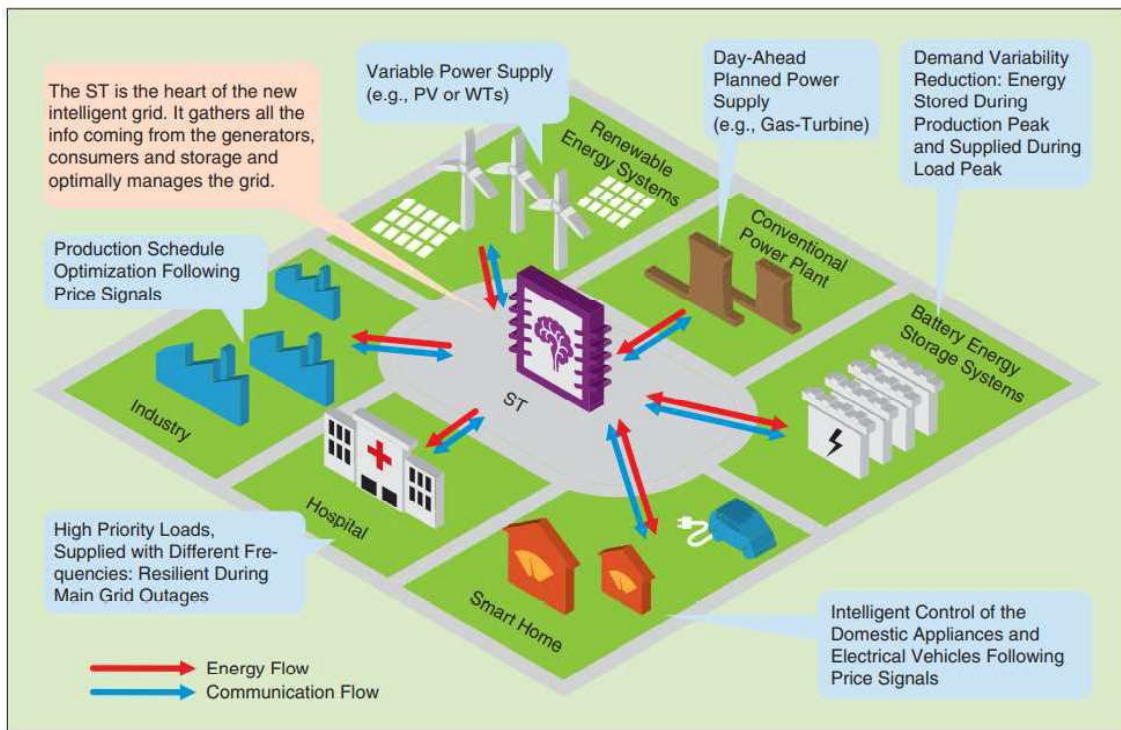


Figure 2.2: Envisioned role for the ST in power systems [11]

By replacing the CLFT, ST is an enabler of the smart grids, being a device able to play different tasks [23], [24], [47], [49]:

- Measurement of grid variables;
- Running optimisation tasks for power management and power quality;
- Communication in real-time with devices in upper and lower control layers;
- Acting as master controller guiding collective-control actions;

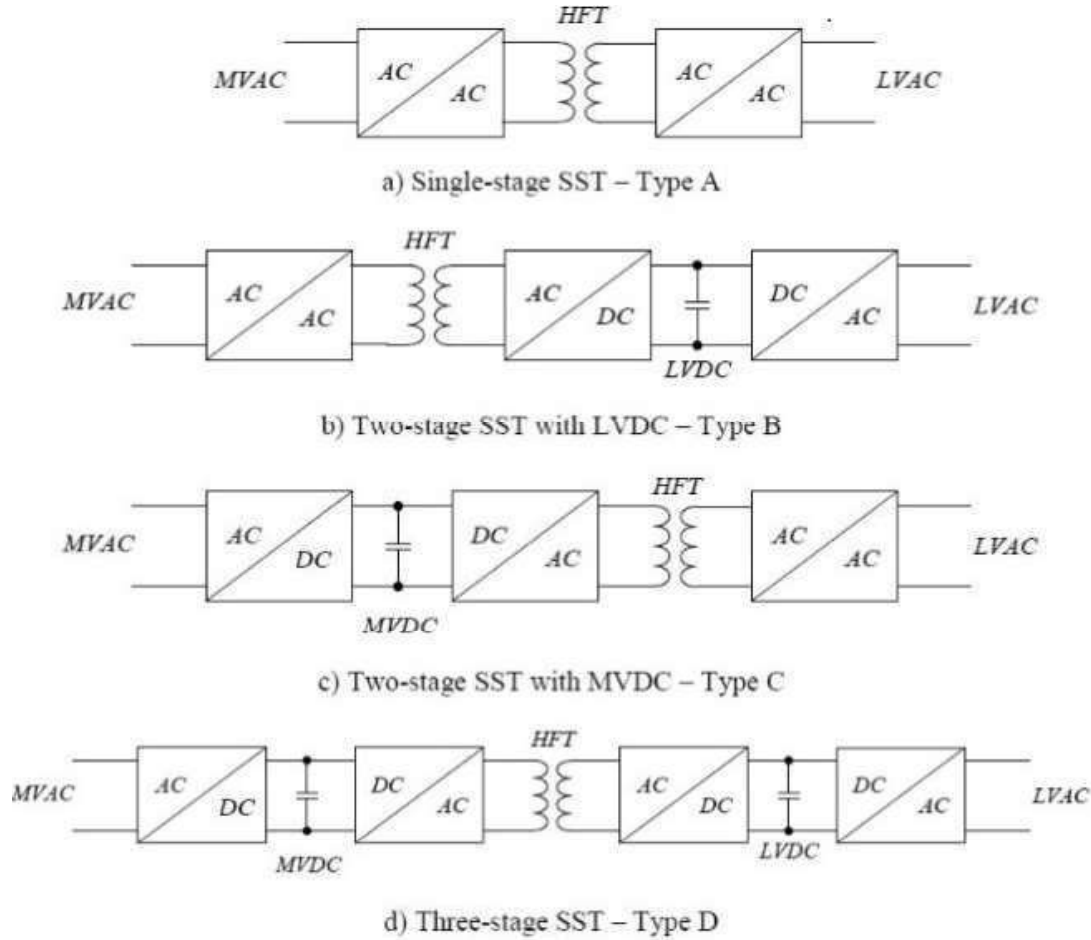
In the literature, four core features are highlighted towards the application of ST in the distribution grids:

1. **Connection to the MV level:** ST is designed to interface with the MV grids either in AC or DC forms which requires ability of the power electronics devices to handle with high power levels.
2. **Galvanic Isolation via HFT:** Potential separation between both sides. Besides, the HFT operating at high-frequency increases significantly the power density regarding the CLFT.
3. **Controllability:** The solid-state devices operating a high-frequency making possible to develop proper control strategies to shape the current and voltage.
4. **DC connectivity:** This is an important advantage for connecting DC microgrids, DC loads and BESS. The availability of the DC connectivity depends on the topology adopted to the ST, as explained in the next section.

## 2.4 Smart Transformer Topologies

Aiming the application into the distribution systems, the ST can be designed to interconnect AC and DC systems operating at MV and LV. A wide range of combinations is possible to link MV AC, MV DC, LV AC, and LV DC [47], [56]. Besides, there is also the possibility of single or multi-phase systems in the case of AC systems. In the literature, the design of the ST is usually classified based on the number of power conversion stages [22], [45]-[52]: single-stage, two-stage and three-stage. Some works ([22], [49], [51]) have been proposed a slightly different classification to consider the existence of DC links. Accordingly, as depicted in Figure 2.3, the single-stage without DC-link corresponds to type A, two stages with LV-DC link refers to the type B, two stages with MV DC-link concerns to type C, and type D represents the three stages with DC links at both MV and LV. A broader classification is proposed in [49], which encompasses other criteria like voltage levels, control of isolation stages, modularity and number of ports per power stage. As the scope of the thesis is mainly focused on the capabilities of the ST, the analysis of advantages and limitations of each topology based on the number of power conversion stages is sufficient to understand which is the most proper one for distribution grids applications.





**Figure 2.3:** Classification of the ST topologies based on the number of power conversion stages [57]

The simplest configuration is the single-stage (type A), which corresponds to only a direct conversion stage with a HFT link to step-down the voltage (from the MV side to the LV side). By its simplicity, this configuration has a low cost and reduced weight in comparison to other topologies [22], [50], [52]. This configuration has no DC links available, which is a significant drawback for distribution grids and renewable sources integration applications. Due to the absence of DC links, a power transient at the input is transmitted to the output side [58]. The topology A demands large filters due to the lack of regulation of the input and output sides [59]. Additionally, the type A structure is characterized by high losses, large current ripple, and incompatibility with reactive power compensating devices [51].

The two-stages topology may assume two different configurations depending on whether the DC link is in the MV side or LV side (type A and type B). The two-stage configuration is reported in the literature as not proper to be used in applications

requiring high voltage operation due to the need for a complex switching structure, a large number of switching devices, and difficulty ensuring zero voltage switching [52], [50].

Finally, type D provides the maximum possible functionalities and controllability and, hence, the best topology to develop ST for distribution grid applications. DC connectivity at both MV and LV is highlighted as a significant advantage since it allows the connection of BESS, DG units, DC loads, and EV charging stations without AC conversion stages [11], [12], [52], [51], [59]. In contrast, this configuration requires a complex control with the development of dedicated control loops for each one of the stages, influencing the costs, dimension and weight of the ST [50]. The larger number of switching devices can conduct to higher switching losses reducing the efficiency and creating increased challenges for the thermal management of the entire equipment [59].

## 2.5 Three-Stage Smart Transformer

### 2.5.1 Operation and Control Functionalities

Figure 2.4 represents the traditional structure of a ST under a three-stage configuration: High Voltage Stage, Isolation Stage and Low Voltage Stage. Considering an operating condition in which the power flows from the MV grid to the LV grid, the input AC voltage is converted into an MV DC voltage through the three-phase AC/DC converter. Thus, the MV AC/DC converter operates in the rectifier mode.

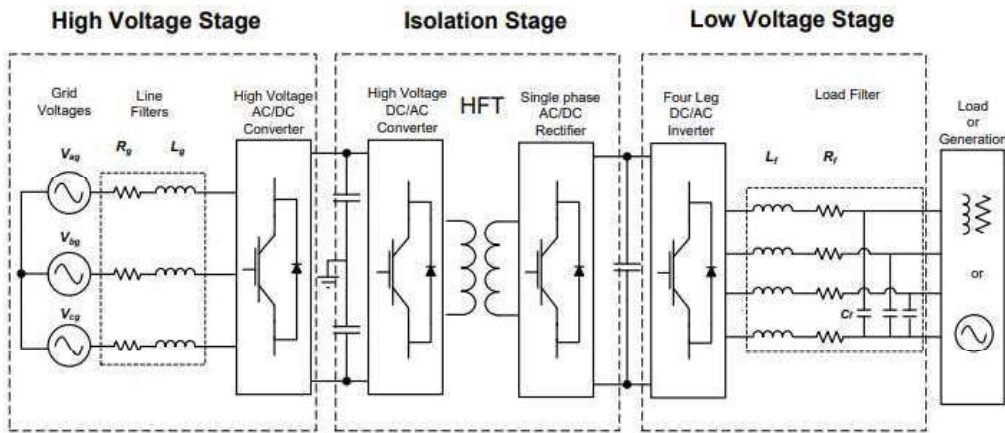


Figure 2.4: ST under a three-stage configuration [57]

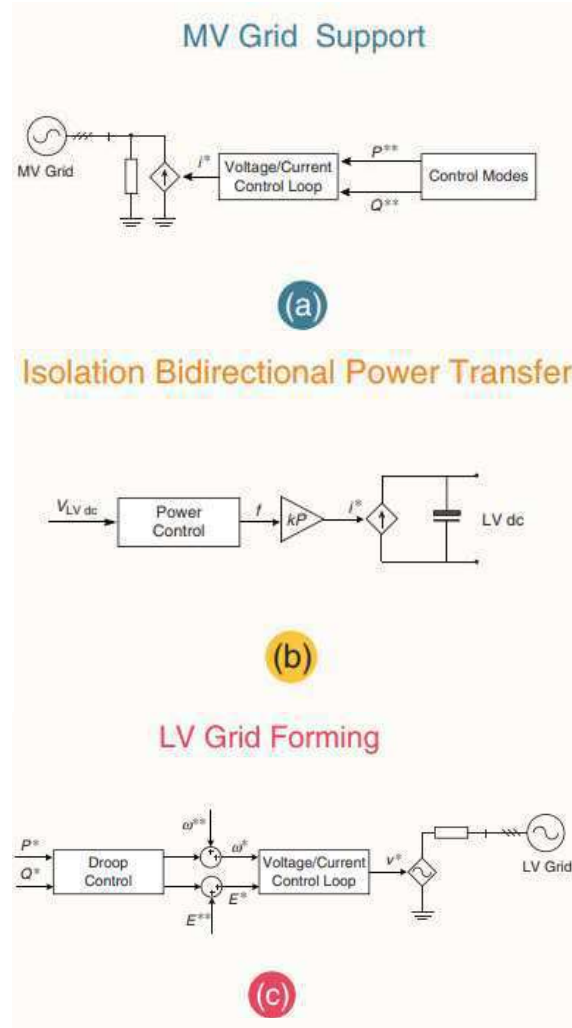
Then, the power flow will go through the isolation state which comprises the HFT



and two converters on both sides MV and LV. The first one converts MV-side DC voltage into a high-frequency square-wave voltage which is applied to the primary of the HFT. On the secondary side of the HFT, the second convert transforms the square-wave signal into an LV DC. Lastly, the LV-side DC-AC converter provides an AC voltage waveform from the LV-side DC-link. Under an operating condition in which the generation on the LV grid is higher than the consumption (power flow reversal), the working principle of the ST will be similar, swapping the functions of the input and outage stages.

The MV convert plays two main roles in terms of control [11], [48], [57], [60]: control the MV DC link voltage and control the reactive power in the AC grid. In the first case, the active current is controlled to ensure that the MV DC link voltage is kept at the nominal value. The balance in the DC/DC link should be conceived considering the directionality of the power flow. Concerning the reactive power, the ST can operate with unit power for the MV side, not demanding reactive power from the MV grid to supply the LV loads [11], [48]. Alternatively, it can participate in the voltage support by changing the reactive power output through a Q/V droop curve or remotely via a set-point requested from a centralised controller located in the HV/MV substation. Given that the reactive power for MV represents a degree of freedom, the reactive power can be controlled separately from the active power and each phase [11], [48], [60].

Considering the bidirectional operating conditions of the MV inverter, Allende et al. propose the representation of the MV converter as a current source with high parallel impedance [48], as stated in Figure 2.5. This represents the operation of the MV inverter in the grid-feeding (GFe) mode. However, the MV inverter can also operate in Grid-Forming (GFo) mode, controlling the MV grid voltage to support the islanded operation [11], [12], [61]. Ko et al. address the operation of the MV and LV in GFo mode, assuming that a BESS is placed in the DC-link [61]. Aiming at the universal operation of the ST (i.e., GFo in MV and LV or GFo in the MV), the authors propose a controller for the isolation stage without the need of changing the control variables in that stage.



**Figure 2.5:** Simplified representation of ST control-stage converters: a) MV grid support; b) Isolation Bidirectional power; c) LV grid-forming converter (adapted from [48])

)

These aspects are relevant for the scope of this thesis since the inverters that interfaces storage or generation units and the electric grids are usually classified into two main groups: [62],[63],[64]:

- **Grid-feeding inverter (GFe):** correspond to a current-controlled voltage source that aims to deliver a controlled amount of power (active and reactive). They do not have the capability to impose voltage and frequency.
- **Grid-forming inverter (GFo):** corresponds to voltage sources that defined the phase angle and magnitude of its output voltage. This type of inverter is associated with storage devices that provide energy buffering capabilities. These units

will be crucial to define frequency and voltage references when MG and MMG are operating in the islanded mode.

The DC/DC stage performs the control of the voltage in the LV-DC link capacitor and the galvanic isolation between the MV and LV grids [57], [60]. A simple representation of the DC/DC stage operation is a current source and an output capacitor to control the bidirectional power flow between the MV and LV sides [48] (Figure 2.5 b)).

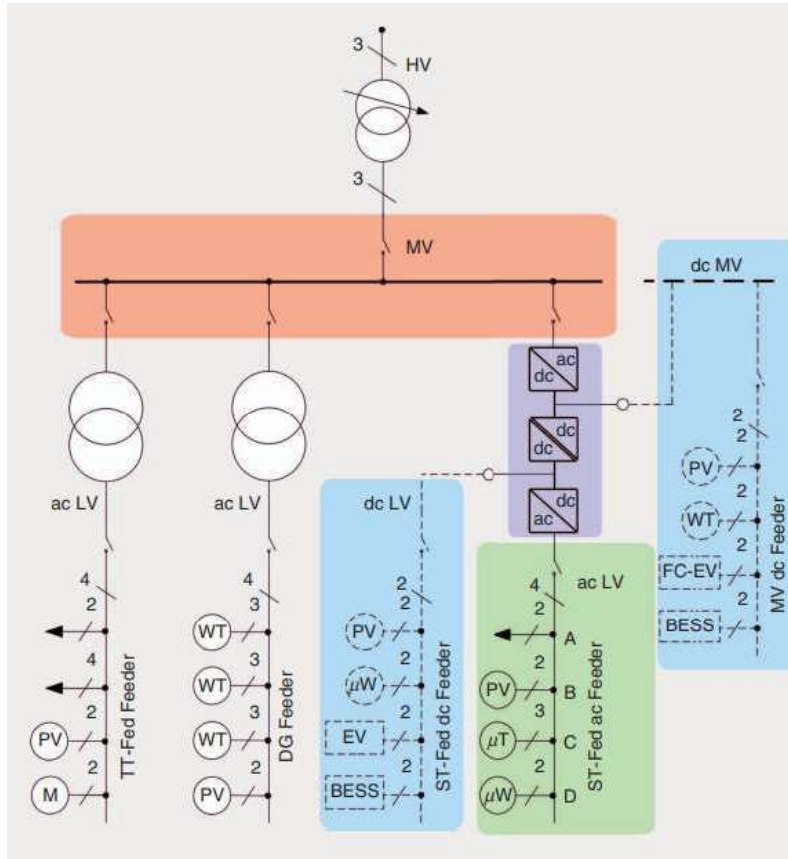
Regarding the LV, it is projected for providing a three-phase sinusoidal voltage waveform independently from the load conditions [11], [48], [57], [60]. Hence, its operation principle can be represented by an ideal AC voltage equipped with droop controllers in series with an impedance [48] (Figure 2.5 c)).

### 2.5.2 Provision of Grid Services

ST is then envisioned to provide ancillary service for MV and LV sides under a three-stage configuration with two DC links in the distribution grids context (Figure 2.6). From the MV grid perspective, the ST can control the current absorption as a function of the active power consumption in the LV grid and losses. In turn, the reactive power corresponds to an additional degree of freedom since it can be controlled independently from the LV side and separately from each phase [23], [11], [12]. The decoupling of the reactive power allows the development of control strategies to avoid voltage violations and congestion in the MV grid. The existence of the DC links enables that the reactive power on the MV side is not affected by the reactive power requests on the LV side. Therefore, the ST can operate with a unit power factor for the MV side [11], [12], [23], [48]. Although there is a fully decoupled for the reactive power, the separation of the MV and LV AC grids is constrained by the active power link [12]. Hence, the two grids can be controlled separately, but taking into account the active power link between the two sides.

Moreover, the decoupling is an additional advantage of the three-stage configuration once it allows the direct connection of several sources without the need for extra AC/DC conversion stages [12], [50], [51]. The MV DC link can operate as a connection point hosting DC loads, fast-charging EV stations, BESS and DG units like medium-scale wind and solar power plants [12], [51], [52]. The LV DC-link also offers the possibility of hosting BESS and DC loads avoiding intermediate AC/DC conversion stages in the user's facilities. Additionally, DC connectivity is an enabler for deploying

local and regional DC grids and DC microgrids [52], [51]. Another feature derived from the existence of two DC-links is the capability to act as an active filter decoupling the harmonics between the MV and LV AC grids [23], [12]. This corresponds to an important benefit for reducing the stress in the distribution grid assets and enhancing the power quality.



**Figure 2.6:** Envisioned role of the ST in the distribution grid[12]; Legend: TT: traditional transformer; PV: photovoltaic; M: machine; DG: distributed generation; EV - Electric Vehicles; FC-EV - Fast Charging Electric Vehicles

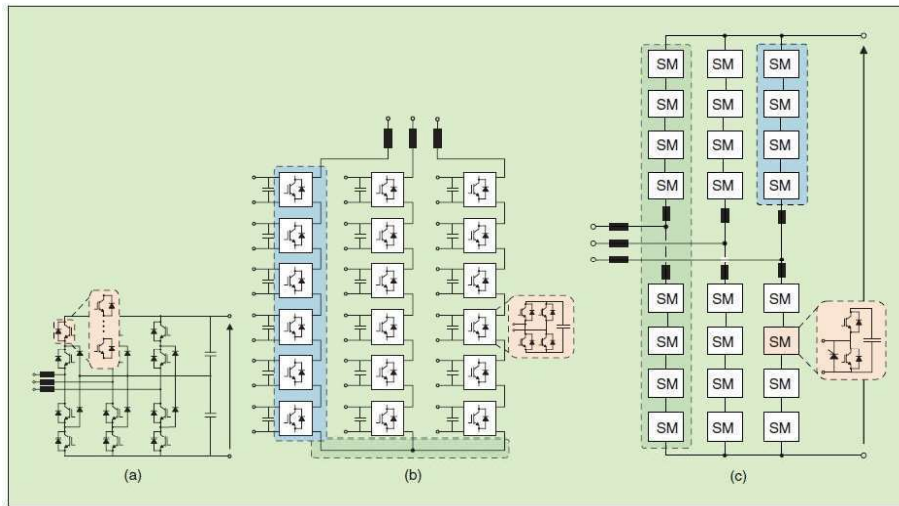
On the LV side, ST is designed to provide sinusoidal voltage waveforms with nominal values in amplitude and frequency regardless of the current requests on the LV grid, [12], [48], [50], [51]. This presupposes the operation as a three-phase balanced source independently from the current waveforms imposed by the LV loads, which can be non-linear and unbalanced. One of the promising features of the ST is the capability of the LV inverter for modifying the voltage amplitude and frequency [11], [12], [48]. Such ability allows exploiting the contributions from grid-connected DER equipped with frequency-power droop controllers and the dependence on the voltage magnitude of the load power. Through controlling the voltage magnitude and

frequency, ST induces load consumption and generation changes to provide services like load reduction, reverse power flow limitation and overload control of the ST [11], [12]. ST can also provide LV ride through (LVRT) capability [23] for voltage sag mitigation, operating as a dynamic voltage restorer with proper design to fulfil the length of the ride through according to the grid codes.

## 2.5.3 Constructive Aspects

### 2.5.3.1 Medium Voltage Stage

The literature points the multilevel converters as the most appropriate solutions for the MV converters of the ST [11], [52], [49], [50]: Neutral Point Clamped (NPC) converters, Multilevel Modular Converters (MMC) and Cascaded Half-Bridge (CHB) converters.



**Figure 2.7:** MV converter topologies: (a) Neutral Point Clamped, (b) Modular Multi-level Converter, (c) Cascaded Half-Bridge [11]

A multilevel topology like the NPC converter (Figure 2.7 a)) is a natural choice for the MV converter. It requires the use of series-connected devices or wideband gap transistors to fulfil the blocking voltage requirements [11]. NPC converter presents as advantages the simple control, the DC link's availability, and the fact of being a mature technology already used [11], [50]. This main drawback is the lower energetic inefficiency since the reduced number of levels requires larger filters with a higher switching frequency [11], [50].

CHB converters (Figure 2.7 b)) are usually applied in MV drivers and they are more modular than the NPC converter. In addition to modularity, the operation at low

frequencies of the basic cells and the reduced complexity of the control are the main advantages of this solution [50]. However, the absence of the DC link represents a significant disadvantage for the CHB converters [11]. As the ST is envisioned to be an enabler of hybrid AC/DC connections in the distribution grids, the CHB converters' application in cases in which the MVDC link is mandatory can hinder its use.

Another technology to be adopted as solution in the MV converter is the MMC (Figure 2.7 c)), which has as advantages the modularity, operation at low frequency and DC availability [11], [50]. On the contrary, it requires complex control and requires bulky capacitors that can increase the overall cost [50]. Besides, increasing the number of cells allows that the output voltage has reduced harmonic distortion, improved efficiency and the possibility to build fault-tolerant arrangements [52].

### 2.5.3.2 Isolation Stage

The next part of the three-stage ST is the DC/DC converter. This part requires specific features [11]: high current capability on the low voltage side, high-frequency isolation, HV capability on the MV side and high rated power. The design of the DC/DC converter can adopt two ways. The first one relies on applying HV-rated devices, whereas the second solution uses the modularity concept in which the modules share the voltage and the power. Although the second solution has a higher number of devices than the first one, it presents several advantages [11]: low electromagnetic interference emission ( $dv/dt$ ), the potential in using standard and low voltage rating devices. The modularity itself also represents a significant advantage, enabling higher fault tolerance in this stage due to LV-rated power devices' employment.

Several types of converters have been studied to be applied in this stage [49], [50] such as series resonant converter (SRC), dual-half bridge (DHB), dual-active bridge (DAB), asynchronous-quadruple-active bridge (AQAB), and synchronous quadruple-active bridge (SQAB). Nevertheless, DAB and SRC are the ones that have gained more attention to developing the ST due to their advantages in soft-switching, high efficiency and power density [11], [49], [50].

DAB operates with active control of the transferred power, which is a significant advantage when the ST's applicability requires the control of the output voltage or power flow control [11]. On the other hand, SRC reaches efficient operating points through the zero-current switching operation [49]. Besides, SRC provides a well-regulated output voltage for a wide range of loads with minimal sensors, but



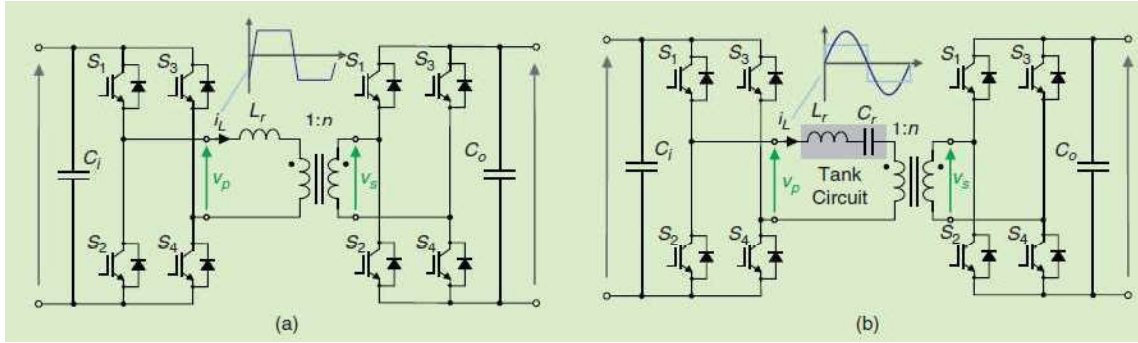


Figure 2.8: DC/DC converters: a) Dual Active Bridge; b) Series-Resonant Converter [11]

they present a lower power flow control capability [11], [50]. Compared to the DAB, SRC has its operation strongly affected by the accuracy of the resonance frequency [50]. The power transfer between the two sides is performed exploiting the resonance frequency of the LC circuit [49]. Therefore, the SRC performance can be deteriorating with the loads' changes or aged active components.

The HFT is a core component of the ST since the operation at high frequency allows the reduction of the total volume and weight regarding the CFLT. The design of the HFT encompasses the analysis of several parameters [22], [49], [51]: core material and its geometry, winding material and configuration, insulation, and thermal management.

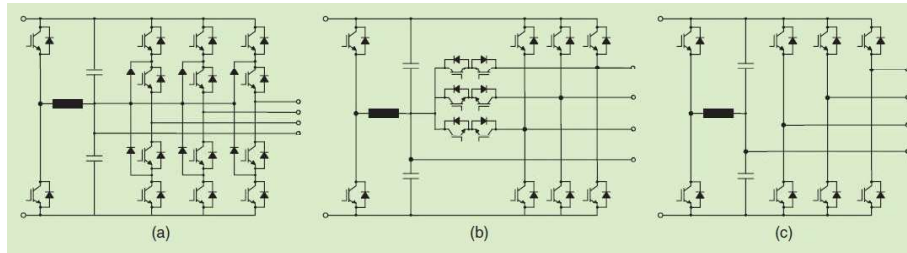
The operation at high frequency reduces the core and windings sizes, but this is counterbalanced with the increase in losses due to hysteresis and eddy current. Therefore, the selection of the core material is relevant for designing the HFT. This selection should consider the following factors [49]: low core losses, high saturation flux density, high continuous operating temperatures capability, and high relative permeability. References [49] and [51] provide detailed analysis on the design and selection of materials for the HFT (e.g., core material, winding material and arrangement and isolation requirements).

In general, ST design requires a multi-objective process for computing the optimum frequency that allows size reduction and high efficiency [65], [66]. That process can be conducted considering the characteristics of different core materials in the analysis.

### 2.5.3.3 Low Voltage Stage

The LV converter interfaces the device with the LV distribution grid. This stage has to support the highest current among all the conversion stages of the ST and operates under unbalanced load conditions. Due to the single-phase nature of the loads and the

need of local grounding for safety reasons, the LV side of the ST must provide access to a neutral point. The middle-point of the LV DC-link can be used as the neutral point for the LV grid [11]. However, this solution can lead to an unequal energy distribution among DC-link capacitors requiring additional DC/DC converter to control the voltage oscillations [11].



**Figure 2.9:** LV converter topologies: (a) Neutral Point Clamped (NPC) converter, (b) T-type converter, (c) four-leg converter [11]

According to the literature, there are three feasible solutions to be applied in this converter [11], [49], [50]: NPC converter, T-type converter, and four-leg converter (Figure 2.9). Nevertheless, the four-leg converter is highlighted as the more efficient solution in applications demanding accurate control for neutral current [57]. This converter should be able to regulate the voltage waveform on the LV side independently from the load conditions thereby the four-leg is a preferred solution. The extra leg will represent an additional degree of freedom in order to provide an increased capability than the traditional three-leg converters.

#### 2.5.4 Other constructive features

Semiconductor switches are a key element in the ST. Consequently, its selection becomes essential in designing ST. Nevertheless, their application in the ST should respect some conflicting criteria [11], [50], [49]: low losses, high blocking voltage, and high current capability features. Traditionally, high-voltage insulated-gate bipolar transistors (IGBT) have been adopted for application in the higher power range [11], [50], [49]. However, they have reduced blocking voltage which requires a higher number of components and more control [11], [49], [51]. Another possible solution in the market is the Metal Oxide Semiconductor Field-effect Transistor (MOSFETs), but the unipolar characteristic makes it more difficult for applications in HV compared to IGBT [12], [12], [51]. However, MOSFETs are usually a solution for DC/DC due to their low losses with high switching frequencies [12], [51]. Recent semiconductor technologies like Silicon Carbide (SiC) IGBT and SiC MOSFET are also considered



for high-voltage applications with wide-bandgap capability with acceptable on-state losses [12], [50] [51].

The ST need to have cooling systems for the PEC. As described in [12], the design of the cooling systems may follow the traditional approaches for semiconductors considering power dissipation, ambient temperature, junction temperature, and thermal resistance in the power path between the junction and the ambient. This paper provides several considerations about the design of the cooling systems of the ST for the different power stages. An optimal design for a liquid/air cooling for an ST can be found in [67].

As ST is envisioned as a device to play the role of communication interface, its design should be adapted for different information flows. First, the ST needs to communicate with the local electric appliances and DER located downstream; then, it can communicate with the appliances in the upper control layer or with other ST in case of the grid has multiple ST. According to [11] and [68], these information flows require higher data transmission rates and broader coverage areas. The communication requirements are described in [68] for several grid services that the ST can play.

Lastly, the ST will need to have brakes and protection circuits to protect the different components. An important issue lies in the need for MV DC breakers due to the existence of an MVDC link. However, as stated in [11], the DC breakers can be unnecessary by modifying essential MV converter cells. Considering ST modular solutions, circuits for fault detection and isolation are normally implemented to protect healthy cells or modules from transients during the occurrence and clearance of faults [69].

## 2.6 Computational Modelling

ST is envisioned as a device to be integrated into distribution grids to improve the operation and power quality considering the increasing penetration of DER. Hence, it is needed to have computer-based simulations to analyze its impact in the distribution grids. ST modelling is challenging since the devices comprises several components like switches, power conversion stages, and HFT. Besides, ST can assume different topologies depending on the applicability, which can affect the computational model.

According to [45], the ST models are divided into three types: steady state models,

switching (detailed) models and average models. That reference provides a summary of the ST modelling, and the correspondent simulation tool and topology adopted.

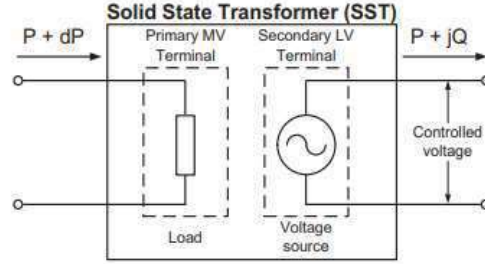


Figure 2.10: Smart transformer model for power flow studies [70]

The steady-state models are the ones less developed in the literature. An ST model for power flow studies was developed in OpenDSS [70]. The goal was to analyze the impact on the distribution systems performance by replacing LFT by the ST in MV/LV substations. The model corresponds to two terminals representation (Figure 2.10) in which, on the secondary side, the loads (active and the reactive power) are supplied with a constant voltage value; on the primary side, the ST is represented as load demanded only active power. Given the bidirectionality of the active power flow, the load may have negative values whenever the ST is injecting active power to MV side. A model for including the ST in optimal power flow studies was developed in [71] to assess the impact on the generation costs reductions where ST are placed in HV/MV systems. In this case, the authors develop a detailed representation of the conversion stages.

As stated in [45], most of the available models are switching models that require long simulation times because they use significantly shorter time-step sizes (range of microseconds). In the literature, it is possible to find plenty of works presenting detailed models for the ST. Some of them are dedicated to developing the switch modelling for the bidirectional three-stage ST such as [72]-[73]. Those models present limitations to be applied to large systems once they lead to extensive simulation times. To overcome this issue, some authors exploit the Dynamic Average Models (DAM). Those models rely on approximating the converters' behavior by applying the moving average operator at the switching frequency to the detailed switching model [74]:

$$\bar{x} = \frac{1}{T} \int_{t-T_s}^t x(t) dt \quad (2.1)$$

in which  $x(t)$  corresponds to any variable (voltage or current) and  $T_s$  is the switching time interval. In this approach, the switching effects are removed without compromising the dynamic behavior of the converters [74], [75]. In this sense, DAM is feasible to simulate the power conversion stage's transient behavior for larger time-step sizes.

A comparison between DAM and detailed switching model is presented in [76] for a 20 kVA ST that interfaces a LV grid with a 12 kV distribution system voltage. The DAM was able to reproduce the dynamic behavior of the detailed switching model. The adjustment of average models is addressed in order to simulate the dynamic behavior of the switching counterparts since the purpose is to analyze the integration of the ST in distribution grids. The developed average model was implemented in PSCAD integrated into a three-phase system with a substation and different load ratios. A fine-tuning process on the existing average models is presented in [77] for replicating the dynamic behavior of the switching counterparts in developing system and protection studies. Reference [78] performs theoretical analyses for developing the average model for the isolation stage considering a DAB. The performance of the average model was validated through the comparison with to the time-domain simulations. In [79] is developed a simplified average model for each stage of the ST: rectifier, DC-DC converter and LV inverter. The idea is to design and tune controllers for each stage. Several tests were carried out under linear, non-linear, balanced and unbalanced load conditions to prove that the developed control strategies using the average models fulfil the design purposes.

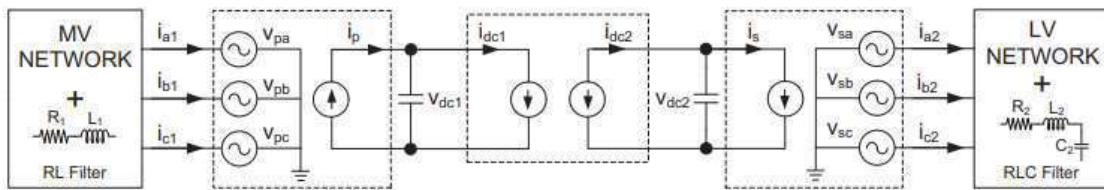


Figure 2.11: Average model for a bidirectional three-stage configuration [75]

In [75] is developed a DAM for a three-stage bidirectional ST to be implemented in real-time simulation platforms speeding-up the simulation time. For that purpose, the authors developed a DAM for each stage (input stage, isolation stage and output stage) as shown in Figure 2.11. The developed model has been used in a test system which comprises an overhead MV feeder. The authors use the SimPowerSystems to test the

DAM approach under different operating conditions: voltage sag at the ST primary, load variation in the secondary-side, load unbalance caused by a two-phase load, nonlinear and unbalanced secondary currents, power flow reversal and secondary overcurrent caused by a three-phase short-circuit. Moreover, the authors compare the obtained results using this DAM with a detailed model presented in [80]. From this comparison, one may conclude that the DAM has a good performance regarding the detailed model to approximate the transients of voltages, currents, and powers.

A state-space average model is proposed in [81] to analyse the dynamic behavior of a distribution system with high penetration of renewables sources. The ST average model is developed to capt the nonlinear, nonsmooth, dynamic phenomena triggered by the switching comands. In turn, a dynamic phasor model for analyzing the stability of a modular and cascade ST is proposed in [82]. The main conclusion resulting from the phasor model's application is the reduction of the simulation time, becoming feasible its application in the real-time operation.

From the literature, one realizes that DAM proves to be a proper solution for modelling accurately the dynamic behavior of the ST in simulation studies avoiding long simulations time.

## 2.7 Challenges and Opportunities

### 2.7.1 Reliability and Efficiency

Although ST offers a wide range of advanced functionalities for future distribution grids with a large amount of DER, it has a shorter lifetime and lower efficiency than the CLFT [52], [46], [35]. Towards the broad implementation in the distribution grids, ST should be competitive in terms of efficiency and reliability regarding the CLFT. Reliability is a challenging task for the ST since the CLFT lifetime is in the range of decades requiring reduced maintenance over that time. The current state of the power semiconductor technology does not allow ST to achieve a high level of reliability like the CLFT (higher failure rate and lower lifetime). Modularity can be applied in the ST design to improve the ST's reliability and efficiency by internally routing the power between multiple cells [49], [69].

Efficiency is pointed out as one of the main challenges for deploying the ST

into the distribution grids. The CLFT usually has efficiencies above 98%. It is not yet possible for the ST to find a common reference value for the device's efficiency in the literature. However, a three-phase 10-kV/400-V 500-kVA prototype [83] for real implementation in a distribution grid achieved an efficiency of around 93.7%. This efficiency was measured in operating conditions below the rated power. The efficiency of an ST interconnecting 13.8 kV and 480 V distribution grids was computed in [84] through experiments aiming to measure device losses. The authors report an efficiency of around 96.75% at the rated power (100 kVA) in that work.

The ST contains a considerable number of components such as HFT, semiconductors, heatsinks, control circuits, cooling systems and auxiliary equipment [52], [46], [35]. As described and analysed in [69], the power converters of the ST present several types of losses: switching losses, conduction losses, filter losses and additional constant losses. Considering that the ST is generically comprised of HFT and power conversion stage, the overall efficiency of the device is strongly affected due to the association of several components. Additionally, several factors can influence the efficiency of the ST, like the load factor, power factor, topology and characteristics of the semiconductors switches [52], [51].

While the efficiency of the CLFT does not suffer significant variations with the load conditions, the ST has higher efficiency for a limited range of operating conditions around the rated load. The efficiency can meaningful decrease when the ST operates in light load conditions [52], [35]. That fact is mainly driven by the load-independent loss contributions like switching losses and magnetic losses of the HFT. Modularity is a usual solution for improving the efficiency of the ST by activation and deactivation of modules [69], [51].

The overall efficiency is also affected by the design and the operation frequency of the HFT. This requires an optimisation process to maximise the power density and efficiency [85], considering the material characteristics (temperature, flux density, dielectric strength). It is also expected that evolution in the semiconductors field will improve the efficiency of the FT. In the literature is also reported that the new semiconductors based on SiC enable the operation at higher temperatures with lower switching losses.

### 2.7.2 Cost

The cost is one of the most critical points for replacing the traditional CLFT by ST. Although there are not many ST products in the market to compare with the CLFT costs, in [86] is referred that a 1000 kVA ST has a cost 5 times higher than the CLFT. In [46], the authors provided an estimated cost for the ST with power ratings up to 50 kVA. Despite that 50 kVA is a short rated power for a distribution transformer, it is estimated the ST price is 3.5 higher than the CLFT for that power.

Those estimations essentially considered the material costs. The overall cost of an ST will vary with the topology, PEC, auxiliary circuits (e.g. control devices, driver circuits and instrumentation circuits), filter circuits, cooling systems, and communication devices and protection devices [50]. Nevertheless, the final price is affected by other factors such as labour and manufacturing costs, infrastructures costs, shipping and delivery costs, warehousing costs, commissioning costs, tariffs and taxes.

Furthermore, as described in the last section the ST has a lower efficiency than the LTF, which will correspond to higher operational costs due to the higher losses. Additional operational costs can also be derived from replacing the power electronic devices that typically have lifetimes around 10 years, while the CLFT has lifetime around 30 years.

On the other hand, the full range of controllability is an aspect to be considered on the total cost of ownership estimation. The impact of the advanced functionalities and services provided by the ST is a way to obtain operational cost savings in the electric grids. However, there are few works addressing the quantification of the benefits brings by the ST. Power flow studies were conducted in suburban LV grids in Switzerland [87] to analyze the benefits of replacing the CLFT by the ST. The authors show through a set of steady-state simulations that the ST presents better performance than other technologies to solve voltage violations and provide reactive power compensation during high load periods. The authors conclude that is not yet attractive the investment technology due to the high current costs of the ST, even considering the benefits in terms of losses and reactive power compensation. They recommended performing more detailed studies to analyze the economic potential of the ST considering the wide range of functionality that it can play. Still, in [70], the authors conclude that the low efficiency of the ST contributes to increasing the total losses in the MV and LV distribution grids (losses in CLFT, ST, and in distribution

lines) in periods of light load levels. However, when the grid is operating under high load levels, the capability of the ST to compensate for the reactive power in the MV grid brings benefits for reducing the total distribution grid losses.

The ST needs advanced studies' economic feasibility to estimate the initial investments and payback time. The economic studies should consider not only the constructive costs but also the ST's impact on the electric grids in different perspectives (cost-benefit analysis): voltage control, reactive power compensation, power quality improvement, communication router and data collection capabilities.

### 2.7.3 Volume and Weight

While for applications in the traction field, the weight and size of the ST are crucial, for distribution grid applications, these aspects are less relevant. These aspects can be considered in urban zones where the lack of space, difficulty to move the device (e.g. for underground secondary substations) and environmental framework are important in designing distribution networks.

Naturally, the overall weight of the ST relies on the weight of different stages and respective components that comprise. A utilization factor between 1.25 and 5 is often recommended to make adjustments in the total volume estimation to account for unused spaces [46]. In [86], the comparison between an ST prototype and CLFT for a rated power 1000 kVA revealed that the weight is similar, but ST size is reduced around 20% compared to the CLFT. The outcomes from this comparison are depicted in table 2.3.

**Table 2.3:** Comparison of the performance characteristics between a CLFT and a ST for a rated power of 1000 kVA [86]

| Variable        | CLFT | Factor | ST   |
|-----------------|------|--------|------|
| Losses (W/kVA)  | 13   | × 2.87 | 37.3 |
| Costs (USD/kVA) | 11.4 | × 4.61 | 52.7 |
| Volume (l/kVA)  | 3.4  | × 0.78 | 2.7  |
| Weight (kg/kVA) | 2.6  | × 1    | 2.6  |

### 2.7.4 Protection and Grounding

As an interface between the MV and LV grids, ST is subjected to a set of faults: [88]: internal faults, lightning surges, switching transients, MV and LV short-circuits. The CLFT is a very robust technology for supporting overvoltage and overcurrents. Several



international standards from IEC and IEEE define clearly the required ratings to be supported by the CLFT during fault events. In contrast, there are few works on the protection of ST. The protection of the ST is tremendous challenging once the device is based on PEC. For example, it is supposed that the CLFT stands a fault current up to 25 times their rated current for at least two seconds. Such is not feasible with the current technology of the ST due to the thermal constants of the semiconductor switches.

Based on power electronic converters, ST is subjected to failure modes that are different from those experienced by the CLFT [46], [49], [88]: converter failures (switching elements, driver circuits, instrumentation circuits, controllers and snubber circuits), insulation breakdowns, thermo-mechanical failures and internal arcing current faults in DC stages. Semiconductors are the main restriction to the current and voltage overload capabilities. Typically, the thermal time constants are in the order of 10 to 50 milliseconds for power semiconductor chips [35] and the range of several seconds for the packages of power semiconductor switches [88]. The overrated operation of the semiconductors is limited once the maximum allowable overcurrent ratio is in the range of 1.5 (overcurrents for minutes) to 5 (overcurrents for milliseconds) [46], [88].

The overvoltage capabilities are also critical for the MV side due to the semiconductors' sensitivity to those conditions, even though breakdown voltages resulting from dielectric breakdown or flashover in the air have a short duration (lightning pulses) [46], [88]. For this reason, the semiconductors should be selected in order not to exceed the maximum blocking voltage capability [88].

Protection schemes for ST which have been adapted from those applied in CLFT are presented in [46] and [88]. Nonetheless, there is a need to have additional protection devices due to the ST's reduced capabilities to support overcurrents and overvoltages (compared to CLFT). Both protection architectures have metal-oxide surge arresters on MV and LV sides to respond and to clamp overvoltages. The Figure 2.12 also highlights an essential point for BS application where the MV AC/DC stage acts a rectifier during the startup process. A pre-charging resistor is placed with a bypass switch to limit the inrush currents [88].

From the MV perspective, large MV filter inductances can be required to limit the short-circuit current and also the inrush pulses [35], [88]. Indeed, a simple approach of disconnecting the MV AC/DC stages can not be the proper solution. This approach causes a mismatch in the power flow between the MV and LV, contributing to DC-link voltage drifts. Therefore, it is expected that the filter should



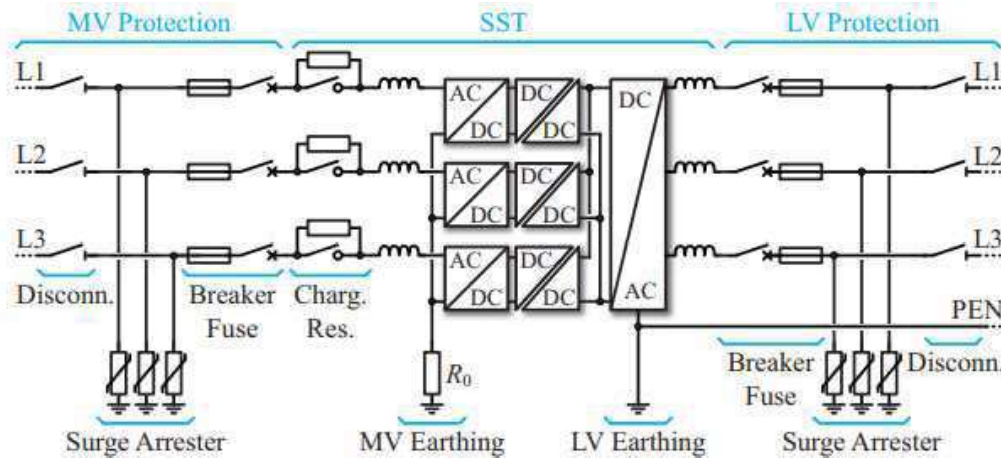


Figure 2.12: Proposed Protection Scheme for ST [88]

support the fault current until a circuit-breaker clears the fault [88]. Furthermore, the MV and LV filters' saturation can reduce the high currents due to short-circuits [46].

At the LV side, the ST is capable of clearing the fault current rapidly. However, the selectivity is not guaranteed once the downstream breakers or fuses will not trip [46]. Usually, the LV fuses require current several times higher than the rated value during some seconds to trip. Consequently, all loads will suffer a blackout, instead of being affected only the loads located in the fault zone. To overcome this issue, ST can inject short circuit current in the LV grid until any fuse located downstream trips to clear the fault [89] [88]. Nonetheless, the current to be injected to induce the trip protection devices in the LV grid should be analyzed since LV fuses can require high current ratings. As referred previously, the ST can support up to 1.5x of the rated current for several seconds, which can not be sufficient to cause the tripping of a fuse protecting a large load.

