FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Black-start Dynamic Requirements and Operation of Energy Storage Systems with High Wind Penetration

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March 12, 2021

Abstract

The increasing installation of renewable generation in the electrical grid obliges this unconventional generation to play a more important role on different aspects of grid operation and control. One service which has not been required so far to the renewable generation is the black-start capability, i.e. the capability to start up a grid which has experienced a blackout.

In the past, the black-start was provided by conventional generation. However, with the decommissioning of old plants and the de-regulation of the electricity markets, black-start is defined as an ancillary service and the responsibility is falling to new type of generation systems. On the other hand, renewable generation has potential limitations because the generated active power is linked to the existence of the energy resources at the time. Therefore, in this context, ESS are regarded as a potential enabler and provider of black-start.

In this work, a simplified model of a power conversion system is developed for an energy storage system and a wind farm.

Furthermore, a black-start is performed recurring to an ideal battery energy storage system, in order to ramp-up the voltage of a wind farm, which is connected to other components/loads in an isolated grid.

The results obtained highlight some of the potential benefits of this joint operation, supporting these systems as enablers of this ancillary service by the systems' operators, and suggesting a flexibilization of the actual requirements of a black-start unit.

Keywords: Battery Energy Storage System, Black-Start, Hybrid Off-grid System, Power Conversion System, Wind Park

Resumo

A crescente instalação de geração de energia elétrica de origem renovável, faz com que esta passe a desempenhar um papel mais importante em diferentes aspectos da operação e controlo da rede. Até então, não foi necessário a consideração de fontes renováveis para a realização do serviço de arranque autónomo, ou seja, a capacidade de reiniciar uma rede que sofreu um apagão.

No passado, o arranque autónomo era fornecido pela geração convencional. No entanto, com o descomissionamento de antigas centrais e a desregulamentação dos mercados de eletricidade, o arranque autónomo é definido como um serviço de sistema e a responsabilidade da sua realização passa a incluir os novos tipos de sistemas de geração. Por outro lado, a geração renovável apresenta limitações, pois a potência ativa gerada está vinculada à existência dos recursos energéticos naquele instante de tempo. Neste contexto, os sistemas de armazenamento de energia são considerados potenciais facilitadores e fornecedores do serviço de arranque autónomo.

Neste trabalho, foram desenvolvidos modelos simplificados de sistemas de conversão de potência para um sistema de baterias e para um parque eólico.

Além disso, será realizado um arranque autónomo com recurso a um sistema ideal de baterias, que realiza o arranque de um parque eólico, funcionando como um sistema híbrido, a alimentar outros componentes/cargas, numa rede isolada.

Os resultados obtidos destacam alguns dos potenciais benefícios para uma operação conjunta, apoiando estes sistemas como possíveis providenciadores deste serviço de sistema por parte dos operadores de sistema e sugerindo uma possível flexibilização dos atuais requisitos exigidos para uma unidade de arranque autónomo.

Keywords: Arranque Autónomo, Bateria - Sistema de armazenamento de energia, Parque Eólico, Sistema de Conversão de Energia, Sistema Híbrido em Rede Isolada

Acknowledgements

I would like to thank prof. Helder Leite for making this thesis possible. I am grateful for the guidance given over these months and for believe that I would do the best job possible.

I would also like to express my sincere gratitude towards my supervisors from Vestas, Rui Pinto Alves and especially Alejandro Bayo Salas for the continuous guidance throughout the work, valuable feedback and for the patience in putting up with my questions.

To my parents and grandparents, for supporting me and encouraging me throughout my life.

To Marina for all the patience during these months, mainly on this particularly difficult time.

And finally, to all my friends for their invaluable support during this journey.

André Félix Teixeira

"Success consists of going from failure to failure without loss of enthusiasm"

Winston Churchill

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Abbreviations

AS	Ancillary Services
BESS	Battery Energy Storage System
BS	Black-Start
ESS	Energy Storage System
GFL	Grid-Following
GFM	Grid-Forming
RES	Renewable Energy Sources
PCS	Power Conversion System
PEC	Power Electronic Converter
PV	Photovoltaic
VSC	Voltage Source Converter
WF/WP	Wind Farm/Park
WPP	Wind Power Plant

Chapter 1

Introduction

This work focuses on the integration and modeling of Battery Energy Storage Systems (BESSs) on an islanded system with high wind penetration. Since the common interface of the ESS to the grid is the Voltage Source Converter (VSC), its potential for operation purposes is explored, and ultimately its capability of performing a Black-Start (BS).

In this chapter, it is presented the main reasons for the development of this work, as well as the objectives of it. Moreover, this chapter describes in detail the chapter structure of this thesis.

1.1 Context and Motivation

In recent years, with the rapid development of the economy, the world's demand for energy has been increasing. On one hand, the typical industrialized countries, in Europe and North America, are becoming more energy dependants. On the other hand, with the surge and enormous development of countries such as China and India in the past decades, the production of electric energy has, undoubtedly, growth as supported in Figure 1.1 [1]. The projections made by the U.S. Energy Information Administration (EIA) in its International Energy Outlook 2019 report [2] pointed that world energy consumption will grow by nearly 50% between 2018 and 2050, with the majority of this growth coming from countries that are not in the Organization for Economic Cooperation and Development (OECD).

For the past two decades, the awareness of the fact that the planet's resources are limited and the harmful effects caused by Green House Gases generated by the conventional sources of energy on the environment's sustainability, driven by economical incentives promoted a change in the paradigm with the massive integration of Renewable Energy Sources (RES), such as Wind and Photovoltaic (PV) [3]. For instance, the European Union (EU) is committed to increase the integration of RES on generation in order to obtain around 50% of its reference scenario of total power generation in 2050, fostering the low carbon policies [4].

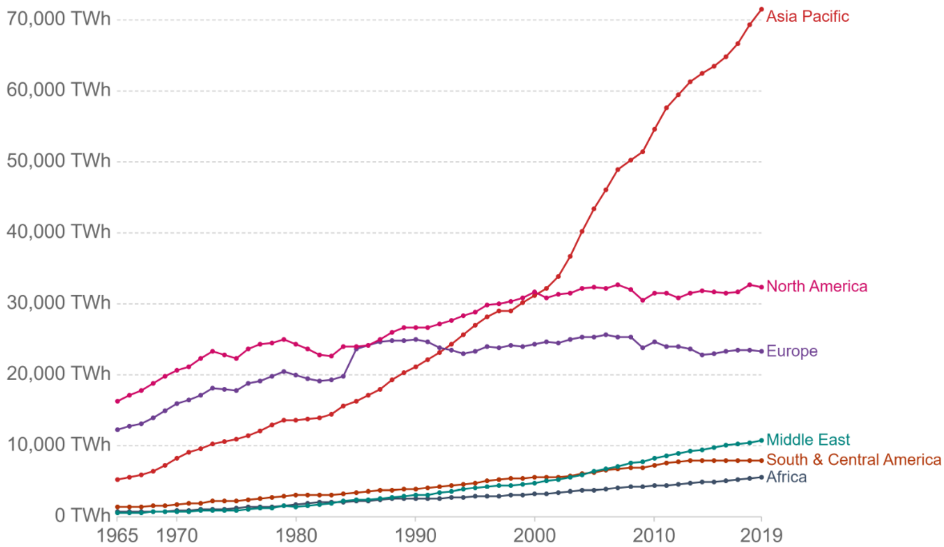

Figure 1.1: Primary energy consumption by world region in terawatt-hours (TWh). Source: BP Statistical Review of World Energy (2019)

Nevertheless, renewable generation has probabilistic nature, generally presenting a variable behavior, with uncertainty, and non-dispatchable, which imposes some challenges to the efficiency and flexibility of the integration of Renewable Energy Sources (RES), limiting its integration to provide some services [5]. An extreme example are islanded systems where, so far, diesel generators are used to compensate the power mismatch when RES is unable.

Islanded power systems are traditionally composed of diesel generating units with intrinsically elevated production costs per energy unit due to the need for fuel transportation and the small scale of these thermal generators, contributing to the CO_2 footprint. Thus, the integration of RES on those systems have been highly procured as a solution due to economic and environmental pressure to decommissioning the diesel-fired generating sources, and reduce the operation costs and CO_2 emissions [6]. Regardless, the operation of remote and isolated power systems is often very challenging because of their small system inertia . Moreover, with the increase of renewable penetration, the system is faced with two additional challenges. On the one hand, the intermittent characteristics of renewable sources such as wind and PV pose demanding security and reliability difficulties, since the system global inertia is already small. On the other hand, these generators have a limited capability to adjust their power output, mainly because of their physical constraints, as in limit ramp capacity and minimum operation point, raising concerns on the flexibility requirements [7]. Indeed, beyond a certain amount of intermittent renewable power, it is not possible to cut some conventional thermal plants to balance generation and load because these conventional thermal power plants are used to provide the necessary reserve margin to balance the power system instantaneously [8].

Energy storage devices (e.g. BESS) are being proposed as the solution to solve some of the problems aforementioned, overcoming some of the RES limitations. In fact, in recent years there has been a lot of research of these technologies, which will result in a decrease in its investment costs, seen as the main barrier to its integration. These devices have high power and energy density with great conversion efficiency and can respond fast in the four quadrants providing active and reactive power simultaneously to the microgrid, being able to tackle the ramp response, spinning reserve, and flexibility challenges posed by RES [6, 9]. In islanded systems, where the construction of a Power Hydro System may not be feasible or not economically justified, current technologies in BESS provide a cheaper solution, with a more flexible location, and provoke less footprint than conventional solutions.

In the future, renewable generation is expected to take over, or at least to represent, a substantial role in participating in ancillary services and off-grid applications. In this context, BESS are regarded as a potential technology to overcome some of the technical barriers from RES, forming the so-called Hybrid system as stated and explored in, e.g., the works of [10]. The capability to perform a Black-Start, in order to reduce the interruption time and the inherent economic loss, can be seen as a critical tool and the most defiant challenge for these systems [11].

In this dissertation, a Power Conversion System (PCS) model based on Voltage Source Controller method will be developed considering the operation of a battery storage system. All those operations are utterly related to power control and conversion, which are a fundamental part of the operation of these hybrid systems, and can determine seriously its performance and the lifetime of BESS. Hence, this presents an excellent opportunity to study the role of PCS in the BESS emergence. Finally, it is considered the possibility of performing the process of black-start of an islanded system composed of loads and a wind farm, which is a very simple system but versatile enough to understand some of the dynamics and challenges faced during the black-start operation.

1.2 Thesis scope and objectives

The idea of integrating energy storage systems in islanded power systems, to tackle some of the emerging challenges of the electric sector, particularly the ones related to the presence of renewable sources is not new. Nevertheless, there are several questions still unanswered about the feasibility of a start-up using this approach.

- What are the challenges of recurring to a BESS after the event of a blackout instead of conventional generators?
- How can BESS contribute to the proper start-up and energizing process of a Wind Farm?

In this work, it is purposed a control and operation strategy using an energy storage with a specific controller to enable the black-start.

The main objective of this dissertation is to explore the integration of that BESS model in a Wind Farm developed, to study the capability of performing system operations, as a black-start. This may represent an important feature since the RES is growing and its application on remunerated ancillary services is being considered.

1.3 Structure

This thesis is organized in 6 main chapters.

In the present chapter 1, an introduction to the theme is made, with its due framework, motivation, objectives, and structure of this dissertation.

Chapter 2 addresses some of the European policies and efforts towards decarbonisation. At the same time, provides information about ancillary services, emphasising the black-start requirements and their particular challenges, and some grid codes of several European countries.

Chapter 3 presents a bibliographic review of the most relevant types of energy storage. It describes in detail some characteristics of BESSs, the commercially available technologies as well as their applications and potential benefits for the scope of this work. In this chapter, is also covered the operation of a wind turbine.

Chapter 4 explains the PCS model designed for the BESS and the simplifications and assumptions made. In this chapter the BESS model is explored, conjugated with the Wind Farm developed, and feeding an off-grid system as a load, in isolated mode.

Chapter 5 compiles the most relevant results obtained.

Finally, in Chapter 6, the conclusions drawn during the work are presented and possible future work is pointed out.

1.4 Work Development in Business Environment

The development of this work was done at the leading wind turbine manufacturer Vestas Wind A/S in partnership with Faculdade de Engenharia da Universidade do Porto (FEUP).

Vestas is the energy industry's global partner on sustainable energy solutions. Vestas' work contemplates the design, manufacture, installation, and service of wind turbines across the globe, being the world's number one on installing wind power with over 117 GW of wind turbines in 81 countries. Through the company's industry-leading smart data capabilities and over 104 GW of wind turbines under service, Vestas uses data to interpret, forecast, and exploit wind resources and deliver best-in-class wind power solutions to its clients, bringing sustainable energy solutions to power a bright future [12].

This thesis was developed at Porto Design Center facilities in cooperation with the Plant Electrical department and supervised by Doctor Alejandro Bayo.

Chapter 2

Black-Start context in islanded systems

This chapter provides some guidelines of European energy policies towards decarbonization, and how the inclusion of renewable sources is proposed to meet the proposed targets. A summary of the ancillary services is covered, with emphasis on BS. Finally, some current requirements are highlighted for the realization of this process in some grid codes of different European countries, as well as the consideration of inclusion of renewable sources and energy storage in the BS and restoration process.

2.1 European Policies for Decarbonisation

Article 194 of the Treaty on the Functioning of the European Union (TFEU), according to the Energy Union (2015), establishes the five main aims of the EU's energy policy are to [13]:

- Diversify Europe's sources of energy, ensuring energy security through solidarity and cooperation between EU countries;
- Ensure the functioning of a fully integrated internal energy market, enabling the free flow of energy through the EU through adequate infrastructure and without technical or regulatory barriers;
- Improve energy efficiency and reduce dependence on energy imports, cut emissions, and drive jobs and growth;
- Decarbonise the economy and move towards a low-carbon economy in line with the Paris Agreement;
- Promote research in low-carbon and clean energy technologies, and prioritise research and innovation to drive the energy transition and improve competitiveness.

The current policy agenda is driven by the comprehensive integrated climate and energy policy adopted by the European Council defined the following targets by 2030:

- A reduction of at least 40% in greenhouse gas emissions compared to 1990 levels;
- An increase to 32% of the share of renewable energies in energy consumption;
- An improvement of 32.5% in energy efficiency;
- The interconnection of at least 15% of the EU's electricity systems.

To achieve these goals several documents were released, highlighting the following:

- **COM(2015)0080** - Energy Union strategy with the aim of building an energy union that gives EU households and businesses a secure, sustainable, competitive and affordable energy supply
- **COM(2016)0860** - 'Clean energy for all Europeans' package, which consists of eight legislative proposals:
  - **Governance of the Energy Union Regulation ((EU) 2018/1999)** - covering governance;
  - **Electricity Directive ((EU) 2019/944), Electricity Regulation ((EU) 2019/943), and Risk-Preparedness Regulation ((EU) 2019/941)** - electricity market design;
  - **Energy Efficiency Directive ((EU) 2018/2002), and Energy Performance of Buildings Directive ((EU) 2018/844)** - energy efficiency;
  - **Renewable Energy Directive ((EU) 2018/2001)** - renewable energy;
  - **EU Agency for the Cooperation of Energy Regulators (Regulation (EU) 2019/942 establishing ACER)** - rules for the regulator.

Owing to the major role of electricity in decarbonisation, several research and development projects regarding batteries as electricity storage devices have been under course, since they have been identified as key enabler technologies of a low-carbon economy. For instance, in the document COM(2018)0293 a strategic action plan is defined, emphasizing more their applicability for electric vehicles, but still referring power systems, such as micro-grids in that matter [13].

2.1.1 Renewable Energy

The revised Renewable Energy Directive (Directive (EU) 2018/2001), as part of the 'Clean energy for all Europeans' package, aimed at keeping the EU a global leader in renewables and, more broadly, helping the EU to meet its emissions reduction commitments under the Paris Agreement. The new directive establishes a new binding renewable energy target for the EU for 2030 of at least 32% of final energy consumption, with a clause for a possible upwards revision by 2023 and an increased 14% target for the share of renewable fuels in transport by 2030.

In order to cope with this targets, on November 2020, the Commission published a dedicated EU strategy on offshore renewable energy entitled 'An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future' (COM(2020)741), that assesses the potential contribution of offshore renewables, and goes beyond a narrow definition of the factors of energy production [14].

This document concluded that offshore renewable energy is one of the most promising routes to increase future power generation in the coming years in a way that meets Europe's decarbonisation objectives and expected rise in electricity demand in an affordable manner. Europe's oceans and sea basins hold a vast potential, which can be harnessed in a sustainable and environmentally sound way, complementing other economic and social activities. This Strategy sets out the scaling up of offshore renewable energy and its use as an EU priority. Offshore renewable energy potential is present, in different forms, in all European oceans and sea basins, including islands and outermost regions. Its development would have positive industrial, economic and social impacts spread across the EU and its regions [15].

2.2 Ancillary Services

TSOs are responsible for the grid operation, nevertheless their capabilities to ensure a stable operation is limited. Since the grid de-regulation, new markets appeared to compensate connectors for providing the necessary function to ensure such a stable grid operation.

The functions or services needed by a TSO to guarantee power system security (reliable and secure power system operation) are termed Ancillary Services [16]. The term ancillary services are used to refer to a variety of operations beyond generation and transmission that are required to maintain grid stability and security. Traditionally the equipment assigned to provide these services were conventional generators, however, the integration of intermittent generation and the development of smart grid technologies have prompted a shift in the equipment that can be used to provide ancillary services. These services can be procured from different stakeholders [17]. The authors in [18] have mentioned that as per the definition, the number and types of the services may be different. Nevertheless, the ancillary services in regard European context, are used to provide the stakeholders with the following capabilities [19]:

1. Loss Compensation
2. Frequency Control
3. Black-start Capability
4. Voltage or reactive power Control
5. Oscillation damping
6. Congestion management

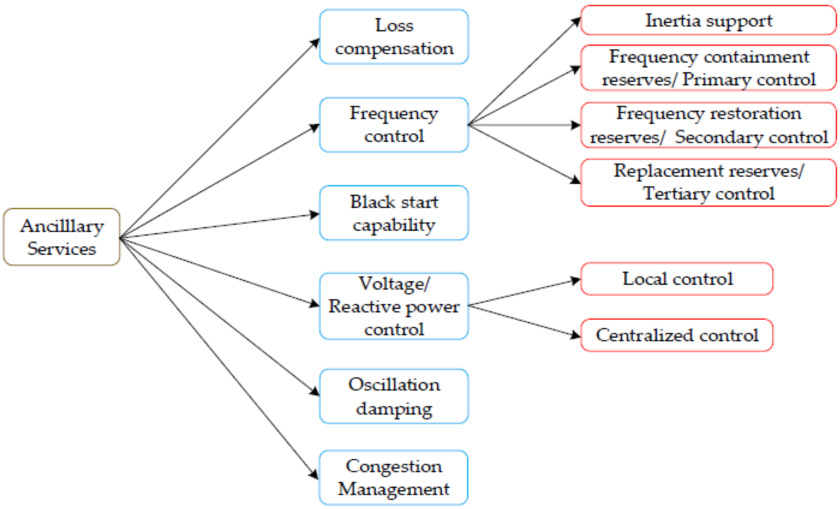

Figure 2.1: Ancillary services classification [19]

From the several ancillary services pointed out, black-start will be emphasized.

2.3 Black-Start Applications

2.3.1 Overview

In recent years, numerous blackouts around the world have been occurred causing great financial losses and inconvenience to people [20]. On August 13^{th} 2003, a cascade blackout occurred throughout Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey, and Ontario, Canada [21]. The blackout of 61,800 MW lost lasted around 4 to 7 days before the power fully restored, which affected around 50 million people. One of the majors' blackouts registered happened in India on July 30^{th} and 31^{st} 2012, two blackouts occurred and lasted several hours causing over 620 and 700 million people, respectively, with the electricity lost [22]. More recently, the South Australian blackout of 2016 was a widespread power outage in South Australia that occurred as a result of storm damage to electricity transmission infrastructure on 28 September 2016. The cascading failure of the electricity transmission network resulted in almost the entire state losing its electricity supply, affecting 850,000 customers [23].

Black-Start is a process of restoring a power system to operation after a complete or partial blackout. This is achieved recurring to generating units (black-start units - BSU), which are able to inject energy into the system, without relying on external energy sources to the power generating facility [24]. Once these units have energized the network, they will serve to facilitate the start-up of other generators, in order to stabilize the system normal operation faster. In addition, these units should be also able to consume and produce reactive power, in order to control the voltage.

This service is an indispensable part of the power system being included in the group of the ancillary services (AS). Nevertheless, there is some divergence in AS market perspective. In some countries, black-start is mandatory for predefined conventional power plants, such as diesel generators or hydroelectric generators, while in others there exist bilateral contracts. Although, in a way or another, this service is remunerated [25], which can present an opportunity for BESS and RES.

In recent years, the penetration level of inverter-based resources (IBR) (such as wind energy, photovoltaic and BESS) has continued to increase, which has aroused interest in understanding the technical potential and associated costs of using these resources to provide black-start support [26]. The ability of a voltage source converter-based high-voltage DC system to black-start large inductive loads was demonstrated in [27]. Expectedly, in order to ensure a robust grid energization in the event of a blackout, black-start capabilities should be distributed and provided by different energy providers spread along the power system and not only by few powerful plants, that way increasing service availability [28].

Wind energy, due to its abundance and cleanliness, is the fastest growing RES, showing huge promise for the future to be a major electricity source. This is reinforced by its price decreasing per kWh, in the latest years [29].

In this context, due to the larger presence of off-shore wind farms (OWFs) in the production scenario, the interest of BS capability in OWF is increasing. Some demonstration projects have been undertaken to use RES, as very recently in [30], and although this particular case was executed with an on-shore windfarm, this is may be achieved by an OWF. Moreover, this gains more interest, since off-shore WPP don't have to deal with the space constraints and poorer wind conditions verified on an on-shore scenario [31].

2.3.2 Black-Start Requirements

After the event of a blackout, energizing an electrical power grid imposes several challenges regarding voltage and current transients. An understanding of the nature of these transients, the mechanisms that cause them, and the possible ways to mitigate them are necessary to develop an appropriate energization process.

The BS-service can be defined as a provider, or combination of providers which can cope with three basic requirements:

1. Independent start-up of external supplies, following a partial or total shutdown;
2. Energizing of the transmission/distribution network;
3. Provide block loading (or load acceptance) of local demand in a stable power island;

Additionally, a BSU may be required to provide an increase of power to other stations and participate on the synchronization process. In that regard, not all power generation has the capacity, or is required, to provide BS capability.

Considering a traditional bottom-up restoration process, the BSU is composed of the following [32], illustrated in Figure 2.2:

- The self-starter: an asset that initiates the start-up without supply from the grid, e.g. diesel generator or BESS, after that it should power the auxiliaries of the generating unit;
- The cranking path between the self-starter and the main generating unit. This can be ignored if both are located on the same site;
- The main generating site: it is responsible for re-energizing the grid. It may be composed of 1 or more power and storage units. It needs to be capable to deal with the active power concerning block load, and mainly with the high reactive power flows during the restoration of a dead grid.