In [90], the authors propose a protection scheme under a smart grid environment to take advantage of communication systems between terminal breakers and considering the current direction to detect the faulted zone. These two characteristics of the protection scheme allow faster identification of the fault zone and prevent ST from injecting a large short circuit current. This scheme takes advantage of the system configuration and ST capabilities for minimising the need for additional communications in the protection strategy. The ST is disconnected from the MV grid whenever a fault in that system conducts the voltage below 0.8 p.u. Then, ST goes into the operation in the islanding mode by managing the BESS and other DER connected

downstream. However, the algorithm also considers the current direction characteristic in order to determine what ST will be disconnected or remain connected.

Another vital aspect for the protection schemes is concerned to the grounding of the ST. In the three-phase CLFT, the grounding aims to reduce ground currents, ground fault currents and limit ground potentials. For those transformers either the primary side as the secondary sides can provide access to establish a point-of-grounding. Given the different power conversion stages in the ST (AC/DC stage, DC link stage, DC/AC stage), the presence of active elements (inductors and capacitors) and input/output filterings circuits, the definition of grounding point is a challenging task. As described in [46], the points-of-grounding may differ according to the topology adopted to the ST. Accordingly, this publication provides analyzes on the grounding for the following three-stages topologies: unidirectional with passive DC-Link, unidirectional with active DC link, bidirectional with passive DC-link and, bidirectional with active DC-link.

A protection scheme is developed in [91] to deal with the overload and short circuits in the semiconductors regarding the internal faults. This protection scheme is developed for a three-phase ST with a modular design. Firstly, the scheme detects the internal fault, and then a post-management fault mechanism is implemented to ensure the continuous operation of the device.

### 2.7.5 SWOT analysis

In the face of the benefits and challenges described in this chapter, a brief SWOT (strengths, weaknesses, opportunities, and threats) analysis for the ST is presented in this section.

As a strength, the ST brings the potential of providing grid services, enhancing the level of controllability in distribution networks. The need to achieve the international goals of decarbonization is leading to increased integration of DER in the distribution grids. On the demand side, electric mobility will introduce new consumption behaviors associated with EV charging. Consequently, electric utilities will need devices providing controllability and flexibility to manage the grid with a large amount of distributed resources and under uncertainty in the consumptions. Therefore, ST is envisioned as a device to act as an energy buffer and communication interface. Moreover, DC connectivity is a tremendous advantage for deploying DC grids and

connections for storage systems.

The development in semiconductors technology is enabling cost-effective solutions for application in high voltages. Additionally, as reported in this chapter, the ST has been a research topic for both research communities: power electronics and power systems. It is thus expectable to achieve remarkable advances in the ST, from prototyping to real implementation.

On the other hand, the current price is still high to lead the utilities to invest in ST widely. As stated in the section, the investment on ST can not only consider the capital costs. The wide range of controllability of the ST can contribute to reducing operational costs. Nevertheless, there is a lack of studies to determine and quantify the benefits brought by the ST. Other barriers for the acquisitions of ST by the electric utilities are the reduced reliability and efficiency compared to the CLFT. The semiconductors have higher failure rates and reduced lifetime than CLFT, representing additional operational costs regarding the CLFT. In addition, the CLFT is a well-established technology with high efficiency. At the same time, the CLFT has lower efficiency since it is a device based on power electronic components and with a lower level of maturity.

The advancements in the research field, the development of cost-effective semiconductors for high voltages and the need for utilities for procurement for new devices to improve power controllability and power quality can be crucial factors to unlock the deployment of the ST.

**Table 2.4:** SWOT analysis for the ST (adapted from[52])

| Strengths                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           | Weaknesses                                                                                                                                                                                                                                                                                                                                                                                        |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>• Enable degrees of freedom for developing new control strategies in distribution grids</li> <li>• Provide ancillary services to the distribution grids: power factor correction, voltage support, reactive power support, harmonic filtering</li> <li>• AC/DC integration</li> <li>• DC connectivity for storage devices</li> <li>• Ease integration in the smart grids (smart nodes)</li> <li>• Eliminates oil</li> </ul>                                                  | <ul style="list-style-type: none"> <li>• Higher cost than the traditional electromagnetic transformer</li> <li>• Lower reliability than the traditional electromagnetic transformer</li> <li>• Lack of studies to evaluate the benefits provided by the ST in the distribution grids</li> <li>• Semiconductors supply shortage</li> <li>• Electromagnetic interference</li> </ul>                 |
| Opportunities                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       | Threats                                                                                                                                                                                                                                                                                                                                                                                           |
| <ul style="list-style-type: none"> <li>• Advances in high voltage semiconductors</li> <li>• Reduction in price due to mass production</li> <li>• Higher penetration of renewable due to mature technology and competitive price</li> <li>• Government goals and international climate agreements to reduce polluting emissions</li> <li>• Rise of electric vehicle</li> <li>• Higher number of distributed energy resources in electric grids require higher levels of observability and controllability</li> </ul> | <ul style="list-style-type: none"> <li>• Cost remains too high compared to benefits</li> <li>• Stall in the development of higher power semiconductors</li> <li>• Global economic situation after the pandemic situation</li> <li>• Reduced interest in the electric utilities to invest in a high cost device</li> <li>• Reduced lifetime compared to the electromagnetic transformer</li> </ul> |

## 2.8 Conclusions

This chapter starts by explaining the reasons that have been highlighting the ST to be a promising solution for distribution grids. As a result of the energy transition, the distribution grids attain significant attention due to the increasing integration of large amounts of DER. Most of those units can vary their power output in the short-term since they are based on renewable sources. Also, new loads like the EV will change consumption behaviors. Consequently, these changes will demand an enhanced level of observability and controllability in the distributions grids. All these factors bring challenges to the distribution grid such as voltage control, frequency stability, reverse power flow and protections coordination.

Therefore, ST may play an essential role in future power systems by enhancing traditional CLFT features. As described in the previous sections, there is plenty of research working in developing of ST aiming its role within the future distribution grids: decoupled operation, proper control to operate during voltage disturbances, reactive power injection, voltage control for both sides, harmonics filtering, and compensation for disturbances caused by nonlinear and unbalanced loads. ST can also be envisioned as a communication interface managing the information flows between the distribution system's lower and upper control layers.

Within the topologies addressed in the literature, the three-stage configuration is pointed out as the most proper for applications in distribution grids. This configuration enables a wide range of exploitable solutions in terms of controllability. It provides DC connectivity in the MV and LV, which can foster the development of hybrid AC/DC microgrids, the connection of EV charging stations, solar PV plants and BESS. The connection of the storage system is considered essential to develop islanding operation and BS strategies for MV and LV. In this regard, the ST will act as a key enabler of the islanded operation, managing the local DER located downstream and coordinating with the upper control layer.

Since this thesis aims to develop dynamic simulations for islanding operation and BS strategies, a relevant statement from the literature is the possibility of the MV and LV inverters to act as grid-forming and grid-feeding units. Operating as a grid-forming unit will be decisive in defining the voltage references in terms of magnitude and frequency in islanding operation once the main grid is unavailable.

The literature also states that the DAM are adequate solutions for accurately modelling the dynamic behavior of the ST instead of switching (detailed) models. This finding is extremely relevant because the DAM allow speeding up the simulation time without compromising the accurate reproduction of the average dynamic behavior of the electric variables. In the scope of dynamic simulations for islanding operation and BS strategies, the goal is to analyze the grid behavior for dozens and hundreds of seconds, which is not compatible with detailed switching models. Accordingly, one can conclude that the dynamic average models are feasible to reproduce the dynamic behavior of the ST.

Finally, this chapter presents several considerations on the opportunities and challenges for deployment of the ST in the distribution grids. Several challenges like the efficiency, size, reliability and cost need to be improved, aiming to be on the track of commercialization. As a device based on power electronics components, the grid protection schemes also need to be adapted due to the specificities of the ST. Currently, the lower efficiency and reliability of the ST compared to the CLFT does not contribute to rising of the interest of the electric utilities for investing in this high-cost device.

New developments in those aspects will be critical to electric utilities in investing in this technology. For such, the development in the semiconductors field can decisively decrease the overall cost and improve the ST efficiency, making it a cost-effective solution for electric utilities.

## Chapter 3

# Applications of Smart Transformers in Power systems

### 3.1 Introduction

The application of the ST in power systems is analyzed in this chapter. While the previous chapter addressed the main features, control functionalities, modelling and challenges of the ST, this chapter provides a literature review on its applications in the power systems. The purpose is to identify how the capabilities of the ST described in the previous chapter are being applied to improve the grid operation and power quality. Given the scope of this thesis, this chapter also addresses the type of works where ST have been used on the islanding operation and restoration procedures.

### 3.2 Power Flow Control and Capacity Enhancement

One of the ST's potentialities is the possibility to manage the power flow between MV and LV. The ST capabilities are demonstrated in [92] for a radial distribution system adopting a configuration where one of the LV feeders is fed by a ST. Furthermore, it is considered that one feeder (left side in the figure 3.1) has mainly installed DG units while the other feeder supplies mostly load.

Both LV feeders are connected following the traditional open switch scheme. Due to the decoupling between the MV and LV sides in the ST, several degrees of freedom can be used for grid management purposes: voltage magnitude and frequency for the LV side and active and reactive power injections on the MV side. For the MV side, ST can inject reactive power for the voltage support or inject active power when

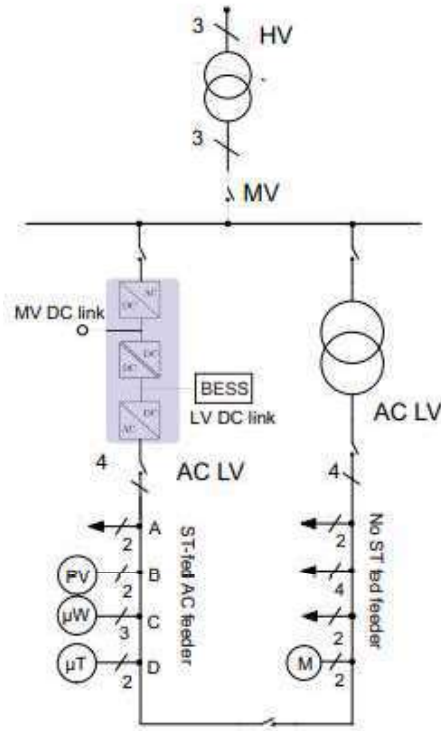


Figure 3.1: ST based system used in [92]

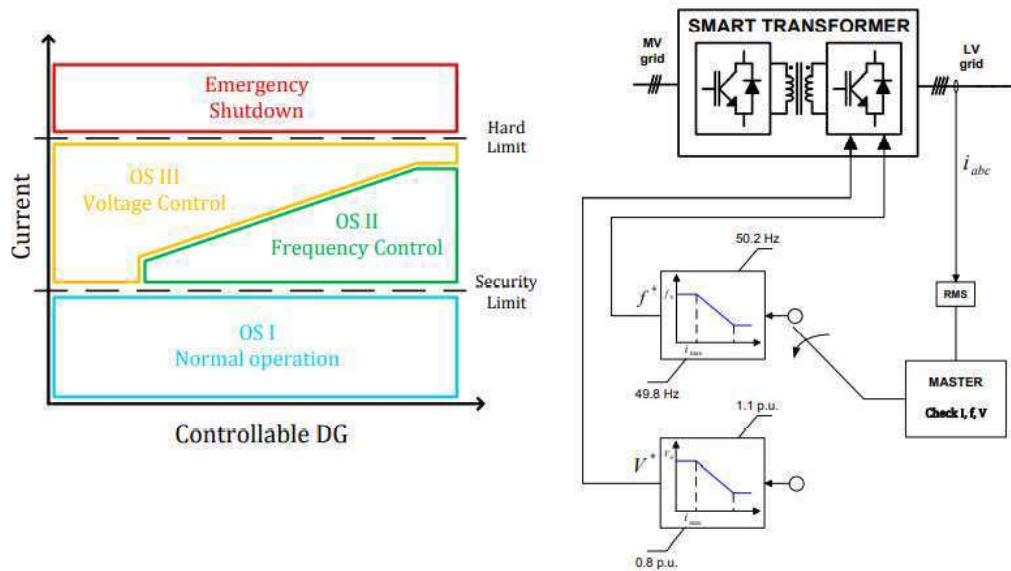
the BESS needs to be discharged. When there is a surplus of generation from the DG units, it can be stored in the BESS of the ST. The authors proposed three operating modes [92]: power balancing control, minimization of voltage deviations, and grid supporting through the BESS. In the first operating mode, considering a LV side's meshed operation, the goal is to balance active and reactive powers between the two feeders. The second operating condition takes advantage of the ST's ability to perform control per phase, which is suitable for the typical operation of the LV grid with unbalanced loads. When the per phase computation is insufficient to keep the voltage within limits, the alternative is to minimize voltage deviations using sensitivity voltage coefficients [92]. Therefore, the voltage limits are maintained, defining set-points for the LV inverter's active and reactive power. Lastly, the third operating mode uses the BESS to supply the loads during the consumption peak periods. Both inverters MV and LV can inject active power in that case. However, in the LV inverter, the set-point for the active power is defined to avoid voltage violations.

De Carne et al. presented a control strategy for the revers power flow in LV grid fed



by a ST [93]. Those operating conditions result from the higher generation regarding consumption. Since the DG units are equipped with power-frequency (P-f) droop characteristics, their active power output will change with the LV frequency variations. This controller is implemented through a linear relation between the LV grid frequency and ST-DC link voltage [93]. The LV side's voltage frequency is changed following this linear relation when the DC/DC controller achieves saturation during the reverse power flow. The power flow regulation between the two DC stages is performed by the DC/DC controller to maintain the LV DC link voltage in its nominal value. However, when DC/DC controller achieves the saturation due to DC link voltage increases, the frequency of the voltage waveform is changed according to a linear characteristic (LV-frequency-DC link voltage).

A coordinated frequency and voltage controller was initially proposed in [94] for avoiding the overload operation of the ST. This controller is applied since ST has a limited overload capability for a short time due to the power semiconductors' thermal limitations. The overload control acts on the voltage' magnitude and frequency on the LV side [94].



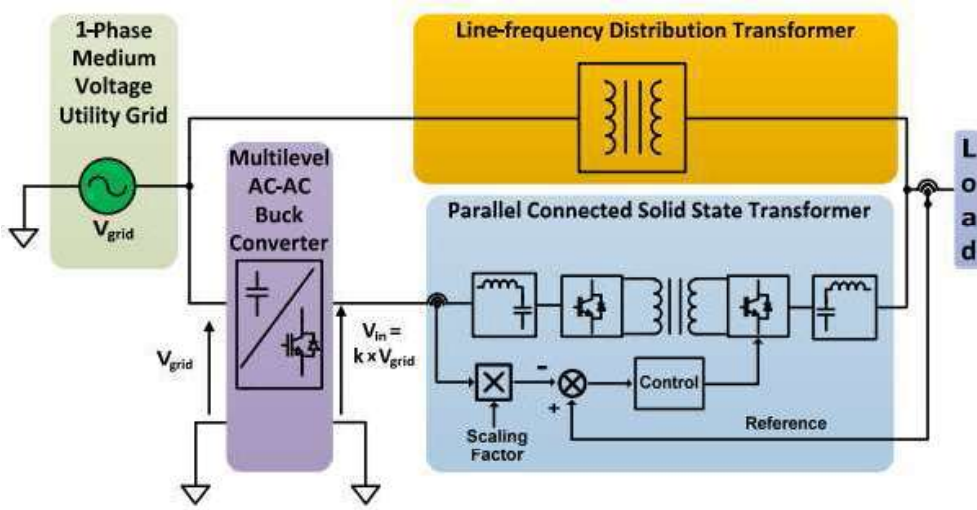
**Figure 3.2:** Coordinate frequency and voltage overload concept based on the amount of DG controllible (left); master controller for the ST overload control (right) [94]

As depicted in Figure 3.2 (left side), the controller covers four operation zones. First, when the RMS current in the LV terminals of the ST reaches the threshold limit, the LV frequency will change (OS II). Due to frequency change, the DG units will provide

power-frequency support since they are equipped with P-f droop characteristics. If the frequency is modified until the minimum threshold (49.8Hz), the next action will be to act on the voltage. Consequently, the master controller acts on the voltage magnitude (OS III). This is performed by reducing the voltage magnitude to decrease consumption, assuming that the loads are constant impedance type. The lower permissible limit for the voltage magnitude is 0.8 p.u. When the current achieves the hard limit, the solution to avoid the ST overload is to shut down the ST to safeguard the hardware components. As fast as the overload situation is solved, the ST operation returns back to the ordinary operation zone (OS I), and the master controller disables the frequency and voltages controllers. .

A ST with a BESS can also be used for enhancement of the hosting capacity in radial MV feeder as described in [95]. For that purpose, a ST is replacing the CLFT in a secondary substation. Initially, sensitivity coefficients are computed based on the Jacobian matrix of the Newton-Raphson method to understand the effects of active and reactive power along the MV feeder. In this work, a sensitivity analysis is performed for determining the size of the converters (BESS converter, ST DC-DC converter, ST MV converter) under three operating conditions to support the MV grid: only active power, only reactive power and both active and reactive powers. The sensitivity analysis is conducted considering load and generation increases over the MV feeder. For the simulation defined in [95], the ST improved the hosting capacity of the MV feeder for the three operating conditions described above.

In [96], the ST is used to add capacity to an existing distribution network served by an CLFT. The approach places a ST in parallel with the existing CLFT ("plug-and-play" arrangement) and an additional AC-AC buck converter. The authors suggest the multilevel AC-AC buck converter to adapt to higher MV utility inputs voltage. The flexibility provided to the traditional CLFT, mainly with the possibility of controlling the power flow in both directions, is the main advantage of this configuration. The controller of this parallel operation is designed to CLFT support the load consumption up to 50 kVA. Above that value, ST switches on for sharing with the CLFT the load increase burden. The proposed approach was simulated in PSIM, considering a 50 kVA CLFT in parallel with a 50 kVA SST.



**Figure 3.3:** Smart Transformer and AC-AC buck converter to add capacity to an existing conventional transformer in distribution networks [96]

The concept of Multi-Fed Power Electronics Transformer (MF-PET) is described in [97] where the main difference regarding the ST structure is the placement of two inverters in the higher voltage side (figure 3.3) with bidirectional ability. In such a case, the inverters are connected to different distribution feeders, and the power transference is controlled, assuming that one of them is the source delivering the surplus of active power tho the other (operating as a rectifier) [97]. The authors present a small-scale laboratory prototype for the MF-PET to demonstrate the distribution grids' flexibility by this concept.

Although most ST applications for power flow management is focused on the distribution side, the ST can also operate as a flexible interface between transmission and distribution grids. For that purpose, Chen et al. present the ST's steady-state modelling for including it in optimal power flow (OPF) studies to evaluate the device's benefits in large power systems [71]. The decoupling between both sides in terms of voltage and reactive power flow is exploited to optimise power flows and reduce generation costs. As the secondary voltage can be regulated independently from the input side, the ST can inject reactive power to the higher voltage side. The secondary side's voltage regulation is performed to take advantage of the loads' sensitivity to the voltage variations [71]. Thus, the consumption can be lowered through the voltage reduction, allowing a decreased of the active power flow request to the primary side. The OPF analysis was carried out for the New England IEEE 39-bus test system to evaluate the ST effect in the grid, by varying the number of devices from zero to a

grid full of ST (in all substations). In this work, the benefits resulting from the ST's integration are remarkable in improving the voltage profiles and lower losses regarding the scenario without ST. The load control performed to the voltage change proves to help reduce the generation cost in the most expensive generators. However, as stated by the authors, further studies are needed to understand the impact of the implemented voltage control on customer appliances. Complementary, the optimal placement of ST is a topic to be adequately addressed to define the strategic location optimizing the grid operation and investment costs.

### 3.3 Voltage Control

ST also provides the ability to support voltage control for both sides. Unlike the CLFT, ST regulates the voltage at the LV side independently from its input voltage on the MV side.

The increased need for new voltage control approaches in distribution grids due to the high integration of DG can be addressed using different solutions that exploits: reactive compensation devices [15], distributed generators [98] and tap-changers. Shunt capacitors, shunt reactors, and power electronic-based devices like Static Var Compensators (SVC) [99] can provide reactive compensation. Those devices have functionalities to regulate reactive power injection into the distribution grids as a function of their terminals' voltage. However, this solution has a small effect on LV grids due to its resistive characteristic (high R/X ratio) [15]. On the contrary, in higher voltage grids with an inductive predominance, the impact will be higher. The DG units connected to the distribution grids can also be considered for voltage support.

Tap-changers in the distribution transformers have been the traditional solution to support the voltage control in distribution grids. Usually, in an MV/LV substation, the secondary side's voltage can be adjusted by changing the no-load voltage regulating transformers' tap position. Nevertheless, the local generation's variability along the day can require a significant number of tap changer operations to keep the voltage within the allowable limits. In future scenarios with high generation penetration in LV grids, the voltage regulation can no longer be performed through no-load voltage regulating transformers. In the traditional approaches, the tap-changer position is determined without considering the bidirectionality of the power flows. The voltage control's primary function is to compensate voltage drops over the LV feeders (unidirectional power flow to supply loads). Besides, the tap position is computed in the planning

phase once the tap changing is only possible in no-load conditions.

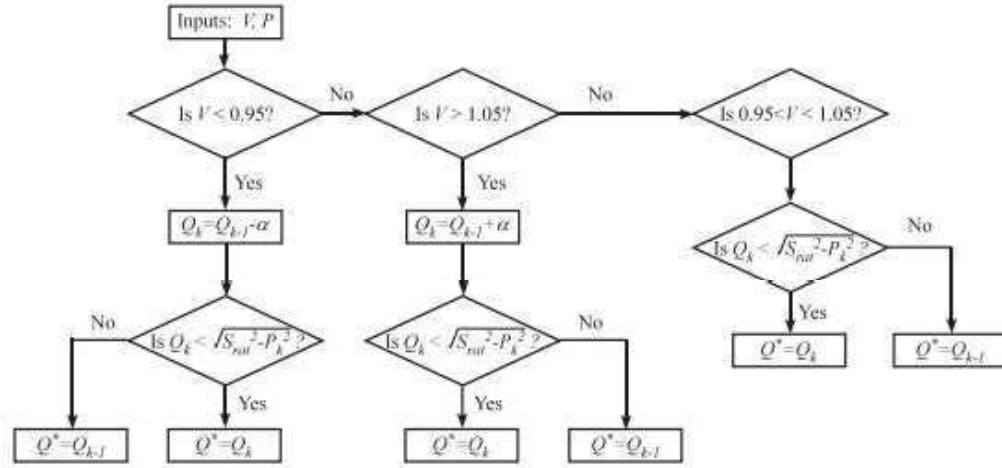
On load-tap changer (OLTC) has been highlighted as a solution for an extensive voltage regulation range in LV grids [100], avoiding the power-off during the voltage control process. However, the mechanical OLTC presents limitations in response to constant tap changes since this will require frequent maintenance (deterioration due to exiting arc during the tap changing process) and consequent increased operational cost. The voltage regulation process through mechanical OLTC is slow, non-continuous and step-by-step (discrete controller). Hence, solid-state OLTC based on power electronic apparatuses are a solution to have a faster operation of the tap-changer, enabling a continuous voltage regulation process.

Being a device based on power electronics, ST allows developing new voltage control strategies in MV and LV grids. Accordingly, in [101] it is proposed a new approach where the ST is used as an interface between the DG units and the electric grid. This approach exploits the ST capability to inject power in each phase independently of the remaining two. Unlike the CLFT, ST adjusts the per-phase power injection considering the LV network needs. The authors intend to exploit this feature for enhanced voltage control and line congestion management. The proposed algorithm is performed every 15 minutes. First, a state estimation of the LV grid is carried out to compute the voltage magnitude and phase at each bus. As the second step of the algorithm, sensitivity coefficients are computed regarding the DG units' active and reactive power injection. Finally, a centralized online controller is responsible for solving an optimization problem to define new set-points (P and Q) to the DG units, guaranteeing the distribution grid's safe operation. The authors evaluate the proposed algorithm using the IEEE 34 nodes test system assuming two different cases [101]:

- **Case A:** each DG unit has a rectangular capability with 0.95 lag-to-lead and is connected to the grid with a traditional transformer;
- **Case B:** each DG unit is connected to the grid through a ST with a triangular capability varying from 0.95 p.u. lag to 0.925 p.u. lead;

In the first case, the DG units output has a balanced control; thereby the proposed algorithm cannot manage the voltage and lines congestion in the three phases. It is observed that active and reactive powers are almost in the maximum value over the day because the algorithm adjusts the DG set-points to the most overloaded phases.

On the contrary, different profiles (voltage, active power, and reactive power) are obtained in the second case since the ST executes a phase-per-phase control. In particular, the reactive profiles of the DG does not reach the maximum injection, like in case A.



**Figure 3.4:** Algorithm flow chart for voltage control in MV distribution grids using smart transformers (implemented in [102])

A volt-var control (VVC) is implemented in [102] using the ST to inject or absorb reactive power (Figure 3.4). This control is applied for regulating the voltage in the HV side of the ST, considering a three-stage configuration and that ST replaces all magnetic transformers in the distribution grid. Nonetheless, there will only be reactive compensation in the so-called pilot nodes, corresponding to the critical nodes for voltage control purposes. The remaining ones operate with a unity power factor. The developed algorithm is mentioned as "DQDV" once modifications in the bus voltage result from reactive power changes [102]. Therefore, the algorithm aims to compute the reactive set-point to ensure that bus voltages are within limits [0.95 p.u.; 1.05 p.u.]. This approach is different from the application of Q/V droops in which the reactive power is adjusted whenever the voltage is outside the dead-band values. The "DQDV" algorithm only reacts when the voltage limits are violated: above 1.05 p.u. and below 0.95. The ST will keep the same reactive power output when the bus voltage is within the permissible limits. The authors used the IEEE 24-bus as a base test system for implementing the "DQDV" algorithm. Besides the original radial test system, the authors modified the IEEE 24-bus to consider a meshed configuration. For both test systems, the developed algorithm was able to avoid voltage violations. It was demonstrated that the reactive power injected by the ST following the local control



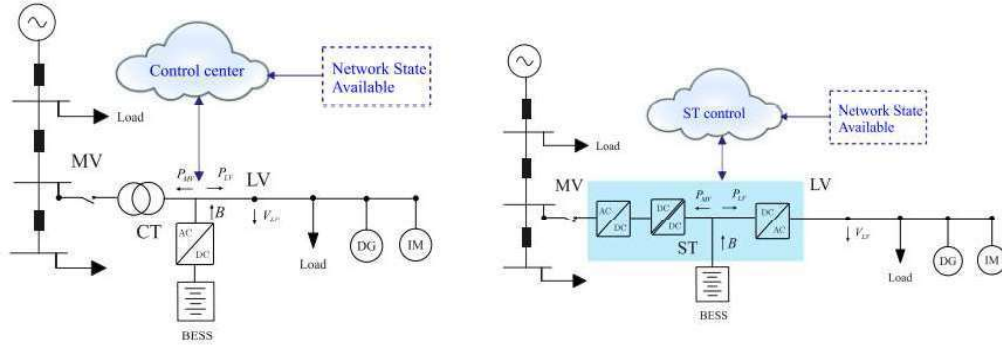
significantly impacts the voltage profiles.

The authors used the IEEE 24-bus as a base test system for implementing the "DQDV" algorithm. Besides the original radial test system, the authors modified the IEEE 24-bus to consider a meshed configuration. For both test systems, the developed algorithm was able to avoid voltage violations. It was demonstrated that the reactive power injected by the ST following the local control has a significant impact on improving the voltage profiles.

The ability of the ST to support the voltage control in MV grids is also exploited by using Q/V droop [103]. The MV inverter injects reactive power as a function of the voltage deviation regarding the reference value. The steady-state analysis was performed on a daily basis to evaluate the benefits provided by the ST for the voltage control under extreme operating conditions [103]: high load/low generation and low load/high generation. Moreover, the authors also intended to identify the ST's proper size to ensure the voltage is within the desired range. Also, the location of the ST is a subject addressed to analyze how the different ST placement locations influence the voltage control. In this work, the Q/V droop strategy was evaluated in PSCAD/EMTDC for the UK distribution grid in 11 kV. As the main highlight of this work, one can stress that the ST is able to sustain the voltage profile in the MV distribution feeder, but a minimum ST size is necessary to avoid violation of the lower voltage limit.

Conversely, in [104] the ST is exploited for both MV and LV grids in a decoupled manner. There is a full decoupling of reactive power flows between the two grids in a configuration in which the ST has a storage device placed in the DC-link (MV and LV). Such configuration is exploited to participate in the active power flow dispatching for the LV side, controlling the storage charging/discharging, as a function of the consumption and generation forecasts for the day ahead. Concerning the voltage control, the ST will support both sides using separate control due to the reactive power decoupling. For the LV side, the objective is to define the proper voltage level in order to minimize the voltage deviations in the grid. This is performed assuming that ST receives information on the grid state provided by smart devices located over the grid [104]. In turn, the reactive power set-point for the MV inverter is set, solving a constrained optimization problem aiming to minimize the voltage deviations from the nominal value [104].

As depicted in Figure 3.5, two network topologies were considered to assess



**Figure 3.5:** Grid configuration used in [104] for voltage control: storage device connected through a AC/DC converter in the conventional transformer terminals (left); storage system integrated into a smart transformer (right)

the benefit of using the ST in distribution grids. The first one comprises a CLFT interconnecting MV and LV grids with a storage device installed at the LV level through a DC/AC power converter. For the second one, a ST is interfacing both grids and is equipped with a storage system, ensuring the full decoupling between the two sides. The simulations were carried out using the IEEE 34 nodes MV reference network with aggregated active and reactive power injections, except for the node where the ST is interfacing the MV and LV grids. For the LV grid, it was considered the CIGRE LV benchmark grid. Improving on the voltage levels in the MV and LV grids were achieved when a ST equipped with a storage device is the interface between the MV and LV grids.

The ST's capability to provide ancillary services to distribution and transmission grids is addressed in [105] for exploiting the voltage-dependent loads. The underlying idea is to compute load active and reactive power sensitivities to voltage or frequency variations. The authors applied the on-load identification method for two purposes [105]: soft load reduction and voltage-based overload control. Instead of applying a load-shedding scheme following a disturbance in the upstream levels, the load consumption can be decreased by changing the voltage. The ST induces a consumption decrease according to the load sensitivity by modifying the LV side voltage, thus promoting a softer reduction. The same rationale can be applied to set the voltage level that relieves the ST overload [105], reducing the current flowing through it.

The application of the methodology deployed in [105] relies on the knowledge of the load sensitivity regarding voltage and frequency variations. Considering the voltage-based ST overload control with constant power loads, the example described



previously will have a contrary effect, increasing the consumption. For this reason, this methodology needs to compute the load sensitivity with acceptable accuracy in order to avoid control actions in the wrong directions. Taking advantage of the ST's capabilities to change the frequency and voltage for the secondary side independently of the MV conditions, the load sensitivity measurement is performed through variations of those variables [105]. In this work, the load identification was performed by applying a trapezoidal disturbance in accordance with the method developed in [106]. ST measures the line current and phase-to-ground voltages for specific time steps during the voltage variation. The active and reactive powers are computed using those measurements; then, they are stored together with the RMS voltage. Thus, the sensitivities are computed by the differences in the active and reactive power variations between the specific time instants under the respective voltage variations. This process runs over the time window defined for the application of the voltage disturbance. Finally, load sensitivities correspond to the averaged values obtained during the time window.

As mentioned by the authors, in real applications, the on-line load identification could be performed every 5 or 10 minutes to estimate the amount of voltage droop to have a consumption reduction of around 5%. However, the proliferation of DG units in the distribution grids affects the load voltage sensitivity. Indeed, the ST will measure the aggregate load dependence on voltage variation. Additionally, the DG units' participation in voltage control will also impact the load voltage sensitivity measurement, requiring improvements on the methodology presented in [106]. Aiming to validate the developed voltage-based load control, the authors used the Control-Hardware-In-Loop (CHIL) method through the RTDS (Real-Time Digital Simulator) system for an LV grid fed by a ST. The simulation outcomes show that the developed methodology provides higher accuracy for load sensitivity estimation than the methods based on a statistical analysis of historical data and passive loads. The ST's capability for changing the LV voltage to reduce consumption is compared with the conservation voltage reduction (CVR) technique. This comparison was performed for a 400 V distribution network with 90 customers, corresponding to a subset of the Manchester area's distribution grid.

The voltage-dependent loads in a ST-fed LV grid are also considered in [107] for supporting voltage droops events. ST will support the MV control until the OLTC in the primary substation transformers acts on the tap changer to adapt the substation bus voltage. Since ST is based on power electronics components, it offers a faster response to the voltage than the traditional OLTC. As OLTC can take dozens of seconds

to adapt the substation bus's voltage level following a disturbance, for a while, ST can inject reactive power for supporting MV voltage.

The proposed methodology's underlying idea is to consider two control layers [107]: reactive power injection in the MV grid and changing the LV voltage to decrease the LV consumption. As fast as the MV inverter reaches the maximum ampacity, ST switches to a second control layer to reduce consumption through the voltage change. The voltage change is also applied following an on-line load control along the same lines as described in [105]. Shaping LV consumption increases the MV inverter's ampacity, enabling additional reactive power to support the MV voltage. To demonstrate the proposed control strategy's feasibility, the authors consider the IEEE 34-bus test feeder to represent an MV grid and the CIGRE Microgrid benchmark for the LV grid. A ST is placed in a node serving as an interface between the MV and LV grids. The simulation performed in PLECS/MATLAB shows that with a single ST is possible to reach improvements around 2% in the MV voltage profile a voltage droop caused by the wind plant disconnection, considering the two layers controls. The control strategy presents a voltage improvement, which is double regarding the ST's only reactive power injection. Although the improvement seems reduced, the control strategy was applied considering a single ST, whereby the integration of ST in the future smart grid environment can leverage this potential for voltage control.

Like in the two previous works, the reactive injection capability is also addressed in [108] to support balanced and unbalanced voltage sags. When a ST is interconnecting MV and LV grids, a voltage sag in the primary side will not be transmitted to the LV grid due to the decoupling. ST can inject reactive power in the MV for voltage regulation during balanced and unbalanced voltage sags. In ordinary operation, the MV inverter is in a constant power mode, but there is the requirement to inject an additional amount of reactive power to support the voltage during sag events [108]. Despite that, reactive injection capability is limited due to active power delivery to the LV loads. In this sense, a flexible control approach is proposed to coordinate the MV converter, LV inverter, and battery energy storage system (BESS).

During grid voltage sags, the LV inverter operates in a coordinated way with the MV inverter. LV inverter will decrease the voltage magnitude until 0.9 p.u, whenever the reactive power requirement causes the overpassing of the apparent rated power of the MV converter. In that case, the voltage reduction decreased the consumption relieving the loading of the MV converter. Even though this LV voltage adjustment is not enough, the controller will enable the BESS to supply the LV consumption. BESS's

active power set-point is then defined based on its state of charge (SOC), allowing the MV converter's higher relief and maximizing the reactive power injection. The control strategy is similar for balanced and unbalanced voltage sags. However, for unbalanced voltage sags, the control strategy is designed to inject positive and negative currents to increase the positive sequence voltage and decrease the negative sequence voltage [108].

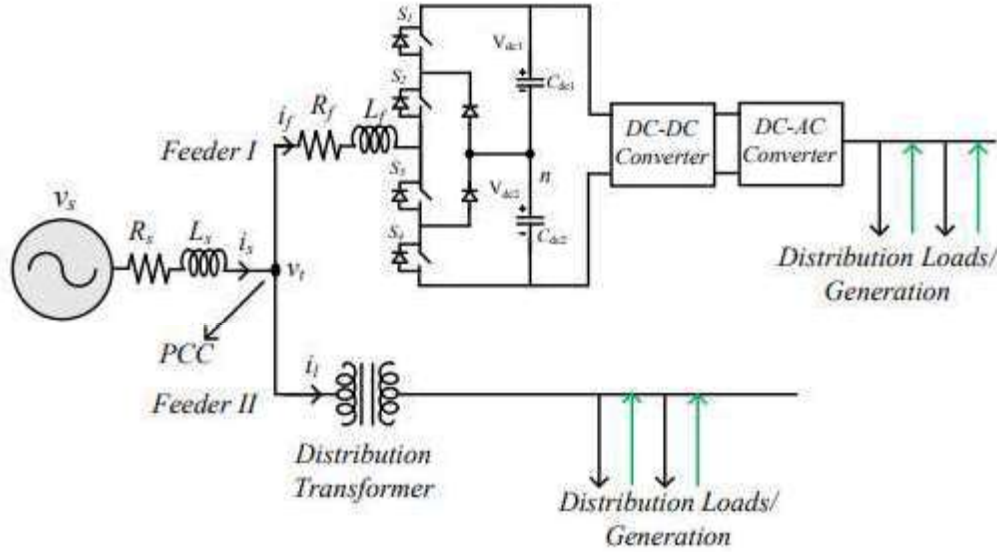
A voltage-based approach is developed in [109] to control the active power exchange between a microgrid and the main grid. The utility grid communicates to the point of common coupling the desired active power exchange. Then, the ST is responsible for changing the microgrid voltage level operating as an OLTC. Consequently, the DG units will respond to the voltage change adapting their outputs since they have voltage-based droop control. This strategy demonstrates ST's role as an interface between utility grids and microgrids, receiving information from the upstream level and aggregating information coming from the devices located downstream.

### 3.4 Power Quality

A three-stage configuration for the ST with two DC-links is the most promising configuration to be adopted in distribution systems since it enables the decoupling of the two grids. This feature is valuable for power quality purposes creating a "filter effect" [110], meaning that a disturbance in one side can not affect the other side. A typical operating condition in LV distribution grids is load unbalancing. Those conditions result from the not balanced loads in the distribution feeders, non-linear loads, and the increased integration of single-phase solar PV panels in LV grids or other types of loads like EV. With the CLFT, an unbalanced operation in the LV side will be imposed on the primary side. However, as demonstrated in [110], the ST can be used to define balanced voltage and currents for the LV side, independently of the load conditions on the LV side.

Experimental research was carried out in [111] to demonstrate the power quality improvements through the ST. This research proves that ST can mitigate the impact of grid disturbances from the opposite sides. Thus, the voltage maintains a sinusoidal waveform and unity power factor at the primary side even though the LV loads are unbalanced, nonlinear or asymmetrical. In turn, the LV voltage waveform is unaffected by the voltage sags at the primary side. The experimental setup was designed to be

applied under source and load disturbances in a ST model (2.4kV/240V/120V - 20kVA).



**Figure 3.6:** Power distribution system consisting of two feeders in which one of them is fed by a smart transformer [112]

A control strategy is designed in [112] to prove the ST' ability to improve the power quality in the MV grids providing balanced voltage sinusoidal waveforms. For that purpose, the authors consider a two feeder system (Figure 3.6) where a ST replaces the CLFT in one feeder. The LV loads served by the ST will not be affected by disturbances in the upstream level and will be supplied through balanced sinusoidal voltages. For the MV side, the control strategy is designed considering the possibility to supply unbalanced, reactive and harmonics components of the feeder I [112]. This control strategy is designed assuming that ST is operating below its maximum capacity most of the time, and therefore, it can support the improvement of the power quality on the MV side. The presented solution is developed to create current references in the MV rectifier, taking into account the load condition on both feeders.

In [113], a three-phase four-wire dynamic voltage restorer is developed to compensate series voltages in a distribution system. The load side does not sense grid faults in this strategy since the dynamic voltage restorer maintains a balanced sinusoidal voltage waveform. Under balance or unbalanced conditions, the designed strategy was robust for reducing the total harmonic distortion (THD) on the voltage in the load side when the utility side suffers disturbances (sags, swells and harmonics).

Gorla et al. perform a harmonic analysis for a three-stage cascaded modular solid-state transformer [114]. This paper aims to study the effect of the MVDC voltage balances schemes in the grid current's total harmonic distortion (THD). The studies have shown that power balance control in the ST's isolation stage is a better solution to reduce the THD of the grid current than the voltage balance control in the first stage. Also, aiming the THD reduction of the grid current and filter's volume and cost, in [115] it is studied the impact of placement an LCL filter between the electric grid and the ST. LCL filter is considered in this study because it provides a better harmonics damping and a reduction in the volume and cost. A PI controller complements this solution with two parts for the input and output stages. This solution reduces the THD compared to the situation without the LCL filter.

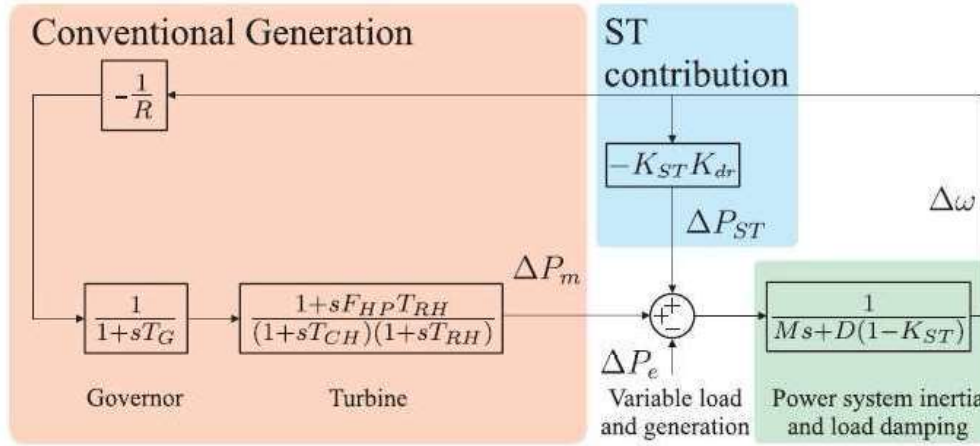
The ST's potential for connecting the utility grids and data centers is addressed in [116] to protect critical loads from grid disturbances. As critical facilities, data centers require a high power quality level for avoiding damages to sensitive equipment. Commonly, those facilities have installed additional devices, so-called "power conditioners", to protect sensitive electronic equipment from grid perturbations. With a ST interfacing the utility grid and the data center, the voltage THD is smaller than an CLFT, as demonstrated by the simulations performed in this work. Besides acting as filtering of the grid disturbances, ST can reduce the need to install power conditioners.

### 3.5 Frequency Support

The three-stage with two DC links configuration allows the decoupling between MV and LV grids in terms of voltage and frequency control. The ST's ability to change the frequency can be exploited to control the ST overload and the reverse power flow, as described in Section 3.2. Indeed, the ST can change the LV frequency to interact with the local generation equipped with P/f droop controllers and frequency-dependent loads. This type of control strategy can alter those units' outputs of active power to support the grid during emergencies situations. Hence, ST should be prepared to operate with a different range of frequency within the allowable limits. As stated in [117], the power converters' controllers can not present the most appropriate harmonic control to be operated in variable frequency frameworks. A frequency-adaptive control scheme based on the fractional-order repetitive control and the frequency-adaptive phase-locked can be applied to improve the power converters controllers' stability

under variable frequency conditions [117].

The ST is also envisioned to support the real-time frequency control in the subsequent moments to large frequency variations. In those events, the voltage-dependent loads can help the power-frequency control of the overall system. By changing the voltage, ST will cause a variation in power consumption to support the primary frequency control. Such is necessary since MV and LV are interfaced through ST, and therefore, they are asynchronously connected. However, as explained in the section 3.3, the load response's modelling face to voltage variations requires to know in advance the voltage-sensitivity of the consumption.



**Figure 3.7:** Efficiencies of different power rated low-frequency transformer and solid-state transformers for distribution systems[46]

Aiming to analyze the ST's participation in the primary frequency control, in [118], the authors consider an equivalent power system model comprised of a governor-turbine system of a thermal power station, modelling the effect of rotating machines inertia and load damping (see Figure 3.7). The ST in this equivalent system's modelling is based on a droop curve representing the voltage-dependent loads' active power response under frequency deviations [118]. Figure highlights in blue the ST modelling to evaluate its contribution in the power-frequency control, where  $K_{ST}$  represents the amount of load fed by STs and  $K_r$  is a constant gain of ST frequency/power characteristic. Through PHIL evaluation, this work concludes that with about 20 % of ST-controlled load in the test system, the frequency transient reduces around 100 mHz, which avoids the activation of load shedding schemes.

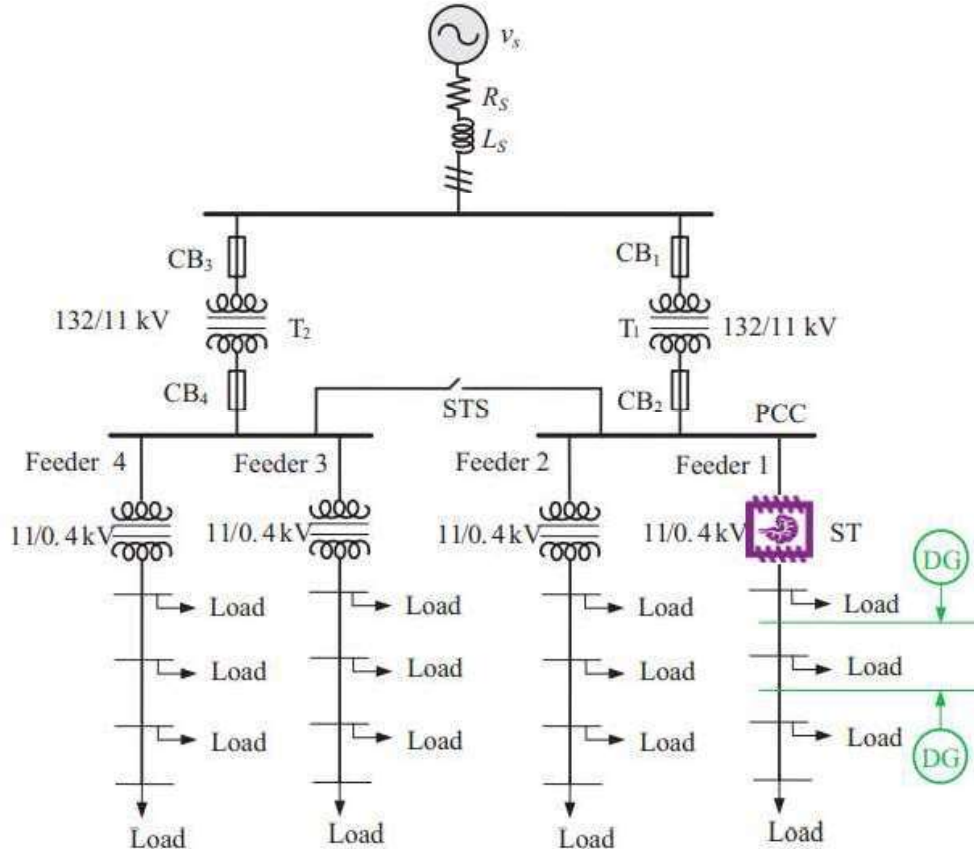
The ST as an AC/DC grids interface is exploited to provide power-frequency



support to the upstream AC grid [119]. In this regard, advanced functionalities based on droop-controllers are developed in ST to modulated the ST electrical variables: DC grid voltages, LV AC grid voltage and frequency. The variation of those variables makes it possible for DERs located in AC/DC grids to contribute to frequency disturbances in the upstream grid by modifying the active power output.

### 3.6 Islanding Operation

The DC-link enables the connection of the storage devices, which enables the islanding operation for both cases: faults in the upstream AC system or performing maintenance actions. Using the BESS or generation units connected to the DC link, ST can supply loads located downstream from it and other MV feeders. As described in [120], during the transition to the islanded operation, the MV inverter changes its operation mode from the current control mode (CCM) to voltage control mode (VCM). The MV inverter injects or absorbs active power into/from the MV grid during the normal operation, depending on the local power balance inside the LV located downstream. The MV inverter can support the demand from other MV feeders based on the units' power balance connected to the DC link in islanded mode [120]. Additionally, a communication infrastructure in the distribution grid allows evaluating the available resources to supply the loads. The load shedding scheme can help the power balance inside the distribution system during the islanded mode. In turn, the LV inverter has the same functionalities in both operation modes islanded and normal. It provides a balanced voltage waveform with a constant frequency for the LV grid [120].



**Figure 3.8:** Efficiencies of different power rated low-frequency transformer and solid-state transformers for distribution [121]

The same rationale is also employed in [121] to support partial disconnections of the HV/MV system (Figure 3.8). After a fault in the transformer  $T_2$ , it trips off, and the normally-open switcher (STS) is turned on. Thus, transformer one will supply all substation load. However, the demand can overpass the transformer's rated power leading to the overloading operation. In that case, the disconnection of some loads is a preventive measure for relieving the substation transformer. Considering a ST located in feeder 1, it can support the demand in its LV side and the MV grid loads. Based on the storage device's availability and generated power from DG placed in the DC-link, the ST can partially cover the MV load, alleviating the substation transformer.

Both works [120] and [121] address the islanding operation and the ability to support a portion of the loads due to partial disconnection of the HV/LV transformers in the primary substation. The purpose is to demonstrate the ability of the ST to keep the service operating in the grid-forming mode. Those publications aim mainly to



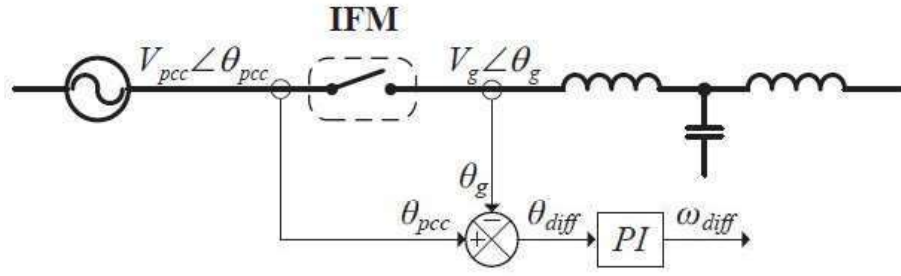
evaluate the waveforms (voltage and current) in the ST's MV and LV sides during some milliseconds (after the transition to new operating modes). The purpose is to demonstrate the ability of the ST to keep the sinusoidal waveforms when the main grid is not available. In these works, it is assumed that the DER and BESS connected to the DC link have sufficient capacity for ensuring the operation as a grid-forming unit during the simulation time. However, they do not consider how the overall power-frequency control is performed during the transition from the interconnected mode to the islanding operation and subsequent moments, assuming that several DER units can be equipped with P/f droop controllers. It is not described how the ST control functionalities can be coordinated with a fleet of DERs located in the MV and LV grids to support the frequency control for several dozens of seconds or minutes. In particular, it was not yet addressed how the ST can be included within for supporting primary and secondary frequency control when MG and MMG are operating in islanded mode.

### 3.7 Black Start and Start-Up Process

This capability to operate in islanded mode using the storage system's energy and local generation enables service restoration procedures in the distribution grids. A BS procedure was initially proposed in [122] where a single-phase ST with a rated power of 20 kVA is the main BS capability unit in a small microgrid. The ST with distributed generation and storage connected to the DC link is responsible for launching the microgrid's BS procedure. For that purpose, the input changes its operation mode from rectifier to inverter. On the other hand, the ST without distributed generation or distributed storage in the DC link maintains its operation like in the grid-connected mode. An important point to be stressed is related to the DC link energization in the BS procedure's first moments. The BESS is responsible for energizing the LV DC-link. After the DC-link energization, the ST can start the connection of loads located downstream. Then, the DC voltage in the HV dc-link ramps up to 12 kV; when this value is achieved, the ST is connected to the main grid to support the load restoration in the higher voltage side.

The master-slave concept could be an alternative to the droop controllers for the parallel operation of several ST during the BS procedure, as described in [123]. In this case, the ST with the largest amount of DER connected to the DC link will be the master in the microgrid. The remaining ST will inject into active power the grid when they have a local generation or storage higher than the local load (operation in the grid-tie mode). Those with load more elevated than the local production or without storage

availability will behave like loads absorbing power from the grid [123]. In this case, the input inverter operates in the rectifier mode. During the BS procedure, the master-slave operation implies a communication infrastructure to enable interaction among the STs. The supervisory control schemes are implemented in the master and slaves ST to monitor the load level and availability of the distributed resources, allowing them to change their operating modes [123]. The control schemes are slightly different because of the inability of the slaves to start functioning in the absence of the grid voltage.



**Figure 3.9:** Block diagram of phase matching controller for reconnecting the ST with the grid during a black start procedure [124]

Based on the two previous works, further research was performed in [124] to develop a seamless black start procedure and smooth reconnection with the main grid (Figure 3.9). In this regard, the proposed strategy is based on the combination of the droop controllers and the capacitor voltage control of the LCF filter placed in the HV side of the ST [124]. The active power is assumed to be proportional to the phase difference, while the reactive power is proportional to the magnitude difference between the grid and capacitor voltage [124]. Therefore, the droop controllers regulate the active and reactive power in the ST with BS capability, computing the capacitor voltage phase and amplitude. The HV inverter can vary the power flow direction by modifying the grid power's reference achieving a smooth transition between operation modes. For a seamless reconnection with the main grid, a phase matching is described in [124] to synchronize the ST with the grid. The main idea in this case is to add an angular frequency value to the drooper controller in order to converge to zero the phase difference between the grid and the ST inverter. In this sense, with equal frequencies on both sides, the reconnection's safest point is the voltage zero-cross point.

The works developed in [122],[123], and [124] provide meaningful insights regarding the exploitation of the ST capability for launching a service restoration in

distribution grids. The different power conversion stages and respective controllers' operation modes are described in those works to establish a BS procedure. Those works' scope was to analyze the behaviour of ST electrical variables in the first moments of the BS procedures. There is a lack of research on how the ST can be modelled in the long term dynamics behaviour, namely for the power-frequency control in distribution feeders. One can also infer that is not addressed in the literature how can be designed service restoration in MV feeders, combining CLFT and ST. Although the work available in the literature demonstrate the feasibility of the ST to support the BS procedures, it is still to be defined the set of rules for conducting a BS procedure within the distribution grid. Additionally, for power-frequency control purposes, the ST inverters' coordination with other DERs located over the distribution grids during the islanded mode is a topic not yet addressed in the literature.

On the other hand, after a blackout, the unit with black start capability is responsible for energising the grid assets. Assuming that the ST is the element responsible for playing this role, an initial problem may arise on its energization and start-up. The power semiconductors have limited capacity to deal with large inrush currents (thermal fatigue) that can arise when the ST is energised. Considering the start-up process of the ST from the MV grid, the large surge current to charge the DC-link capacitor can damage the semiconductors devices and the filter inductors at the input stage [125].

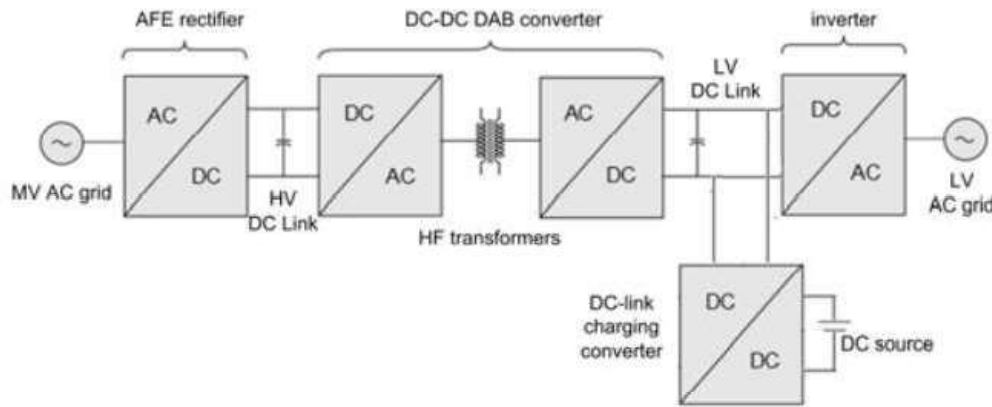


Figure 3.10: Pre-charging scheme adopted in [125] for a three-phase ST

A method to pre-charge the DC-link capacitor with some voltage level before connecting with the upstream grid is applied in [125], reducing the large surge currents. First, the DC source will charge the LVDC link; then, the DAB regulates the DC-link voltage and charges the HVDC-link. As higher is the HVDC link voltage,

the surge current peak is smaller. The experimental results suggest charging the HVDC-link to a level higher than the AC voltage peak to reduce the surge current peak [125]. However, this process leads to a longer charging time.

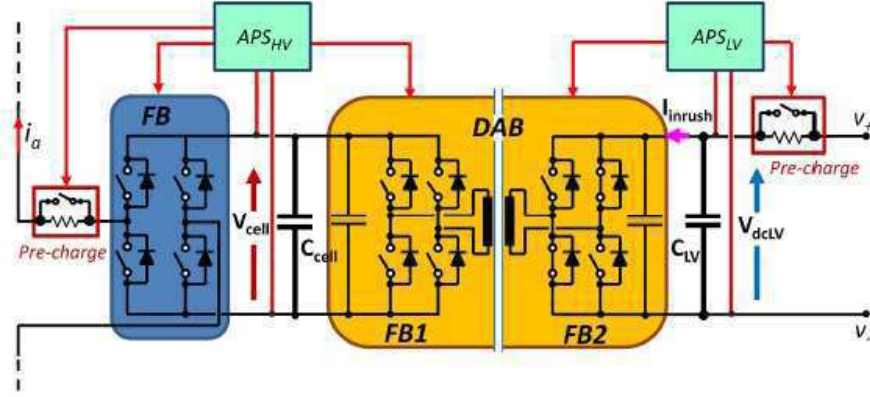
Liu et al. provide a theoretical analysis and the respective experimental validation of a stage-by-stage start-up scheme for a ST [126]. This start-up scheme consists of charging the ST through the HV side, and each conversion stage is enabled one by one (Figure 3.10). As stated in this work, the DC-DC converter and HFT will suffer large input inrush current during this start-up scheme. Still, the same work demonstrates that the DC-links' pre-charging contributes to reducing the initial inrush current. Based on this work, a new start-up scheme is presented in [127], aiming to reduce the inrush current that flows through the DC-DC converter and HFT. The idea is to minimize the voltage difference between the primary and secondary sides of the DC-DC converter. This is performed through the proper synchronisation between the input stage (acting as a rectifier) and the DC-DC stage by controlling the phase-shift angle [127]. The controller maintains the phase-shift angle in the maximum value during the start-up scheme to increase the DC-DC converter's output voltage monotonically [127]. Hence, a pre-charge process of the DC-link capacitor before connecting with the grid can be adopted as a solution to reduce the initial inrush current. This pre-charging process can be done through the LV or by the renewable sources or BESS connected to the LVDC link.

The usage of auxiliary power supply (APS) to support the ST's energization process is addressed in [128]. The APS units' function is to support the ST's auxiliary circuits during the start-up process. These units can be fed to the internal DC-links or through the AC external voltage grids [128]. Feeding the APS units through the corresponding DC links is the solution adopted in [128]; despite the APS's threshold voltage being not reached, the start-up process is running without control. Furthermore, feeding APS by the DC links enhances the ST's flexibility to operate in different modes:

- G<sub>Fo</sub> on the HV side and G<sub>Fe</sub> on the LV side;
- G<sub>Fo</sub> on the LV side and G<sub>Fe</sub> on the HV side;
- G<sub>Fe</sub> for both sides;

Figure 3.11 depicts the ST topology adopted in [128] to develop the start-up processes for the different operation modes. This structure has two full-bridge (FB) on

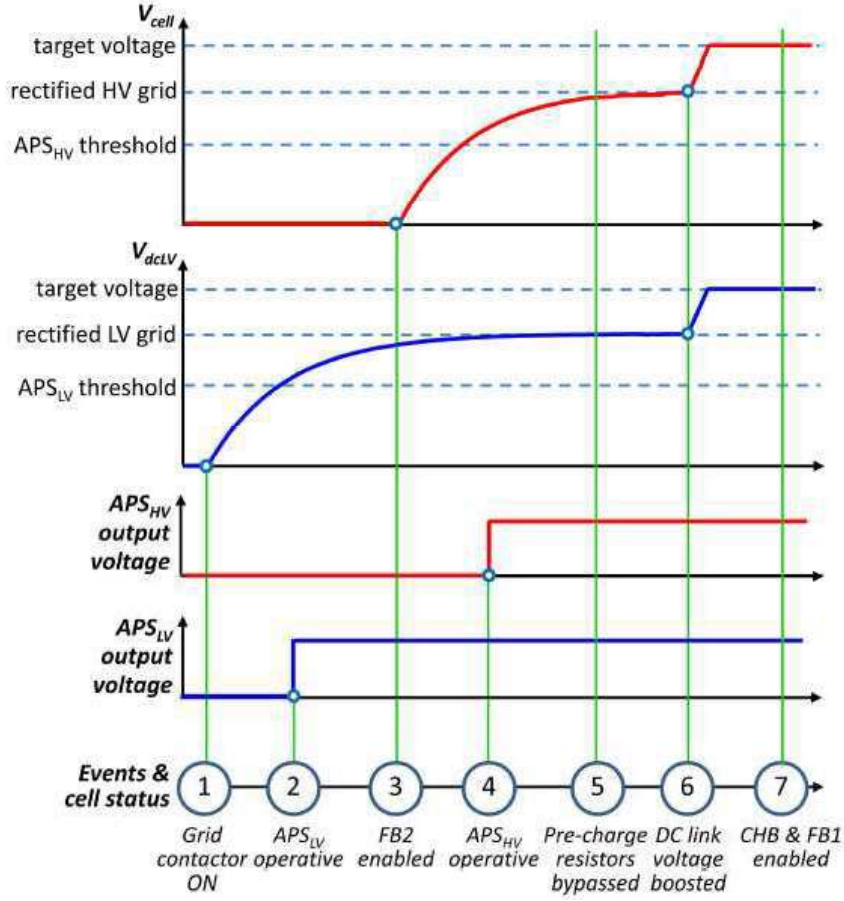
the HV and LV sides, a DAB and the two capacitors, which are represented as  $C_{cell}$  and  $C_{LV}$ . Besides, two APS units supplied through the respective DC links,  $APS_{HV}$  and  $APS_{LV}$ .



**Figure 3.11:** Simplified scheme for representing a cell of the modular ST topology in start-up process [128]

The operation modes influence the way how the start-up scheme is conducted. Assuming the grid-forming function for one of the sides, the ST will establish the reference for voltage in terms of frequency and magnitude. In turn, acting as grid-feeding, the voltage can be set by an external source. In [128], the focus is to carry out studies for the operation modes described in the first two items of the list above.

The proposed start-up process for the ST operating as Gfo on the HV side is depicted in Figure 3.12. As the procedure initiates by the LV side, firstly, the voltage on the  $C_{LV}$  starts to increase. During the LV capacitor charging process, the APS unit located in the LV side is activated, enabling to control the full-bridge (FB) 2. In turn, FB 2 can control the charging of the HV capacitor. Meanwhile, the APS placed on HV side achieves the threshold voltage, enabling the FB 1. Later, when the voltages on both capacitors match the grid rectified values, the pre-charge resistors are bypassed. Finally, the capacitor voltages are conducted to the target value.



**Figure 3.12:** Start-up procedures proposed in [128] when the smart transformer operates as a grid-forming unit for the HV side

The operation as GFo unit for the LV side is similar but in the reverse sequence (Figure 3.13). The start-up process begins from the HV side with the cell capacitor charging. As soon as the voltage on the APS HV achieves the threshold voltage, the control of FB1 and FB become operational. The voltage on the capacitors will increase until they are equal to the target grid-rectified voltage, allowing the pre-charge resistors' bypass. Then, through proper control, the capacitor voltages are conducted to their target value. In the last step of the process, the APS units support enables all the SST control functionalities. Consequently, LV DC/AC converter can start its operation as GFo for the LV side.

When ST is operating as GFe for both sides (3.14), the start-up procedures are more straightforward than previous cases once the grid is already available. The solution is to synchronize the rectifier and DC/DC stage following a procedure similar to the one described in [127].



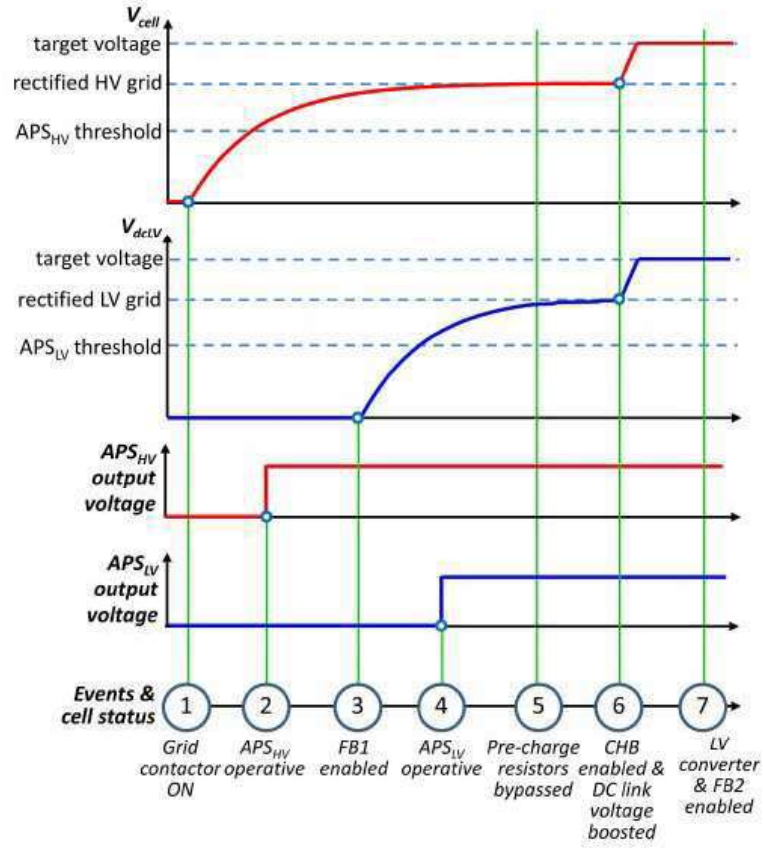
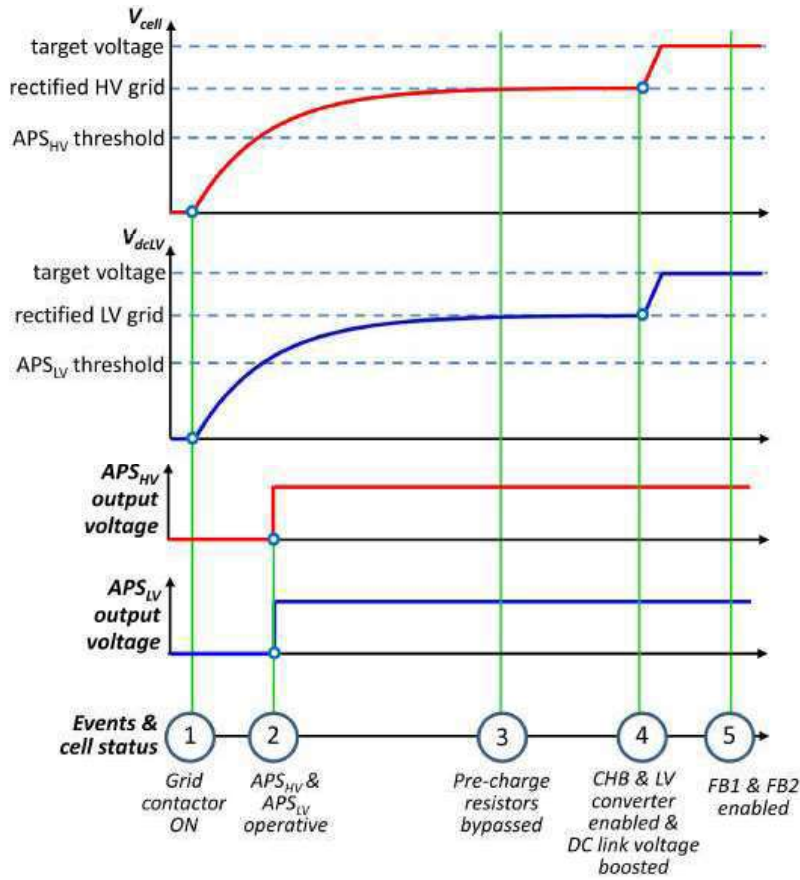


Figure 3.13: Start-up procedures proposed in [128] when the smart transformer operates as a grid-forming unit for the LV side

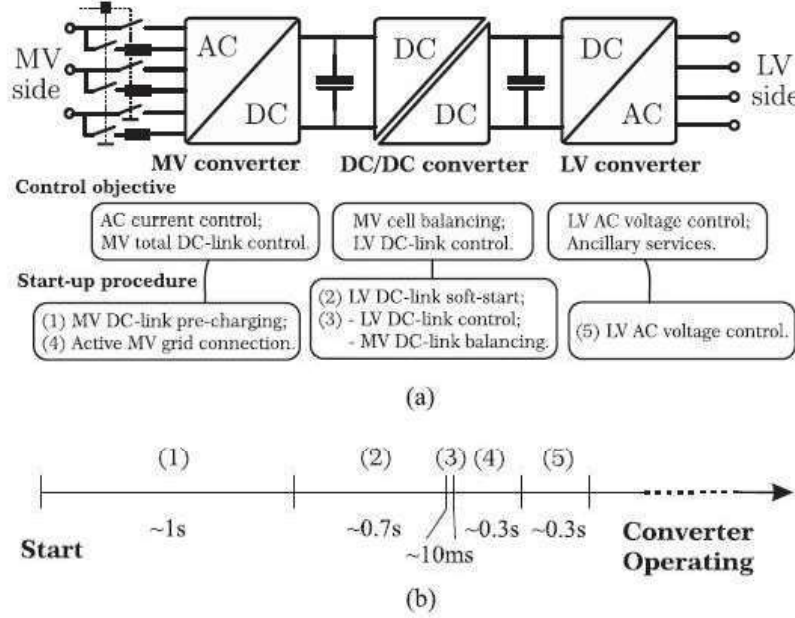


**Figure 3.14:** Start-up procedures proposed in [128] when the smart transformer operates as a grid-feeding for HV and LV sides

A soft start-up process, for a three-stage ST supplied through the MV side is also developed in [129]. Two concerns are on the basis for designing this new start-up process [129]: balancing the DC-link voltages on the MV side and soft charging of the DC-link voltages on the MV side.

Figure 3.15 provides a control objective of the conversion stage and the duration of each step of the start-up process. As mentioned previously, the conventional approach to place a precharge resistor between the grid and the input stage (AC/DC) is used to reduce the large surge current. Then, it is possible to charge the MV DC-link capacitors. The ST is operating in no-load condition at this step, absorbing power from the grid to charge MV DC-link. The second step is to overcome the voltage imbalance resulting from the MV capacitors charging. The authors propose a new modulation (soft-shift start modulation) to be applied in each DAB converter [129]. This subsequent activation of the DAB converters is useful to control DC-link voltage





**Figure 3.15:** a) Control objective of each conversion stage in the start-up procedure presented in [129]; b) start-up procedure timeline;

in the LV side, and the balance of the MV DC-link [129]. After the total activation of the DAB converters, the goal is to control all MV stages. Lastly, the control of the LV-side converter is assumed to be operated as G<sub>Fo</sub> unit. Large currents can arise during the LV-side converter start-up process if the loads are not disconnected. The LV-side converter will energize the LV feeders to establish the grid's voltage level in the first moments. As most DER are converter-based, while the voltage does not reach a stable value, these units can not be connected to the grid. However, in a smart grid environment, the higher level of controllability and the communication infrastructure can support the coordination of the loads and DERs connection for ensuring a soft start-up of the LV-side converter

### 3.8 Conclusions

This chapter provides a literature review on the applications of the ST in power systems. Based on the main characteristics of the ST described in the previous chapter, an analysis was performed to identify what applications are being developed considering the ST connected to the power systems.

From the literature review presented in this chapter, one can state that most of the works address voltage control. The possibility to support the voltage for the MV and

LV grids independently is one of the most significant advantages of the ST. The ST can support the voltage in the MV grid by compensating for the reactive power. Besides, the reactive load is not requested to the MV side, which can increase the capability of the MV inverter to inject reactive power. The voltage control can be performed on the LV side in a smart grid environment by exploiting the communication capabilities to define set-points for the active and reactive power and taking advantage of the BESS connected to the DC-link.

The decoupling resulting from the DC links is a degree of freedom to develop voltage control strategies and improve the power quality. In some works, the ST is exploited to create the filtering effect, avoiding that a disturbance in one side being transmitted to the other side. The LV inverter is usually projected to operate as a grid-forming unit providing sinusoidal balanced voltage waveforms independently of the load disturbances. Indeed, the unbalanced conditions in the LV grids and harmonics due to non-linear loads are not transmitted to the MV since the ST can create the filter effect. The same can be exploited when disturbances occur on the MV side. For instance, during voltage sags events, the ST can inject reactive power to support the voltage without there is the transmission of the disturbance to the LV side.

In the literature, several works also exploit the capability of the ST to change the frequency and voltage on the LV side. The rationale is to induce variations in the generation and consumption. Changing the frequency is possible to cause the variation in the active power output of the DER equipped with P-f droop controllers; on the other hand, the voltage variation can induce variations in the consumption since the loads are dependent on voltage. This characteristic can be exploited for different purposes, such as avoiding reverse power flow, preventing the overload of the ST and supporting the frequency control of the power systems to avoid the actuation of load shedding.

There are also some works exploiting the capabilities of the ST to operate in islanding mode and to launch BS strategies. This capability is developed considering the MV inverter can operate as a GFO unit providing three-phase balanced sinusoidal waveforms. The active power provision is performed through the BESS or DER connected to the DC link. This assumption is followed either for islanding operation and BS strategies. Nevertheless, these works demonstrate the abilities of the ST to operate in that modes through detailed simulations, which are conducted for

milliseconds or some few seconds. The goal is to analyze the short transients in the power conversion stages and provide the voltage reference in terms of magnitude and frequency. In addition, there also are in the literature several works demonstrating how to overcome the issues concerned with the inrush current and energizing of the DC link issue in the first moments of the BS procedure. Several methodologies are developed using a step-by-step process, assuming that the ST can be energized through the MV grid (grid-feeding for MV grid) or auxiliary units placed in the DC link (grid-forming for MV grid).

Despite several works addressing the islanding operation and BS using the ST, there is still to exploit how the ST capabilities can be coordinated with the fleet of DER connected to the MV and LV grids. These DER can be equipped with P-f droop controllers and thus participate in the power-frequency control. For that purpose, it will be necessary to establish a set of control strategies to coordinate the ST inverters with the DER units to establish a successful operation in islanding mode.

The literature also proves that the ST can initiate a BS procedure. BS strategies aim to restore the load in the minimum elapsed time. The DC-link in the ST enables the connection of a storage device, which enables it to operate as GfO unit during a BS procedure. However, the literature does not describe how to determine the optimal placement of ST in distribution feeders in order to initiate a BS procedure. The ST can be the main BS capability unit within the distribution grid; its location can be crucial. Build-down and top-down strategies can be designed for service restoration in distribution grids incorporating ST. Both strategies can run in parallel to minimize the load restoration time. The BS procedure launched from the ST may be synchronized with a service restoration that is autonomously running by a MG. The set of rules for service restoration in distribution grids incorporating ST is still to be defined regardless of the strategy adopted. It is also necessary to develop solutions for primary frequency and secondary frequency control throughout the BS procedure.

Furthermore, to perform a set of simulations for the islanding operation and BS strategies, it will be necessary to define proper models to analyze the average dynamic behaviour of the electric variables. These simulations aim to simulate the distribution grid behaviour for dozens of seconds or minutes. Although the existing works deal with these operation modes, the models are developed to emulate the behaviour for milliseconds or a few seconds, which are not compatible with the goals of this thesis.



## **Chapter 4**

# **Control Strategies for Multi-Microgrid Islanding Operation with Smart Transformers**

### **4.1 Introduction**

The previous chapter reviewed the applications of ST in power systems. The capabilities of the ST allow different applications on electric grids such as power flow control, voltage control, reactive power compensation and harmonic filtering. Under the three-stage configuration, the ST enables the connection of a storage device in the DC-link. As reported in the last chapter, this feature can be exploited to operate in islanded mode and launch the service restoration procedure in distribution grids.

As a consequence of the power systems decentralization, the distribution grids will have large amounts of DER connected. Besides, most of these units are connected to the electric grid through PEC. Grids dominated by inverters might be the future of power systems. The large amount of DER will require increased observability and controllability levels to manage all the distributed resources. ST will support the active integration of DER in the distribution grids by providing advanced functionalities, which also includes the support to the islanded mode. The resilience of the power systems needs to be preserved when facing disruptive events caused by extreme weather conditions or cyberattacks. The concepts of MG and MMG have been highlighted as effective solutions to improve the resilience of power systems. Basically, these concepts aim to develop function-

alities to allow the autonomous operation of grid portions by managing local resources.

A new operational framework for supporting the autonomous operation mode can be designed assuming that ST is connected in MV to LV substations. With the possibility of connecting a storage device to the DC-link, ST will have a central role as the enabler of the islanding operation. In this case, the ST with storage will operate their associated power inverters as GfO units within an inverter dominated grid. This chapter contains the presentation of the MMG framework with ST and its overall control and management architecture. The models adopted to analyze ST dynamic behaviour in islanded mode are presented. Besides, the appropriate control functionalities of DER and their corresponding power electronic interfaces are also described. The chapter also encompasses the additional control solutions to properly coordinate the ST with DER connected to MV and LV grids to ensure system survival in the moments after islanding.

## 4.2 Literature Background

### 4.2.1 Microgrids and Multi-Microgrids Concepts

MG and MMG are regarded as viable solutions to integrate the DER at the LV and MV distribution networks. They can be defined as electric bounded areas in the distribution grid, incorporating generation sources, distributed storage and controllable loads with the ability to be self-sufficient cells in the power system [9],[8], [130], [131]. While an MG is generally defined at the LV level, the MMG arises as an extension of the MG concept. MMG corresponds to a higher-level structure [10], [132], created at the MV level by comprising several MG and DER units connected on adjacent MV feeders.

MG and MMG as flexible cell of the power systems have the ability to operate interconnected to the upstream grid and autonomously. Accordingly, two operation modes are envisioned [9],[130],[131]:

- **Interconnected Operation Mode:** The MG or MMG are partially or fully supplied by the upstream grid. On the other hand, they can inject power into the upstream system when the generation within the MG or MMG exceeds the consumption. Thus, the operation of the MG and MMG can be performed with

different objectives such as the minimization of the network operating costs, improvement of the technical operation (e.g., avoiding voltage violations, losses reduction, congestion management) and provision of ancillary services to the main grid.

- **Emergency Operation Mode:** As a consequence of a disturbance in the upstream systems or to perform planned action (e.g., maintenance actions in distribution transformers), the MG and MMG can operate autonomously. In case of the unsuccessful transition to the islanded mode or due to a generalized blackout, the local resources of the MG and MMG can be used to launch a service restoration procedure. In the emergency operation mode, it is necessary to have a proper coordination strategy among storage devices, microgeneration units and loads.

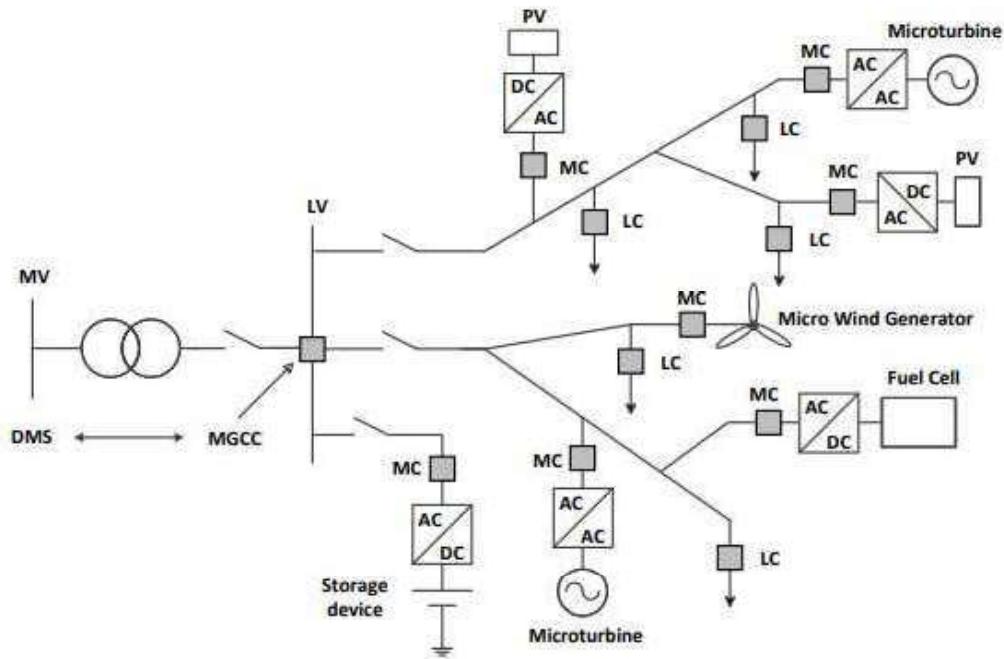


Figure 4.1: MG architecture [62]

The control of MG and MMG is usually performed through the following control methodologies [133]: centralized, decentralized and hierarchical.

Fully centralized control [134], [135], [136] relies on data collecting to a single controller that will be in charge of computing the control actions to be sent to the units connected to the MG or MMG. As the control actions are centrally computed through the information sent by the local points, high computational needs can be required to

run the algorithm for managing the MG and MMG. This control methodology has also as disadvantage the need of an extensive communication links to establish the information transmission between the local points to the central controller. In case of long distances between the local points and the central controller, this type of solution becomes impractical due to its high cost. Additionally, the centralized methods has a reliability problem because a failure in the central controller will compromise the operation of all MG or MMG. Indeed, the MG and MMG are envisioned as cells to improve the reliability and resilience of the power systems, whereby the low reliability of a centralized control structure is not compatible with that purpose.

In the decentralized control methodologies [137],[138],[139], each controller unit play its role only considering the local information and not account for the interaction with other units. This type of techniques correspond to droop approaches in which the local controllers regulate the output voltage and frequency trough the active and reactive powers. As the control actions are based on the local measurements, there is no need of using a communications which is a significant advantage to improve the reliability of the control strategy. However, this sort of control architecture has also shortcomings given the strong coupling between the operations of the units connected to the MG and MMG. There will always be necessary a minimum level of coordination among the DER within the MG and MMG, which is not possible only through local variables. Thus, a fully decentralized solutions is not feasible to be adopted for controlling MG and MMG.

Thus, hierarchical control structures [140],[141],[142] arise as a combination of the centralized and local control strategies described previously. This type of strategy is commonly used to control and manage the MG and MMG. Figure 4.1 represents a typical structure of an MG with its controllability and management components. The control and management systems allow the real-time monitoring and control of the DER units connected to the MG and the interaction with external agents like the SCADA (Supervisory Control and Data Acquisition) and DMS (Distribution Management System) from the distribution system operator (DSO). As exemplified in Figure 4.1, a hierarchical arrangement is typically assumed to manage the resources either in interconnected or islanded mode.

The hierarchical structure is headed by the MG Central Controller (MGCC) located at the MV/LV substation which interacts with DER located in the LV distribution grid. DER units are equipped with local controllers. These local controllers are different



according to the type of DER, as depicted in Figure 4.1: micro source controller (MC) and load controller (LC).

#### 4.2.2 Microgrids and Multi-Microgrids as Resilience Resource

Several research works have been developed over the last years to exploit the ability of MG and MMG to operate in the autonomous mode. The exploitation of this operation mode aims to improve the resilience of the distribution grids enabling portions of the grid to operate islanded from the upstream system.

In [143], it is presented a mathematical model to identify the formation of MG with DG in distribution grids. With the same goal, an approach is developed in [144] to identify the optimal islanding scheme. For that, the authors propose a ranking of islanding zone which are defined upon their stability indices. The formation of adaptive MMG combined with load switching sequences and mobile energy resources is addressed in [145]. In order to prevent severe consequences of blackouts, an intentional islanding scheme is developed in [146]. The authors intend to divide the power grid into a number of self-sustained islands for improving the transient stability from the interconnected to the islanded mode.

A control decentralized method is presented in [137] to control multi parallel DG units with GFC capabilities in the islanded operation mode. The use of a resilience index is presented in [147] to assess the possibility of AC/DC MG to supply local loads after sudden disruption events in the electric networks. An optimization algorithm is developed to solve the load shedding considering the load priority and penalty cost of load curtailment. Also, an approach using some customer loads with appliances controllers is exploited in [148] to avoid dynamic instabilities in the transition to the islanded mode. The authors intend to mitigate the switching transients effects, which can be caused by two main factors: reduced system inertia as a result of the proliferation of inverters and disconnection of the inverters during the transients. A multi-period dispatch model is developed in [149] incorporating frequency-aware islanding constraints. In this work, the primary control is considered in the optimization method by the discretization of continuous-time attributes. The authors aim to determine the primary reserve requirements through the simulations of under or over frequency events, instead of a previous specification of the upward and downward primary reserves.

A new methodology is developed in [150] for both operation modes interconnected and autonomous. While in the first mode the MG operate independently from each other, in the emergency operation mode some MG can provide power support to other ones. This strategy uses a two-layer cyber communication. The lower is concerned to the energy management system within each MG; the upper level establishes the link between neighbor MG in order to support the power distribution between them. In [151], it is performed an analysis to evaluate the feasibility of networked MG for improving the resilience of distribution grids considering different scenarios and levels of disruption. It is considered the MG concept to manage distribution grid in the islanded mode the with DER, namely roof-top solar photovoltaic and BESS.

The operation of the multi-part MG is addressed in [152] to determine the optimal scheduling for operating the MG resources. This study addresses the normal and emergency modes. In the normal operation mode, the authors considered a market with generation and demand bids from the individual MG and also the purchases and sales prices from/to the main grid. On contrary, in the emergency operation mode, it is considered a centralized energy management system to set up the optimal operation of the MMG to supply critical loads and part of the non-critical loads. A hierarchical outage management system under an MMG framework is presented in [153] to improve the resilience in distribution grids during emergencies situations. In this work, it is developed an algorithm to schedule the resources of each MG. In a second phase, the DSO manages eventual power transfer among MG.

Most of the works mentioned above consider optimization processes to identify the optimal formation of MG and schedule the operation of resources in the islanded mode for a couple of hours. However, in [62] is presented the definition of control strategies to evaluate the MG dynamic behaviour under islanded operation without grid-connected synchronous generators. The exploitation of the EV capabilities to participate in the power-frequency control in MG is also addressed in [154] and [155]. In [156], it is presented a hierarchical architecture for controlling the frequency and the active power in the islanded mode under an MMG structure. The works presented in [62], [154] and [155] present basic principles to develop control strategies to address the MG operation in islanded conditions, mainly to provide stable voltage and frequency regulations in the absence of synchronous generators. As the scope of this thesis is to analyze the long-term behaviour of the MMG in islanded mode, the concepts presented

in those researchs can be adapted to be part of this new MMG framework with ST.

#### 4.2.3 Microgrids and Multi-Microgrids: Operation and Control in Islanded Mode

As mentioned previously, an important feature of MG and MMG is the possibility to operate islanded from the main grid, increasing the reliability and resiliency of the distribution networks. The transition to the islanded mode requires specific control strategies for ensuring safe and stable operation. Some technical issues need to be addressed in that operation mode [8, 9, 130]: power and voltage control, power balancing and load following. Therefore, the islanded mode is more challenging than the interconnected mode once proper control strategies are needed to deal with the power balance within the MG and MMG following a sudden disturbance that creates a mismatch in the active power. The references for the voltage magnitude and frequency no anymore defined by the main grid, being necessary to have units playing this role. In the islanded mode, DG units equipped with synchronous machines or storage systems associated with grid-inverters are important to maintain voltage and frequency, while sharing active and reactive powers. Since DG units and storage systems may have limited capacity, the balancing power within the MMG system will require the proper coordination and management of all DER.

MG and MMG will integrate plenty of DER, namely DG units, microgeneration, responsive loads and storage devices. In absence of synchronous generators in the islanded zone, the existence of storage devices is crucial to enable autonomous operation. When the MG or MMG shift to the islanded mode, an energy buffering is needed to guarantee the initial energy balance. The energy storage can be provided by different technologies like flywheels, supercapacitors and batteries [157, 158]. Regarding the batteries, they can be static when they are connected at a specific point of the grid or mobile when associated with EV. Reviews on the storage technologies are provided in [157] and [158]. The reference [158] provides a review, analyzing the key factors, issues and challenges to develop storage systems in MG applications. The storage technologies are normally characterized by their energy storage capacity, response time and cost [157, 158]. High power density and fast response are the first important characteristics during the transition from the interconnected mode to the islanded mode [157, 158]. The energy storage capacity can be also important if the MG or MMG need to operate islanded for long periods, mainly when the generation units have a

low level of primary energy resources to produce electric energy.

With the proliferation of the storage systems, it is expectable that they may be connected in a distributed manner along the distribution grids, instead of being connected, for example, in the MV/LV substations. Alternatively, the proper placement of storage devices in the distribution systems can be performed through optimization algorithms as presented in [159] and [160]. In addition, the storage can be provided through the flexibility of the EV to operating in the vehicle-to-grid (V2G) mode [161, 162].

A common characteristic of the MG and MMG is the use of power electronic interfaces (DC/AC or AC/DC/AC) to convert the power output in the AC form. Indeed, some MG and MMG components like solar PV panels, storage units and EV are connected to the electric grid via power electronic interfaces. The interfacing inverters between the MG and MMG components with the electric grid are usually classified into two main group: GFe and GFo as described in 2.5.

As DER are coupled to the grid as GFo or GFe units, a proper control architecture is required to coordinate them in order to ensure a stable operation of the MMG in islanded mode. Hierarchical control structures by combining local and centralized strategies are used to control and manage the MG and MMG. These control solutions include applications in four levels [133, 163]:

- **Level 0 - Voltage and Current Loops**
- **Level 1 -Primary Control** based on droop characteristics of the DER units within the MG and MMG used to stabilize the frequency and voltage following a disturbance.
- **Level 2 - Secondary Control** aims to perform the corrective actions to eliminate the frequency and voltage steady state deviations after the response of DER units equipped with the droop control.
- **Level 3 - Tertiary Control** intends to manage the power flow with the upstream network by defining the optimal scheduling of DER units and loads for the interconnected and islanded operation modes.

The levels 0 and 1 are implemented at the DER level using the local measurements. Under an inverter dominated grid, the DER power electronic interfaces can support

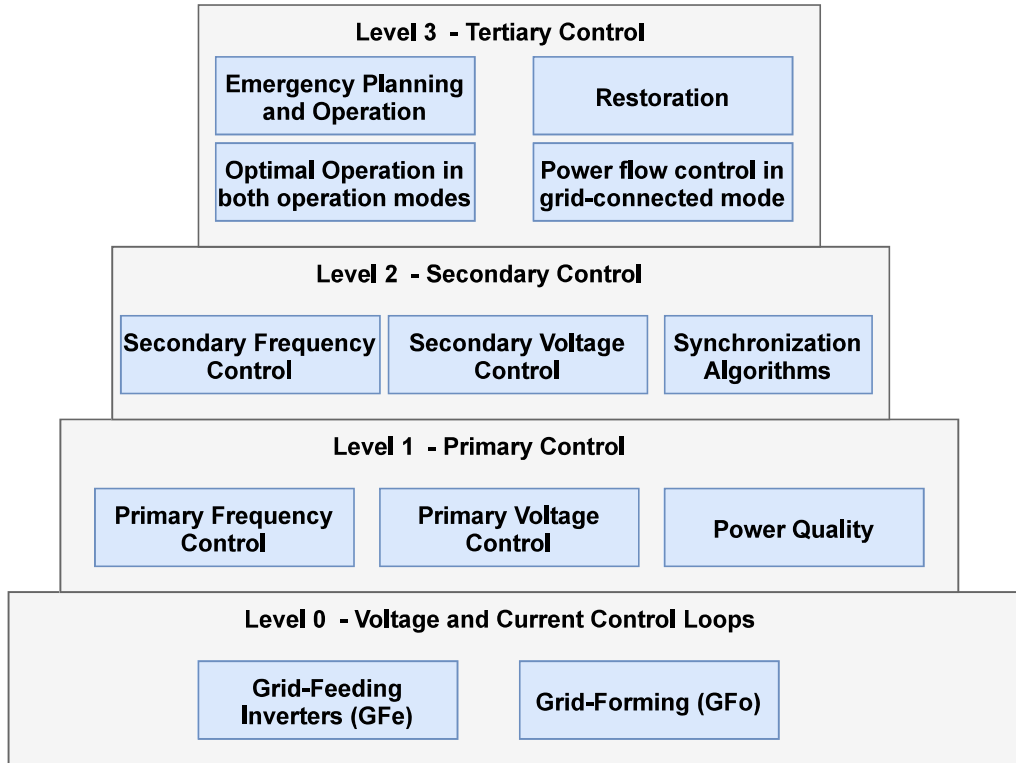


Figure 4.2: Multilevel hierarchical control (adapted from [133, 163]):

the power frequency and voltage regulation through droop controls. The droop controls in GFo units aims to emulate the behaviour of synchronous generators by creating the voltage references in terms of frequency and magnitude in accordance with active power-frequency droop (P-f droop) and the voltage magnitude-reactive power (Q-V droop). When facing a disturbance, GFo units will adjust the active power output as a function of their droop characteristics. Droop controls are useful since they do not need communication infrastructure for the load sharing between the inverters when the MMG or MG are operating in islanded mode. However, Q-V droops consider a coupling between the voltage magnitude and reactive power. The LV MG has a high R/X ratios, which corresponds to a limited effect of the reactive power control on the voltage. For that reason, alternative methods for the droop controls are usually described in the literature like P-V and Q-f droops [164], compensation of line impedance effect [165], and power-angle droop control [166].

The active power-frequency droop (P-f) does not conduct the frequency to the nominal value. This will be solved through the secondary control. It can be carried

out at local level based on the frequency measurement or through a centralized algorithm [167]. Local secondary control can be implemented by using a local proportional-integral controller. The centralized secondary control actions take advantage of the controllability of some DER, reducing the power requirements of the storage devices. Based on the information transmitted from the lower layers, a centralized controller can determine new set-points [154] for the controllable DERs in order to restore the frequency and voltage to the nominal values. Layer 2 of the multilevel control also incorporate additional functionalities to restore the voltage and synchronize the microgeneration units (e.g., supplying critical loads) with the MG [133, 163].

Tertiary Control has the purpose of managing the power flow with the upstream network by defining the optimal scheduling of DER units and loads for the interconnected [133]. In case of disruptive events, the MG or MMG can be requested to operate in the islanded mode from several hours to days provide that enough primary energy is available either from power sources or stored. In order to ensure a stable operation for a long period, the tertiary control may assume other roles like energy planning, restoration of the secondary control reserve, managing possible branch congestion or voltage violations and ensuring the storage capacity restrictions [133, 163]. Moreover, the tertiary level can also incorporate functionalities to guide a restoration procedure after a blackout.

### 4.3 Multi-Microgrid Control Architecture With Smart Transformers

In the scope of this thesis, the MMG framework for the islanded operation is adapted from the approach presented in [156] and developed by Nuno Gil in his research [132]. The control architecture adopted by Nuno Gil follows a hierarchical structure for coordinating the islanding operation and BS strategies within the MMG. However, in that work, the islanded operation was not projected to an MMG entirely comprised of power electronic interfaces. The islanding operation is mainly addressed considering thermal and hydro units connected to MV grids as the main units used to provide frequency and voltage support during the islanding operation.

The MMG framework adopted in this thesis assumes that in some secondary

substations (SS), the traditional electromagnetic transformer is replaced by a ST (Figure 4.3) with a three-stage configuration (AC/DC/AC). As described in chapters 2 and 3, the three-stage configuration (Type D) for the ST is the one that provides more degrees of freedom for developing new control functionalities. It offers the possibility of connecting a storage device in the DC-link, which is a feature exploited in the upgraded version of the MMG framework.

Two configurations are envisioned for the ST: with storage device and without storage device, as depicted in Figure 4.3. As discussed in section 4.2.3, the islanding operation requires GFO units to provide frequency and voltage references. In absence of synchronous generators, these units are usually associated with storage devices that are able to provide energy buffering. Thus, the ST with the storage device will be the key enabler of the islanding mode by providing fast power response for MV and LV grids. Within the scope of this architecture, it is possible to envision the autonomous operation of the MMG system, when islanded from the main grid (due to faults in the HV system or as a result of planned maintenance actions). In this particular operating condition, the ST will have a key role in defining frequency and voltage control strategies, as well as an element through which other DER are properly coordinated.

Therefore, the envisioned framework for the MMG assumes DG units connected to the MV grid and MG incorporating a wide variety of DER connected to LV grids via power electronic converters. A large number of devices to be controlled rises the size and complexity of the system, which requires a control and management architecture organized in a hierarchical way (Figure 4.4). The development of the hierarchical architecture relies on a bidirectional communications infrastructure in order to achieve significant observability and controllability of the MMG system.