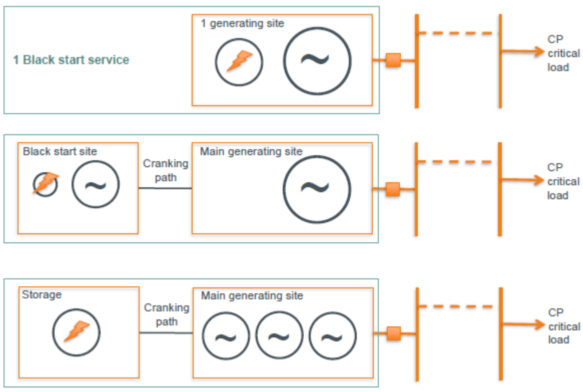

Figure 2.2: Possible configuration of a Black-start service proposed on Elia Market [32]

Some of the minimum technical requirements based on several European grid codes are addressed, considering the three most important activities referred to previously, while maintaining the frequency and voltage values within acceptable limits to keep the system stable. For an extensive comprehension it is suggested a further reading on those codes.

1. **Self-start**: According to ENTSO-E Grid Codes [24] Article 15.5, a power-generating module with black-start capability shall be capable of starting from shutdown without any external electrical energy supply, within a time frame specified by the relevant system operator, in coordination with the relevant TSO. Some power stations are equipped with small diesel generators which can be used to start larger generators, that in turn will be powering the main generating units. According to [33], large pump-storage plants are also viable options for system restoration, since those systems can be restarted quickly, and usually present a large inertia and large reactive power absorption capabilities.

2. **Reactive power requirements**: During the restoration process the BSU assets must be able to absorb the high amount of reactive energy, consequence of the connection to the grid elements (cables, overhead lines) under low loaded conditions. For instance, in Belgium the current requirement defines 30 MVar absorptive capacity. However, this value is not sufficient in some regions and for some re-energization procedures. In response to that, the

absorption requirement can be partly covered by shunt reactors or other reactive compensation devices installed by Elia, ultimatelly reducing the requirement from BSUs [33]. The National Grid in UK defines a capability of at least 100 MVAr leading for a generating plant connected at 400/275 kV, although depending on the local system configuration. Moreover, it states that the BSU must also be capable of withstanding the magnetic inrush and transient voltages associated with this charging duty [34].

3. **Voltage management**: Regarding voltage the ENTSO-E Grid Codes [24] Article 15.5 defines that a BSU shall be capable of automatically regulating dips in voltage caused by connection of demand. and control voltage automatically during the system restoration phase. The EirGrid (Ireland) in its proposal document [35], states that when feeders are being energised and load is picked up, this process should keep voltage as low as possible, in order to reduce the MVAr generation of unloaded transmission feeders. Soft-energisation is preferred instead of sequential-energisation, since the transmission path can be built at a reduced voltage. in parallel to the BSU startup. This method is also advisable mainly because of the high inrush currents during the energization of the BSU step-up transformer, which can result in voltage dips [33, 35]. From the moment all generation stations have received supply, the transmission system should be restored feeder by feeder, limiting the increments of reactive power generated by the developing system. Additionally, the load restoration should be suitably interspersed with feeder restoration to limit the MVAr absorption of the generators to an appropriate value. Special care should be taken to avoid energising a high voltage (over 110 kV) long transmission line with an unloaded transformer connected to the remote end, due to possible resonant effect with resultant high overvoltages [35].

4. **Frequency management**: Article 15.5 from ENTSO-E Grid Codes [24] states that a BSU needs to be able to control frequency in case of overfrequency and underfrequency within the whole active power output range between minimum regulating level and maximum capacity as well as at houseload level. This module should be also capable of operating limited frequency mode for over/under frequency (LFSM-O/U). The EirGrid [35] advises that the initial load restoration should be carried out in the smallest steps possible in order to minimise system frequency and voltage deviations. The system or local frequency should be at least 50 Hz (preferably higher) before restoring any load, with one generator (swing generator) on the subsystem operating in isochronous speed control mode, to control this value. Moreover, given the uncertainties about the exact power consumption after a period of non-supply and to cope with the fluctuations in offtake of reconnected grid users, BSUs should not be operated near their maximum active power limit during the initial stages of restoration. This is advisable to avoid frequency instabilities, and so a reserve capacity should be respected. Elia recommends that a 70% of maximum power production should not be exceed, when initiating the restoration plan [33]. In its turn, EirGrid points to a limit of 50% [35].

5. **Block loading requirement**: This requirement regarding active power is stated in the ENTSO-E Grid Codes [24] as the capability from BSU to regulate load connections in block load. The instantaneous block-load demand by Belgium TSO is of at least 10 MW, considering an inductive power factor equal or superior to 0.8 [33], and 35-50 MW for UK (National Grid) [36]. During block-loading, the frequency should be maintained on a range of 49-52 Hz accordingly to Elia [32], as for National Grid this interval is more wider with a range of 47.5-52 Hz [36]. The BSU defined for restoring the backbone has a usually higher requirement of minimum installed capacity than a similar case covering a regional zone [37]. For example, Elia grid code requires at least 85-140 MW for restoring the 380 kV backbone, and 65-115 MW for a zonal restoration process [33].

Further conditions about the restoration process can be explored in [37], which encompasses the following steps:

- Fuel Supply;
- Synchronization;
- Islanding and Trip to Houseload;
- Restoration Times;

A summary of the major capabilities for BSU are listed on table 2.1. This table compiles the information provided mainly by [33, 35, 36].

Table 2.1: Key technical BSU capabilities and justification adapted from [37]

Technical Capability	**Why is required?**
High availability on both the main and auxiliary generating plant (typically 90%).	System shutdown is an high impact and low probability event, but could happen at any time.
Ability to start up the main generator from shutdown independently, without the use of external power supplies.	During black-start restoration, the transmission system is not energized, a provider will need to be able to start up independently.
Ready to energize part of the transmission system within a certain time after instruction from TSO.	Faster energization results in faster restoration.
Reactive power capability to energize the immediate transmission/distribution system(s) and to withstand the magnetic inrush and transient voltages associated with this energization.	Energizing the local system is one of the first steps in restoring the network.

Capability to • accept instantaneous block-loading demand • control voltage/frequency levels within acceptable limits during block-loading process.	Ultimate goal of power system restoration is load recovery.
Ability to provide at least 3 sequential black-starts.	During system restoration, the system will be less stable than under normal operation so the likelihood of faults/trips is increased.
Facilities to ensure • safe shutdown of all generating units without the need for external supplies • state of readiness for subsequent start-ups.	It may be that multiple attempts are required to deliver restoration.
Back-up fuel supplies to enable the provider to run for a minimum duration following a BS-instruction	Alternative fuel sources will provide increased resilience in the restoration.

In Table 2.2, a summary is presented about the requirements aforementioned defined by the National Grid Electrical System Operator (UK) and Elia (Belgium).

Table 2.2: List of black-start requirements by ELIA and National Grid Electrical System Operator (ESO) [38]

Category	**Requirement**	
	National Grid ESO	**ELIA**
Self-start	Yes	Yes
Time to connect	$\leq 2h$	1.5-3 h
Service availability	$\geq 90\%$	Depending on provider
Voltage control	$\pm 10\%$	Time dependent
Frequency control	47.5 - 52 Hz	49 - 52 Hz
BS service resiliency of supply	$\geq 10h$	
BS auxiliary unit(s) resiliency of supply	$\geq 72h$	$\geq 72h$
Block loading capability	$\geq 35MW$	$\geq 10MW$
Reactive capability	$\geq 100MVArleading$	Depending on provider
Sequencial start-ups	≥ 3	≥ 3
Short-circuit level (following the start of a system disturbance)	$t \leq 80ms : I \geq \frac{240MVA}{\sqrt{3}.U}[kA]$ $t > 80ms : I \geq \frac{100MVA}{\sqrt{3}.U}[kA]$ $U \equiv connectionvoltage[kV]$	
Inertia value	$\geq 8000MVA.s$	

Previously, and indeed presently, one large provider is typically capable of delivering all of these features. Nevertheless, these requirements could be met by a combination of providers in some situations. The arrangement must be considered on a case by case basis, as not all provider combinations may be capable of providing the necessary services to execute a BS and perform a restoration. In future, these requirements will definitely need to be met by a combination of providers, as it is very unlikely that any single non-traditional technology type or DER site will have the capability to provide all of these services, leading to a procurement of technical capability.

This change of paradigm is just starting to be realized, leading some TSOs to consider new possible sources to perform a BS. For instance, National Grid ESO is now trialing a competitive procurement event for Black-Start Ancillary Services, and although many service requirements are the same as the existing ones, there is starting to exist some relaxation, as some specific quantities may be modified to reflect the capabilities of smaller and more distributed generators and other energy resources. For example, the block loading MW capability has reduced by 15 MW, from 35 MW to 20 MW [36]. As a note, in Table 2.3 are pointed out some of the proposed changes.

Table 2.3: Examples of proposed changes to technical specifications for Black-Start [36]

Existing BS requirement	**Retained principle and proposed changes**
Ability to start up the main generating plant (at least one unit/module) of the station from shutdown without the use of external power supplies.	Desired but not mandatory for all Black-Start Stations. Onus would be on National Grid ESO to ensure enough Stations had self-start capability within a power island area.
Ready to energize part of the NETS or, if appropriate, the Electricity Distribution System within two hours of instruction from National Grid ESO.	More suitable timeframe could be appropriate given the capabilities of fast-acting technologies.
The reactive capability to energize the immediate Transmission/Network Distribution System(s). This capability will depend on the local system configuration, but generating plant connected at 400kV or 275kV with a capability of at least 100MVAr leading (as measured at the commercial interface) should almost invariably meet this requirement. The generator must also be capable of withstanding the magnetic inrush and transient voltages associated with this energization.	To make provisions for lower voltage levels and lower levels of reactive power. Not feasible to dictate a MVAr value for a single generator as this will vary considerably. Withstand capability requirements should remain unchanged.
The capability to accept instantaneous loading of demand blocks, preferably in the range 35 MW–50 MW, and controlling frequency and voltage levels within acceptable limits during the block loading process (under these conditions, frequency can be within the range 47.5 Hz–52 Hz);	Smaller (less MW) blocks of demand in accordance with smaller distribution power island sizes. Ability to control frequency and voltage should remain unchanged.

Resilience of Supply, Black-Start Service – deliver contracted service for a minimum time of ten hours.	Smaller timeframes potentially required to account for less reliability and availability of resource.
Resilience of Supply, Black-Start Auxiliary Units – run continuously at the rated output for a minimum of three days.	Smaller timeframes potentially required to account for less reliability and availability of resource.
Ability to control voltage level within acceptable limits during energisation/block loading (±10%).	Requirement should remain unchanged.
Ability to manage frequency level when block loading (47.5 Hz–52 Hz).	Requirement should remain unchanged.

2.3.3 Technology capability – Resilience and restoration characteristics of emerging generation technologies

The diagram in Figure 2.3, illustrates the three principal phases of a Black-Start event, with the partial or total system shutdown as a precursor, followed by the restoration phase where Black-Start generation begins to energise the wider network.

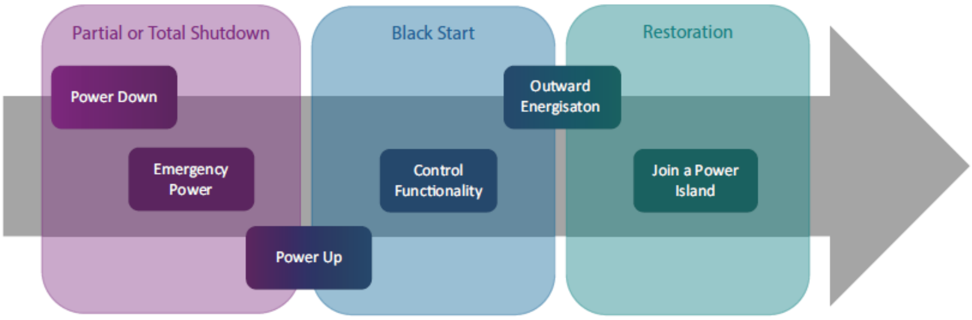

Figure 2.3: Principal stages of Black-Start and Restoration [36]

Each of the three phases is described further in [36], alongside more detailed descriptions of some specific characteristics and functionality required from Black-Start providers during each phase. Notice that some of them were already mentioned in the previous section, although since new technologies are in consideration a few more are added, accordingly to the National Grid report [36].

Shutdown Resilience

- Site de-energisation
- Emergency power
- Intervention resources
- Control and communication system
- Auxiliary starting generation

BS Performance

- Self-starting
- Network energisation and reactive power
- Grid-forming
- Block loading
- Frequency control
- Availability and intermittency

Restoration Capabilities

- Joining a Power Island
- Performance in a Power Island

The following sections provide a summary of the findings from research and stakeholder engagement activities and highlight the capabilities of some of the non-traditional technology types, Wind and BESS [36].

2.3.3.1 Wind Power

Table 2.4: Shutdown resilience characteristics of wind [36]

Site de-energisation	Turbines shut down automatically and go into a standby/idle mode until power is restored to the grid. Some wind turbines have battery banks that operate the emergency pitch control of the turbines.
Emergency power	The technology typically has on-site emergency power, sufficient for restoration of communications, protection and control. If the shutdown is extended over a long duration, the UPS may only have several hours' capacity. Current Black-Start provision of three days–7 days running of the auxiliaries is not currently achievable unless on-site generation is procured.
Intervention resources	The majority of sites are unmanned with a certain level of control and communications observed from a remote-control center. Intervention times would therefore vary considerably depending on the location of the site.
Control and communication system	The UPS duration of a few hours most likely won't be long enough under an extended shutdown period. However, the site will be able to restore control and communication systems ready to receive notifications from the System Operator for as long as the UPS has capacity.

Auxiliary starting generation	Almost all sites rely on a primary auxiliary connection from the network for starting. Some sites have a diesel generator as a back-up supply for the auxiliary power. Some sites rely on contracts with diesel generator services to deliver the diesel generator to site as and when required.

Table 2.5: Black-Start performance of wind [36]

Self-starting	Most wind farms tend to rely on a primary auxiliary power from the network to self-start. A diesel generator or an electrical energy storage system has the potential to provide the power to start a wind turbine. Ramp up times are comparably faster than that from some traditional BS providers. A suitably sized auxiliary power supply would currently be required to enable a self-start. Self-starting can be considered against the individual components of energising the turbines, energising the cable arrays and the substation.
Grid-forming	Most wind farm connections are currently through grid-following inverters and these are not presently able to produce their own voltage signal to energise a network, instead latching on to a pre-existing signal. Nevertheless, a software change coupled with a grid-forming inverter is understood to be a feasible option to unlock this capability.
Network energisation and reactive power	Reactive power capabilities will depend on the wind turbine technology employed (full-scale inverter typically has the best capability). Large wind farm sites connected at 400kV or 275kV are expected to provide at least 100MVAr of leading (absorbing) reactive power (as per current requirements), and are able to withstand the magnetic inrush and transient voltages associated with re-energisation of lines, cables and transformers. The ability to energise the network will largely depend on the availability of the wind resource, the wind farm capacity and the energisation of the network load.
Block loading	Load restoration in smaller blocks could be achievable by wind farm sites depending on the wind availability and the duration of the supply.

Frequency control	The grid-decoupled nature of both doubly-fed induction generators and fully converter-fed synchronous generators (electrically excited or permanent magnet) as applied in modern wind turbines implies a low contribution to network inertia in the conventional sense. Associated voltage and frequency control is dependent on the technology of the wind farm-to-grid connection and the availability of compatible control algorithms. Some work has been done to incorporate algorithms into the wind turbine converter control systems to address this. In terms of frequency control, this will also depend on the available wind resource since low wind conditions will limit the capacity of the wind farm to ramp up active power supply [39].
Availability and intermittency	Wind resource is intermittent and may not be available or sufficient for a Black-Start at such times as necessary. For a given wind speed however, there is the capability to control the output of a wind turbine.

The process of restoration should start with individual turbines being fed from auxiliary power (that is separate to power provided from the network), this is done to begin energising and operating the wind farm. Presently, in practice this arrangement is just performed at a few sites.

One of main challenges would be for the turbines to provide reactive power to energise the inter-array cables of the wind farm. With this in mind, the controls for the turbine and internal converter need to be developed to operate in a weak grid and are currently not typically designed as such.

A diesel generator or some type of energy storage back-up power supply would still be required to energise the substation. A further challenge is for the turbines to provide the reactive power to energise the main export cable. A point to note is that significant work in regards to control, communications, auxiliary power, is still be required to make this technically feasible.

Table 2.6: Restoration capabilities of wind [36]

How early can the technology join a Power Island?	Existing network regulations prevent wind farms in the UK from operating in island mode and joining a Power Island. However, if sufficient wind resource is available, and the control and protection systems are adapted, wind energy with its own internal auxiliary starting power will be able to join a Power Island early in a restoration process.
How will the technology perform once if the Power Island?	The performance of the technology is largely based on the availability of wind resource and the amount of power required in balancing the load. Coupled with energy storage and other generation, the technology will be able to provide support functions for frequency, voltage and inertia in a Power Island.

How can this performance be used to the advantage of the Restoration?	The technology is able to provide voltage support, frequency support, reactive power support and block loading depending on the power island strength, the size of the block load and the wind farm capacity. The technology has the ability to accelerate the overall restoration process.

2.3.3.2 BESS

Table 2.7: Shutdown resilience characteristics of battery storage [36]

Site de-energisation	The technology can safely shutdown when a widespread and extended shutdown occurs, upon site de-energisation, charging (or discharging) of batteries will cease. Procedures in place to shutdown safely without external supplies.
Emergency power	The energy stored in the batteries will depend on the state of charge/discharge when the shutdown occurs. The technology typically has on-site emergency power, sufficient for restoration of communications, control, and charging the battery if needed. If the shutdown is extended over a long duration, the UPS may only have several hours' capacity.
Intervention resources	If unmanned, the response from the initial Black-Start trip needs to be quick as the site should be ready to re-energise within 2 hours of instruction from the system operator. A back-up communications link may be available on-site but typically is not a remote feature, therefore manned sites have an inherent time-advantage through restoration of local controls.
Control and communication system	A UPS will provide the site with enough power to restore control and communication systems ready to receive notifications from the SO and keep the battery charged for several hours. The battery may go into a power saving or standby mode so that it won't discharge or use excess energy until a notification from the SO is received. The UPS would not be able to provide continuous power in an extended shutdown, since its duration is typically several hours, and not the 72 hours outlined in current Black-Start procurement requirements.
Auxiliary starting generation	The auxiliary generation on a battery storage site typically is a UPS, as the battery itself is capable of self-starting. Thus, the main issue is the state of charge of the battery at the time of the shutdown and whether it holds enough capacity to perform as procured.

Table 2.8: Black-start performance of battery storage [36]

Self-starting	Battery storage sites will have a UPS on site that can power auxiliaries, and if the battery has enough charge at the time of a shutdown, the site is able to restore and self-start locally. Demand duration needs to be considered since the battery storage system will typically be able to store energy for several hours and provide power for a limited time.
Grid-forming	Battery storage sites are typically installed with parallel grid operation in mind and therefore are not usually grid-forming capable, instead latching on to a pre-existing signal via their grid-following inverter. Nevertheless, some are capable of providing a grid-forming signal, typically those that are part of a microgrid, although additional cost in the software and hardware upgrades are to be considered.
Network energisation and reactive power	Battery storage can contribute to network energisation in terms of balancing the network and supporting grid stability. The battery storage can respond to changes on the network instantly depending on the control settings and is also able to change between charging and discharging states fairly quickly. The reactive power capability of battery storage is usually four-quadrant controllable operation and therefore enabled to react and respond to the network to export or import the necessary compensation. The ability of battery storage to support grid stability and balancing generation and demand is a key attribute of this technology and is paramount in forming power islands where the frequency and voltage may vary out with normal network operating limits at rates faster than usual conditions.
Block loading	Battery storage block loading capability is dependent on the rated capacity of a site, and the discharge time is limited by the battery storage capacity. Storage sites can be installed as multiple units located at strategic points on the network to provide a net effect. As long as the battery has charge, the ramping rates are steeper than traditional generation although it depends on the power rating of the battery.
Frequency control	As battery storage can respond to changes on the network, large frequency swings are able to be eased by the settings in the control system of the battery. Frequency sensitive mode may be enabled and, depending on the size, the capability to provide more frequency support is there. Due to the fact that battery storage can act as generation or demand, the site may help the network by changing states as long as the controls of other battery storage sites on the network are all communicating so that two independent sites do not react to each other's changes immediately.

Availability and intermittency	Battery storage has no intermittency issues as such, since the resource depends on how much energy the battery has stored. The availability of power from battery storage sites is dependent on their state of charge. Their operational window may be short however, often in an islanded network the role of battery storage is that of a network stabiliser and thus it does not fully charge or discharge. Instead, the battery storage responds in real-time to the network and will be charging and discharging interchangeably depending on the connections to the network, block loading, generation connecting to the Power Island, etc. The main limitation of battery storage in this context is the size of the plant.

A battery storage site could readily join a Power Island, with its performance dependant on the state of charge of the batteries at the time of the restoration effort, and the site's capacity. The steep ramp rate and ability to energise quickly are both advantageous in a Power Island. If the battery is co-located with intermittent generation e.g. wind or solar, this would greatly improve the service provision from each technology type as they would provide complementary capabilities. Stand-alone battery storage systems would require a large capacity to unlock maximum benefit in a restoration.

Table 2.9: Restoration capabilities of battery storage [36]

How early can the technology join a~ Power Island?	If the battery storage had grid-forming capability, then the battery storage may create a Power Island and sustain this as other generation technologies and demand are energised and synchronised to the Power Island. If the battery storage is grid-following, as is currently the case, then it may have auxiliary generation ready to synchronise to the wider Power Island.
How will the technology perform once if the Power Island?	Battery storage will stabilise the Power Island by providing facilities that can be used to efficiently balance the network through the reactive range, charging and discharging of the battery. The operational window is short and so there are recognised benefits of co-locating with an intermittent resource to maximise benefit. It may also help with the large frequency swings when expanding the Power Island.
How can this performance be used to the advantage of the Restoration?	Battery storage may be used potentially to form a Power Island and then later in the restoration process as a grid stabiliser as either a source of demand or generation, depending on the needs of the Power Island. As the operational window is shorter than other technologies; if it is able to charge during the restoration then this will prolong the usability of a battery storage site in the restoration process as it is functionally capable of several important aspects of network restoration.

2.4 Island Operation

The challenge during island operation is to manage the active and reactive power demand that results from variable load behaviour and distributed generation, which can result into a sudden imbalance.

Power electronics are the enabling technology to convert classical power systems into those systems – smart grids –, since they allow controlling the power flows and bus voltages in the milliseconds range. The power electronic converter is composed of a power circuit, which can be realized by various configurations of power switches and passive components, plus control/protection systems. The link between the two is achieved through gate/switch signals and feedback control signals.

The main function of the converter is to promote energy exchange between two (or more) subsystems according to pre-specified performance specifications. Subsystems often have different properties in terms of frequency, phase angles, voltage/current waveform, and the number of phases, so they cannot be directly connected [40]. In particular, AC-DC converters with bidirectional power capability are the key elements to make possible the operation in isolated systems and distributed generation systems. The diferent configurations of variable speed wind turbines need power converter structures based on two AC-DC converters, as the VSC designed for standalone operation. Each converter needs active and reactive power control capability in order to extract the optimum power from the wind turbine while exchanging the appropriate reactive power with the power grid.

During island operation, the massively reduced short-circuit power leads to larger voltage excursions during imbalances of load and generation. In addition, the power quality still remains an important issue.

Chapter 3

Hybrid Operation

This chapter provides some explanation of the structure of modern wind turbines and their operation. Additionally, some information about the integration of ESS is covered, mainly batteries. Some of the most promising available technologies are taken into consideration, possible applications, and its capacity to tackle some of the current challenges is described. At last, an hybrid operation is discussed.