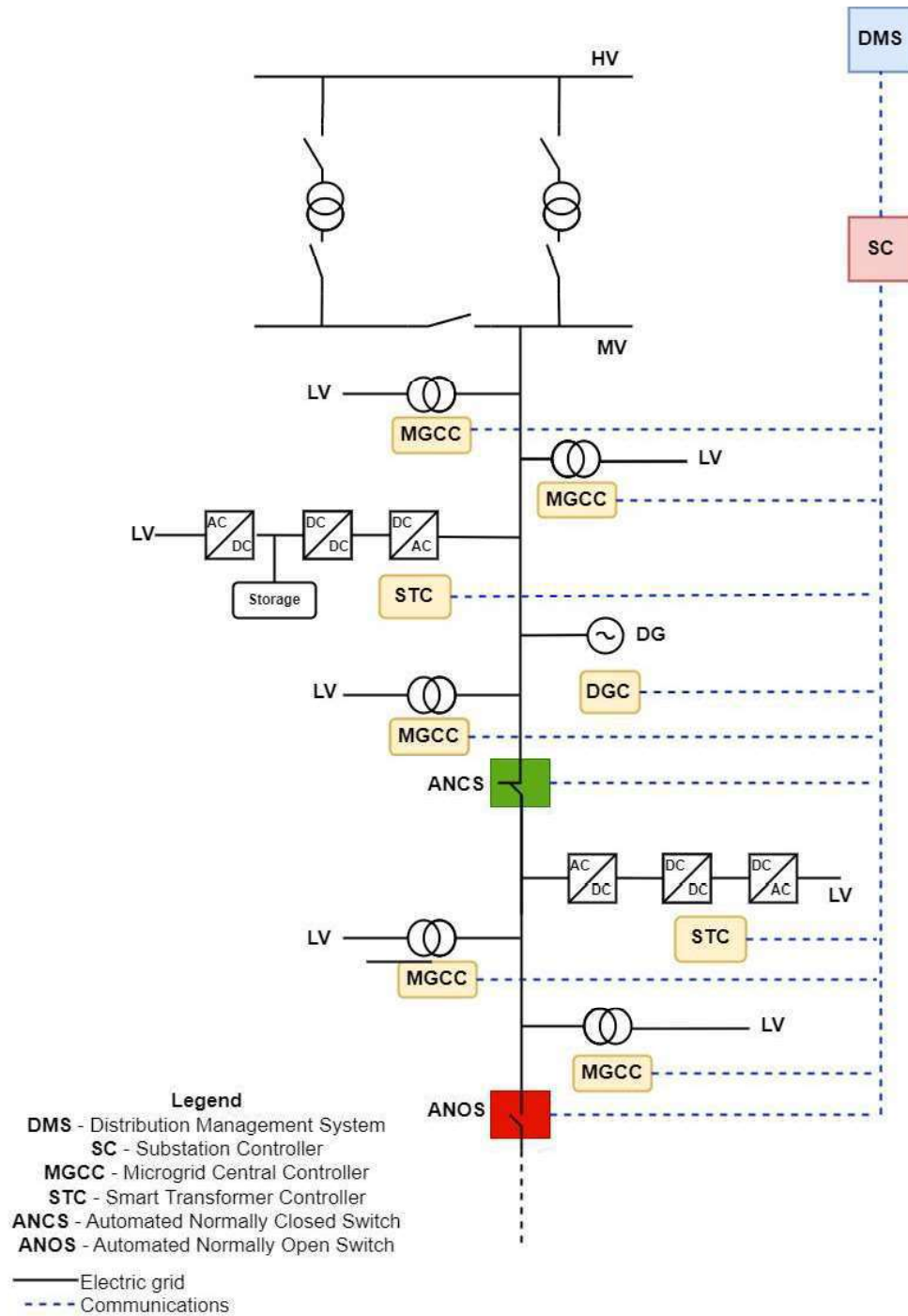


Figure 4.3: MMG concept incorporating the ST.

Communication systems are subjected to failures and delays that depend on several factors (e.g., protocols, traffic volume, characteristics of the communication channel, failures in the telcos). Also, some limitations come from monitoring and measurements devices or the inability of controllable devices to constantly modify their operating



point. These aspects may be limitations to an outstanding performance of the MMG system and, consequently, compromise a fully reliable and stable operation of the MMG. Nevertheless, these limitations are not different to those normally faced by the current arrangement of the distribution grids. In this research the islanded operation is therefore simulated assuming that the communication infrastructure is fully available to perform the required control actions.

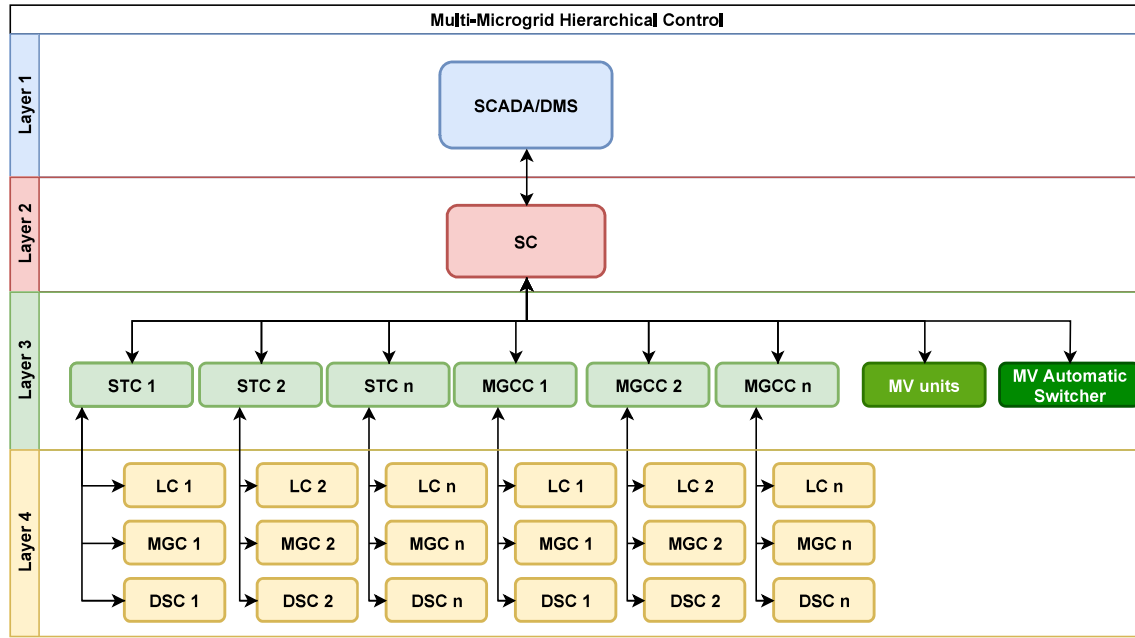


Figure 4.4: Hierarchical control structure for the MMG with ST

The head of the MMG hierarchical control structure (layer 2 in Figure 4.4) is the substation controller (SC) that is supposed to be housed at the primary substation (HV/MV). SC performs the technical management when MMG is operating disconnected from the HV system. It will be in charge of the data acquisition from the lower control layers. This data will be used to run the algorithms that support the technical management of the entire MMG system. The SC is also assumed to serve as a communication interface between the Distribution Management System (DMS) (layer 1 in Figure 4.4) and the MMG management functionalities (incorporated in the SC). For instance, when the upstream grid is again available the SC and DMS need to communicate to synchronize the MMG with the main system.

At the control layer 3 (Figure 4.4), the MGCC (in a similar approach to which was described in subsection 4.2.1) or the ST controller (STC) (when the MV is fed by a ST)

are responsible for managing the LV grid, playing the role of data aggregator from local controllers hosted downstream:

- **LC** - Load Controllers
- **MGC** - Microgeneration Controllers
- **DSC** - Distributed Storage Controllers

In layer 3 (Figure 4.4), the SC also communicates directly with the DG units connected to the MV grid (DGC) and automated switchers in the MV that can be operated remotely to change the grid reconfiguration. These devices can be normally opened or normally closed.

Both MGCC and STC incorporate control functionalities to manage LV resources. Beyond the functionalities incorporated to manage the LV grid, STC also has proper algorithms to manage and control the ST. Like the SC, the MGCC and STC also have functionalities to manage the DER units located downstream. If the MG has BS capability, it can operate autonomously by coordinating DER units until the synchronization with the MV grid takes place. In this case, the MGCC or STC will be the main entities in charge of monitoring and controlling during the service restoration process.

In order to run the functionalities that are supporting the MMG operation in islanded mode, the data from the lower levels (e.g., voltage and current measurements, active power and reactive power outputs, state of the devices, loads priority) are periodically sent to the SC through the hierarchical architecture. After receiving the information, the SC can determine new adjustments for the MMG units, like for instance, corrective actions to bring the frequency or voltage to the nominal values. The new orders are received by MGCC and STC. The last ones can then manage the DER located within each MG to fulfil the instructions sent by the SC. Concerning the DG units, the set-points are directly transmitted by the SC.

## 4.4 Power Converter Modelling

This thesis considers an MMG framework dominated by inverters. In order to analyze the dynamic behaviour of the MMG in the islanded mode, it is necessary to use proper

models for the inverters interfacing the DER and the electric grid. As reported in the subsection 4.2.3, the typical approaches for dealing with power converters in power systems are based on G<sub>Fo</sub> and G<sub>Fe</sub> concepts.

On the other hand, the ST is envisioned as a key enabler of the MMG islanded operation, being crucial the development of accurate models to include it in the dynamic simulations. As reported in Chapter 2, average models for the ST have been developed to emulate the behaviour of the ST electric variables. These models have been compared to the detailed model and they proved to be adequate to properly simulate the ST behaviour. Thus, the models developed in this research to include ST in dynamic studies are RMS models, not considering the solid-state switches, harmonics or switching losses. Additionally, the development of the ST model has been oriented to enable the operation of its inverters in the G<sub>Fo</sub> and G<sub>Fe</sub> modes. From the electric power system view, the ST can then be modelled through the control functionalities envisioned for the MV and LV inverters.

In line with the works reported in the literature, the G<sub>Fo</sub> and G<sub>Fe</sub> control strategies are considered in order to properly represent the power converter interfaces existing in the ST and DER. Therefore, the G<sub>Fo</sub> and G<sub>Fe</sub> models are the basic models for emulating the grid dynamic behaviour while exploiting the ST as an enabler of the MMG islanding operation mode. G<sub>Fo</sub> and G<sub>Fe</sub> models are described as follows in the next sections.

#### 4.4.1 Grid-Forming Mode

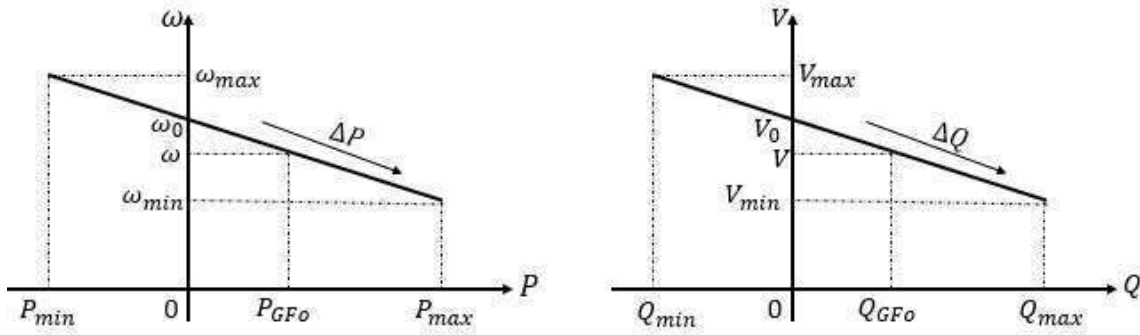
The G<sub>Fo</sub> mode is usually associated with power converters connected to storage devices where a grid forming behaviour is required [62, 63, 64, 154, 155]. In inverter dominated grids, the existence of a G<sub>Fo</sub> is mandatory for setting the voltage waveform (frequency included to which other units will be synchronized). This control mode is also applied to the capability of performing primary voltage and frequency regulation through built-in droops. Thus, the magnitude and frequency of the output voltage waveform is controlled through power-frequency (P-f) and voltage–reactive power (Q-V) droop characteristics:

$$\omega = \omega_o - K_P \times P \quad (4.1)$$

$$V = V_o - K_Q \times Q \quad (4.2)$$

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

When the MMG is in the transition to the islanded mode, the local power balance is supported by the GFo. The power imbalance cause frequency and voltage variations according to the active power-frequency and reactive power-voltage droops (Figure 4.5. By using the local information in its terminals, the GFo unit reacts to the system disturbances emulating the behaviour of the conventional synchronous machines.



**Figure 4.5:** GFo droop characteristics: active power–frequency (left) and reactive power–voltage (right) droop.

This thesis considers a three-phase balanced model of a GFo unit implementing the previously described droop concepts. In the modelling adopted in this thesis, the active and reactive power outputs of the GFOo inverter are computed from the measurements of output voltage and output current. Then, they are filtered with a low pass filter in order to obtain the fundamental components before applying the droop functions, as it is illustrated in Figure 4.6. The active power determines the angular frequency of the output voltage by the active power/frequency droop ( $K_P$ ). Likewise, the reactive power determines the magnitude of the output voltage by the reactive power-voltage droop ( $K_Q$ ).

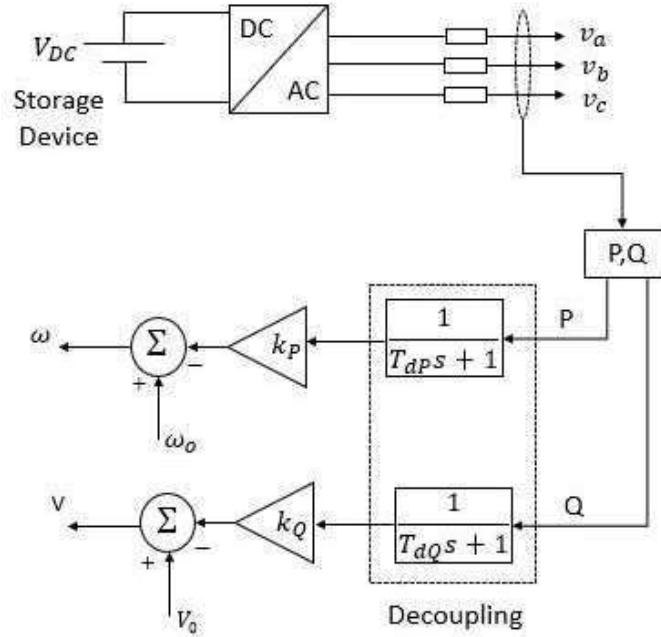


Figure 4.6: GFe model

#### 4.4.2 Grid-Feeding Mode

The GFe control is projected to operate under a grid-connected mode, injecting a given active and reactive power into the network. The set-points that define the active and reactive power levels are determined through specific algorithms or control functionalities. In addition to the active and reactive power flow control, the GFe inverter also controls the DC-link voltage in the cascading DC/AC stage [62, 63, 64, 154, 155]. Thus, the GFe inverter maintains the DC-link voltage in a specified reference and the reactive power output at the desired set-point. The variations on the DC-link are mainly related to changes in the active power flow. Accordingly, the adopted model for the GFe inverter considers a DC-DC converter stage that is responsible to keep the DC voltage constant as a function of the power flow exchange with the electric grid [62, 63, 64, 154, 155].

The DC power at the capacitor ( $P_C$ ) is the difference between the power received from the generation source ( $P_S$ ) and inverter output power ( $P_{Inv}$ ), assuming that losses are neglected (Figure 4.7):

$$P_C = P_S - P_{Inv} \quad (4.3)$$

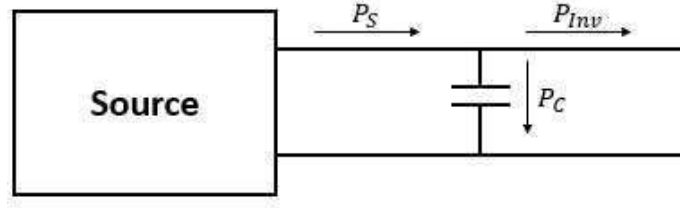


Figure 4.7: DC-link capacitor power balance

The power flow in a capacitor can then be written as:

$$P_C = V_{DC} \times I_{DC} \quad (4.4)$$

in which  $V_{DC}$  and  $I_{DC}$  are the voltage and current at the capacitor. Besides, the voltage at the DC link can be defined as:

$$V_{DC} = \frac{1}{C} \int I_{DC} dt \quad (4.5)$$

Combining the equations 4.3, 4.4 and 4.5, the dynamics at the DC link can be modelled in the frequency domain using the Laplace transform. Variations in the power flow through ST cause a DC-link voltage error, which can be corrected by a proportional-integral controller, to adjust the active power to be absorbed or delivered to the MV grid as described in the block diagram of Figure 4.8.

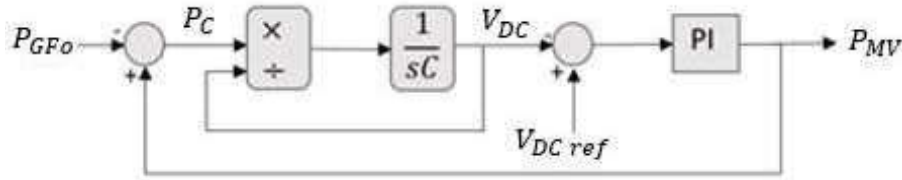


Figure 4.8: Controller block diagram DC link

With the definition of the active power set point and the desired reactive power output, the interaction with the grid is made through a controlled current source where the current is computed from the active and reactive power and from the converter terminal voltage (no large voltage sags are under consideration in this work), as shown in Figure 4.6.

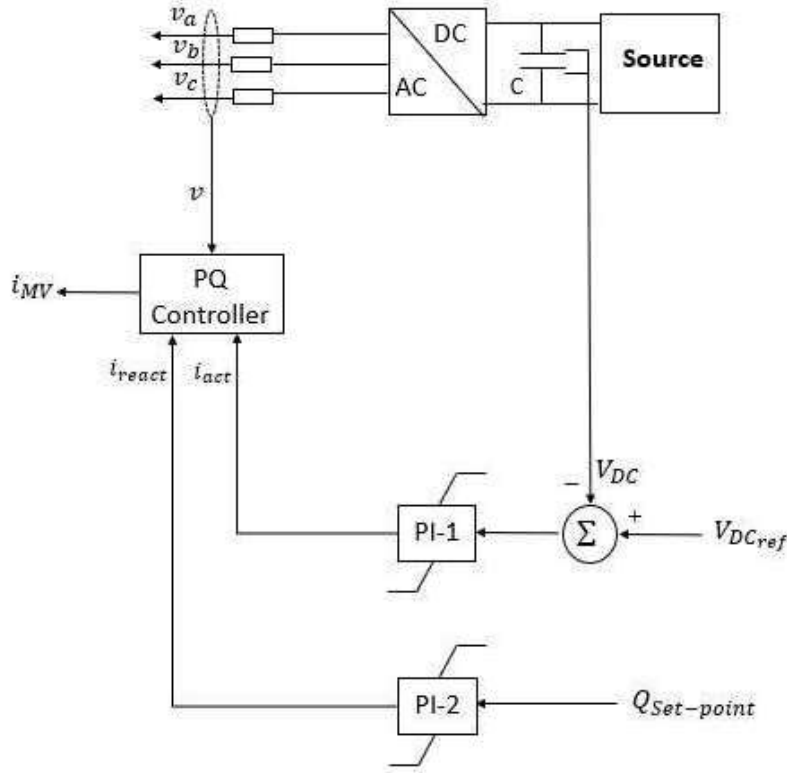


Figure 4.9: GFe model

## 4.5 Smart-Transformer Local Control Functionalities for Multi-Microgrid Islanding Operation

The framework assumed for the MMG considers that DER units connected to LV and MV distribution grids are typically inverter-interfaced. In addition, the ST brings further power electronic conversion stages to the distribution system, thus requiring:

1. the definition of at least a grid forming unit for supporting islanding operation of the MV side of the MMG system and
2. the operation of the LV side inverter of the ST always as a grid forming unit.

Furthermore, the ST may have two different configurations depending on the connection of a storage device in the DC-link. With a storage device, the power buffering can support the MV and LV grids, assuming that there is sufficient state of charge (SOC) to support the grid operations in a range of minutes to hours. Conversely,

without a storage device, there is no energy buffering and consequently only the LV inverter can operate in the GFo mode. These two configurations demand proper models to incorporate the ST in the dynamic simulations of the islanded mode.

#### 4.5.1 Smart Transformer with Storage

When the ST has a storage device connected to the DC-link, it is able to provide the necessary power buffering. Thus, ST can operate as GFo inverter for the MV and LV units. In this regard, the storage device will inject active power for both the MV and LV grids of the MMG. In this case, there is a fully decoupling (including active power) between the two subsystems.

Considering an MMG with a significant amount of renewable-based generation units, the excess of generation regarding the consumption during normal operating conditions can be stored in the storage device connected to the DC-link. When facing disruptive events like faults in the upstream system and general blackouts, the stored energy can be used to support the systems, improving reliability and resilience. In this sense, the combination of storage systems and generation from renewables is extremely valuable to support the grid operation in the islanded mode.

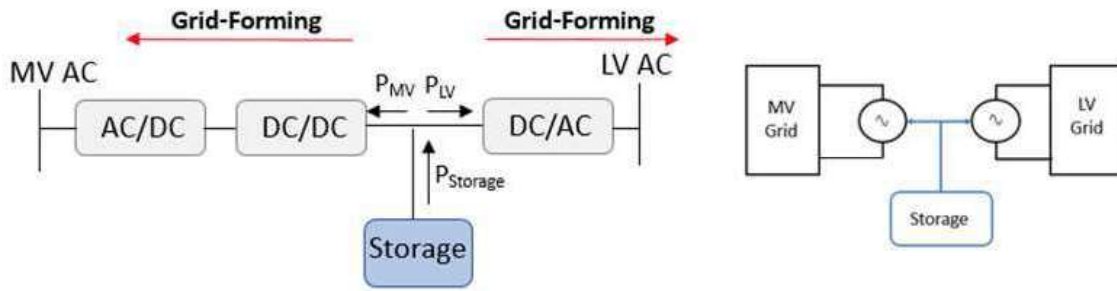


Figure 4.10: ST with an integrated storage device

When operating as a GFo units for both the MV and LV sides, the ST can be modelled as two independent droops-controlled AC voltage sources (Figure 4.10 and Figure 4.11) following the principles presented in 4.4.1. While in the islanding mode, the two inverters generate references for voltage and frequency for the Mv and LV grids. The energy for the two voltage sources is provided by the energy storage system, assuming that it can provide the required power to balance the system when a disturbance occurs. It is considered there is no energy limitation nor power



restrictions for the energy storage device, taking into account the time intervals of the dynamic simulation studies addressed in this research (tens of seconds). In case of power limitations might take place, the inverters will not be capable to operate in the GFo. As consequence, the MMG islanded mode will be at risk, mainly if MMG has only one GFo unit.

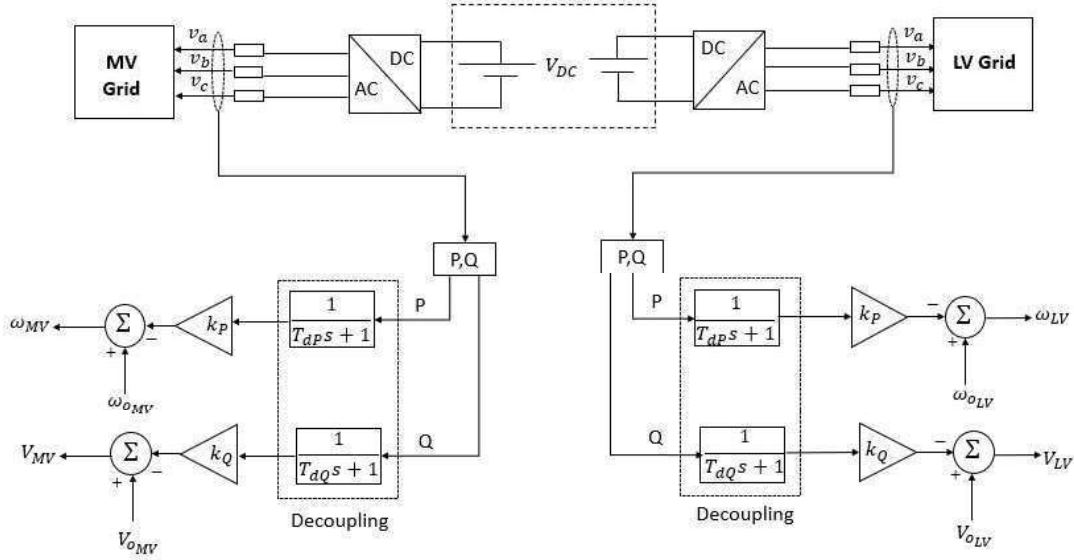


Figure 4.11: Model for the ST with storage

#### 4.5.2 Smart Transformer without Storage

When the ST does not have a storage device connected to the DC-link, only the LV inverter will act as GFo unit (Figure 4.12 and Figure 4.13), corresponding to an AC voltage source with the droop characteristics presented in 4.4.1. In this arrangement, there is no power buffering to support the MV inverter as GFo unit. The MV inverter will operate as GFe (as described in 4.4.2), injecting or absorbing active power depending on the balance between the generation and consumption in the MG. The decoupling between the MV and LV grids exists for frequency, voltage and reactive power, but not for the active power.

The common point between the two inverters will be the active power. As represented in the Figure 4.13, the active power output of the LV inverter will be an input in the GFe inverter.

The reactive consumption in the MG is not requested to the MV, since the reactive power can be generated locally at the ST level. Thus, the MV inverters can support the voltage control through Q/V droop controllers or set-points independently from

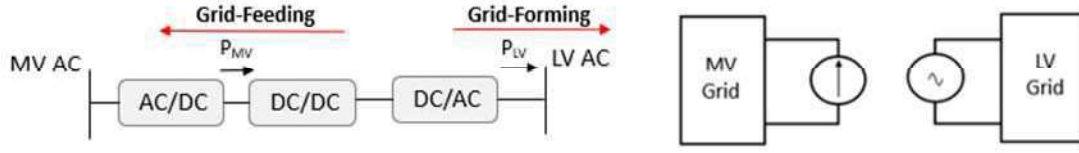


Figure 4.12: ST without storage device

the LV side. The SC can define a new reactive set-point to the ST for supporting the voltage regulation in the MV grid. As the two AC subsystems are decoupled due to the ST, a disturbance at the MV will not directly cause a response by the DER located in the LV (mainly if they are equipped with droop controllers). For that reason, proper coordination strategies need to be considered in order to enable the participation of LV DER in the overall primary support of the MMG. This coordination strategy is addressed in the next sections.

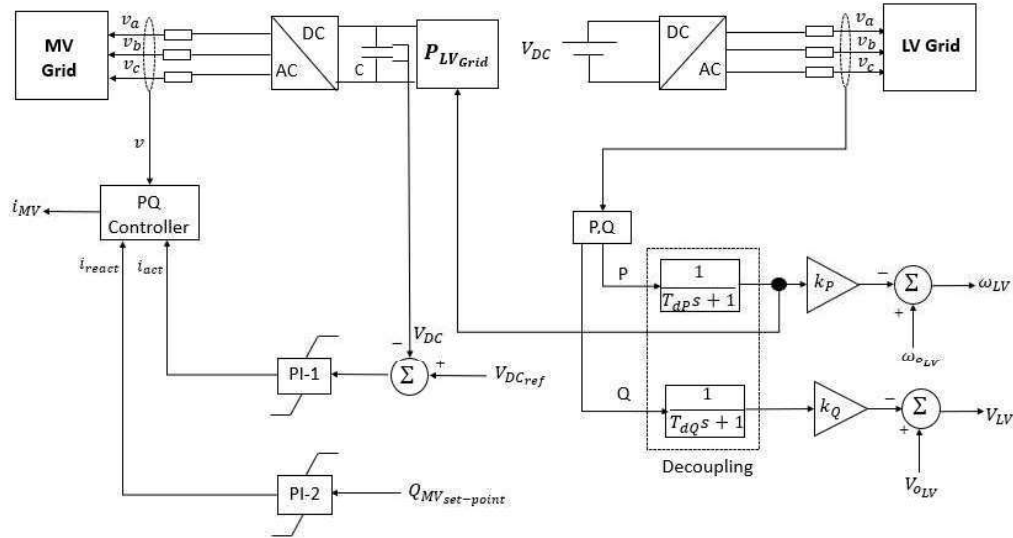


Figure 4.13: Model for the ST without storage

## 4.6 Primary Voltage and Frequency Control

### 4.6.1 Single-Master and Multi-Master Operation

Two operation modes can be considered depending on the number of ST with storage in the DC stage: Single-Master operation (SMO) and Multi-Master operation (MMO).

For the first mode, a single ST is equipped with a storage device, acting as a GFo unit (master) unit for the MV grid. ST without storage are operating as GFe inverter (slaves). The main GFo unit operates according to the droop principles described in 4.4.1. Under the MMO approach, two or more ST are equipped with storage and, thus, operating as GFO inverters for the MV and LV grids. In this operation mode, the primary frequency regulation at the MV level of the MMG system is shared among several ST operating as GFo. While facing a disturbance, the GFo inverters will respond to the power unbalance in the MMG in accordance with the individual droop characteristics:

$$\Delta P = \sum_{n=1}^n \Delta P_i \quad (4.6)$$

where  $\Delta P$  is the total unbalance between the MG generation and load in the MMG and  $\Delta P_i$  is the active power injected by the  $i$ -th GFo unit. Both frequency deviation and power-sharing among the GFo units can be computed by the following system of equations:

$$\begin{bmatrix} 1 & K_{P1} & 0 & \dots & 0 \\ 1 & 0 & K_{P2} & \dots & 0 \\ \dots & \dots & \dots & \ddots & 0 \\ 1 & 0 & 0 & \dots & k_{Pn} \\ 0 & 1 & 1 & \dots & 1 \end{bmatrix} \cdot \begin{bmatrix} \omega' \\ \Delta P_1 \\ \Delta P_2 \\ \dots \\ \Delta P \end{bmatrix} = \begin{bmatrix} \omega_{Grid} \\ \omega_{Grid} \\ \dots \\ \omega_{Grid} \\ \Delta P_n \end{bmatrix} \quad (4.7)$$

where  $\omega'$  corresponds to the post-disturbance MMG angular frequency (rad/s) and  $\omega_{Grid}$  is the pre-disturbance MMG angular frequency (rad/s).

As demonstrated by the equation 4.7, the power-sharing among several GFo units in the MMO mode relies only on the local measurements without the need for communication links among them. Although the MMO allows sharing the burden of the power unbalance among different GFo units, the frequency will not reach the nominal value. Secondary frequency control actions are needed for correcting the primary frequency deviations supported by the GFo units.

In order to complement the frequency control assured by GFo inverters of the ST, other DER connected to the MV and LV grid are envisioned to support the overall primary frequency control. Under the MMG framework adopted in this thesis, the DG, microgeneration and DES are modelled as GFe inverters. These units are endowed of P-f droop characteristics to support grid balancing following a frequency deviation, as

described in the following sections.

#### 4.6.2 Frequency Coordination Control at the Smart-Transformer

The three-stage configuration with two DC-links creates decoupling between the MV and LV grids. Consequently, the DER units in the MG fed by a ST will not automatically take part in the power-frequency control after a disturbance in the upstream system. As described in the chapters 2 and 3, ST is capable of changing the frequency to induce variations on the active power output of DER equipped with the P-f droop controllers.

The LV inverter of the ST is envisioned to operate as GFO unit, which makes it possible to change the frequency in the MG for responding to frequency events in the MV grid. In this regard, the LV frequency can be modulated by changing the ideal value of the angular frequency as a function of the MV frequency. For that purpose, a new droop-based rule control is implemented in this thesis to simulate the modulation of the MG angular frequency as a function of the MV frequency. The following set of equations and Figure 4.14 describe the droop-based rule:

$$\omega_{oLV} = \begin{cases} \omega_{oi} + k_{fMV}, & f_{MV} > 50.2\text{Hz} \\ \omega_{oi}, & 49.8 \leq f_{MV} \leq 50.2\text{Hz} \\ \omega_{oi} - k_{fMV}, & f_{MV} < 49.8\text{Hz} \end{cases} \quad (4.8)$$

where  $\omega_{oLV}$  is the idle angular frequency for the LV grid,  $\omega_{oi}$  is the initial value for the idle frequency,  $k_f$  is the droop slope and  $f_{MV}$  is the frequency in the MV grid.

This control strategy aims to ensure the participation of DER connected to the LV grid (microgenerators and DES) in the overall power-frequency control strategy for the MMG, not requiring communications between the ST and local controllers. As shown in Figure 4.14, this control strategy has a frequency dead-band that can be adjusted (in the range of [49.8; 50.2] Hz). The rationale is to avoid the response of LV resources to events resulting in small frequency variations. Regarding the LV angular frequency-MV frequency droop characteristic, the  $k_f$  value was identified by a trial and error procedure. Further research can be conducted to optimize its design as a function of the resources connected to the grid.

When both inverters of the ST are operating in the GFO mode, it is considered that the storage device connected to the DC-link responds to the MMG needs without storage capacity restrictions. Therefore, in this case the modulation of the LV frequency in the

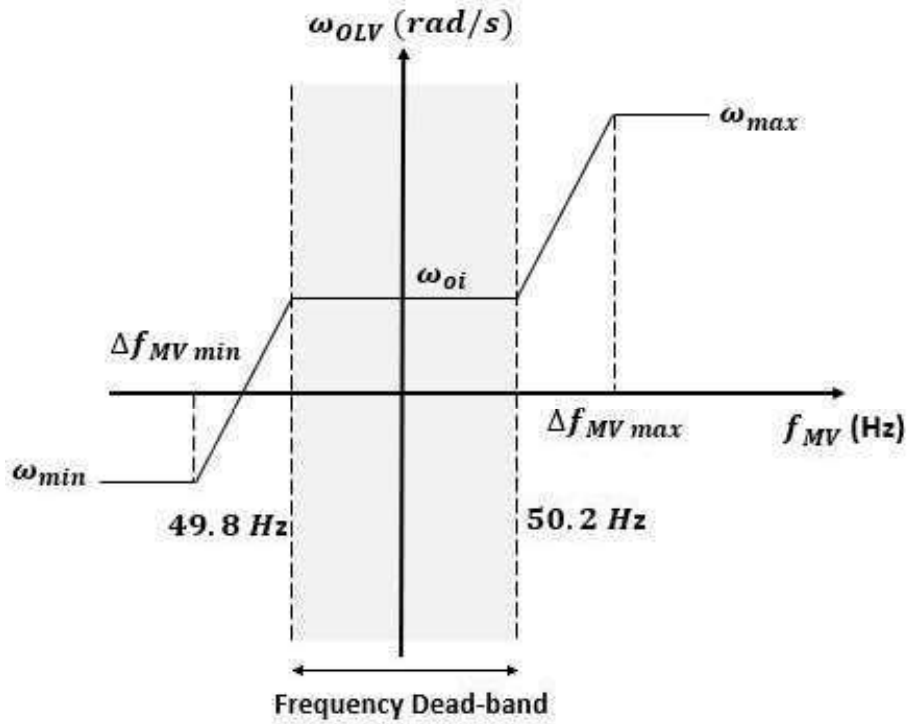


Figure 4.14: LV angular frequency-MV frequency droop characteristic

moments subsequent to the islanding transient (short time frame of few minutes) is not applied. For larger periods of time, the supervisory control solutions performed by the SC can be applied to modulate the generation in the MG, if necessary. Therefore, the control strategy by using a LV angular frequency-MV frequency droop characteristic is only implemented in the ST without storage device.

### 4.6.3 Solar Power Generation

The simplest mathematical representation of a PV array is the diode model which reflects the current-voltage characteristics of the cell [168]. Given the characteristic of the V/I of the PV cells, they usually have a control scheme for extracting the maximum energy of the panel. The control module in charge of achieving the optimal operation point is denominated as Maximum Power Point Tracker (MPPT) [168, 169, 170, 171]. In a basic arrangement, the PV system has the PV array linked to the MPPT (Figure 4.15). This module usually corresponds to a DC/DC converter controlled by specific algorithms to set up the MPPT. A DC/AC converter is the interfacing between the PV system and the grid.

Despite several MPPT algorithms can be found in the literature [170, 171], it is

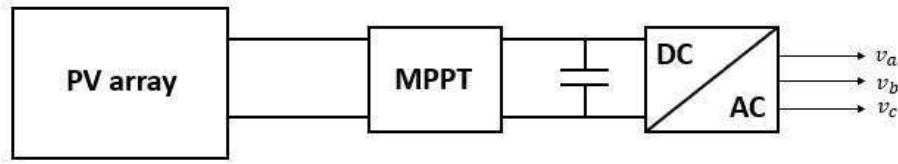


Figure 4.15: Simple configuration of a PV system

not under scope of this thesis to address how to model them neither analyze their performance. Hence, the model adopted for the solar power generation considers that these units are operating with the ability to extract the available power from the solar resource.

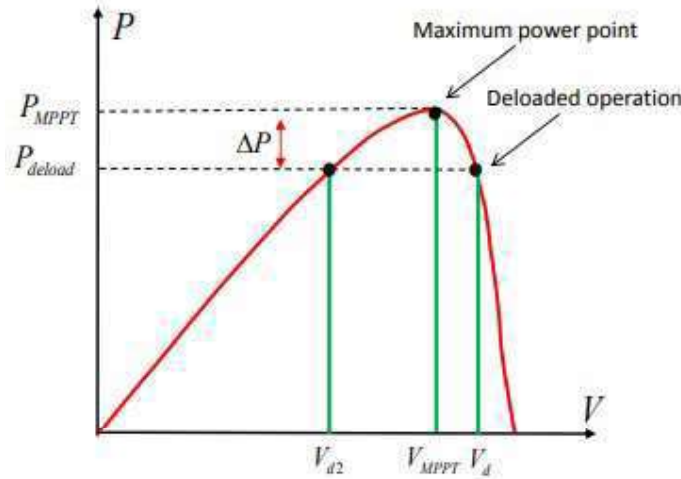


Figure 4.16: Deloading process in solar PV plants [172]

Conversely to conventional generators, PV systems do not have rotating mechanical parts. There is no kinetic energy to be used for power-frequency support. The increasing growth connection of solar generation systems to the electric grids is leading to the development of solutions to allow their participation in the power-frequency control [172, 173]. For that, the active power  $P$  generated by a solar PV cell is controlled by adjusting the output voltage  $V$  as depicted in Figure 4.16. The solar PV cell is then operating in the "over-voltage" mode in order to provide reserve capabilities. When solar power system is working on the deloading mode instead of operating in the MPPT point, there will be some reserve to provide active power in moments after the islanding. With the power reserve available, the solar power plants can also emulate the frequency droop characteristics. The same rationale can be applied in cases of over frequency event. In this case the solar systems equipped with the P-f droop controller

can reduce the injected power in order to support the overall MMG power-frequency control.

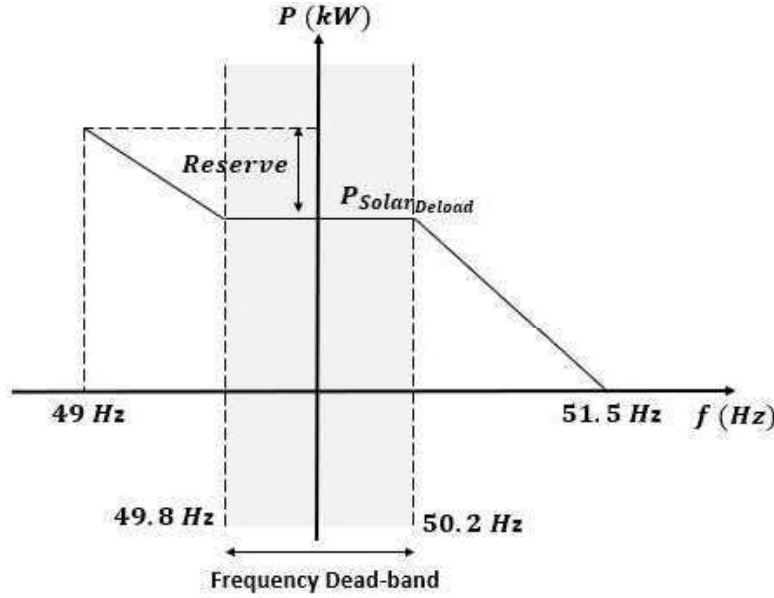


Figure 4.17: Power-frequency droop characteristics in solar power generation

Thus, an active power-frequency modulation is implemented for frequency deviations to simulate the participation of the solar generation systems in the downward and upward reserves (Figure 4.17 and Figure 4.18). The model adopted for the solar power generation assumes that these units are equipped with control algorithms capable to guide the solar systems for providing participation in the frequency control as aforementioned above.

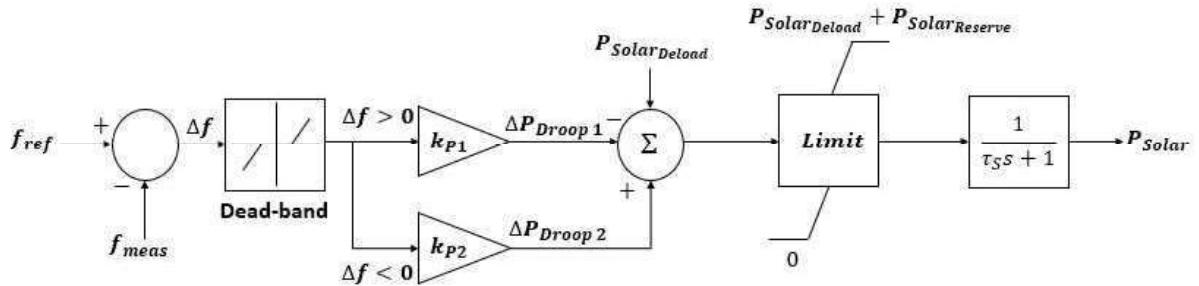


Figure 4.18: Block Diagram for the power-frequency droop in solar power generation

A frequency dead-band (that can be parametrized) is also implemented for the activation of this regulation functionality, as depicted in Figure 4.17 and Figure 4.18. In this case, whenever the frequency achieves a value higher than 50.2 Hz or smaller than



49.8 Hz, the droop control is activated to respond to the frequency's variations. In the model presented in Figure 4.18,  $\tau_s$  represents the time response of the PV inverters of the solar power generation and it is in the range of 0.5. The interfacing with the grid of the solar generation is done through a GFe inverter model as described in the section 4.4.2.

#### 4.6.4 Distributed Energy Storage

The DES connected to different points of the LV distribution grid will adjust the power exchanged with the grid following the droop characteristic presented in Figure 4.19. When facing a disturbance that causes a frequency deviation to become outside of the dead-band ([49.8;50.2] Hz), the DES will change the active power. Following an over frequency disturbance, if the storage device is operating as a "generator" (lower line in 4.19) and thus injecting active power into the grid, it decreases its power injection. On the contrary, if it is operating as "load" (charging), the storage increases the power consumption (higher line in 4.19). If the disturbance causes a large frequency deviation, the storage systems can even change their operation mode (from "generator" to "load") in order to support the overall power-frequency control within the MMG.

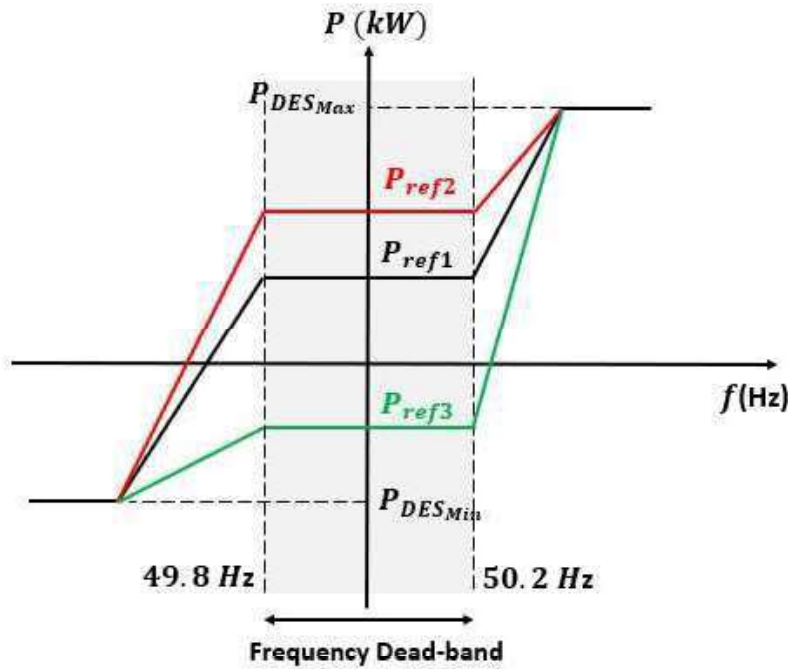


Figure 4.19: Power-frequency droop characteristic for DES units

Similarly, when facing an under-frequency event, the storage devices operating in the charging mode ("load") will decrease their consumption or change the operation



mode to discharging depending on the frequency deviation. The storage devices operating in the discharging mode ("generator") will increase their injection.

For any case, the participation of the DES in the primary frequency control is restricted to its rated power, which defines the maximum/minimum value to inject/absorb into/from the grid. The DES will have a value to characterize the maximum power capacity of those devices:  $P_{DESmax}$  and  $P_{DESmin}$  (Figure 4.19). In the scope of this research, it is supposed that MGCC or ST can change remotely the power consumed or injected by the DES. These actions are taken in accordance to set points received from the centralized secondary frequency control, as it is described in the next section. The block diagram that describes the power contribution of the DES when facing grid frequency changes is similar to the one implemented in the solar PV power generation. The interface with the grid is modelled as GFe GFe unit.

#### 4.6.5 Primary Voltage Control

The MMG framework adopted in this research considers the ST as an interface device between the MV and LV distribution grids. When a storage device is connected to the DC-link, the MV inverter is modelled as GFo. Concerning the voltage control, that unit defines the voltage reference in terms of magnitude. Following the V-Q droop characteristics, the GFo unit defines the voltage reference as a function of the reactive power consumption within MMG. As the distribution grids are usually operated in a radial structure, it can happen that the voltage in the furthest buses can be below the nominal value. In high loads conditions and reduced local generation scenarios, the voltages can reach values significantly below the nominal one. In high loads and reduced generation scenarios, the voltages can reach values significantly below the nominal one. This situation can be particularly critical in the SMO strategy, where only one GFo unit is regulating the voltage. When the MMG is being operated under a MMO strategy, the voltage reference is defined simultaneously by the several GFo units connected to the different MV nodes.

The ST can provide reactive power to the LV grid without requesting the MV sides. This represents an advantage for keeping an adequate voltage profile in the MV feeder. In addition, the MV inverters of the ST without the storage device can provide reactive power support. The reactive power injected or absorbed can be defined through a Q-V droop [174, 175]. Thus, complementing the V-Q droop control in the GFo, ST without storage can provide reactive power depending on the local voltage measurement. A

Q-V droop is implemented in the ST operating as GFe to the MV grid (Figure 4.20).

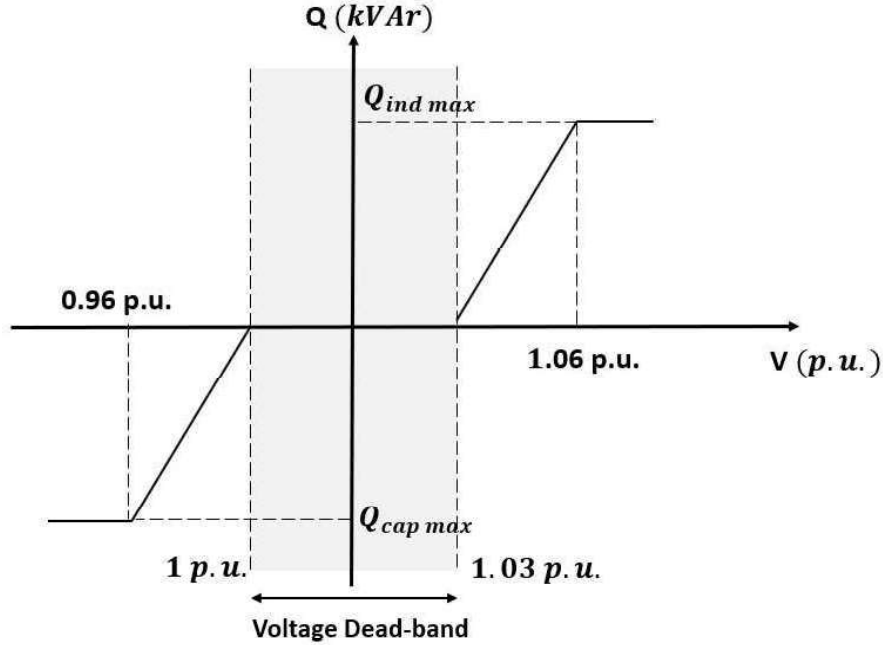


Figure 4.20: Q-V droop characteristic in the ST without storage

When the local voltage measurement is smaller than the nominal voltage, the ST operating as GFe unit will inject reactive power to the MV grid. The MV inverter will inject the maximum value of reactive power ( $Q_{cap_{max}}$ ) as the voltage achieves the minimum value (0.96 p.u.). This value will rely on the MV inverter size (apparent power). In addition to the reactive power, the MV inverter also absorbs or injects active power. The injection/absorption of active power depends on the power balance within the MG. For example, if the active power is fully balanced within the MG (consumption equals the generation), there is no active power exchange with the MV grid. Consequently, the MV inverter has a higher capacity to inject reactive power since it is exempted from injecting or absorbing active power. On the contrary, if the voltage is higher than the 1.03 p.u., the MV inverter of the ST absorbs reactive power. Like in the case previously described, the ability to absorb reactive power also depends on the MV inverter size, which corresponds to the ( $Q_{ind_{max}}$ ).

This voltage control strategy seeks to keep the MV voltage profiles within admissible values during emergency operation conditions like the islanded mode. In the MV distribution lines, the inductance of the distribution lines is sometimes predominant

regarding the resistance. Thereby, the reactive injection (or absorption) can be a proper strategy for voltage support in the subsequent moments after the disconnection from the upstream grid. Advanced functionalities can be developed in the scope of the tertiary control actions to define optimal set-points for the reactive power while minimizing the losses.

## 4.7 Secondary Frequency Control

The ST with the storage device connected to the DC-link will be the key unit to operate in the GFo mode for the MV and LV sides in the islanded mode. During the transition to the islanded mode, this unit will ensure the power balance by injecting or absorbing active power while the frequency does not achieve the nominal value. While the primary frequency control aims to maintain the grid stability and the balance between load and generation by automatically adjusting the active power output of the DER according to the P-f droop controllers, the secondary frequency control brings the frequency to the nominal value (50Hz). The secondary frequency control determines new active power set-points for the DER resources connected to the MMG for that purpose. Besides, a local frequency control is required to eliminate the frequency error after the centralized control actions in the ST without storage. In this arrangement, the ST is simultaneously subjected to two droop mechanism: active power-frequency and LV angular frequency-MV frequency. For that reason, the centralized secondary control actions cannot be sufficient to conduct the LV frequency to the nominal value.

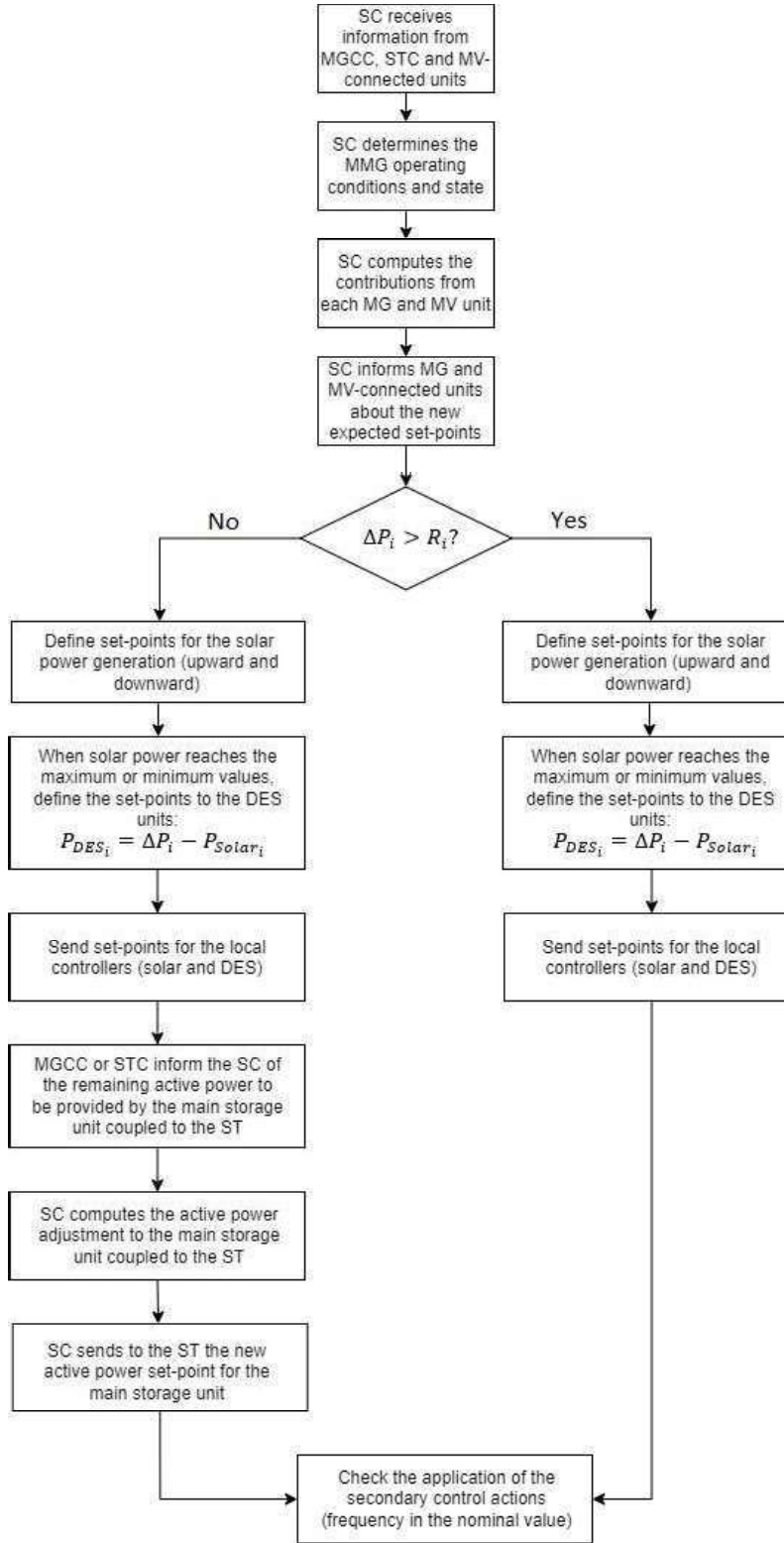
### 4.7.1 Centralized Frequency Control

The primary frequency control is supported by the ST equipped with a storage device (operating as GFo unit) and DER units equipped with P-f droop controls. Secondary frequency actions are then required to restore the frequency to the nominal value. The centralized secondary frequency control corresponds to a tool integrated into the SC. This tool will run after the transition to the islanding mode in order to bring the frequency to the nominal value. While primary control actions are based on the local measurements, secondary frequency control relies on the communication infrastructure to send the set-points to the DER. The centralized control takes advantage of the capabilities of the solar-based microgeneration, DES units and storage unit coupled to the ST for providing active power reserve.

Therefore, the secondary frequency control actions aim to bring the frequency to the nominal value within the MMG. After the transition to the islanded mode, the ST with the storage device and DER compensate for the power unbalance. The proposed centralized secondary frequency control will act as much as possible on the DER units connected to the MMG to match the generation to the load. The underlying idea is to balance the load and generation through the DER without using the main storage unit connected to the ST. After the primary frequency control actions, the power unbalance to be compensated is measured at the MV GFO terminals. The secondary control will define new active power set-points to eliminate that unbalance. With enough reserve capacity within the MMG, the main storage unit coupled to the ST would not have injection or absorption of active power to support the secondary frequency control (neglecting the electric losses in the MMG).

Nevertheless, if the power unbalance is higher than the reserve, the storage coupled to the ST can participate in the secondary frequency control. Either DES and the ST-coupled storage have enough SOC to support the requests from the secondary frequency control during the simulation times addressed in this thesis. For that, the storage units can operate during normal conditions in order to guarantee adequate SOC for supporting the MMG after disturbances. For large periods of time operating in islanded mode, tertiary control actions are required to optimally schedule the DER resources considering the load and generation forecasting. This is not a subject of this thesis since the goal is to identify the control functionalities for operating a MMG in islanded mode with ST and a fleet of DER.

In the scope of this thesis, an algorithm is implemented for defining the centralized frequency control actions for the MMG (Figure 4.21). Firstly, there is the characterization of the MMG operating conditions. Each local controller sends data (electrical measurements, reserve level, status of the devices) to the MGCC or STC. In turn, MGCC and STC will aggregate the data from the local controllers located downstream. There is direct communication between the DG units connected to the MV grid and the SC. Then, SC receives the information aggregated by the lower control layer (MGCC, STC, DGC) to determine the adjustments for the MG and MV grid-connected units.



**Figure 4.21:** Algorithm for management of the MMG resources in the secondary frequency control actions

The definition of new set-points is essentially based on the active power unbalance ( $\Delta P$ ) after the transition to the islanded mode and on the reserve level within the MMG ( $R$ ). The power unbalance ( $\Delta P$ ) characterizes the severity of the disturbance triggered by an unplanned disconnection from the upstream grid. The unbalance corresponds to the difference between active power generation and consumption within the MMG. The contributions from DG units and MG connected are determined by computing participation factors ( $f_{pi}$ ) using the data provided by the MGCC, STC and MV-connected units. The active power set-points for the MG and MV-connected units are defined as follows:

$$\begin{cases} f_{pi} = \frac{R_i}{R} \\ \Delta P_i = \Delta P \times f_{pi} \\ \sum_{i=1}^n \Delta P_{MG_i} + \sum_{i=1}^n \Delta P_{MV_{Grid_i}} = \Delta P \end{cases} \quad (4.9)$$

where  $\Delta P_i$  is the active power set-point adjustment for the unit  $i$  (MG or MV-connected),  $\Delta P$  is the active power unbalance following a disturbance,  $R_i$  is the reserve capacity of unit  $i$  (MG or MV-connected) and  $R$  is the total reserve level within the MMG.

The reserve level within the MMG relies on the ability of the DES and solar power generation units to change the active power in accordance with the set-points defined by the SC. As described in sections 4.6.3 and 4.6.4, either DES and solar power units are capable of providing active power reserve. As the DES units can inject or absorb active power and the solar generation units are operating in the deloading mode, the MMG will have upward and downward reserve:

$$\begin{cases} R_{up} = \sum_{i=1}^n R_{up_{MG_i}} + \sum_{i=1}^n R_{up_{MV_i}} \\ R_{down} = \sum_{i=1}^n R_{down_{MG_i}} + \sum_{i=1}^n R_{down_{MV_i}} \end{cases} \quad (4.10)$$

where  $R_{up}$  and  $R_{down}$  correspond to the MMG total reserve capacity up and down,  $R_{up_{MG_i}}$  and  $R_{down_{MG_i}}$  are the reserve capacity up and down of MG  $i$ ,  $R_{up_{MV_i}}$  and  $R_{down_{MV_i}}$  represent the reserve capacity up and down of MV-connected unit  $i$ .

Within each MG, the reserve level corresponds to the additional active power that can be provided (upward and downward) by the DES and solar generation units:

$$R_{MG_i} = R_{DESi} + R_{Solar_i} \quad (4.11)$$

where  $R_{MGi}$  is the reserve capacity up and down of MG  $i$ ,  $R_{DESi}$  corresponds to the reserve capacity up and down of DES in the MG  $i$  and  $R_{Solari}$  is the reserve capacity up and down of solar-based microgeneration units located in the MG  $i$ .

After the computation of the participation factors, the SC will send the set-points to the MV units and to the MGCC or STC, in case of the LV grid is served by a CLFT or a ST. At the LV level, the MGCC and STC will manage the local resources within the MG considering the availability of the DER units. As depicted in Figure 4.21, the MGCC and STC manage the DER within the MG following pre-defined priority order. Firstly, they act on the solar-based microgeneration and, then, in the storage devices. When the MGCC and STC detect that the adjustments on the solar-based microgeneration are insufficient to ensure the requested level for the active power flow between MV grid and MG, the next step is to take action on the active power of the DES devices.

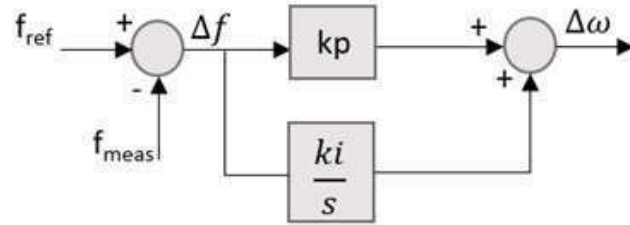
When the active power adjustment is higher than the reserve level within the MG, the storage unit of the ST can be part of the centralized secondary frequency control. After the adjustment on the solar-based microgeneration and DES devices, the power unbalance above the reserve level will be compensated by the main storage unit placed in the ST.

#### 4.7.2 Smart Transformer in the Secondary Control – perspective of the LV side

As described in the section 4.6.2, the ST without a storage device will vary the LV frequency in accordance with the droop control function between LV angular frequency-MV frequency (Figure 4.14) whenever the MV grid frequency is outside the pre-defined dead-band (for example [49.8;50.2] Hz). Simultaneously, those resources are also subjected to the control actions defined by the centralized frequency control. However, enabling centralized secondary frequency control does not guarantee that the ST-connected MG reaches the nominal frequency as a result of the active power set-points defined for their resources. Hence, this research considers a local integral control to eliminate the frequency deviation in the ST-connected MG. As the LV inverter is operating as G<sub>Fo</sub> unit, the local secondary control can be performed by updating the idle frequency of the P-f droop function (Figure 4.22). An integral controller is implemented to determine the new idle frequency considering the LV MG frequency deviation in order to update the active power droop characteristic. This local control mechanism changes the ideal frequency value of the G<sub>Fo</sub> inverter, while maintaining

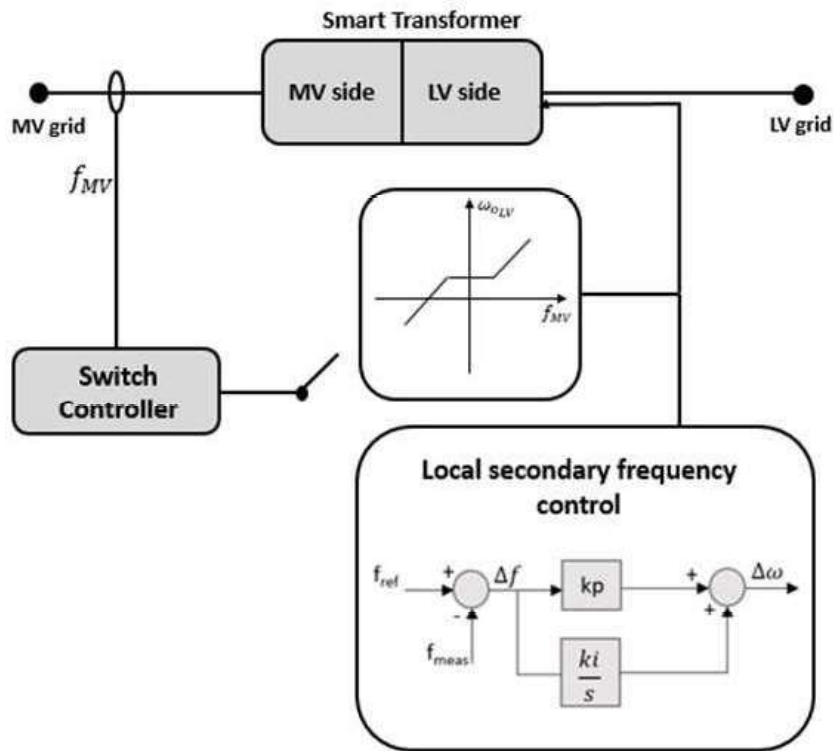


the output power constant.



**Figure 4.22:** Primary and secondary frequency controls in the ST without storage

The ST without a storage device will have a switched controller as represented in Figure 4.23. This controller allows the switching between droop control that enables the transposition of MV frequency disturbances for LV side the and local secondary control. When the centralized frequency control actions are finished, the GFO switches to the integral controller to eliminate the frequency error.



**Figure 4.23:** Switcher for the local frequency control in MG fed by ST



## 4.8 Load and Microgrids Modeling

In the scope of this research, the evaluation of the MMG with ST to operate in islanded mode is carried out through dynamic simulations considering only a three-phase balanced operation. Even though LV grids are characterized by phase unbalance, the scope of this thesis is to identify the main control requirements to coordinate the ST with plenty of DER connected to the MV and LV grids. For performing the dynamic simulations, each MG is represented by a single bus to which are connected loads (constant impedance), solar-based microgeneration and the DES device. The model for the microgeneration units and DES are in accordance with the descriptions provided in previous sections.

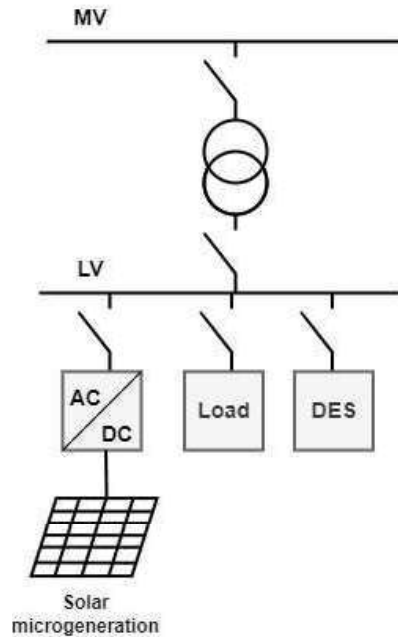


Figure 4.24: MG representation for MMG islanded simulation

## 4.9 Conclusions

This chapter described the control strategies to operate the MMG under islanded mode. As explained in this chapter, the MMG framework adopted envisions the ST as an interface element for some MV/LV substations instead of the traditional electromagnetic transformer. In this regard, a set of control functionalities was defined

for the ST inverters interfaces in order to ensure a successful operation of the MMG in the moments subsequent to the islanding. Under the new MMG framework, ST with storage is the main unit for ensuring the frequency control for both sides: MV and LV. ST is capable of emulating the behaviour of a virtual synchronous machine enabling the voltage and frequency control within the MMG in the islanded mode. When the ST does not have a storage device, the operation as GFo is only guaranteed to the LV side. The MV inverter is operated as GFe. In this case, the MV inverter can also support voltage control through the injection or absorption of reactive power. Additionally in the ST without storage, a coordination strategy is implemented to induce the participation in the frequency control of the DER's located in LV grids served by ST. Owing to the decoupling between the MV and LV sides, those DER would not be able to support the overall power-frequency control within the MMG. When the MG is fed by a ST with a storage device, it is assumed that there is enough storage capacity to support the power-frequency control during the simulation time.

Furthermore, the MMG framework presented in this chapter also considers that the DER connected to the MV and LV grids are inverter-interfaced. It is envisioned that these units are endowed with P-f droop controllers to support the power frequency control. The primary control actions provided by the ST and DER allow the stabilization of the MMG system after the islanding. These first actions are only based on the local measurements without the need of using the communications between central controlling entities and the DER units within the MMG. Then, secondary control actions are required to bring the frequency to the nominal value.

Secondary control is performed by the SC that is the head of the hierarchical control structure. New set-points for the DER connected to the MMG are defined based on the MMG reserve levels. The definition of the new set-points relies on the bidirectional communication infrastructure. The lower control layers send to the upper levels the information needed to perform the centralized frequency control. The SC sends back to the lower control layers the set-points to be implemented by the MMG units to restore the frequency to the nominal value. Whenever the reserve level is smaller than the power balance, the storage unit coupled to the ST participates in the centralised frequency control. The simulation results of the control strategies described in this chapter are presented in chapter 6.

# Chapter 5

## Smart Transformer as Enabler of Black Start Strategies in Multi-Microgrids

### 5.1 Introduction

Following a disturbance in the MV, HV or transmission systems that does not allow a successful transition to the islanded mode, a general blackout will occur in the MMG. New approaches to the restoration problem can be envisioned at the distribution grid with extensive development of the MG and MMG concepts. If it is not possible to restore the service via the upstream system after a pre-defined time, a BS procedure can take place in the MMG by exploiting the capabilities of the ST and DER.

The control strategies and the hierarchical control structure presented in chapter 4 can be used for launching a restoration procedure. Under the framework developed in this thesis, new BS strategies for MMG are developed, considering that the ST plays a central role regarding the coordination and management of the overall procedure. This chapter describes two BS strategies in MMG with ST. In the first strategy, a build-down approach is developed for service restoration in the MMG. The ST will have a central role in launching the BS after the blackout event since their power inverters can operate as GfO units for MV and LV Grids. In addition to the build-down approach, another BS strategy can be developed in which the black start is launched in parallel in several LV MG with BS capability, followed by the synchronization of the LV MGs with the upper MV grid – the MMG where the BS is also taking place. In this case, it is necessary to define proper coordination mechanisms to have a successful BS procedure running simultaneously in the MV grid and MG. This last strategy will allow a speedup of the

load restoration.

## 5.2 Literature Background

### 5.2.1 Conventional Power Systems Blackstart Strategies

#### 5.2.1.1 Overview

Over the last years, several disruptive events have demonstrated the destructive power of storms and how they can widely spread in the electric grids causing major power outages and significant damages to the electric infrastructure [3, 4, 5]. Additionally, cyberattacks have also been demonstrated threats to the regular operation of the power system. The dissemination of ICT in power systems exposed the electric utilities to cyber attacks [6]. By intervening in the data exchange processes or injecting false data, malicious attackers can disturb the grid operation causing major power outages, economic losses and system instability. These cyber-attacks can affect the systems that support the grid operation, influencing the operators' visibility on the electric system and the decision-making process. Although transmission and distribution grids are designed to prevent eventual cascading failures, the increased frequency of disruptive events has exposed the vulnerabilities of the current safeguards measures implemented by electric utilities.

Traditionally, electric utilities have developed methodologies for restoring the system quickly after disruptive events. When power systems are facing such events, the full system restoration and the repair of the damaged grid assets can take days or even weeks specially when grid infrastructures are large affected. In this process, it is crucial to get information from experts in the electric grid infrastructure operation and maintenance. The information is useful in several domains, such as identifying trouble points, repairing critical and priority equipment, and restoring service after destructive events.

Following a power system blackout, the restoration processes are triggered to maximize the load restoration with minimum elapsed time. The service restoration process is conducted, taking into account the operating conditions and the stability and security of the system. The conventional procedures for power system restoration are normally developed before emergencies. However, service restoration is a process

performed in real-time and, therefore, it can be subjected to unforeseen situations that can affect the plans prepared in advance. In such situations, the operators need to tackle constraints that generally are not encountered during the normal operation. They deal with several stability issues in the early stages since the grid is weak due to the short voltage support capability and low inertia leading to large frequency excursions and voltage deviations.

The service restoration is a complex task from a mathematical point of view since it corresponds to a combinatorial multi-objective, multi-stage, non-linear and constrained optimisation problem. The complexity of the BS often leads electric utilities to develop methodologies based on heuristic approaches combining the experience from human operators with off-line simulations studies for the restorations plans. The simulations studies for assessing the feasibility of the restoration plans can involve different types of analysis such as power flow, transient stability, voltage stability, electromagnetic transients, long term dynamics and short-circuits.

Given the size and specific characteristics of each regional or national power system, it is not possible to develop a universal methodology for service restoration. The restoration plans include step-by-step procedures that consider pre-defined guidelines and operating procedures, which can vary according to regulation and company practices. For instance, the definition of the BS procedure in Europe is usually created in accordance with the rules defined by the Network Code for Emergency Restoration (NCER) [176]. Under the NCER a TSO from a member state must develop and promote the public consultation of a System Restoration Plan (SRP) before submitting the regulatory authority for approval. NCER is part of the European Network Codes and Guidelines that aims to ensure a fully functioning and interconnected energy market. This network code seeks to set up a set of common requirements and principles for operation in emergency situations in power systems. It establishes the measures and procedures of TSO, DSO and significant grid user (SGU) when the power system faces a blackout or is in a restoration state.

#### 5.2.1.2 Restoration Plans

The restoration plans correspond to comprehensive documents that set up the requirements, principles, strategies and guidelines for the service restoration in its own grid and the coordination functions with other entities and neighbor systems. These plans

involve the following components [177]:

- Standards or grid codes;
- Restoration philosophy and strategy;
- Restoration stages, process and steps;
- Communications procedures and protocols;
- Guidelines to energize various facilities (such as transmission lines, transformers and shunt devices), to synchronize generators, and to restore load;
- Guidelines for power system performance monitoring and adherence (e.g., Voltage and frequency control);
- Protection coordination issues;
- Island synchronization guidelines;
- Guidelines for interconnection with neighboring systems;
- Market interactions during the restoration process;
- Staffing and responsibilities;
- Training and drills;

### 5.2.1.3 Service Restoration Strategies

Despite the restoration procedures being dependent on the specific characteristics of the regional or national power systems, two main type approaches are reported in the literature [178]: build-down (top-down) and build-up (bottom-up).

The first strategy is based on sequential restoration processes that aim to build the system skeleton. The energizing process is initiated at the higher voltage levels, and then it is conducted to the lower voltage systems. The build-down approaches are normally associated with power systems where just a few power plants are able to create the skeleton of the grid (BS capability). Then, these facilities are used to energize the transmission system and provide power to the auxiliary systems of other generation power plants without BS capability. After energizing the auxiliary systems, new plants can restart and support the BS procedure. From now on, the restoration service follows the traditional step by step process to restore loads and generation.

The build-down approaches can lead to extensive times for load restoration compared to the build-up.

In the build up or bottom up approach the power system is divided into several subsystems (electrical islands). Each island needs to have at least one BS unit to energize the transmission lines and supply the priority loads. Later, these islands are synchronized among them. The definition of the island's boundaries can be done considering the geographical location of the generation facilities, substations of the consumption centers and the respective technical restrictions to launch the service restoration in that area.

Distribution utilities restore service through switching actions that energize healthy feeders [179]. These actions aim to identify alternative pathways from other substations or distribution feeders to supply critical loads. Accordingly, service restoration processes involve the remote operation of switches (normally open or normally closed) and sending out field crew to investigate and check the fault locations. In addition, the fault location relies on customers' calls due to the low observability in the low voltage levels. However, smart meters are important to support the distribution utilities in the service restoration. Control centers' operators use the data sent to the outage management systems by the smart meters to support fault detection, location, and load restoration [180].

Remotely controllable switches placed in the distribution grids are useful for power restoration since they improve measurement, monitoring, control, and communication capabilities within the distribution grids. When the distribution system faces a sustained fault or a partial blackout (e.g., fault in the transformer of HV/MV substations), the automated devices sectionalize the faulted zone to restore the maximum loads. Nevertheless, the load restoration at the distribution level is a challenging problem given the variety of technical issues to be addressed in finding the optimal restoration plan. The restoration problem in distribution grids is increasing its complexity due to the proliferation of DG units. Although with an increased complexity, the islanded operation of MG and MMG brings new possibilities to improve the resilience and reliability by exploiting local resources. If the typical restoration path from the main grid is not available, DG units and batteries can supply the de-energized zones. Under the MG and MMG concepts, the whole or part of the distribution grid can be restored. This will require more interaction between the DMS and DER located in the distribution system to coordinate a successful restoration and improved coordination between the TSO and DSO. MG and MG can be a BS resource to the upstream systems, which



brings new opportunities to supply loads in the power system when the main system is unavailable.

#### 5.2.1.4 Service Restoration Steps

Basically, four steps can be identified in the high-level process of the restoration service as shown in Figure 5.1



Figure 5.1: Illustrative examples of restoration steps

Each step is described as follows [177]:

- **System Status Evaluation:** Following a wide blackout, the first step to restoring the service is to immediately evaluate the system's conditions by analyzing the availability of transmission and generation resources. This assessment will depend upon the availability of remote terminal units (RTU), SCADA and energy management system (EMS). Communication with neighbor transmission systems is essential, but it is also dependent on the availability of the communication infrastructure. Even though some data is missing, given that those type of equipment are out of service and/ or are damaged, it is of utmost importance to review all the available data to get a reasonable characterization of the available resources to launch the restoration procedure.
- **Determine Restoration Strategy:**Through the assessment performed in step 1, the restoration strategy is revisited and revised, considering the existing conditions of the system and the availability of the main transmission lines and generation power plants. Thus, operators create a high-level restoration sequence. The revised strategy is then communicated to other affected entities like neighbor TSO and DSO.
- **Implement Restoration Procedures:**This step involves restoring the transmission lines, generation and substations while maintaining proper voltage and frequency performances. In the early stages of the implementation, voltage and frequency control is critical to avoid a new collapse. Therefore, the restoration process is



conducted following guidelines documented in the restoration plan. Also, islands can be synchronized in this phase after they have been stabilized.

- **Interconnection with other Transmission Systems:**After stabilizing the regional or national systems, the tie lines with neighbor transmission systems can be used to expedite the restoration process. Besides, assistance to a neighbor transmission system can be necessary. Depending on the guidelines, sometimes it is a higher priority to supply cranking power paths to neighbor systems than supply load.

#### 5.2.1.5 Technical Issues during Service Restoration

The development of safe and stable restoration procedures need to ensure several technical issues as follows [177, 181]:

- **Blackstart Capability:**The existence of generation units with BS capability is crucial to launch the restoration procedure. These units energize the grid and provide active power for the auxiliary systems of other generation units without BS capabilities. Some generation units cannot restart by themselves, while the grid is not energized. In some power systems, the BS procedure relies on a few units with BS capability to restart independently. In the bulk power systems, the features of thermal units restrict the BS process given the minimum critical time to restart due to the cold start. Several factors can influence the availability of the thermal station, like the time interval between the shutdown and restart and interval time between the technical minimum and the full load.
- **Power-Frequency Control:**Generation and load need to be matched during the system restoration to maintain a stable operation for avoiding large frequency deviations. In early stages, the load should be incremented with small steps since the grid is weak due to the small numbers of generators in operation (the grid presents a low inertia). As more generators are connected, the power system is better prepared to accommodate large load step increases. The load to be supplied in each step of the restoration process is normally defined in the restoration plan. The restoration plans previously developed indicate what are the priority substations to be connected in the early phases. This allows the operators to know in advance the estimation of the amount of real and reactive power loads to be picked up at any time.

- **Voltage Stability and Reactive Power Control:** Firstly, in the early stages, the energization of the transmission lines may provoke over-voltages . Some sustained overvoltages can initially arise due to the capacitive charging currents of lightly loaded transmission lines. Fast transient voltages can be caused during the energization of large sections of the transmission systems and the connection of shunt capacitors. Besides, harmonic resonance voltages can also appear in the early stages of the restoration procedure. The sustained over-voltages can create saturation of the power transformers, which raises the harmonic component during the no-load and light load conditions. After the energization phase, during the connection of loads, systems need to have the ability to support the voltage as the reactive power increases. In bulk power systems, this characteristic depends on synchronous generators' reactive power capability curves. The reactive power is also supported by the capacitor banks connected to the substations bus.
- **Communications and Switching Operations:** The service restoration process requires that the operators remotely act on the switches and circuit-breakers to create the cranking paths for energizing the system and supplying loads. For that, it is necessary to have visibility on switch and circuit-breakers states and to have the capability to operate them remotely. To reconnect the grid assets, switching strategies can be adopted by the electric utilities, like opening all the switches and circuit breakers or only opening the devices necessary to restore the power system. The ability to remotely operate breakers and switches requires an operational communications infrastructure. Hence, the communication system needs to be functional with and without external electric power.

### 5.2.2 Distributed Energy Resources, Microgrids and Multi-Microgrids in Blackstart Strategies

In the typical operating practices of the electric utilities, the DG units are disconnected following a disturbance. Afterwards, they are reconnected to the electric system as soon as the system is restored. However, the capability of MG and MMG to operate islanded makes it possible of using DG during major power outages. Following blackouts, the restoration in the distribution system depends on the availability of the upstream grid. The capability of autonomous operation from MG and MMG can be exploited to launch BS procedures after a blackout event.

Obviously, the use of MG and MMG as a resource with BS capability demands that the grid infrastructure is intact. If the MG and MMG infrastructures are fully destroyed following a major disturbance, it will not be possible to launch the BS procedure. Sometimes the disruptive events damage parts of the distribution or transmission grids, while others remain healthy. In some cases, the healthy zones have DG with BS capability, which allows the service restoration in those areas by exploiting MG and MMG concepts.

The combination of grid reconfiguration actions with DG islanding is addressed in [182] for MV networks. The methodology has four main steps: 1) identification of islanding schemes, 2) restoration of grid connectivity, 3) network reconfiguration and optimization of load scheduling. A multi-step strategy is proposed in [183] for service restoration in distribution grids with increasing penetration of DG units. In this work, only a restricted number of reconfigurations is allowed in order to consider the DG start-up requirements. The service restoration in distribution grids is also addressed in [184] by developing a two-stage strategy for generating a set of solutions with a sequence of control actions. The first phase provides restoration solutions combining the traditional network reconfiguration with DG units capable of operating in the GfO mode. The second stage aims to obtain an optimal sequence of actions to restore the service in the out-of-services zones. A resilience-oriented method is developed in [185] to develop service restoration procedures in secondary distribution grids. For that purpose, DG units are included to serve critical loads. This strategy relies on a hierarchical control arrangement in which a central controller controls both loads and DG units. In this methodology, the authors consider a look-ahead load restoration considering technical grid limits and DG operating constraints.

A new service restoration procedure is proposed in [186] incorporating MG with DER. This strategy intends to identify the operating modes of DG equipped with synchronous generators and the state of smart switches located in the distribution grids. This restoration strategy relies on communication links to establish cooperation among different advanced DMS, MG energy management systems and DER management (DERMS). A BS procedure in hybrid MG is defined in [187] using the information entropy theory. This technique is applied to characterize the BS capability from the DG since the main issue is to choose the main unit with BS capability. Restoration service in distribution grids using DG is addressed in [188] to maximize the load restored and the optimal allocation of DG units. The authors include the modelling of

time-dependent DG reserve energy in the optimization process. The usage of MG with renewable-based generation sources is addressed in [189]. The rationale is to use this type of MG to provide BS capability while the main power plants are initiating the power restoration service.

The capability of MG to energize distribution feeders in the restoration process is addressed in [190] to improve the self-healing capacity. A spanning tree search algorithm is proposed to obtain possible solutions for the restoration plan. In this strategy, the MG is modelled as a virtual feeder for ensuring that the DG limits are represented as electrical constraints of the distribution feeders. The MG islanded operation can be represented in the algorithm as an additional topology constraint of the distribution feeder. A spanning tree search algorithm is also used in [191] for exploring the MG capability for energizing distribution feeders after natural disasters. The algorithm is applied to identify the islanded and unserved critical loads to be picked up by MG.

The exploitation of the MG as BS resource is also analyzed in [192]. The authors integrate the MG model in a stochastic mixed-integer linear program. They consider the MG as a single facility capable of aggregating all the DER connected to the LV grid. A similar approach is developed in [193] to consider the MG as an emergency source to supply critical loads while the main grid is not available. The difference to the previous approaches lies in the inclusion of the DG dynamic performance as a constraint in the optimization process. Moreover, the authors also consider other aspects such as voltage and frequency limits and availability from DG units within the MG.

A decentralised multiagent system (MAS) is developed in [194] for solving the service restoration as a multi-objective optimization problem. This methodology supports the service restoration in distribution grids considering the controlled DG units islanding. The authors also exploit the EV under the V2G concept to support the service restoration in this work. In the same line, a fully decentralized MAS is also proposed in [195] for the service restoration problem in distribution networks combining grid reconfiguration with intentional islanding. A MAS is also applied in [196] to define the optimal configuration to restore the service in distribution grids after the detection and location of the fault zone. In this methodology, DG units are also considered to energize the out-of-service zones.

The effect of MG's unbalanced operation conditions in service restoration is also studied in the literature. Reference [197] presents the service restoration procedure adopting for the MG a three-phase network model instead of single-phase network models to represent the unbalanced conditions of the distributions grids. The restoration service in distribution feeders under unbalanced conditions is also analyzed in [198]. The DER is included in bottom-up and top-down restoration strategies in this work.

In a sequence of a general blackout, the TSO and DSO need to coordinate the service restoration reliably and safely. However, in the traditional operation philosophy, both transmission and distributions systems are operated, not considering the capabilities and restrictions of each other and the possible mutual impacts. These aspects also affect the power system restoration process. On the other hand, the increased integration of DG at the distribution side brings the need to consider these resources as part of the power restoration processes. Thus, an integrated restoration strategy for the transmission and distribution system is proposed in [199]. In this methodology, the traditional top-down strategies used at the transmission level is combined with bottom-up approaches where the DG capabilities are considered.

The works previously described usually formulate the service restoration as an optimization problem. Some of them combine the network reconfiguration problems with the formation of MG that can support the BS procedures. Therefore, existing works focus on steady-state, network reconfiguration (incorporating the BS capability of MG) and energy optimization for the medium and long term. Few works cited above consider the dynamic characteristics of the electric grid in the optimization process. The dynamic simulation to demonstrate the ability of MG to launch a BS following a blackout is performed in [200]. In this work, the authors consider the invert-based resources, namely storage systems operating as GFO unit for service restoration in LV distribution grids. The authors present a sequence of actions for launching the BS procedure as well as the control strategies to operate the MG in the islanded mode. The control strategies are similar to the one presented in [62] where it is demonstrated the capability of the MG to operate islanded from the main grid. A BS procedure is demonstrated in [201] under hierarchical control for coordinating the DG units connected to the MV system and the MG at the LV level. Both dynamic and energy optimization are considered in [202] for generating optimal restoration

sequences in distribution systems and MG. The dynamic behavior of inertial DG units with synchronous governors is derived and linearized to be included in the optimization problem.

A BS procedure for MMG is proposed in [203] considering single-phase and three-phase MG. The BS procedure is established under a hierarchical control structure using a bidirectional communication infrastructure. The BS procedure encompasses several stages. Firstly, it is necessary to identify the main power unit to launch the BS in each MG. When each MG operates in the stand-alone mode, the main power unit (storage system) is responsible for accommodating the fluctuations from load and PV generations. Then, a master MG is selected. This MG will provide the voltage and frequency references to the other MG after verifying the synchronization conditions. After the synchronization with the master MG, the slave MG are transferred to the grid-connected mode. Although this work exploits a BS within a MMG, they do not address how the distributed resources can support the overall-power frequency control.

The works above aforementioned demonstrate the increasing interest in developing new BS procedures considering the capabilities of DG units and battery converters. These distributed resources can be exploited under the MG and MMG concept to enable the autonomous operation of portions of the distribution grids. However, as it was stated in chapter 3 the exploitation of ST capabilities in service restoration scenarios is poorly addressed in the literature. The next section described how to develop BS for BS in MMG by jointly exploiting the ST and DG and battery converts capabilities.

### 5.3 Power System Restoration versus Multi-Microgrid Restoration

The application of the restoration plans relies strongly on the experience of human operators, on the simulation capability of the sequence of actions that System Operators should exploit and on the adoption of advanced tools to help human operators driving the system through the restoration stages. MMG has reduced size and fewer devices to control compared to the bulk power system, which enables the automation of the restoration process. However, even with higher levels of automation in the power systems, the human component is regarded as important to ensure a safe



operation. Above all, the safety of people and assets is the key concern for electric utilities, leading to integrating the human component in some processes.

Operating rules based on previous experience should be part of the algorithms incorporated in the BS procedures regardless of the BS automation. For example, it will be important that the algorithms know which is the main unit with BS capability for launching the service restoration. After verifying with the DSO systems that it is not possible to restore the service via the upstream grid, the SC needs to check that the ST can initiate the service restoration.

The task of finding cranking paths for service restoration in transmission systems could be hard given the significant damages on the grid asset and system complexity (meshed grid). This can be critical if the path for the main unit with BS capability is completely damaged. On the contrary, in the MMG this task can be easier given the reduced size of the system and the radial structure of the distribution grids. If MMG infrastructure is not significantly affected by the disruptive event, a BS can be promptly initiated to supply the local loads. Here, human intervention could exist (interaction between control centers and field crews) to check that the grid infrastructure is healthy and that the MV feeder for BS implementation is properly delimited. After this checking, an operator can send an order to initiate the automated restoration.

As described in subsection 5.2.1.1, it is common to open all circuit breakers and switches in the initial moments of the restoration procedure in conventional systems. In a MMG environment, a similar strategy can be adopted to avoid large inrush currents due to the energization of the electromagnetic transformers and large frequency deviations due to loads that remain connected. The mitigation of inrush current is desirable to the ST since it is a device comprised of power electronics components. The semiconductors have reduced capacity to support overvoltages and overcurrents. It is also a proper method to avoid damages to sensitive loads due to transient effects during the connection of generators and loads.

Regarding the restoration strategies to be adopted, both build-down and build-up can be developed within the MMG. The ST will always be the key enabler for launching the BS for both strategies. At the LV level, several MG may have BS capability, enabling them to launch a BS process without depending on the MV system. On the other hand, as the ST is a key enabler of the BS strategy, the main

restoration procedure will occur from the MV side by coordinating the DG or battery converters connected to the MMG. When none MG can operate autonomously, the ST will lead a restoration procedure as the single BS unit within the MMG. Therefore, the flexibility provided by the control strategies to coordinate the ST with DG units under a hierarchical structure allows the development of BS procedures by combining build-down and build-up strategies.

## 5.4 Blackstart Strategies in Multi-Microgrids with Smart Transformers

### 5.4.1 General Description

In the following sections BS strategies using the ST within a MMG will be described. The service restoration process is always a challenging task. With regard to MMG, it is expected that the procedure can be sped up because of the hierarchical control structure used to manage the MMG and the possibility to launch the BS procedure in parallel in the MG within the MMG. The management of the MMG in islanded mode headed by the SC allows to automate at least some steps of the procedures, which reduces the human intervention. Under the framework adopted in this research, the SC will coordinate the restoration process through a set of rules to be followed during the BS. These rules will be integrated in the software of the SC. The rules correspond to a sequence of control actions to be taken on by the SC over the devices in lower control layers.

Similarly to the conventional power system (as described in subsection 5.2.1.4), the BS procedure within the MMG with ST is carried following some main steps:

1. Restart the BS units: the ST with a storage device or GfO units in LV grids when MG have BS capability;
2. Building the MV and LV networks;
3. Controlling frequency and voltage;
4. Connecting controllable loads and generation;



5. MG synchronization with the MV grid when MG initiate autonomously a BS procedure;
6. Restore the frequency to the nominal value;
7. MMG synchronization with the upstream grid, when it becomes available;

The service restoration is triggered by the SC following a general blackout in the power system or due to faults in the distribution systems. In the last case, the BS can be initiated if there is no possibility to energize the MV grid from the upstream system (e.g. faults in HV lines, HV/MV transformer or MV bus). The grid reconfiguration can be applied to find alternative paths (from other substations or distribution feeders) to supply the loads. Figure 5.3 shows the making-decision process to be implemented by the SC to manage the MMG following the collapse of the upstream grid.

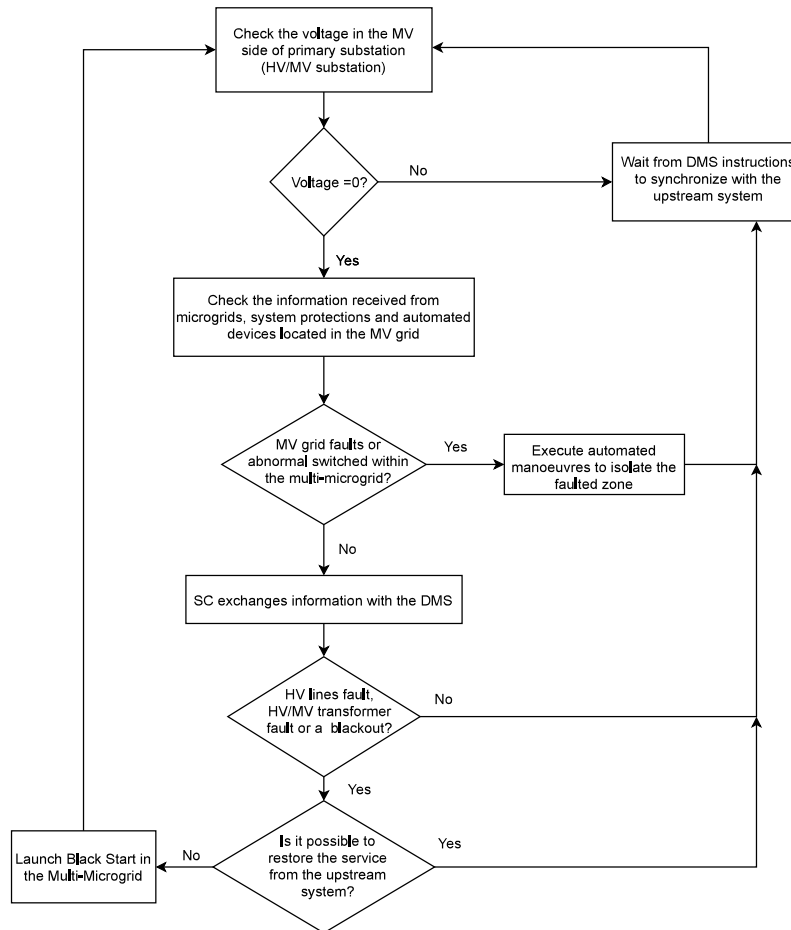


Figure 5.2: Flowchart defining the conditions to trigger MMG black start procedure

After finishing the BS process in the MMG, there is the possibility to synchronize the MMG with the upstream system. For that purpose, it is necessary to check one of the following conditions:

- the upstream grid is back again to the normal operation state and the electric utility intends to operate the MMG in the interconnected mode with the main grid;
- the upstream grid is still in service restoration mode and the MMG is requested to supply other zone in the distribution grid;

The SC manages the BS procedure using the last available information on the MMG conditions in the previous moments to the islanding. Based on the pre-conditions before the islanding, the SC can select the set of rules for that scenario. The rules to be implemented by the SC during the BS procedure vary according to the scenario in the moments before the blackout event (e.g, peak load and low local generation, light load and high local generation).

As mentioned in the list of main steps, a key requirement for launching the restoration procedure is the existence of units with BS capability. In the framework assumed in this thesis, the ST with storage is the main unit with BS capability. The ST start-up is performed to energize the MMG . Given the capability of the ST to operate in the GFo mode, this unit will provide power-frequency support during the load and generation connecting process in coordination with DG units and or battery converts equipped with P-f droops. Another situation can be envisioned when the MG also have BS capability. In this case, there must be at least one GFo unit in the MG located at the LV bus of the MV /LV substations or at any other point of the LV grid. The MG must be synchronized with the MMG during the BS at a given time. The two strategies are described in the following sections.

#### 5.4.2 General Assumptions

The restoration process in the MMG relies on the hierarchical control structure described before. Therefore, a successful restoration process depends upon the availability of the communication infrastructure, which is of utmost importance for the bidirectional communication between control layers. Small auxiliary power units are needed to support the adequate function of the communication infrastructure when the main power grid is not available. This is a similar issue to what is faced by the

electric utilities in conventional power systems.

Some major concerns need to be considered regarding the main BS unit - the ST with the storage device. As explained in chapter 3, ST is subjected to large inrush currents to charge the DC-link during the start-up process. This requires the implementation of step by step procedures to mitigate these problems. The same situation arises when the ST without storage is energized through the MV side. It is assumed that those processes are already implemented according to the principles well documented in the literature in order to allow the initial stages of the BS procedure. As this thesis aims to analyze the long-term dynamic behavior over the BS procedure, the initial phase that includes fast transients related with the ST energization is not modelled.

As reported in chapter 4 this research assumes that the storage devices have a sufficient SOC to meet the energy requirements during the islanded operation. The storage device coupled to the ST also needs to be designed to support the frequency control during the simulation time addressed in this research. In addition, under normal operating conditions can be defined an operation mode that ensures the availability of the main storage units to support the islanded mode for some hours. The same principle is applied when the MG has BS capability, thanks to the GFO units located in the LV grids.

Another important assumption is concerned with the information update. The SC heads the BS procedure to bring, as much as possible, the system to the load and generation conditions before the blackout event. In this regard, the SC will resort to the information stored in its database, which contains information on load, generation, injection/absorption of DES units before the blackout, the technical requirements of the DER and electrical characteristics of the grid. There must be periodically data exchange between the different control layers to the SC has updated information on the grid operating conditions.