3.1 Wind Turbine Operation

3.1.1 Structure of modern wind turbines

A wind energy conversion system is composed by a turbine tower which carries the nacelle, and the wind turbine rotor, consisting of rotor blades and hub. Most modern wind turbines are horizontal-axis wind turbines with three rotor blades usually placed upwind of the tower and the nacelle. On the outside, the wind turbine is usually equipped with anemometers and a wind vane to measure the wind speed and direction [41]. The key components of the wind turbine (the gearbox, mechanical brake, electrical generator, control systems, yaw drive, etc) are contained on the nacelle, as illustrated in Figure 3.1.

3.1.1.1 Tower and foundation

One of the most important pieces of the wind turbine assembly is the tower that it is mounted upon. Mounting a wind turbine on the highest possible tower results in increased power production due to the stronger winds present at higher altitudes. In addition, the effects of the wind shear caused by the surrounding terrain is also much less at higher altitudes, providing yet another reason to mount the turbine as high as possible.

There are obviously some limitations on the tower's height and its suitability for a given application. One such consideration is the structural requirement necessary to support the turbine

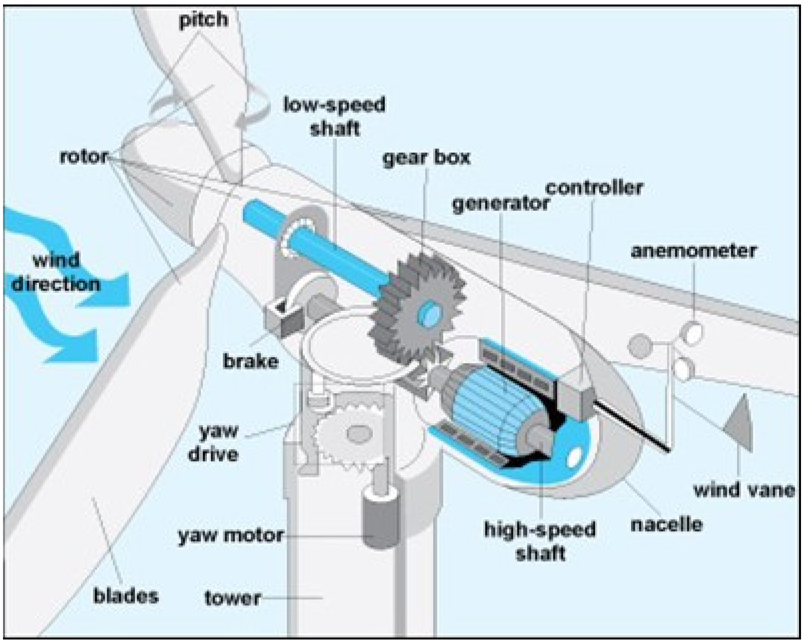

Figure 3.1: Wind Turbine Schematic [42]

being considered, included how much the turbine weighs as well as what types of environmental forces (high winds, snow, rain) it will have to sustain over time, and the foundation itself in order to guarantee its stability at all operating conditions [43]. In the case of an off-shore wind turbine, the foundation design is more complex, requiring development of highly cost effective solutions. Further, environmental and energy gain considerations require of wind farms to be located farther from shore at consequently deeper waters, making the process more difficult [44].

3.1.1.2 Rotor

The rotor is the heart of a wind turbine and consists of multiple rotor blades attached to a hub. It is the turbine component responsible for transforming the wind energy into mechanical motion. As the overall diameter of the rotor design increases, the quantity of energy that the rotor can extract from the wind also increases. Therefore, turbines are often designed around a certain diameter rotor and the predicted energy that can be drawn from the wind [43].

- **Rotor Blades**: are a crucial and basic part of a wind turbine. The design of the individual blades also affects the overall design of the rotor. Rotor blades collect the energy present in the wind and convert its kinetic energy into the rotation of the hub. Its design is inspired on the airplane wings, using the same “lift” principle: below the wing, where the stream of air produces overpressure; above the wing, a vacuum is created by the stream of air, those two forces induce rotation.

- **Hub**: is the centre of the rotor to which the rotor blades are attached. The hub directs the energy from the rotor blades on to the generator. If the wind turbines have a gearbox, the hub is connected to the slowly rotating gearbox shaft, converting the energy from the wind into rotation energy. If the turbine has a direct drive, the hub passes the energy directly on to the generator.

- **Power control of the wind turbine**: Wind turbines are generally designed to yield maximum power (nominal capacity) at a rated (or nominal) wind speed in the range of 11–15 m/s (around 40–54 km/h) for most commercial units. In the case of stronger winds, a maximum constant level of power is defined to fed to the grid and thus avoids damaging the wind turbine.

  Wind turbines operation is divided in three modes [45]:

  – Below rated wind speed operation
  – Around rated wind speed operation (usually at nominal capacity)
  – Above rated wind speed operation

  If the rated wind speed is exceeded the power has to be limited. Therefore, all wind turbines are designed with a power control that achieves this goal and avoids a run-away situation. There are different ways of doing this safely on modern turbines, mainly recurring to pitch control and stall control techniques.

  1. **Pitch Control**: This control concept operates by turning the rotor blades into or out of the wind according to the control laws. An anemometer mounted atop the nacelle constantly checks the wind speed and sends signals to the pitch actuator, adjusting the angle of the blades to capture the energy from the wind most efficiently.

     The electronic controller checks the power output of the turbine several times per second, and when the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. On the other hand, the blades are turned back into the wind whenever the wind drops again. The rotor blades thus have to be able to turn around their longitudinal axis (to pitch).

     During normal operation (below or around rated wind speed) the controller generally pitches the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle in order to maximize output at all wind speeds.

  2. **Stall Control**: In a stall-regulated wind turbine, the blades are locked in place and do not adjust during operation. Instead the blades are aerodynamically designed and shaped to increasingly "stall" the blade angle of attack with the wind to both maximize power output and protect the turbine from excessive wind speeds.

     Stalling works by increasing the angle at which the relative wind strikes the blades (angle of attack), and it reduces the induced drag (drag associated with lift).

  The main advantage of stall control is that it avoids moving parts in the rotor itself, and therefore a complex control system since they do not have the same level of mechanical and operational complexity as pitch-regulated turbines. In this way, stall-regulated turbines are often considered more reliable than pitch-regulated ones. On the other hand, stall control represents a very complex aerodynamic design problem, and related design challenges in the structural dynamics of the whole wind turbine, e.g. to avoid stall-induced vibrations. In addition, pitch-regulated wind turbines are generally considered to be slightly more efficient than stall-regulated ones.

3.1.1.3 Nacelle with drive train and other equipment

The nacelle contains all the machinery of the wind turbine, i.e. the drive train including the mechanical transmission (rotor shaft, bearings and the gearbox) and the electrical generator, and other equipment such as the power electronic interface, the yaw drive, the mechanical brake, and the control system, among others. Because it requires rotating in order to track the wind direction, it is connected to the tower via bearings.

- **Drive Train**

  1. **Mechanical Transmission**: The gearbox is the major component of the mechanical transmission. Large scale wind turbines tend to have very slow rotational speeds, due to their huge diameters. These speeds are insufficient to operate their generators at maximum efficiency, so there is the need to include a gearbox transmission between the rotor output shaft and the generator input shaft. In the case of multi-pole synchronous generators coupled to the electric grid via a full scale power converter, which decouples entirely the generator system from the utility grid, since it can operate at low speeds the gearbox can be omitted. Hence, a gearless construction represents an efficient and robust solution that is beneficial, especially for off-shore applications, where low maintenance requirements are essential.
  2. **Electrical Generator**: The generator is the element of the wind turbine that converts the mechanical motion of the rotor into electrical energy. The blades transfer the kinetic energy from the wind into rotational energy in the transmission system, and the generator is the next step in the supply of energy from the wind turbine to the electrical grid. There are two major types of electrical generators for converting mechanical energy: synchronous and asynchronous generator.

- **Other Equipment**

  1. **Power Electronic Converter**: Wind turbines function at variable rotational speed; thus the generator electric frequency varies and needs to be decoupled from the grid frequency through a power electronic converter system. The power electronic converter enables wind turbines to operate at variable (or adjustable) speed, and thus permits to provide more effective power capture than the fixed-speed counterparts. In variable speed operation, a control system designed to extract maximum power from

the wind turbine and to provide constant grid voltage and frequency is required according to the type of wind turbine used.

The power converter is an interface found between the load/generator and the grid. Depending on the topology and the applications present in the system, power can flow into the direction of both the generator and the grid.

Converters are made by power electronic devices, and circuits for driving, protection and control. Two different types of converter systems are currently in use: grid commutated and self commutated converters. Grid commutated converters are thyristor converters containing 6 or 12 pulse, or even more, that can produce integer harmonics. This kind of converter does not control the reactive power and consume inductive reactive power.

The other type of converter, self-commutated converter systems, are pulse width modulated (PWM) converters that mainly use Insulated Gate Bipolar Transistor (IGBTs). In contrast to grid-commutated, self-commutated converters control both active and reactive powers. PWM-converters, therefore, have the capacity to provide for the demand on reactive power and a high frequency switching that make them produce high harmonics and interharmonics.

2. **Yaw Drive**: The yaw drive is an important component of modern horizontal axis wind turbines yaw system. To ensure the wind turbine is producing the maximum amount of electric energy at all times, the yaw drive is actively controlled to keep the rotor facing into the wind as the wind direction changes. This is accomplished by measured the wind direction by a wind vane situated on the back of the nacelle.

3. **Mechanical Brake**: A wind turbine has two different types of brakes. One is the blade tip brake and the other is a mechanical (or stick) brake. The mechanical brake is placed on the small fast shaft between the gearbox and the generator. This mechanical drum brake or disk brake is only used as an emergency brake, if the blade tip brake fails. The brake is also used when the wind turbine is being repaired to eliminate any risk of the turbine suddenly starting. Such brakes are usually applied only after blade furling and electromagnetic braking have reduced the turbine speed, as the mechanical brakes would wear quickly if used to stop the turbine from full speed.

4. **Control System**: The wind turbine control system is involved in almost all decision-making processes in the safety of the wind turbine. At the same time, it must supervise the normal operation of the wind turbine and carry out the measurements for monitoring, control, statistical use, etc. The control system is usually based on a number of dedicated computers, specially designed for industrial use, which continuously monitor the condition of the wind turbine and collect statistics on its operation.

3.1.2 Wind Turbine Concept

Wind turbines can either be designed to operate at fixed speed or at variable speed. Variable speed wind turbine generators permits to provide more effective power capture than the fixed speed counterparts [46]. In fact, variable speed wind turbines have demonstrated to capture 8-15% more energy than constant speed machines. In variable speed operation, a control system designed to extract maximum power from the wind turbine and to provide constant grid voltage and frequency is required. As well as becoming larger, wind turbine designs were progressing from fixed speed, stall-controlled and with drive trains with gear boxes to become pitch controlled, variable speed and with or without gearboxes [43].

Among variable speed wind turbines, direct-in-line systems and doubly-fed induction generator (DFIG) systems have increasingly drawn more interests to wind turbine manufactures due to their advantages over other variable speed wind turbines and currently have the most significant potential of growth [41]. Direct-in-line systems consists of a direct-driven (without gearbox) permanent magnet synchronous generator (PMSG) grid-connected via a full-scale power converter, while DFIG systems are built with a common induction generator with slip ring and a partial-scale converter connected to the rotor windings. Both modern pitch-controlled variable speed wind turbines technologies are emerging as the preferred technologies and have become the dominating type of yearly installed wind turbines in recent years [47].

3.1.2.1 Type IV Wind Turbine

This configuration corresponds to the direct-in-line full variable speed controlled wind turbine, with the generator connected to the electric grid through a full-scale power converter, as illustrated in Figure 3.2 [48].

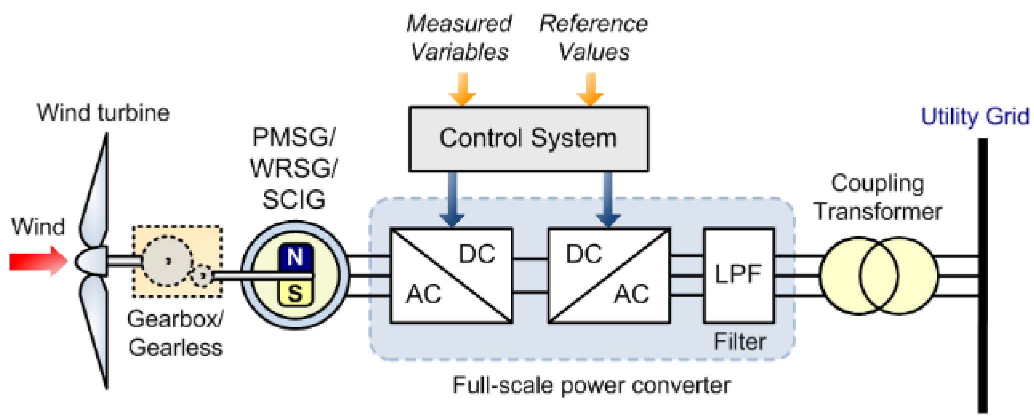

Figure 3.2: Topology of a full-conversion generator (Type 4) [43]

A synchronous generator is used to produce variable frequency AC power. The power converter connected in series with the wind turbine generator transforms this variable frequency AC power into fixed-frequency AC power. This power converter also allows controlling the reactive power compensation locally generated, and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator, WRSG) or permanent magnet excited type (permanent magnet synchronous generator, PMSG). Accordingly to the industry standards, this wind turbine is classified as a Type 4, including generators that are completely decoupled from the grid through a full-scale power converter, which is composed of a back-to-back four-quadrant AC/DC/AC converter design based on insulated gate bipolar transistors (IGBTs), allowing the physical generator to operate over a wide range of speed variability [49]. Some full variable speed wind turbine systems have no gearbox (shown in dotted lines in Figure 3.2) and use a direct driven multi-pole generator.

The full scale power converter decouples entirely the wind turbine generator from the utility grid, facilitating grid codes such as fault ride through and grid support features required from modern applications. In addition, since a direct-in-line system can operate at low speeds, the gearbox can be omitted (direct-driven).

Moreover, using a permanent magnet synchronous generator, the DC excitation system is eliminated and allows reducing weight, losses, costs, and maintenance requirements (no slip rings are required). Even more, due to the intensified grid codes around the world, direct-driven PMSG wind turbine systems could be favoured in the future compared to DFIG wind turbine concepts [48].

This type of turbines presents some capabilities that are relevant mentioning [50]:

- These WTGs are capable of varying the reactive power at a given active power and terminal voltage, which enables voltage control;
- The voltage control capabilities of individual WTGs are typically used to control the voltage at the collector bus or on the high side of the main power transformer;
- Type 4 WTGs can vary the grid side converter current, allowing control of the effective power factor of the machines over a wide range. Reactive power limit curves for different terminal voltage levels are typically provided;
- The response of WTGs to short circuits on the grid depends largely on the type of WTG. While the response of Type 1 and Type 2 WTGs are essentially similar to that of large induction machines used in industrial applications, the response of Type 3 and 4 WTGs is dictated by the WTG controls. For instance, in turbines employing full-rated power converters as the interface to the grid (Type 4), currents during network faults will be limited to slightly above rated current. This limitation is affected by the power converter control, and is generally necessary to protect the power semiconductor switches.

3.1.3 Technical exigencies for grid connection of Wind generation

Technical requirements are often called “grid codes”, which are guidelines that can be summarized as a technical document containing the rules governing the operation, maintenance and development of the transmission system. Typically, the majority grid and connections requirements concerning wind generation interconnection, focuses on the following phenomena [43]:

- Fault Ride-Through (FRT) capability
- Voltage and frequency operating range
- Reactive power control and voltage regulation
- Active power control and frequency control
- Voltage flicker emission
- Harmonics emission

Regarding the main subject, BS, the technical requirements even though they aren't specified as grid code requirements, but more like challenges, can be stated as the following:

- The black-start provider should compensate any active and reactive power mismatch existing in the island network. Therefore, in practice, this means that the drive train, and turbine rotor must be able to withstand the and compensate the power deviations and withstand the resulting torque changes.
- Wind turbines make use of motors in the yaw to enable the turbine operation. Before black starting, those motors must be energized from somewhere else.
- Wind turbines have a significant reactive power capability, around 50% of their rating, which can be certainly used to compensate the typical reactive power mismatches resulting in the energization of loads and components in the island system.

3.2 Types of Energy Storage

Energy management and load shifting by storing energy from the time of generation until needed accommodates resource diversity and can improve infrastructure utilization, as more non-dispatchable generating technologies deploy [51]. An Energy Storage System (ESS) is a system capable to shift energy through time. For instance, at low demand periods, it can extract electrical energy, acting as a load, and then use it at peak times, injecting electric energy into the electrical grid, i.e., replacing a generator.

Generally, it is considered two main categories of energy storage devices based on the form of stored energy. The non-electrical (mechanical) convert other energy forms such as thermal and kinetic energy into electrical energy, e.g., flywheels, Compressed-air and, Pumped Hydro Storage (PHS), briefly explained on Appendix A. In the electrical energy storage devices (chemical and electromagnetic), it can be included the capacitors and the BESS [52].

Here it will be discussed the principles of application of the last two, pointing out some advantages and limitations.

3.2.1 Batteries

A battery is constituted by one or more electrochemical cells, storing or providing energy through electrochemical reversible reactions. Each cell is composed of two electrodes, the anode (positive), and the cathode (negative), immersed in an electrolyte, which can be solid, paste, or liquid [53].

The electrodes are where the redox reactions take place. The electrolyte, which separates the electrodes and is usually constituted by a solution containing dissociated salts, enables ion transfer between the two electrodes [6].

During the discharge process, the anode is oxidized, providing electrons, while the cathode electrode is reduced, accepting electrons through an external circuit connected to the cell terminals, as exemplified in Figure 3.3. By applying an external voltage across the electrodes, the reactions are reversible and the battery is charged [54].

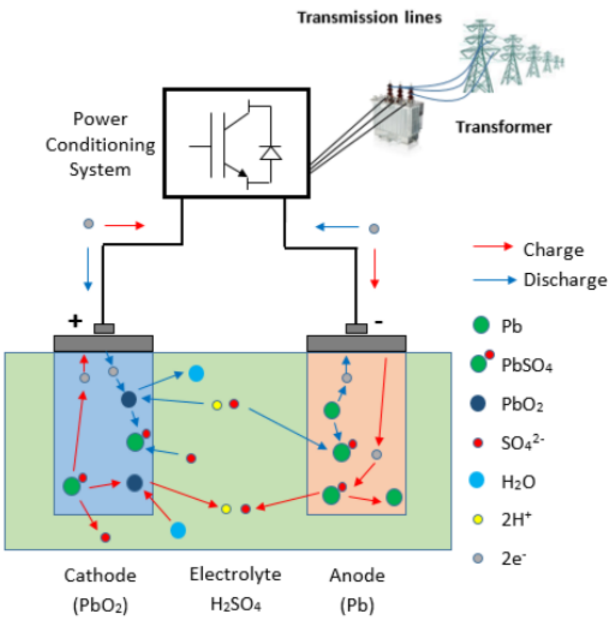

Figure 3.3: Schematic diagram of Pb-acid battery energy storage system [55]

The different technologies will be detailed and compared in Section 3.3.3. Presently, batteries are a suitable option for small-medium storage of electricity and its development make them a viable option to exploit.

3.2.2 Capacitors

Capacitors consist of two conductive metal foil electrodes separated by an insulating dielectric material usually made of ceramic, glass, or plastic film. The stored energy is the result of the electric field generated by the opposite charges. When a voltage is applied, these opposite charges appear on the electrode surface [56]. Compared with traditional batteries, these devices can charge faster, almost instantaneously, and provide higher specific power, but they have a higher self-discharge rate and lower energy density [53].

Supercapacitors (also know as ultra-capacitors, electrochemical capacitors or electric double-layer capacitors) are energy storage devices with enhanced features, comprehending an unusually large amount of energy storage capability relatively to its size [57, 58]. Their structure includes two metal electrodes with a carbon surface, separated by a porous membrane soaked in an electrolyte, which simultaneously has the role of an electronic insulator and ionic conductor, as ilustrated in Figure 3.4 [57].

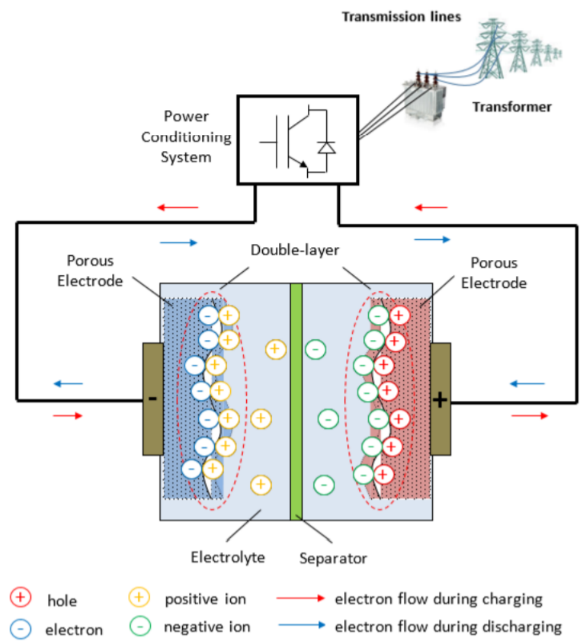

Figure 3.4: Schematic diagram of electrochemical double-layer capacitor [55]

Supercapacitors ideally store electrical energy in the electrostatic field of the electrochemical double layer, instead of performing any chemical reactions, thus presenting little degradation over hundreds of thousands of cycles, contributing to a longer lifetime when compared to batteries. These equipments exhibit very high efficiency (approximatelly 95%) due to low resistance, reduzing the loss of energy, good reversibility, light weight and low toxicity of materials used [58]. Moreover, it presents very high rates of charge and discharge, because of the ions in the solution transfer to the electrode surface faster. Furthermore, a higher power density is achieved than batteries, mainly to the short time constant of charging. In oppose, a lower energy density is provided because of the limited surface area of the electrode, making the amount of energy stored per unit weight considerably lower in comparison to a battery [57, 59].

The voltage changes with the stored energy, as shown in the Equation 3.1. In order to efficiently store and recover energy, complex electronic control and switching equipment are required.

$$W = \frac{1}{2}CV^2 \tag{3.1}$$

To summarize, the supercapacitor has a high power capacity but is short in duration, while the battery technology provides a high energy capacity but low power. Battery-capacitor hybrid ESS can combine the advantages of these two technologies, implied in the work of [60], a related topic for future research.

3.3 Battery Energy Storage Systems

The installed capacity of BESSs is expected to rise in the next few years. For instance, the International Renewable Energy Agency (IRENA) estimates that the world needs 150 GW of battery storage to meet the desired target of 45% of power generated from renewable sources by 2030.

This chapter aims to cover some of the technological principles of BESSs, explaining how these elements can be inserted in the systems' structure and its range of applications, in order to improve the grid.

3.3.1 Structure

The battery energy storage system includes not only the battery storage device itself, but also the interface which is connected to the power distribution network. To couple the battery storage devices with the AC grid usually requires a Power Conversion System (PCS). It should be also taking into consideration the protection equipment, the monitoring/control systems, a step-up transformer harmonic filters, and other ancillary equipment to control the systems' environment (such as ventilation, cooling/heating systems) [6]. The Figure 3.5 illustrates the basic structure of BESSs.