Beyond the assumptions depicted early, the following ones are also adopted:

- The MMG is disconnected from the upstream grid (MV circuit breaker is open);
- Loads, DG, microgeneration and DES are disconnected;
- The MMG feeders are fully sectionalised;

- Remotely controlled automatic switch devices are available in the MMG;
- Three-phase balanced operation;
- The load restoration is performing according to its priority (1,2, and 3);
- The sequence to connect loads and generation units is known in advance;
- Synchronization capability between different points within the MMG;

### 5.4.3 Build-Down Approach

#### 5.4.3.1 Preparation Phase

In the build-down approach, the ST with storage is the single unit with BS capability. Under a MMG dominated by inverters, the BS capability lies in storage units. As the ST inverters operate as GFO units for both sides, it will be the key enabler of the MMG restoration by providing references for voltage and frequency throughout the BS procedure.

The DMS informs the SC to initiate the BS procedure in the early phase. Firstly, the SC will verify that all the switches are open to avoid undesirable inrush currents and overvoltages that can damage some appliances during the grid energizing. Then, the SC communicates with the STC to assess if the storage unit can initiate the BS procedure. Assuming that an algorithm is implemented in normal operating conditions to ensure a specified level of SOC for emergencies, this step aims to verify that this requirement is fulfilled. If this condition is not satisfied, there is no possibility to launch the BS procedure. It will be needed to wait for the availability of the upstream system to supply the loads. Otherwise, the SC instructs the STC to trigger the start-up procedure of the ST with storage.

Afterwards, the ST will energize the MV and LV grids. Once all switches are open, the energizing process is carried out at the MV grid. Then, the electromagnetic transformers are energized by the MV side. Each transformer is energised individually to avoid a large inrush current when energizing all of them simultaneously. A voltage ramp can be employed in each transformer to avoid large inrush currents. The ST without storage devices are also energized from the MV following a step by step start-up scheme. Finally, the SC communicates with MGCC and STC to energize the LV grids by turning on switches and circuit-breakers. At

the end of the energizing phase, the skeleton of the grid is created. Consequently, the MMG already has minimum conditions to start the load and generation connecting.

#### 5.4.3.2 Development of the Black Start Procedure

Additional actions need to be taken for initiating the connecting of loads and generation units. It is mandatory to disable the local secondary frequency control implemented in ST without storage. During normal operating conditions, this functionality is enabled. This action aims to allow the power-frequency support from DER connected to the LV grid via the MV frequency-LV angular frequency droop.

Besides, an instruction is sent to connect the DES units with a null active power value ( $P=0$ ) request to support the power-frequency control. In this way, those units are connected to the electric grid without consuming or injecting active power. Still, their active power output varies according to the frequency variations ( $P$ - $f$  droop) during the connection of loads and generation. After concluding the connection of loads and generation units, the centralized frequency control is enabled to bring the frequency to the nominal value. The local secondary control is also enabled to correct the error frequency in the LV grid fed by ST.

#### 5.4.3.3 Load Restoration

The BS process will be conducted to restore the loads as a function of their priorities. Three types of priorities are assumed to the loads:

- Priority 1 ( $P_1$ );
- Priority 2 ( $P_2$ );
- Priority 3 ( $P_3$ );

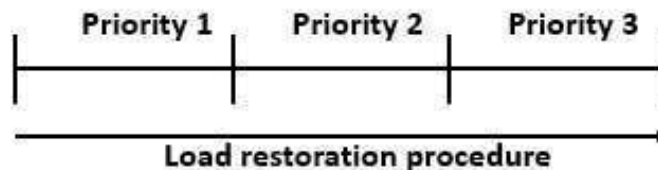


Figure 5.3: Load restoration procedure

The MGCC and STC will inform the SC about the load distribution per the priority levels. As soon as a priority level is fully restored, the SC conducts the BS process, advancing for the following priority until the load is fully supplied. The load priority can be defined directly by the distribution system operator. The system operator can assign a priority to each LV feeder based on the characterization of the consumption in the zone where the MMG is located. For example, it can be given higher priority to connect consumptions for public safety, healthcare facilities, water stations and public lighting. Lower priorities can be associated with industrial and residential consumption. The characterization of the loads is then included in the BS procedure to define the restoration sequence. As an alternative, the MGCC can also characterize the load within its MG, taking into account the consumers' availability to participate in the BS program. Under a smart grid environment, the consumers can define what loads they allow to be supplied later in the home energy management system. Then, MGCC aggregates the load in different priorities according to the preferences defined by the consumers.

#### 5.4.3.4 Synchronization with the upstream grid

As soon as the steps described previously are concluded, the MMG is ready to synchronize with the upstream grid. However, this synchronization just occurs when the upstream grid is available. Facing wide blackouts, the entire system recovery can take extensive periods. In this case, the MMG may need to operate in autonomous modes for several hours. The SC needs to perform other types of functionalities to optimize the distributed resources located within the MMG. Those functionalities should take into account the generation and forecast for the coming hours. When the HV system is available, the DMS communicates with the SC to proceed with synchronization. The HV system energizes the HV/MV transformer allowing the voltage to return to the MV busbar of the substation. The ST with a storage device as a master unit will be used to adjust the frequency and voltage of the MMG to synchronize with the upstream system.

#### 5.4.3.5 Sequence of actions

Taking into account the descriptions provided in the last sections the SC will manage the BS procedure according to the following sequence of actions:

1. **Disconnect MV/LV transformers, DG, microgenerators DES units and loads.**

After a general blackout all the DER (load, microgeneration, storage), electro-

magnetic transformers and ST should be disconnected in order to avoid large frequency and voltage deviations when energizing the MV network.

2. **Sectionalizing the MMG around each ST with BS capability.** The ST with a storage device in the DC link is isolated from the MV and LV grids for checking the capacity of the storage unit to support the BS Procedure (full charging/low charging) and the conditions to launch the start-up scheme.
3. **Building MV/LV networks.** The ST with storage is the main unit with BS capability (G<sub>Fo</sub> unit). This unit is used to energize the MV/LV networks: overhead lines, cables, and MV/LV transformers.
4. **Energization and start-up of the ST (without storage).** The ST operating as G<sub>Fe</sub> for the MV side is energized from the MV side and then will energize the LV microgrid.
5. **Disable the local secondary frequency control in the ST without storage.** In order to guarantee the participation of the LV DER in frequency, the local secondary frequency control is deactivated. In this way, the LV frequency will be modulated as a function of the MV frequency in MG served by SC without storage device.
6. **Connecting of the Distributed Energy Storage.** The DES devices located in the LV MG are connected, with pre-defined initial set-point ( $P=0$ ). The underlying idea is to provide support to the primary frequency control during the process of load and generation connection.
7. **Management of connection of loads and distributed generation through the interaction among SC, STC, MGCC and local controllers.** The SC control is responsible for managing the black start procedure, sending the order of connection for the MGCC, STC and MV units. At the MG level, MGCC and ST will then send instructions to the local controllers to connect load and generation.
8. **Enabling the centralized secondary frequency control.** Based on the participation factors computed by the SC, the centralized frequency control defines the new set-points to bring the frequency to its nominal value during the islanded operation. The SC sends the new set-points directly to the DG units and MGCC and ST. Then, the MGCC and STC managed the DG and DES units located in the MG in order to fulfil the active power adjustments requested by the SC.

9. **Enabling the centralized secondary frequency control.** When MG are fed by ST, the local frequency control is activated in order to eliminate the steady-state frequency error.
10. **Reconnecting to the upstream system.** The HV/MV transformer should be previously energized from the HV side. Then the synchronization conditions with the upstream level are verified and the SC coordinates in cooperation with the DMS the maneuvers to synchronize both systems.

Figure 5.4 summarizes the main steps of the build-down restoration approach.



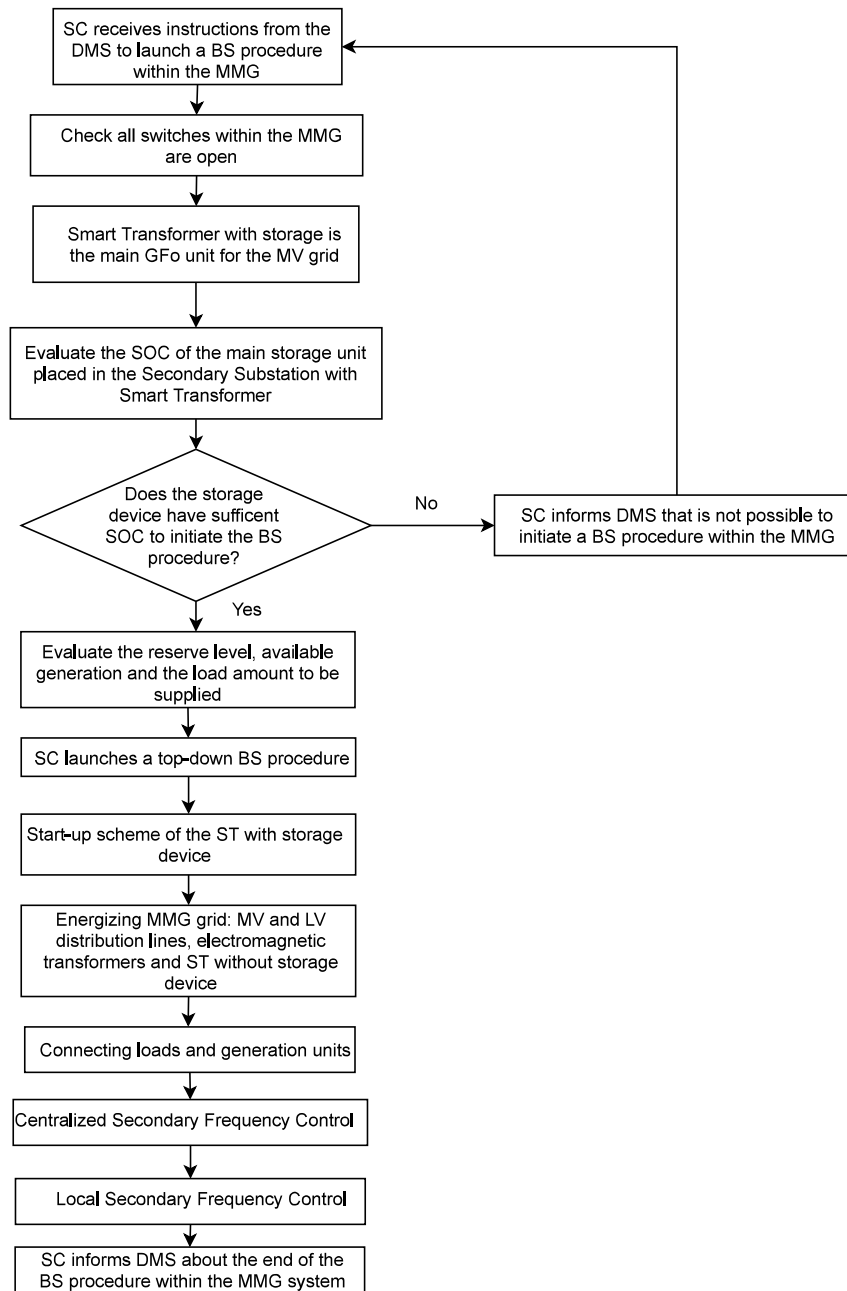


Figure 5.4: Flowchart with the main steps for the build-down restoration approach

## 5.4.4 Parallel Restoration Approach

### 5.4.4.1 Preparation Phase

For the framework envisioned in this thesis - MMG dominated by inverters - two types of units are eligible as BS capability units:

- ST equipped with a storage device in the DC link (operating as GFo unit for the MV grid);
- Storage device connected to the LV busbar (operating as GFo unit for the LV grid);

According to these possibilities, the service restoration within the MMG can consist of BS procedures running simultaneously in parallel. The ST equipped with a storage device at the MV level conducts a build-down BS process. MGs with BS capability (fed by CLFT) will launch the service restoration for their LV grids regardless of the process running at the upstream grid. The storage device connected to the LV busbar in the secondary substation (SS) operates as GFo unit for the LV grid. The number of BS processes running autonomously in the LV grids will depend on the number of MGs with BS capability. The possibility of several BS processes running in parallel contributes to the speed-up of the load restoration, reducing the time to supply the loads and restore the service. However, the several BS processes running within the MMG require proper coordination.

The SC communicates with the MGCC to identify which MG can launch a BS procedure in the MG. By identifying the MG with that capability, the SC instructs the respective MGCC to launch the service restoration in their MG. Simultaneously, the SC also give instructions to the ST with a storage device to launch the BS procedure at the MV grid following the steps described in the build-down approach.

The service restoration procedure in the MG starts by ensuring that switches in the MMG are all open before energizing the grid. The GFo unit associated with the main storage device is responsible for energizing the LV grid. The energizing of the electromagnetic transformer is performed through the MV side via ST with storage. It should be stressed that the LV circuit-breaker of the MV/LV substation is still open since MG has BS is operating independently from the MV grid.

#### 5.4.4.2 Development of the Black Start Procedure

Similar to the build-down approach, in the MG the BS procedure also sends orders to DES units to connect with a null active power for supporting the power-frequency control. When the MG is running the BS procedure, secondary frequency control actions are not enabled. The idea is to synchronize the MG with the MV grid to increase the robustness the MMG during the service restoration. The secondary frequency

control actions only take place when the following steps are finished: connection of loads and generation units and the synchronization MG with BS capability.

#### 5.4.4.3 Load Restoration

The MGCC also manages the LV grid's load restoration according to previously defined priorities (similar to the build-down approach). However, during the BS procedure, the load restoration can be stopped when the LV GFO inverter achieves a specified rated power value (apparent power). This rule aims to avoid the overloading of the inverter, which can compromise the development of the BS procedure. It is expectable that the GFO unit in the LV grid has a smaller rated power compared to the GFO inverter on the MV side. The MG waits for instructions to synchronize with the MV grid when these situations occur. After synchronizing with the upstream grid, the load restoration will be part of the BS procedure running on the MV grid.

#### 5.4.4.4 Microgrids with Black Start Capability

As mentioned in the section 4.8, the MG is represented by a LV single bus for simulation purposes. In the parallel restoration approach, it is considered that the GFO unit is connected to the LV bus in the MV/LV substations. Figure 5.5 depicts the representation of MG with and without BS capability.

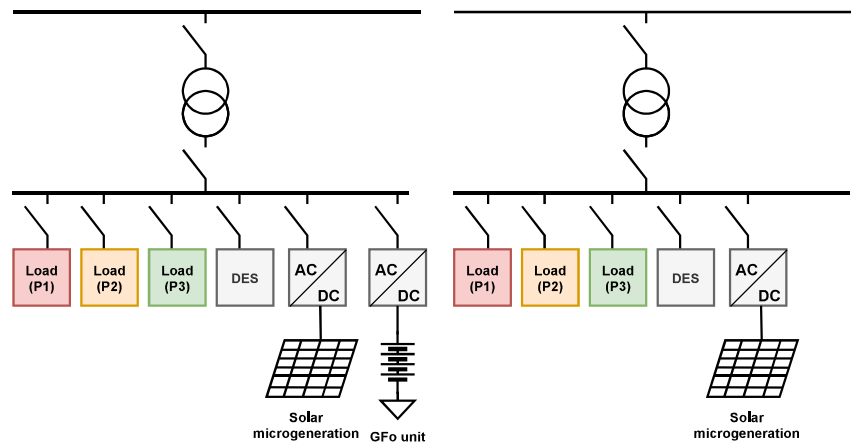


Figure 5.5: Representation of MG with (left) and without (right) black start capability

#### 5.4.4.5 Synchronization of MG with MV grid

Throughout the BS process in the MG, the load restoration remains on standby whenever the GFO units achieve a range from 50-70% of their size (apparent power). Then,

the SC informs the MGCC that is necessary to synchronize the MG with the MV grid. After that, the MG will initiate a smooth reconnection to the MV grid. Like in the bulk power systems, the synchronization of the MG with the MV grid follows a set of procedures for minimizing the transient currents. In this research, such synchronization has the following steps:

- Checking the synchronization conditions
- Adjusting voltage and frequency at the GFo unit terminals to prepare the synchronisation
- Act on the circuit breaker on the LV side of the transformer to reconnect the MG with the MV grid

In the initial phases of the BS process, it was considered that the MV grid energizes the MV/LV transformer (LV circuit breaker is open). The first condition is to check if the MV system and LV grid fed by an electromagnetic transformer have the same phase sequence. Then, it is needed to measure the RMS voltage values at the GFo unit and LV side of the transformer. The first condition to synchronize the MG with the MG grid is to conduct the voltage in the GFo to a value that reduces the voltage difference (regarding the secondary side of the electromagnetic transformer) below 3% ( $\Delta V$ ). The new voltage reference value is updated by the value of the deviation between the RMS values as follows:

$$\Delta V = V_{RMS}^{MG} - V_{RMS}^{MMG} \quad (5.1)$$

$$V_{0_{new}}^{MG} = V_0^{MG} - \Delta V \quad (5.2)$$

where  $V_{RMS}^{MG}$  and  $V_{RMS}^{MMG}$  are respectively the voltage RMS values in the MG and MMG and  $V_0^{MG}$  is the current voltage reference in the GFo inverter located in the MG.  $V_{0_{new}}^{MG}$  corresponds to the voltage adjustment in the LV GFo unit.

The second condition guarantees the equality of frequencies between the MG and MV grid ( $\omega^{MG} = \omega^{MMG}$ ). The LV frequency is adjusted to match the MV frequency for that purpose. The LV frequency reference is adjusted in accordance with the droop characteristic of the GFo inverter. By combining equations 5.3, 5.4 and 5.5, the new

frequency value is computed by equation 5.6.

$$\omega_0^{MG} = \omega^{MG} + k_p^{MG} \times P_{MG} \quad (5.3)$$

$$\omega_0^{MMG} = \omega^{MMG} + k_p^{MMG} \times P_{MMG} \quad (5.4)$$

$$\omega^{MG} = \omega^{MMG} \quad (5.5)$$

$$\omega_0^{MG} = \omega^{MMG} - k_p^{MMG} \times P_{MMG} + k_p^{MG} \times P_{MG} \quad (5.6)$$

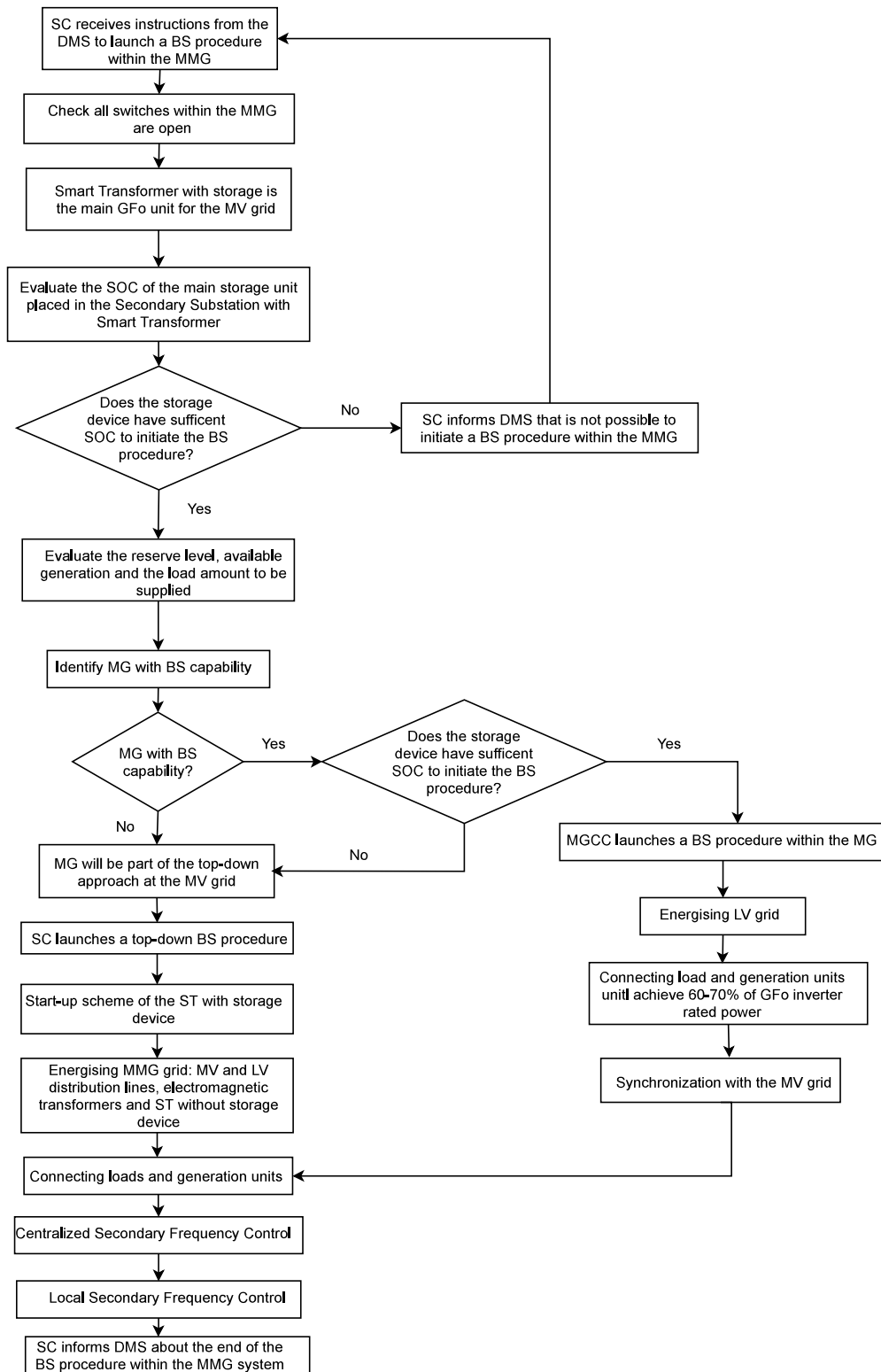
In addition, the checking of the phase difference between the GFo unit and the LV side of the transformer is also a necessary condition. When the synchronization takes place this phase difference must be around zero to minimize transient currents. The frequency adjustment is performed by introducing a frequency deviation in order to create a relative movement between the phasor corresponding to the voltage at the GFo terminals and the phasor corresponding to the LV side of the electromagnetic transformer. Thus, the MG frequency adjustment action defined in the equation 5.6 is adapted according to equation 5.7:

$$\omega_0^{MG} = \omega^{MMG} - k_p^{MMG} \times P_{MMG} + k_p^{MG} \times P_{MG} + 2\pi \times \Delta f \quad (5.7)$$

where  $\Delta f$  is the frequency deviation that is included to get relative displacement between the phasor corresponding to the voltage at the MMG terminals and the phasor corresponding to the voltage on the MG.

#### 5.4.4.6 Sequence of actions

The sequence of actions in the parallel restoration approach is similar to the one performed on the build-down strategy. The main difference lies in the parallel BS process running at the MG with BS capability. The sequence of action is summarized in Figure 5.6.



**Figure 5.6:** Flowchart with the main steps for the parallel restoration approach

## 5.5 Conclusions

This chapter presented BS strategies for the MMG with ST. A BS procedure can be initiated following a disruptive event if the MMG can not successfully transition to the islanded mode. The principles, rules, and processes used by electric utilities in conventional power systems can be adapted and transposed to define BS procedures within the MMG system. Partially or fully automated BS procedures can be developed by taking advantage of the hierarchical control structure, and the capabilities of the ST and DG and DES units connected to the MMG. BS procedures at the MMG will reduce the load restoration time since the service restoration is not dependent on the availability of the upstream system.

Under the framework adopted in this thesis, the ST in a three-stage configuration with a coupled storage device is the key enabler of BS procedures within the MMG. In a MMG without synchronous generators, the inverters of the ST operating as GfO units provide voltage and frequency references during the service restoration procedure. Two approaches were described in this chapter: build-down restoration and parallel restoration. In the first one, the ST with a storage device is the only BS unit for launching the restoration procedure; in the second one, a BS procedure is also developed simultaneously at several MG, provided they are equipped with BS capable resources.

Furthermore, control functionalities described in chapter 4 are also applied in the service restoration process under an MMG environment to support the power-frequency control in islanded mode. Those control strategies help to coordinate the operation of the ST with the fleet of DG units and or battery converts connected to the MV and LV grids throughout the BS procedure. The simulation results of both BS strategies are provided in the next chapter.





# Chapter 6

## Simulation Results

### 6.1 Introduction

Chapters 4 and 5 presented the control strategies to adopt in a MMG framework with ST when the system is operating islanded from the main grid and dealing with a service restoration procedure after a blackout situation. The main objective of this chapter is to present the results of the proposed control strategies through numerical simulations. Hence, a simulation platform in the Matlab/Simulink environment was developed. The control strategies and models described in chapter 4 for the solar-based generation, DES and ST were implemented in the simulation platform. In order to demonstrate the robustness and the flexibility of solutions developed, the simulations were carried out under different scenarios.

The results of unintentional islanded from the MMG are the first ones to be presented. A base scenario is described for MMG islanded operation without the participation of DG and DES units in the primary frequency control. The underlying idea is to demonstrate the basic operating principles of MMG islanded operation when the ST with storage is the main G<sub>Fo</sub> unit. Then, two different scenarios are considered regarding the active power flow exchange with the upstream system. First, it is considered a scenario where the MMG is importing power from the upstream system. The consumption within the MMG is then higher than the production. Second, a scenario of exporting active power from the MMG to the upstream grid is simulated. This scenario intends to demonstrate how the coordination between ST and DER can support the MMG survival following unintentional islanding in future scenarios with high generation levels in distribution grids. For those scenarios, solar power generation only provides a downward reserve.

Simulation results from the service restoration under the MMG with ST are presented in the second part of the chapter. As presented in chapter 5, two restoration approaches are simulated in the MMG: build-down and parallel. The BS procedures are simulated considering that the generation is higher than the consumption in the MMG (before the islanding the MMG was exporting to the upstream system). The BS procedures are simulated assuming that the solar generation provided upward and downward reserve, the DES units have maximum and minimum values for the active power they can inject or absorb. The simulation scenario aims to bring back the MMG to an initial operating condition characterized by an excess of generation regarding consumption. The ST will be part of the secondary frequency control. The goal is to use the storage units to accommodate the excess renewable generation within the MMG.

## 6.2 Multi-Microgrid Test System

The single line diagram of the MV test system used in this thesis was adapted from a real case (Figure 6.1). It corresponds to an overhead 15 kV MV feeder connected to the MV bus of a HV/MV substation. The MV feeder supplies eight secondary substations (SS) with conventional electromagnetic transformers in the traditional structure. The electric parameters of the MV feeder is presented in Appendix A.

The MV structure was adapted to simulate a new framework where the distribution grid comprises electromagnetic transformers and ST as the interfaces between MV and LV grids. Accordingly, the simulation studies were carried out assuming that the SS 1, 4 and 8 are equipped with ST.

The simulations associated with the transition to the islanded mode assume two variants: SMO and MMO. In the SMO, it is considered that only the SS 1 has a storage device. Therefore, this unit operates as G<sub>Fo</sub> inverter for LV and MV side. The remaining SS (without storage) operates as G<sub>Fo</sub> for the LV side and G<sub>Fe</sub> inverter for the MV grid. On the other hand, to simulate the MMO, a new storage device is connected in SS 8. In this case, there are two MV G<sub>Fo</sub> inverters located at SS 1 and 8. The build-down service restoration approach simulations were also performed considering that the ST with storage is located in SS 1. For the parallel restoration

approach, it is assumed that SS 3 and 6 have a GFO unit connected to the LV bus.

The models of the MMG components adopted in this research and the proposed control strategies were implemented in the MatLab/Simulink environment. The models' parameters for performing the simulations are presented in Appendix B.

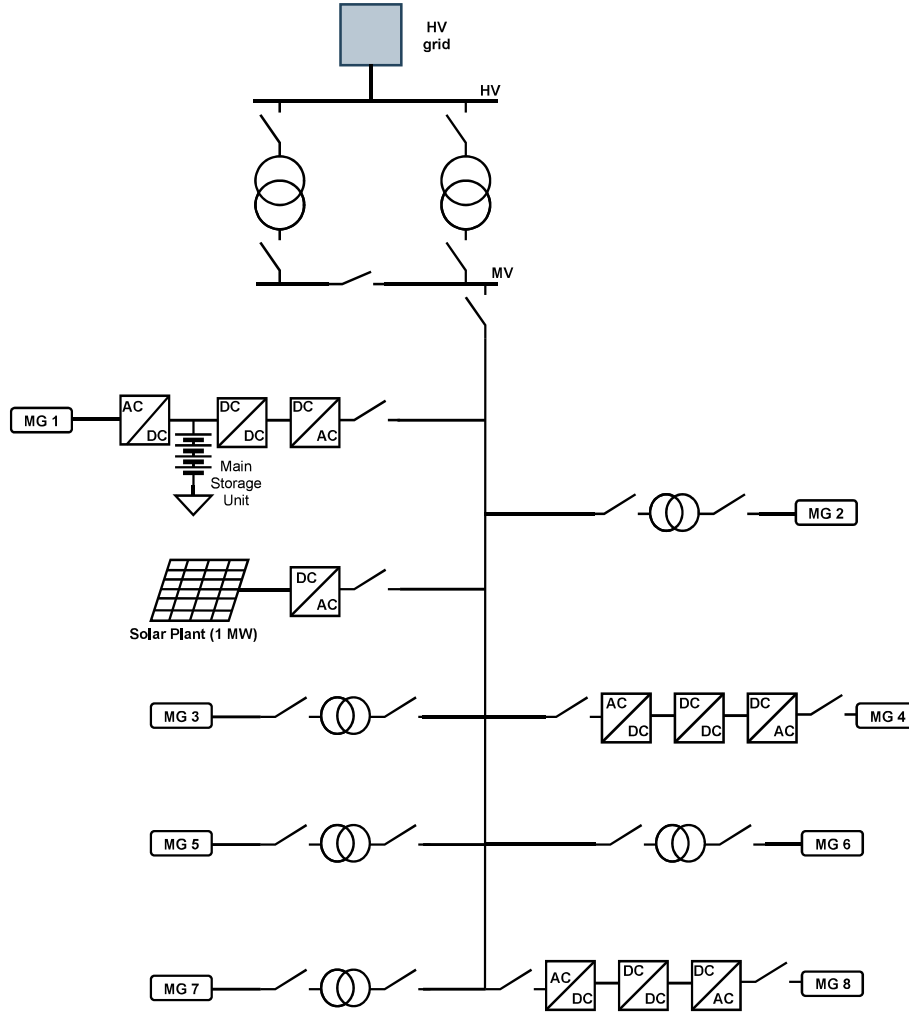


Figure 6.1: Multi-Microgrid test system

### 6.3 Transition to the Islanded Mode

This section presents the simulation results from the transition to the islanded mode. Initially, the MMG operates interconnected to the upstream system and suddenly disconnects from the main grid. Firstly, a base scenario is presented to illustrate the role of the ST when the MMG is islanded. Then, two scenarios are simulated

considering active power importing and exporting from/into the upstream system. The DG and DES units are equipped with P-f droop controls to support the primary frequency regulation in these two scenarios.

### 6.3.1 Base Scenario

#### 6.3.1.1 Simulation Conditions

A base case was created to demonstrate the ST's roles in the MMG islanded operation. In this example, just loads and generation are considered in the MMG. The DES units are not part of this base case. This example also assumes no generation from the solar plant connected to the MV grid. The production within the MMG comes from the microgeneration units connected to the LV grids. Besides, the P-f droop characteristics of the solar-based generation were not activated. Thus, only the ST with a coupled storage is responsible for supporting the transition to the islanded mode of the MMG system.

Since DER does not participate in the frequency control in this scenario, the secondary control is based on a PI controller, implemented in the ST equipped with a storage device. The centralized secondary frequency control does not occur in the base scenario to define new setpoints for the DER connected to the MMG system. The local secondary frequency control was also applied to the ST without storage devices. They have a local secondary frequency controller to correct the frequency deviations at the LV side. Those ST do not also have the  $\omega_{oLV}/f_{MV}$  droop in this base case. They operate decoupled from the MV grid in terms of frequency and reactive power, but not active power.

The simulations consist of the MMG disconnection from the HV grid and load-following in islanded operation. The goal of the simulation is to demonstrate the role of ST with storage as the central unit for supporting the MMG islanded operation. The MMO is also tested to demonstrate the MMG islanded operation when two units are operating as GFo. This is a similar situation to the conventional power systems where several synchronous generators are sharing among them the power-frequency support. In the simulated scenario, it was considered that the MG grid is importing power from the upstream level. Table 6.6 describes the load and generation conditions in the moments before the islanding from the main grid.

**Table 6.1:** Load and generation conditions in the base scenario

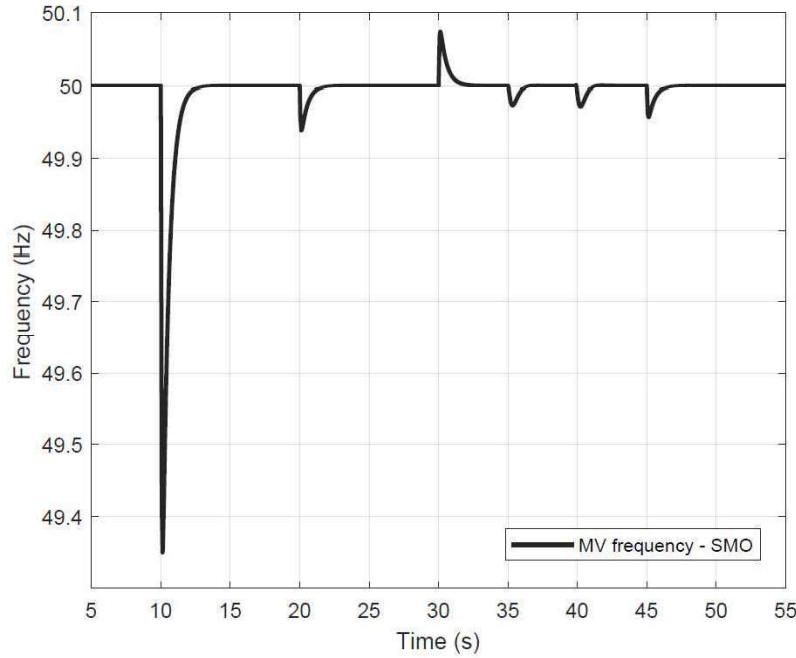
| Base Scenario |             |               |                 |
|---------------|-------------|---------------|-----------------|
| Unit          | Load P (kW) | Load Q (kVAr) | Generation (kW) |
| MG 1          | 75          | 23            | 35              |
| MG 2          | 90          | 27            | 20              |
| MG 3          | 80          | 24            | 0               |
| MG 4          | 85          | 26            | 40              |
| MG 5          | 70          | 21            | 15              |
| MG 6          | 75          | 23            | 40              |
| MG 7          | 80          | 26            | 0               |
| MG 8          | 75          | 23            | 0               |
| Total         | 630         | 193           | 150             |

The following set of successive events were considered in the MMG when performing the transition to the islanding mode:

- **t=10 s:** sudden disconnection from the upstream system;
- **t=20 s:** load increases 50 kW in SS<sub>3</sub>;
- **t=30 s:** generation increases 60 kW in SS<sub>2</sub>;
- **t=35 s:** load increases 55 kW in SS<sub>4</sub>;
- **t=40 s:** generation reduction 30 kW in SS<sub>8</sub>;
- **t=45 s:** load increases 35 kW in SS<sub>7</sub>;

### 6.3.1.2 Single-Master Operation

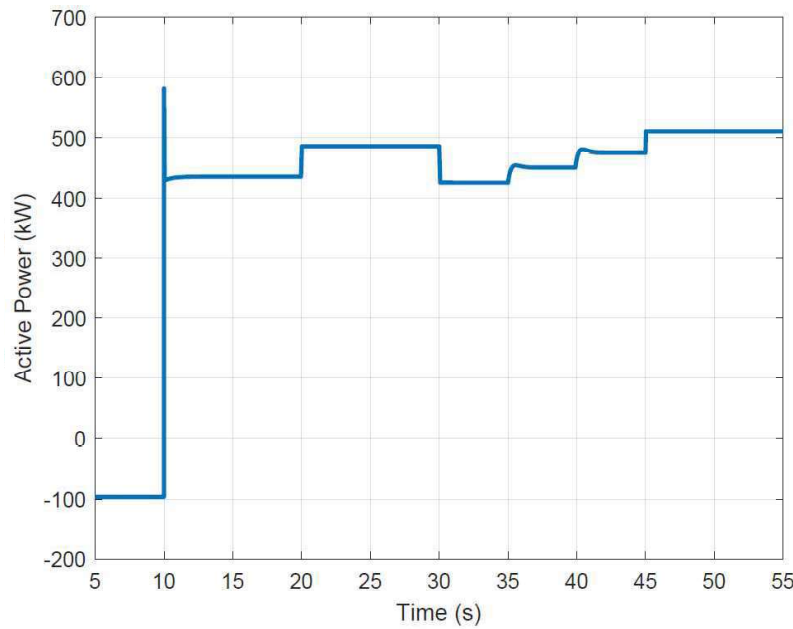
In the SMO, the ST placed at the SS 1 is the only unit operating as G<sub>Fo</sub> for the MV grid. In the moments before the islanding, the MV G<sub>Fo</sub> is absorbing power from the MV grid. At t=10 s, the disconnection from the upstream system causes a frequency variation, as depicted in Figure 6.2. The MMG frequency is contained throughout the action of the G<sub>Fo</sub> inverter of the ST existing in SS<sub>1</sub>, either in the moments subsequent to the islanding as well during the simulated load-following situation. It is also noticeable that the MV frequency returns to the nominal value due to the local secondary frequency control. The frequency variation is rapidly mitigated due to active power injection from storage coupled to the ST in SS 1. The ST ensures this initial frequency support, and then the local frequency control brings back the frequency to the nominal value.



**Figure 6.2:** MV grid frequency in the base scenario (SMO)

This action exemplifies the ST's role in distribution grids to support a successful transition to the islanded mode. The ST with a coupled storage provides a fast power response to ensure the successful transition to the islanded mode. The MV inverter acts as the main GfO unit by defining the voltage and frequency references to the MMG system. This is crucial to ensure that the distribution grids remain operational during the transition to the islanded mode in the absence of synchronous generators connected to the MMG. The energy stored that has a renewable origin (e.g., solar generation) supports the grid operation in emergency mode, enhancing the reliability and resilience of the distribution grids.

Following the frequency stabilization at the nominal value (50 Hz), the load and generation variations are supported by the MV GfO inverter. This unit adapts its active power output according to the net-load variations over the simulation time, as shown in Figure 6.3. When facing load increases in some MG, ST with a coupled storage inject active power into the MMG; in the opposite case, when any MG increases its generation (or decreases consumption), the GfO inverter reduces the active power injection. Therefore, the GfO unit accommodates the MV net load when the MMG shifts to the islanded mode. MG 1 is fed by a ST; thus, the generation and load changes are directly accommodated by the LV GfO inverter. Consequently, the load-frequency control at the MV grid is not influenced by this MG, given the fully decoupling between the two sides.



**Figure 6.3:** Active power output in the MV GFo for the base scenario (SMO)

This research considers that the storage system located in the ST has no energy limitation to provide power-frequency support to the grid during the simulation time. Nevertheless, the MMG framework presented in this thesis develops control strategies by exploiting the DG and DES connected to MV and LV grids. These functionalities will be demonstrated in the next sections. Without the participation of those resources in the overall power-frequency control, the GFo inverter will be required to have an increased power-frequency regulation role.

Figure 6.4 shows that the frequency is stabilized at 50 Hz in the MG fed by ST after the disconnection from the upstream system. Their frequencies are fully decoupled from the MV since the LV GFo inverter can provide sinusoidal waveforms independently of the conditions on the MV side. Figure 6.5 shows that frequency only varies when load variations occur downstream of the MG served by ST. This case stresses the decoupling capabilities provided by the ST. Without the implementation of the droop described in section 4.6.2, the DER connected to these MG will not be part of the overall power-frequency control. On the other hand, this example also shows that the ST can be an interesting solution to protect sensitive loads from significant disturbances taking place in the MV grid.

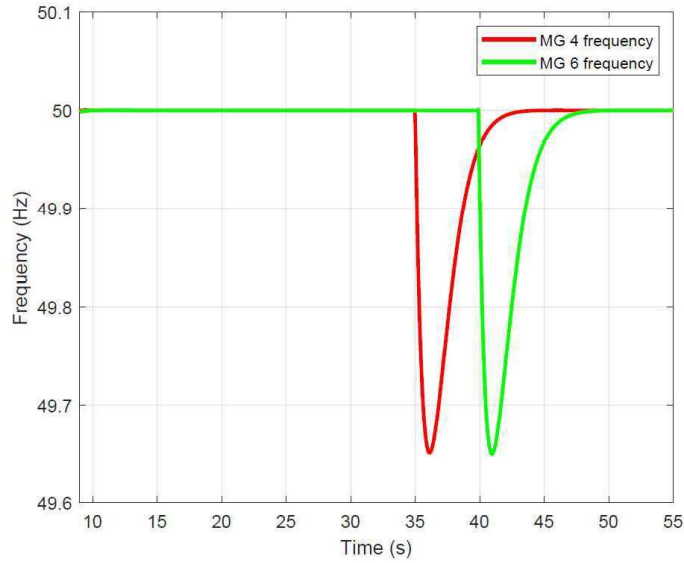


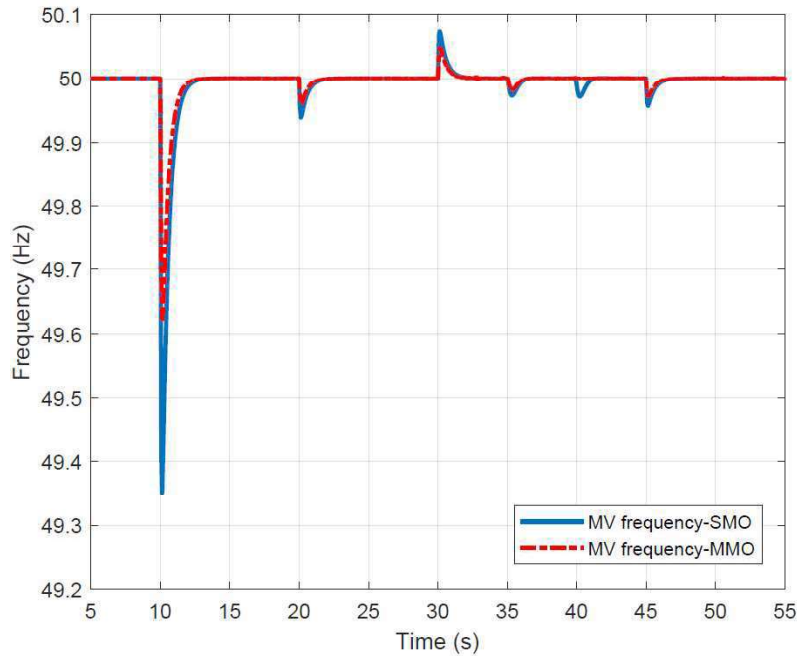
Figure 6.4: MG 4 and MG 8 frequencies in base scenario (SMO)

### 6.3.1.3 Multi-Master Operation

The simulation of the MMO was conducted adopting a new storage device placed in the SS8. Thus, two ST devices provide primary frequency control. The active power-frequency droop characteristic in the SS 8 has a value two times higher than in the SS1. The simulation results show that the frequency deviation experienced by the MMG will be smaller than in the previous case (Figure 6.5). By comparing the frequency deviations on both operation modes, one can observe that the initial frequency deviation is higher in the SMO. The MV net-load variations are shared between the two MV GfO units and the new ST with storage device will supply directly the MG through the energy stored.

Due to the fully decoupling, the net-load variations in the LV side are not requested to the MV side, being directly supplied by the storage device connected to the DC-link. In the MMO, at  $t=40$  s, the frequency does not change because the MG 8 is now fed by a ST. The the LV GfO supports the generation reduction, and there is no impact on the MV frequency since the storage supplies the load through the LV GfO inverter.





**Figure 6.5:** Frequencies in MG 4 and MG 8 for the base case (MMO)

With an additional ST with storage in the MMG system, the load-frequency burden is supported by two MV G<sub>Fo</sub> units. Since the droop characteristics are different for both MV G<sub>Fo</sub> inverters, the active power contribution from each inverter is different. Figure 6.6 shows the power-sharing between the two inverters. The active power output from the two inverters have similar behaviors. However, the active power provided by the ST in SS<sub>1</sub> is around two times smaller than in the SS<sub>8</sub>, due to its droop value. Similarly to the conventional power systems, a MMO is a less severe situation to transition for the islanded mode in a MMG since it enables a smaller frequency deviation compared to the SMO. Although there is an initial frequency deviation, it can be mitigated through proper control strategies by exploiting the DG and DES capabilities to support the power frequency control.

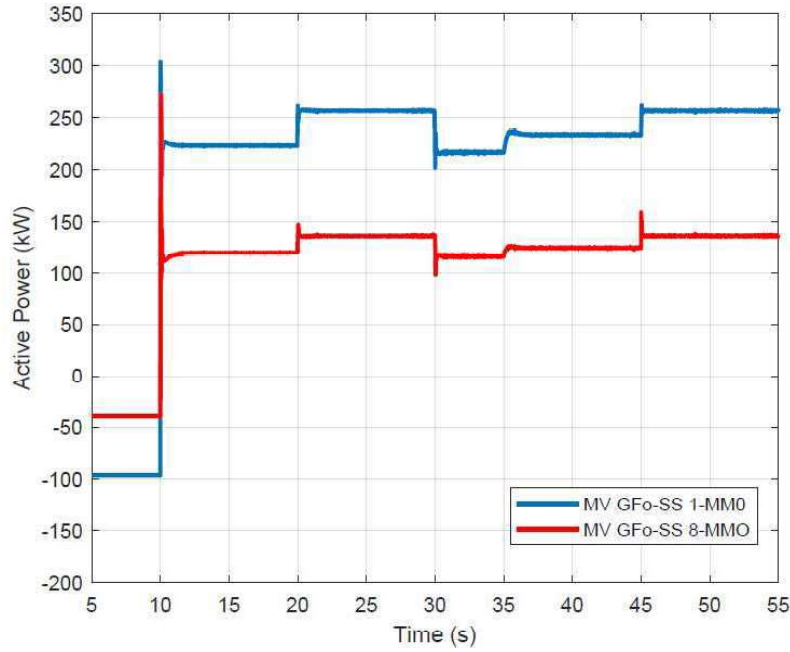


Figure 6.6: Active power output in the GFo units for the base scenario (MMO)

### 6.3.2 Exporting power to the upstream grid

The last section showed through a base scenario the islanded operation of the MMG. This section presents the results of the MMG islanded operation in which solar-based generation and DES units participate in the power-frequency control. The solar-based generation (solar power plant and microgeneration) can only provide a downward reserve, while DES units are equipped with the P-f droop controls to support the primary frequency control in both directions (upward and downward). A first scenario is considered where the MMG exports active power to the upstream system due to the excess of generation regarding consumption. An opposite case is also assumed, where the MMG system is importing active power from the upstream system. Both operation modes, SMO and MMO, are simulated in each scenario

#### 6.3.2.1 Simulation Conditions

This scenario represents a high share of renewables connected to the MMG in normal operating conditions. The generated power from the solar power plant and microgeneration is higher than the consumption when the MMG operates interconnected to the upstream grid. Table 6.6 shows the load and generation conditions when the MMG is disconnected from the upstream system. As depicted in Table 6.6, DES units absorb or inject active power when the MMG is disconnected

from the upstream system. The active power is positive when the DES units absorb active power and negative when injecting.

**Table 6.2:** Characterization of the exporting scenario

| <b>Exporting Scenario</b> |                           |                  |                     |
|---------------------------|---------------------------|------------------|---------------------|
| <b>Unit</b>               | <b>PV Generation (kW)</b> | <b>Load (kW)</b> | <b>Storage (kW)</b> |
| <b>Solar Plant</b>        | 500                       | -                | -                   |
| <b>MG 1</b>               | 70                        | 150              | 25                  |
| <b>MG 2</b>               | 20                        | 52               | -50                 |
| <b>MG 3</b>               | 15                        | 26               | -40                 |
| <b>MG 4</b>               | 155                       | 129              | -20                 |
| <b>MG 5</b>               | 40                        | 52               | 35                  |
| <b>MG 6</b>               | 50                        | 52               | 40                  |
| <b>MG 7</b>               | 40                        | 26               | -25                 |
| <b>MG 8</b>               | 100                       | 78               | 40                  |
| <b>Total</b>              | 990                       | 565              | 5                   |

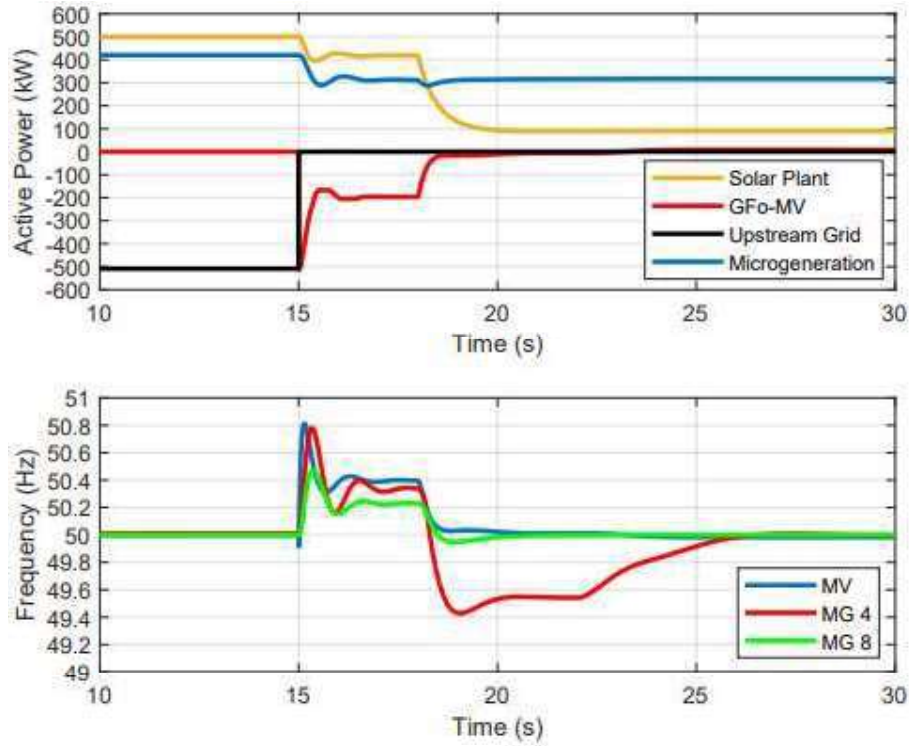
### 6.3.2.2 Single-Master Operation

Since the solar generation is higher than the consumption, the MMG is injecting power to the upstream system during the normal operation. As shown in Figure 6.7 (black line on top), in the moments before the unintentional islanding, the MMG is exporting power to the upstream system (around 500 kW).

Following the disconnection of the MMG ( $t=15$  s), the MV GfO inverter has a key role acting as master of the MMG system. This unit absorbs the active power surplus from the MV grid that was initially injected into the HV grid (red line on top in Figure 6.7). This demonstrates the ST's main role has in the first moments after the islanding to ensure a successful transition to the islanded mode. The MV frequency increases after the disconnection from the upstream system since the MMG is exporting power to the upstream system (red line on the bottom in Figure 6.7).

After the islanding, the frequency is stabilized due to the prompt response from the MV GfO inverter unit and from the distributed resources equipped with the P-f droop characteristics. The solar power plant, solar-based microgeneration and DES units adapt their active power according to the droop characteristics to react to the frequency deviation. Consequently, the frequency is stabilized some seconds after the disconnection from the upstream system in a value different from the nominal one

(around 50.4 Hz). On the other hand, assuming that the storage associated with the ST has no energy restrictions, the MG 1 is being supplied directly by the stored energy. If this MG also has an excess of generation regarding the consumption, the LV GFo will absorb power to charge the storage system connected to the DC-link of the ST. As the ST with storage ensures a fully decoupling between MV and LV grids, the MG 1 does not influence the power-frequency control action in the MV grid.



**Figure 6.7:** Exporting scenario in SMO: Active power outputs; MV, MG 4 and MG 8 frequencies (down)

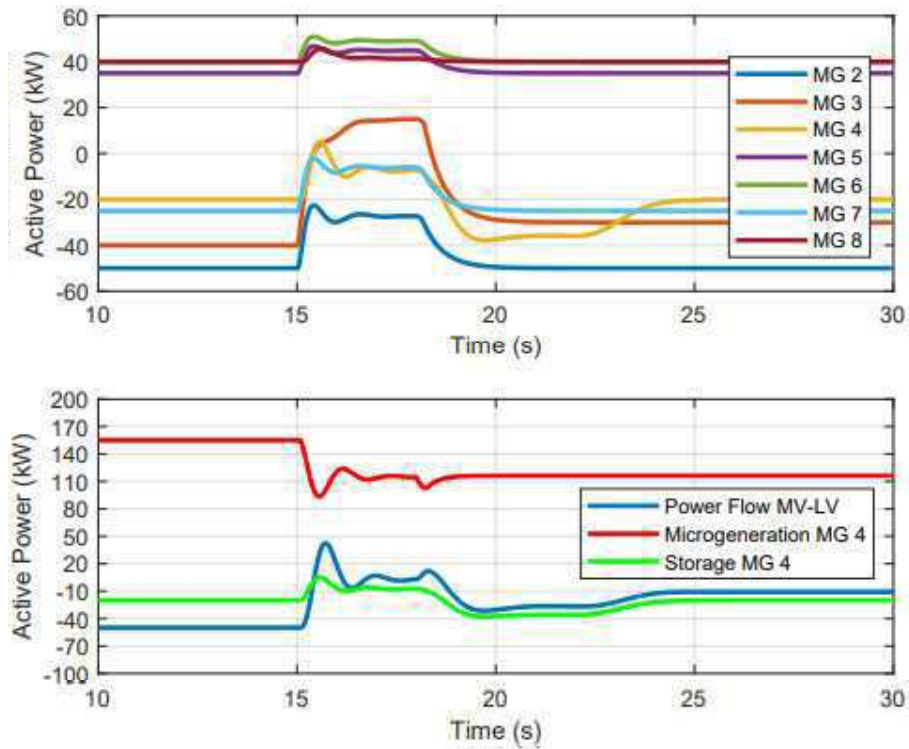
As depicted on the top of Figure 6.7, the generation from the MV-connected solar power plant (yellow line) and microgeneration (blue line) reduces the active power injection in the moments after the islanding ( $t=15$  s). The microgeneration represented in that Figure 6.7 corresponds to the sum of the solar-based generation from all MG (except MG 1).

When the frequency is stabilized after the disconnection from the upstream system, it is different from the nominal one. The MV GfO unit remains absorbing active power from the MMG. However, from  $t=18$  s, the secondary frequency control is enabled and, thus, the active power absorbed by the storage device

coupled to the ST is continuously reduced close to zero. The centralized secondary frequency control corrects the power unbalance that still exists after the primary frequency control actions. The SC computes the new set points for the solar power plant, microgeneration and DES units based on the information about the reserve level within the MMG. The downward reserve is essential to define new set-points for the generation facilities. Figure 6.7 on the bottom shows that the solar plant connected to the MV grid is the main contributor for the secondary control. As major generation facility, it has the highest participation factor for the centralized secondary control. Microgeneration from the MG also contributes to the centralized secondary frequency control. Nonetheless, the contributions are smaller than the solar power plant once they have lower reserve levels and, hence, minor participation factors.

The droop characteristic LV Angular frequency-MV frequency ( $\omega_{oLV}/f_{MV}$ ) is implemented (presented in subsection 4.6.2) to ensure the participation of DER located downstream from SS served by ST without storage. Figure 6.7 (on the bottom) shows that this droop fulfils the role for which it was designed, transposing the frequency disturbance in the MV grid to the MG in order to induce the participation of LV resources in the primary frequency control. The frequencies in MG 4 and MG 8 have similar behavior to the MV frequency, which allows the involvement of the LV DER in the MMG overall power-frequency control. However, the secondary control action and the droop controller  $\omega_{oLV}/f_{MV}$  are simultaneously operating, which leads the MG 4 frequency to a value different from the nominal one (49.5 Hz). Hence, at  $t=22$  s the ST integral control is activated to conduct the frequency again to 50 Hz, since the centralised secondary frequency control has already finished its operation. The combined effect of the  $\omega_{oLV}/f_{MV}$  droop and centralised secondary control is not so severe in MG 8 as in the case of MG4. The frequency in MG 8 decayed only slightly below 50 Hz. Then, the integral controller implemented in the LV GFO inverter is enabled to eliminate the frequency error.

The DES units also contribute for stabilizing the frequency in the moments after the islanding, as described in Figure 6.8 (on top). Before the islanding, the DES in the MG are absorbing or injecting active power into/from the MMG. The DES can represent EV charging stations or storage devices connected to the LV grids.



**Figure 6.8:** Exporting Scenario in SMO: Active power from the distributed storage (on top); Power flow between MV grid and MG 4, microgeneration and storage in MG 4 (down)

From the analyzes of 6.8 (on top), it is observed that the DES in the charging mode (active power positive) increases their absorption of active power from the MMG system in order to mitigate the frequency deviation. On the contrary, the DES units injecting active power to the grid (active power negative) reduce their injection to support the power-frequency control at the MV level. In MG3, the DES will pass to the absorption mode, operating as "load" to the MMG system. Figure ?? illustrates the important task of combining the contributions of DES units with renewable generation in future scenarios to improve grid resilience. It is also noticeable that DES units come to the initial active power set-point. The contribution from the DES units is only necessary in the subsequent moments from the islanding to stabilize the frequency. Since there is an excess of generation regarding consumption, the secondary control defines new active power set-points by only acting in the solar power plant and microgeneration units. In this case, the DES units are not necessary to participate in the centralised frequency control actions.

The bottom of Figure 6.8 shows the power flow through the ST 4 and the active

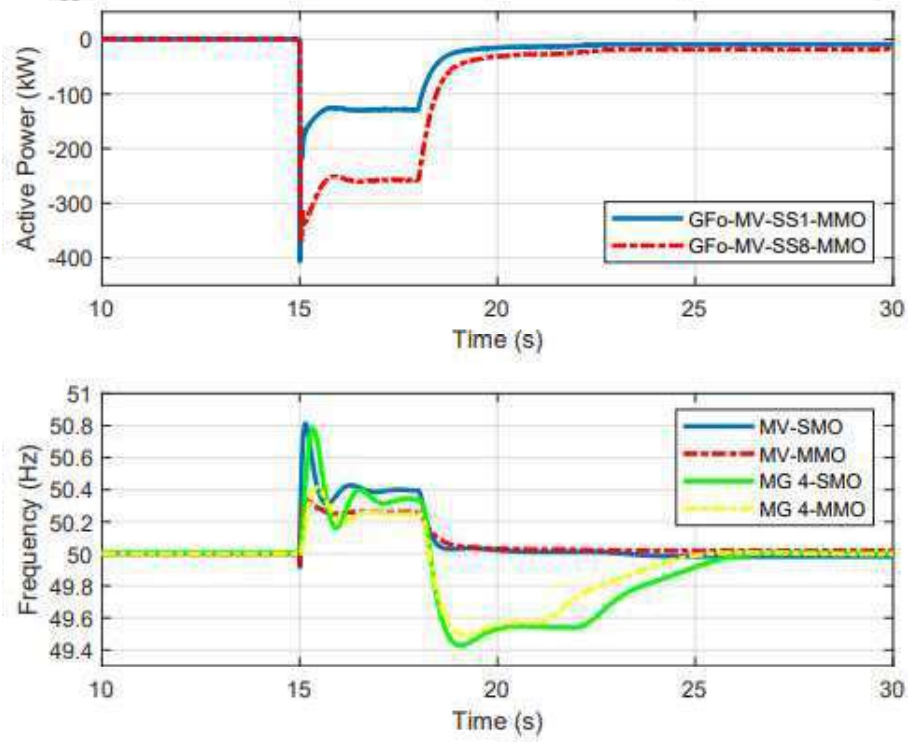
power from the microgeneration and distributed storage in the MG 4. Before the islanding, the ST was injecting active power into the MV grid. The generation is higher than the consumption in this MG. Additionally, the distributed storage is also discharging, contributing to the reverse power flow through the ST. Following the disconnection from the upstream grid, the power flow becomes positive, meaning that the ST is absorbing active power from the MV grid. This change in the power flow through the ST results from the participation of the microgeneration and DES units in the primary frequency control. It is noticeable that the active power from the distributed storage returns to a value similar to the one verified when the MMG operates in the interconnected mode. In turn, the microgeneration changes its active power output, which illustrates that the storage units only participate in the primary frequency control given the high value of the downward reserve.

### 6.3.2.3 Multi-Master Operation

In the MMO, the MMG has two ST with storage SS 1 and SS 8. Additionally, as the ST 8 has a storage device in the MMO, the MG 8 is operating fully decoupled from the MV side. Thus, the MG 8 is not part of the overall power frequency control assuming that there are no energy restrictions to the storage device coupled to the DC-link of the ST. Hence, due to the full decoupling operation between the two sides, the active power balance is not requested to the MV side, being supplied directly by the storage coupled to the ST. In the MMO, MG 1 and MG 8 are not burdening the power-frequency control at the MV side since they are served by ST-coupled storage with no energy restrictions during the simulation time.

The power unbalance after the islanding is supported by the two G<sub>Fo</sub> units located in SS 1 and SS 8. The active power output from each G<sub>Fo</sub> unit is represented at the top of Figure 6.9. Once there are two G<sub>Fo</sub> inverters, the response of G<sub>Fo</sub> located in SS 1 has a power response that is slightly half to the one verified in SMO. Following the unintentional disconnection from the main grid, the frequency deviation experienced by the MMG is smaller than in the SMO, as shown in Figure 6.9 (down). In that figure, dashed lines represent the frequencies in the MV grid and MG 4 in the MMO. From Figure 6.9, it is noticeable that the frequency deviations either in MV grid and MGs (fed by ST) are smaller compared to the SMO (continuous lines).





**Figure 6.9:** Exporting scenario with MMO: active power from the MV GFo inverters (top); MV, MG 4 and MG 8 frequencies after islanding (down);

Due to the centralized secondary frequency control, the active power output of each GFo inverter is close to zero. In this case, the power unbalances correspond to the sum of the active power output from each MV GFo inverter. Accordingly, the centralized control computes the participation factor to adjust the active power in the solar generation units based on the total power unbalance. Once the generation is higher than the consumption, the power response from the MV GFo is only needed in the subsequent moments of the islanding. Nonetheless, the MV GFo inverters are the main controlling units since they provide voltage and frequency references.

### 6.3.3 Importing power from the upstream grid

While the last section demonstrates the simulation results from the transition to the islanded mode considering an exporting scenario, this section addresses the importing scenario. As in this case the solar-based generation has only a downward reserve, the main contributions to the frequency variation are provided by the GFo and DES units in the LV grid.



### 6.3.3.1 Simulation Conditions

In the importing scenario the MMG is absorbing active power from the upstream grid. It corresponds to a situation where the consumption is higher than the generation within the MMG. Table 6.3 represents the load and generation conditions when the disconnection from the upstream occurs. Like in the exporting scenario, the distributed storage units are also charging or discharging. The right column in Table 6.3 indicates the active power state from the distributed energy storage units.

Table 6.3: Characterization of the importing scenario

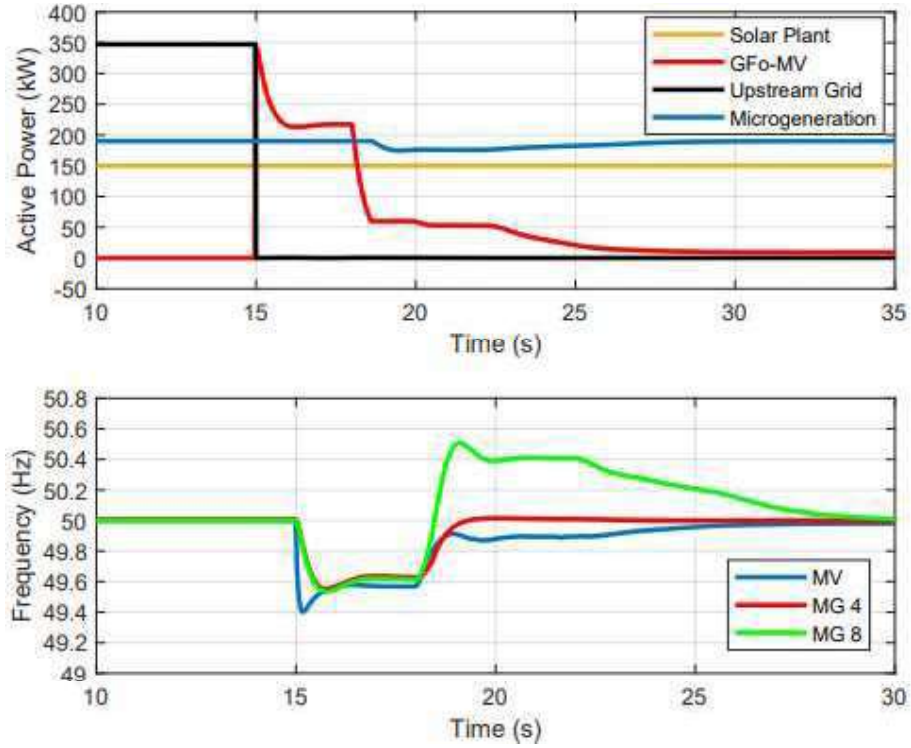
| Importing Scenario |                    |           |              |
|--------------------|--------------------|-----------|--------------|
| Unit               | PV Generation (kW) | Load (kW) | Storage (kW) |
| Solar Plant        | 150                | -         | -            |
| MG 1               | 50                 | 100       | 20           |
| MG 2               | 0                  | 85        | 15           |
| MG 3               | 15                 | 65        | 40           |
| MG 4               | 100                | 75        | -20          |
| MG 5               | 20                 | 85        | -25          |
| MG 6               | 10                 | 100       | 25           |
| MG 7               | 0                  | 45        | 35           |
| MG 8               | 45                 | 175       | 25           |
| Total              | 390                | 730       | 115          |

### 6.3.3.2 Single-Master Operation

Figure 6.10 (on top) depicts the variation of the active power from the GfO unit (red line). The MV GfO provides fast power response when the transition to the islanded mode occurs. The GfO has no initial power exchange with the MMG, similar to the exporting scenario. Since the MMG is facing an under frequency situation, the MV GfO will inject active power into the MMG, ensuring the MMG system's stability during the transition to the islanded mode. The solar-based generation (solar power plant and microgeneration) keeps its active power output once there is no upward reserve.

Since the MMG is operating under an importing scenario, the frequency is stabilized around 49.6 Hz (Figure 6.10 at the bottom) due to the primary frequency control actions provided by the ST and DES units. Since the MMG is operating under an importing scenario, the frequency is stabilized around 49.6 Hz due to the primary

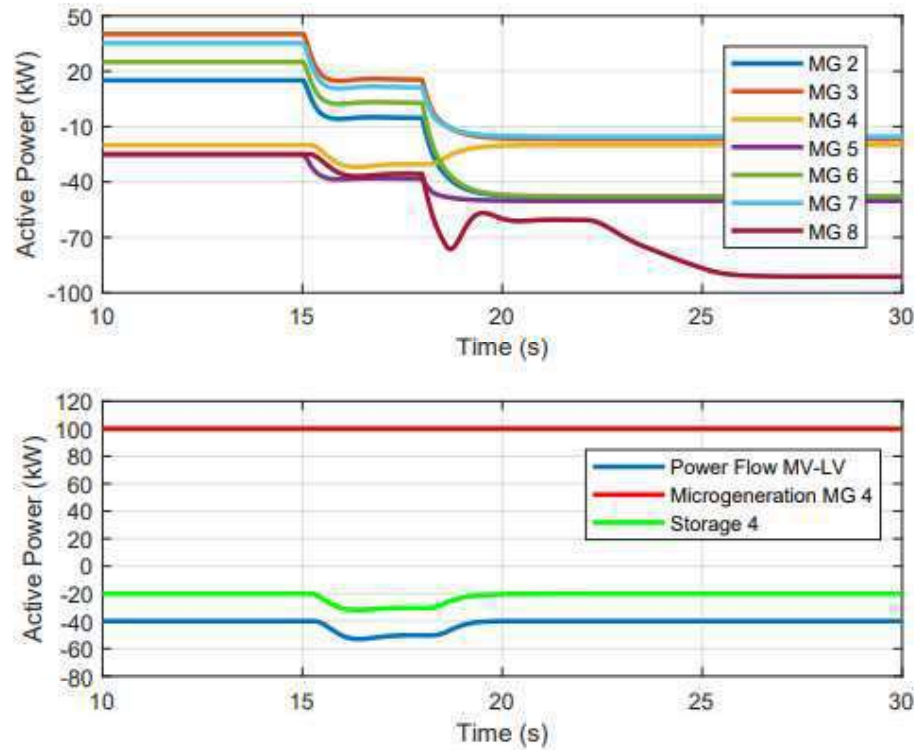
frequency control actions provided by the ST and DES units. Due to the MV-frequency and LV angular frequency control droop ( $\omega_{oLV}/f_{MV}$ ), the frequencies in MG 4 and MG 8 have a similar behavior that guarantees DES units' participation in the primary control.



**Figure 6.10:** Importing scenario in SMO: Active power outputs; MV, MG 4 and MG 8 frequencies after islanding (down)

At  $t=18$  s, the centralized frequency control is enabled to bring the frequency to the nominal value. The power unbalance that corresponds to the active power output of the MV GFo unit is eliminated by computing new active power set-points. These set-points are computed by the SC using the information on the MMG reserve level. Once there is no upward reserve, the new-set points are only computed for the DES units. It is visible in Figure 6.11 (on top), that DES units have an active power setpoint different from the previous moments to the islanding. After the enablement of the centralized frequency control, all DES in the MMG inject active power in order to bring back the frequency to the nominal value. Given that there is no upward reserve from the solar power plant, the DES provide the main contribution to bring the frequency to the nominal value. This is the opposite situation to that one verified in the exporting scenario, where the DES came back to the initial set point since the reserve was

provided by the solar-based generation. Due to the excess of solar production, the centralized frequency control acted in the generation units to bring the frequency to the nominal value.



**Figure 6.11:** Importing Scenario in SMO: Active power from the distributed storage (on top); Power flow between MV grid and MG 4, microgeneration and storage in MG 4 (down)

### 6.3.3.3 Multi-Master Operation

When the MMG is operating in the MMO mode during the importing scenario, the two MV GFo units in SS 1 and SS 8 inject active power to support the frequency in the subsequent moments to the islanding, as depicted in Figure 6.12 (on top). The power response from the two GFo units is different because they have different P-f droops. After activating the centralized secondary frequency control, the active power output from GFo units is close to zero. The centralized control defines adjustments to the DES units to bring the frequency back to the nominal value. The new adjustments are only computed for the DES units since solar-based generation is not providing upward reserve. The SC computes the new set-points based on the power unbalance in the MMG, which corresponds to the sum of active power in the MV GFo units.

A highlight from Figure 6.12 (at the bottom) concerns the MV frequency deviation after the islanding. The MV frequency deviation in MMO is smaller compared to the SMO mode. In the MMO, the MG 8 is fully decoupled from the MV grid and does not influence the power frequency control on the MV side. This deviation is inside the frequency dead-band and thereby is not sufficient to activate the  $(\omega_{oLV}/f_{MV})$  droop. Consequently, the MG 4 frequency remains at 50 Hz after the disconnection from the upstream system.

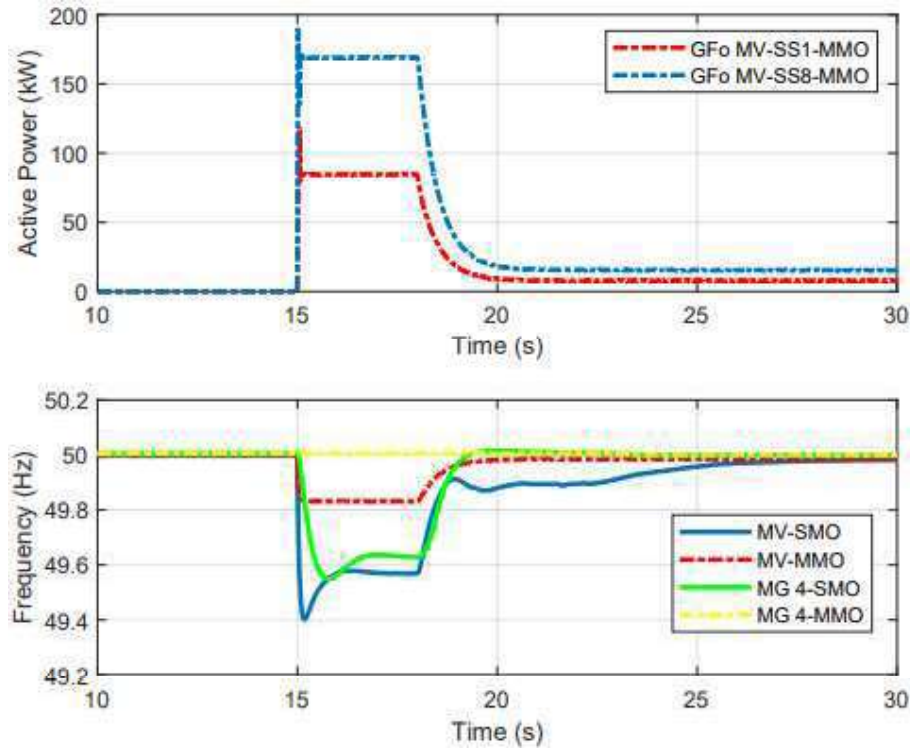


Figure 6.12: Exporting scenario with MMO: active power from the GfO units; MV, MG 4 and MG 8 frequencies after islanding (top)

## 6.4 Long Term Simulation of Multi-Microgrids Black Start Procedure

This section presents the simulation results from the long-term simulation of the BS procedures in the MMG. The section is divided into two parts; the first concerns the build-down approach, whereas the second corresponds to the parallel service restoration. The solar-based generation can provide upward or downward reserve in both service restoration strategies. Moreover, in the simulation scenarios for the BS procedures, the DES have maximum and minimum values for the active power

that they can inject or absorb. A new variant for the centralized secondary frequency control is tested in which the active power adjustments are mainly performed by acting on the storage devices: main storage coupled to the ST and distributed storage in the LV grids. The simulation results presented in this section assume that the network energization phase has already been finalized. The grid skeleton is already created, and then the connection of loads and generation can start.

## 6.4.1 Build-Down approach

### 6.4.1.1 Simulation Conditions

Following an unsuccessful transition to the islanded mode, the ST with storage assumes the main role in leading the MMG service restoration. It corresponds to the single unit with BS capability within the MMG. A build-down service restoration strategy is initiated to connect loads and generation to restore the MMG system to the pre-disturbance conditions.

After a specified time, the SC communicate with the DMS system to check if it is needed to initiate the BS procedure using the MMG resources (ST,DG and DES).When the DMS informs the SC that it can initiate the BS procedure, the SC runs the algorithms involving BS procedure. Firstly, the SC will check that the main storage unit has conditions to initiate the BS procedure. Once the main storage unit has conditions to launch the BS procedure, the BS start-up scheme is initiated as described in the chapter 5. Then, the ST energizes the MMG system.

Table 6.4 characterizes the network status regarding load and generation in the moments preceding the blackout event.In this table, the load values are presented by priority order ( $P_1$ ,  $P_2$ ,  $P_3$ ). Concerning the reactive power consumption, it was assumed that the loads are operating with  $tg\phi = 0.4$  lagging.In Table 6.4,  $P_{DES}$  corresponds to the maximum and minimum active power levels that can be supported by the DES for this operating condition.It should be noticed that the conditions existing before the islanding correspond to an operating condition where the generation is higher than the consumption in the MMG. The BS procedure shows how the capabilities provided by ST, DG and DES are exploited to restore the service for those conditions.

Table 6.5 describes the build-down approach's sequence of actions (connection of loads and generation). The sequence of actions is performed assuming that the MMG (MV and LV grids) was previously energized and the DES units were connected to the grid without absorption and injection of active power ( $P=0$ ). This load restoration procedure is assumed to follow a rule-based approach defined by the system operator to restore the service in the distribution grid. The main objective of this research is not to determine the optimal sequence of actions for the service restoration. Instead, it intends to demonstrate the feasibility of the developed functionalities to integrate ST in MMG service restoration processes actively.

**Table 6.4:** Load and generation scenario before the black start

| <b>Load and generation scenario before the black start</b> |                                        |                                        |                                        |                            |                                            |                                            |
|------------------------------------------------------------|----------------------------------------|----------------------------------------|----------------------------------------|----------------------------|--------------------------------------------|--------------------------------------------|
| <b>Unit</b>                                                | <b>Load<br/>P<sub>1</sub><br/>(kW)</b> | <b>Load<br/>P<sub>2</sub><br/>(kW)</b> | <b>Load<br/>P<sub>3</sub><br/>(kW)</b> | <b>Generation<br/>(kW)</b> | <b><math>P_{DES_{min}}</math><br/>(kW)</b> | <b><math>P_{DES_{min}}</math><br/>(kW)</b> |
| <b>Solar Plant</b>                                         | -                                      | -                                      | -                                      | 700                        | -                                          | -                                          |
| <b>MG 1</b>                                                | 65                                     | 45                                     | 30                                     | 35                         | -5                                         | 5                                          |
| <b>MG 2</b>                                                | 80                                     | 50                                     | 35                                     | 65                         | -4                                         | 4                                          |
| <b>MG 3</b>                                                | 70                                     | 40                                     | 25                                     | 40                         | -6                                         | 6                                          |
| <b>MG 4</b>                                                | 40                                     | 25                                     | 20                                     | 25                         | -6                                         | 6                                          |
| <b>MG 5</b>                                                | 90                                     | 30                                     | 30                                     | 50                         | -3                                         | 3                                          |
| <b>MG 6</b>                                                | 70                                     | 50                                     | 20                                     | 55                         | -6                                         | 6                                          |
| <b>MG 7</b>                                                | 80                                     | 40                                     | 30                                     | 75                         | -5                                         | 5                                          |
| <b>MG 8</b>                                                | 50                                     | 25                                     | 25                                     | 25                         | -6                                         | 6                                          |
| <b>Total</b>                                               | 545                                    | 305                                    | 215                                    | 1170                       | -41                                        | 41                                         |

#### 6.4.1.2 Results

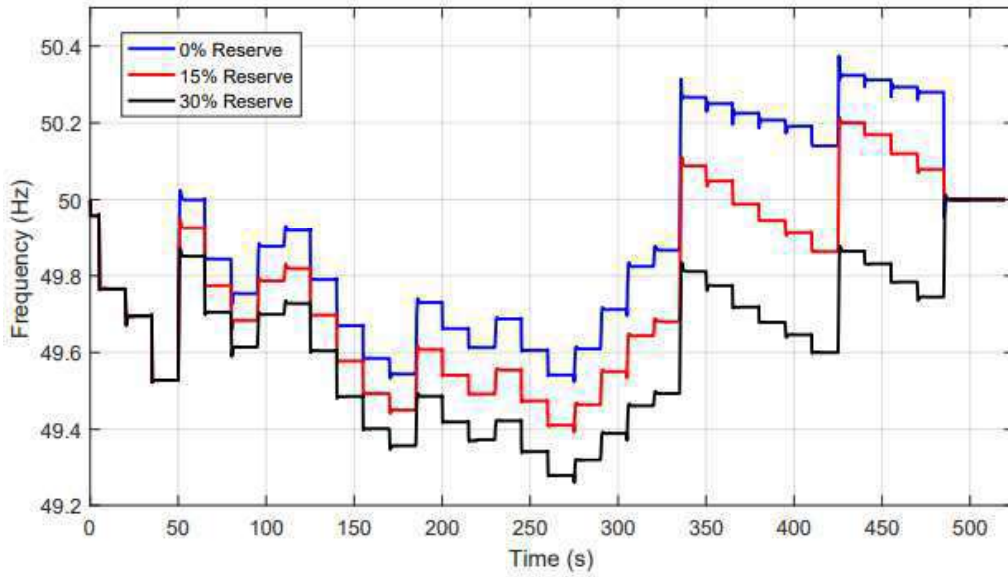
Figure 6.13 presents the MV frequency behavior throughout the BS procedure following the build-down approach. This figure shows the evolution of the frequency for the three reserve level scenarios. Some large frequency variations are registered at  $t=50s$ ,  $t=185s$ ,  $t=250s$  and  $t=200s$ . They are related to set-points sent to the solar power plant. In this BS procedure, it is considered that the solar PV plant connected to the MV grid is not delivering the full available power when connected to the grid. Instead, the available power is connected step by step in order to avoid large frequency excursions

**Table 6.5:** Restoration procedure with the sequence of actions in build-down approach

| <b>t(s)</b> | <b>MV Grid</b>                       | <b>t(s)</b> | <b>MV Grid</b>                                               |
|-------------|--------------------------------------|-------------|--------------------------------------------------------------|
| 5           | Loads in MG 2 (P <sub>1</sub> )      | 260         | Loads in MG 7 (P <sub>2</sub> )                              |
| 20          | Loads in MG 4 (P <sub>1</sub> )      | 275         | Generation in MG 5                                           |
| 35          | Loads in MG 5 (P <sub>1</sub> )      | 290         | Generation in MG 6                                           |
| 50          | Solar Power Plant P=250 kW           | 305         | Generation in MG 7                                           |
| 65          | Loads in MG 7 (P <sub>1</sub> )      | 320         | Generation in MG 8                                           |
| 80          | Loads in MG 8 (P <sub>1</sub> )      | 335         | Solar Power Plant=250 kW                                     |
| 95          | Generation in MG 2                   | 350         | Loads in MG 8 (P <sub>2</sub> )                              |
| 110         | Generation in MG 4 (P <sub>1</sub> ) | 365         | Loads in MG 2 (P <sub>3</sub> )                              |
| 125         | Loads in MG 3 (P <sub>1</sub> )      | 380         | Loads in MG 3 (P <sub>3</sub> )                              |
| 140         | Loads in MG 6 (P <sub>1</sub> )      | 395         | Loads in MG 4 (P <sub>3</sub> )                              |
| 155         | Loads in MG 2 (P <sub>2</sub> )      | 410         | Loads in MG 5 (P <sub>3</sub> )                              |
| 170         | Loads in MG 4 (P <sub>2</sub> )      | 425         | Solar Power Plant P=200 kW                                   |
| 185         | Solar Power Plant P=100 kW           | 440         | Loads in MG 6 (P <sub>3</sub> )                              |
| 200         | Loads in MG 3 (P <sub>2</sub> )      | 455         | Loads in MG 7 (P <sub>3</sub> )                              |
| 215         | Loads in MG 5 (P <sub>2</sub> )      | 470         | Loads in MG 8 (P <sub>3</sub> )                              |
| 230         | Generation in MG 3                   | 485         | Enable the centralized secondary frequency control           |
| 245         | Loads in MG 6 (P <sub>2</sub> )      | 500         | Enable the local secondary frequency control in MG 4 and MG8 |

due to high excess of active power in the MMG. In practice, the connection with all available power at once can lead to untimely actuation of systems protections. The frequency varies according to the connection of loads and generation. However, frequency deviations when connecting loads and generation are different depending on the reserve provided by solar-based generation. For example, until around  $t=300$  s, the BS is mainly connecting loads, which leads the frequency to values smaller than 50 Hz. Nevertheless, without reserve level, the frequency deviation (regarding the nominal value) is smaller than in scenarios with reserve (15% and 30%). For the situation without reserve, solar power generation is connected to the MMG with the maximum available power which is helpful when the frequency is below the nominal value.



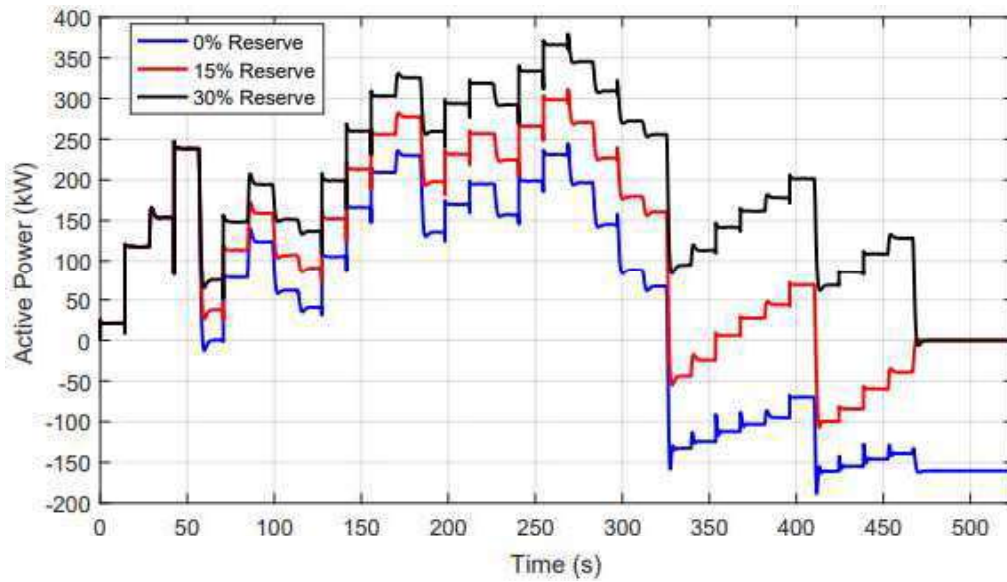


**Figure 6.13:** MV frequency in the build-down approach for the three simulations scenarios

After  $t=300$  s, more generation is connected to the MMG which leads the frequency to values higher than 50 Hz when the connection of loads and generation is finished (around  $t=470$  s) for the scenario without reserve. In the scenario with 15% of reserve, the frequency is also slightly above 50 Hz. An opposite situation occurs when the solar generation units are operating with a 30% reserve. By the end of connecting loads and generation, the frequency is below 49.8 Hz. Thus, the load is higher than the consumption. In the BS procedure, the centralized frequency control acts mainly in the DES units and in the main storage unit to bring back the frequency to the nominal value.

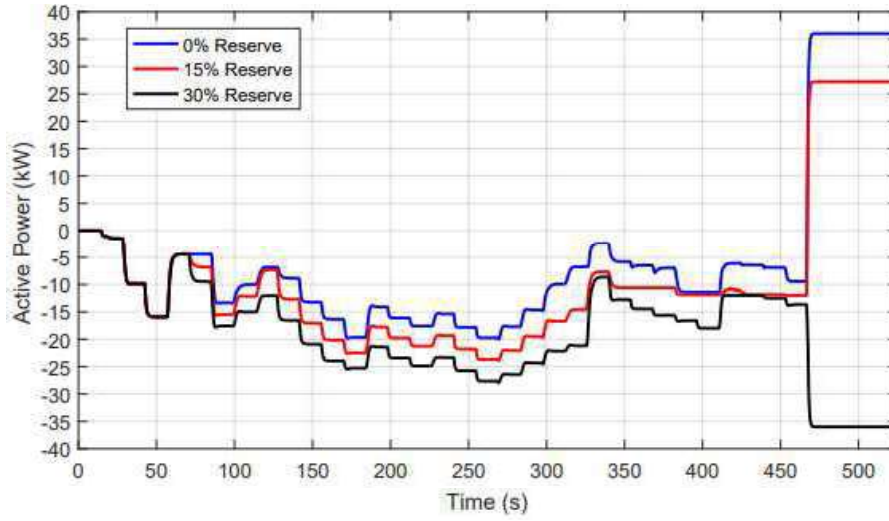
As shown in Figure 6.14, without reserve the MV GfO unit absorbs the excess active power from the MMG system after the enablement of the centralized frequency control ( $t=485$  s). In the BS simulations, the centralized secondary frequency control acts in the main storage unit coupled to the ST and distributed storage units. In turn, in scenarios with reserve (15% and 30%), the active power from the GfO is close to zero.





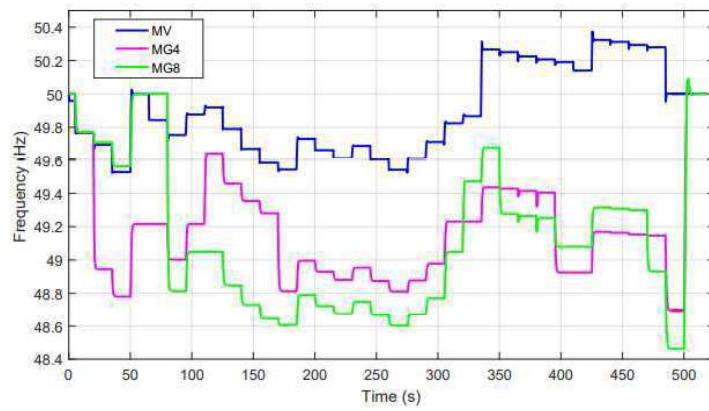
**Figure 6.14:** Active power of MV inverter acting as grid-forming unit in build-down approach for the three simulation scenarios (build-down approach)

Complementary, Figure 6.15 also demonstrates the effects of the centralized secondary frequency control. This figure illustrates the active power variation from the DES units. When the centralized frequency control is enabled (around  $t=485s$ ), in the scenario without reserve the maximum available power from the DES units is used to operate as load. In the scenario, with 15% reserve is not necessary to use all available reserve power ES units to bring the frequency to the nominal value. Lastly, in a scenario with 30% reserve, all the available reserve is used for injecting active power into the MMG.

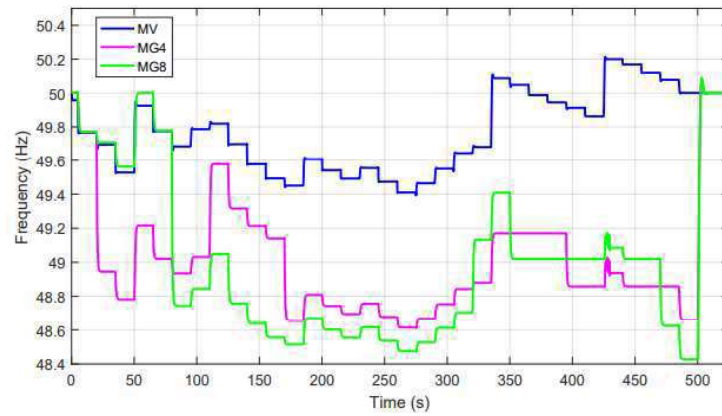


**Figure 6.15:** Active power of the distributed energy storage units for the three simulated scenarios (buid-down approach)

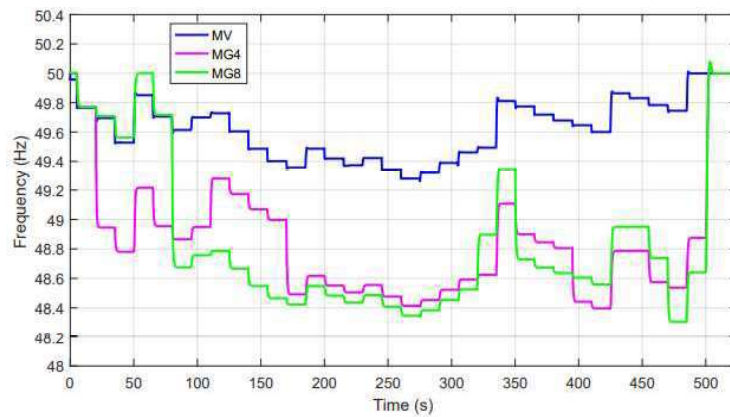
Figures 6.16, 6.17 and 6.18 represent the frequency behavior in MV, MG 4 and MG 8 throughout the BS procedure for the three simulation scenarios (0%,15% and 30% of reserve). The frequencies in the MG fed by ST has similar behavior to the MV frequency due to the operation of the  $(\omega_{oLV}/f_{MV})$  droop. This allows that the microgeneration and DES units located downstream of the ST without storage contribute to the power-frequency response during the BS procedure. However, as it is noticed in the referred three figures, the frequencies in MG 4 and MG 8 may assume large frequencies deviations. These large deviations can be admitted (for short periods of time) since the MMG is an emergency operating mode to restore load, bring the frequency to the nominal value, and keep the voltage within admissible values. Furthermore, the large frequency deviations in the MG 4 and MG 8 can be avoided through proper optimization of the  $(\omega_{oLV}/f_{MV})$  droop control. Finally, at the  $t=500$  s once the MV frequency returned to the nominal value, the integral control can be enabled to conduct the frequencies in MG 4 and MG 8 back to 50 Hz.



**Figure 6.16:** Frequencies in MV, MG 4 and MG 8 in the scenario without reserve (build-down approach)



**Figure 6.17:** Frequencies in MV, MG 4 and MG 8 in the scenario 15% of reserve (build-down approach)



**Figure 6.18:** Frequencies in MV, MG 4 and MG 8 in the scenario with 30% of reserve (build-down approach)

### 6.4.1.3 Voltage Profiles

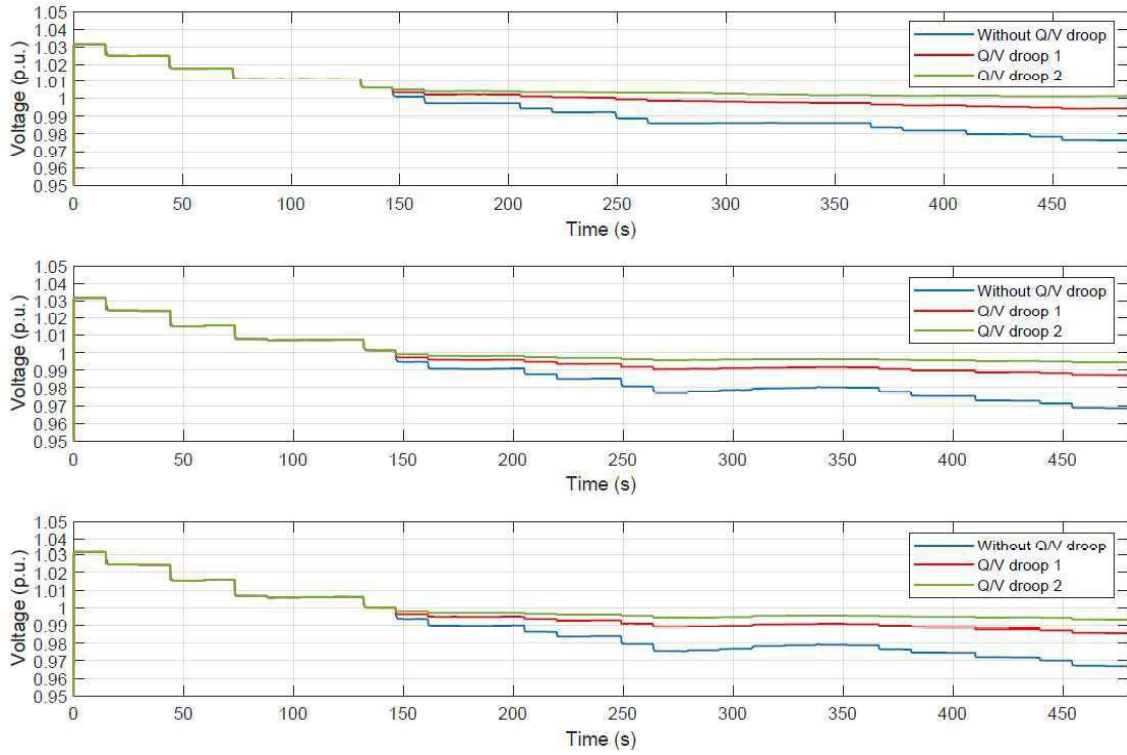
As described in subsection 4.6.5, the ST without storage can support voltage by injecting reactive power. The reactive power injection is performed via a Q/V droop implemented in the ST operating as GFe inverters for the MV side. The MV GFe unit defines the voltage references as a function of the reactive power consumption within the MMG (voltage-reactive power droop). In addition, the ST without storage provide reactive power to the MMG to improve the voltage profile (reactive power-voltage control drop).

Although not corresponding to an optimized strategy, this approach can be adopted during the emergency mode. These functionalities are activated during the service restoration process to improve the voltage profiles. Due to the radial characteristics of the distribution feeder, the voltage profiles can be negatively impacted in the furthest buses. The ST as an interface between MV and LV grids brings advantages regarding the voltage support to the MV side. Due to the decoupling introduced by the DC-link, the reactive power is generated locally to supply loads in MG, not being requested to the MV grid.

The simulation results for the scenario with 15% of the reserve are shown in the next figures. These figures demonstrate the benefits of the ST (without storage) in providing voltage support. For simulation purposes, three conditions were implemented:

- without Q/V droop;
- Q/V droop 1 (0.4 kVAr/kV);
- Q/V droop 2 (1 kVAr/kV);

Three buses were selected to demonstrate the effect of the Q/V droop control in voltage support: SS 1, SS 3 and SS 7. The idea is to analyze the voltages profiles in three different grid points, which are the beginning of the MV feeder, middle point, and furthest bus.