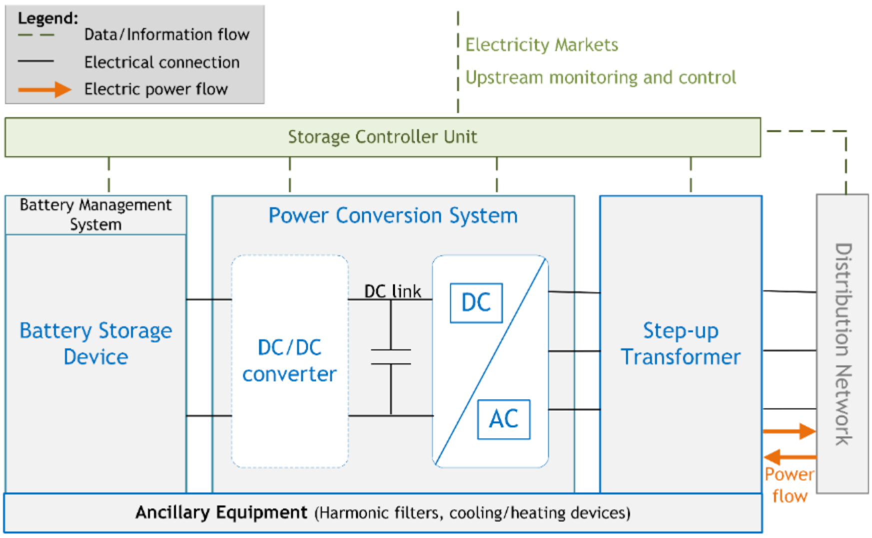

Figure 3.5: Generically structure of a Battery Energy Storage System [6]

The battery storage device consists of several electrochemical cells connected in series and/or in parallel to provide the required capacity and voltage. A BESS will incorporate a Battery Management System (BMS) that is responsible for monitorizing and managing the operations of these cells to keep it in a safe range. Also, the BMS measures relevant information such as the State of

Charge (SoC), i.e., the level of charge of an electric battery relative to its rated capacity, the State of Health (SoH), and the temperature in the cells [61].

A power conversion system (PCS) is required to convert the DC power input/output provided by the battery storage device to AC. It is based on power electronics to allow bi-directional power flow with the distribution grid. Moreover, ensuring complete control over the active and reactive power of the BESS (e.g. insulated gate bipolar transistors (IGBTs) controlled with a pulse width modulation technique) [62].

Since usually there is a nominal voltage difference between the battery installation side and the grid side, a step-up power transformer is required to fully connect the storage device and PCS to the distribution network at the point of common coupling (PCC) [62]. Therefore, the step-up transformer will increase the output voltage of the PCS to adapt it to the voltage level of the distribution network. There should be considered a harmonic filter to fix the distortion output signals of the voltages and currents originated at the PCS, as these waveforms aren't pure sinusoids.

The storage controller unit (SCU) embedded monitoring, control, and communication functions. This component monitors battery equipment, keeping constant communication with BMS and all other equipment (PCS, transformers, and other ancillary equipment). In addition, SCU can monitor electrical measurements on PCC to achieve full control of BESS. The SCU communicates with the rest of the electric system (e.g. DSO, electricity market operator, or other stakeholders), receiving and sending active and reactive power set-points to the PCS, in order to optimize the BESS functionality [61, 63].

The design and needs of the different components of a BESS may vary depending on technological, security, complexity, and sizing requirements.

3.3.2 Key Characteristics

In this chapter, are pointed out some of the key characteristics of BESS regarding their integration on power systems. These parameters are relevant and may be discussed on a more complex model, as their consideration can result in different solutions that would not adequately reflect the technical and economic impacts of these systems,i.e., choosing a rather technology in detriment of another. For this purpose, only a quick reference is taken.

The key features of BESS are transversal to different battery technologies, and may be divided into functional and non-functional parameters, as resumed in the diagram below.

The storage capacity is the maximum energy that an ideal BESS (without internal energy loss) can inject into or absorb from the grid without charging or discharging. Notice that the storage capacity may not correspond to the useful storable energy of the system. For instance, the State of Charge (SOC), or the energy level of the BESS, may need to be kept between a maximum and minimum value.

- Key characteristics
  - Functional parameters
    - Storage capacity
    - Charge/Discharge power limits
    - Rated power capacity
    - Efficiency
  - Non-functional parameters
    - Useful life
    - Cycle life
    - Total Ownership Costs
    - Modularity

The charging and discharging power limits respectively correspond to the active power that the battery system can absorb from or inject into the grid at a given time [64]. The charge and discharge power limits are usually expressed in the C rate, which is the rate at which the battery can be charged or discharged, to be respectively, fully complete or empty in one hour.

The rated power capacity corresponds to the maximum apparent power exchange between the BESS and the grid. The capability of the BESS in exchanging active and reactive power with the grid is provided by the PCS and, therefore, it can be limited by its rated capacity.

The efficiency of BESS can be regarded as the energy that the system can inject into the grid for each energy unit it accumulates [65]. This definition corresponds to the average round-trip efficiency of the BESS. This parameter includes the energy loss the different components that compose a BESS (such as battery storage devices, PCS and step-up transformers).

The key non-functional parameters are pointed out as the ones that have no influence or almost no restriction on the operation of BESS. As for instance, the useful life of BESSs is the time during which the systems operate until they cease functioning, or the degradation of their battery device affects the performance of the system in such a way that the BESS can no longer fulfil its purpose.

The cycle life is defined as the number of charge and discharge cycles that the battery can perform at a specific depth of discharge (DoD). The DoD of a cycle is the energy released by the battery during the cycle and is part of its storage capacity [65].

Total ownership costs (TOC) includes all life cycle costs of BESS, such as Investment costs, maintenance costs, end-of-life (EoL) costs and replacement costs [6].

The modularity of a BESS means that the unitary size of the battery device component is a module or container of battery cells (also including auxiliary equipment and BMS). The total storage capacity refers to the total size of the BESS, resulting from the addition of several battery containers/modules [66].

3.3.3 Battery Storage Technologies

Battery storage devices are the main differentiating components between BESSs of different technologies and therefore are relevant in terms of their applicability in the power grid. At present, there are many battery technologies, although they are at different stages of maturity and different application levels in grid storage projects.

This section gives a quick brief of the battery technologies considered to be more representative in development taking into account the maturity as well as the number and size of existing projects based on these technologies. Such technologies are lead-acid, lithium-ion, sodium-sulfur batteries, and vanadium redox batteries [6].

To start with, a distinction must be made between conventional and flow batteries. Conventional batteries store energy in solid electrodes, in contrast, flow batteries convert electrical energy into chemical potential, which is stored in two liquid electrolyte solutions in an external tank, generally, its size determines the battery's capacity. Furthermore, in contrast with conventional batteries, the power and energy ratings of redox flow cells are independent variables [67]. Flow batteries may require additional equipment, such as pump sensors and control units [55]. Of the aforementioned technologies, all are classified as conventional batteries, except for the vanadium redox batteries, which are flow batteries.

According to the work of [68], the global battery energy storage system installed capacity and distribution by 2016 can be seen in Figure 3.6.

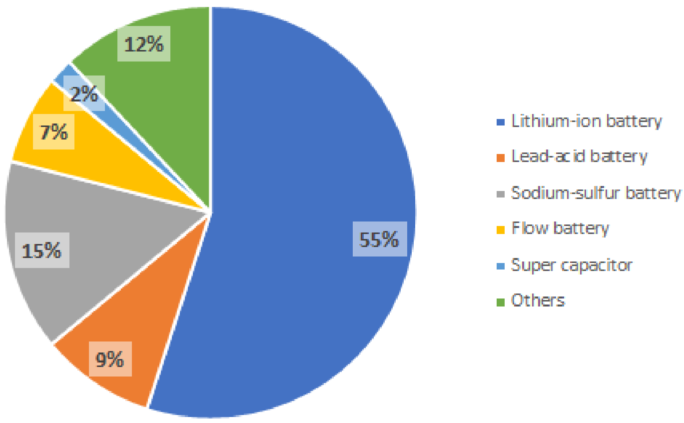

Figure 3.6: Global battery energy storage system installed distribution by technology in 2016

Although the exact values or ranges of values of several parameters are not consensual and may significantly differ, it is presented two tables adopted from the works of [68] (Tables 3.1 and 3.2), resuming the performance of several batteries, and discussing some of the advantages and disadvantages of different batteries. There are a few reasons for these intervals, which are mainly related to the state of improvement and development of each technology, the existence of several manufacturers of the same battery technology, and also some lack of experience on grid-scale projects.

Table 3.1: Parameters comparison of different battery technologies

Battery technology	**Rated Power (MW)**	**Energy Density (W h/kg)**	**Discharge Duration (h)**	**Energy Efficiency (%)**	**Lifetime**	**Cycles**
Lead-acid	<36	<50	<8	75-85	3-12	500-1200
Lithium-ion	<102	<200	<6	90-94	5-15	1000-10000
Sodium-sulfur	<50	<240	<8	75-86	5-10	2500-4000
Vanadium redox	<28	<30	<10	70-85	5-15	12000-18000

Table 3.2: Advantages and disadvantages of different battery technologies

Battery technology	**Advantages**	**Disadvantages**	**Energy storage applications**
Lead-acid	Low capital cost	Limited life cycle, long charging time and high self-discharge rate Environmental pollution	Hot spare, frequency control and load adjustment
Lithium-ion	High energy densities, high efficiency, and long life cycle	High production cost, requires special charging circuit	Frequency control, load shifting and power quality
Sodium-sulfur	High power and energy densities, high efficiency	Production cost and safety concerns	Load adjustment and standby power
Vanadium redox	High power, long life cycle, fast charge and discharge	High production cost, large area	Load shifting, emergency standby and power quality

3.3.4 Applications of the Battery Energy Storage Systems

Over the years, BEES has attracted more and more interest, involving applications for power quality regulation, bridging power, and energy management in power system operations.

Power quality refers to the degree of reliability and maintenance of power supply, nominal voltage levels, unity power factor, nominal frequency levels, and a purely sinusoidal waveform with zero harmonics and no transients. These services comprehend operations within seconds to a few minutes, being the fastest to act.

Bridging power services are responsible for guaranteeing the difference between limited generation capability of energy sources and highly variable electricity demand, ensuring the continuity of service, working within minutes to an hour.

Other applications facilitate energy management and provide time shifts ranging from hours to days or even months to decouple the time required for electricity generation and consumption [55].

In the present chapter, some BESS potential applications are enumerated, keeping in mind that there are more and, some may be more appropriate than others depending on the technology mature level.

3.3.4.1 Capacity Firming

Due to changes in weather conditions, rapid output fluctuations of renewable resources may occur. In order to mitigate this effect, a fast-response BEES capable of providing high ramp rates and cycling times can be applied. The facility could be charged/discharged within a period of seconds to minutes, to smooth generation from variable RES, thereby eliminating rapid voltage and power changes on the grid.

When the actual output of renewable energy is lower than the predicted BESS discharges. On the contrary, when it is higher than the forecasted production, the BESS charges taking that extra generation. Therefore, the BESS can ensure a more predictable and constant power output from the renewable source with increased controllability [6, 55].

3.3.4.2 Oscillation Damping

RES penetration increasing can potentially compromise system stability against disturbances, especially in weak or isolated grids. BESS can provide a fast response and high ramp rates within a one-minute time-frame, avoiding system instability and consequent brownout, by absorbing and discharging energy during sudden decreases in power output over short duration variations [69].

3.3.4.3 Frequency Regulation

Frequency regulation is needed to maintain a balanced system. Traditionally, this is done recurring to steam or internal combustion engines. Nevertheless, those systems are ramp-limited, due to the inability to quickly respond to operator dispatch signals.

BESS are able to adjust the energy output almost instantaneously, being used in such applications, as it is required a high cycle life and fast response rates in combination with good ramp rates. In that way, the frequency is maintained within the network standards, improving power system stability [9, 70].

3.3.4.4 Voltage Regulation

Voltage profiles in the grid must be maintained within admissible/regulatory limits (e.g. ±10% of nominal voltage). The voltage is usually controlled by the taps of the transformers. Modern systems face the dynamic challenges imposed by the penetration of RES at the distribution level, as these voltage profiles tend to become more volatile as there are multiple power injections. In that regard, BESS can improve voltage drops and rises by appropriately absorbing/injecting active and/or reactive power [6, 55].

3.3.4.5 Low Voltage Ride-Through

Low voltage ride-through (also denominated fault ride-through) defines the ability of a generator to stay connected to the grid during a short-term voltage drop or a complete system failure. In power systems, it's essential to maintain the supply power online, in order to avoid possible cascade events, in which case the voltage may drop further and fall far enough to force another generator to trip, and so on. When connected to an external grid, the integration of a BESS system with high power capability and instant response capability enables continuous connection of power plants and reduces the risk of network collapse [71, 72].

3.3.4.6 Congestion Relief

Congestion may occur either on high voltage transmission lines or more locally on the distribution system. There are several reasons for this situation to happen, as in the event of an overload at the distribution equipment, due to extremely high penetration of distributed generation or when the transmission line is unable to cope with the growing demand [73]. If power generation or load demand exceeds the maximum delivered capacity, the energy in excess must be curtailed, otherwise system upgrades must be made.

BESS is capable of providing the excess energy, mitigating the power constraints imposed by insufficient delivery capacity. Instead of being curtailed, excess generation could be stored and injected back when the delivery capability is available again. In addition, the increased demand can be met by simply shifting the power generation time from peak hours to off-peak hours without causing additional losses to the transmission line [55]. In this way, both transmission curtailment is reduced and investment upgrades can be postponed, whilst improving the utilization factor of the existing network.

3.3.4.7 Load Leveling

Load balancing is another example of decoupling generation and consumption in time. BESS can be charged storage during periods of low demand and discharged as needed. Therefore, the gap between peak and off-peak is reduced, reducing the requirements of peaking generators to a minimum [74]. Electricity storage technologies allow the load curve to become flattered, thereby improving generation efficiency.

3.3.4.8 Peak Shaving

Peak shaving installations are usually a concern for consumers rather than utilities. The operational principle of peak shaving is similar to that of load balancing. However, the main goal here is to reduce peak demand.

By using BESS, the installation of peak-responding capacities can be avoided. Therefore, utilities can reduce the operating costs of generating electricity during peak demand periods. Moreover, consumers have economic benefits and can save electricity bills [9].

3.3.4.9 Spinning Reserve

Primary reserve is provided by plants that are operating and synchronized (spinning) to the system and thus is referred to as spinning reserve [75].

In order for the storage system to respond to a generation or transmission outage, the energy storage system is maintained at a specific level of charge [9].

BESS, with their fast response, can keep the network continuity. Making it possible for the generators to keep operating at optimum power output, without keeping some inactive capacity for spinning reserves. Besides, it can substitute back-up generators that are running idle.

The need for fast-responding, partially loaded power plants capable of providing the necessary contingency reserves results in uneconomic dispatch and increases in the capital and operational and maintenance costs, reinforcing the requirement for BESS applications especially in isolated systems [55].

3.3.4.10 Unit Commitment

The UC defines the appropriate scheduling of generators for certain time periods.

Typically, the minimum generation capacity of conventional units limits the RES integration, resulting in curtailments. As the penetration rate of variable renewable energy increases, utilities are over-dispatching and maintaining part load of power plants to avoid restrictions. This implies uneconomic dispatch due to increased start-up costs and operation at inefficient output.

BESS can facilitate this process, compensating forecast errors in the case of an under-predicted renewable source, enhancing a joint operation in a more efficient manner.

3.3.5 Battery Storage Modelling

BESS models can be categorized as electrochemical, electrical, and mathematical. Each model type has a variety of proposed models, with different levels of complexity, capable of capturing specific purpose battery behavior, from battery design to performance evaluation [76]. In this work, only electrical model is approached.

The electrical model is an equivalent circuit model composed of multiple voltage and current sources, resistors, and capacitors for designing and simulation with other circuits and systems [77]. These models are based only in electrical components, ignoring the electrochemical properties of the battery. For example, capacity decay is usually represented by a capacitor whose capacity decreases linearly, while the effect of temperature is modeled by a resistor-capacitor combination [78].

An electrical model presents some limitations, as for instance, it's not possible for circuit simulators to predict both the battery useful life, and its voltage-current performance under different conditions of SoC and temperature. This model are restricted to some types of analyses and can't be used, e.g., for planning purposes.

The electrical models that have been developed can be divided into Thevenin-based, impedance-based and runtime-based models, as shown in Figure 3.7.

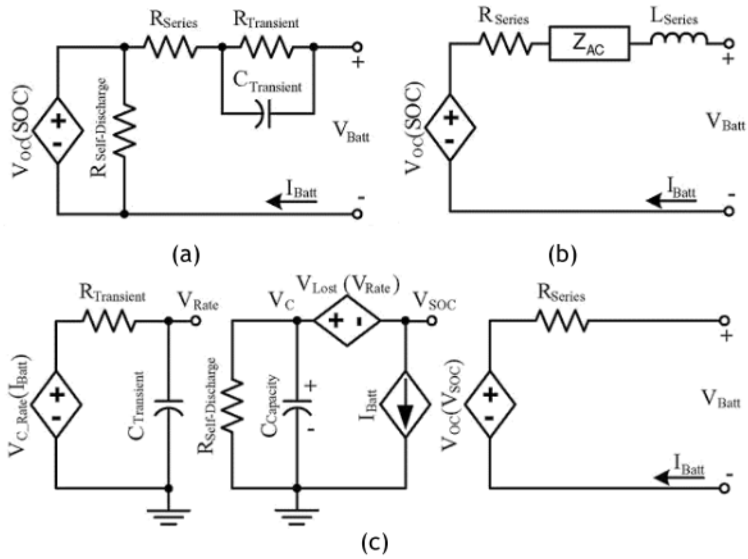

Figure 3.7: Electrical models for BESS: a) Thevenin-based; b) impedance-based; (c) runtime-based electrical models [6]

3.4 Grid-Forming in Hybrid Operation

In the work of [79], where a study and comparison of several European Network Codes for AC and HVDC connected Renewable Energy Sources are considered, BS and islanding operation requirements are starting to be included as options for WPPs in the ENTSO-E network codes, allowing the system operator to request these functions to support grid recovery.

Motivated by grid codes increasing technical demand, there has been an effort to enhance and re-adapt the control structure of wind turbines, to make them capable of providing some services that are a part of the restoration process, as low-voltage ride-through and fast frequency response. More advanced requirements, like inertia emulation, power oscillation damping, and reactive current injection are expected to be achieved, as well [80]. This is possible due to the advanced functionalities of the full-scale PEC interface of modern WTs, as previously discussed.

Wind turbines due to their fast start-up times can be included earlier in the restoration process to provide reactive-power support and pickup load, thus decreasing the impact of a blackout event by reducing the restoration time and power not supplied times [81]. However, since the majority of the current WTs assume a grid-following (GFL) strategy in the beginning of the restoration procedure, this can lead to a recurrence of blackout as the grid is generally not stable enough [82]. The early participation of WPPs in successful bottom-up network energization can be facilitated instead by grid-forming (GFM) control of WTs, allowing them to operate together as an AC voltage source without relying on an external grid, and supply load in a power island [83].

Zhu et al., in [84] show that earlier participation of WTs in the restoration procedure is feasible as GFM control allows black-start and stand-alone island operation with better inherent synchronous-machine-like inertial response during a transient that can help absorb the initial impact of energization and ensure smooth load pickup, thus mitigating large voltage/frequency excursions that might occur during restoration. Additionally the major energization transients are dealt by the energy storage system and SVG, while the WTs behave only as passive GFL power sources to meet the load demand during the last stages of restoration.

Traditional GFL WTs can be used with an external power supply (e.g. diesel generator or energy storage) and a synchronous var generator (SVG) or STATCOM, combining services into a joint/hybrid black-start unit, facilitating WT participation in black-start procedure as proposed in [85]. The external supply provides startup power and sets the reference voltage and frequency for the isolated system, the SVG/STATCOM supports the var requirement of the cables and transformers and stabilizes the voltage, after which the WTs connect to meet the load power demand.

In [86], Rocabert et al., defines that GFM converters are controlled in closed loop to work as ideal AC voltage sources, presenting low-output impedance. On the other hand, GFL converters are controlled as current sources with high parallel output impedance and cannot operate in islanding or stand-alone mode as they require a GFM converter or local synchronous generator to set the bus voltage and frequency. The main objective of GFM control is to operate the VSC as an ideal AC voltage source of a given amplitude and frequency.

In the work of [83] several grid forming strategies have been implemented. For this work, the grid forming will be implemented on the energy storage system. Moreover, a current controller is considered instead of the usual virtual synchronous machine approach encountered in the literature.

Chapter 4

Building and Analysis of Off-Grid Models

In the present chapter, the PCS models developed are discussed. This is divided into 3 different parts, as enumerated:

1. BESS model assuming an infinite ideal source;
2. Energy storage building up voltage and ramping up a Wind Park;
3. Model 2 feeding off-grid loads (Figure 4.1);

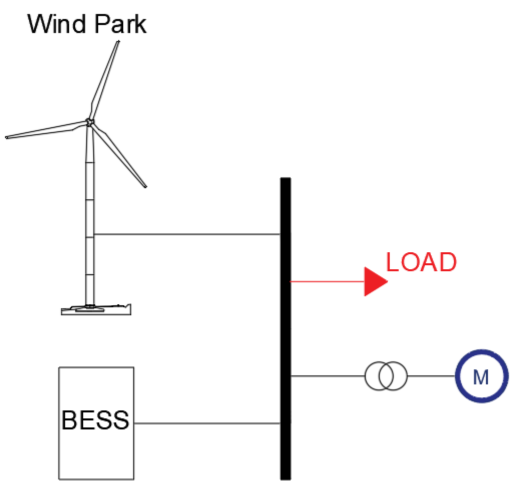

Figure 4.1: Wind Park and BESS connected feeding off-grid loads

For every model, it is described the most relevant facts for its construction, as well as some of the simplifications assumed. Simulink from Mathworks will be used to design those models.

4.1 Battery Energy Storage Model

The model developed is centered in the so-called two-level Voltage Source Converter (VSC), adapted from [87]. The system comprising an ideal storage unit and its connection to the grid by means of a power converter is analyzed. A control scheme able to control independently active and reactive power is described and justified. The system under analysis is shown in Figure 4.2.

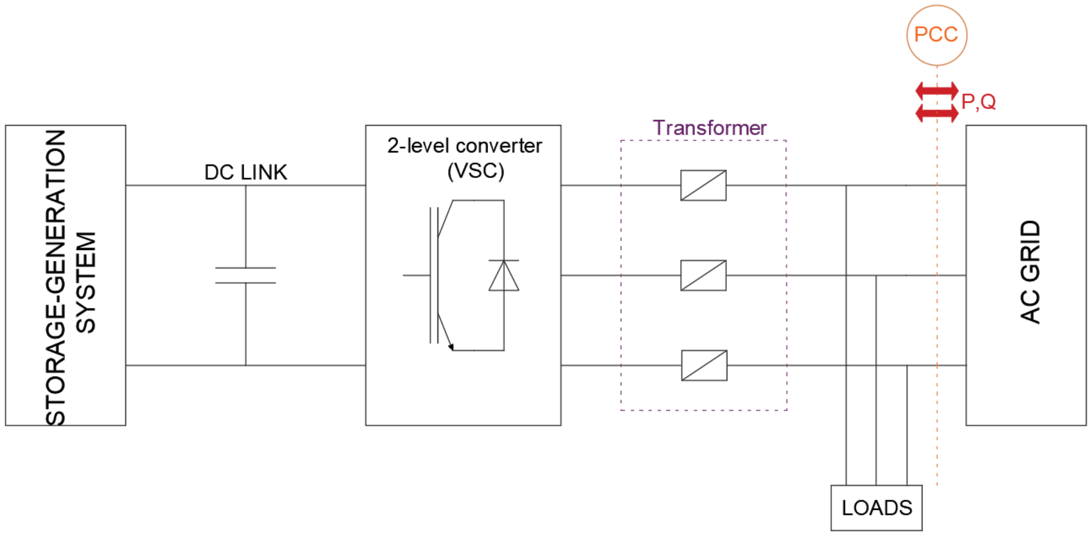

Figure 4.2: Generic system comprising the VSC converter and the three-phase utility grid

The considered grid is a three-phase three-wire grid. The PCS is a two-level Voltage Source Converter controlling the exchanges of power between the AC side and the DC side. It is composed of three branches with two IGBT/diode pairs (Isolated Gate Bipolar Transistors), whose middle point is connected to the grid by means of an inductive component. The converter is controlled by firing pulses produced by a PWM generator. Proper modulation of the IGBT switch allows the generation of the required three-phase voltage on the AC side to control the flow of active and reactive power.