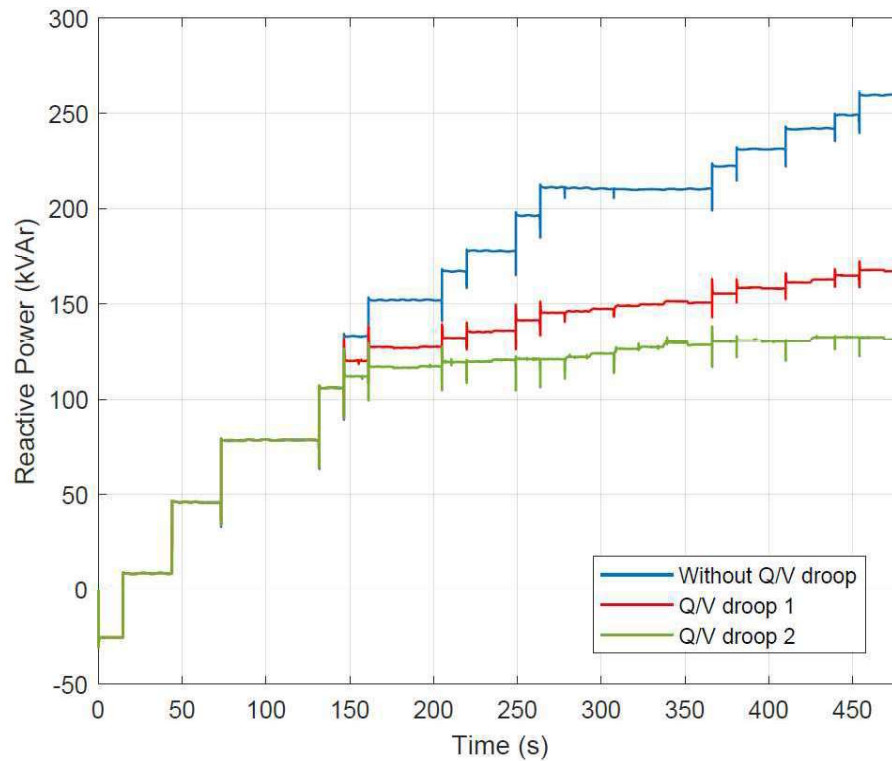


**Figure 6.19:** Voltage profiles in SS 1 (on top), SS 5 (at the middle) and SS 7 (at the bottom) during the build-down service restoration approach

Figure 6.19 depicts the voltage profiles for the selected buses: SS 1 (on top), SS 5 (at the middle) and SS 7 (at the bottom). The voltage in SS 1 is lower than 1 p.u. by the end of the connection of loads and generation (blue line on top). Since the ST is located close to the primary substation, voltage decreases throughout the BS procedure (radial characteristic of the MV feeder). In this case, the ST with a storage device is the only unit providing primary voltage control. When the ST operating as GFe to the MV side injects reactive power, the voltage improves in the SS 1. For example, with the Q/V droop 2, the voltage is around 1 p.u. after connecting all loads and generation units. One can verify a similar situation in SS 5 and SS 7; Q/V droops improve the voltage profile. In the furthest bus (SS 7), without droop, the voltage is slightly below 0.97 p.u. However, when the ST injects reactive power, the voltage is close to the nominal value.

Figure 6.20 shows the reactive injection by the ST with storage device. From that figure, one observes the effect of the Q/V droops in reducing the reactive power request to the main unit (ST with storage device). In turn, Figure 6.21 shows the reactive power injection from the ST without a storage device for the different Q/V droop values. It

is noticeable that reactive power injection is higher in the furthest bus (SS 8). Since throughout the service restoration, the ST injects reactive power to improve the voltage profile. These results show simple control strategies by exploiting ST capabilities for improving voltage control during abnormal operating conditions. After finalizing all the BS procedures, and if the MMG needs to keep operating islanded, advanced voltage control strategies can be employed to optimize the reactive power, considering losses minimization.



**Figure 6.20:** Reactive power from the MV grid-forming unit in the build-down approach

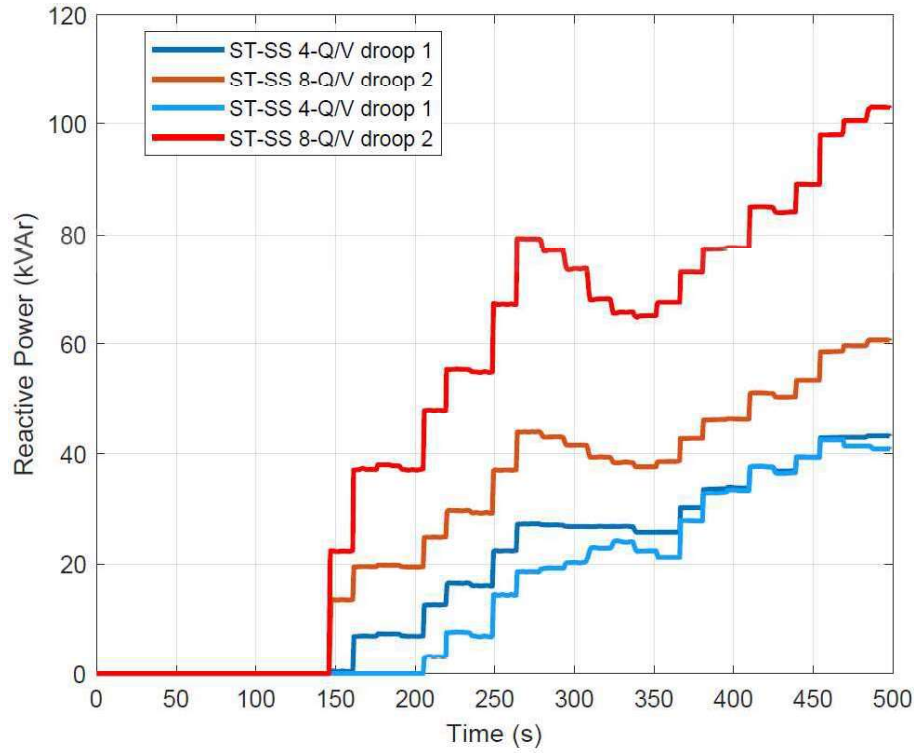


Figure 6.21: Reactive power from ST without storage device

## 6.4.2 Parallel Restoration Approach

### 6.4.2.1 Simulation Conditions

In the parallel service restoration approach, the load and generation conditions are similar to those in the build-down approach. However, in this restoration strategy, the MG 3 and MG 6 have GFo units connected to the LV bus in the MV/LV substation. Thus, these MG can launch BS procedures independently of the conditions in the MV grid. After confirming that it is needed to launch a BS procedure in the MMG, the SC communicates with MGCC of those MG. If the GFo units are fulfilling the condition to initiate the service restoration, the MGCC will manage the BS in the MG. Thus, there BS procedures in each MG are running simultaneously within the MMG. The ST with the main storage unit at the MV grid is the main BS unity. The GFo units need to be synchronized to the MV grid when they achieve a range from 50-70% of their apparent power. The GFo units in MG3 and MG6 have the following nominal power capacities: 75 kVA and 140 kVA. As previously explained, these values are necessary to determine the moment to synchronize the MGs with the main grid. Table 6.6 describes the sequence of action of the three BS procedures that are running simultaneously



within the MG. As depicted in table 6.6 , MG 3 and MG 6 at some point during the service restoration are synchronized with the MG.

**Table 6.6:** Restoration procedure with the sequence of actions in MV grid, MG 3 and MG 6

| t(s) | MV Grid                                                       | MG 3                                                            | MG 6)                                          |
|------|---------------------------------------------------------------|-----------------------------------------------------------------|------------------------------------------------|
| 5    | Loads in MG 2 (P <sub>1</sub> )                               | Loads: 15 kW (P <sub>1</sub> )                                  | Loads: 20 kW (P <sub>1</sub> )                 |
| 20   | Loads in MG 4 (P <sub>1</sub> )                               | Loads: 10 kW (P <sub>1</sub> )                                  | Loads: 20 kW (P <sub>1</sub> )                 |
| 35   | Loads in MG 5 (P <sub>1</sub> )                               | Generation: 20 kW                                               | Generation: 10 kW                              |
| 50   | Solar power plant P= 250 kW                                   | Loads: 15 kW (P <sub>1</sub> )                                  | Loads: 10 kW (P <sub>1</sub> )                 |
| 65   | Generation in MG 7                                            | Generation: 20 kW                                               | Generation: 15 kW                              |
| 80   | Generation in MG 8                                            | Loads: 10 kW (P <sub>1</sub> )                                  | Loads: 10 kW (P <sub>1</sub> )                 |
| 95   | Generation in MG 2                                            | Loads: 20 kW (P <sub>1</sub> )                                  | Generation: 10 kW                              |
| 110  | Generation in MG 4                                            | -                                                               | Loads: 10 kW (P <sub>1</sub> )                 |
| 125  | Loads in MG 2 (P <sub>2</sub> )                               | -                                                               | Generation: 10 kW                              |
| 140  | Preparing the synchronization of MG <sub>3</sub>              | Adjusting voltage and frequency to synchronize with the MV grid | Loads: 15 kW (P <sub>2</sub> )                 |
| 155  | Synchronization of MG <sub>3</sub> with MV grid               |                                                                 | Loads: 10 kW (P <sub>2</sub> )                 |
| 170  | Generation in MG 4                                            |                                                                 | Generation: 10 kW                              |
| 185  | Solar power plant P= 100 kW                                   |                                                                 | Loads: 15 kW (P <sub>2</sub> )                 |
| 200  | Loads in MG 5 (P <sub>2</sub> )                               |                                                                 | Loads: 10 kW (P <sub>2</sub> )                 |
| 215  | Preparing the synchronization of MG <sub>6</sub>              |                                                                 | Adjusting voltage and frequency to synchronize |
| 230  | Synchronization of MG 6 with MV grid                          |                                                                 |                                                |
| 245  | Loads in MG 3 (P <sub>2</sub> )                               |                                                                 |                                                |
| 260  | Loads in MG 7 (P <sub>2</sub> )                               |                                                                 |                                                |
| 275  | Generation in MG 5                                            |                                                                 |                                                |
| 290  | Generation in MG 7                                            |                                                                 |                                                |
| 305  | Generation in MG 8                                            |                                                                 |                                                |
| 320  | Solar power plant P= 250 kW                                   |                                                                 |                                                |
| 335  | Loads in MG 8 (P <sub>2</sub> )                               |                                                                 |                                                |
| 350  | Loads in MG 2 (P <sub>3</sub> )                               |                                                                 |                                                |
| 365  | Loads in MG 3 (P <sub>3</sub> )                               |                                                                 |                                                |
| 380  | Loads in MG 4 (P <sub>3</sub> )                               |                                                                 |                                                |
| 395  | Loads in MG 5 (P <sub>3</sub> )                               |                                                                 |                                                |
| 410  | Solar power plant P= 200 kW                                   |                                                                 |                                                |
| 425  | Loads in MG 6 (P <sub>3</sub> )                               |                                                                 |                                                |
| 440  | Loads in MG 7 (P <sub>3</sub> )                               |                                                                 |                                                |
| 455  | Loads in MG 8 (P <sub>3</sub> )                               |                                                                 |                                                |
| 470  | Enable the centralized secondary frequency control action     |                                                                 |                                                |
| 495  | Enable the local secondary frequency control in MG 4 and MG 8 |                                                                 |                                                |



### 6.4.2.2 Results

#### Medium Voltage Grid

Figure 6.22 presents the MV grid frequency during the recovery process for the three simulated scenarios (0%, 15% and 30% for the reserve of solar power). The frequency varies throughout the process per the connection of loads and generation. The frequency in the three scenarios has similar behaviors, but the reserve level from the solar generation units influences the frequency variation over the BS process.

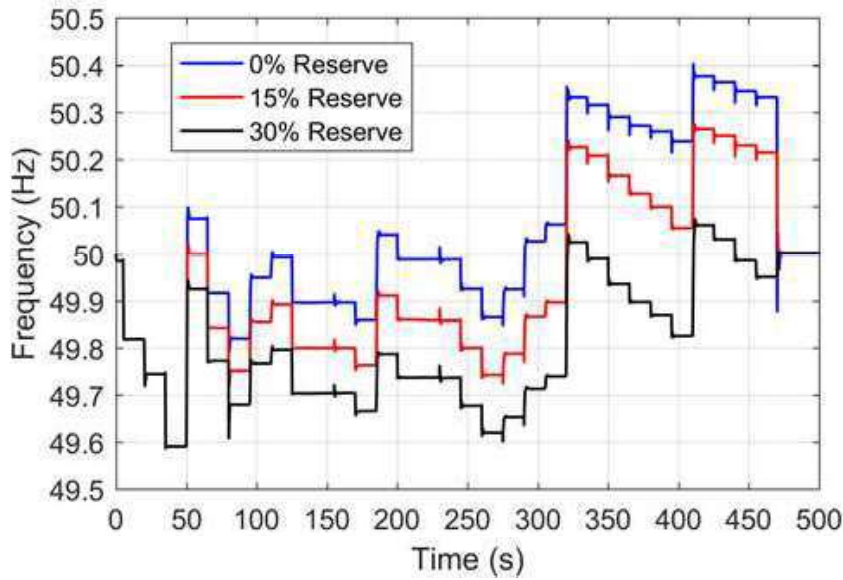
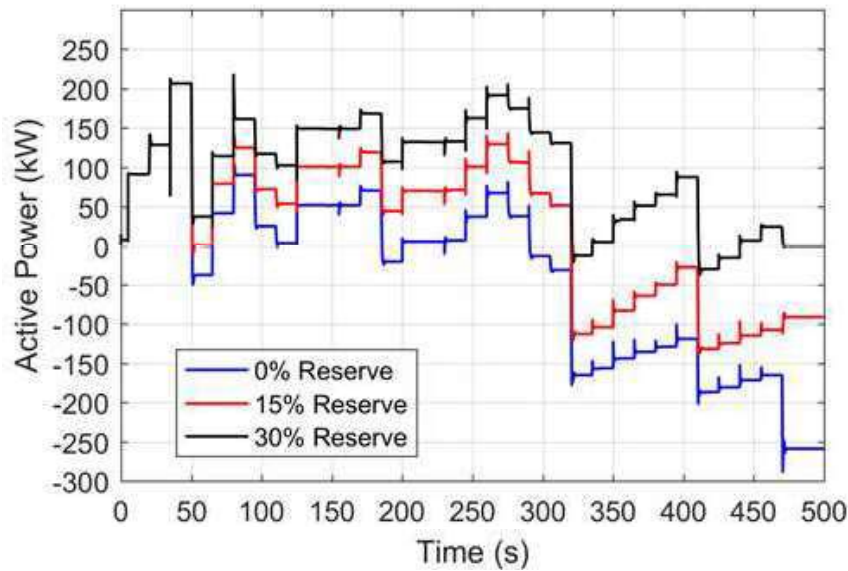


Figure 6.22: MV frequency for the three simulations scenarios (parallel restoration approach)

Throughout the load restoration process some large frequency variations are visible around  $t=50$  s,  $t=215$  s,  $t=320$  s and  $t=410$  s. These deviations are related to the active power set-points sent by the SC to the solar park. The load restoration follows the rule established for connecting the loads according to the priority. From Table 6.5, it is possible to observe that the load restoration for priority 1 is concluded before the synchronization with the connection of the last load with priority 1 in MG 6 at  $t=110$  s. In turn, the load restoration for priority 2 is finished at  $t=335$  s in MG 8. The full load restoration process is finished at  $t=455$  s, which corresponds to the connection of the last load with priority 3. During the restoration procedure, the MG 3 and 6 with the MG grid are also synchronized with the MV grid. The synchronizations of these MG are also noticed in 6.22 around  $t=155$  s and  $t=230$  s through small transients in the MV frequency.

Once the load restoration process is finished, the centralized secondary frequency control is enabled. Around  $t=470$  s, before the operation of the centralized secondary frequency control, the frequency has significant deviations in scenarios with 0% and 15% of the reserve. The frequency is higher than 50.2 HZ in those scenarios and therefore a larger corrective action is necessary to bring the frequency to the nominal value. When the load restoration is concluded, the MV frequency is higher in the scenario without solar power reserve. In this scenario, the solar power units inject all available power, contributing to the power generation in MMG being higher than the consumption. A similar situation also occurs in the intermediary scenario (15% reserve). An opposite situation occurs with 30% of the reserve. In this case, the frequency is slightly below 50 Hz at the end of the load restoration process. The solar units operate in the de-loaded mode, meaning that they are not injecting all the available power.

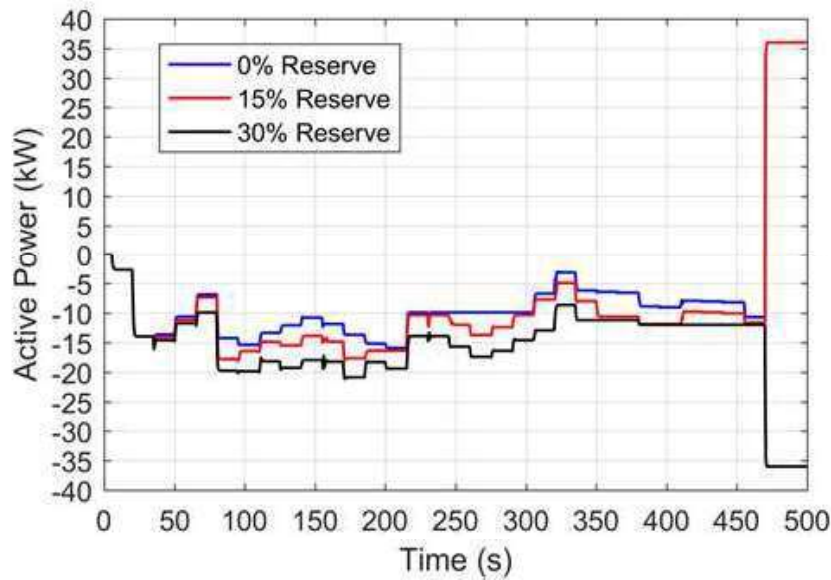


**Figure 6.23:** Active power of MV inverter acting as grid-forming unit (parallel service restoration approach)

During the BS process, the MV inverter of the ST with a storage device has a crucial role in acting as GFo unit, varying the active power output according to the connection of loads or generation, as exemplified in Figure 6.23. In addition, due to different reserve scenarios, the storage devices need to accommodate the excess or lack of active power in the MMG to bring the frequency to 50 Hz. As depicted in Figure 6.23, after the centralized secondary frequency control activation, the MV inverter absorbs around 100 kW and 250 kW for scenarios with 15% reserve and without

reserve, respectively.

The DES units are the first resource to be dispatched to eliminate the frequency deviation. However, these actions are not enough to accommodate the entire surplus of active power in scenarios with a 0% and 15% reserve of solar power. Instead of curtailing the available solar power, the remaining power is absorbed by the central storage unit located in the SS1 (ST with Storage). For the scenario with a 30% reserve, the active power of the MV inverter is almost zero after the activation of the centralized secondary control ( $t=470$  s). The new set-points for the DES units located in the MGs are enough to eliminate the lack of active power. In this case, the DES will operate in the discharging mode injecting active power into the MMG system.



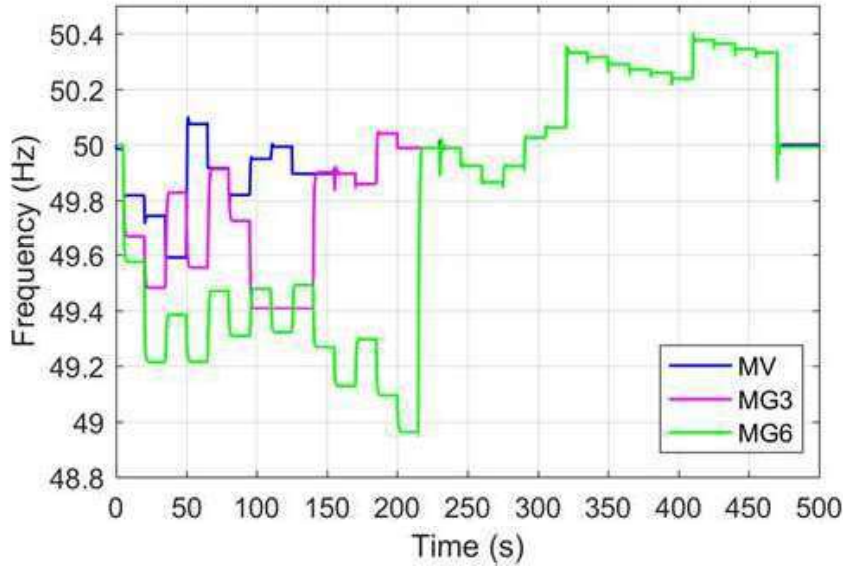
**Figure 6.24:** Active power of the distributed energy storage units (parallel service restoration approach)

Figure 6.24 shows the aggregated active power response from all DES units connected to the MMG over the BS procedure. In this figure, a negative value means that the DES devices are injecting power into the grid. As described in chapter 4, the active power is supported by different distributed storage units equipped with P-f droop characteristics. They support the power frequency control by modulating their active power output following the frequency deviations on MV or LV sides. When the centralized secondary frequency control is enabled, in scenarios with a 0% and 15% reserve, the DES units will absorb active power (“loads”). In turn, with 30% reserve

scenario, DES units are injecting active power in the MMG (black line in Figure 6.24).

### Microgrids with Black Start Capability

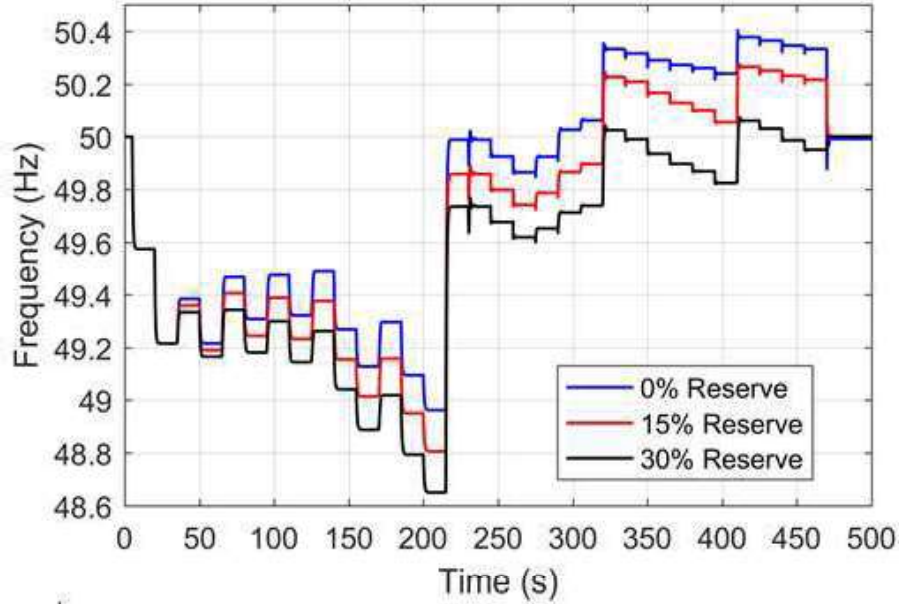
In parallel to the restoration procedure running in the main MV grid, the MGs with BS capability (MG3 and MG6) are also performing a local service restoration (as depicted in Table 6.5). Like in the MV side, the frequencies in MG 3 and MG 6 vary as a function of the connection of loads and generation units. Also, the reserve levels affect the frequency deviations in the MG6. Figure 6.25 depicts the frequency behavior in the MV grid, MG 3 and MG 6 during the BS procedure in the scenario without reserve.



**Figure 6.25:** MV, MG 3 and MG 6 frequencies during BS procedure for the scenario without reserve (parallel service restoration approach)

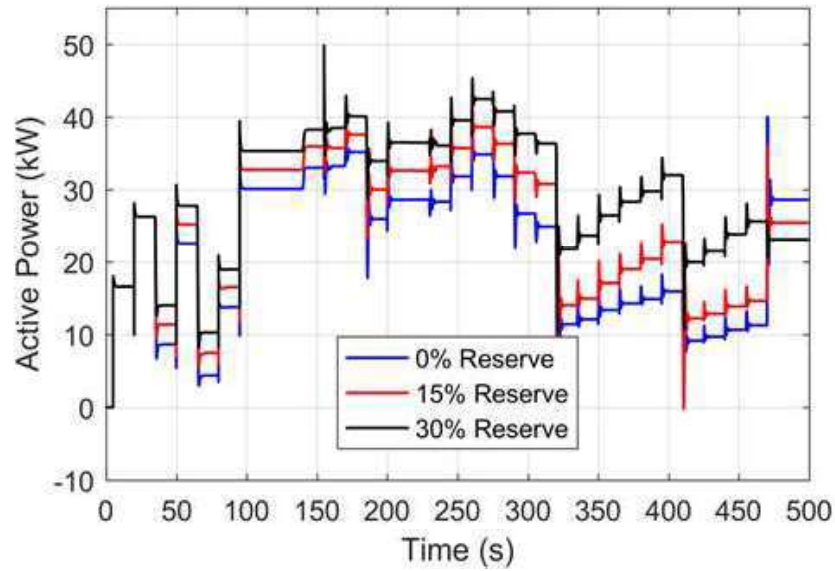
When the synchronization conditions are achieved, SC and MGCC communicate between them to equalize the frequencies and reduce the voltage deviations to execute the synchronization. Around  $t=155$  s and  $t=230$  s, Figure 6.25 presents small transients associated with the synchronization of the MGs with the main grid. The synchronization of both MG with the MV grid is performed according to the rule presented in section 5.4.4.5. Before synchronization, it is observed that the frequencies in MG 3 and MG 6 achieve a value similar to the MV frequency. For both LV GFO inverters, a set point is defined to ensure that frequencies between MV and LV grids are quite the same to allow a smooth transient ( $\omega^{MG} = \omega^{MMG}$ ). After the synchronization, MG3 and MG6 frequencies will follow the MV frequency imposed by the ST with the

main storage unit, as shown in 6.25. Figure 6.26 exemplifies the frequency behavior in MG6 for the simulation scenarios. Like in the MV side, the reserve levels affect the frequency deviations in the MG6. It is visible in this figure, around  $t=215$ , the frequency adjustment to synchronize with the upstream system. The angular frequency in the LV Gfo is adjusted to ensure a smooth synchronization with the MV grid.

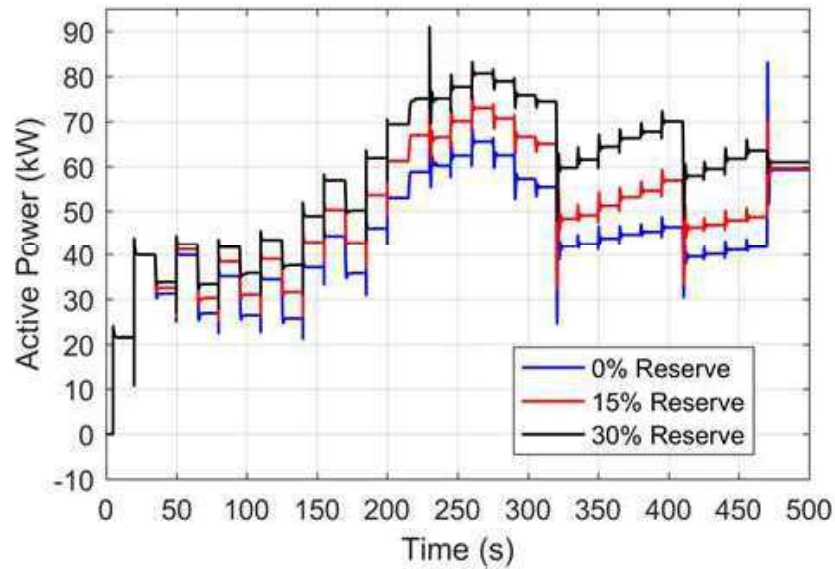


**Figure 6.26:** Frequency in MG 6 for the three simulations scenarios (parallel service restoration approach)

Figures 6.27 and 6.28 depict the apparent power of the Gfo inverters of the MG 3 and MG 6 for the simulation scenarios. When the LV Gfo inverters achieve 50%-70% of their rated power (apparent power), the MG's load restoration process stops. In the moments prior to the synchronization, the Gfo in MG3 achieves active power values around 40 kVA and 50 KVA, whereas GFO in MG6 reaches around 70 kVA and 90 kVA (Figure 6.29). Then, the MG waits to synchronize with the MV grid. For example, as illustrated in Figure 6.25 MG 3 waits around 50 s to synchronize with the MV grid.



**Figure 6.27:** Active power of MG 3 inverter acting as grid-forming unit for the three simulations scenarios (parallel service restoration approach)



**Figure 6.28:** Active power of MG 6 inverter acting as grid-forming unit for the three simulations scenarios (parallel service restoration approach)

After the activation of the centralized frequency control, those units present an active power higher than zero, meaning they are injecting power into the MMG (6.27 and 6.28). For example, in the scenario with a 30% reserve of solar power, the active power in the MV of the ST is almost null, while the GFo units in MG3 and MG6



are injecting power. Obviously, several factors such as losses in the MMG can affect the output power of those units. Other approaches can be exploited to coordinate the storage units of all GFO units to divide the burden of the secondary frequency control.

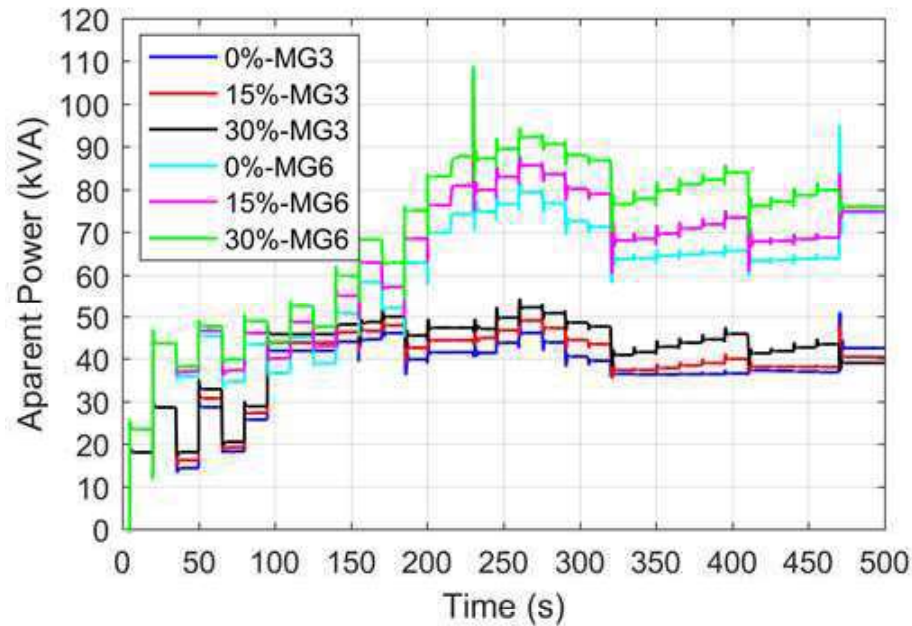


Figure 6.29: Apparent power MG3 and MG6 inverters acting as grid-forming unit for the three simulations scenarios (parallel service restoration approach)

### Microgrids fed by Smart Transformers

Figure 6.30 represents the frequency behavior in the MV grid, MG4 and MG8 in the scenario without reserve. These MGs are served by ST without storage device. The frequencies in the MGs fed by ST (MG4 and MG8) show a similar trend in comparison to the frequency in the MV side. This results from implementing the droop functionalities, which induce LV frequency in MG 4 and 8 to follow the MV frequency.

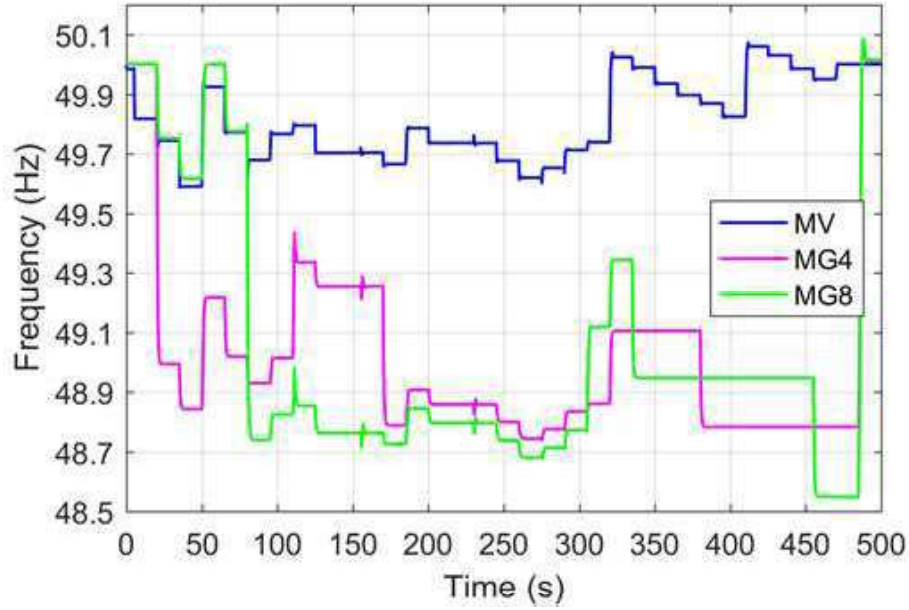


Figure 6.30: Frequencies in MV, MG 4 and MG 8 for the scenario of 30% of reserve

However, sometimes the frequency in the MG 4 decreases or increases due to the connection of loads inside this MG. A similar situation occurs for the MG 8 when load or generation are connected in this LV grid. The LV frequencies will suffer higher frequency deviations for those cases because two controls are acting simultaneously:  $\omega_{oLV}/f_{MV}$  and  $P/f$ . Furthermore, from Figure 6.30, one can observe that the MG4 and MG8 are not operating at 50Hz after the activation of the centralized secondary frequency control ( $t=470s$ ). When MV frequency achieves 50 Hz, the frequency in those MGs is different due to the droop's mechanism ( $\omega_{oLV}/f_{MV}$ ). For that reason, it is needed the activation of the local frequency control to bring the frequency to 50 Hz in MG4 and MG8. Around  $t=485s$ , the local secondary frequency control is responsible to conduct the MG4 and MG8 frequencies to 50 Hz. From that moment, all the system is operating with the nominal frequency.

## 6.5 Conclusions

The simulation results described in this chapter focused on assessing the control strategies for MMG islanded operation with ST. The control strategies presented in chapter 4 were tested in different scenarios to demonstrate the MMG's feasibility to operate islanded from the upstream system. ST with a coupled storage act as GFO unit for the MMG, providing fast power response during the transition to the islanded



mode. This unit provides voltage and frequency references in a MMG environment dominated by inverters. Therefore, the ST with a storage device emulates the behavior of a synchronous machine providing frequency and voltage control. Additionally, solar-based generation and distributed storage connected to the MMG system can participate in the primary frequency control, allowing frequency stabilization in the moments after the islanding.

Following the frequency stabilization due to the primary response provided by ST and DER, a proper secondary frequency control is needed to bring the frequency to the nominal value. This chapter demonstrated that the hierarchical control can support the definition of new set-points for the DER and ST to restore frequency to the nominal value. The active power adjustments are defined based on the reserve level within the MMG. The capability of the MMG with ST to operate islanded from the main system was demonstrated for importing and exporting scenarios. When MMG is exporting active power to the upstream system, the solar-based generation jointly provides primary frequency control (downward reserve) with the storage devices. The secondary control actions define new active power set-points for those generation units in order to bring the frequency to the nominal value. In an opposite scenario, when the MMG is importing power from the upstream grid, the generation cannot provide upward reserve. Hence, DES devices assume an important role since they will inject active power helping the frequency to return to the nominal value.

The second part of this chapter demonstrated the application of the MMG black start strategies described in chapter 5. The simulation results show how the ST and DER can be coordinated to develop service restoration strategies within the MMG without synchronous generators. The BS procedures were simulated, considering that the solar-based generation provides upward and downward reserves. Moreover, the DES units have limitations concerning the maximum available power to be injected or absorbed. The simulations conditions for the BS considered that the MMG need to return to an operating condition with higher generation regarding consumption. In this case, it was demonstrated that the main storage and distributed storage can accommodate the excess of generation. This is different from what was tested in the transition to the islanded mode, where the secondary frequency control balances the DER in order to not depend significantly on the main storage unit. These simulations demonstrate the flexibility of the solutions that can be envisioned to operate the MMG in the islanded mode under a framework with ST, dominated by plenty of DER

inverter based units.

Two restoration strategies can be derived: build-down and parallel restoration approach. The ST with storage is the single unit with BS capability in the build-down approach. This device has proven to be capable to play a key role when launching the BS procedure within the MMG. Another approach can be envisioned where MG also have BS capability. In this case, beyond the restoration conducted by the ST with storage, several restoration procedures occur simultaneously. The MG can initiate a BS procedure by themselves, but at some moment, they need to coordinate the synchronization with the upstream. The solar-based generation and distributed storage also provide frequency control on both restoration strategies. The obtained results demonstrate the feasibility of developing innovative restoration procedures at the distribution level with ST implementation.

Finally, although not being the main subject of the thesis, it was also demonstrated how the ST without storage can provide voltage support by injecting reactive power. This capability was demonstrated for the build-down approach. The voltage profile is improved when the ST is equipped with Q/V droops. Consequently, the voltage support relies not only on the ST with a storage device but also on the ST operating as GFe for the MV grid.

# Chapter 7

## Conclusions

### 7.1 Final Remarks

The technological advancements in the power electronics field lead to the development of the ST. This device is envisioned to play a key role in distribution systems. It is capable of providing control functionalities that allow voltage support, reactive power compensation, power flow control and harmonic filtering. The capabilities of the ST can be helpful to design new solutions to tackle the increasing integration of DER into the distribution grids. As reported in the literature, DC connectivity provides the possibility of connecting a storage device. This characteristic is highly advantageous for developing specific control strategies for islanding operation and service restoration. This thesis developed that topic to demonstrate how ST can support the islanded mode under a MMG framework dominated by inverters. The formation of islands in the distribution grids is an alternative to increase power systems resilience. Hence, this thesis brings a new perspective for improving grid resilience by exploiting the capabilities of DER and ST.

The successful operation of the MMG in islanded mode requires solving several technical issues. First, there is the need for energy buffering to provide a fast power response in the moments subsequent to the islanding. The ST with a storage device plays this role since it operates as G<sub>Fo</sub> unit for MV grid. Second, there are control issues to ensure a stable and safe operation. For that purpose, this thesis provided the following contributions:

- The ST performs primary frequency control with a storage device operating as G<sub>Fo</sub> unit for the MV grid. This unit acts then as a synchronous virtual machine

creating voltage and frequency references. The DG units, microgeneration and DES units are also equipped with P-f droop, enabling them to participate in the primary frequency control.

- Secondary frequency control is performed in a centralized manner by the SC. This mechanism corrects the power unbalance by sending new active power set-points for DG, microgeneration, and DES through the communication infrastructure. The main storage unit can also participate in the centralized frequency control if necessary.

When a disturbance causes a general blackout, it is impossible to restore the service from the upstream grid, the ST with a storage device can provide BS capability. This thesis identified a set of rules to conduct BS procedures within the MMG under a build-down process or by exploiting a parallel restoration procedure, which allows speed up the load restoration.

The work conducted in this research brings contributions to the islanded operation in distribution grids, considering a new framework where ST is replacing the CLFT. It provides a new perspective to face the islanded operation in future scenarios where the distribution grid is inverter-dominated. The control strategies developed for the islanding operation and the rules identified for the service restoration strategies were successfully evaluated through numerical simulations.

## 7.2 Answering the Research Questions

The research process conducted in this thesis started with the formulating of two research questions. The answers to the research questions presented in chapter 1 are presented as follows.

- **Q1:** *How can the Smart Transformer be included in a Multi-Microgrid framework with a fleet of distributed energy resources?*

The literature stresses that the three-stage configuration is the one that brings more degrees of freedom to develop new control functionalities for the distribution grids. The ST replaces the electromagnetic transformers in the MV /LV substations within the MMG framework. From the literature, one also infers that the ST inverters are being designed to operate as G<sub>Fo</sub> and G<sub>Fe</sub> units. When the MMG operates interconnected to the upstream system, they can provide grid services such as reactive power injection,

voltage control, power flow control and harmonic filtering. Moreover, one important feature of the ST is DC connectivity, which enables the direct connection of storage devices - batteries. This characteristic is advantageous since it brings new opportunities to operate the MMG in islanded mode by using the energy stored in the DC link battery. Two arrangements can be envisioned for the ST within the MMG framework: with and without storage. When equipped with a storage device, ST can operate as G<sub>Fo</sub> units for both sides, assuming no energy restrictions. In this case, there is a fully decoupled operation between MV and LV grids. Without a storage device, the ST just operates a G<sub>Fo</sub> for the LV grid, while the LV C<sub>Fo</sub> G<sub>Fo</sub> inverter provides three-phase sinusoidal voltage waveforms independently of the conditions on the MV grid. In turn, The MV inverter operates as C<sub>Fe</sub> G<sub>Fe</sub> unit. There is decoupled operation in terms of reactive power and frequency in this second arrangement, but not for the active power. .

Under a MMG framework comprised of plenty of DER connected to the grid through inverters, the ST introduces new conversation stages. Hence, the MMG can be managed under a hierarchical control in order to coordinate the functionalities provided by DC, distributed storage and ST. SC is the head of an hierarchical control. At the intermediary level, the MGCC and STC manage their MG. MGCC and STC establish communication with the local controllers (lower layer). The operation of the hierarchical structure relies on the availability of the communication infrastructure.

- **Q2:** *How to exploit the flexibility of Smart Transformer to improve the robustness of the Multi-Microgrid operation in islanding mode and restoration procedures?*

As stated in Q2, ST operates as G<sub>Fo</sub> unit for both sides when it has coupled storage. When the MMG transition to the islanded mode, the ST is the key unit for ensuring the MMG stability by providing fast power response and defining voltage and frequency references. Additionally, the DG and DES units can be equipped with P/f droops to support the primary frequency control following the islanding. When islanded from the main grid, the SC is in charge of the technical management of the MMG. Thus, the SC performs the centralized secondary frequency control to bring the frequency to the nominal value. SC computes new set-points for the DG and DES units based on the reserve level within the MMG. The goal is to distribute the power unbalance measured in the MV G<sub>Fo</sub> terminals per the DG and DES. Regarding the ST without storage, the DG and DES connected to the MG will not support the overall primary frequency control due to the decoupling provided by the DC-link. For that, this thesis proposed a new control droop to adjust the LV frequency. The underlying idea is to induce the

participation of DG and DES in the primary frequency control.

When the MMG experiences an unsuccessful transition to the islanded mode or after a general blackout, the MMG can launch a BS procedure. Two BS procedures are designed in this research for restoring the service within MMG: build-down and parallel service restoration. In the first case, the ST with storage (G<sub>Fo</sub> for MV grid) unit is the single unit with BS capability. The SC manages the service restoration process following rules pre-defined and embedded in its software. DG units, microgeneration, and DES units can support the power frequency control since they are equipped with P-f droop controls during the restoration process. The control strategy described previously for the secondary frequency control is also used to bring the frequency again to 50 Hz. The second procedure considers that some MG can have BS capability. Thus, two BS procedures are running simultaneously; one at the MV level where the ST with storage provides the main BS capability, while a second one is running at each MG level, which are led by G<sub>Fo</sub> units connected to the LV bus of the MV /LV substation.

### 7.3 Future Work

This thesis intended to research control strategies for islanded operation and restoration service under a MMG framework with ST. Beyond the contributions provided by this research, additional developments are required to improve the control strategies for MMG islanded operation and BS procedures. Some improvements that have been noticed over the research work and topics not tackled result in the following set of suggestions for further work:

- **Unbalanced operation of MG:** This thesis addresses the operation of the MG under a three-phase balanced operation. However, distribution grids at the LV level are four-wire unbalanced systems. Therefore, the ST model and control strategies need to be adapted to deal with the unbalanced characteristics of the LV grids. Microgeneration, distributed storage units and loads can be single-phase, which increases the unbalanced operating conditions in the LV distribution grids.
- **Voltage Control in the MMG in islanded mode:** When the MMG is operating in the islanded mode, the G<sub>Fo</sub> via the voltage-reactive power droop control supports the voltage control within the MMG. In addition, the ST without storage operating as G<sub>Fv</sub> unit for the MV can also support the voltage control by injecting

reactive power. Those functionalities were applied in the scope of this research. However, new methodologies are needed to optimize the voltage and reactive power while minimizing the losses within the MMG in the islanded mode.

- **Including hybrid AC/DC grids:**The ST under a three-stage configuration is envisioned as an interface for AC and DC grids. The control strategies for the islanded mode and the service restoration procedures can be adapted to also include MV and LV distribution grids in DC.
- **MMG islanding operation in stressing conditions:** The control strategies presented in this research for the islanded mode and restoration procedure considers that the storage systems have no energy restrictions during the simulation time. Additional control measures are required to deal with power and energy limitations in the main storage device coupled with the ST and distributed storage units. Further research can be conducted to adapt the control strategies for tackling extreme operating scenarios.
- **Optimal placement of ST in distribution grids:** The evaluation of the control strategies for the islanded mode and the service restoration procedures were developed, selecting the ST placement randomly in the distribution feeders. It is expectable that the ST will coexist with electromagnetic transformers in the distribution grids. The optimal placement of the ST to be the key enabler of the islanded operation and to provide grid services in the interconnected operation is a topic to be developed to optimize the cost-benefit ratio in acquiring this device.
- **Review the conventional service restoration procedures to include the DG and DES capabilities and ST:**The traditional restoration plans need to be revisited to include the DER capabilities in coordination with other measures usually taken by distribution system operators like grid reconfiguration and mobile diesel generators. The distribution operators can include DER in their restoration plans since they can support the load/generation balance management in black start processes when equipped with droop controllers. The deployment of the ST with capabilities to connect a storage device allows initiating service restoration procedures in distribution grids with plenty of DER connected to the electric grid through a power electronic converter. Also, the coordination between transmission and distribution systems operators needs to be enhanced due to the integration of DER at the distribution level. The distribution resources can also provide BS capability to the transmission system, replacing large power plants

connected to the transmission grid and contributing to the energizing of parts of the transmission grid.



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# Appendices





# Appendix A

The parameters of MMG system is presented in the next table.

**Table 1:** Parameters of grid-feeding and grid-forming controllers

| Bus i       | Bus j      | L (km) | $R(\Omega/km)$ | $R(X/km)$    |
|-------------|------------|--------|----------------|--------------|
| Substation  | SS1        | 5.350  | 0.073          | 0.113        |
| Main Feeder | SS1        | 0.750  | <b>0.073</b>   | <b>0.113</b> |
| SS1         | SS2        | 2.150  | 0.073          | 0.113        |
| Main feeder | SS2        | 0.230  | 0.129          | 0.201        |
| SS2         | Solar Park | 0.230  | 0.129          | 0.201        |
| Solar Park  | SS3/SS4    | 4.150  | 0.073          | 0.113        |
| Main feeder | SS3        | 0.350  | 0.731          | 0.394        |
| Main feeder | SS4        | 1.895  | 0.073          | 0.113        |
| SS3/SS4     | SS5/SS6    | 3.425  | 0.073          | 0.113        |
| Main feeder | SS5        | 1.125  | 0.731          | 0.394        |
| Main feeder | SS6        | 1.0575 | 0.731          | 0.394        |
| SS5/SS6     | SS7/SS8    | 3.235  | 0.129          | 0.201        |
| Main feeder | SS7        | 1.655  | 0.731          | 0.394        |
| Main feeder | SS8        | 0.750  | 0.731          | 0.394        |



# Appendix B

The parameters of grid-feeding and grid-forming controllers are presented in the next table.

**Table 2:** Parameters of grid-feeding and grid-forming controllers

| Parameter      | Designation                                                | Value                    | Unit        |
|----------------|------------------------------------------------------------|--------------------------|-------------|
| $f_o$          | Idle frequency                                             | 50                       | Hz          |
| $V_{oMV}$      | Idle voltage (Medium Voltage)                              | 15300                    | V           |
| $V_{oLV}$      | Idle voltage (Low Voltage)                                 | 415                      | V           |
| $C$            | DC link capacitor                                          | 0.0005                   | F           |
| $k_p$          | Proportional gain of PI (grid-feeding)                     | 2                        | -           |
| $k_i$          | Integral gain of PI (grid-feeding)                         | 4                        | -           |
| $V_{dc_{ref}}$ | Voltage reference of DC link (grid-feeding)                | 600                      | V           |
| $k_f$          | Medium voltage frequency/LV angular frequency droop        | 0.10                     | rad/s/Hz    |
| $k_i$          | Integral gain of PI (local secondary frequency controller) | 1                        | -           |
| $k_{P_{MV}}$   | Active power droop (Medium Voltage)                        | $-1.2566 \times 10^{-5}$ | rad/s/W     |
| $k_{P_{LV}}$   | Active power droop (Low Voltage)                           | $-1.2566 \times 10^{-4}$ | rad/s/W     |
| $k_{Q_{LV}}$   | Reactive power droop (Low Voltage)                         | $-3.0 \times 10^{-6}$    | V(p.u.)/VAr |
| $k_{Q_{MV}}$   | Reactive power droop (Medium Voltage)                      | $-3.0 \times 10^{-8}$    | V(p.u.)/VAr |