The storage system is connected to the DC side. The DC side is modeled as a current source connected to a shunt capacitor (Figure 4.3). As for the AC side, it can be modeled by the Thevenin equivalent model of the power grid or in an extremely simple system by an AC voltage source. The synthesized or modulated voltage is applied by means of three controllable voltage sources modulating the obtained voltages from the control. This assumes the averaging of the pulse-width modulated signals and, as a consequence, this representation neglects the harmonic phenomena inherent in the VSC [87].

In essence, the VSC operation is equivalent to a voltage source that, when controlling the resulting current through the series reactor, results in a current controlled operation.

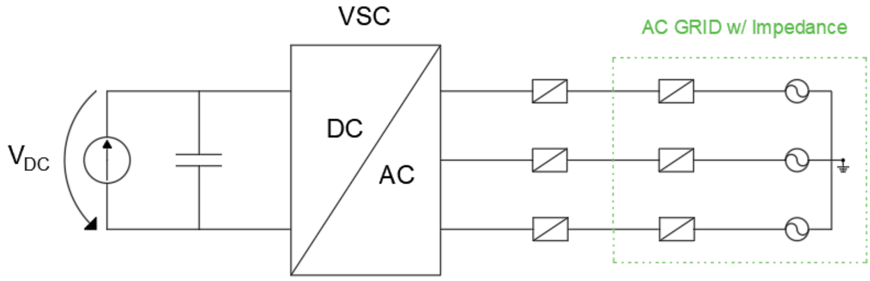

Figure 4.3: VSC converter with the DC side modelled as a current source and a shunt capacitor

4.1.1 General control scheme

The VSC allows to control of two electrical variables in the dq0 frame, allowing to separately control active and reactive power. Active power reference depends on the nature of the source connected on the DC side. For instance, in storage systems the reference voltage may be defined, to adjust the reactive power to the grid depending on the operation of the EMS of the system connected. This configuration uses the general control scheme illustrated in Figure 4.4.

The control scheme is based in a two level cascaded control system. The upper level controller is responsible to deal with the regulation of the DC bus voltage, control of active and reactive power flow, while the lower level controller regulates the AC currents in the d and q components.

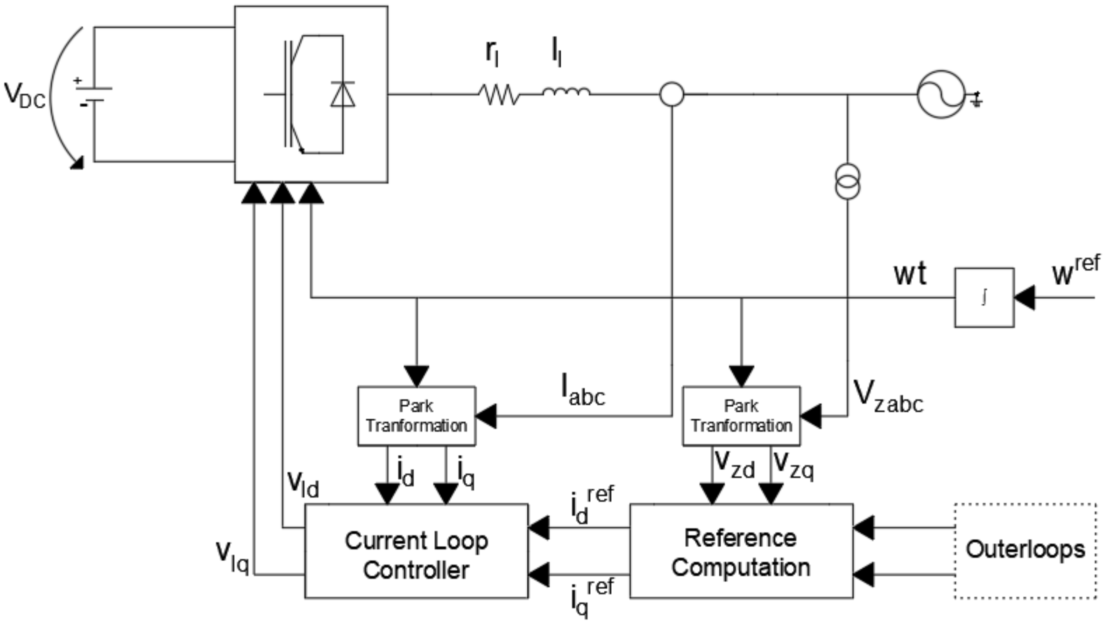

Figure 4.4: Grid converter control general scheme for storage generation systems

The controllers deal with currents and voltages in the dq0 reference frame rotating to adjust the electrical grid angle.

The following model encompasses a grid-forming strategy using a voltage-controlled oscillator (VCO), being responsible to hold voltage and frequency in autonomous operation of isolated systems. In order to achieve this, the outerloops illustrated in Figure 4.4 are defining the desired voltage magnitude and frequency.

4.1.2 Space Phasors and Two Dimensional Frames

The VSC needs to control the resulting voltages and currents, which are naturally sinusoidal components. The control of sinusoidal components is not straightforward because:

1. Controllers require a very high gain at the sinusoidal frequency;
2. Any filter and delay results in phase shifts which require a compensation;
3. The controlled signals need to be converter from DC (active and reactive power and dc voltage) to AC.

To overcome such complexity, sinusoidal variables are projected into the synchronous frame in order to convert such AC signals into equivalent DC components.

The two-dimensional frames, composed mainly by the $\alpha\beta$-frame and by the dq-frame, represented in Figure 4.5 along with the abc-frame, simplify the analysis and control of a VSC system. Both the $\alpha\beta$-frame and the dq-frame transform the problem of controlling a system of converters, as is the case with the three-phase VSC, to a problem of two similar subsystems. Additionally, the dq-frame transforms a sinusoidal command tracking problem to an equivalent DC command tracking problem. For that reason, proportional-integral (PI) compensators can be used for the control, as they present an ideal infinite gain at the DC. Commonly, components of power systems are expressed and studied in dq-frame. Thus, the representation of VSC systems in the dq-frame facilitates design and analysis tasks based on methods usually applied for power systems.

The instantaneous decoupled control of the reactive and active power exchanged with the AC system is possible in dq-frame control. Contrarily to the $\alpha\beta$-frame control, whose control variables are sinusoidal functions of time.

The dq-frame control of a grid-imposed frequency VSC system features DC quantities in the steady-state as control variables. This is achieved since the dq-frame is rotating at the same angular speed imposed by the grid. Moreover, if one of the axes (d or q) is placed over some vector, e.g., current or voltage, one of the components will represent the vector magnitude and the other will be null. This attribute facilitates the compensator design therefore reducing the complexity of the dq-frame control system. Additionally, since the control variables are DC quantities, zero steady-state error is achieved by including integral terms in the compensators.

The Park transformation is used for this work, being detailed on Appendix B.1. It's important to note that if $v_q = 0$, the real and reactive power components are proportional to i_d and to i_q, respectively. In this case, the reference value of v_q is intentionally set to zero, accordingly to the grid-forming strategy employed. In any case, if a grid-following strategy was being studied this scenario could be achieved recurring to a Phase-Locked Loop (PLL), as the one referred on B.2.

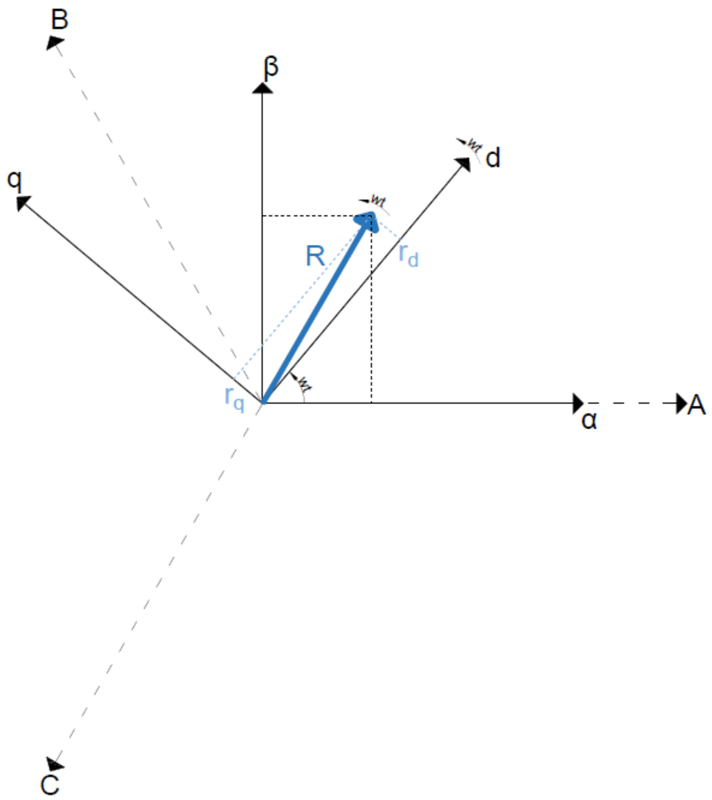

Figure 4.5: Representation of a vector on the dq-frame

4.1.3 VSC converter modelling

Although the VSC converter is based on the discrete states of the switching of the IGBTs, for control design purposes it is convenient to derive a more simplified equivalent model. As mentioned previously the VSC converter uses a simplified model decoupling its AC and DC part, instead of a modulation signal to control. For instance, the AC part is composed of controlled voltage sources, where the input signals are: the established angle, and the voltages provided by the current control loop (v_{ld} and v_{lq}). To perform this, an inverse Park Transformation (dq0 to abc) is needed.

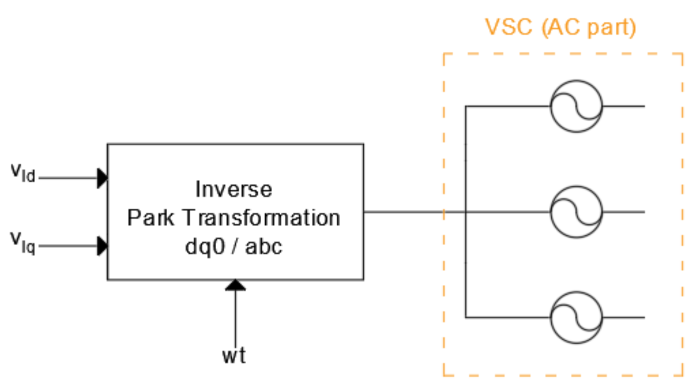

Figure 4.6: VSC equivalent AC side

As for the DC part, an infinite voltage source representing a BESS is considered connected to the system (Figure 4.7). The controlled current source in the DC side reflects the active power exchanged between the AC and the DC side and assures the system power balance. The DC current of the source can be computed neglecting converter losses as

$$I_{lDC} = \frac{P_{meas}}{V_{DC}} \tag{4.1}$$

where V_{DC} is the DC bus voltage and P_{meas} is the active power exchanged between the VSC converter and the grid in the AC side. This means that ideally the current that goes through the capacitor C should be zero and that the active power on the DC side and the AC side should be roughly the same during steady state conditions.

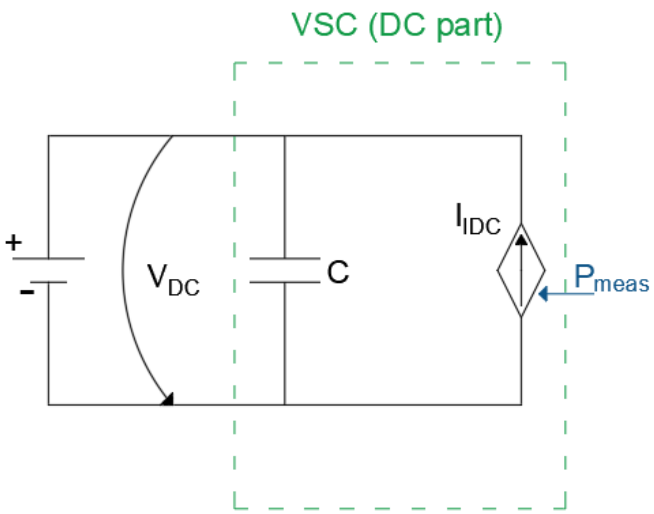

Figure 4.7: VSC equivalent DC side

4.1.4 Current-Mode Control of the Real and Reactive Power Controller

In order to control the i_d and i_q there are mainly two different control approaches. The first one is know as the Multi-variable control, where the d and q components are controlled recurring to a single two dimension controller. Nonetheless, it will be applied a second approach which consists in decoupling and independently controlling the d and q components.

The implementation of the overall current controller is sketched in Figure 4.8.

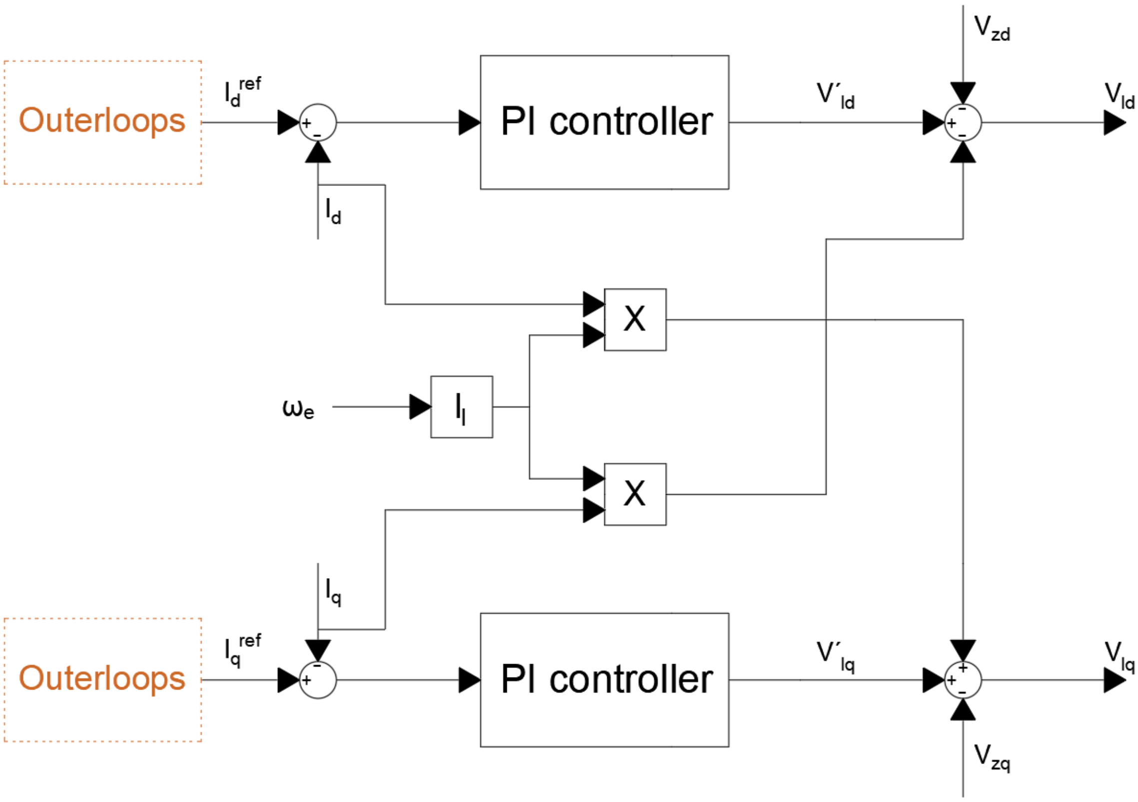

Figure 4.8: Schematic of the Current Loop Controller

$$\begin{bmatrix} v_{ld} \\ v_{lq} \end{bmatrix} = \begin{bmatrix} v'_{ld} - v_{zd} - i_q \omega_e l_l \\ v'_{lq} - v_{zq} + i_d \omega_e l_l \end{bmatrix} \tag{4.2}$$

where v'_{ld} and v'_{lq} are the outputs of the current controllers and v_{ld} and v_{lq} are the voltages to be applied by the converter.

Substituing those in the voltage equations (see B.3),

$$\begin{bmatrix} v'_{ld} \\ v'_{lq} \end{bmatrix} = \begin{bmatrix} r_l & 0 \\ 0 & r_l \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} l_l & 0 \\ 0 & l_l \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{4.3}$$

To obtain the transfer function among the controller voltages and converter currents the Laplace transformation is applied, deriving the following expressions

$$\frac{i_d(s)}{v'_{ld}(s)} = \frac{1}{r_l + l_l s} \tag{4.4}$$

$$\frac{i_q(s)}{v'_{lq}(s)} = \frac{1}{r_l + l_l s} \tag{4.5}$$

The PI controller is designed using the Internal Mode Control technique [88], resulting the following controller

$$G_{cid}(s) = G_{ciq}(s) = \frac{K_P s + K_I}{s} \tag{4.6}$$

where the proportional and integral gains constants are calculated as

$$K_P = \frac{l_l}{\tau} \tag{4.7}$$

$$K_I = \frac{r_l}{\tau} \tag{4.8}$$

with τ referring to the closed loop time constant of the electrical system, r_l is the inductance equivalent resistance, l_l is the inductance value, and the angular velocity ω_e=2πf.

f (Hz)	60
r_l **(p.u.)**	0.005
x_l **(p.u.)**	0.12
l_l **(p.u.)**	x_l/ω_e
τ **(ms)**	1

In order to determine the values of r_l and l_l, on international system units, the values of S_{base} of the system, and V_{base} are defined. Recurring to these values Z_{base} is calculated, in the following equation.

$$Z_{base} = \frac{V_{base}^2}{S_{base}} \tag{4.9}$$

Finally, the resistance and inductance values come as:

$$r_l(SI) = r_l(pu) * Z_{base} \tag{4.10}$$

$$l_l(SI) = l_l(pu) * Z_{base} \tag{4.11}$$

The feed forward v_{zd} and v_{zq}, applied to the current loop controller (Figure 4.8) considers two transfer functions that filter everything out above the 3rd harmonic, rejecting some disturbances.

4.1.5 Outerloops

The outerloops will provide the currents reference values (d and q components) to the current controller, as illustrated in Figure 4.9. There are several strategies to define these values recurring to different variables, such as the active power (P), frequency (f), reactive power (Q), or even voltage (V). Moreover, these inputs can be combined depending on the approach implemented, also their own measured value can be set to follow some reference value with a proper controller (e.g., PI controller), thus providing the current reference.

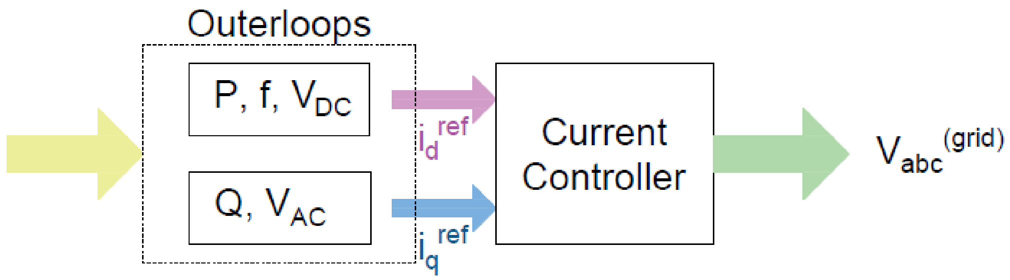

Figure 4.9: Generic control scheme

For this work, it will be considered the active current reference (i_d^{ref}) based on the frequency or more explicitly regarding the voltage angle (v_{zq}), and this value should be 0, defining the grid-forming system. The voltage magnitude v_{zd} will define the set-point for the reactive current reference (i_q^{ref}). This variable is in charge of defining the voltage required in the start-up process. Both of them will use a PI controller, as in Figure 4.10.

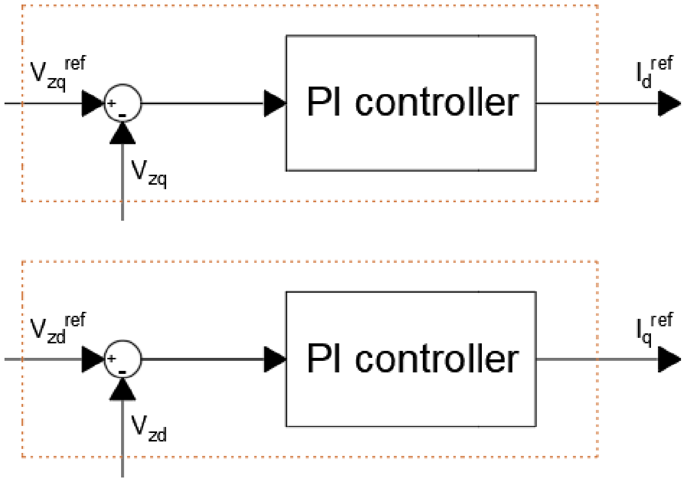

Figure 4.10: Outerloops for currents references

The proportional and integral gains of the controller were changed to get the bandwidths which result in a better interaction with the external components of the PCS. First, only a proportional gain was applied and then the integrator part was added, checking the responses.

4.2 Wind Park

At this point of the document, its described the model adopted for the Wind Park based on the work "Detailed Modelling of a 1.5MW Wind Turbine based on Direct-driven PMSG" developed in [89].

The main objective here is to perform a black-start on the Wind Farm recurring to the BESS system previously developed. The energy storage system is connected in parallel (Figure 4.11) and is in charge of building up and ramping up the voltage during the start-up process. It is assumed an unique bus scheme, disregarding the transmission lines and its energization process, and subsequent transformers in the substation, as in an HVDC connection like the one in [83].

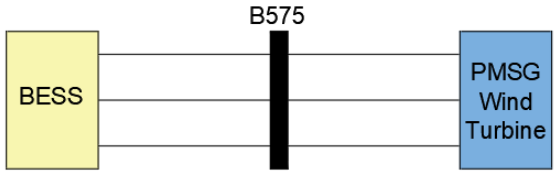

Figure 4.11: Generic system Wind Park and BESS

Another important feature of this system is the control of the active power as a result of the wind speed.

4.2.1 Adaptation for a Wind Park model

This model is composed by several layers/levels being important to distinguish the following:

- System level: defines the parameters of the wind turbine, such as rated line-to-line voltage, rated power, rated frequency, number of pole pairs and DC capacitor voltage. Furthermore, the generator that is providing the start-up procedure, in this case the BESS, is connected here on bus B575.

- Wind Turbine level: composed by the circuit of a single wind turbine (Figure 4.12) containing the parameters of the permanent magnet synchronous machine block, DC chopper, DC capacitor, two universal bridges emulating the grid-side converter and the machine-side converter, a transformer, and a filter. Furthermore, the reactive power reference value can be defined, and there is a block that defines the torque in relation to the defined wind speed (Figure 4.13).

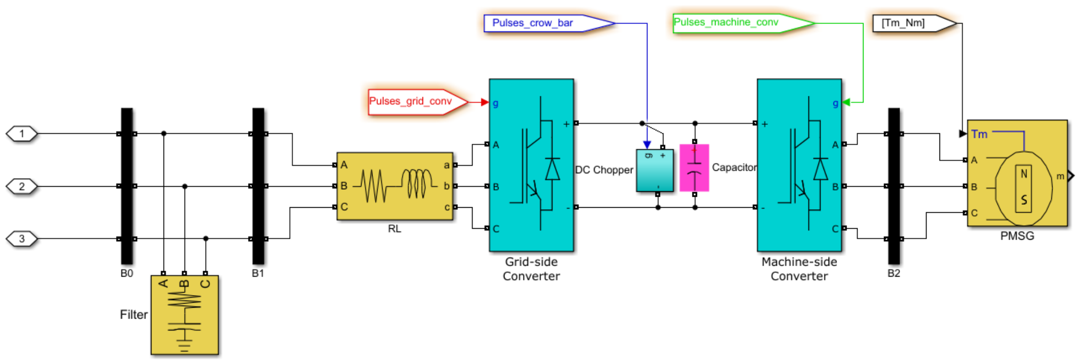

Figure 4.12: Single Wind turbine main elements

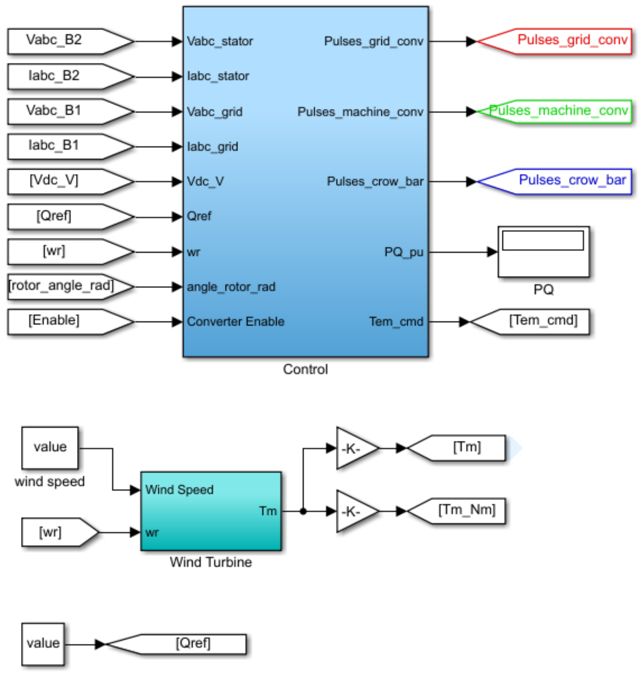

Figure 4.13: Single Wind turbine inputs for the control level, reactive power reference, and wind speed definition

- Control level: divided into 5 main blocks, as illustrated in Figure 4.14

1. Filtering, measurements and transformations: filters the voltages and currents measured on the stator and on the grid side, the DC voltage of the capacitor, the reactive power, rotor angle, and angular velocity; there is an intern PLL that maintains the proper frequency balance accordingly to the defined grid voltage; some abc to dq0 frame transformations are made; the active and reactive power are measured at this block;

2. Speed regulator and Pitch control: using the angular velocity as an input it defines an electromagnetic torque command signal;

3. DC chopper: is included as a fail-safe protection mechanism which shorts circuits the output of the system under failure conditions such as overvoltage, using the DC voltage measured and comparing it with pre-set limitation values;

4. Grid-side Converter Control system;

5. Machine-side Converter Control System (or Rotor-side Controls);

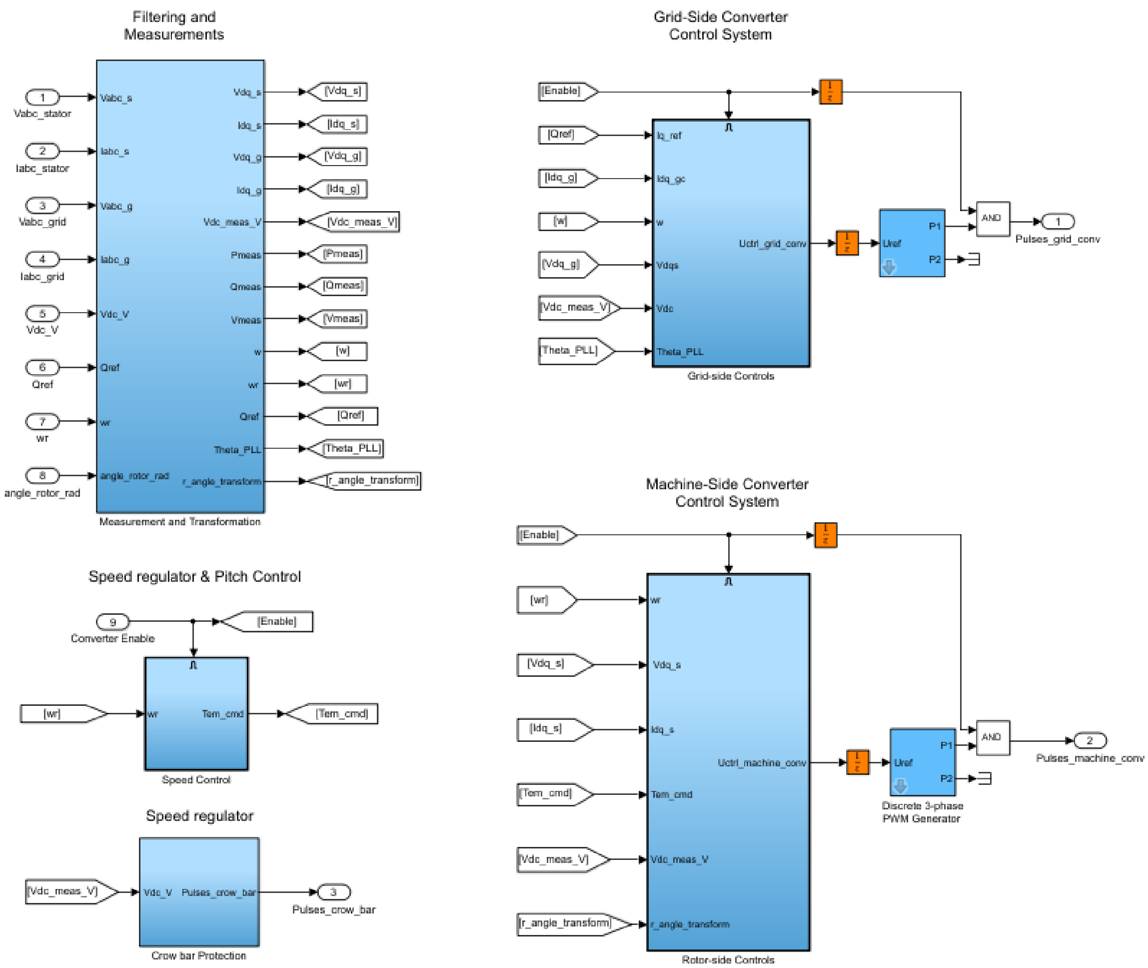

Figure 4.14: Wind turbine control blocks

In order to scale up the wind turbine model, which is composed of only one wind turbine, the turbine model is interfaced with the rest of the network via an equivalent current source, representing a parallel connection of N current sources. At the same time, in order to ensure the proper interaction of the rest of the system with the turbine model, the turbine model is fed via a voltage source modulating the voltage measurement at the full-grid network. This is sketched in Figure 4.15.

$$I^{system} = I^{1WT} * N^{WT} \tag{4.12}$$

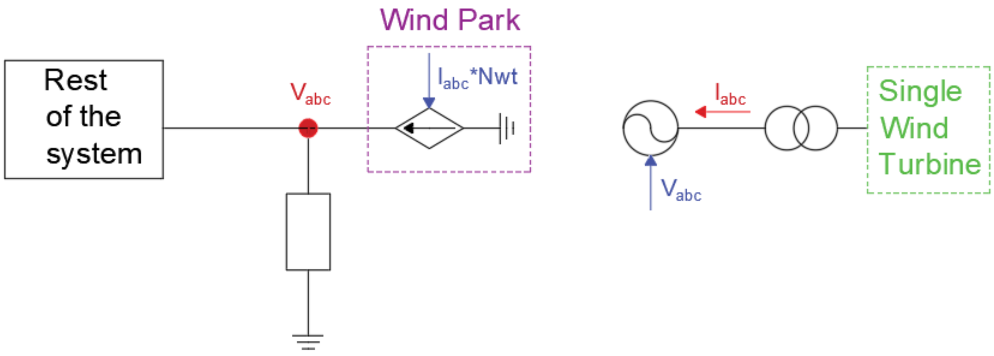

Figure 4.15: Scheme of the Wind Park

This re-adaptation can be seen on Figures 4.16 and 4.17. The measured RMS values of voltages and currents (Vabc_B575 and Iabc_B0) are per unitized and need to be transformed in international system units. Additionally, the input signal on the controlled sources should be phase-to-ground in peak value. In order for this system to work there was the need to define some initial condition and memory blocks, otherwise the system would enter in algebraic loops and go unstable.

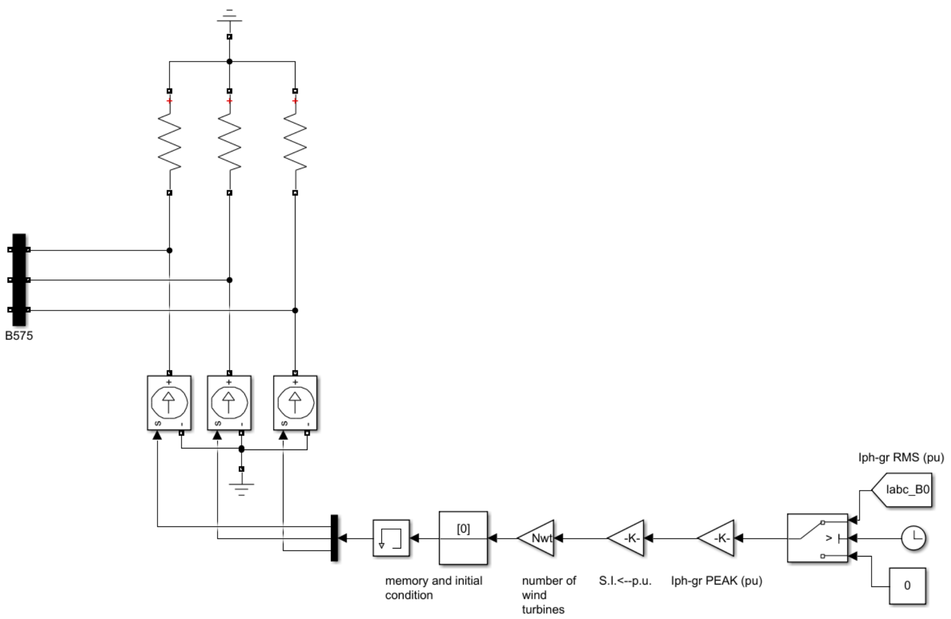

Figure 4.16: System re-adaptation with Current-controlled sources

In Figure 4.16, there is a gain block that defines the number of parallel wind turbines considered for the system. Also, high value resistances in parallel with bus B575 and the current-controlled sources are added to avoid the series connection of a current source with inductive elements because, otherwise, the solver cannot solve the derivative equation of the current through an inductor.

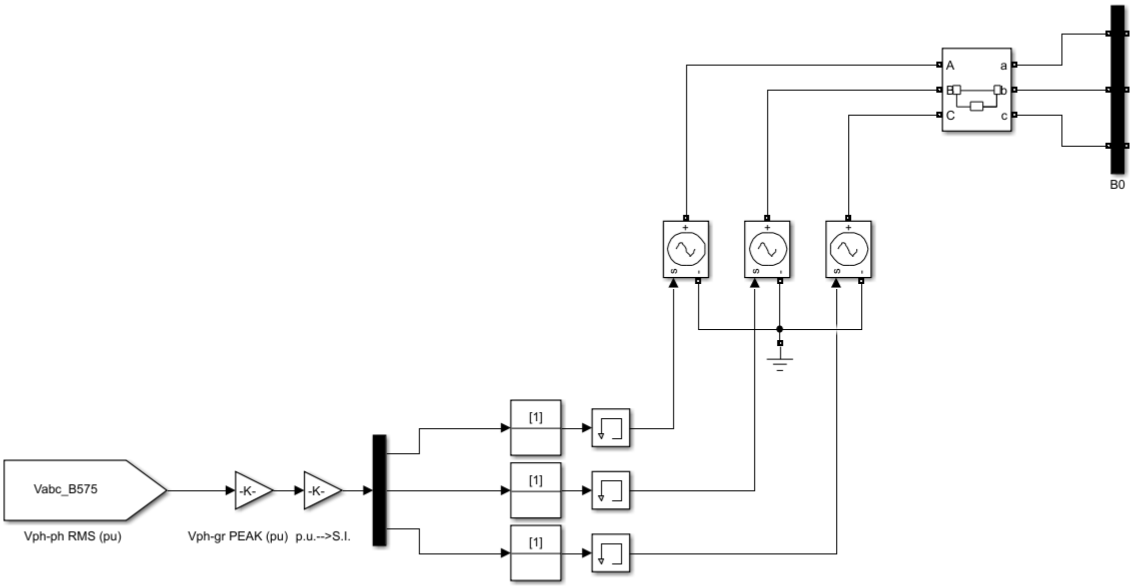

Figure 4.17: Single Wind turbine re-adaptation with Voltage-controlled sources

Figure 4.17 presents the voltage-controlled sources defined in order to keep the voltage of the single wind turbine system the same as the voltage at bus B575.

4.2.2 Tuning Process

For this case, there aren't considered any loads, only the BESS is connected in parallel to the WPP at bus B575 (Figure 4.18) to perform the BS.

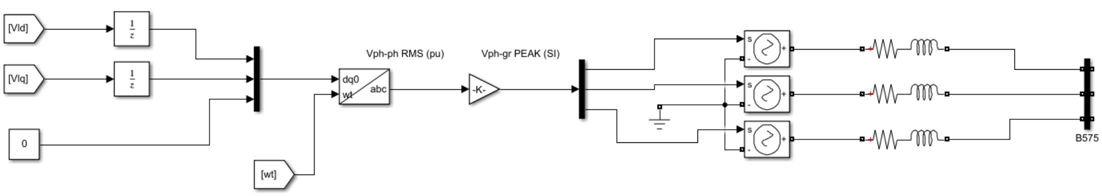

Figure 4.18: BESS connected to the WPP at bus B575

In Table 4.1, the base values considered for this study are indicated. The WPP is considered composed of 10 equal wind turbines in parallel.

Table 4.1: Base values

V_{base} **(V)**	575
N^{WT}	10
S_{base} **(MVA)**	15
f (Hz)	60

To start with, a slack bus is defined, fixing the voltages v_{ld}, v_{lq}, v_{l0} with the values 1, 0, 0, respectively. This is done, for a better understanding of how the entire system behaves, and some of its results can be consulted at Appendix C.1. For instance, if the active and reactive power are analyzed on Figure C.1, it's important to refer that the disturbances mainly present between 5 and 10 seconds are due to the dynamic responses of the wind turbines. It is also observed in Figure C.1 that the active power value is dependent on the wind speed, as it increases as the wind value increases. In this case, a ramp was considered starting with an initial value of 6 m/s, as explained in Table 4.2.

Table 4.2: Initial simulation procedure

t (s)	
0	BESS fixates voltage at 1 pu
1	Current Iabc_B0 is injected into the system
4	Wind speed starts with an initial value of 6 m/s, ramping up with a slope of 6/26 m/s
30	Wind speed reaches and is constrained at a constant speed of 12 m/s
50	Simulation finishes

The results obtained are used as a reference in the tuning process of the PI controllers from the outerloops. As previously explained this procedure was done by adjustment, considering a step applied where the time constant is measured, taking into account that this value should be higher (or physically slower) than the time constant value defined for the innerloops. First, starting just with proportional control and after that using both proportional and integral parameters. In Table 4.3, there is a resume of the most notable values tried out, and those values are used equally on both controllers, since trying different values among the two controllers didn't produce any improvements. Moreover, the v_{zd}^{ref} (Figure B.4) value was fixed with constant 1, so that this situation is similar to the slack bus.

Table 4.3: Tuning process of the PI controllers for the outerloops

Case	**P**	**I**	
1	1	-	stable
2	0.5	-	unstable
3	2	-	better response than case 1
4	2.5	-	unstable
5	2	2	unstable
6	2	5	better response than case 3
7	2	10	better response than case 6
8	2	12	unstable

The more approximate responses (Appendix C.2) obtained correspond to the considered case 7 in Table 4.3, with the controller's proportional and integral values of 2 and 10, respectively.

4.2.3 Start-up

The process of energizing the grid comprehends the need to energize the inductances and capacitances up to the voltage level. In a BS this is starting from zero, considering a completely unloaded system, and the voltage should go up to the operating point stably. During the energization, the grid-forming component needs to provide the necessary reactive power to energize the different electromagnetic components.

There are some points relevant to mention, as this energy storage is considered ideal, its dynamics aren't fully taken into consideration. Nevertheless, the scope is to focus on the converter and study how everything should be controlled during the BS. Another important point to be considered is the strategy implemented of changing the voltage at different places in order to use the same voltage.The ramping up strategy of the voltage is used to avoid transformers from entering in saturation. Later, this topic will be discussed when the loads are represented on the full system.

4.3 Loads

In this work, the loads considered are typically PQ constant loads and an asynchronous induction machine (AIM). Also, a transformer is considered between the power system and the AIM.

During a start-up equipments as transformers and induction machines present a high power demand. For instance, the inrush currents of transformers and the need for the initial high energizing process are the main reasons for this power demand. In this situation, the performing of a black-start needs to handle the "cold load pickup" in terms of both active and reactive power.

An abrupt change in voltage applied to the terminals of a transformer can drive the core into saturation. These voltage changes may be caused by switching operations, external fault or fault clearances, or in the energizing process. When saturated, a transformer can draw a current that can be several times higher than the nominal current. The most severe saturation occurs during energizing processes, where the currents absorbed by the transformer are called inrush currents [90], a transient current up to 10 to 15 times larger than the rated transformer current can flow for several cycles. Converters may need to inject all that current being required to compensate for all the disturbances, as a consequence, those are exposed to such large over-current events. This is a problem, since these elements are limited to their physics and power electronics which can't cope with those currents.

For the PQ loads models blocks of RL parallel loads are used. Its active and inductive reactive power consumption is defined by a given percentage of the total system power base. The induction machine model considers a pre-set squirrel-cage rotor model of Simulink with the characteristics specified on Table 4.4. The considered input is based on the torque applied, in pu.

Table 4.4: Induction Machine parameters

Nominal Power (MVA)	2.2
V^{ph-ph} **(V)**	575
f (Hz)	60
Pole pairs	2
Stator Resistance (pu)	0.01117
Stator Inductance (pu)	0.04832
Rotor Resistance (pu)	0.006
Rotor Inductance (pu)	0.04832
Mutual Inductance (pu)	2.424

There are breakers between the grid and the PQ loads, and the induction machine, where the time of connection is defined. Additionally, in the case of the induction machine, there is the need to use a transformer between it and the grid, as illustrated in Figure 4.19. Also, high-value resistances (around 1 kΩ) are put in parallel between the transformer and the machine.

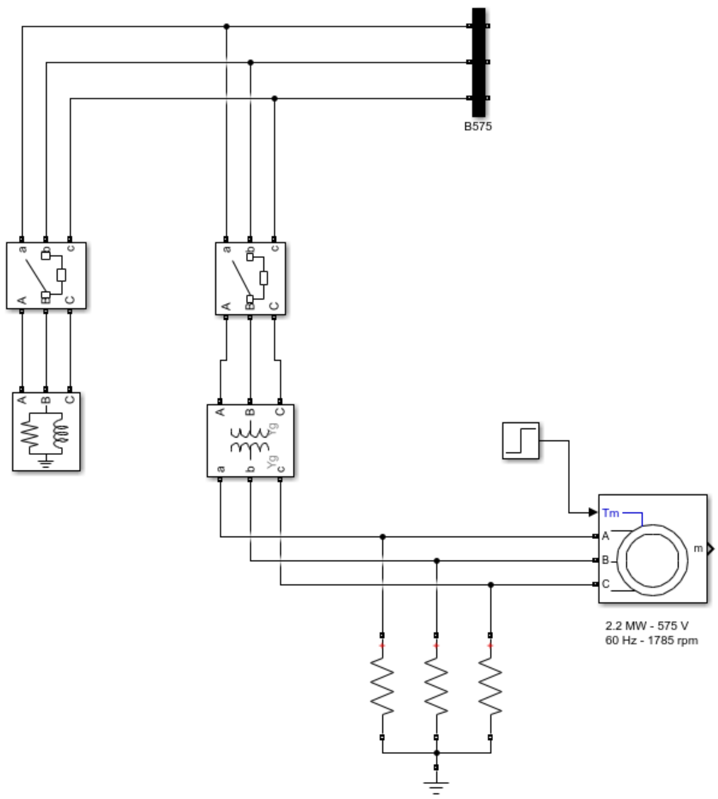

Figure 4.19: Loads

Chapter 5

Results

The objective of this chapter is to validate the feasibility of BS by means of the BESS. It will be proved that the BESS is able to combine the operation of the WPP with the loads, while ensuring balance on the transients that occur during the energization.

The results obtained consider the sequence of events indicated in Table 5.1, keeping in mind that the loads are just starting to be connected gradually after the voltage finishes to ramp-up, with a value of 1 pu. The loads are defined in Table 5.2 in percentage of the energy storage S_{base} specified in Table 5.3, and are connected at specific times, in order to keep the system's balance. The WPP is assumed to be composed of 10 wind turbines in parallel, with a total power of 15 MVA. Thus, a few things are changed in comparison to the tuning process. For instance, to provide better results, with less disturbance, in the beginning, the wind speed is fixed at a constant speed of 12 m/s. The reactive power reference value for the WPP now considers a voltage controller on every turbine, so that will compensate for any reactive power mismatch. The voltage in BESS's controller is defined as a ramp to make the process smoother and more realistic. The transformer among the grid and the induction machine can saturate during the simulation.

Table 5.1: Simulation procedure

t (s)	
0	BESS starts to ramp up voltage on the WPP starting from 0, with a slope of 0.25 pu/s Wind speed fixed at 12 m/s (constant)
4	Voltage reaches 1 pu and is constrained to this value
4.2	WPP starts to feed by means of current Iabc_B0, injected into the system Load1 is connected
5.2	Load2 is connected
6.2	Load3 is connected
7.2	Load4 is connected
7.7	Load5 is connected
8.2	Load6 is connected
9.2	Induction machine is connected, with Torque=0 pu
11.5	Induction machine is operating at nominal values (Torque=1 pu)
15	Simulation finishes

Table 5.2: PQ loads defined in percentage of S_{base}

Load	**P**	**Q**
1	0.5	0.05
2	0.55	0.05
3	0.5	0.05
4	0.5	0.05
5	0.5	0.05
6	0.1	0.05

Table 5.3: Base values for complete system

V_{base} **(V)**	575
N^{WT}	10
S_{base} **(MVA)**	4.5
f (Hz)	60

5.1 Power Balance

The first part of this energization is to build the voltage on the WPP. The BESS is in charge of this process, ramping it up until 1 pu after 4 seconds at bus B575, as previously explained on 4.2.1. At this part, the power balance of the system will be checked.

In Figure 5.1 is possible to see this ramp, and then at 4.2 seconds there is the first peak related to the connection of the first load. The several peaks detected correspond to the connection of the different loads, the connection of the induction machine, and to the applied torque. After a few seconds the system returns to the set value of 1 pu.

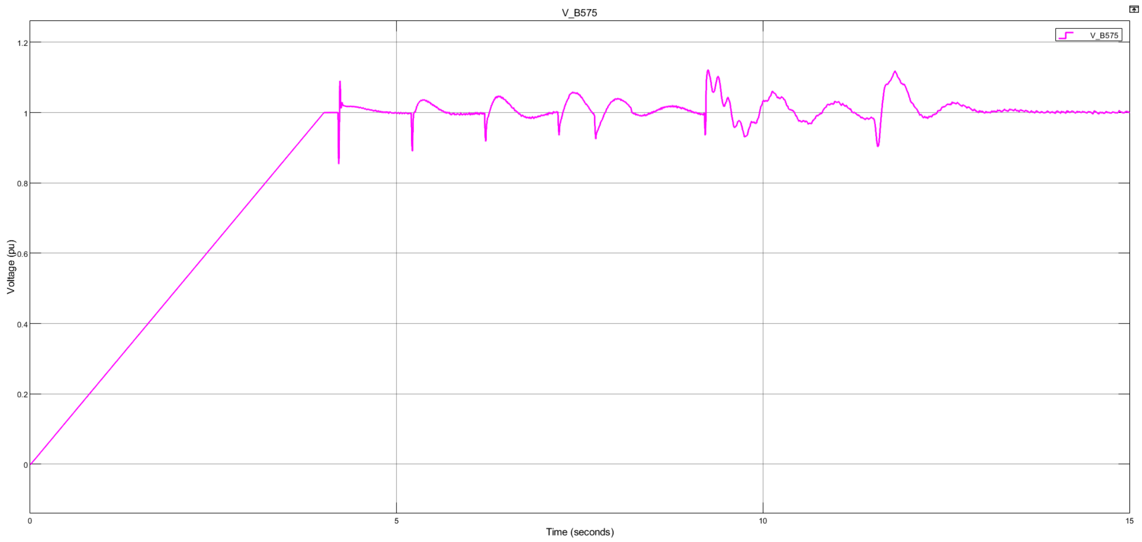

Figure 5.1: Voltage magnitude at bus B575 (pu)

The Wind Park is mainly responsible for providing the active power demanded by the loads. In Figure 5.2 it's represented the active (red) and reactive (blue) powers going from the WPP to the loads. The active power increases as the loads are connected, in this case, this value is negative due to the convention assumed. As previously explained this must be done slowly, and the power balance needs to be maintained, otherwise, the system will go unstable.

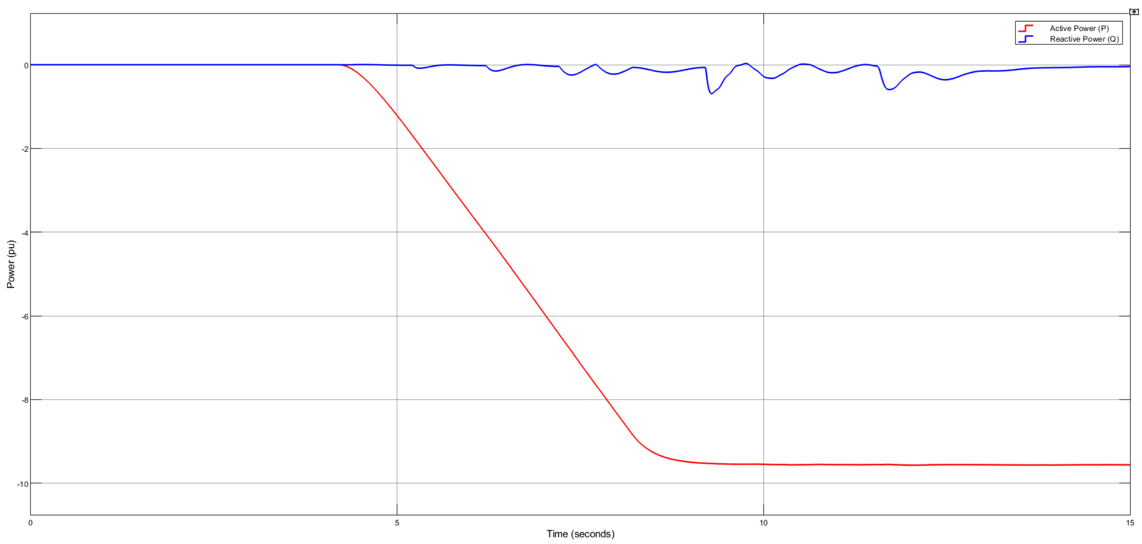

Figure 5.2: Active and Reactive power provided by the WPP

Considering the six PQ constant loads and the motor operating at nominal values, this results on total active power need of around:

$$\sum P_i = 4.5 * (0.5 + 0.55 + 0.5 + 0.5 + 0.5 + 0.1) + 2.2 = 11.925 + 2.2 = 14.125MW$$

The WPP can provide a value of 15 MW, and if the graphic above is analyzed, the active power stabilizes at a value of around -9.5 pu. This value is not referred to the power base previously defined, but actually to the rated power of a single turbine, which is 1.5 MVA, resulting in a total of:

$$P_{WPP} = |-9.5| * 1.5 = 14.25MW$$

Additionally, some reactive power is also provided, predominantly when the motor is connected.

The graph in Figure 5.3 points one of the most important features of using an energy storage system, and advantage of this hybrid operation. Notice that when the value is positive means that the BESS is providing energy, when it's negative it's absorbing, this again is due to the convention used for the circuit.

The first two peaks correspond to the connection of the first two loads, determining that the BESS was providing the extra active power demanded, since the wind park hadn't reached the necessary values. This fast response is crucial and contributes to the system's stability. The BESS is requested again to provide active power when the induction machine is connected at 9.2 seconds, and when the torque is applied at 11.5 seconds. After that, the BESS is absorbing the difference between the active power demanded by the loads and the extra provided by the WPP. Another subject worth mentioning is the fact that the power, provided or absorbed, doesn't surpass the defined limit of 4.5 MW, this was achieved due to the controlled connection times of the loads.

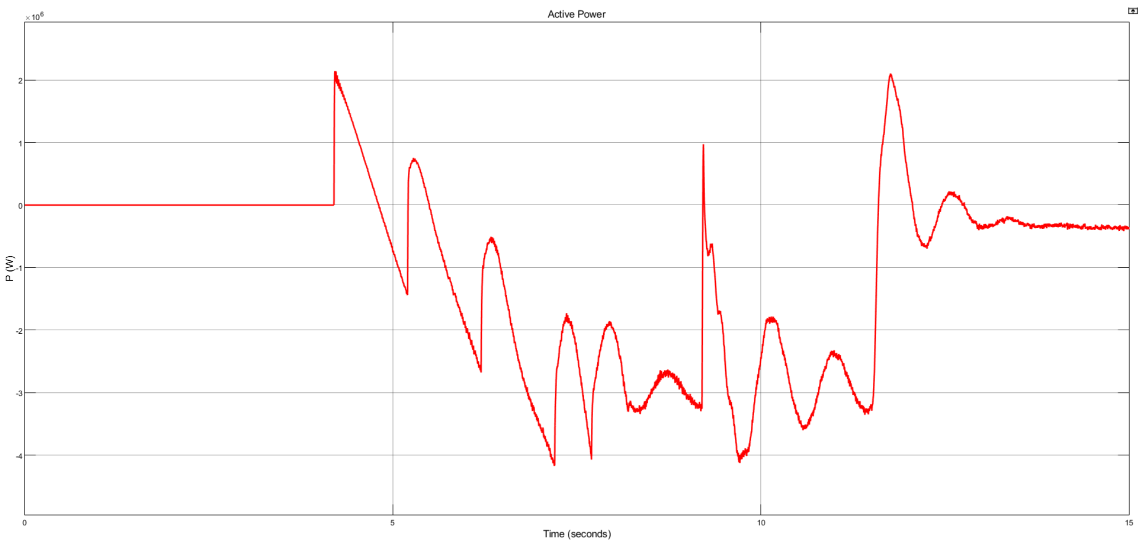

Figure 5.3: Active power measured on the BESS

Figure 5.4 is related to the reactive power, mainly provided by the BESS. This value is increasing as more loads are being connected, still there are some disturbances because of the system's dynamics. The total value required considers the pre-determined PQ loads and any reactive power needed by the induction machine.

$$\sum Q_i = 4.5 * 0.05 * 6 + Q_{AIM} = 1.35 + Q_{AIM} Mvar$$

This value is around 2.5 Mvar as can be noted when it stabilizes.

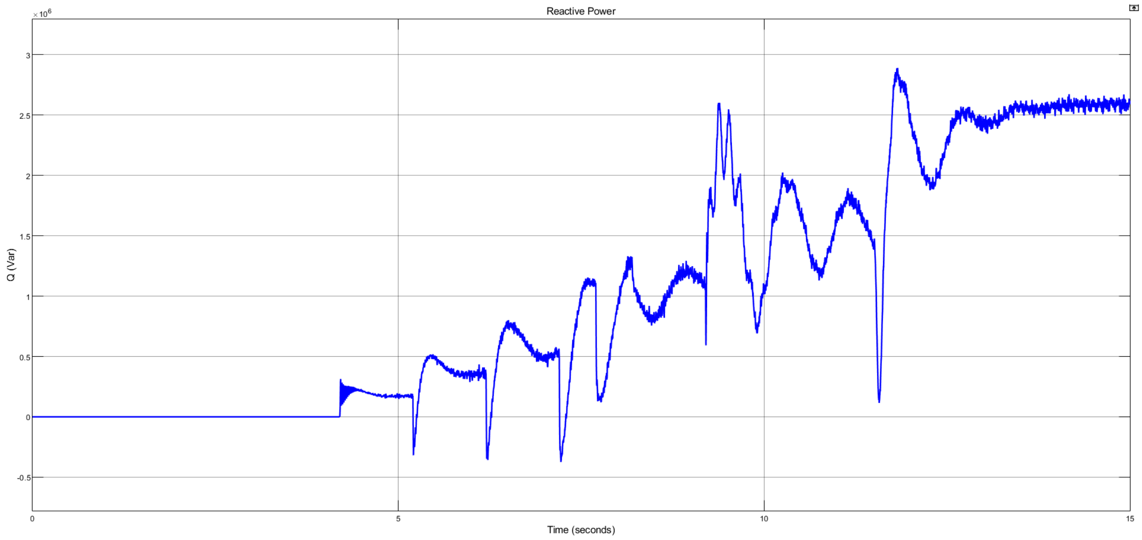

Figure 5.4: Reactive power measured on the BESS

The next graphs (Figures 5.5, 5.6, 5.7) are related the the induction machine, which should be operating as a motor.

In Figure 5.5 the rotor speed is represented. Until the breaker closes, this value is fixed at constant 1, when the machine is connected to the system there's a notable disturbance occurring, eventually tending to 1 again, since it's operating with no load. After the torque step is applied a new disturbance happens, and the machine speed will decrease and stabilize at a new operating point.

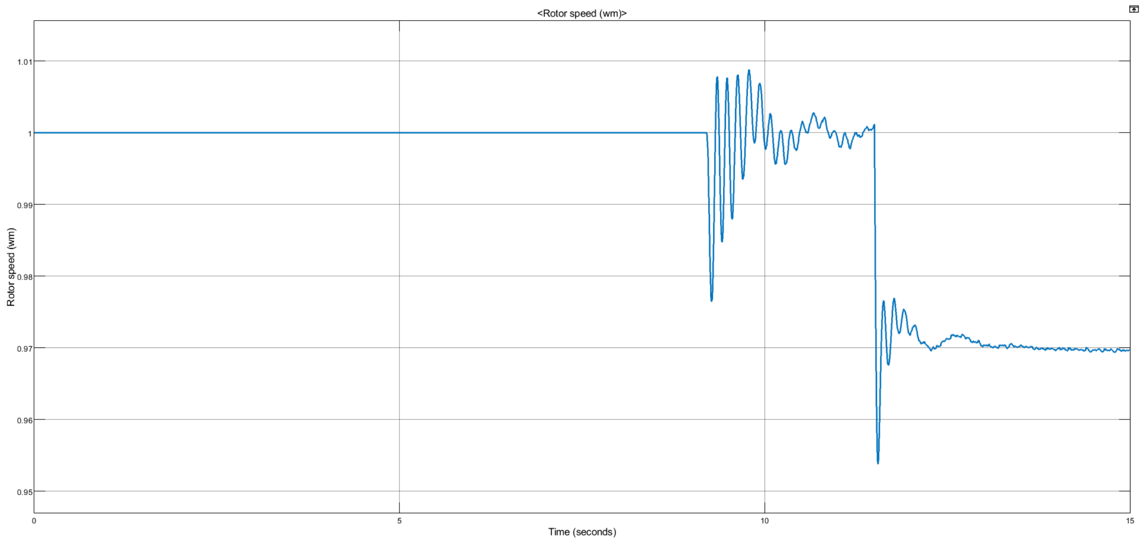

Figure 5.5: Rotor speed of the AIM

Figures 5.6 and 5.7 represent the active and reactive power required by the induction machine, respectively. For the active power, the value is around the 2.2 MW determined for the nominal operation point, after 11.5 seconds when the torque is applied. As for the reactive power, the necessary value is about 1.2 Mvar, confirming the total values previously noted. Thus, the balance of the system is guaranteed by the joint operation.

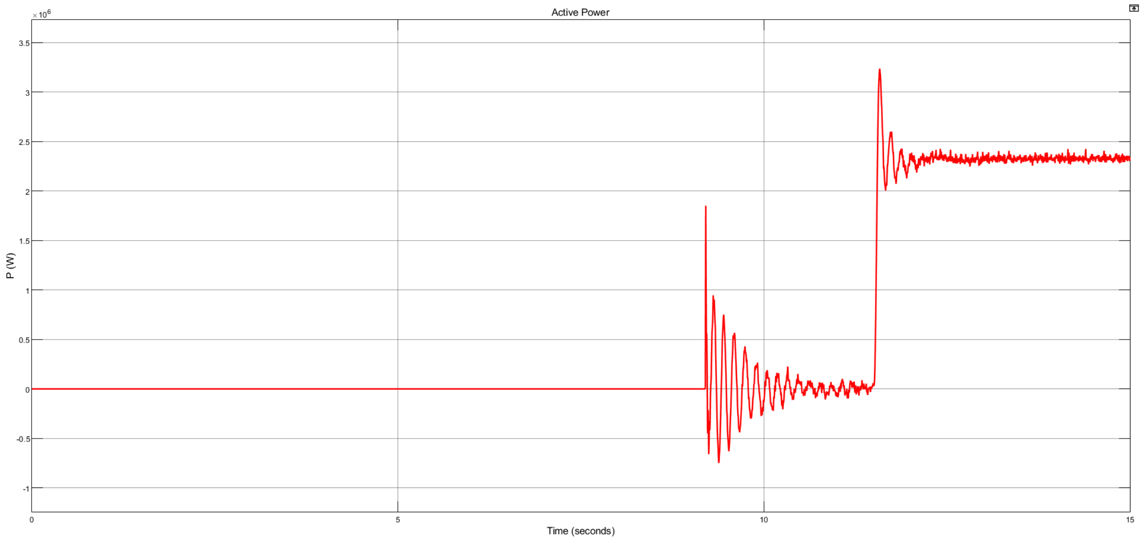

Figure 5.6: Active power demanded by the AIM

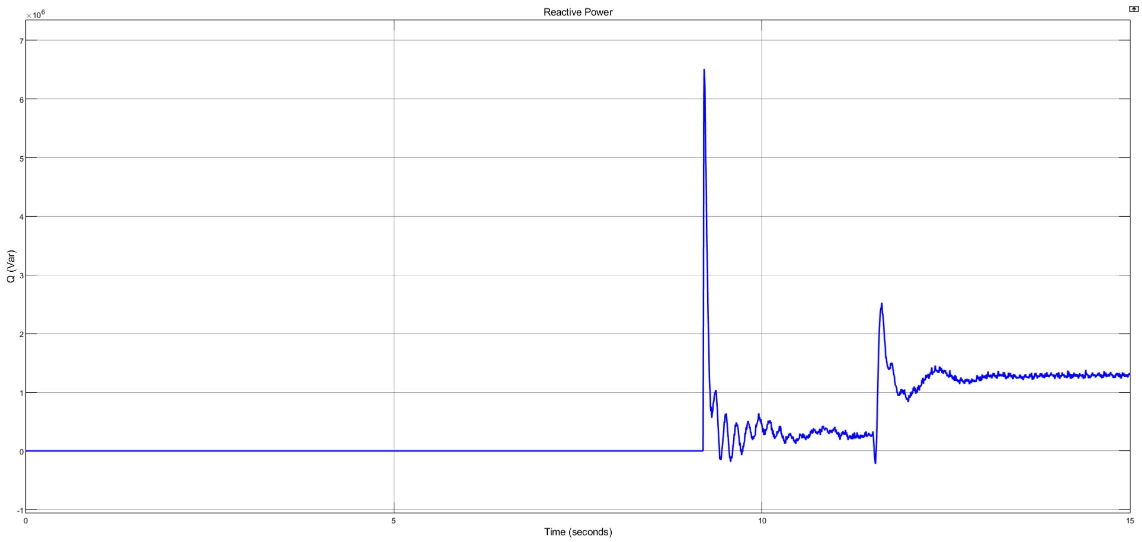

Figure 5.7: Reactive power demanded by the AIM

5.2 BESS

At this point, some results will be show regarding the controller, proving that the reference points set are being followed. For instance, the graph in Figure 5.8 shows the voltage ramp (dotted red) defined in the outerloop, being followed by the voltage signal (blue) - v_{zd} - measured, that can recover after the disturbances provoked by the loads. This voltage magnitude doesn't surpasses 10%, a reference limit value suggested by the National Grid on Table 2.2.

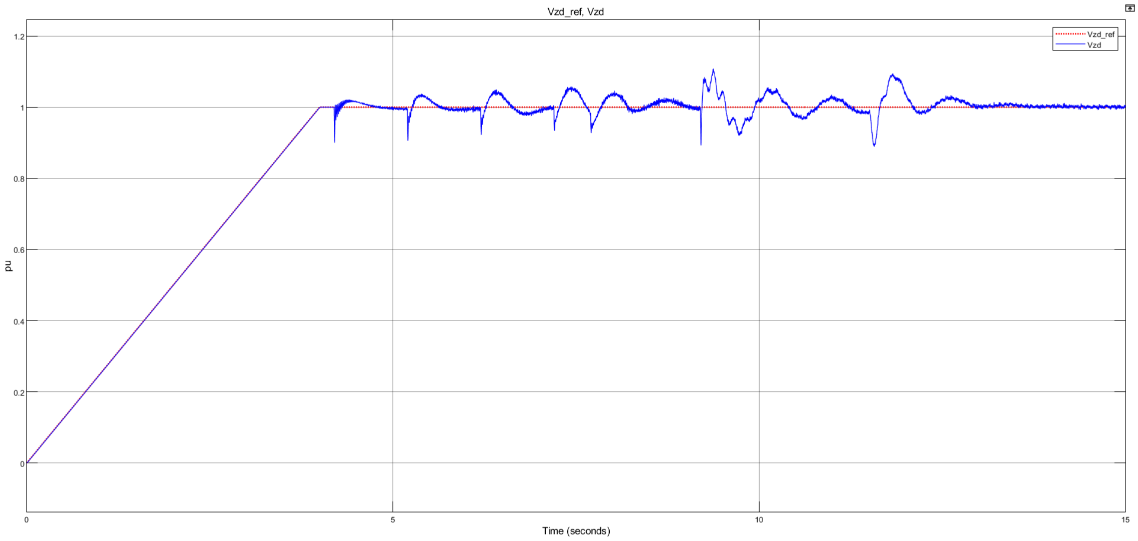

Figure 5.8: Voltage magnitude defined (pu) (v_{zd}^{ref}, v_{zd})

Figure 5.9 provides the current reference value (dotted red) that enters the inner loop, and the current i_d. Notice that this value is positive when the BESS is providing, and negative when its absorbing, according to the same logic as the active power graph of Figure 5.3.

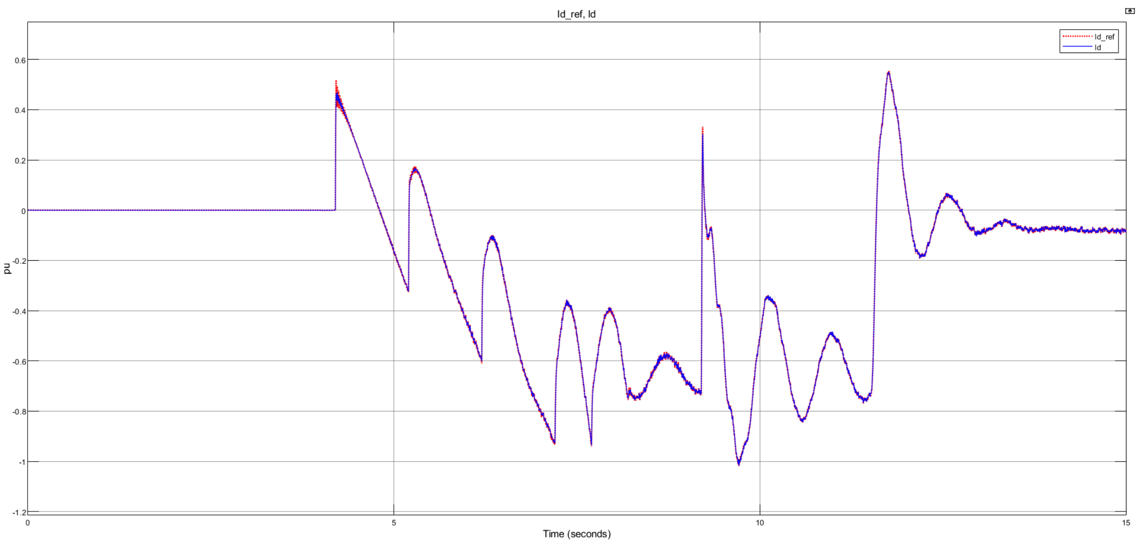

Figure 5.9: Current (pu) (i_d^{ref}, i_d)

One important thing to care is that those peak values doesn't exceed 1 pu. Otherwise, these value should be limited, in order to protect the power electronic converter. This could be achieved by considering saturation on the input signals (i_d^{ref}, i_q^{ref}) on the current controller inner loop.

Chapter 6

Conclusions and Future Work

In this chapter, the conclusions obtained during the execution of this work are pointed out, and some future works are suggested.

6.1 Conclusions

In this dissertation, it was developed a model of a PCS composed by a Wind Farm and some loads, in order to perform a black-start. A BESS is initial providing the necessary voltage to start the Wind Farm. This is done in islanded mode, assuming an unique bus.

In the literature, there are several works regarding virtual synchronous machine, mainly for the operation on weak grids, although, the current control is being avoided in most cases. Generally, a high short-circuit ratio impedance of the grid is defined, and due to the Thévenin, the currents on the converter are limited. Nevertheless, those assumptions are not correct for BS procedure, as those elevated currents can't be ignored, since the physics of power electronics converters can't cope with them.

In this work, a grid-forming strategy was implemented considering a current loop controller. Therefore, breaching the gap of grid-forming functionality together with the suitability of current controller enabling the safe operation of power electronics. This type of controller permits the decoupling and independent control of the d and q components.

As demonstrated by the results the BESS can effectively contribute to the early stage of energization after a blackout, additionally maintaining grid stability. Besides being able to build the necessary voltage to restart the WPP, its fast dynamic response is crucial to maintain the power balance. For instance, as the loads are starting to be connected, the BESS can provide the active and reactive power to compensate for any mismatch between generation and demand, of course within certain limits. During the restoration process, the BESS can either function as source of demand or generation, depending on the needs of the Power Island. The results obtained highlight some of the advantages summarized in Tables 2.8 and 2.9.

This is very important, as it can make the process of BS faster, ultimately reducing the time during power outages, and their inherent armful socioeconomic effects. Moreover, with the increasing RES generation and considering its inclusion in the BS process, this hybrid operation demonstrated that can tackle some of the challenges previously mentioned, presenting a serious opportunity to stakeholders to participate on this remunerated service.

So far there's the generic thought that BS can only be enabled by conventional generators, such as depicted by the National Grid, by means of short-circuit currents, or inertia requirements,e.g., in Table 2.2. However, this dissertation shows that inverter-based technologies are capable of performing BS, and thus requirements could be more technologically independent, allowing other technologies to provide these services.

6.2 Further Work

Future works, should take in considerations an optimal sizing of ESS to explore those capabilities. One particular feature that should be added and analyzed is the possibility of limiting the current controller. One of the most challenging event, during energization, are the overcurrents involved, due to the electromagnetic elements. In this case study, this process was controlled and took that in consideration. Nevertheless, this is in general one of the most difficult obstacle to deal with.

In this work, an infinite ideal source for the BESS was considered. In the future, it would be important to consider a non-ideal system, that considers the dynamics of the ESS. As an example, it could be considered for the battery an electrical model like the one pointed at 3.3.5. That way, the model would be more realistic, and some functional parameters, such as the state of charge, or the charging/discharging rating could be studied.

Finally, different types of control strategies that consider current controller could also be explored.

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Appendix A

Other types of Energy Storage

A.1 Pumped Hydro storage

Pumped storage is by far the largest form of grid energy storage. As of 2020, the US Department of Energy's Global Energy Storage Database reports that PHS accounts for approximately 95% of all active tracking energy storage devices in the world. The total installed throughput capacity exceeds 181 GW. [referencia]

Pumped-storage hydroelectricity is a method of storing and producing electricity to supply high peak demands by moving water between reservoirs at different heights. At times of low electricity demand, excess power generation capacity is used to pump water into higher reservoirs to store energy for later use. When there is a higher demand, the water is released back to the lower reservoir through the turbine to generate electricity.

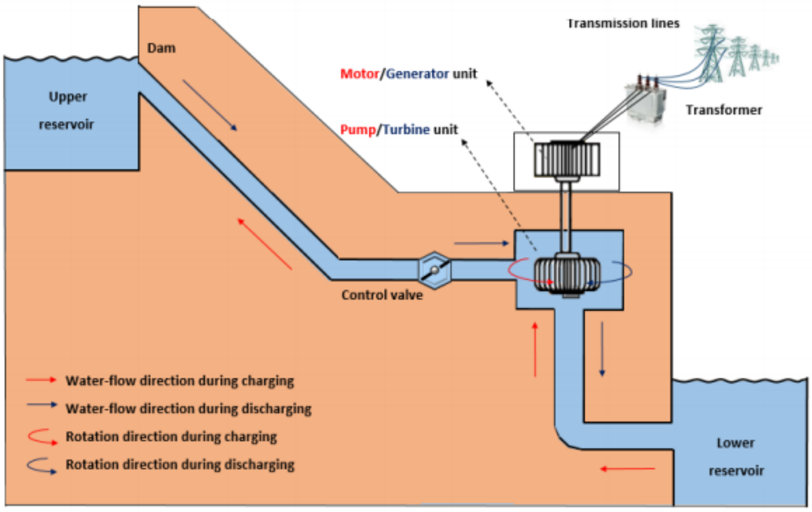

Figure A.1: Schematic diagram of pumped hydro storage plant [55]

Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70–85% of the electrical energy used to pump the water into the elevated reservoir can be regained. Currently, this technology is the most cost-effective means to store large amounts of electrical energy on an operational basis.

Along with energy management, pumped storage systems help control electrical grid frequency and provide reserve generation. For instance, thermal plants are much less able to respond to sudden changes in electrical demand, potentially causing frequency and voltage instability. Like other hydroelectric power plants, pumped storage power plants can respond to load changes within a few seconds, flattening out those variations [91].

PHS presents several advantages due to the flexibility, reliability, and safe operation provided, adding that is a non-polluting source of energy and renewable. Nevertheless, the construction of a hydroelectric power plant requires a large investment and the need for proper geographical conditions, as large variations in height or water availability are needed. Mainly, during the construction phase, it brings numerous environmental consequences, as for interventions in nature due to damming of water, changing water flow, and the construction of roads and power lines. Finally, droughts can potentially affect this, since electricity generation and energy prices are directly related to how much water is available [92].

A.2 Flywheels

Flywheels can be described as a mass that rotates around an axis. In those systems, electricity powers an electric motor that spins and increases the speed of the flywheel, thereby converting electrical energy into kinetic energy, which is proportional to the rotor inertia of the flywheel and the square of its angular velocity [93]. If the system demands more energy, the flywheel starts working as a generator, slowing down through the deceleration torque, therefore retrieving the stored kinetic energy into the electric motor [94].

Flywheels can provide both high energy and power density for short duration discharges, offering high rates of charge and discharge for extended life cycles. Nevertheless, in order to store energy in an electrical power system, a large-capacity flywheel is required, which results in increased friction losses and reduced efficiency, compromising its application for long-term storage. In addition, the high investment costs and security issues associated with this technology make them unclear for large systems [95].

A.3 Regenerative Fuel Cells

A fuel cell is an electrochemical device that converts a suitable fuel (typically hydrogen) into electrical energy [96].

Hydrogen is provided through the process of electrolysis of the water, in which electricity splits water into its simplest components of H and O_2. After that, hydrogen is fed to the negative electrode of the fuel cell, reacting with the oxygen of air, and producing water and electricity, which can be recycled and reused to produce more hydrogen.

These cells are similar to batteries, since they both contain two electrodes separated by an electrolyte. Nevertheless, they do not store electricity by recharging and the fuel has to be produced externally [55].

Regenerative fuel cells are devices that combine the function of a fuel cell and electrolyzer into one device, and can be characterized as long-term EES devices, as they offer an elevated specific energy accounted and a good cycle capability. However, hydrogen presents several difficulties on accommodation and transportation, besides liquid hydrogen being very expensive. For now, the range of application should be limited for stand-alone renewable energy systems [55, 9].

Appendix B

Auxiliary Content for the BESS Model

B.1 Park Transform

The Park transform is a space vector transformation of three-phase time-domain signals from a stationary coordinate system, abc, to a rotating coordinate system dq0. The transform applied to time-domain voltages or currents, considering an a-phase aligned with the d-axis, is implemented using the following equation:

$$\begin{bmatrix} r_d \\ r_q \\ r_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} cos(\theta) & cos(\theta - \frac{2\pi}{3}) & cos(\theta + \frac{2\pi}{3}) \\ -sin(\theta) & -sin(\theta - \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} r_a \\ r_b \\ r_c \end{bmatrix} \tag{B.1}$$

The angle $\theta = \omega t + \delta$ is the angle between the rotating and fixed coordinate system at time t and δ is the initial phase shift of the voltage. Note that for a balanced system the 0-component must be zero.

The inverse transformation from the dq0 frame to the abc frame is obtained by:

$$\begin{bmatrix} r_a \\ r_b \\ r_c \end{bmatrix} = \begin{bmatrix} cos(\theta) & -sin(\theta) & 1 \\ cos(\theta - \frac{2\pi}{3}) & -sin(\theta - \frac{2\pi}{3}) & 1 \\ cos(\theta + \frac{2\pi}{3}) & -sin(\theta + \frac{2\pi}{3}) & 1 \end{bmatrix} \begin{bmatrix} r_d \\ r_q \\ r_0 \end{bmatrix} \tag{B.2}$$

Considering the instantaneous power theory in the synchronous reference frame for a steady-state, balanced, sinusoidal condition, the apparent power is given by:

$$\underline{V}^{dq} = \frac{v_d + jv_q}{\sqrt{2}} \tag{B.3}$$

$$\underline{I}^{dq} = \frac{i_d + ji_q}{\sqrt{2}} \tag{B.4}$$

Based on the two previous equations the power of a three phase system yields

$$\underline{S} = P + jQ = 3\underline{V}^{dq}(\underline{I}^{dq})^* = 3(\frac{v_d + jv_q}{\sqrt{2}})(\frac{i_d - ji_q}{\sqrt{2}}) \tag{B.5}$$

Rearranging equation B.5, active and reactive power can be expressed as;

$$\begin{cases} P = \frac{3}{2}(v_d i_d + v_q i_q) \\ \\ Q = \frac{3}{2}(-v_d i_q + v_q i_d) \end{cases} \tag{B.6}$$

B.2 Phase-Locked Loop (PLL)

A Phase-Locked Loop is used to determine the angle and the angular velocity of the electrical network. A three-phase PLL consists in a feedback of the q-axis voltage component filtered by a PI controller. The output of the controller corresponds to the angular velocity of the electrical grid and the integration of this signal corresponds the grid angle. A scheme of the PLL is illustrated in Figure B.1.

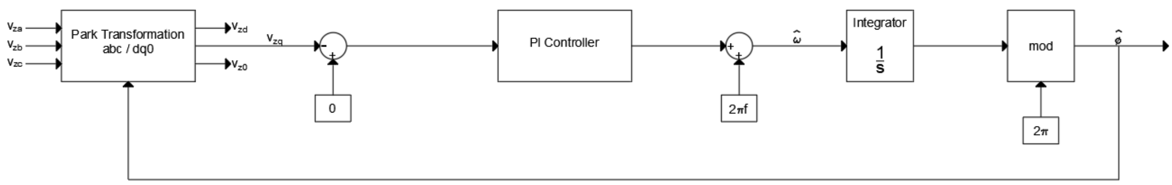

Figure B.1: Schematic of the PLL

The PI controller is defined by the following expression:

$$G_C(s) = \frac{K_p s + K_i}{s} \tag{B.7}$$

The proportional and integral parameters are tuned for proper results. Additionally a "mod" block is needed to limitate the angle aforementioned between 0 and 2π.

B.3 Voltage Equations in the dq-frame

In order to obtain the voltage equations, it is considered the equivalent model of the AC side of the VSC converter, illustrated in Figure B.2.

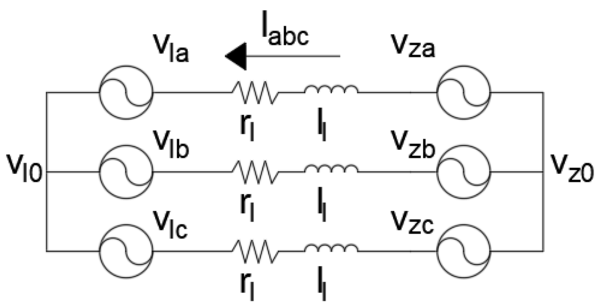

Figure B.2: Equivalent model of the AC side of a VSC

The voltage equations can be described in matrix form as

$$\begin{bmatrix} v_{za} \\ v_{zb} \\ v_{zc} \end{bmatrix} - \begin{bmatrix} v_{la} \\ v_{lb} \\ v_{lc} \end{bmatrix} - (v_{l0} - v_{z0}) \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} r_l & 0 & 0 \\ 0 & r_l & 0 \\ 0 & 0 & r_l \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} l_l & 0 & 0 \\ 0 & l_l & 0 \\ 0 & 0 & l_l \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{B.8}$$

where v_{zi} and v_{li} are the three-phase instantaneous voltages from the grid and the converter in the abc-frame, respectively. The inductance equivalent resistance is represented by r_l, and l_l is the inductance value. $v_{l0} - v_{z0}$ is the voltage difference between the converter and the grid neutral. For instance, when there is not neutral conductor, or it is connected to the ground, it can be stated that:

$$v_{l0} - v_{z0} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \end{bmatrix} (v_z^{abc} - v_l^{abc}) \tag{B.9}$$

Moreover, for three wire balanced systems, $v_{l0} - v_{z0} = 0$ and $i_0 = 0$.

Applying the Park transformation to B.8, it results on the following

$$\begin{bmatrix} v_{zd} \\ v_{zq} \end{bmatrix} - \begin{bmatrix} v_{ld} \\ v_{lq} \end{bmatrix} = \begin{bmatrix} l_l \omega_e & r_l \\ r_l & -l_l \omega_e \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & l_l \\ l_l & 0 \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \tag{B.10}$$

B.4 Other components of the BESS model

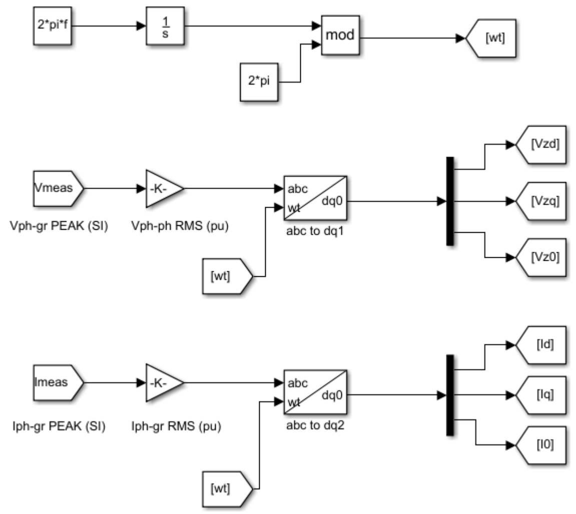

Figure B.3: Voltage and currents abc to dq0 transformation

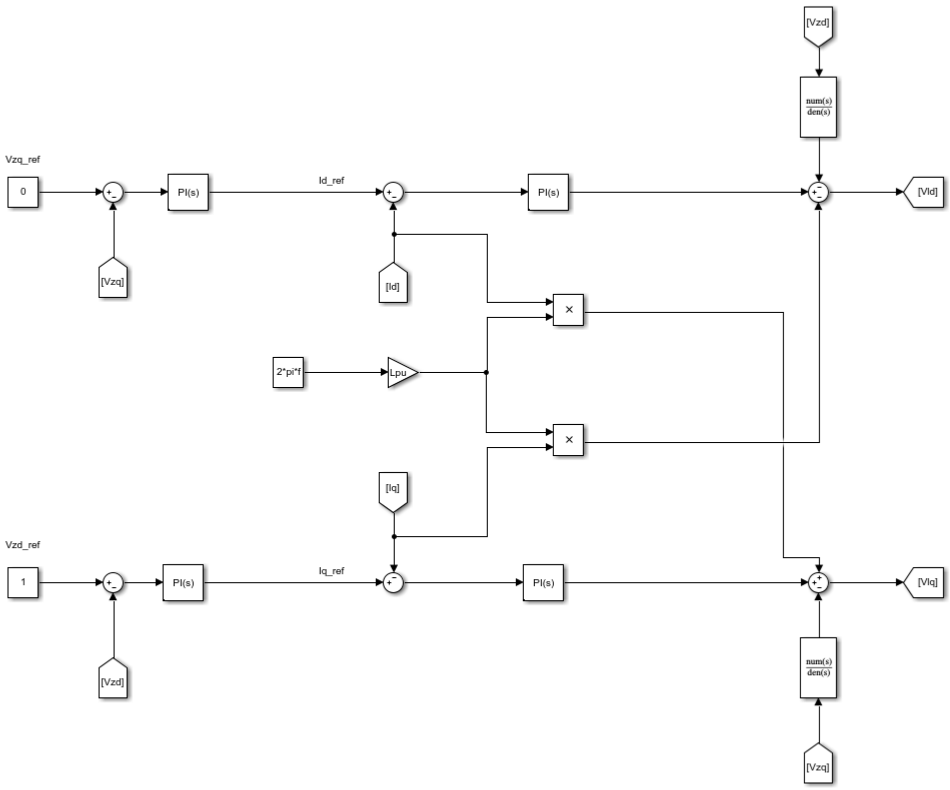

Figure B.4: Current loop controller

Appendix C

Auxiliary Results

C.1 WPP start-up considering slack bus (no loads)

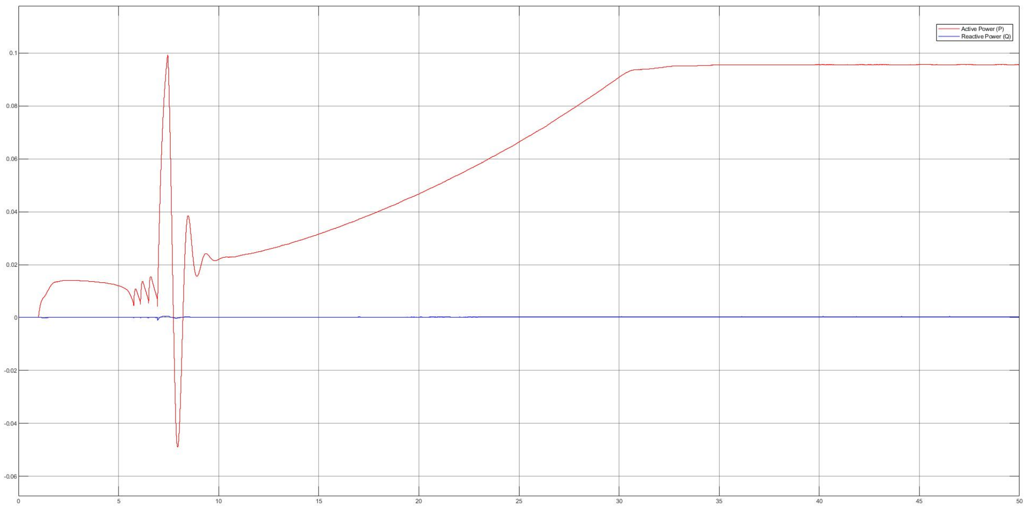

Figure C.1: Active (P) and Reactive (Q) of the system, considering a slack bus

C.2 WPP start-up considering the VCO (no loads)

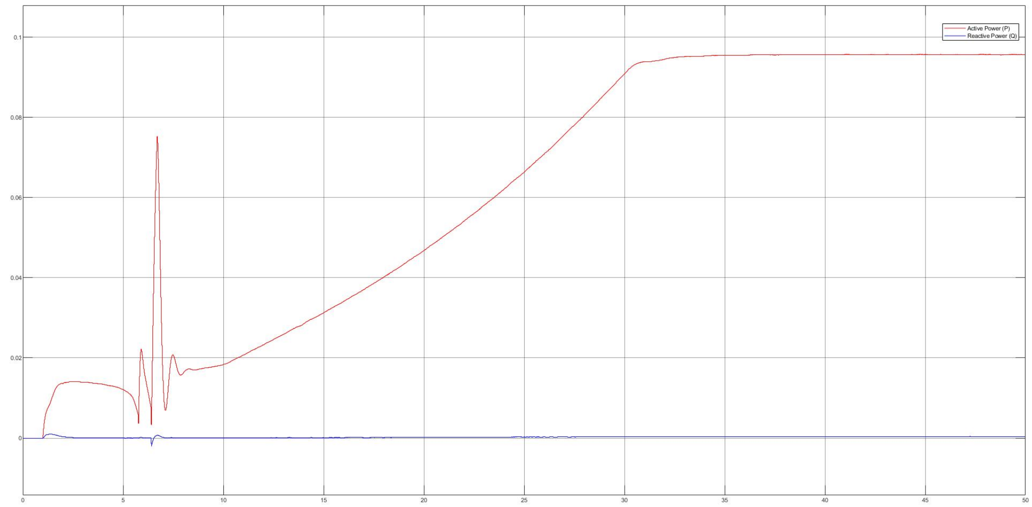

Figure C.2: Active (P) and Reactive (Q) of the system, considering both P=2 and I=10

C.3 Voltages and Currents measured on the BESS in the Full System

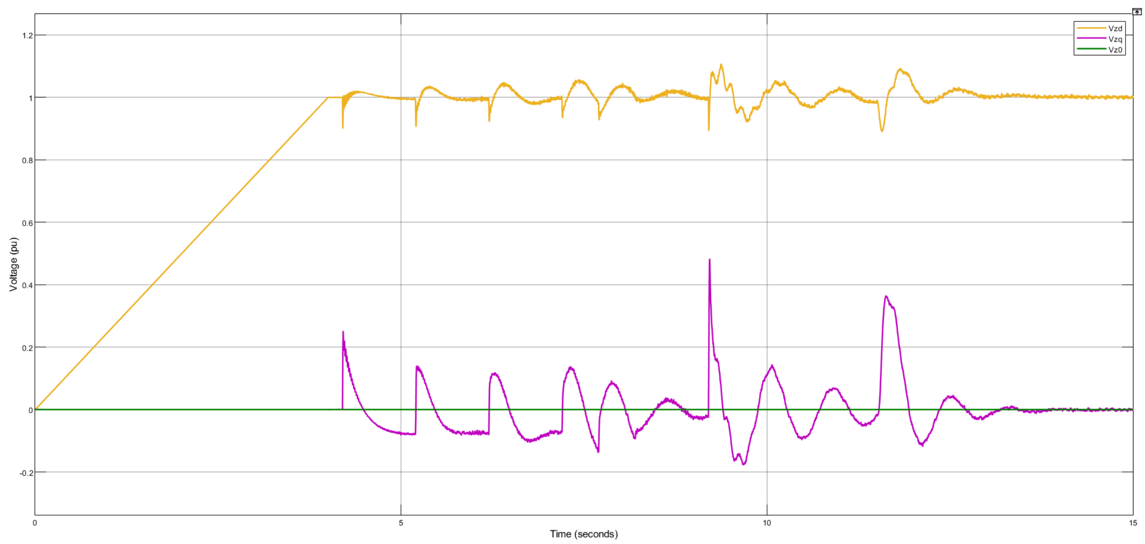

Figure C.3: Voltages (pu) measured on the BESS (v_{zd}, v_{zq}, v_{z0})

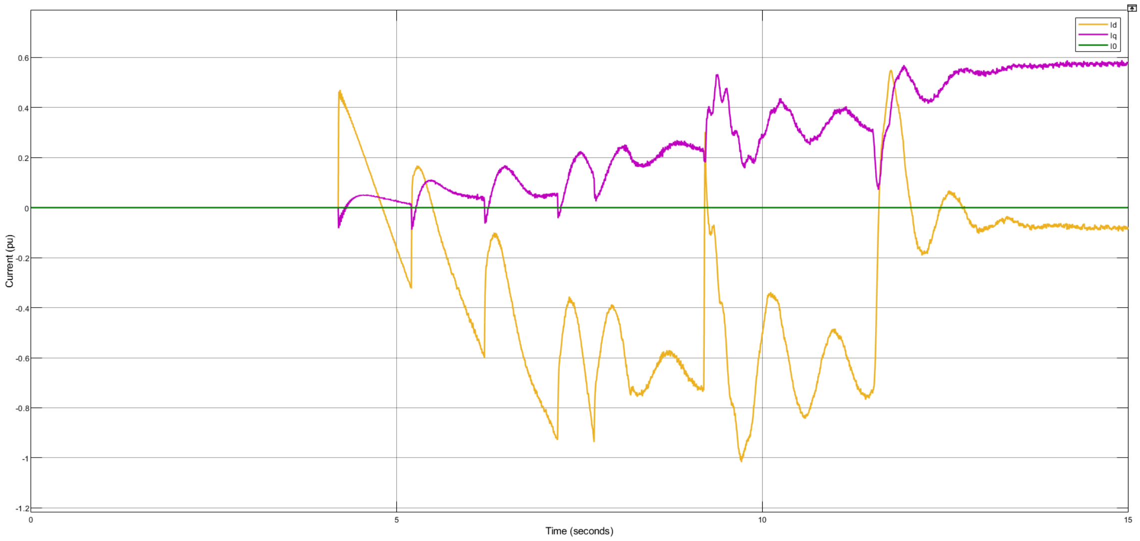

Figure C.4: Currents (pu) measured on the BESS (i_d, i_q, i_0)